

UPCommons

Portal del coneixement obert de la UPC

<http://upcommons.upc.edu/e-prints>

This is an Accepted Manuscript of an article published by Taylor & Francis in *Hydrological Science Journal* on June 2020, available online:
<https://www.tandfonline.com/doi/abs/10.1080/02626667.2020.1784424>

A review of flood impact assessment approaches for underground infrastructures in urban areas: A focus on transport systems.

Edwar Forero-Ortiz^{a,b*}, Eduardo Martínez-Gomariz^{a,b} and Manuel Cañas Porcuna^c

^a CETaqua Water Technology Centre, Barcelona, Spain; ^b Flumen Research Institute, Civil and Environmental Engineering Department, Technical University of Catalonia, Spain; ^c Transports Metropolitans de Barcelona, Projects and Maintenance area, Infrastructure Service, Catalonia, Spain

*Corresponding author. Email: eforero@cetaqua.com, edwar.forero@gmail.com.
Correspondence details: CETaqua. Crtra. d'Esplugues, 75, 08940, Cornellà del Llobregat, Barcelona, Spain

A review of flood impact assessment approaches for underground infrastructures in urban areas: A focus on transport systems.

Flooding events can produce significant disturbances in underground transport systems within urban areas and lead to economic and socioenvironmental well-known consequences, which can be worsened by variations in the occurrence of weather and climate extremes. A better comprehension of these impacts and their conditions is consequently needed. Hence, this paper presents a state-of-the-art literature review on flood impact assessment in metro systems, analysing their purposes and their shortcomings. This document shows the adaptation measures dealing with specific classes of pluvial flood damages, besides identifying prospective paths towards the application of suitable actions facing actual and projected hazards in metro systems worldwide.

Keywords: impact assessment; flood risk; urban pluvial flooding; resilience; hydrodynamic modelling; metro system; subway.

1. Introduction

In the last few decades, there has been a surge of interest in studying how to increase the efficiency, efficacy, value, and sustainability of public urban high capacity transportation systems, due to the noticeable benefits of the implementation of better systems for enhancing the conditions of the urban areas.

This paper aims to provide a comprehensive and systematic review regarding the flood risk assessment in underground transport systems, exploring the impact sources, existing assessment methodologies and current countermeasures, with a special focus on the related impacts of pluvial flooding events.

This article analyzes the data gathered and discusses each one of the identified hydrological hazards threatening Metro systems and examines the results of the literature review and reviews the possible damages due to pluvial flood events on Metro systems.

The adaptation measures chapter presents the adaptation measures that have been implemented worldwide. A discussion and future research directions section provides a logical synthesis of the findings, with a deeper, more profound understanding of the literature review, highlighting the importance of this study help fills existing gaps in the field. The purpose of the closing section is to propose possible improvements to strengthen adaptation measures facing climate change impacts on Metro systems.

2. Methodology

The role of the flood risk assessment in underground transport systems has received increased attention across a few disciplines in recent years, although earlier studies of this topic have been limited to a small number of cases, mainly restricted to Asian Metro systems. To solve this gap, the aim of this research has therefore been to critically review the different approaches used to assess the impact of the flooding events on the Metro systems.

Whilst studies on hydrological hazards on Metro systems are a growing field, to date relatively little research has been carried out on the study of pluvial flooding events affecting Metro systems. It must also be highlighted the importance of lack of studies related to climate change-driven hazards on Metro systems. As indicated in the United Nations Global Assessment Report (GAR) 2019 report (UNDRR 2019), most of the disasters in urban areas worldwide between 1985 and 2015 were caused by hydrological hazards, with the exception of the North American area. The United Nations concludes that localized hazards, including flash floods, urban flooding and other time-specific events, are responsible for extensive damage to infrastructure and livelihoods, representing the highest economic losses and the larger impact to development assets as Metro infrastructure (UNDRR 2019).

Researchers have not treated the hydrological hazards on Metro systems in much detail. Despite the long history of events that have negatively impacted the underground infrastructure of Metro systems around the world, majority of the research studying such risks has been conducted in China and Japan, due to the concurrence of large flood events in major Metro systems such as Shanghai (Deng *et al.* 2016, Huang *et al.* 2017), Osaka (Hamaguchi, Ishigaki, Shimada, *et al.* 2016, Terada *et al.* 2017, Sugimoto *et al.* 2018) and Tokyo, with the world's largest underground flood storage infrastructure (Wu *et al.* 2018a, Grigg 2019).

3. Reviewing hydrological hazards threatening Metro systems

Hazards have regularly affected the performance of Metro systems. Having more extreme and variable weather conditions as an outcome of climate change conditions, the role of creating more sustainable transport systems by mitigating the impacts, and decreasing the severity of the consequences when a disaster occurs, is fast becoming a key instrument in urban planning and disaster risk management (Mal *et al.* 2017) through hydroinformatics applications.

As the most common natural hazard, flooding events describe a severe threat to cities, limiting the recovery capacity of the cities' systems when they are exposed, lowering their resiliency (Batista and Gourbesville 2016). The pluvial flooding episodes of Metro systems around the world are presently recurrent and frequent - the influence of Climate Change is expected to increase the likelihood of extreme rainfall events (Min *et al.* 2011), clearly indicate the importance of considering floods as a major hazard to Metro systems.

This study has examined the peer-reviewed literature on flooding in Metro systems, what follows in Table 1 is a brief overview of the scientific sources written in English

which provide representative findings of this emerging trend. When analysing the data from the literature review regarding pluvial floods impacting on Metro systems, it is possible to remark how all the authors are Southeast Asian origin, which indicates the high degree of interest in this subject from the scientific community of that geographical area. To avoid subjective interpretations, literal extracts are included for each of the parts that make up the studies analyzed.

This is not surprising considering that Guangzhou and Shanghai, two of the most populated cities in the People's Republic of China, have a history of recurrent flooding in their Metro system, which has a high impact on their urban sustainability (Moher et al. 2009, Moreno et al. 2014, Lyu et al. 2016, Li et al. 2018). The historical cases of flooded metro systems go beyond those mentioned above, high-impact events such as those analyzed by Lyu et al (Lyu, Shen, Zhou, et al. 2019) (2019), underline the idea that this problem affects Metro systems at a global level.

Table 1. A comprehensive survey of peer-reviewed studies on flooding in Metro systems

Title / Source / DOI	Aim	Methodology	Results
Modeling of urban flooding including underground space (Herath and Dutta 2004)	This paper reports flood events in underground buildings in Japan in the last three decades and offers a 3D modelling system intended for reproducing urban floods.	A distributed hydrological model coupled to a 1D river network and a coupled 2D diffusive model for the surface flooding was used as a flood model applied to the city of Fukuoka, Japan.	The water volume entering the underground space was obtained and validated, with the overflow over the embankment with the flood wave propagation and heights. The behaviour of the flood event inside the underground system was not evaluated.
Experimental study on evacuation from underground space by using real size models (Ishigaki et al. 2006) - 10.2208/prohe.50.583	This research creates a full-scale stair model with the same specifications as the stairs that connect to an underground mall and metro station, performing an experiment assuming evacuation from the stairs when the underground space was flooded, and used a full-scale door.	An experiment was conducted assuming evacuation to the ground by opening the basement door, and the results of an attempt to quantitatively evaluate the difficulty of evacuation from the underground space are summarized.	Water level limits for flood evacuation events range, for adult men, between 0.41 and 0.43 m, adult women 0.35 and 0.38 m, and for children, between 0.29 and 0.31 m. Taking into account worst conditions at the time of flood events, this upper limit value for the evacuation even at a low water depth can be less than the estimated ones.
Criterion and its application for safety evacuation during underground flooding (Onishi et al. 2008) - 10.2208/prohe.52.841	This study conducted an evacuation experience experiment using a full-scale model to quantitatively evaluate the degree of evacuation difficulty, when the underground space was flooded, using indexes from past studies, to create a new index and assessing its applicability.	This paper assesses the flow velocity and water depth of the passage under the weir condition, and the average walking distance of the subject in the passage obtained from evacuation experiments. The research performs evacuation assessments by inundation depth, by unit width momentum, by unit width specific force, and applies the evacuation difficulty index in flood estimation.	This study shows how understanding the application of specific force is desirable for assessing evacuation challenge when underground space is flooded. Studying the danger points using the specific force provides a more realistic evacuation simulation. With these results, the evacuation supervisor of underground infrastructure can improve an evacuation plan

