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Emergency Response Resilience to Floods Operationalised with Applied Geoinformatics

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Abstract in English

In cities, timely emergency response (ER) presupposes timely citywide accessibility enabled by the road transport system's uninterrupted functioning. However, in this era of increasing frequency and intensity of extreme weather events and hydrometeorological hazards, delays or blockages challenge timely accessibility. Therefore, the thesis aims to contribute to saving lives by reducing losses in critical infrastructure (CI) functioning for adaptive emergency response (ER) provision towards the population's and the emergency responders' safety. For this purpose, the urban ER system is presented as a complex adaptive system of systems (SoS) that, under the stressor of floods, can adapt and transform so to retain its critical functionality considering safety and security aspects.

For a deepened understanding of flood risks, their cascading impacts and interrelation with the resilience of a complex adaptive SoS, the thesis introduces an operational resilience framework that adopts an interdependent resiliencies concept and combines a top-down and a bottom-up spatial scaling approach. The SoS resilience concept, as applied to an urban ER system, introduces an operational framework for the urban emergency response resilience (ERR) that follows the 4R model (4Resilience characteristics: robustness, resourcefulness, redundancy, rapidity of response) in an interdependent form. The usefulness and intent of adopting the urban ERR concept from European stakeholders and researchers and emergency response and civil protection officials are analysed with semi-structured interviews. The CAS theory applied to the urban ER system enables its division to the agent, system and network level and identifies the hierarchy between its constituent systems. The road transport system is higher in the hierarchy due to its pivotal role in the urban ER system's behaviour and, therefore, is the 'zero-point' for further flood risk assessments. The graph theory and the complex network theory assist with graphical representations and compartmentalisation of the urban ER system to its systems, networks, and components and digitisation using geographic information systems (GIS) for ERR assessments.

The ERR to regular and extreme scenarios of riverine floods and flash floods is assessed with a multi-criteria risk-based time-dependent accessibility indicator (RITAI) for Cologne's fire brigade system in Germany. The RITAI utilises applied geoinformatics with geographic information systems (GIS) to identify first-, second and third-order flood risks in various scales and levels of this urban ER system, with a top-down and an eight-step GIS-based spatial upscaling approach. Safety and security aspects are considered with the RITAI's benchmarking according to the fire trucks' safe driving capacity through flooded waters, the flood depths and the road types. After defining analyses' units on a road network level, a developed semi-automated GIS-Toolkit integrates flood depth and flood-impacted road type-dependent speeds in the road network database for each of the selected flood scenarios. The resulting flood-risk informative road networks are utilised for large-scale road network resilience capacities, assessed with changes in transport characteristics. Later and after the definition of city units, citywide connectivity and accessibility assessments are conducted with network analyses. For a pattern identification of the fire brigade system's ERR to floods, the RITAI is assessed and visualised in each city unit, after classification according to Cologne's fire brigades' official ER time thresholds - eight minutes. Geovisualisation and fuzzification techniques are utilised for simplification and aggregation of the information. Flood-impact statistical curves are also generated for aggregation of information and preparedness of response to escalating or compound flood events. The data utilised were retrieved from open sources and fire brigade and flood management local officials in raster, vector, Excel files and official reports and were visualised in maps. The data undertook cleaning and transformation for interoperability purposes and further handling. The RITAI's general application and handling of data can be time-consuming, with the processing costs depending highly on the selected units of analyses and the computer's memory capacity. The results, i.e., large-scale road network exposure, redundancy and resourcefulness, citywide accessibility route plans and spatial hexagonal urban ER system connectivity and ERR matrixes, are visualised in maps. They indicate that the citywide ER efficiency in cities depends highly on large-scale geolocated flood extent and flood depth information and the road type and the rescue vehicles' capacity for safe drivability through flooded waters. It is identified that the regular and extreme flash floods scenarios follow a similar geographical locality of occurrence. However, the extreme flash flood scenario causes a higher ERR decrease, which indicates its dependence on the road type exposed to floods and the geolocation of flood intensities. Moreover, in cities, the local enhancement of the road network's resilience (absorption, adaptation and transformation) capacities, considering the emergency responders' safety, enhances the fire brigade system's ERR to floods. The local extension of CI functioning is achieved by enhancing resourcefulness (transformation capacity) with an extension of the road transport system's endogenous redundancy (adaptation capacity). This extension further extends its exogenous redundancy of alternative accessibility route paths, enhancing the fire brigade system's response capacity. Additionally, statistical analyses of the road transport system's resilience capacities in case of escalating floods revealed that its resilience capacity for ER provision is highly decreased. Finally, ERR assessments indicate that the ER provision will potentially be highly incapacitated in case of an extreme riverine flood scenario and highly delayed with an extreme flash flood scenario. It is also identified that east Cologne needs further attention in the preparedness phase for timely ER under flooded conditions. Nevertheless, the results depend on the correctness of data used, their resolution and unit of analyses, which can cause biases in the calculation processes. Biases in interpreting the results are reduced by simplifying the system's connectivity and ERR information in hexagonal spatial matrixes.

With the concept of ERR and its operationalisation approach, current silo-thinking disaster risk management (DRM) approaches are enriched with CAS, resilience, security and spatial thinking, enabling holistic and collaborative risk mitigation strategies. For this purpose, an identified lacking connection between the application fields of emergency rescue systems, civil protection and critical infrastructure protection (CIP) is now established with the suggested urban ER system. Additionally, the enhancement of the ERR and the communities' resilience through timely ER provision is achieved with enhanced geospatial preparedness for adaptive management. Applied geoinformatics and GIS provide the means for identifying, assessing, visualising and timely exchanging a range of systemic and cascading first-, second-and third-order flood impacts for adaptive management. Adaptation is attained with approaches that consider safety and security aspects and enable accurate assessments of, for example, operational costs associated with the transfer of heavy rescue equipment, emergency humanitarian logistics, community and CI resilience. The concept's flexible and interdisciplinary character is valuable for further applications to various SoS and scenario- and place-based multi-criteria risk analyses and interdependency analyses valuable for training purposes in different countries, urban districts, and counties where floods are not typical. The thesis also discusses in detail further methodological improvements, enrichments and potential use cases.

Zusammenfassung

In Städten setzt eine rechtzeitige Notfallreaktion eine rechtzeitige stadtweite Erreichbarkeit voraus, die durch ein ununterbrochenes Funktionieren des Straßentransportsystems ermöglicht wird. In dieser Ära, in der extreme Wetterereignisse (EWE) und hydrometeorologische Gefahren immer häufiger und intensiver auftreten, wird die rechtzeitige Zugänglichkeit jedoch durch Verzögerungen oder Blockaden in Frage gestellt. So gefährden beispielsweise Verzögerungen oder Blockaden, die beim Fahren unter suboptimalen Überschwemmungsbedingungen auftreten können, die Sicherheit der Einsatzkräfte und damit der Bevölkerung. Daher zielt die Arbeit darauf ab, einen Beitrag zu den übergeordneten Zielen der Rettung von Menschenleben zu leisten, indem Verluste in der Funktionsfähigkeit kritischer Infrastrukturen (KRITIS) reduziert werden, um eine adaptive Notfallreaktion zur Sicherheit der Bevölkerung und der Einsatzkräfte zu ermöglichen.

Zu diesem Zweck wird das städtische Notfallsystem als ein komplexes adaptives System von Systemen (SoS) vorgestellt, das sich unter dem Stressor von Überschwemmungen so anpassen und transformieren kann, dass seine kritische Funktionalität unter Berücksichtigung von Sicherheitsaspekten erhalten bleibt. Für ein vertieftes Verständnis der Hochwasserrisiken, ihrer kaskadierenden Auswirkungen und der Wechselbeziehung mit der Resilienz eines komplexen adaptiven SoS wird in der Arbeit ein operationelles Resilienz-Framework vorgestellt, das ein Konzept Interdependente Resilienzen anwendet und einen Top-Down- und einen Bottom-Up-Ansatz zur räumlichen Skalierung kombiniert. Die Ansätze ermöglichen Rückkopplungsschleifen von großen zu kleinen Skalen in Bezug auf die Resilienz-Kapazitäten seiner konstituierenden Systeme, die nach einem gefährlichen Ereignis offengelegt werden und die Resilienz Kapazität des komplexen adaptiven SoS unter Berücksichtigung seiner Umgebung definieren. Das SoS-Resilienzkonzept, wie es auf das städtische Notfallsystem angewendet wird, führt die Resilienz der städtischen Notfallreaktion ein. Das Notfallreaktionsresilienz-Rahmenwerk folgt dem 4R-Modell (4Resilienz-Eigenschaften: Robustheit, Einfallsreichtum, Redundanz, Schnelligkeit der Reaktion) in einer voneinander abhängigen Form. Der Nutzen und die Absicht der Übernahme des städtischen Notfallreaktions-Resilienz Konzept von europäischen Interessenvertretern, Notfallreaktionsbeamten und Wissenschaftlern werden mit halbstrukturierten Interviews mit Experten aus den Forschungsbereichen analysiert. Die auf das städtische Notfallreaktionssysystem angewandte KAS-Theorie ermöglicht dessen Aufteilung auf die Agenten-, System- und Netzwerkebene sowie die Identifizierung der Hierarchie zwischen den einzelnen Systemen. Das Straßenverkehrssystem ist aufgrund seiner zentralen Rolle im Verhalten des städtischen Notfallreaktionssystems in der Hierarchie höher angesiedelt und stellt daher den "Nullpunkt" für weitere Hochwasserrisikobewertungen dar. Darüber hinaus helfen die Graphentheorie und die Theorie komplexer Netzwerke bei der graphischen Darstellung und der Zerlegung ihrer Systeme und Netzwerke in ihre Komponenten, was ihre Digitalisierung mit geographischen Informationssystemen (GIS) und Netzwerkanalysen für die Bewertung der Resilienz der Notfallreaktion ermöglicht wird.

Die Notfallreaktionsresilienz zu regulären und extremen Szenarien von Flusshochwasser und Sturzfluten wird mit einem multikriteriellen risikobasierten zeitabhängigen Erreichbarkeitsindikator (RITAI) für das Feuerwehrsystem von Köln (in) Deutschland, bewertet. Der RITAI nutzt angewandte Geoinformatik mit geografischen Informationssystemen (GIS) für die Identifizierung von Hochwasserrisiken erster, zweiter und dritter Ordnung in verschiedenen Maßstäben und Ebenen des städtischen Notfallreaktionssystems, mit einem Top-Down- und einem achtstufigen GIS-basierten räumlichen Upscaling-Ansatz. Sicherheitsaspekte werden beim Benchmarking der RITAI berücksichtigt, und zwar in Abhängigkeit von der sicheren Fahrkapazität der Löschfahrzeuge durch überschwemmte Gewässer, der Fluttiefe und dem Straßentyp. Nach der Definition der Analyseeinheit

auf der Ebene des Straßennetzes integriert ein entwickeltes halbautomatisches GIS-Toolkit für jedes der ausgewählten Hochwasserszenarien die von der Überschwemmungstiefe und dem Straßentyp abhängigen Geschwindigkeiten in die Straßennetzdatenbank. Die sich daraus ergebenden informativen Straßennetze mit Hochwasserrisiko werden für großräumige Resilienzkapazitäten des Straßennetzes genutzt, die unter Berücksichtigung der Veränderungen seiner Transporteigenschaften bewertet werden. Nach der Definition von Stadteinheiten werden stadtweite Konnektivitäts- und Erreichbarkeitsbewertungen mit Netzanalysen durchgeführt. Zur Vereinfachung der Informationen werden Geovisualisierungs- und Fuzzifizierungstechniken eingesetzt. Zur Aggregierung der Informationen und zur Vorbereitung der Reaktion auf eskalierende oder zusammengesetzte Hochwasserereignisse werden auch statistische Hochwasserauswirkungskurven erstellt. Die verwendeten Daten wurden aus offenen Quellen, von Feuerwehr- und Hochwassermanagementbeamten vor Ort in Form von Raster-, Vektor- und Excel-Dateien sowie offiziellen Berichten abgerufen und in Karten visualisiert. Die Daten übernahmen die Bereinigung und Transformation für Interoperabilitätszwecke und die weitere Bearbeitung. Die allgemeine Anwendung der RITAI und die Handhabung der Daten kann zeitaufwendig sein, wobei die Verarbeitungskosten stark von den ausgewählten Analyseeinheiten und der Speicherkapazität des verwendeten Computers abhängen.

Die Ergebnisse, d.h. die großräumige Belastung des Straßennetzes, die Redundanz, der Einfallsreichtum und die stadtweite Erreichbarkeit von Routenplänen sowie die räumliche sechseckige Anbindung an das städtische Notfallreaktion-System und Notfallreaktionsresilienz-Matrizen werden in Karten visualisiert. Sie zeigen, dass die stadtweite Notfallreaktions-Effizienz in Städten stark von der großräumigen geolokalisierten Hochwasserausdehnung, der Information über die Hochwassertiefe, dem Straßentyp und der Kapazität der Rettungsfahrzeuge für eine sichere Befahrbarkeit durch überschwemmte Gewässer abhängt. Ferner wird festgestellt, dass die regulären und extremen Sturzfluten einem ähnlichen geografischen Ort des Auftretens folgen. Ihre Auswirkungen auf die stadtweite Notfallversorgung sind jedoch unterschiedlich, wobei das extreme Sturzflut-Szenario einen höheren Rückgang der Notfallrisikokosten verursacht, was auf die Abhängigkeit vom Straßentyp, der Überschwemmungen ausgesetzt ist, und der Geolokalisierung der Überschwemmungsintensitäten hinweist. Darüber hinaus erhöht in Städten die lokale Verbesserung der Widerstandsfähigkeit des Straßennetzes (Absorptions-, Anpassungs- und Transformationskapazitäten) unter Berücksichtigung der Sicherheit der Notfallhelfer die volkswirtschaftliche Rentabilität des Feuerwehrsystems bei Überschwemmungen. Diese lokale Ausdehnung der Funktionsfähigkeit der KRITIS wird durch die Verbesserung der Einfallsreichtum (Transformationskapazität) nach der Ausdehnung der endogenen Redundanz des Straßentransportsystems (Anpassungskapazität) erreicht, was deren nahezu analoge Beziehung offenbart. Die Erweiterung der endogenen Redundanz des Straßennetzes führt zu einer Erweiterung der exogenen Redundanz alternativer Erreichbarkeitswege, die folglich die Reaktionsfähigkeit des Feuerwehrsystems verbessern. Darüber hinaus haben statistische Analysen der Belastbarkeitskapazitäten des Straßennetzes im Falle eskalierender Überschwemmungen gezeigt, dass die Belastbarkeit des Straßentransportsystems für die Notfallversorgung stark vermindert ist. Bewertungen der Notfallreaktionsresilienz deuten darauf hin, dass die Notfallversorgung im Falle eines extremen Flusshochwasser-Szenarios stark beeinträchtigt und bei einem extremen Sturzflut-Szenario stark verzögert sein wird. Schließlich wird auch festgestellt, dass Osten Köln in der Vorbereitungsphase für die rechtzeitige Bereitstellung von Notfallprodukten unter Hochwasserbedingungen weiterer Aufmerksamkeit bedarf. Nichtsdestotrotz hängen die Ergebnisse von der Richtigkeit der verwendeten Daten, ihrer Auflösung und der Einheit der Analysen ab, was zu Verzerrungen in den Berechnungsprozessen führen kann. Verzerrungen bei der Interpretation der

Ergebnisse werden durch die Vereinfachung der Konnektivität und der Informationen über die Resilienz der Notfallreaktion hexagonalen räumlichen Matrizen reduziert.