Title / Source / DOI	Aim	Methodology	Results
Numerical analysis for evacuation possibility from small underground space in urban flood (Yoneyama et al. 2009) - 10.1007/978-3-540-89465-0_21	This research aims to accurately foretell the flooding process befalling in small underground spaces, including staircases through a numerical simulation.	A three-dimensional numerical simulation model with the volume of fluid (VOF) method was applied to a staircase and a small underground space under an urban flood state. The simulated staircase was a full-sized hydraulic model, and the small underground area was a hydraulic model at a 1/15 scale.	The numerical simulation model could be implemented to the staircase throughout urban flooding events, besides the results concerning the small underground space are coincidental with the experimental outcome.
Assessment of safety on evacuating route during underground flooding (Ishigaki et al. 2009) - 10.1007/978-3-540-89465-0_27	This research discussed the method of safety assessment on the evacuating route based on experimental outcomes and flood simulation data in an underground space.	Applying the relationship between the specific force values per unit width and the evacuation speed, the evaluation of the safety of the evacuation routes when the underground flooding occurs was obtained, and the data were obtained to improve the evacuation plan.	The safety assessment of the evacuation routes was assessed using the calculated water depth and the flow velocity of the flood applying a 2D model of shallow flow and the relationship between the specific force, with the evacuation velocity also being obtained based on the evacuation tests.
Underground inundation analysis by integrated urban flood model (Toda et al. 2009) - 10.1007/978-3-540-89465-0_31	This study developed an integrated urban flood model which can predict both surface and underground inundation due to heavy rainfall.	An integrated horizontally two-dimensional unsteady flow model with unstructured meshes is applied for the land surface for Kobe City, one of the large cities in Japan. The risk of underground flood there due to heavy rainfall is studied in detail and effect of setting steps at the entrance is discussed.	This research found that setting of steps at each entrance is one of the effective measures to reduce the risk at underground inundation.
Inundation risk assessment of underground spaces in the downtown of Fukuoka City, Japan (Hashimoto and Park 2010) - 10.2495/FRIAR100131	The purpose of the present study is to investigate the use and characteristics of the underground spaces and to develop an inundation risk assessment method of underground spaces.	The floodwater behaviour the two types of underground spaces is simulated. Then, based on the simulation, a method for risk assessment of inundation of underground spaces due to a flood event is proposed.	Inflow water volume, inflow discharge and inflow time for filling the underground space with the flood water are important parameters for the inundation risk assessment of small-scale underground spaces. Flood flow depth and

Title / Source / DOI	Aim	Methodology	Results
			velocity at any position are important parameters for the inundation risk assessment of large-scale underground spaces.
Evacuation of aged persons from inundated underground space (Ishigaki et al. 2010) – 10.2166/wst.2010.455	This study presents a method of assessing the safety of aged people in the event of flooding in an underground space.	Safety assessment on two varieties of evacuation ways was done by using modelled water depth and flow velocity of inundation by a 2D shallow flow model, the relation between the specific force and evacuation speed were analyzed.	The safe evacuation of the aged people turns unlikely at short times during underground flooding if water depth rapidly rises to 1 metre.
Vitae system based agent modeling and simulation of survivability-critical evacuation in underground flooding (Liu et al. 2010) - 10.1109/ICSMC.2010.5641730	The authors of this study build on a previous publication (Liu et al. 2009) in which they developed a preliminary model in the context of evacuation to deal with a water-related hazard to underground space.	This research develops a "Vitae System" model as a systematic framework for the adaptive evacuation plan in a critical state by the synthesis of three key factors as survivability, vitality, and communication.	This study presents a model with a new outlook to the evacuation simulation, particularly in survivability-critical state. The combination of three functions in "Vitae System" aids to evaluate the evacuation procedure for hazards counting but not restricted to an underground flood scenario.
Risk assessment of rainstorm waterlogging on subway in central urban area of Shanghai, China based on scenario simulation (Quan et al. 2011) - 10.1109/GeoInformatics.2011.5981176	This paper examined and assessed the waterlogging risk of the metro system in the central urban area of Shanghai, China.	A simplified urban waterlogging model was employed to reproduce flooding events in the main area of Shanghai, overflowing evacuation routes of metro stations in three different scenarios. The waterlogging risk on the metro was evaluated based on waterlogging induced frequency.	The assessment process did not take rainfall water depth in metro station exits into account, which would affect the losses estimation caused by rainfall waterlogging and the accuracy of risk assessment to a certain level.
Safety evacuation from underground mall during urban flooding (Inoue et al. 2011) - 10.2208/jscejhe.67.I_973	In past urban floods in Kyoto City, there have been cases where evacuation from underground spaces was delayed and human lives were lost. To	It was performed a numerical analysis using a storage tank model made of acrylic and apply the analysis to inundation analysis of underground spaces, considering	The outcomes present that flooding processes and safety of evacuation are quite different in the two evaluated cases, with and without the consideration of drainage system. The inflow

Title / Source / DOI	Aim	Methodology	Results
	<p>solve such problems, studies on inundation analysis and evacuation of underground spaces have been conducted, targeting the Oike underground shopping area.</p>	<p>the evacuation potential of flat and stairs when assessing evacuation from underground shopping malls.</p>	<p>conditions into underground spaces are related to calculation results of rainwater flooding.</p>
<p>Effects of counter measures for reducing underground inundation caused by pluvial flooding (Morikane et al. 2012) - 10.2208/jscejhe.68.i_1003</p>	<p>This paper evaluates the difference in evacuation risk due to the difference in occurrence times between daytime and night-time by performing evaluations in the case of large underground spaces, passages, stores, and metro underground stations. Also, they consider the difference in measures against flooding in an underground space was evaluated in terms of the damage amount.</p>	<p>This paper modelled pluvial and underground flooding by InfoWorks CS software in a mega-underground mall, using the shallow flow model with a structural mesh. Countermeasures effects for decreasing underground flood were studied with the criteria of safe evacuation obtained by some previous evacuation tests.</p>	<p>The main results obtained by this study indicates that developing an evacuation plan should have in consideration the variations between metro systems and malls, due to the size of the infrastructure, and among business hours and time out. By intensively stopping the water at the underground dangerous entry site, the reduction in the strength of unit width ratios during underground flooding is confirmed as a measure to reduce the impacts of flooding in the evacuation phases.</p>
<p>Characteristics of underground mall inundation by flush flood in short time heavy rainfall (Ozaki et al. 2014) - 10.2208/jscejhe.70.I_1417</p>	<p>The purpose of this research was to analyze inundation events on underground infrastructure using three types of model torrential rains, analysing the inflow points from the ground to the underground, the amount of inflow and the current infrastructure. The study also proposed and assessed flood control measures that caused expansion or worsening of the flood control.</p>	<p>This research applied three types of model heavy rain and inundation characteristics due to the difference in rainfall. Also, based on the simulation results, the study examined the points that should be considered when underground mall managers formulate flood control and evacuation plans for inland flooding due to short-term torrential rain.</p>	<p>This research found that inflow volume, the start time of inflow and velocity spread are quite different in the three cases, but the location of inflow is almost the same. These results showed that, regarding countermeasures, there should have a quick response to the flush flood by high-intensity rainfall.</p>

Title / Source / DOI	Aim	Methodology	Results
Analysis and GIS mapping of flooding hazards on 10 May 2016, Guangzhou, China (Lyu et al. 2016) – 10.3390/w8100447	This article adopted a Geographic Information System to analyze the influencing factors of a flood event, as well as to map the effect of the metro system using the Multiple Buffer operator on the flood distribution area.	A rainfall analysis of different suburban areas because of the floods of 10 May 2016 was conducted analysing flood-prone areas and the flooding of the metro system.	In the event of 10 May 2016, metro line 6 in Guangzhou, China was flooded because of its low altitude in comparison with the city centre. Areas with metro lines were more vulnerable to flooding, suggesting an adjustment of the severity of flooding hazards standard.
Study on vulnerability of mega-underground space to extreme flood (Hamaguchi, Ishigaki, Ozaki, et al. 2016) - 10.2208/jscejhe.72.i_1363	The purpose of this study was to understand how and where floodwater propagates and at what point in large-scale underground space and to examine the vulnerability of large-scale underground space to flooding.	In this study, InfoWorks CS was applied for the flood analysis of the water-sewer network and the ground flow being calculated simultaneously, the analysis method of the ground part was the dimensional shallow water flow model.	The paper found that up to 60% of flooded water intrudes into underground spaces if no countermeasures were taken. Inundation depth and area in the underground shopping mall are different in the four types of extreme floods, and the flooded water enters connected metro stations. This means that administrators of underground space must make different countermeasures for each type of extreme floods.
Experimental studies on safety evacuation from underground spaces under inundated situations (Baba et al. 2017) - 10.2208/journalofjsce.5.1_269	This paper presents experimental results of evacuation tests from underground spaces under flooded conditions.	The challenges of evacuation from underground spaces were studied by applying three real-scale models (a car, a door, and a staircase), and the limits for safety evacuation are discussed.	The paper found that water depth of 0.3 – 0.4m would be a risky condition for safety evacuation through staircases and doors, while water levels of 0.7 – 0.8m would represent a critical state for safety evacuation through the doors of a car.
Cooperative survival principles for underground flooding: Vitae System based multi-agent simulation (Higo et	This research provides survival principles through a novel evacuation-simulation model with survivability-critical states, comparing three strategies of evacuation and rescue behaviours.	A simulation model was implemented to an underground flooding scenario, three evacuation and rescue approaches in life-threatening conditions are	This study provides a new perspective for extreme disaster events adopting a new evacuation simulation model. This model can match as a tool to analyse how to protect lives