Mit dem Konzept von Notfallreaktionsresilienz und seinem Ansatz zur Operationalisierung werden aktuelle silodenkende Disaster Risk Management (DRM)-Ansätze mit KAS, Resilienz, Sicherheit und räumlichem Denken angereichert, was ganzheitliche und kooperative Risikominderungsstrategien ermöglicht. Zu diesem Zweck wird mit dem vorgeschlagenen städtischen Notfallreaktionssystem nun eine identifizierte fehlende Verbindung zwischen den Anwendungsbereichen der Notfallrettungssysteme, des Katastrophenschutzes und dem Schutz Kritischer Infrastrukturen (SKI) hergestellt. Die Verbesserung der Notfallreaktionsresilienz und der Widerstandsfähigkeit von Gemeinden durch rechtzeitige Bereitstellung von Notfallreaktion wird mit einer verbesserten georäumlichen Vorbereitung für ein adaptives Management erreicht. Angewandte Geoinformatik und GIS bieten die Mittel für die Identifizierung, Bewertung, Visualisierung und den zeitnahen Austausch einer Reihe von systemischen und kaskadierenden Hochwasserauswirkungen erster, zweiter und dritter Ordnung im Hinblick auf ein vertieftes Verständnis der Hochwasserrisiken und ein adaptives Management. Die Anpassung wird mit Ansätzen erreicht, die Sicherheitsaspekte berücksichtigen und die eine genaue Bewertung z.B. der mit der Verlegung von schwerem Rettungsgerät verbundenen Betriebskosten, der humanitären Nothilfelogistik, der Belastbarkeit von Gemeinden und KRITIS ermöglichen. Der flexible und interdisziplinäre Charakter der vorgeschlagenen Konzepte kann für weitere Anwendungen auf verschiedene SoS unter Verwendung unterschiedlicher Gefahrenszenarien wertvoll sein. Sie können für szenarien- und ortsbezogene multikriterielle Risikoanalysen und Interdependenzanalysen in verschiedenen Stadtbezirken, Landkreisen und Ländern, in denen Überschwemmungen ebenfalls nicht so häufig vorkommen, zu Schulungszwecken weiter genutzt werden. In der Arbeit werden auch weitere methodische Verbesserungen, Anreicherungen und mögliche Anwendungsfälle ausführlich diskutiert.

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Life: Sustainability of our complex adaptive System of Systems (body and soul) to everlasting encounters with various stressors, causing shocks or damages.

Joy of life: Quick adaptability and transformation to external stressors for maximum System of Systems flexibility, towards Resilience. Quicker bounce-back to desirable states (either to ones before a stressor's occurrence or to new ones), while having learned from the experience, absorbed the consequences from the shock or damage and transformed towards better preservation of our joyful state.

To my parents, Ιωάννης Τζαβέλλας and Μαρία Τζαβέλλα

To my fiancé, Bert Jan Hobbeling

You preserve my joy of life

Without you, I would not be able to make it so far.
Without you, I would not be able to bounce back quickly to joyful states.

Σας ευχαριστώ και σας αγαπώ όσο δεν πάει...!

List of Contents

List of Figures

List of Tables

List of Abbreviations

A	accessibility
AF	after flood
BF	before flood
CAS	complex adaptive system
CI	critical infrastructure
CIP	critical infrastructure protection
CIR	cities resilience index
DRM	disaster risk management
DRR	disaster risk reduction
EMS	emergency medical services
ER	emergency response
ERR	emergency response resilience
ERPS	emergency route planning speed
ERS	emergency rescue services
EWE	extreme weather events
FD	flood depth
FFS	free flow speed
FRM	flood risk management
GIS	geographic information systems
NA	network analyses
PR	PRegnolato function
RNMC	road network’s mobility capacity
SFDRR	Sendai Framework for Disaster Risk Reduction
SoS	system of systems
TTR	travel time reliability
UFTTR	urban flood travel time reliability

1. Introduction

Extreme weather events (EWE) have increased in frequency and intensity the last decades due to climate change, consequently increasing loss events [1] and many suddenly occurring hazards, such as floods, cyclones and bushfires [2, 3], provoking the increase of the likelihoods of compound hazards and cascading impacts on societies [4]. Many studies on the subject have already identified that climate change is the cause of the increase in EWE frequency and intensity, as reported in [1, 3-15]. The Paris Agreement in 2016 acknowledged that climate change is a common concern for humanity, and in the Global Assessment Report [16] on disaster risk reduction (DRR), it is declared that the future losses from disasters are expected to increase even more since *"most disasters that could happen have not happened yet"*. Expressly, the European Academies Science Advisory Council [5] underlines that "*..the amount of floods, with other hydrological events, have quadrupled since 1980 and have doubled since the year of 2004… Meteorological events, such as storms, have doubled since 1980*". This consensus was initially recognised from the international agreement for disaster risk reduction (DRR), the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) of the United Nations Office for Disaster Risk Reduction [16]. The SFDRR is intended to ensure that:

- disaster risk, at each level and across all the sectors, is a critical factor in the planning and the development, disaster preparedness, recovery and reconstruction and
- it is applied covering risks of all scales (large to small and vice versa), frequencies (low and high) and types of disasters (sudden and slow-onset) caused by environmental, natural, human-caused, biological and technological hazards.

However, as mentioned in a recent global assessment report on disaster risk reduction [17], specifically for disasters triggered from climate change, there is the possibility that the mitigation or repair of impacts from realised systemic and cascading risks will not be possible and "*changes are urgent and must be proportionate to the scale of threat".* Therefore, there is an increasing consensus that the adaptive management should address the risk explicitly and suitably [15, 18-20] and inform the decision-making based on a deepened understanding of the environment and the diversity of emergent risks and opportunities [21]. Specifically, in [22], adaptive management is defined as an *"iterative organised process that aims to reduce the uncertainties by increasing the knowledge and the understanding, while enabling improved management-related decisions over time"*. EWE, together with the natural disasters and the failure of the climate change adaptation, are placed in the top five of the Global Risks Landscape by the World Economic Forum [23] since they can bring significant uncertainties in the different management cycles. For example, the interrelation of these risks and their impacts are also highlighted in the case of a water crisis potentiality and its consequent disruptions to critical infrastructure (CI) and essential services [24] (building urban resilience).

In regards to the concerns about the increase in frequency and severity of disaster events and their consequences that bring into the forefront emerging opportunities of cascading impacts, scientists agree that post-event response has to become more efficient and draw on science [25-30], considering, for example, the second-and third-order impacts of floods to the timely emergency response. The need for timely emergency response is reflected in one of the four priorities of action of the SFDRR that calls for "*strengthening preparedness for response*" [31]. On the other hand, strengthening preparedness and response to EWE-induced disasters and cascading impacts is a challenge for the scientific community, practitioners and decision-makers.

The challenge is even higher in complex urban areas, which are nests of highly connected and complex networks of dense human settlements and CI, contributing to the economic growth and well-being of the population (transportation, energy, water), followed by uncertainty in the analyses process conveyed from such phenomena. Concretely, in order to curb the impact of natural and human-caused hazards, the Agenda 2030 for Sustainable Development [32] recommends the development of cities that are safe, inclusive, resilient and sustainable (Goal 11) through the:

- protection and safeguarding of the world's cultural and natural heritage (Target 11.4),
- reduction of deaths and damages that are caused by disasters (Target 11.5)
- increase in the number of cities that adopt and implement integrated policies and plans
- for a resilient to disasters future, with holistic disaster risk management - DRM (Target 11.b).

Cities are complex and highly dependent on functional interdependent infrastructure systems [33], which are more than a simple aggregation of individual services. The neighbouring character and affinity of the infrastructure systems cause the increased system of systems' (SoS) complexity [34], characterising cities as complex. In the computer science domain, different definitions exist for the SoS, where they are defined as *a set of systems, which are independently operational and manageable,* which indicate the complexity risen when attempting to manage a SoS [35]. Therefore, the resilience of a SoS can be defined as the *architectural ability of the SoS to defend against emerging new threats* [35], i.e. architectural adaptation of the SoS to handle external EWE-triggered perturbations.

It is presented in the thesis that the adaptive and transformative design of a SoS enables the development of such frameworks, integrating **resilience thinking** in resilience operationalisation methodologies and developed tools following the complexity theory. When managing complexity, it is argued that changes from one phase occur if the system reaches a critical state. Minor influences may increase fluctuations of a greater magnitude, indicating that the system is unstable [36], revealing cascading effects that underlie crises or disasters. When a threshold is reached, cascading effects may become evident and often underlie crises and disasters [36, 37].

EWE could never be considered a disaster [38]. However, the same EWE, occurring in a densely populated environment, such as the urban areas, with a high amount of interconnected CI, are calamitous, having severe consequences for the management of cities in the long term [1] and consequently for the safety of the population. For this reason, a security perspective is urgent to be mainstreamed in DRR and *"there is ample room for deepening the understanding of the complex links between security and disasters, including disasters prompted by climate change*" [39], that is, ample room for adaptive management.

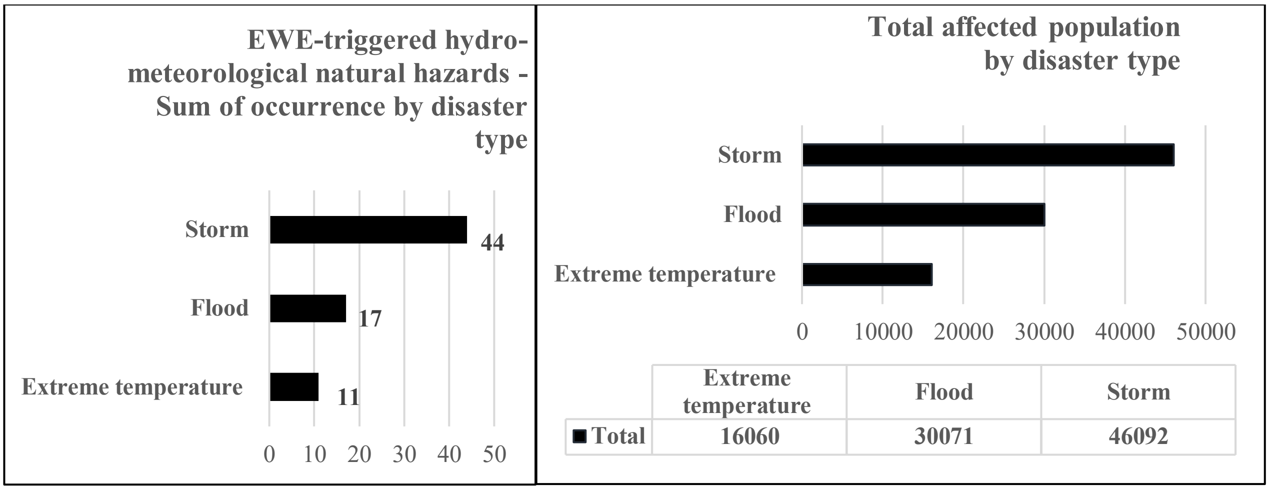
Therefore, this thesis suggests that an evaluation of systemic and cascading impacts of EWE with a deepened understanding of their effect must be included in pre-disaster planning for strengthened emergency preparedness for resilient emergency response (ER) as well as risk mitigation measures, which have gained interest both in the scientific and the practitioners' communities, but still with a silo-mentality. Silo-mentality entails approaches that isolate one CI system for EWE-induced impacts (CI security), limiting the research results with one scenario, focusing on pure inherent technological impacts without considering the impacts of the system's environment (socio-ecological). Hence, there is an increasing need for DRM conceptual frameworks, methodologies and tools that are integrative, adaptive in regards to the goals and transformative, including natural hazard impacts on several technical, operational and organisation levels, using feedback loops from various hazard scenarios for the enhancement of the safety of the urban population. Such informative feedback loops are characteristics of SoS with CAS properties.

Therefore, it is proposed that placing the focus on the SoS architecture design enables comprehensive resilience assessments by defining its constituent systems and their established relationships (networks), which determine the capacities at a SoS level. These capacities are impossible for any system operating in isolation, and they require synchronisation of the capacities of the constituent levels, providing a higher level of a SoS capacity [35]. Resilience is revealed after a hazardous event, and in the case of floods [40], the integration of resilience thinking into the development of an operational resilience framework is proposed in the thesis. It is also suggested that resilience thinking supports the interdependent resiliencies concept, enables the detailed resilience assessments of each constituent system of a SoS separately and collectively, achieves the identification of risk and critical states on many levels and scales.

Resilience thinking in the resilience approaches is even richer since it deals with the dynamics of a complex adaptive system (CAS) and the actual uncertainty and addresses the issue of *"how to make use of the knowledge gained by living with changes"* [41]. With resilience thinking, a deep understanding of such impacts is achieved with the transformation in risk management called for in the SFDRR [4]. For all the reasons mentioned above, resilient ER in complex urban areas is warranted and can be achieved by transforming DRM approaches away from traditional silo-based ones. This transformation presupposes the integration of resilience thinking, spatial assessments and operationalisation tools, combining information from different scales of the system. It is categorically presented that **DRM is enriched with a resilience-thinking, which is integrated into a developed ER resilience (ERR) framework applied on an urban SoS with CAS properties** and deals with direct, indirect but also emergent risks, triggered from various intensities and probability levels of EWE on various scales, such as the riverine floods and flash floods.

Flood impacts in complex adaptive cities and interdependent critical infrastructures: emergent risks identified - Floods in Europe and Germany

It is broadly accepted that climate change may increase the magnitude and frequency of the riverine floods [42-44], affecting people's lives (as observed in recent years in Figure 1) and CI generating substantial economic losses. Urban areas, which are accumulations of highly interconnected CI, face various hazards, such as floods, with various consequences beyond their boundaries that damage their CI and affect the broader economy [11, 45, 46]. Flood risk probability of occurrence has increased as the number of rare EWE, such as floods, are increasing and will continue to [47] around Central Europe [8], Germany (see Figure 1) and specifically in local areas, as the city of Cologne [48] located in the west of Germany. As mentioned in [49], analyses of various flood events revealed that a significant amount of flooding was not associated with riverine floods but occurred far from any rivers, also in areas that were not characterised as flood-prone before the event [50-52]. The probability of occurrence of EWE increases significantly with an almost analogous increase of intensity [48], even on a regional scale. Large-scale floods, i.e. flash floods, have the potential to create significant financial losses [53]. Increased exposure to weather-related disasters of people and amounts of assets located in high-risk areas from natural hazards have led to increased losses. For example, even if the impacts of flash flood events are often limited to small scales compared to large riverine ones, in Germany, the damages sum up to several million euros annually due to the increased number of events [50].



	Extreme temperature	Flood	Storm
■ Total	16060	30071	46092

Figure 1: Number of reported EWE-triggered hydrometeorological natural hazards of Western (Central) Europe (left) between 1990-2019 and affected population of Germany by type of natural hazard (right)[1]

In recent decades, it is observed that the research and governmental actions that are taken on an international and European level have a focus on riverine floods, with damages that sum up to billions of euros for a single event [54, 55]. Even though many European countries have their flood protection and prevention policies, the Flood Directive [56] provides the background for joint action at an international level. This directive aims to guide towards the implementation of DRR approaches - reducing adverse consequences of flooding events. The EU Member States have implemented it in three consecutive stages:

- flood risk assessments at a preliminary phase, completed in 2011,
- flood risk and hazard maps for flood-prone areas, produced in 2013
- flood risk management plans, concluded at the end of 2015 [57].