Title / Source / DOI	Aim	Methodology	Results
al. 2017) 10.1016/j.eswa.2017.04.034	-	simulated and analysed with each other contingent on the evacuation outputs.	even after original evacuation schemes are cancelled by extreme hazards.
Application of Bayesian approach to dynamic assessment of flood in urban underground spaces (Wu et al. 2018b)	This paper uses the Delphi method to define the Bayesian conditional probabilities as an integrated Bayesian Network for assessing the flood progression and consequences in underground spaces.	The suggested Bayesian Network framework can describe the flood disaster operators, carriers, flood mitigation actions, and on-site feedback data. The risk pattern of expected flood scenarios can be quantitatively estimated.	The suggested framework can assess underground flood development process and recognize the significant influencing factors, supporting the decisionmakers related to flood disaster emergency response.
Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach (Lyu et al. 2018) – 10.1016/j.scitotenv.2018.01.138	By means of the analytic hierarchy process (AHP) and the interval AHP (I-AHP) methods, the flood risk in the Guangzhou metro system is assessed.	The flood risk assessment used two components: the assessment index structure, and different input factors. To set a consistent weight for each factor, the AHP and I-AHP methods were adopted to assess the relative importance of the variables. The weight of each assessment factor was incorporated into the GIS to get the regional flood risk.	More than 50% of Guangzhou's metro lines are highly exposed to flood risk. Comparisons between the AHP and I-AHP results revealed that the I-AHP method offers a broader range of high flood risk than the AHP method.
The potential effect of a 100-year pluvial flood event on metro accessibility and ridership: A case study of central Shanghai, China (Li et al. 2018) - 10.1016/j.apgeog.2018.09.001	Applying a gravity-based approach to estimate the potential effect of a 100-year flood on accessibility and ridership, this paper studies ridership conditions on metro stations under extreme flooding events.	Accessibility to metro stations was estimated through three impedance functions (inverse power, negative exponential, and modified Gaussian) by three access modes (walking, cycling, and driving), during road floods surrounding the entrances.	Flood levels obtained in modelling processes between 0.1 and 0.2 m were determined on 95% of roads for the most likely flood scenario, and water levels between 0.2 and 0.3 m reached 47% and 15% of streets respectively, forcing significant constraints on access to metro stations, especially when cycling and driving to accesses when undergoing flood events.

Title / Source / DOI	Aim	Methodology	Results
Inundation Risk Assessment of Underground Space Using Consequence-Probability Matrix (Han et al. 2019) - 10.3390/app9061196	Through considering both flood intensity and evacuation difficulty, a methodology for assessing the risk level in flooding events is evaluated, employing a 2D hydraulic flow model, and the flood intensity.	The risk analysis process studied the level of evacuation complexity, the walking speed, and the spatial layout of rooms. Under the scenario with stormwater runoff entering an underground space, zones far away from the inlet regularly would have low-risk levels.	The methodology proposed by the study along with a flooding model can be applied to any underground space regardless of the location of stairs, the number of exits, shape of rooms, or layout of the floor, contributing to alleviating flood damage.
Scenario-based inundation analysis of metro systems: a case study in Shanghai (Lyu, Shen, Yang, et al. 2019) - 10.5194/hess-2019-28	To assess flood risk at Shanghai metro stations, this study proposes an integrated algorithm that combines a rainwater management model with a geographic information system. Flood risk is only assessed in the proximity of metro stations.	The flood risk modelling in the centre of Shanghai under 50, 100, and 500-year scenarios were performed, bearing in mind the flood proximity, extend and water depth near to the metro stations. The proposed method was verified by checking from the records of historical floods, for the potential inundation depth around the metro stations.	The results of the study relate extreme precipitation scenarios, the flooded area and the potential inundation depth around the metro stations under different scenarios simulating the overland flow on the ground surface.
Perspectives for flood risk assessment and management for mega-city metro system (Lyu, Shen, Zhou, et al. 2019) – 10.1016/j.tust.2018.10.019	A summary of the risk assessment methods for the flood of metro systems depend on four types of regional flood risk assessment techniques is presented in this document.	The study uses the metro system in Guangzhou, China to apply the methods for flood risk assessment. The risk prevention scheme employs an iterative cycle that involves risk assessment, forethought, forecast, and technological countermeasures.	The paper proposed an integrated approach integrating GIS, GPS and BIM systems developing early warning and risk management operations, to handle flooding risk in metro systems.

Gonzva *et al* (Gonzva *et al.* 2017) mentions the special situation of the Prague metro system as an example of a complete Metro system flooded for several months, caused by over a week of continuous heavy rainfall events in 2002. The single most striking observation to emerge from the flood event was not linked to the risk assessment and protection of the Metro system, despite the economic and social losses that triggered this natural event in the city's population.

Important studies have been discarded concerning pluvial floods in Metro systems in Japan, which has suffered large flood events in the Metro systems of Osaka and Fukuoka cities (Herath and Dutta 2004, Hashimoto and Nonaka 2012, Terada *et al.* 2017) drawing the attention of some researchers who, unfortunately, have published their studies only in Japanese language (Sugimoto *et al.* 2018). Despite this linguistic restriction, these studies are presented and analyzed in this paper; they are key studies reporting full-scale testing of subjects evacuating flooded underground spaces, which provide basic parameters for any numerical or agent-based flooding underground spaces simulation.

Peer-reviewed articles of the hazards generated by pluvial floods in Metro systems are of a very mixed nature and, each of them uses a different methodology to tackle the problem posed, which makes it difficult to compare them directly. Tables 2 to 5 are pretended to critically present the different approaches used to assess these hazards considered in the cited literature review, identifying key components in peer-reviewed papers for embodiment into future studies of pluvial flooding in Metro systems.

Table 2. Identification of key components in peer-reviewed papers for Flood Modelling category

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
Modeling of urban flooding including underground space (Herath and Dutta 2004)	This paper presents for the first time the application of the digital surface elevation model (DSM) is used instead of DEM, which improved the accuracy of the flood simulation. The study used a coupled 1D-2D model considering five main components of the hydrological cycle: Interception and evapotranspiration, river flow, overland flow, unsaturated zone flow and saturated zone flow; working with the locations and dimensions of hydraulic access to the underground space were defined for assessing the flow into the facilities.	An important conclusion of the simulation of pluvial/fluviol flooding in underground spaces considers that the risks are increased when the available water dispersal area is smaller, so the importance of the interconnection of underground spaces that allow the water depth and velocity in flood events to decrease is emphasized.
Underground inundation analysis by integrated urban flood model (Toda et al. 2009) - 10.1007/978-3-540-89465-0_31	The methodology applied in this study integrates the basic steps in the analysis of an underground infrastructure flood, counting a scheme to assess the influence of increased step heights in water access points throughout flood events.	Through the application of the model developed in the study, it is plausible to foretell the risk of underground flood by heavy rainfall or overflow from a river, in a more practical way than usual. Nevertheless, the article is not enough detailed to reproduce the outcomes.
Characteristics of underground mall inundation by flush flood in short time heavy rainfall (Ozaki et al. 2014) - 10.2208/jscejhe.70.I_1417	This research discussed flood measures for short torrential rains in an underground shopping centre; mall administrator and constructors can improve flood-evacuation planning schemes and times with this methodology.	Based on the flood analysis of the underground shopping mall, this study defined the floodwater scope and depth, also some countermeasures applied to the vulnerable spots in the underground shopping mall and its structure were projected.
Analysis and GIS mapping of flooding hazards on 10 May 2016, Guangzhou, China (Lyu et al. 2016) – 10.3390/w8100447	This article associates for the first time a record of previous rainfall flooding events by and performs a hazard analysis for a previous flood	It outlines how topographic characteristics are critical criteria for the temporal and spatial distribution of floods in Metro systems and establishes whereby the existence of

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
	event, considering the increase in rainfall due to the Climate Change influence.	flood-prone areas is intimately related to the impact of flood events, so protective measures should focus on such areas.
The potential effect of a 100-year pluvial flood event on metro accessibility and ridership: A case study of central Shanghai, China (Li et al. 2018) - 10.1016/j.apgeog.2018.09.001	This study analyses the approachability of metro stations, but only up to their entrance it does not carry out an analysis of accessibility inside the Metro system, but outside the access, ways to reach the halls of the stations.	Due to the great user's bottleneck episodes manifested in the Shanghai Metro, being the most used Metro system in the world, the preliminary accessibility results of this study give an idea of the complex dynamics of the influence of flooding at the surface level of the accesses of a Metro system.
Scenario-based inundation analysis of metro systems: a case study in Shanghai (Lyu, Shen, Yang, et al. 2019) - 10.5194/hess-2019-28	The article proposed an approach to projecting the flooding risk on a metro system on a regional scale by integrating SWMM model into a GIS framework to simulate the overland flow, estimating the surface flooding depth in the surrounding areas to the entrance of a metro station.	An equation is determined relating the water depth during flooding nearby the metro station, the surface water depth, a criterion of the drainage capacity of the metro station and the configuration of the access gradient to the station under examination.