The Flood Directive [56] has forced riverine flood-prone cities to extend their flood control infrastructures, but despite the efforts, there have been many large-scale flood disasters, for example, in Germany, the floods in Dresden (2002) [58] and of the river Rhine in 2013. Nevertheless, researchers continue to contend that flood-control infrastructure for cities, e.g., [59, 60], is an indispensable part of flood protection strategies, reflecting the entrenched *management paradigm* of controlling nature. On the other hand, flood-control infrastructure does not constitute a reliable mitigation approach for climate change uncertainties [61]. The challenge is even more significant in cities with densely interfaced and interdependent CI. Therefore, the destructive impacts of EWE-triggered floods cannot be entirely prevented with flood-control infrastructure, as it is difficult to predict their probability of occurrence, which leads to the increased need for strengthened preparation.

Floods and interdependent urban complex adaptive CI in urban complex adaptive cities - need for integrative emergency management.

Towards DRR in Germany, the topic of CI is in focus at a national level, integrated into a national strategy [62], a protection concept [63], business continuity, risk management [64] and risk analysis [65, 66] guidelines, including aspects such as vulnerability analyses [66, 67]. Furthermore, smart

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[1] Data downloaded from EM-DAT - The Emergency Events Database, Search Period: 1990-2019, Universite Catholique de Louvain (UCL) - CRED, D. Guha-Sapir - www.emdat.be, Brussels, Belgium www.emdat.be. Accessed 09.2019

cities are characterised by various interconnected and interdependent virtual and physical services that form complex eco-technological systems that provide advanced services to the institutions and the population to manage public resources in optimal ways and involvement of citizens in decisional and adjustive processes.

The smart city concept is interpreted as a process addressed to make cities sustainable and resilient, responding quickly to new challenges [68]. However, such high interconnectivity can lead to increased vulnerabilities: the 'vulnerability paradox'. Therefore, the ability of institutional operators and service providers to face and manage emergencies is a relevant issue. It makes collaboration between the public and private sectors even more necessary [69]. Furthermore, at the *CIPRE conference* in The Hague in May 2017, Mr Pepijn van den Broek from the International Safety Research Europe BV mentioned: *"The EU has the Civil Protection Mechanism, and Critical Infrastructure has a protection mechanism, but there is no coordination mechanism for Emergency Management. There is no list of effects that occur after a CI failure." (personal notes as an attendee at the conference).* There is constantly an increasing need to identify the interdependencies of the various CI and integrate such information into existing or future resilience concepts.

For this reason, emergency preparedness and response, in the era of highly interfaced and interdependent CI and high-intensity perturbations from unexpected EWE, need integrative approaches towards DRR. It is argued that it is possible, to some extent, to be prepared for their occurrence and consequences by trying to least mitigate or partially prevent their effects in highly complex cities. Therefore, it is essential to pursue a deepened knowledge of the connectivity and interdependencies amongst CI systems vital for their resilience [70] to external perturbations, such as the EWE. CI are complex systems, and failures can occur, resulting in domino failure effects on different interconnected CI impacting the population living in close (but also far) geographical proximity to those failures. These domino effects of CI failures and their effect on the population of an area can be identified through different analyses. As mentioned in the report of Argonne, the national laboratory of the U.S. Department of Energy [71], *analysis capabilities should evolve towards integrating methodologies and tools*. Evolvement entails a better integration and comprehension of cyber and physical dependencies, coupling and response behaviours, types of failures, and operational characteristics and state (or efficiency) of CI assets. However, detailed information is more often found in guidelines isolated for individual sectors, e.g., hospitals, emergency power supplies, and fuel supplies.

There is, therefore, a constantly increasing need to identify the interdependencies of the various CI and the cascade disaster-related risks. For this purpose, dependency curves were initially conceived and developed for an individual asset, with the concept being expanded for systems. Precisely, bottom-up dependency curves combined with top-down approaches can capture the overall interactions among several sub-systems (e.g., CI, population, economy, and government) to better understand a region's resilience [72]. Therefore, another topic emergent from one of the seven global targets of the SFDRR [31] emphasises the need for more monitoring indicators to significantly reduce disaster damage to CI and basic services' disruptions [73]. Following these needs, eight European countries collaborated on research that has been conducted in the European project "Smart Resilience - Smart Resilience Indicators for Smart Critical Infrastructures", coordinated by the European virtual institute for integrated risk management (EU VRI EWIV), for the identification of indicators towards smart, resilient CI, leading to the so-called "smart resilient" cities. Therefore, critical elements in DRM are the knowledge of interdependencies towards enhancing the CI resilience, including strengthening the system's links (robustness) and planning for alternatives (soft and hard redundancies and resourcefulness) to enhance a region's resilience and of communities.

Knowledge of the interdependencies of CI assists a better understanding of the dynamics of their interplay. Scientists argue that a poor understanding of these dynamics may result in poor coordination between decision-makers and disaster managers and, consequently, in ineffective response in the course of a disaster, before, during and after [74-76]. Dependency curves are the tools used to determine changes in the impact on a systems' goal as a function of time [77]. One improvement of the dependency curves suggested from [71] is their integration in an emergency operations capability. **The dependency curves provide a deepened understanding of the consequences of an incident and support incident management activities.** Therefore, it is also supported in the thesis that generating dependency curves can be the first step towards the enhancement of the capability of the emergency operations, as argued in [72], to determine the changes of the impact on a geographic area and thus create simple dependency curves with widely used spatial tools, such as GIS [77]. **Approaches and tools utilised to develop such curves serve to aggregate the information in various scales essential for a deepened understanding of the risk, specifically in cities with complex interfaced and interconnected CI.**

Integrative risk management, the concept of interdependency identification from a CI resilience perspective, combining CIP and emergency management strategic goals, was analysed partially in the project "CIRmin - Critical Infrastructures Resilience as a Minimum Supply Concept. CIRmin was funded by the German Federal Ministry of Education and Research (BMBF) for several scenarios [78]. One example is that interdependencies of CI are analysed and combined qualitatively (via interviews with local stakeholders and cross-impact analysis via workshops) and quantitatively (via GIS-based upscaling spatial assessments) with interdependency analyses of CI, identifying cascading and emergent risks towards enhanced crisis-preparation in the face of an extreme riverine flood scenario in Cologne [79]. For an integrative risk management strategy, a GIS-based methodological approach was chosen to be combined with cross-impact analyses to analyse the intersecting relevant elements of the individual systems and their relationships both structurally and spatially. In [80], a practical alternative to the extensive data collection and evaluation is necessary for a wholly quantitative assessment of the complexity of the overall system under study.

Flood impacts afar from direct ones - emergent risks - need for integration in emergency response planning

Since floods have direct impacts on the population and the CI that can be assessed with diverse interdependency analyses approaches, international attention has also been given to indirect flood impacts. Specifically, international attention has been drawn to the indirect financial impacts of the floods caused by reduced CI functioning.

Hence, for example, the European Floods Directive 2007/60/EC [56] addresses flood impacts on financial activities caused by transportation disruptions and the need for capturing the diversity of the consequences caused by flood events [46, 81-83] are an essential focus. Floods and their range of impacts portrayed by:

- direct (e.g., physical damage to transport infrastructure) and
- indirect (e.g., disruption to traffic flows, business interruption. increased emissions, health, and environmental effects) impacts

are of significant focus for developing integrative and adaptive decisional processes towards their mitigation.

Although direct damages could be consistent [84], in [85] it is asserted that the reductions of the performance of transport systems due to flooding is the most disastrous factor for the societies, and it has been estimated at around one hundred thousand British pounds per hour, for each main road affected [86, 87]. Meanwhile, studies show that roads are among the leading causes of deaths in cities during flooding due to vehicles being driven through flooded roads. For example, studies reveal that the risk of being involved in a car accident while experiencing EWE and EWE-triggered hydrological events (e.g., floods) is up to 25 times higher [88-90]. Others as [91, 92] address, that accidents are related to the risk of driving through flooded road network. Furthermore, studies have proven that most fatalities during floods occur from attempts to drive or walk through flooded roads [85, 92-96]. When risks are interpreted for decision-making based on experience, people consider multiple characteristics of risks, apart from the severity of the threat or the magnitude of the potential consequences. They also rely on their ability to act for the uncertainties and ambiguities of the risk. Therefore, vehicle-related flood fatalities, rescues, and safety of the operating personnel due to driving through floodwater are a significant emergency management issue for emergency services.

Timely ER provision becomes even more challenging with the increasing occurrence of EWE and EWE-triggered hazards such as riverine floods and flash floods, specifically in complex urban areas. ER, and the pre-set strategic goal that is timely ER provision for securing the population's safety is jeopardised and driven towards failure and fatalities when emergencies demand driving through flooded road networks.

Furthermore, the operations’ costs (in time and money) are increasing when the transfer of equipment or resources should be rerouted due to highly flooded roads. Driving, and in general, operating under flooded conditions, puts at risk the lives of the emergency responders and the emergency rescue assets (vehicles and equipment). This type of risk is tightly connected with the risk perception of the emergency responders, which is different from the civic drivers, and as mentioned in [97], the rerouting behaviour is different; the call of duty is placed above personal safety. There are studies [97, 98] conducted on the Australian State Emergency Service (SES) personnel that have associated the risk perception of driving through flooded roads with a misperception of height or flood depth, water velocity and location type [99]. Against training instructions that prohibit such risky driving behaviour, 54.8% had driven through floodwaters, with most personnel experiencing operations under flooded conditions. In Germany and the city of Cologne, interviews with local officials revealed that driving slowly, when and where the conditions allow (own risk perception) is conducted in cooperation between the personnel for clearing the flooded road from floating objects. According to the Thomas Theorem from the sociology domain, *“if men define several situations as real, they are real in their consequences”*, which means that the perception of a situation is not objective; the interpretation of a situation causes the actions. From a risk perspective, the theorem could also be translated as follows: an interpretation of the level of risk causes the actions taken, and the results of the actions will reveal if the interpretation was simply a misconception of the situation and a misjudgement of the actions taken. Some studies present the number of fatalities caused by driving through floodwaters, which portrayed a constant increase, most of which are caused while driving four-wheeled trucks [97, 99]. Such statistics and outcomes support the expectation that the occupational exposure and the nature of the emergency service work is a risk factor that needs further attention since they lead to the result that the misperception of the risk from emergency responders is caused due to increased duty-related responsibility. Throughout the thesis, based on the theoretical background presented, it is supported that there is a growing need for integration of safety thresholds into developed strategies and concepts towards the safety of the emergency responders and security of the emergency rescue assets towards the safety of the population achieved with timely ER.

When emergency rescue vehicles are operating on degraded or even impaired intraurban roads due to flooding, the accessibility and response times increase. **The accessibility concerning response times, specifically in regional scales, is an indicator of relevance for assessments and integration in ER plans since it is tightly related to the critical functionality of the emergency response, that is, timely ER provision.** Accessibility as a concept and its measurement has received significant attention in transport literature and regional science [100-103]. For Germany in [104], the power accessibility indicator (dynamics of commuting accessibility) was analysed on a national level and revealed a trend towards heterogeneity in the commuting network, where the 'city-network' seems to play a significant socio-economic role. This thesis proposes that with the increasing frequency of EWE, **higher importance should be given to the accessibility indicator and analyse its performance under the stressor of various intensities and types of floods.** This information, integrated into emergency management strategic plans, will be valuable for a strengthened preparedness for response, as prioritised in the SFDRR. Strengthened preparedness for response entails developing DRM strategies, conceptual frameworks, and integrative impact models that combine various cascading risks occurring from domino failures ("safe" within thresholds and catastrophic) of the urban ER system after riverine and flash flood occurrences. Nevertheless, DRM still lacks spatial assessment tools that consider those above-identified cascading impacts (risks) of various intensities, enabling fast decision-making through strengthened preparedness called in the SFDRR [31].

1.1 Problem Identification, Research Questions, Layout & Methods

Disaster risks continue to ascend, and international frameworks, such as the SFDRR, call for more action on strengthening the preparedness for response, with adaptive management strategies that address risk explicitly and proportionate to the scale of the threat to advance the decision-making with a deepened understanding of the environment and the variety of emergent risks and opportunities. It is identified from the author that **aspects of safety of the population, the safety of the emergency responders operating under sub-optimal conditions, such as the flooded (EWE-triggered) and security of rescue assets (fire brigade buildings, rescue equipment storages and rescue vehicles), have not been extensively analysed scientifically**. Additionally, **the connection to application fields such as fire brigades, civil protection and critical infrastructure protection is not established yet**. Therefore, the goal of this thesis is to contribute to the overall goals of saving lives by cutting down losses on CI functioning, with the provision of more detailed risk analyses and boosting community resilience by enabling emergency managers to utilise:

- operationalisation adaptive resilience frameworks for SoS with CAS properties, such as the urban ER system (e.g., fire brigade system)
- large-scale hazard scenario-based, system-wide spatial resilience assessments of an ER road network, explicitly assessing its robustness, redundancy, resourcefulness and rapidity, for further performance analyses, with the application of graph theory and network science with GIS tools
- large-scale hazard scenario-based, system-wide exposure, vulnerability and risk assessments of an ER road network, with applied geoinformatics and GIS tools
- large-scale hazard scenario-based, system-wide connectivity and accessibility analysis with ER route plans and accessibility patterns and pre-planning for prioritised resource allocation

- system-wide hazard impact curves and statistical analyses for enhanced preparedness for compound or escalating events through,
- geovisualisation techniques and GIS for the exchange of information between the ERS system and CI operators, providing the means and tools for enhanced collaboration towards the safety of the population, the safety of the emergency responders and safety of the interconnected CI in an urban ER system.

Following the aforementioned conceptual background and identified gaps, the following key research questions (**RQ**) will be answered throughout the thesis.

RQ1	How can urban emergency response resilience (ERR) to riverine floods and flash floods be conceptualised towards operationalisation using graph and CAS theory?
RQ2	What is an urban ER system, and how does CAS theory identify its functional properties?
RQ3	How can the urban ERR of a fire brigade system, to riverine floods and flash floods, be operationalised, considering interdependent cascading and emerging risks on several scales, with GIS?
RQ4	How can spatial assessments be utilised to operationalise the robustness, redundancy, resourcefulness, and rapidity of ERR on several scales?
RQ5	How can large-scale exposure, vulnerability and risk be assessed with applied geoinformatics, GIS tools and graph theory?
RQ6	How GIS and network science enable identifying system-wide connectivity on various scales and levels, enabling citywide accessibility performance analysis with accessibility patterns and ER route pre-planning?
RQ7	How can GIS, graph theory, network science, fuzzification, geovisualisation and resilience matrixes accelerate the processes, raise awareness and form a basis for further collaboration between civil protection, CI operators and emergency managers?

A combination of quantitative and qualitative methods has been used and is presented throughout the text, with verification of use and further suggestions for improvements for further application of the concept of ERR to urban ER systems. In Figure 2, there is a diagram of the multimethodological approach [105], the research questions, the sections discussed, and the methods utilised.