Table 3. Identification of key components in peer-reviewed papers for Evacuation category

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
Experimental study on evacuation from underground space by using real size models (Ishigaki et al. 2006) - 10.2208/prohe.50.583	This research created a full-scale stair model with the same specifications as the stairs that connect to an underground mall and metro station, performed an experiment assuming evacuation from the stairs when the underground space was flooded, and used a full-scale door.	An experiment was conducted assuming evacuation to the ground by opening the basement door, and the results of an attempt to quantitatively evaluate the difficulty of evacuation from the underground space are summarized.
Criterion and its application for safety evacuation during underground flooding (Onishi et al. 2008) - 10.2208/prohe.52.841	This study added evacuation experience to the existing experiment contents from previous research and added conditions such as waterfilled condition by wearing	This study indicates that by applying the evaluation index using a specific force to calculate flooding extent and characteristics, the magnitude of the evacuation difficulty at each point can be accurately assessed.

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
	and conducted an evacuation experience experiment from the viewpoint of the passageway.	
Numerical analysis for evacuation possibility from small underground space in urban flood (Yoneyama et al. 2009) - 10.1007/978-3-540-89465-0_21	This research develops an innovative numerical model to a flood flow in a small underground space, supporting the model by contrasting the calculated data with the experimental outcomes	The developed model by this study can be efficiently adopted to assess the evacuation feasibility by analysing the estimated water depths with the indexes gained from the physical appraisal in underground spaces.
Assessment of safety on evacuating route during underground flooding (Ishigaki et al. 2009) - 10.1007/978-3-540-89465-0_27	Two sorts of evacuation experiment were carried out, the first was through a staircase real-size model, and the other was a walking test through a corridor model. In this paper, the water depth and flow velocity are determined by a two-dimensional shallow flow model as a novel.	According to the outcomes of this paper, the safety of evacuating route can be determined by the stated methodology in this research, suggesting that people could abandon from underground spaces as soon as conceivable.
Evacuation of aged persons from inundated underground space (Ishigaki et al. 2010) – 10.2166/wst.2010.455	This study handles the subject of the stability of aged persons under flood conditions in underground spaces and uses as a primary example a Metro station. This study also embodies some similar studies by similar authors in which they examine the stability of people under the same conditions.	The methodology of this study incorporates stability criteria to set the risk level of people under flood events in Metro systems, together with a study of the practical feasibility of the evacuation routes to be used. This approach makes it possible to define that the evacuation speed of ridership is particularly important as an element of this adaptation measure in the face of such flood events.
Vitae system based agent modeling and simulation of survivability-critical evacuation in underground flooding (Liu et al. 2010) - 10.1109/ICSMC.2010.5641730	This research involves people's natural capacity to react promptly to an external hazard in the setting of disaster evacuation. It presents systematic logic for defining a particular kind of evacuation decision-making in such a decisive circumstance that people have to endure first for a relatively short period of time.	The results describe the influence of the facilities physical arrangement on the evacuation decision-making. The simulation outcomes are contingent on certain conditions, changes in the number of evacuees, people distribution, various flood processes, can modify the results.

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
Safety evacuation from underground mall during urban flooding (Inoue et al. 2011) - 10.2208/jscejhe.67.1_973	This study uses the InfoWorks CS software and its stormwater drainage modelling capabilities, running the analysis of a flood relating the influx of people in the flooded underground space, as well as comparing the forces of the water in the flood event, with the strength of the flow width relationships found in previous studies, referenced in this paper.	This research identified critical spots in a large-scale underground shopping mall during flooding at intervals. Based on the results of the analysis, the study defined guides to be considered in evacuation planning for instance, the evacuation process until inundation starts is imperative and must be done in a short time.
Cooperative survival principles for underground flooding: Vitae System based multi-agent simulation (Higo <i>et al.</i> 2017) - 10.1016/j.eswa.2017.04.034	This research frames an improvement and notable development of earlier studies by the same authors and other ones, including this one (Higo and Okada 2012). According to this study, a pragmatic strategy for producing a more efficient model is to enhance the algorithms, following the KISS principle.	This research involves people's natural capacity to react promptly to an external hazard in the setting of disaster evacuation. It presents systematic logic for defining a particular kind of evacuation decision-making in such a decisive circumstance that people have to endure first for a relatively short period of time.
Experimental studies on safety evacuation from underground spaces under inundated situations (Baba et al. 2017) - 10.2208/journalofjsce.5.1_269	This study employs three real-scale models of a door, staircase, and a car, to experimentally assess the difficulty and limitation of safety evacuation. The relationship connecting the critical water depth conditions and the subjects' age is considered based on the test models results by subjects' gender.	The experimental outcomes determine that a water level of 0.3–0.4m would be a perilous condition for the safe evacuation by staircases and doors and that a water level of 0.7–0.8m would be a critical condition for the safe escape through car doors.

Table 4. Identification of key components in peer-reviewed papers for Vulnerability and Risk Assessment category

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
Inundation risk assessment of underground spaces in the downtown of Fukuoka City, Japan (Hashimoto and Park 2010) - 10.2495/FRIAR100131	A flood risk index is proposed for each type of underground space. Flood volume and time to fill small-scale underground space with water are determined for a time-varying flood flow depth at ground level inlets.	The depth and velocity of water flow at any location are relevant parameters for assessing the risk of flooding of large-scale underground spaces.
Risk assessment of rainstorm waterlogging on subway in central urban area of Shanghai, China based on	This paper is one of the first attempts to analyze pluvial flooding in a metro station by determining the waterlogging risk and extrapolating this risk to the entire Metro line, creating a risk criterion for waterlogging users for each exit of each station.	This research concludes that changing the probability of flood events affecting the Metro is challenging, to reduce the

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
scenario simulation (Quan et al. 2011) - 10.1109/GeoInformatics.2011.5981176		waterlogging risk, it is necessary to reduce the vulnerability or exposure of the components that may be affected.
Study on vulnerability of mega-underground space to extreme flood (Hamaguchi, Ishigaki, Ozaki, et al. 2016) - 10.2208/jscejhe.72.i_1363	This research studies the flood characteristics for each external force, that differ for each water hazard event, and to define specific safety evacuation methods and policies for disaster prevention and mitigation.	The trajectory of the flood varies according to the external force, so adaptation measures to avoid flash floods are now essential for indoor floods. Understanding the outcomes of this research, by introducing a water stop screen at a water inlet with a considerable risk of flooding, water inflow in the underground space can be decreased.
Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach (Lyu et al. 2018) – 10.1016/j.scitotenv.2018.01.138	Another approach using mathematical theories as the Analytic Hierarchy Process is applied in this study. After defining the weight of each assessment factor, the regional flood risk is mapped incorporating not only the hazard, exposure, and vulnerability indexes, moreover, various input factors as the topology of the metro lines.	According to the study, the flood risk criterion of the metro system is related to the surface flood risk of an area with a range of 500 m around the metro lines. The entrance of water into the Metro system is not evaluated itself, only the risk of regional flooding at the surface level.
Inundation Risk Assessment of Underground Space Using Consequence-Probability Matrix (Han et al. 2019) - 10.3390/app9061196	By means of the consequences of floods and the probability of risk as factors for the calculation of risk, the concept of flood intensity is defined as the criterion for establishing the damage, and the complexity of evacuation as part of the risk associated with flooding. This criterion, used in conjunction with the difficulty of ridership clearance, configures the flood risk calculation matrix. The study estimated the flood risk from an input flood depth of 1.0 m, based on the level of evacuation difficulty of each analyzed zone.	This research indicates how the areas closest to the water inlets are those with the greatest risk to Metro users, being affected by the stormwater runoff and the level of evacuation difficulty as the principal factors of flood risk. The importance of having fast evacuation schemes for hard evacuation zones or located near the water inlets of the system is highlighted.

Table 5. Identification of key components in peer-reviewed papers for Adaptation Measures category

Title / Source / DOI	Distinguishing and innovative features in its methodology	Relevant outputs to a future research proposal
Perspectives for flood risk assessment and management for mega-city metro system (Lyu, Shen, Zhou, et al. 2019) – 10.1016/j.tust.2018.10.019	This article is a more advanced development of a previous paper conducted by the principal researcher (Lyu et al. 2018). This research summarizes the main flood assessment developments in metro systems based on regional flood risk methods and integrates added information concerning BIM in the analysis of flood risks around Metro systems.	Two classes of methods are contrasted to estimate flood risks in underground infrastructure, opening, evaluating water depth levels at 500 meters around the metro system entrances, and following, qualitatively and then quantitatively predicting flood scenarios. Some countermeasures are detailed to face water entry into metro stations, including early warning and risk management systems.
Effects of counter measures for reducing underground inundation caused by pluvial flooding (Morikane et al. 2012) - 10.2208/jscejhe.68.i_1003	The stormwater runoff model was set to carry out the flooding analysis, both storm and sanitary sewer and for surface runoff at the same time, due to the characteristics of the water entry points into the underground space.	This study presents how when the flood befalls outside the business hours of an underground shopping mall, the water depth would be higher than during the business hours, and the evacuation risk increases.
Application of Bayesian approach to dynamic assessment of flood in urban underground spaces (Wu et al. 2018b)	A defined framework is applied to use eleven identified basic variables to create a Bayesian network of causes and consequences of flooding in underground spaces, according to their distribution of probabilities and managing their combinations together with adaptation measures for each scenario. These adaptation measures are then integrated into the network model to identify their effectiveness.	The estimated probabilities of each scene change dramatically according to the factors causing the flood, i.e. if the causative factor is an extreme precipitation event such as in our case of interest, the probability of damage function is quite different from the damage caused by a dam failure.

4. Contextualizing floods impacts on metro

As Messner and Meyer (Messner and Meyer 2006) indicated, in flood risk management it is possible to catalogue the types of flood damage, which can be:

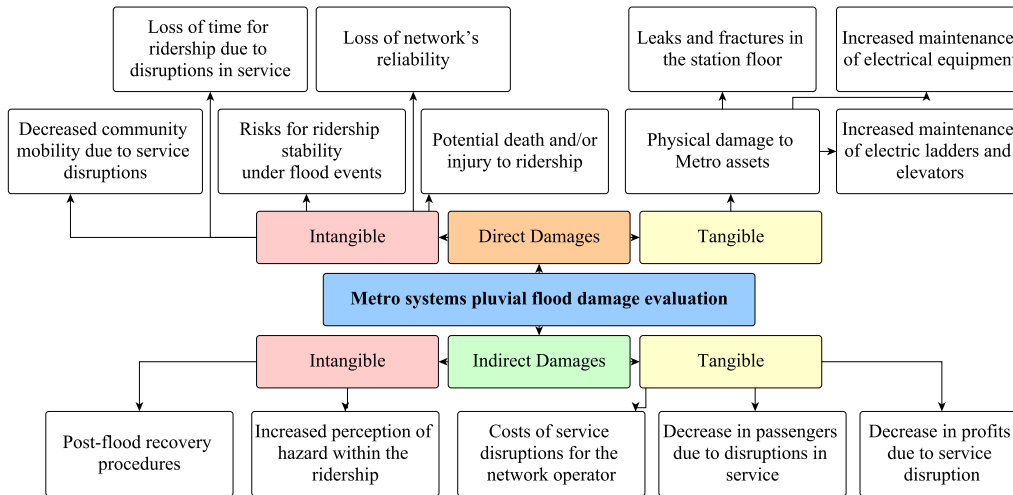
- (1) Direct and tangible damage: is caused by the direct contact of the flood water with infrastructure or goods and which can be interpreted in economic terms.
- (2) Direct and intangible damage: impacts not traded in a market are far more difficult to assess in monetary terms, which have been caused by the direct action of the flood.
- (3) Indirect and tangible damage, when some activity is disrupted due to the flood event, it is possible to describe it in monetary terms.
- (4) Indirect and intangible damage, when some activity is interrupted due to the flood event, but it is not possible to interpret it in monetary terms.

Relating a hazards compendium threatening underground transport systems (Forero-Ortiz and Martínez-Gomariz 2020), there are damages that are not directly referenced in the diverse researches carried out on the potential damages as secondary consequences of flood events, such as feasible human deaths or injuries (Penning-Rowsell *et al.* 2005).

In accordance with the review of damages due to flooding events, Figure 1 specifies the category of possible damages that may occur in a pluvial flooding event on a Metro system. Floods are the most devastating of natural hazards and produce the highest number of deaths. Most of the death and injuries are prompted by a flood or storm that befalls within a few hours subsequent the rainfall event starts. The major deaths throughout flooding are due to drowning, but later deaths are because of various injuries (Şen 2017). Therefore, it should be considered in the context of this study as a

discussion point that sits above the flood damages.

Figure 1. Categories of possible damages due to pluvial flood events on underground Metro systems.



To our knowledge, this research did not find evidence of studies that directly analyze the potential deaths or injuries to users or riders of underground transport systems, or in underground infrastructures due to floods, or of a pluvial nature or any other flood modality, in fact, the available knowledge in the academic literature on the loss of life due to floods is relatively insufficient (Jonkman and Vrijling 2008). Though, there are a wide variety of studies that validate the exceptional importance of loss of life and injuries due to flood events, in a general context.

As intangible losses that are impossible to measure with monetary value, the loss of life and injury to users are significantly influenced by the depth and extent of the flood (Dewan 2013), two conditions relevant to underground flooding. Global population growth increasing accelerated urbanization in flood-prone areas, provoking the need for reliable transportation systems as metro and the weak development of sustainable flood-control policies, will raise floods impacts on underground infrastructure (Jonkman 2005, Forero-Ortiz and Martínez-Gomariz 2020).

The economic impacts of flood events on Metro systems are not publicly accessible, moreover, the available information is based on estimations from expert authors, or from economic studies incidental to the main purpose of assessing flood damage at the urban level. The estimation of indirect and intangible impacts falls even further behind direct and tangible damages estimation assessments, despite their importance. Without a correct estimation of these damages, it is not possible to appropriately evaluate the effectiveness of the risk reduction measures that may be adopted in Metro systems to face pluvial floods.

Although there is research on assessing financial losses due to pluvial flood events (Joseph *et al.* 2014, Jenkins *et al.* 2016, Ke *et al.* 2016, Yang *et al.* 2018), all these approaches take into account only the damage to property and buildings in a general context, and not focusing on the infrastructure and service of the Metro system in the cities where these studies have been carried out. The costs related to the loss of human life and injuries due to flood events, since it depicts a significant challenge its accurate quantification, have not been appropriately studied, remains as the source of the most relevant losses at the economic and social level.

To examine this issue, Sassi *et al.* (Sassi *et al.* 2019) (2019) indicate that despite the existence of methodologies and frameworks for addressing the problem of estimating damages and costs for events of this nature, there is an important uncertainty on the conceivable impacts of climate change-driven events on the economic damages linked with pluvial floods. Furthermore, there is no acquiescence still encompassing the degree and spatial distribution of variation of the economic losses in these cases.

One of the most representative cases of flood damage to a Metro system was caused by Hurricane Sandy in 2012 over New York City, with US\$ 4,755 billion worth of damage

caused mainly by the temporary increase in sea level due to the influence of the hurricane (MTA New York 2012). Unfortunately, this data is not representative for this literature review, because it focuses on floods of strictly pluvial origin. Despite the existence of extreme flood events of pluvial origin in Metro systems around the world, it was not possible to find valid damage estimation data only for underground transport systems.

5. Adaptation measures

Within an integrated flood risk management approach, it is possible to describe resilient measures as structural and non-structural. Non-structural measures aim to maintain the safety of people through the proper management of urban development without physical intervention, and structural measures focus on reducing the risk of flooding by controlling the water flow into vulnerable areas. A successful strategy would combine both of adaptation measures.(Jha *et al.* 2012).

Figure 2 presents a summary of the current adaptation measures applied in Metro systems facing the pluvial flooding events. A total of 18 adaptation measures were taken from five sources listed below. Most of these adaptation measures currently used to prevent flooding in metro systems are currently installed in systems in Japan, mostly in Tokyo (Japan Metro Association 2013), and in New York.

One adaptation measure used in all metro systems worldwide are drainage and pumping systems, due to the influence of the water table on virtually all underground metro systems globally. The contribution of the adaptation measures facing flooding in Metro systems has received little attention by academic researchers. No known empirical research has focused on exploring relationships between the implementation of adaptation measures aiming to manage flooding risks to an acceptable level, and the