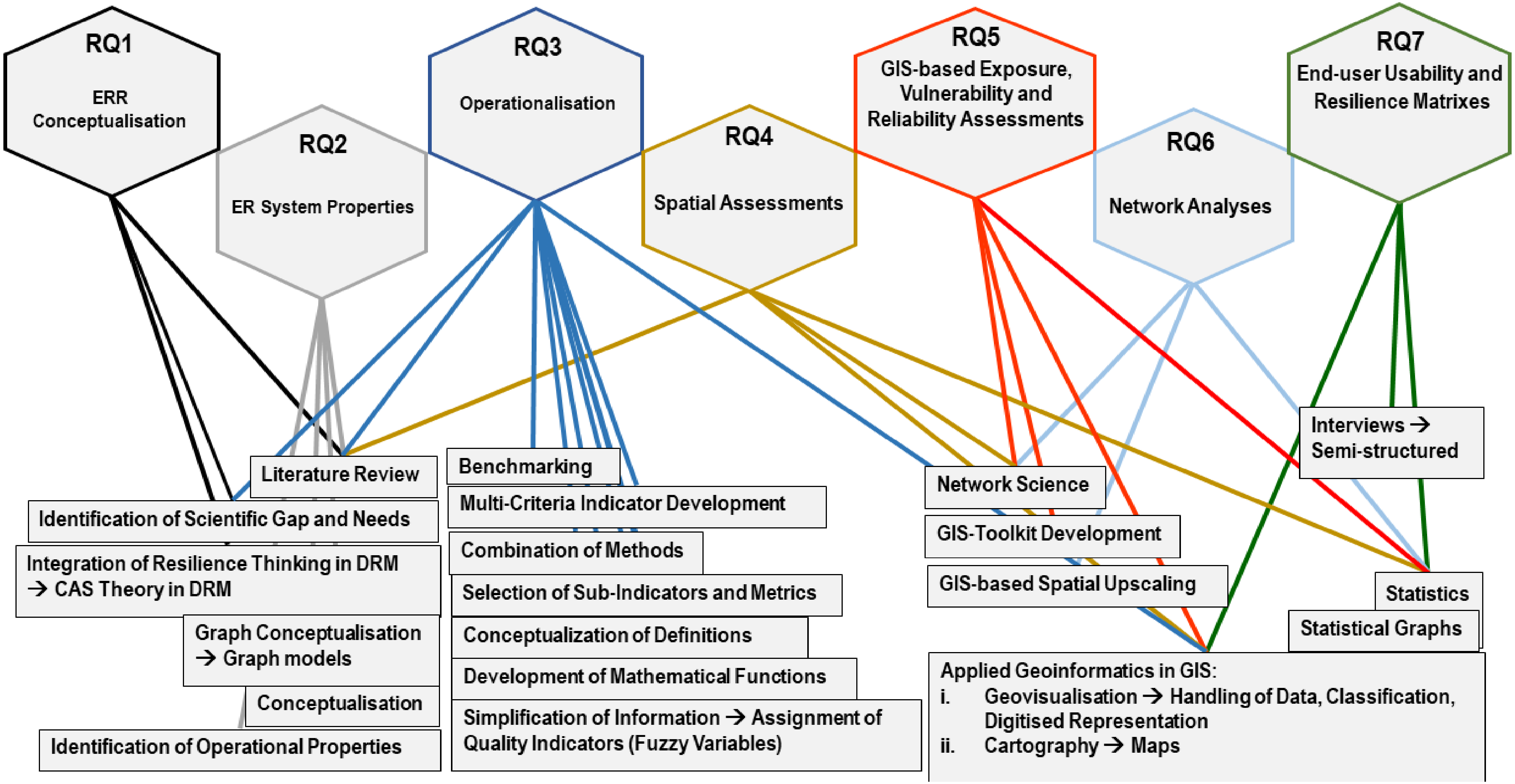


Figure 2: Multimethodological approach, research questions (RQ), sections (S) and methods

2. Resilient Urban Emergency Response (ER) System

Because there is no concept or model of an urban emergency response system ready to suit the needs for addressing its constituent CI and their networks that build relationships between them, it is necessary to conceptualise it and model it. The development of its concept, presentation of its model, definition, and identification of its operational properties are essential since they further enable detailed risk assessments towards its resilience to external perturbations, as presented in the following sections.

2.1 ER System, Interdependent Resiliencies & Operational Framework

Emergency response services (**ERS**) have been used as a case study **for modelling systems of systems** [106]. They have **geographically distributed constituent systems** that **must respond to spatially diverse events promptly**. Major accidents often require firefighters to rescue victims from vehicles or buildings, emergency medical services (EMS) personnel to be dispatched to the injured and transfer them to the nearest hospital, and police to secure accident scenes, direct traffic around it and conduct investigations, which cause traffic disruptions. Even though most of these ERS are unique to their respective organisations, some services' duplications are expected. Fire brigades often provide basic medical assistance, where they would be the first to arrive at the accident scene. In case of floods, they are the first to respond for relief and rescue, and despite the flood situations, they must operate and be timely under any weather condition. Therefore, ERS are forming their system of systems (SoS) in the environments they operate. This external **environment of operation** (complex adaptive urban system - **city**) is also **a complex SoS constituent from clusters of SoS**.

Therefore, it is suggested in this thesis that for a **strengthened preparedness for response** (as called in the SFDRR), it is essential the provision of a zoom-in designation to the individual urban ER systems and of detailed flood impact information of various flood intensities that can affect the functionality of the system (timely ER response or else timely accessibility). So, to answer the **RQ2**, based on the response capacity of an ER system in a compact urban area, **the urban ER system** is defined in the thesis **as a SoS with complex adaptive system (CAS) properties**.

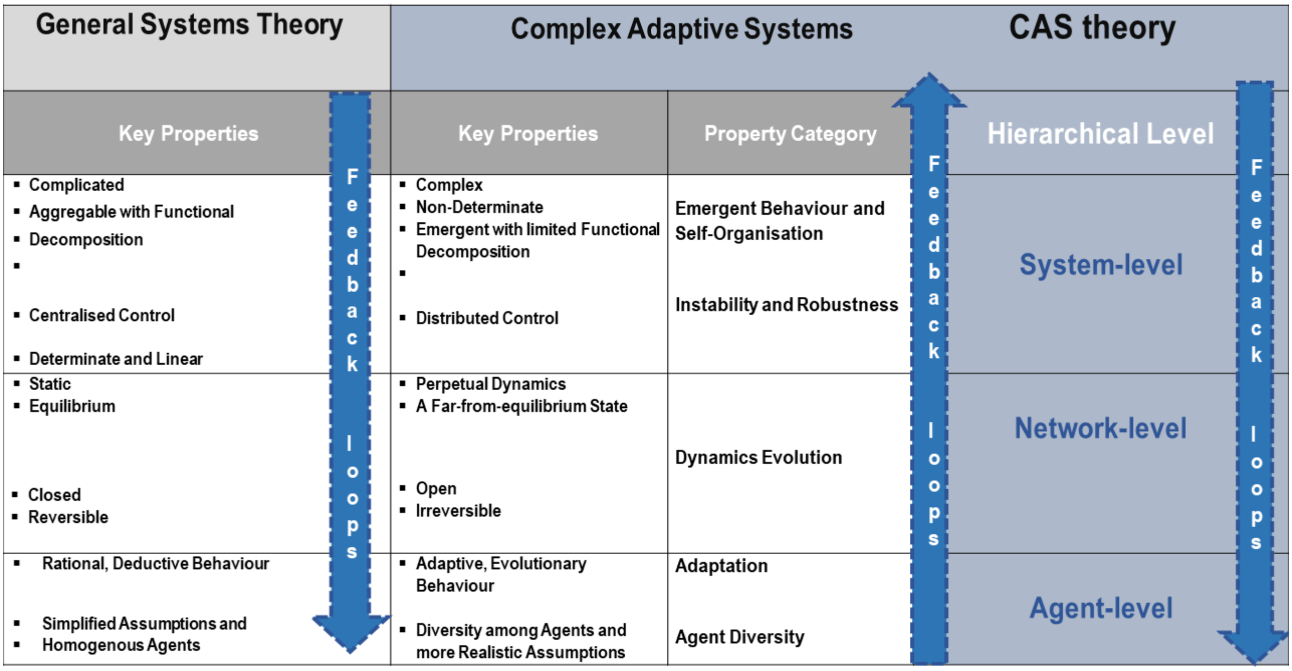
A complex system has multiple **individual agents and components highly connected and interdependent**, to the extent that emergent behavioural phenomena and reductionist approaches, such as simple theory, are not suitable for their explanation [107]. However, through the system dynamics' approach [108], leading to sustainable developments, it is possible. **CAS** (see Table 1) are, furthermore, **non-linear and self-organising systems of various diverse elements (networks and agents)**, whose interactions define the whole system and enable new patterns to emerge that are more than merely the sum of the parts [109, 110].

Self-organising systems are constituent from self-organising networks that, as mentioned in [111], *"optimise the number of attractors without becoming unstable, but they evolve their complexity"* and form the **interactions between the constituent systems** of CAS. **These interactions represent flows of information** with **feedback loops** throughout the system, which are **the source of the system's behaviour** [112].

Most systems and complex adaptive systems cannot be analysed merely by their components but must be viewed holistically [108, 109]. Complex systems such as cities produce self-similar forms identified in urban peripheries and street networks [113-115]. Despite the potential external perturbations, they keep their topological relations allowing for structuring data based on feature adjacency and connectivity principles. As mentioned in [116], a topological relation is preserved if the object is rotated, scaled or translated. This notion is taking from the complex network theory [117, 118], adopted for the systems' research providing the network modelling ability of, for example, the roads, with nodes and edges being the representatives of physical components such as junctions and intraurban streets.

Furthermore, as mentioned in [119], this theory provided a comprehensive approach for evaluating the underpinned generic properties of the complexity of system topology, i.e. robustness and resilience [120]. It is proposed in the thesis that the complex network theory, applied to SoS with CAS properties (i.e., urban ER system), enables operationalisation of such properties, risen from the complexity of a system's topology. Operationalisation is achieved by aggregating risk information from large scales on a network and system level (network, system and their components) to smaller scales, i.e., all the interdependent constituent systems, the entire SoS and their built relationships through networks.

Table 1: Properties of general systems and complex adaptive systems. Adapted based on [121]



General Systems Theory	Complex Adaptive Systems		CAS theory
Key Properties	Key Properties	Property Category	Hierarchical Level
▪ Complicated ▪ Aggregable with Functional ▪ Decomposition ▪ ▪ Centralised Control ▪ Determinate and Linear	▪ Complex ▪ Non-Determinate ▪ Emergent with limited Functional Decomposition ▪ ▪ Distributed Control	Emergent Behaviour and Self-Organisation Instability and Robustness	System-level
▪ Static ▪ Equilibrium ▪ Closed ▪ Reversible	▪ Perpetual Dynamics ▪ A Far-from-equilibrium State ▪ Open ▪ Irreversible	Dynamics Evolution	Network-level
▪ Rational, Deductive Behaviour ▪ Simplified Assumptions and ▪ Homogenous Agents	▪ Adaptive, Evolutionary Behaviour ▪ Diversity among Agents and more Realistic Assumptions	Adaptation Agent Diversity	Agent-level

In general, **from a CAS perspective**, **urban areas should be observed in a cross-sectoral** (local, regional, global) context **with interdependent components of urban development**, interacting as a whole [37]. Various studies characterise the urban areas as socio-ecological systems that impact and are impacted by the natural environment [122] - they are developed considering the environment of the components in which they consist. Furthermore, the **CI** are part of an urban environment, i.e., cities, as mentioned in section 1, and consist of **clustered and highly complex SoS**, which **involve highly complex CI systems**. Therefore, they create unique environments for themselves and society [123], allowing classification according to physical characteristics. Similarly to the **axiom of Aristotle**, seen from a complex systems lens, **the oneness can be seen in the urban ER system as a 'whole/entire (SoS)', with its parts to be the constituent systems, i.e. interdependent CI**.

Aristotle, Metaphysics 8.6 [=1045a]: The whole is superior to the simple unity of its parts
(not a simple aggregation of its sum).

Regarding the difficulty that has been declared/said for both ***definitions and numbers, what is the reason for one****? (one concept?). Because* ***of all that have more parts, and it is not the whole thing (oneness), but the parts, there is some reason;*** *because as in the bodies, in others, is the touch and in others is the stickiness or some other relevant ailment. So* ***the definition is a reason not with sections (parts) just like the Iliad, but a single one***

Word to word translation of the ancient Greek **Aristotle's Axiom** – for a free translation, see in [2]

The CI, composing the entire urban ER, are therefore interdependent through a "reason", as is called from Aristotle, and has been given identity from [70], through the characterisation of their interdependency, or else relative relationship:

- **Physical** interdependency - the material outputs of each CI is dependent on the state of the other
- **Cyber** interdependency - the state of the CI depends on information transmitted through the information infrastructure
- **Geographical** interdependency – state changes in several CI are results from a local environmental event
- **Logical** interdependency – all the connections that are not physical, cyber, or geographic.

Aristotle declared that the whole is superior to its parts. The whole, which can be considered a complex adaptive SoS, is not merely an accumulation of its systems' properties but has superior properties. This notion can be embedded in the SoS with CAS properties, which are complex, dynamic systems with evolving properties, have learned from external shocks, have self-organised individually, have improved their systems, and become more effective against external perturbations to their core capacity (critical functionality). According to [124], capacity is the ability of a system to absorb a disruption without losing its capability, i.e. critical functionality [125]. Also, resilience is defined in [126] as the *system's capacity to respond or adapt to a singular, unique and most often radically surprising event.*

For this reason, it is argued in the thesis that for improvement of the whole, that is, enhanced resistance of a SoS to external perturbations for quick response and recovery, compartmentalisation to its parts is essential. Thus, it is also argued that enables the revelation of cascading risks that often underlie crises and disasters, as mentioned in [37]. The revelation is evident after critical states are reached, and changes from one phase (pre-hazard) to another (post-hazard) occur in the systems [36]. In [107], it is also mentioned that approaching such critical states, minor influences (on large scales) may lead to increasing fluctuations of a greater magnitude (on smaller scales), indicating that the system is unstable. Considering those above, in the context of CI and for analyses purposes, [127]

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[2] http://www.perseus.tufts.edu/hopper/text?doc=Perseus%3Atext%3A1999.01.0052%3Abook%3D8%3Asection%3D1045a Accessed 29.04.2020

suggests their division into network-oriented systems (road network, electricity grid, telecommunication grid) and object-oriented systems (fire brigades, hospitals, schools, elderly homes). This division, according to physical characteristics, allows further compartmentalisation to smaller components.

CI compartmentalisation in smaller components is achieved using the **graph theory and the complex network theory (part of the graph theory)**, which introduced nodes for the characterisation of entities and links to illustrate the relationships between facilities. The compartmentalisation enables further in-depth interdependency identification towards the operationalisation of the resilience of the systems to external stressors. Additionally, the nodes and the links' spatial location are critical elements for analysing complex interactive connectivity and interdependencies in an entire SoS, considering the different risks for the two mentioned above, CI divisions. Consequently, **the compartmentalisation of a SoS, its constituent systems, CI, and networks enabled from the graph theory allow for its digitisation in geographic information system (GIS).** The digitisation of the CI systems and their networks assists with the build of databases in a GIS environment. These databases can include information on the systems' characteristics, enabling their handling for spatial analyses towards identifying and assessing a wide range of flood impacts. Therefore, to answer the **RQ2,** combining the graph theory, the compartmentalisation of the CI, and the complex urban area, the urban ER system is introduced. Furthermore, the thesis argues that the **urban ER system** ***consists of*** *these* ***CI*** *used in an emergency response system in urban areas* ***(complex systems),*** that is*,* ***ERS housing buildings (nodes)*** *and the* ***road network (links)*** *used for ER provision (SoS)*, with ***its governance to depend on three agents and their collaboration.***

The **safety of the population (Agent 1 - civil protection)** is dependent on quick response times, that is, **fast accessibility (Agent 2 - emergency management)**, highly reliant on **reliable road networks (Agent 3 - critical infrastructure protection)**. These three agents in a city decide interdependently and dependently around various strategic protective and safety goals of different foci. Reliable transport systems are valued for their safety, travel time, cost and undisrupted regularity of service [128]. These characteristics are impacted, and regularity of service, that is, drivability towards timely ER (travel time), together with safety and costs (in time and money), become one of the priorities for strengthened preparedness for ER, specifically with increasing urbanisation and increasing EWE in urban areas. Such priorities also call for tight collaboration between the three agents for common agendas, as previously presented.