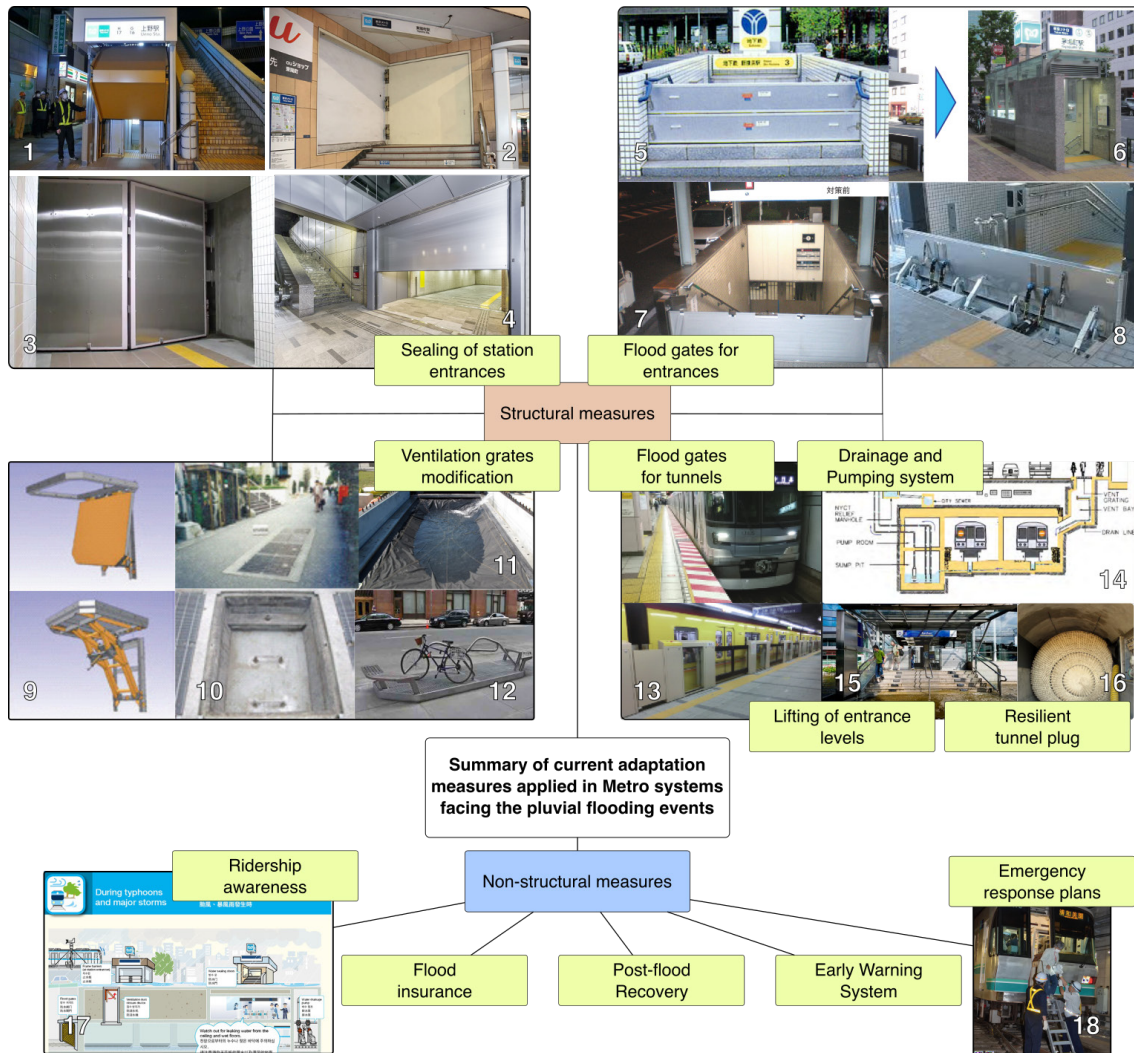
growing interest in measuring, monitoring, and evaluating how these adaptations are economically sustainable.

Table 6. Summary of current adaptation measures applied in Metro systems facing the pluvial flooding events.

<i>ID (Figure 2)</i>	<i>Name</i>	<i>Source</i>
Classification of adaptation measures: Structural adaptation measures		
1	Anti-flood collapsible gate for entrance	(Uchida 2018)
2	Waterproof cross-section door to enter the Metro station	(Tokyo Subway Co Ltd. 2007)
3	Double-opening foldable waterproof door in station access tunnel	(Tokyo Subway Co Ltd. 2007)
4	Waterproof motorized panel shutter	(Sanwa 2018)
5	Removable waterproof board (small opening type)	(Sanwa 2018)
6	Increase in elevation of side walls in accesses	(Sanwa 2018)
7	Leaf type waterproof board (straight type)	(Sanwa 2018)
8	Retractable waterproof panel (manual hydraulic pump type)	(Sanwa 2018)
9	Water immersion prevention machine for vents	(Tōkyō metoro 2014)
10	Flood prevention machine for breathing vents	(Uchida 2018)
11	Big sheet of waterproof fabric designed to cover subway entrances and keep the water out	(Cities Project - NPR 2015)
12	Raised ventilation grates	(Metropolitan Transportation Authority/Rob Wilson 2008)
13	Waterproof gate along the metro station avoiding tunnel flooding	(Uchida 2018)
14	Typical metro drainage and pumping system	(Metropolitan Transportation Authority/Rob Wilson 2008)
15	Lifting of entrance levels	(Tokyo Subway Co Ltd. 2007)
16	Resilient entrance tunnel plug	(Cities Project - NPR 2015)
Classification of adaptation measures: Non-structural adaptation measures		
17	Ridership awareness publications	(Tōkyō metoro 2014)

<i>ID (Figure 2)</i>	<i>Name</i>	<i>Source</i>
18	Flooding emergency response plan and execution	(Tōkyō metoro 2014)

Figure 2. Summary of current adaptation measures applied in Metro systems facing the pluvial flooding events.



6. Discussion and future research directions

Thus far, previous studies attempted to evaluate the impact of pluvial flooding on Metro systems traditionally adopting functionalist perspectives relied upon the existence of flood-prone areas is intimately related to the impact of flood events, focused only in the surrounding surface areas of the metro station accesses. Preceding studies have failed to show any consistent association between the hydraulic

characteristics of the pluvial flood events modelled, and the water flow that enters the Metro systems evaluated.

In recent years, factors linking water depth around a metro station to the risk of flooding of metro lines have been highlighted through a mathematical approach (Lyu, Shen, Yang, *et al.* 2019). However, this review found evidence that no previous study has given sufficient consideration to the increase in rainfall at the urban level due to the effects of Climate Change, and its direct effect on the increase in vulnerability of Metro systems at the local, regional and global levels (Madsen *et al.* 2014).

Researchers have not treated minimum operating conditions of metro systems, i.e. service limits, nor the ease of evacuation of stations during rain-flood events, these topics have been analyzed in-depth. Without defining these service thresholds with respect to the ability of trains to operate under flood conditions, it is also not possible to define the effectiveness of adaptation measures, nor how the application of such measures positively or negatively affects the vulnerability related to the operation of the system under flood conditions, not only pluvial-driven one. No study has specified at least one approach to establish the impact of adaptation measures on the reduction of hazards associated with rainwater flooding in Metro systems. This discussion raises the importance of separating the issues of passengers/riders' safety criteria from the service limits for infrastructure

Due to the inherent variability of climatic circumstances especially for long time horizons, many of the adaptation measures are not being considered for implementation by metro system managers, leading to the use of insurance as a flexible measure of response to such possible impacts (Imperative *et al.* 2008, Gurenko 2014, Wilson *et al.* 2020). The infrastructure of metro systems traditionally undergoes few changes in a

spatial-temporal framework, however, in regions such as East Asia, such systems are growing rapidly, which makes clear the need to provide solutions beyond insurance, which cannot respond integrally to the risks of a flood but only help to restore normal services, that is, increases resilience, but does not act on the direct mitigation of risks.

Some of the cross measures to urban services to face floods can be linked to the reduction of risk in Metro systems, such as, the implementation of redundancies in the urban electrical network. As a secondary effect, this redundancy offers a greater operating capacity of the pumping systems to pump the water from the tunnels and stations of the metro system up to a water level lower than the service limit of the metro trains.

Without defining these service thresholds concerning the ability of trains to operate under flood conditions, the safety of passengers/riders for direct inundation by water and/or indirect abandonment in tunnels or stations with worsening environmental conditions, it is also not possible to define the effectiveness of adaptation measures, nor how the application of such measures positively or negatively affects the exposure related to the operation of the system under flood conditions, not only pluvial-driven one.

Collectively, these studies do not outline a critical role in the application of adaptation measures and the estimation of the reduction of risks caused by floods. An examination of the applicability of adaptation measures to minimise floods in Metro networks must also consider Climate Change effects, the recovery capacity of the service in the system but not only as algorithms to define another backup service but also with real data extracted from service management companies. This assessment can help with analysing the flood factors and their direct and indirect relationship with the availability

of the Metro service.

Further researches should include analysis on the safety of users/riders from direct water flooding and/or indirect abandonment in tunnels or metro stations with failed infrastructure and worsening environmental conditions. Several publications discuss in-depth the development and application of models for estimating fatalities and injuries due to flood events (Di Mauro *et al.* 2012, Gouldby *et al.* 2015). Unfortunately, research focused on the development of such models for underground conditions has had minimal progress at the academic level.

7. Conclusions

This document was undertaken to evaluate the available literature regarding pluvial flooding events on Metro systems. The relevance of the integration of the stormwater management models into GIS to evaluate flood risk in the surroundings of the entrances of the Metro system is clearly supported by the current findings. The results of this study also support the view that developing frameworks to assess the flood processes through decision making methods have been proved useful in expanding our understanding of how pluvial flooding events impact on Metro systems. Despite its exploratory nature, this study offers some insight into the gaps presented in this research topic.

Extreme rainfall events will be more frequent due to causes associated with climate change, and these events will have greater negative repercussions due to the accelerated growth of cities, both for their size and complexity and for the number of inhabitants.

When analysing the literature review, it was found that the topic of rain floods in Metro systems around the world is a topic that, despite its inherent importance to its existence and assistance to the daily life of cities, has not been sufficiently addressed in the

academic world.

Beyond the mathematical appraisals computed by some articles to set and guarantee the continuity of the passenger transport service through other public transportation methods, it is important as the following step to analyze in detail the interactions between the flood events caused by rainfall, and the admissible flood thresholds, before the service disruption. Remarkably, only one examined article suggested an indirect approach to the study of this process.

Thus, it is particularly important to implement not only structural countermeasures but also soft adaptation measures that seem to be not considered in many underground Metro systems such as evacuation procedures for ridership, evaluated by some of the analyzed studies.

The availability of pluvial flooding information and forecasting is also important as a non-structural measure. Metro stations should show in real-time both in the station and through digital media, whether the station is enabled to operate under flood conditions. This measure should work without the intervention of service management personnel enabling users to know the behaviour of the flood event.

This dataset would also provide to station supervisors to launch pre-flood protocols before inundation events, for which evacuation and flood prevention activities require strengthening cooperation between the stakeholders in each area. The resilience of an entire urban area depends on strategic services such as the massive transport provided by Metro systems, so minimizing risks to both the physical infrastructure and users will allow the restoration of normal operating functions, increasing resilience at the local level.

The integration of a GIS with a Hydrodynamic 1D-2D coupled model will lead to more precise methodologies for estimating the impact of these floods on Metro's underground systems. It is necessary to generate a robust model that allows to establish with greater precision the volume of water entering the Metro systems, which will reduce the costs and complexity of quantifying the magnitude of the floods, and therefore, of the estimates and quantifications of the risks and of the recommendations for their mitigation.

Prior studies have not been able to account for all aspects of the hydraulic and hydrological processes that condition the entry of water into Metro systems. Following analysis of pluvial flooding events on Metro systems, is necessary to deepen the analysis of the relationships between the urban drainage system, which, in rainfall flood events, should be able to capture and transport excess surface runoff, and the water flows that enter the Metro system during these flood events.

These cases of flooding of underground metro systems modify the rain-runoff transformation processes in urban areas, representing these flows as losses that do not directly enter the existing drainage system and causing the Metro network to become. Without this being its function, storage tanks and water transport systems due to the hydraulic insufficiency of the collection structures, which also modifies the design and actual hydrographs of the events.

Specify the procedures by which progress with implementation of the adaptation measures facing pluvial flooding events can be monitored and evaluated represent a breakthrough for future studies, being relevant to both, urban transport system administrators and policy-makers.

It is suggested that the association of these factors is investigated in future studies,

proposing a strategic, innovative, integrated approach to managing pluvial flood risk for metro services accomplished by selecting and combining structural, hard- engineered measures and non-structural management measures.

These findings raised significant issues that have a bearing on the lack of academic studies related to potential deaths and injuries that may occur in underground transportation systems, beyond all research focused on the evacuation of underground infrastructure.

Funding details

This research was funded by the RESCCUE project, which is sponsored by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700174, whose support is gratefully recognised.

Acknowledgments

The contents of this research are a part of the findings of the project RESCCUE, which has obtained funding from the EU H2020 (grant agreement n. 700174). Re-use of the knowledge enclosed in this paper for commercial and/or non-commercial purposes is allowed and free of charge, on the requirements of compliance by the re-user of the research, not distortion of the original meaning or information of this research and the non-liability of the RESCCUE project partners and/or TMB for any consequence stemming from the re-use. The RESCCUE project partners and TMB do not accept any liability for the errors, consequences or omissions herein contained.

Disclosure statement

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

- Baba, Y., Ishigaki, T., and Toda, K., 2017. Experimental studies on safety evacuation from underground spaces under inundated situations. *Journal of JSCE*, 5 (1), 269–278.
- Batica, J. and Gourbesville, P., 2016. Resilience in Flood Risk Management - A New Communication Tool. *In: Procedia Engineering*. 811–817.
- Cities Project - NPR, 2015. To Flood-Proof Subways, N.Y. Looks At Everything From Plugs To Sheets : NPR [online]. Available from: <https://www.npr.org/2015/10/08/446600221/to-flood-proof-subways-n-y-looks-at-everything-from-plugs-to-sheets?t=1556618716556&t=1562776996834> [Accessed 10 Jul 2019].
- Deng, J.L., Shen, S.L., and Xu, Y.S., 2016. Investigation into pluvial flooding hazards caused by heavy rain and protection measures in Shanghai, China. *Natural Hazards*.
- Dewan, A., 2013. *Floods in a Megacity: Geospatial Techniques in Assessing Hazards, Risk and Vulnerability*. 1st ed. Dordrecht: Springer Netherlands.
- Forero-Ortiz, E. and Martínez-Gomariz, E., 2020. Hazards threatening underground transport systems. *Natural Hazards*, 100 (3), 1243–1261.
- Gonzva, M., Barroca, B., Gautier, P.É., and Diab, Y., 2017. Modeling disruptions causing domino effects in urban guided transport systems faced by flood hazards. *Natural Hazards*, 86 (1), 183–201.
- Gouldby, B., Lhomme, J., Jamieson, S.R., Hornby, D., and Laeger, S., 2015. A flood risk analysis model with topographical inundation and life-loss. *Proceedings of the Institution of Civil Engineers: Water Management*, 168 (3), 116–128.
- Grigg, N.S., 2019. Global water infrastructure: state of the art review. *International Journal of Water Resources Development*, 35 (2), 181–205.

- Gurenko, E.N., 2014. *Climate Change and Insurance: Disaster Risk Financing in Developing Countries*. Earthscan.
- Hamaguchi, S., Ishigaki, T., Ozaki, T., and Toda, K., 2016. Study on vulnerability of mega-underground space to extreme flood. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 72 (4), I_1363-I_1368.
- Hamaguchi, S., Ishigaki, T., Shimada, H., Ozaki, T., and Toda, K., 2016. Underground inundation by storm surge caused by super typhoon. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 71 (4), I_1387-I_1392.
- Han, Y., Shin, E., Eum, T., and Song, C., 2019. Inundation risk assessment of underground space using consequence-probability matrix. *Applied Sciences*, 9 (6), 1196.
- Hashimoto, H. and Nonaka, Y., 2012. Flood-risk assessment of the dense downtown in fukuoka city, Japan. *WIT Transactions on Ecology and the Environment*, 159, 41–52.
- Hashimoto, H. and Park, K., 2010. Inundation risk assessment of underground spaces in the downtown of Fukuoka City, Japan. *WIT Transactions on Ecology and the Environment*, 133, 143–153.
- Herath, S. and Dutta, D., 2004. Modeling of urban flooding including underground space. In: *2nd APHW conference 5-8 July 2004 Singapore /Asia Pacific Association of Hydrology and Water Resource*. 1–9.
- Higo, E. and Okada, N., 2012. Agent modeling for evacuation and amateur rescue under survivability- critical states in underground flooding: By vitae system based multiagent simulation. *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, 2768–2774.
- Higo, E., Okada, N., Hipel, K.W., and Fang, L., 2017. Cooperative survival principles

- for underground flooding: Vitae System based multi-agent simulation. *Expert Systems with Applications*, 83, 379–395.
- Huang, Q., Wang, J., Li, M., Fei, M., and Dong, J., 2017. Modeling the influence of urbanization on urban pluvial flooding: a scenario-based case study in Shanghai, China. *Natural Hazards*, 87 (2), 1035–1055.
- Imperative, A.C., Jacob, K., and Observatory, L.E., 2008. MTA Adaptations to Climate Change – MTA Adaptations to Climate Change A Categorical Imperative . *Earth*, 1–48.
- Inoue, T., Kawanaka, R., Ishigaki, T., Ozaki, T., and Toda, K., 2011. Safety evacuation from underground mall during urban flooding. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 67 (4), I_973-I_978.
- Ishigaki, T., Asai, Y., Nakahata, Y., Shimada, H., Baba, Y., and Toda, K., 2010. Evacuation of aged persons from inundated underground space. *Water Science and Technology*, 62 (8), 1807–1812.
- Ishigaki, T., Kawanaka, R., Onishi, Y., Shimada, H., Toda, K., and Baba, Y., 2009. Assessment of safety on evacuating route during underground flooding. *Advances in Water Resources and Hydraulic Engineering - Proceedings of 16th IAHR-APD Congress and 3rd Symposium of IAHR-ISHS*, 141–146.
- Ishigaki, T., Toda, K., Baba, Y., Inoue, K., and Nakagawa, H., 2006. Experimental Study on Evacuation From Underground Space By Using Real Size Models. *Proceedings of Hydraulic Engineering*, 50, 583–588.
- Japan Metro Association, 2013. Subway [online]. *SUBWAY*. Available from: <http://www.jametro.or.jp/publication/index.html>.
- Jenkins, K., Surminski, S., Hall, J., and Crick, F., 2016. Surface water flood risk and management strategies for London: An Agent-Based Model approach. *E3S Web of*