The presented graphical model and its digitised form represent an urban ER system, aiming to untangle the complexity of the ER SoS in complex cities for further flood impact assessments. The cities are represented merely as a beehive of various city units, with each city unit to be representative of the clustered population and interfaced CI of their cover area (city units/scale of city-system analysis). They also serve as potential incident areas that need timely ER, despite the weather or flood impacts on the ER complex adaptive SoS. For simplification, the ER SoS will be referred to as an urban ER system with CAS properties.

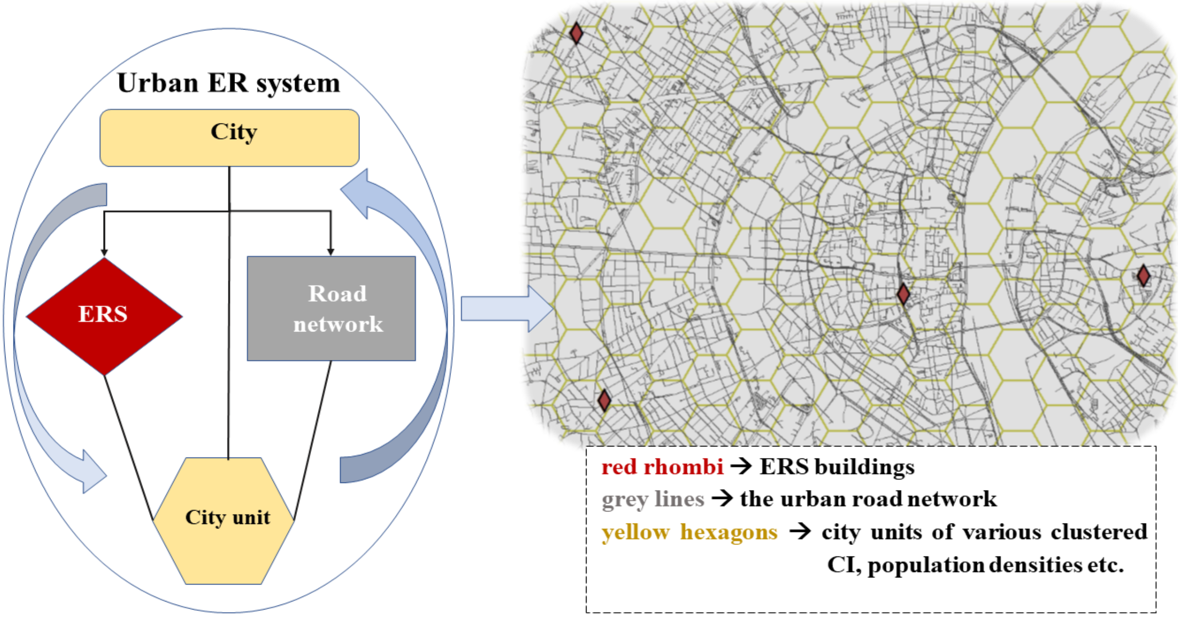


Figure 3: Graphical model of an urban emergency response system with complex adaptive properties (left) and (right) digitisation of the model in a hexagonal spatial matrix

The **representation of a SoS with CAS properties**, such as the **urban ER system** as presented in this thesis, **employs a graph** and uses the techniques provided by the branch of mathematics called graph theory. Throughout the thesis, it is argued that the representation of the urban ER system with a graph **enhances its redundancies and resourcefulness towards resilience** when also **combined with the complex network theory**, which reveals, as previously mentioned, the relationships between the constituent systems and the entire urban ER with its environment. Firstly, with the complex network theory, various analogies between specific graph metrics are possible to be established (i.e. authority and degree), as well as several risk variables - exposure, resilience (capacities), vulnerability, reliability - enabling the exploitation of these analogies for a deep knowledge of a natural hazard's impact on the exposed system (structure, weaknesses, etc.). Secondly, it is possible to use the graph as a tool for the propagation of the damage into the entire system, not only for direct but also indirect and cascading effects, and ultimately, to better understand the risk mechanisms of natural hazards in a complex adaptive SoS, towards adaptive and integrative risk mitigation strategies.

CAS theory has been applied in the concept of CI, where the complex interfaced and interdependent CI are presented as a SoS with CAS properties [121]. It has also been applied in urban resilience concepts, seeing **cities as a CAS** that, after a shock, need a constant feedback loop for adaptation and transformation to new "normalities" [107] that are enhanced or decreased resilience states. Resilience is a notion of relevance since it is interdisciplinary and has been included worldwide in DRM strategies as it offers a systemic approach to risks and analysis of risks, their conveying issues, the territories, population and management services [129]. Despite the synchronous nature of resilience in the DRR discourse, rare agreements exist regarding preferred methods for building disaster resilience in disaster and hazard affected communities [130-132]. In [133], it is mentioned that a CAS aims to provide an understanding of a complex emergent behaviour at a macro level by zooming in at micro-level interactions between inhomogeneous components. It is also mentioned that all CAS are characterised by their ability to learn from their environment, i.e., transformative characteristics.

Consequently, CAS can be constitutionally characterised by a panarchy or the ability to be influenced dynamically or adapt to changes that emerge endogenously or exogenously of the system [134, 135]. Therefore, **CAS thinking is relevant in DRM approaches when dealing with EWE and EWE-triggered hazards**.

DRM from a CAS thinking assists to find common ground for integrative DRR approaches through a resilience lens [136], specifically in complex systems. The application of systems thinking (including CAS) in understanding disaster resilience is not new [109, 137, 138]. CAS highlight the importance of researching disaster resilience (dynamic concept) through the theoretical point of view of the CAS theory [136]. DRM has utilised concepts, such as risk and vulnerability, to explain the susceptibility of humans to disasters with the formulation of possible explanations and tools for reducing the risk. **EWE that impact extreme flows** have resulted in a shift towards flood resilience and have caused a cultural change in (flood context-specific DRM) flood risk management (FRM), **suggesting the integration of complex adaptive systems (CAS) theory in FRM approaches** [139].

When resilience is defined, conceptualised and operationalised, it requires a combination of top-down and bottom-up FRM approaches and an overall integrative approach to identify the interdependence between temporal and spatial scales [139]. Therefore, **CAS engineering entails the transformation of the systems and their transition to a new normality.** Thus, the systems are characterised by a constant flux through informative feedback loops that call for adaptation and transformation. In systems (SoS) that most cities are, these informative feedback loops are cascading impacts, after perturbations from a stressor (e.g. floods), analysed with identification of various interdependencies between interfaced CI. Towards this direction, the concept of CI was introduced in [140], where a conceptual framework incorporating potential risk cascades in current FRM approaches suggests that CI resilience should be a function of hazard, vulnerability/resilience.

Considering the cascading impacts of floods presented in **section 1**, the thesis suggests that it is necessary **for the urban ER system**, is essential the **identification of perturbations first in large-scales**, caused by **direct but also emergent flood risks**, **towards resiliency of the system** under flood stress, **followed by transformation**, i.e. resilience thinking. Transformation is meant the risk of failure of the critical functionality of the system, identified through endogenous and exogenous redundancies of the system, reflected on its resourcefulness for rapid recovery and further potential transformation (it will be covered in sections 3.2 and 3.3). When specifically aiming to answer the first main **RQ1**, it is argued that the resilience of an urban ER system must focus on spatial assessments of the flood impacts on safety and time of response (delayed ER or incapacitation), which jeopardises the safety of the population and causes economic losses, for a range of scales. Therefore, ER system efficiency (performance/serviceability) assessments must include flood impacts on:

- the population - via timely response
- vehicle-related flood fatalities - by considering safe driving mobility through flooded waters
- operational costs (in time and money) - by providing flood-depth adaptive route pre-planning and
- the collaboration of task forces - by aiming to undisrupted collaboration after transforming the system (e.g. regulations, re-locations of ERS buildings).

The safety of the population (civil protection) is dependent on quick response times. It depends on fast accessibility (emergency management) and is highly reliant on a travel time reliable road network (critical infrastructure protection). TTR's most commonly accepted definition views reliability as *"the probability that the system can function to an acceptable level of performance, for some given period"* [141]. TTR is a measure of the serviceability measure, in terms of transport, of the service provided by transportation networks. Therefore, a network that provides a high level of service (i.e. undisrupted transport) has a high level of travel time reliability, i.e. serviceability. For a review of the current terms and TTR measures, see [142]. In the transport network, TTR is vital for assessing the performance of a road network under the influence of EWE, i.e. reductions of traffic speeds and therefore of the TTR from the perspective of transportation agencies and for trip-related decisions of the general public [143].

As a risk identifier and multi-faceted term for vulnerability/robustness/resilience of the transport networks, reliability has been analysed in a wide variety of studies [144-152]. With the increasing urbanisation and the frequency and intensity of the EWE (riverine floods and flash floods) in cities, these are the characteristics that are impacted and are deteriorating the regularity of urban ER systems' service, i.e. timely ER provision, which becomes even more difficult. **Therefore, for a deepened understanding of the flood impacts on the urban ER system,** it is supported throughout the thesis that **understanding the flood impacts (direct and indirect) on its networks is essential.**

Hence, quantifying the features that establish a resilient urban ER system with the combination of graph theory and network science is possible.

> *"Behind each system studied in complexity, there is an intricate wiring diagram or a network that defines the components' interactions. We will never understand the complex system unless we map out and understand the networks behind them" [153]*

Graph theory and network science [154] establish themselves as an appropriate field of study to tackle matters of system resilience, as already previously mentioned. Networks have measurable properties that can quantitatively and directly assess the resilience [155-159] of complex systems. Graph theory, as applied to network science, assists with simple graphical models of the road network. As an example, road networks are simply transformed into weighted graphs. In a graphical representation of a road network (Figure 4), intersections and streets can be modelled by nodes and edges. That is, the road network (i.e. weighted graph) is a combination of the notions of distance and location in a dual-graph [160] as introduced in the network analysis of urban streets [161] utilising the complex network theory [117, 118].

In addition, different streets of a road network have different lengths, which is an attribute modelled by assigning the length to each edge number serving as its weight (edge weight). This weight is the cost or else impedance, reflecting real-world attributes such as distance, time and latency. In case of floods, this weight can be the flood-impacted travel time from node to node, which can impair the road network's serviceability. The road network systems are analysed as physical networks, consisting of nodes (intersections) and links (road segments). In the urban street networks, edges are typical representations of street/road segments and the nodes of the junctions where two or more edges intersect [156].

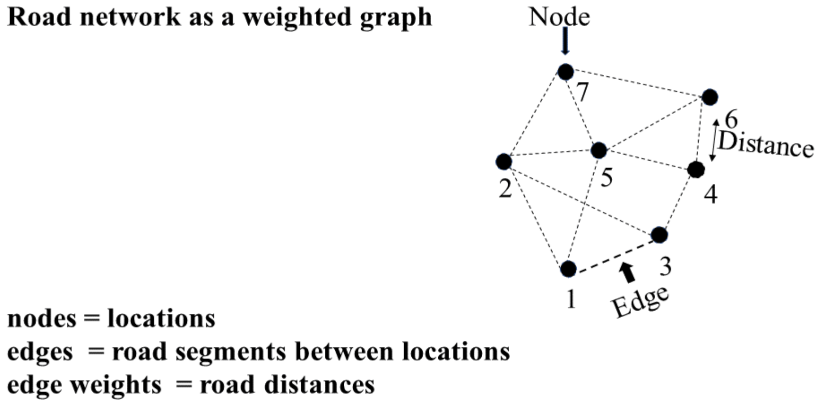


Figure 4: Road network as a non-directed weighted graph - adapted from the theory in [162]

The graphs enable data structure to deal with real-world information and incorporate road traffic dynamics [163]. Furthermore, these characteristics of graphs can be utilised, for example, to improve the ability to avoid or limit the direct and indirect effects (exposure and speed changes respectively) of hazard events (such as flooding) where possible.

Such hazard-related impact analyses need a higher level of comprehension of the behaviour of networks (from a road segment level to the entire road network) under hazard conditions, enabled by the complex network theory [120].

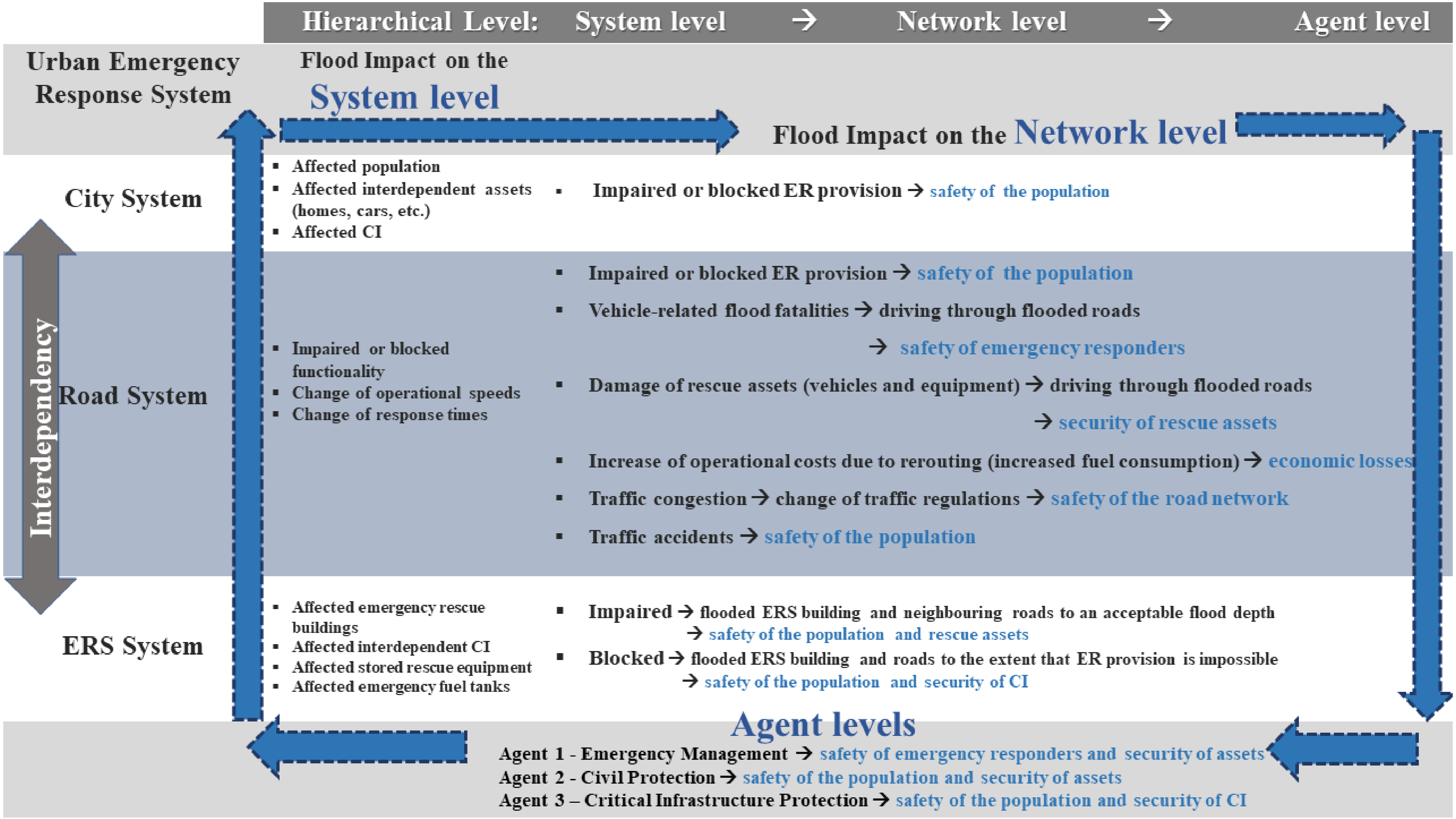
The behaviour of networks and improved modelling methodologies and techniques allow for assessing mitigation alternatives to reduce the hazards' impacts [164]. For this reason, in the case of floods, the impacts on the road network, i.e. physical (on nodes and links), need to be addressed with various climate models enabling simulation ability for current and future events [165] and in large scales [166]. Scientists agree that for enhancing the effectiveness of emergency plans, information on both vulnerabilities and risks must be identified in local scales [167, 168]. Therefore, it is argued throughout the thesis that such agreements entail large-scale flood impact assessments on the road network, followed by propagations to the entire urban ER system.

Large-scale assessments on flood impacts in order to be analysed must be benchmarked considering the critical functionality of the urban ER system, i.e. timely ER provision and safety of the population. An adverse event in an urban area, such as riverine floods and flash floods, flood depth (FD) is appropriate for benchmarking the ER system and will be used further. FD is the primary risk factor taken into consideration in many flood impact-related studies of various research foci, such as (indicatively) risk perception, trafficability, vehicle stability, mobility disruption, mobility preparedness, accessibility, and economic losses and delays, i.e. travel time reliability (TTR) [85, 97, 142, 169-191]. For a resilient (timely) ER provision, identification of various impacts according to flood depth (FD), direct and emergent (indirect of second-and third-level) are presented in Figure 5. Identification of such impacts is supporting these notions from a CI perspective [72], from an FRM one [139] and a combination of both [140]. Categorically, the bottom-up dependency curves can be combined with top-down approaches so to capture global/overall interactions among several sub-systems (e.g., CI, population, economy, and government) for a deepened understanding of the resilience of a region [72] or community [137].

Therefore, this thesis discusses that for research focusing on the emergency response, the benchmarking considering flood depths for safe driving allows for further efficiency assessment of the urban ER system under several flooded conditions to enhance the population's safety. In the era of unexpected EWE, there exists an ever-increasing need to recognise the value and importance of a comprehensive interpretation of the plethora of interacting social and technical processes, considering socio-technical regimes, i.e. the population and their safety in ER plans under various flood scenarios. Therefore, it is argued that the representation of an urban ER system with CAS properties allows for identifying cascading flood impacts on several levels of the network, considering interactions with its environment (see Table 2), and allowing further resilience assessments.

The resilience concept emphasizes the temporal development after an event stressing the rebound phase after an impact [40]. The ability to bounce back to desirable states entails the timely recovery of defined critical functions and basic structures [192]. Timely recovery depends on communities' access to resources and their organisational capacities before and during the occurrence of a disturbance [31, 73, 83]. The emergence of innovative measures also plays a role [193], conceptualising disasters as a *catalyst for change*, enhancing the preparedness phase for resilience [194]. The consideration of the urban areas as dynamic systems (i.e. CAS), suggests that policy responses often derive from an interrelated set of decisions in decision cycles, where factors that shape initial decisions (early phase) affect further decisions [195]. For a CAS, such as the urban ER system, focusing on the operationalisation of only the recovery speed, as a resilience assessment, oversees the ability for transformation into new and less vulnerable states. Therefore, within resilience research and consistency, when considering resilience in FRM, temporal and spatial scales should be explicitly acknowledged [139].

Table 2: The urban emergency response system (ER SoS), with impact levels according to flood depths and their identified direct and emerging risks on an agent, network and system level



Hierarchical Level: System level → Network level → Agent level

Interdependency

Urban Emergency Response System	Flood Impact on the System level	Flood Impact on the Network level
City System	▪ Affected population ▪ Affected interdependent assets (homes, cars, etc.) ▪ Affected CI	▪ Impaired or blocked ER provision → safety of the population
Road System	▪ Impaired or blocked functionality ▪ Change of operational speeds ▪ Change of response times	▪ Impaired or blocked ER provision → safety of the population ▪ Vehicle-related flood fatalities → driving through flooded roads → safety of emergency responders ▪ Damage of rescue assets (vehicles and equipment) → driving through flooded roads → security of rescue assets ▪ Increase of operational costs due to rerouting (increased fuel consumption) → economic losses ▪ Traffic congestion → change of traffic regulations → safety of the road network ▪ Traffic accidents → safety of the population
ERS System	▪ Affected emergency rescue buildings ▪ Affected interdependent CI ▪ Affected stored rescue equipment ▪ Affected emergency fuel tanks	▪ Impaired → flooded ERS building and neighbouring roads to an acceptable flood depth → safety of the population and rescue assets ▪ Blocked → flooded ERS building and roads to the extent that ER provision is impossible → safety of the population and security of CI

Agent levels

Agent 1 - Emergency Management → safety of emergency responders and security of assets
Agent 2 - Civil Protection → safety of the population and security of assets
Agent 3 – Critical Infrastructure Protection → safety of the population and security of CI

Therefore, following the disaster and emergency management cycles, which are often interconnected (e.g. emergencies occur before, during, and after a disaster), it is argued that DRM needs to be advanced. Advancement, considering the needs mentioned above, is achieved with integrative resilience concepts considering cascading risks and impact consequences triggered from EWE in complex city environments towards strengthening the preparedness for response by characterising an urban ER system with CAS properties. The resilience concept allows for considering unexpected events, such as the EWE and their disruption to the emergency response system. Viewing the resilience concept from a CIP lens, integrating "safe failure" into the design structures promotes a higher degree of flexibility, accounting for a diversity of flood-related cascading risks [196]. Therefore, the thesis suggests that a resilience concept dealing with DRR and impacts of EWE, such as floods on the urban ER system, should consider cascading risks on organisational, technical (endogenous), economic and social (exogenous) environments (see Figure 5), viewing the process with resilience thinking due to the complex adaption capacity of the system.

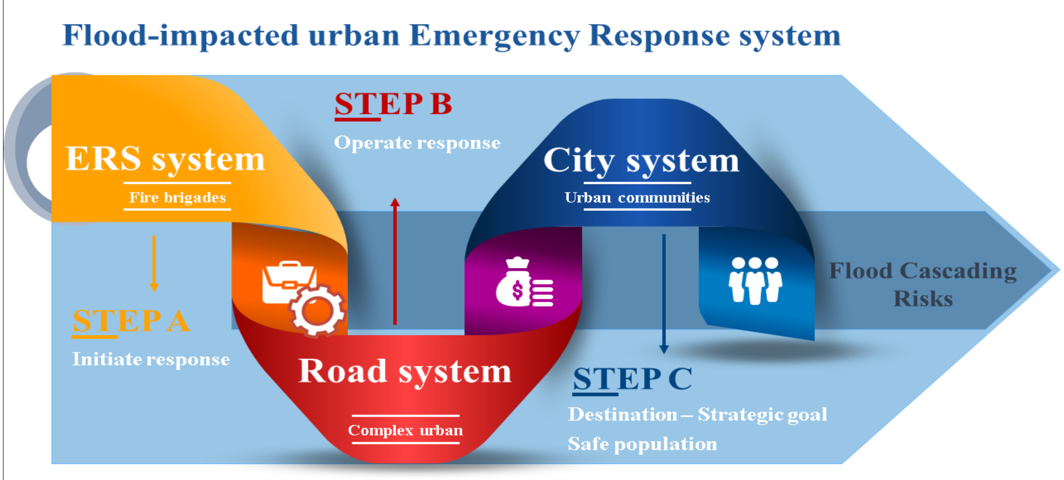


Figure 5: Flood-impacted urban Emergency Response system, indicating organisational, technical, financial and social (endogenous and exogenous) interconnected cascading risks

The research conducted in **the thesis aims to advance the general understanding of the resilience of CAS, such as the urban ER system, and shift the focus from the principal focus of recent studies on *'what can be damaged'* after floods**. That is, a shift away from the silo-based thinking of DRM approaches **to *'how can it operate best under substandard conditions'*, considering users (emergency responders and population) and their behaviours from resilience thinking to restore capacities**. Therefore, the focus of analysis is shifting to resilience-based capacity and efficiency assessments of the urban ER system. These are quantifiable characteristics in many DRM approaches, specifically in regards to infrastructures. In [197], quantitative risk assessments are intelligible and effective for developing risk management practices, only when the disruptions and infrastructure functions are similar to those that have occurred in the past since the impacts are well identified and defined. Risk assessments and related DRM, as currently implemented, have several shortcomings, such as:

- a limited ability to consider new multi-level hazard scenarios due to a lack of past data on the performances

- the limitation of the research to the quantifiable aspects of a system for the prevention of failure of single components with engineered solutions, omitting consideration of the more extensive system and
- the overall acceptance of residual risks without preparation for their future occurrence or preparation for their potential updated states.

An effort to ‘look at the whole’ of an issue is embedded in resilience thinking, according to the commonly used resilience concept [198]; to include a relevant problem environment in one’s definition of a modelling, governance problem or design.

Therefore, for the operationalisation of an urban ER system, resilience is chosen. The resilience concept acknowledges the fundamental interdependence and interrelatedness of all things [199] after identifying critical functionalities and thresholds. As argued and presented in the previous section, resilience thinking is a prerequisite in CAS systems when resilience is defined.

Resilience thinking must be captured in the conceptualisation framework and the definitions of the properties towards operationalisation. Hence, this entails combining top-down and bottom-up FRM/DRM approaches and a more integrated/aggregate approach to the interdependencies between temporal and spatial scales. From a CAS perspective and towards the conceptualisation of the resilience of a SoS, the “interdependent resiliencies concept” is proposed, where resiliencies regard its clustered CI that compose its constituent systems. For the assessment of the resilience of a SoS to hazardous events that reveal its resilience levels, it is suggested, the development of a top-down assessment approach focusing on its resilience features and depending on its constituent systems’ resilience capacity levels, which are further dependent on the resilience of its clustered CI. The **interdependent resiliencies concept**, suggested in the thesis, further proposes the combination of the **top-down approach with a spatial upscaling operationalisation approach** for a **comprehensive resilience assessment of the SoS**, assessing the risk and the resiliencies of its networks and constituent systems on larger to smaller scales in the face of hazardous events (e.g. floods) (see Figure 6). Specifically, in Figure 6, the interdependent resiliencies concept can be operationalised by combining top-down approaches (black arrows) and spatial upscaling methods (red arrow).

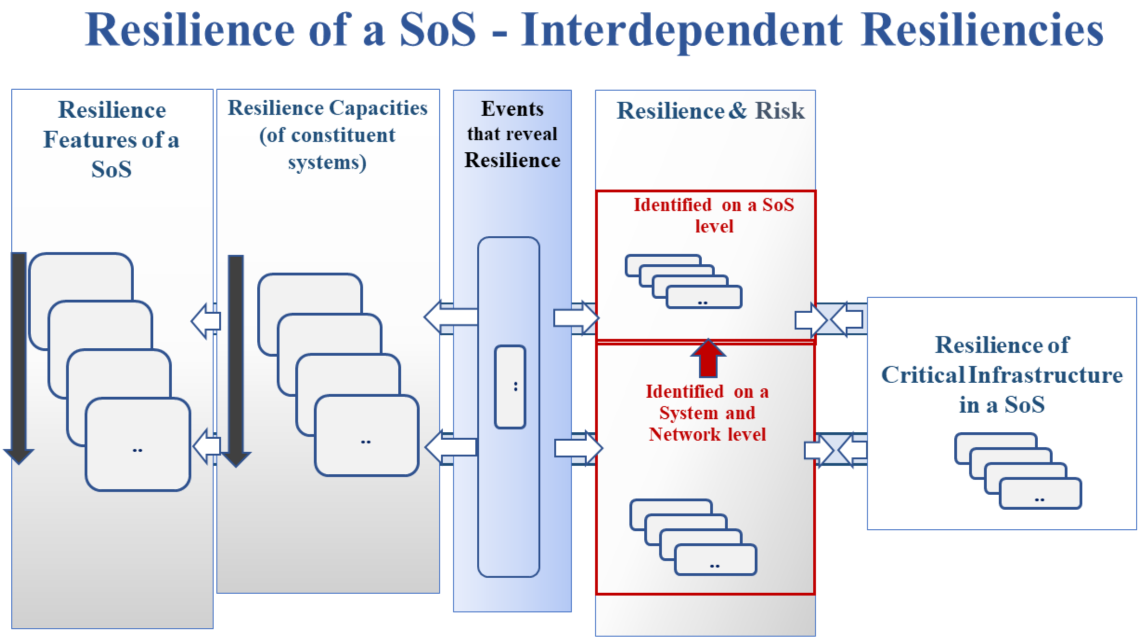


Figure 6: Conceptualisation framework of the resilience of a SoS, towards its operationalisation

So to present the flux of resilience and risk information across the systems and networks of a SoS, for comprehensive assessments of its resilience to hazardous events, white arrows are used. It is stated in [125] that a resilience management framework includes risk analysis as a central component. The risk analysis depends on the characterisation of the threats or hazards, such as floods, vulnerabilities and consequences of adverse events on the systems' capacities, to determine the expected loss of critical functionality.

In [124], capacity is defined as *the ability of a system to absorb a disruption without loss of capability*. For example, the resilience capacity index (RCI) is a term used to describe the ability of a geographical region to adapt to changes and is used to compare the ability of different metropolitan regions to handle disruptions.

This thesis argues that the critical functionality of the urban ER system is determined on the systems' level after EWE-triggered disruptions in the networks' level according to FD levels. Therefore, this enables the encapsulation of the flood impacts on the constituent systems' resilience capacities, modelling simulations towards operationalisation, absorbing, adapting, and transforming rapidly to respond in case of floods, thus making it resilient. Additionally, it is argued that risk assessments conducted on large scales and network levels enable the identification of the constituent systems' capacities of the urban ER system (SoS with CAS properties) for further resilience assessments or flexibility assessments (ill-functioning SoS, but self-organising for future resilience). For this purpose, the impact of the FD levels on the hierarchical urban ER system characteristics is of focus throughout the thesis to benchmark its capacities towards operationalisation. The benchmarking assists the untangling of the system's complexity, as analysed below, and follows the umbrella concept that resilience enables analyses of the interactions across various domains and scales [200].

More specifically to the resilience systems' concept, in Germany, the Federal Ministry of the Interior (BMI) in 2018 refers to resilience, considering the critical functionality of a system, and it is defined as the *ability of a system to resist or adapt to events while maintaining or rapidly recovering its ability* *to function.* The ability to function refers to the criticality assessments conducted on the studied systems, which enable the system's threshold and the definitions of the priorities on a temporal and spatial scale [139], after which criticality levels are assessed according to the risk and expected losses [125]. Furthermore, this is also reflected in the Cities Resilience Index's urban resilience term [201]. The CRI is formed from the consortium of the Rockefeller Foundation, 100 Resilient Cities (100RC), where resilience is described as "*the capacity of individuals, communities, institutions, businesses and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience*". In the Cities Resilience Index [201], the features of resilience are introduced, which cities and CI need: i) flexibility, ii) redundancy and iii) robustness (or hardening). In this report, redundancy refers to the *"spare capacity purposely created within systems for the accommodation of disruptions" characterising redundancy as "duplicating how a need is met"* and flexibility of systems is characterised by their ability to *"change, evolve and adapt to changing circumstances".*

Specific to CI networks, in [202], **redundancy** is defined as *"duplicating the means by which a need is met"* and **flexibility** as*" meeting multiple needs through multiple different components".* These definitions help characterise different scales of the same resilience properties [203] and incorporate resilience thinking from a CAS perspective. In [201], it is also mentioned that "robust" systems are those, which can *"withstand the impacts of hazard event without significant damage or loss of function".* The definition of robustness is adopted from the official transport resilience definition of the United Kingdom [204], "*to withstand the impacts of extreme weather, to operate in the face of such weather and to recover promptly from its effects"*, provided after the devastating EWE in 2013/14 [205].