- Conferences*, 7, 22003.
- Jha, A.K., Bloch, R.B., and Lamond, J., 2012. *Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century*. *Journal of Regional Science*.
- Jonkman, S.N., 2005. Global perspectives on loss of human life caused by floods. *Natural Hazards*, 34 (2), 151–175.
- Jonkman, S.N. and Vrijling, J.K., 2008. Loss of life due to floods. *Journal of Flood Risk Management*, 1 (1), 43–56.
- Joseph, R., Proverbs, D., Lamond, J., and Wassell, P., 2014. Application of the concept of cost benefits analysis (CBA) to property level flood risk adaptation measures: A conceptual framework for residential. *Structural Survey*, 32 (2), 102–122.
- Ke, Q., Haasnoot, M., and Hoogvliet, M., 2016. Exploring adaptation pathways in terms of flood risk management at a city scale – a case study for Shanghai city. *E3S Web of Conferences*, 7, 21002.
- Li, M., Kwan, M.P., Yin, J., Yu, D., and Wang, J., 2018. The potential effect of a 100-year pluvial flood event on metro accessibility and ridership: A case study of central Shanghai, China. *Applied Geography*, 100, 21–29.
- Liu, Y., Okada, N., Shen, D., and Li, S., 2009. Agent-based Flood Evacuation Simulation of Life-threatening Conditions Using Vitae System Model. *Journal of Natural Disaster Science*, 31 (2), 69–77.
- Liu, Y., Shen, D., Okada, N., and Li, S., 2010. Vitae system based agent modeling and simulation of survivability-critical evacuation in underground flooding. *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, 3133–3138.
- Lyu, H.-M., Shen, S.-L., Yang, J., and Yin, Z.-Y., 2019. Scenario-based inundation

- analysis of metro systems: a case study in Shanghai. *Hydrology and Earth System Sciences Discussions*, (March), 1–30.
- Lyu, H.M., Shen, S.L., Zhou, A., and Yang, J., 2019. Perspectives for flood risk assessment and management for mega-city metro system. *Tunnelling and Underground Space Technology*, 84 (September 2018), 31–44.
- Lyu, H.M., Sun, W.J., Shen, S.L., and Arulrajah, A., 2018. Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach. *Science of the Total Environment*, 626, 1012–1025.
- Lyu, H.M., Wang, G.F., Shen, J.S., Lu, L.H., and Wang, G.Q., 2016. Analysis and GIS mapping of flooding hazards on 10 May 2016, Guangzhou, China. *Water (Switzerland)*, 8 (10).
- Madsen, H., Lawrence, D., Lang, M., Martinkova, M., and Kjeldsen, T.R., 2014. Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. *Journal of Hydrology*, 519 (PD), 3634–3650.
- Mal, S., Singh, R.B., Huggel, C., and Grover, A., 2017. *Introducing Linkages Between Climate Change, Extreme Events, and Disaster Risk Reduction*.
- Di Mauro, M., De Bruijn, K.M., and Meloni, M., 2012. Quantitative methods for estimating flood fatalities: Towards the introduction of loss-of-life estimation in the assessment of flood risk. *Natural Hazards*, 63 (2), 1083–1113.
- Messner, F. and Meyer, V., 2006. Flood damage, vulnerability and risk perception – challenges for flood damage research. In: *Flood Risk Management: Hazards, Vulnerability and Mitigation Measures*. Dordrecht: Springer Netherlands, 149–167.
- Metropolitan Transportation Authority/Rob Wilson, 2008. New MTA Grates Double as Seating, Bike Racks – Streetsblog New York City [online]. Available from:

<https://nyc.streetsblog.org/2008/10/01/new-mta-grates-double-as-seating-bike-racks/> [Accessed 10 Jul 2019].

Min, S.K., Zhang, X., Zwiers, F.W., and Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. *Nature*, 470 (7334), 378–381.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., and Group, T.P., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLOS Medicine*, 6 (7), e1000097.

Moreno, T., Pérez, N., Reche, C., Martins, V., de Miguel, E., Capdevila, M., Centelles, S., Minguillón, M.C., Amato, F., Alastuey, A., Querol, X., and Gibbons, W., 2014. Subway platform air quality. Assessing the influences of tunnel ventilation, train piston effect and station design. *Atmospheric Environment*, 92, 461–468.

Morikane, M., Inoue, T., Ishigaki, T., Ozaki, T., and Toda, K., 2012. Effects of counter measures for reducing underground inundation caused by pluvial flooding. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 68 (4), I_1003-I_1008.

MTA New York, 2012. Flood mitigation work begins on seven downtown stations [online]. *New York, USA*. Available from: <http://web.mta.info/nyct/service/FloodMitigationWorkBeginsat7DowntownStations.htm> [Accessed 30 Apr 2019].

Onishi, Y., Ishigaki, T., Baba, Y., and Toda, K., 2008. Criterion and its application for safety evacuation during underground flooding. *Proceedings of Hydraulic Engineering*, 52, 841–846.

Ozaki, T., Asano, N., Ishigaki, T., and Toda, K., 2014. Characteristics of underground mall inundation by flush flood in short time heavy rainfall. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 70 (4), 1417–1422.

- Penning-Rowsell, E., Floyd, P., Ramsbottom, D., and Surendran, S., 2005. Estimating Injury and Loss of Life in Floods: A Deterministic Framework. *Natural Hazards*, 36 (1–2), 43–64.
- Quan, R., Zhang, L., Liu, M., Lu, M., Wang, J., and Niu, H., 2011. Risk assessment of rainstorm waterlogging on subway in central urban area of Shanghai, China based on scenario simulation. *Proceedings - 2011 19th International Conference on Geoinformatics, Geoinformatics 2011*, (40730526), 0–5.
- Sanwa, 2018. Sanwa waterproof products [online]. Available from: https://www.sanwass.co.jp/digital_catalog/pdf/s_100.pdf [Accessed 10 Jul 2019].
- Sassi, M., Nicotina, L., Pall, P., Stone, D., Hilberts, A., Wehner, M., and Jewson, S., 2019. Impact of climate change on European winter and summer flood losses. *Advances in Water Resources*, 129, 165–177.
- Şen, Z., 2017. *Flood modeling, prediction and mitigation*. Flood Modeling, Prediction and Mitigation.
- Sugimoto, K., Okuoka, K., and Tanikawa, H., 2018. Establishment of three-dimensional subway GIS data for inundation analysis in urban area. *Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research)*, 73 (5), I_283-I_289.
- Terada, M., Okabe, R., Ishigaki, T., Ozaki, T., and Toda, K., 2017. Subway inundation by pluvial flooding in densely urbanized area. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 72 (4), I_1357-I_1362.
- Toda, K., Kawaike, K., Yoneyama, N., Fukakusa, S., and Yamamoto, D., 2009. Underground inundation analysis by integrated urban flood model. *Advances in Water Resources and Hydraulic Engineering - Proceedings of 16th IAHR-APD Congress and 3rd Symposium of IAHR-ISHS*, 166–171.
- Tōkyō metoro, 2014. Measures against wind and flood damage | Tokyo Metro [online].

Available from:

https://www.tokyometro.jp/safety/prevention/wind_flood/index.html [Accessed 10 Jul 2019].

Tokyo Subway Co Ltd., 2007. Flood control measures for Tokyo Metro [online].

Available from:

http://www.bousai.go.jp/kaigirep/chuobou/senmon/daikibosuigai/4/pdf/shiryoku_5.pdf [Accessed 10 Jul 2019].

Uchida, S., 2018. What is the “submergence risk” of torrential rain and measures at underground stations in Tokyo? [online]. *Toyo Keizai Online*. Available from: <https://toyokeizai.net/articles/-/234981> [Accessed 10 Jul 2019].

UNDRR, 2019. *Global Assessment Report 2019*. United Nations Office for Disaster Risk Reduction. Geneva, Switzerland.

Wilson, R.S., Herziger, A., Hamilton, M., and Brooks, J.S., 2020. From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, 10 (3), 200–208.

Wu, J., Fang, W., Hu, Z., and Hong, B., 2018a. Application of Bayesian approach to dynamic assessment of flood in urban underground spaces. *Water (Switzerland)*, 10 (9).

Wu, J., Fang, W., Hu, Z., and Hong, B., 2018b. Application of bayesian approach to dynamic assessment of flood in urban underground spaces. *Water (Switzerland)*, 10 (9).

Yang, L.E., Scheffran, J., Süsler, D., Dawson, R., and Chen, Y.D., 2018. Assessment of Flood Losses with Household Responses: Agent-Based Simulation in an Urban Catchment Area. *Environmental Modeling and Assessment*, 23 (4), 369–388.

Yoneyama, N., Toda, K., Aihata, S., and Yamamoto, D., 2009. Numerical analysis for

evacuation possibility from small underground space in urban flood. *Advances in Water Resources and Hydraulic Engineering - Proceedings of 16th IAHR-APD Congress and 3rd Symposium of IAHR-ISHS*, 107–112.