The US Transport Research Board defines **resilient** a **transport system** that can "*withstand the impacts of extreme weather, to operate in the face of such weather and to recover promptly from its effects"* [206]. With a focus on the emergency operations and their interdependence on the reliability of the transport network to provide timely ER, the US Transport Research Board [206] conducted a report highlighting the importance of transit in emergency evacuations with a transport resilience thinking following the terrorist attacks of September 11, 2001, and the Hurricanes Katrina and Rita in 2005. It was highlighted that both the capacity and resilience of transit and highway infrastructure affect the levels of success of the use of transit in an emergency evacuation [207].

These definitions of resilience and its properties either focus on DRM approaches for a city-network, a CI and CI networks, or altogether, have as common ground the extension of functionality margins of the systems, either actively or passively.

The National Academy of Sciences [208] definition of resilience places **risk** in the broader context of a system in its **ability** *"to plan and prepare for, absorb, respond to, and recover from disasters and adapt to new conditions".* Continuing, *"an important feature of resilience captured in this definition is the temporal dimension: the ability to recover and retain critical system functionality in response to a wide range of threats, both known and unknown*." In the thesis and regarding the critical system functionality of an urban ER system, the identification of the hierarchy plays a significant role in pinpointing the "zero point" of the cascading risks, analogous to the functionality for a deepened understanding from larger-scales to smaller ones. Thus, **identification of the hierarchy assists with untangling the systems' complexity and the development of risk mitigation approaches.**

When dealing with SoS with CAS properties, it must be prioritised to find the **hierarchy** between the interdependent networks. For example, the road network is highlighted in Table 2 because it serves as the primary connectivity node between the networks of the urban ER system. For example, its system's degradation after the occurrence of floods is highly affecting the urban population and ERS, as presented.

The CAS are hierarchical and non-linear, and therefore, adapted from [209], a SoS with CAS properties is a system where the 'higher' levels in hierarchy serve the 'lower'. As aforementioned, the **'higher' in the hierarchy in an urban ER** is the **road system** and therefore, its **transport characteristics** (Figure 7) will be the ones considered for **operationalisation**, that is, **accessibility according to connectivity, depending on traffic and mobility disruptions**. **Connectivity** is an indicator used in many **resilience** concepts (social, economic, environmental/physical and institutional) since it brings humans, objects, attributes, and economies to a connected network fostering constant adaptation, transformation and resilience. Moreover, it is supported throughout the thesis that it can be a valuable **indicator for large-scale analyses**, providing insights on the level of resilience of urban areas with an upscaling approach. This notion has been adopted from the concept of local spatial resilience [210]. In the thesis, connectivity is adopted as a weather impact identifier reflecting on the accessibility of an urban area or CI, such as the road network and the ERS buildings. Furthermore, in this era of increased frequencies of EWEs and considering the tight interface and interdependence of the ERS, the road network and the population (capturing the socio-economic environment), it is suggested that: *strengthened preparedness for ER is achieved with connectivity analysis of the urban ER road network, adaptive ER route plans and flood risk- and place-based time-dependent accessibility assessments*.

To that end, **flood impacts** on the system of the ER road network caused by, for example, **speed changes** and consequently **travel time changes**, will affect the **critical functionality of the urban ER system**, i.e. citywide **timely ER**. The latter flood impact is reflected in the **accessibility** component and the **time of response** of the system. So to identify the **robustness** and **flexibility** (**redundancies** and **resourcefulness** levels) **of the urban ER system**, the multi-scale analysis with a zoom-in and zoom-out effect from **larger to smaller scales**, enabling the **information feedback loops**, is required when **assessing the resilience of a CAS system** (urban ER system).

For this reason, and moving away from the so far conducted silo-approaches of accessibility assessments, the three transport perspectives that are included in transportation planning, i.e. as mentioned in [211], are the traffic and mobility, and the focus for the resilience assessment of an urban ER system, conducted in the thesis. The thesis suggests that taking from these transport perspectives for adaptation (see Figure 7), the ER road network's system functionality is operational after consideration of the following focal traffic and road network characteristics:

- **traffic characteristics** of the ER road network – Free-Flow Speeds (FFS) and Travel Time for efficiency assessment of the ER road network and further ER route planning purposes (used from each ERS for operational ER route planning after the occurrence of incidence),
- **mobility characteristics** of the ER road network - road network's mobility capacity (RNMC) for safe driving of rescue vehicles through flooded waters, according to ERS capacity in resources, i.e. rescue vehicles of different heights
- **accessibility** of the ER road network - citywide accessibility based on a travel-cost approach, depending on the **connectivity of the ER road network**, used as a weighting factor for further resilience assessment of the entire urban ER system.

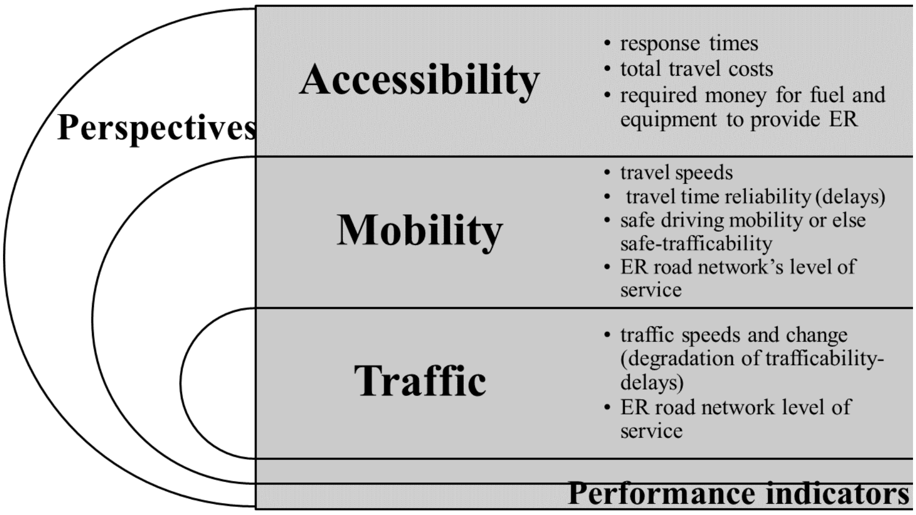


Figure 7: Transport perspectives and performance indicators. Adapted from [211] for ER road networks

The risks of the systems, particularly the impacts of stressors (floods) to the system (direct), its characteristics (indirect second-order) and its environment (indirect third-order), are interdependent, and an adverse event has a cascading impact effect on all its levels. A CAS is in a constant state of flux and is usually balanced between stasis (the extremes of order) and chaos (anarchy). Shifting the emphasis on impact analysis rather than on the probability of occurrence analysis [212] is relevant when dealing with unpredictable EWE such as riverine floods and flash floods on an urban ER system. Therefore, the flood intensity factor is introduced into the curve (Figure 8), providing opportunities for strengthened preparedness for response.

Intensity is defined as a discrepancy from frequent/regular events [10], and therefore, high intensities characterise extreme events. For this reason, a focus on the flood intensity shifts the emphasis of EWE analysis to the impacts' estimation, away from the siloing in current DRM approaches that focus on the determination of the occurrence probability.

Intensity impact analysis is highly relevant also for SoS with CAS properties since a CAS is a best-fit tool for the analyses of systems characterised by a constant change -*"functioning at the edge of chaos"* - [136] and constitutes what can be described as "moving targets" or anarchies [137].

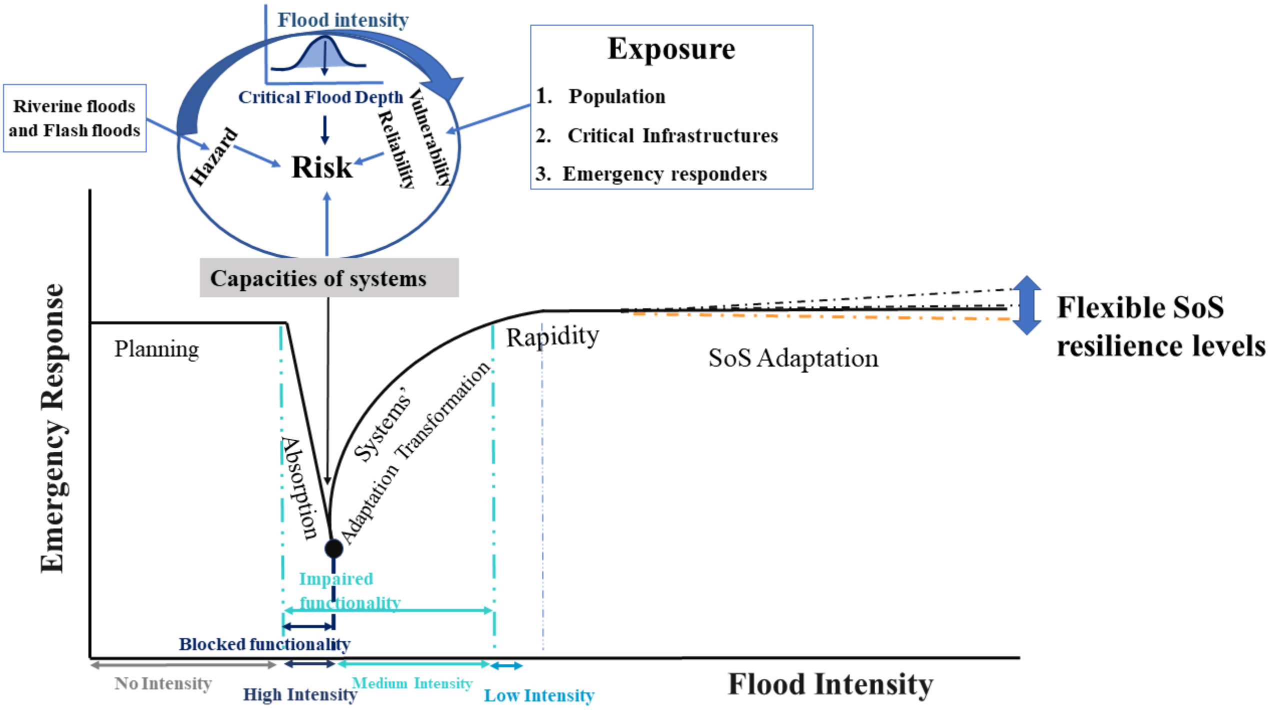


Figure 8: Urban Emergency Response (System of Systems) Resilience curve to riverine floods and flash floods. Based on [125, 213, 214]

Therefore, in answering the **RQ2**, in the SoS functionality profile (Figure 8), **risk in a system is interpreted as the total reduction in the critical functionality**. Additionally, **resilience**, as adopted from [125], **is revealed after a flood event at a large-scale** (bottom-up scaling approach) **and small scale** (resilience of the SoS with CAS properties) and **both**, risk and resilience are **related to the slope** of the absorption curve and **the shape** of the rapidity curve. The slope of the curve is indicative of the temporal effect of the adverse event. **Transformation occurs at the network level for the rapid recovery of the SoS and its return to updated normalities regarding** the initial functionality. It is argued that assessments of transformation levels, it is argued that are indicative of the risk of failure of the functionality of the constituent systems and the entire SoS.

The **ERR curve** is based on the concept presented for the resilience curve from [125], combined with **hazard intensity thresholds integrated into the resilience concept** from [213] and the **concept of operational survival**, introduced from [214]. It is presented in the thesis that **risk** must be interpreted with the **overpassing** of these **thresholds** so as to provide **optimal flexibility to the urban ER system**. This overpassing of thresholds is additionally leading the system to function with a state at “the edge of risk or else chaos”, but still giving the opportunity after absorption of the stressor’s impact, for transformation to a new regime, towards global/overall transformation of the system and resilience. Therefore, the risk could be a part of how systems function, considering risks from a temporal and scale aspect to understand its role better.

Risk as a part of a systems’ function is proposed in [215], where it is stated that *the reduction of risk without an understanding of its role within the larger socio-ecological system might reduce the system’s overall level of disaster resilience.* It has been specifically demonstrated that the determination of the operating performance of an operation, the minimum performance towards sustainability and the planning objectives, are established towards the resilience of the CI [214].

As minimum operating performance is characterised by the level at which the operation can minimally function without causing additional damage or system failure [202]. Such notions are relevant in the **complex adaptive urban ER system** since stability/equilibrium is not an option in complex systems and SoS, and a **decrease of stability** is expected **analogously to the level of complexity** [216]. For example, **wrong decisions** taken at an **agent level, for the routing paths** leading to an incident area, without considering the impact of a flood in the RNMC at the route-planning phase, **increase the probability of the risk** for **delayed or blocked ER provision, as well as, the risk** for **the lives of the emergency responders**. Consequently, the resilience of the system is jeopardised at many levels, as indicated in Figure 5.

As mentioned in section 1, the operating performance is reflected in the dynamic nature of the urban resilience, which presupposes that policy responses often derive from interrelated decisions in decision cycles where factors that shape initial decisions, at an early stage, affect further decisions [195] at a later stage (i.e. driving through flooded waters) - based on the Thomas mentioned above Theorem. Resilience is being used as a term emerging from ecology to describe the capacity of natural ecosystems [217], which are examples of CAS that maintain or recover their functionality in the event of perturbation, considering the rise of systems thinking [200]. In systems-thinking, the performance of the complex systems (following the Axiom of Aristotle) and, as mentioned in [218], is more than the performance of its parts; in the case of complex adaptive SoS, more than the performance of its constituent systems. Therefore, the **resilience analyses** of these systems should **focus on the relations** between **their constituent systems** and **their adapted interactions for a potential emergent performance**, utilising **its flexible identity**.

Cities, as previously stated, are complex and constantly adapting systems, and consequently, ER is following this constant adaptability; therefore, resilience is equally applicable in the way it is managed. For this purpose, **in the case of a SoS such as the urban ER with CAS properties, resilience must also be seen as a cluster of interdependent resiliencies of the constituent systems, their components and relations that reveal their resilience capacities**. As an example, it has been demonstrated in several studies that there is a strong resilience interdependency between the resilience of cities and the CI resilience under the stressor of floods [219, 220].

2.2 Emergency Response Resilience (ERR) to Floods

In this section, the **RQ1** is answered by identifying the critical functionality of a system so to assess resilience combined with evaluations of the temporal profile of system recovery in response to adverse events. Therefore, the ERR management to riverine floods and flash-floods, adopted from [151] and adjusted to the subject, should evaluate cross-domain alternatives designed to enhance the ability of the urban ER system to:

- plan for various intensities of diverse flood type events
- absorb the stress technically and in operations
- transform so to recover rapidly
- predict and prepare for future flood events in order to adapt to their potential flood impacts.
- prepare for potential escalating or compound flood events.

It is widely accepted that different impacts of floods on communities, economies or ecosystems are analysed with quantitative, semi-quantitative and qualitative research (indicator-based approaches and surveys, online or personal) in disaster risk, vulnerability and resilience studies [221]. Most of the resilience concepts are mainly assessed through qualitative approaches or semi-quantitative [151]. For example, [222] identified four dimensions of earthquake resilience: technical, organisational, social, and economic. The measures of resilience such as *robustness, redundancy, resourcefulness and rapidity*, known as the 4R features of resilience, were then aggregated to minimise a function of the probability of system failures, the consequences of such failures, and the recovery time [223]. The 4R features of resilience have been used extensively from scientists since they are widely recognisable and enable interdisciplinary adoption of approaches, methodologies, metrics and tools, and according to the context, they allow for quantification approaches of resilience, which are rare. They are appropriate for a simplification of the complexity of the information that can entail assessments of highly complexed systems and environments and allow for adaptation and transformation, which is essential when assessing SoS with CAS properties (urban ER system), under the stressor of EWE.

Generally, the research aims to advance the perception of risk regarding a wide range of multi-level and multi-scale flood impacts. Recent flood impact studies focus on '*what can be damaged'*, but the thesis focuses on answering the question *'how can it operate best under sub-optimal flood conditions'* at a minimum operational performance in order to restore capacities, while considering safety and security aspects, enhancing the safety of lives and security of assets. As presented in section 2.1, the urban ER system is modelled and narrowed down to those CI, which are tightly interconnected in urban areas and are primarily used by emergency managers in a crisis/disaster event, i.e. the road network and the emergency rescue service of research (ERS). Considering the need for resilience thinking in resilience conceptualisations towards operationalisation frameworks, extending the capacities and resilience of the interfaced systems of a SoS, the resilience of the urban ER system must envisage the:

- CAS identity of the urban ER system,
- the need for integrative resilience approaches due to the increasing EWE (climate change),
- need for identification of cascading impacts (direct and indirect) for integrated
- appropriate benchmarking considering safe driving mobility of the rescue vehicles and timely ER.

Throughout the thesis, the idea of an urban ER system as a SoS with CAS properties has been discussed. The combinatory network relation between the ERS and the city-network is identified as the road network, as presented in Figure 4. Therefore, it is suggested that, when dealing with EWE, the *'geographicalness of a flood'*, i.e. the geographical perspective and its impacts on several scales and levels, need to be assessed for enhancement of the emergency response resilience (ERR) on a city level. Therefore, **Emergency Response Resilience ERR** (Figure 9) *is considered a system of systems that it is expected to plan for and withstand the impacts of extreme weather of various intensities, to operate at a sufficient level after absorption of the impacts, in the face of such weather, and to transform rapidly for recovery.*

A key feature of the resilience captured in the ERR's definition is the **flexible dimension** (see Figure 8), highlighting the ability to transform so to retain critical system functionality in response to various EWE, that is, timely ER delivery under any flood condition. The proposed definition of ERR is considering the definitions of the national academy of science [208] and the transport network resilience [206], **integrating the CIP lens with "flexible" resilience properties (robustness, redundancy, resourcefulness, rapidity)** as defined below. In this case, flexible refers to the flexibility they can include to aggregate information from different temporal and spatial scales and their strong interrelation (interdependent resilience properties – see Figure 9). The definition is aiming to give a **CAS identity to the urban ER system's resilience** definition.

In this way, the flexible ability to the SoS for sub-optimal functioning is provided through the extension of its redundancy and resourcefulness, which is not resulting in high functionality losses (delays or blockages of ER, decreased safety of the population) or damages (rescue vehicles, decreased safety of the emergency responders).

Therefore, an urban ER system, so to be resilient, must be characterised by its:

- **Robustness:** the efficiency of the ER system to sustain its identity, under the direct impact of any stressor, providing safety of the people and security for all its networks objects
- **Redundancy:** the ability of the ER system for absorption of direct and indirect impacts of the stressor towards adaptation and further transformation (passive redundancy), providing alternatives for building capacities (active redundancy)
- **Resourcefulness:** the capacity of resources of the ER system (active and passive risk) under direct and indirect impacts of any stressor
- **Rapidity:** the ability of the ER system to rapidly recover from the direct and indirect impacts of any stressor, sustaining its functionality while transforming to a new updated regime.

The definitions are based on the transport network resilience concept and definitions mentioned earlier.

Nevertheless, despite the conceptualisation of a SoS's resilience and its four key features according to context enabled from its character, as mentioned in section 2.1, there is still a **lack of operationalisation frameworks that combine the CIP perspective and the geographical perspective**. Moreover, focusing on intraurban CI while also considering the interdisciplinary concept of spatial resilience and CI resilience. In general, there is scarce literature using spatial assessment tools for disaster/flood resilience operationalization, which impairs the credibility of the multi-surface resilience concept for both science and decision-making.

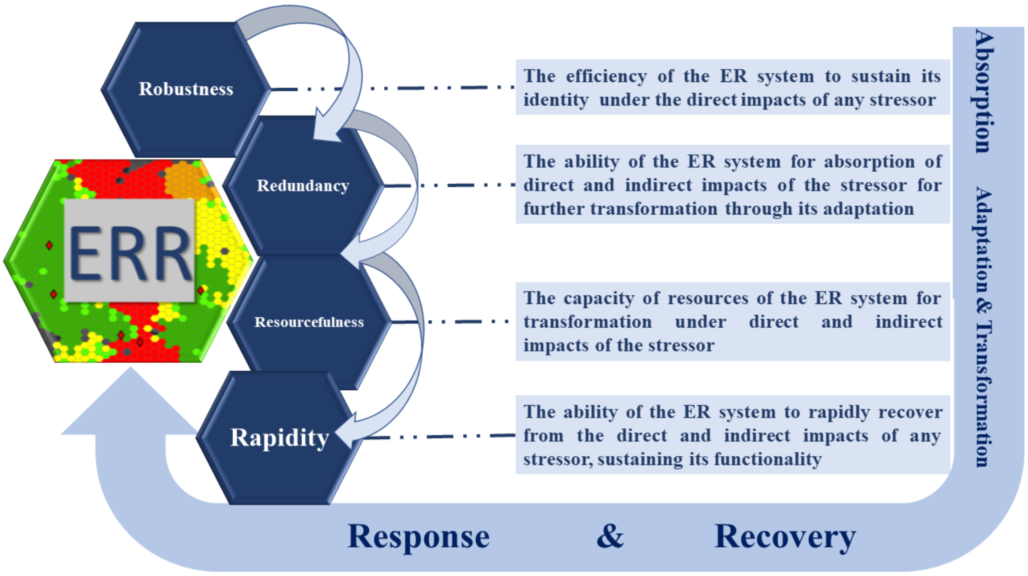


Figure 9: Emergency Response Resilience (ERR), key features and resilience capacities - according to [206, 208]

2.3 GIS & Spatial Thinking for Operationalisation Purposes

In this section, the ERR is conceptualised for operationalisation. Proceeding to answer the **RQ1**, it is highlighted in [224] that common challenges in resilience operationalisation frameworks when building a resilience concept towards becoming more operational are, after specification of boundaries:

i. the definition of analysis' scale, both geographical and temporal, answering the question *'resilience of what to what?'*
ii. the identification of potential end-users ('indicators for whom?') and potential purposes (*'indicators for what?'*)".

Respectively, in a reframing of the resilience concept in [225], the importance of scale was highlighted, and it is stated that many of the processes, which drive and shape resilience, "*operate on larger or smaller scales than the urban or national scale and they often vary between scales"*. Thus, the question in regards to scale was added - *"resilience at what scales?"*

At this point, and towards operationalisation of the suggested ERR concept, more questions are added:

iii. *"which data and tools are needed"*' - in terms of the use of official/authoritative and open-source data and of integrative and interdisciplinary methods used combining different theories and algorithms with geospatial assessment analysis tools and methods) and
iv. "*how can indicator assessment results be gathered, handled (in an interoperable way) and organised in various scales?"* - in terms of geovisualisation techniques that allow for a straightforward interpretation of the flux of information from larger to smaller scales and transferability between the different stakeholders fostering communication and collaboration

Consequently, ERR is conceptualised in a way for the evaluation of the interdependencies among systems and the socio-technical values, as well as the potential cascading impacts, integrating security, safety and geographical factors. For the operationalisation of the concept, scenarios enable resilience analysis to address various futures, appreciating the uncertainty and dynamics of various physical and social factors and the knowledge and understanding over several time spheres [40]. The graph model (in Figure 4) and calculations of operational losses can be further integrated into the resilience planning, enabling the assessment of many event pathways.
In this way, system loss statistics can be determined with different alternative mitigations for various hazard scenarios, such as floods of various intensities. For **inclusion of the 'geographicalness' of a flood and integration of the geography perspective into the ERR concept, applied geoinformatics are used in GIS**. In the author's previous work, it has been demonstrated that **GIS** (and remote sensing) are appropriate for simple data transfer and mapping [226]. It has also been demonstrated that they can also **play a significant role in connecting and analysing data in holistic, integrative ways**, resulting from the **development of user-centred and scale-specific concepts** [227] that **current DRM approaches lack**. GIS can be coupled, for example, with various methodologies for simulation purposes and examination of the socio-economic behaviours of an individual or a group of agents in a complex system, such as cities, in response to the increased EWE, aggravated from climate change, or different natural and human-made disasters.

As previously stated, in the engineering of a CAS for identifying spatial resilience assessment indicators, such as a geolocated change in travel times of a road network exposed to floods, the coupling of bottom-up with top-down approaches is essential. For example, a methodology that couples bottom-up research with the assistance of GIS visualisations is spatial agent-based (ABM) modelling [228]. Identifying risk areas (of population, of CI) is shifting the wheel towards assumptions that GIS can be seen as a vital/critical infrastructure for improving, understanding, and handling risks and disasters.

The need for better and easier decision-making has resulted in the development of spatial technologies [229]. Decision-makers use technology to simplify numerous tasks, and cities become more informed, prepared, and resilient [16]. Spatial technology advancements, such as GIS, are utilised in resilience planning and emergency management. Complex decision-making is required in planning processes to prioritise allocating limited resources to people at risk [230]. Moreover, these difficult decisions are merely spatial, with their failure of implementation laying between the high interconnectedness and complexity of systems, e.g. the urban ER system. Emergency managers include spatial components in assessing the potential hazard impacts or identifying the best evacuation routes during disasters [231]. When dealing with **EWE**, such as riverine floods and flash floods, many of the **critical problems** that arise are **intrinsically spatial**. For example, spatial problems cover issues related to the extent of the disasters, on-site crises and the number of people in need with exact geolocation and emergency fuel tanks needed for operational purposes. Spatial problems are assessed through **extensive risk analysis before, during and** even **after** a crisis/disaster. An essential step of the risk analysis is answering the questions "*What can go wrong? What is the likelihood that it would go wrong? What are the consequences?*" [232]. Answers to these questions help risk analysts identify, measure, quantify, and evaluate risks and their consequences and impacts [233].

Therefore, this thesis argues that GIS offer appropriate tools for answering such questions. They provide the resources for the gathering, handling, analysis, transformation and communication of data associated with the issues mentioned earlier towards operationalisation of ERR.

GIS became recognised and are utilised as a major tool for monitoring and analysing human crises and natural hazards in recent decades, analysing the impact of different natural and human-made hazards on different geographical regions. The development of the capabilities of the GIS visualisation is vital for the analysis of CI dependencies and interdependencies, especially for the visualisation of cascading and escalating failures at a regional level. Through GIS, the fast integration of different kinds of spatial information enables faster decision-making by identifying several types of interdependencies and their visualisation, which accelerates the decision-making processes [79, 80, 226, 234]. This capability offered from GIS visualisations to address second-and third-order dependencies can integrate the results from the analysis approaches to generate cascading and escalating failure curves [235]. It is further argued that the knowledge on such interdependencies of different CI, which occurs through GIS applications and visualisations, can lead to timelier emergency response through meaningful mitigation and preparation plans after conducting risk analysis on defined scales. After identifying the hazards, assessing the risks, and prioritising the values (i.e., assets of greatest value), both tactical and strategic plans can be formulated. The advancements of information communication technologies are essential for improving the efficiency and accuracy of emergency management systems with the utilisation of modern data-processing techniques [236]. Up-to-date and correct information are prerequisites for timely emergency management and response to save lives and assets at risk, achieved with geovisualisation techniques and GIS. Each emergency management phase, utilises geospatial applications (including GIS) [27, 168, 231, 237-243].

The capabilities of GIS regarding modelling and simulations are further utilised to practice response and conduct recovery plans during non-disaster times. They assist decision-makers to understand near real-time possibilities during an event optimising emergency services delivery. **GIS** are ideal for

developing frameworks that assist emergency managers and are tightly **related to the road transport system.** Therefore, regarding **complex problems conveyed from SoS with CAS properties** [244], such as the ER urban system, so to be able to be **solved**, the following are necessary:

- accessible and high-resolution data,
- localised knowledge for update and handling of data,
- built of trusted relations with local CI operators and stakeholders,
- retrieval and verification of data from local stakeholders for applying the methodology suggested in the following sections towards the operationalisation of ERR.

It is furthermore examined that GIS with **Network Analyst tools** provide the means for **connectivity network analysis**, amongst the various **networks of a SoS**, providing critical information for the **preparedness phase**, as well as the **response phase**, in regards to **service ranges of emergency response** through the:

- ODOrigin-Destination cost matrixes - finds and measures the least-cost effective paths (regarding distance or time) throughout the network from multiple origins to multiple destinations.
- Routing - finds the least-cost effective paths (regarding distance or time) from a specific destination to different ones.
- Service area analyses or else service of coverage (SOC) - finds the area that can be reached in a specific time or distance from a specific origin.

In general, routing has become indispensable as a critical infrastructure service for the navigation of fire and rescue vehicles. Therefore, the thesis argues that routing, as a key component of the emergency response, should also be analysed under specific crises after extreme events such as riverine floods and flash floods. Disruptions in routing are affiliated with **disruptions to the transport network**, i.e. road network, which are indicators of **deterioration of the transport resilience**. **EWE-triggered disruptions in routing** are affiliated with the **inherently spatial flood risks**, which bring the **geographical perspective** to the forefront. Additionally, spatial risk assessments deal with road and route interruptions due to EWE [245]. Therefore, it is argued that when the road is considered a weighted graph (see Figure 4) with its nodes and edges, it is untangled. Hence, resilience/reliability/vulnerability assessments to floods for DRR can focus on these road components for further risk analysis and system failure identification.

Research on **transport network reliability and resilience to a variety of disasters** demonstrates that disruptions to particular nodes of the network can result in different degrees of disruption [144] that further result in adversely affected travel on a degraded or network (delays) or damaged network (incapacity of ER delivery-vulnerable/critical). Therefore, it is essential to start utilising **road network analyses** methods [246] by adopting **vulnerability and criticality assessments with geographic context** [147], achievable **with GIS**. Current studies in transportation resilience research focus on the development of frameworks and quantification methods [151]. These approaches include the specification and definition of resilience indicators, such as total traffic delay [152], economic loss [247], and post-disaster maximum flow [248].

Additionally, there is abundant research in the transport system domain integrating vulnerability and criticality assessments such as the:

- traffic densities and flows, including commuters’ flows [174, 249, 250]

- exposure of single links of the transport network to traffic [251]
- road categories related to the average maximum speed [87, 181, 252]
- the level of the reduction in the average maximum speeds that corresponds to a safety speed function [253, 254].

Information related to these features is inherently spatial, and spatial assessment tools that forecast EWE impacts (riverine and flash flood) are necessary. GIS, as mentioned earlier, are ideal for the development of such tools (and frameworks) assisting emergency management with the organisation of data produced and owned by different agencies for analyses and visual displays of important information before and during an emergency event [226, 234]. They are also valuable tools for visualisation of resilience assessments, providing a basis for collaboration and communication between various stakeholders [227] towards the adaptation of the metrics for the transformation of, for example, cities [255] and transportation networks [212, 256]. For planners and decision-makers, it has been demonstrated that **exact geolocated information** regarding the **length of potentially flooded road segments** is **important** information [226], as it reveals the exact location of people and assets, assisting accurate evaluation of the associated risks [12]. Such spatial information provided, also enriched with data gathered from volunteers in the area (people at risk or in surrounding areas), can be valuable tools in the hands of emergency responders for quick identification of the flood extent and timely effective ER [226].

Spatial information is also highly relevant to the geographical concept of place. Additionally, the geographical concept of a place is used as “a part of space” [257]. The perception of a place is generally an all-encompassing integration of location names and other properties [258, 259]. As mentioned in [260], because places are not isolated but interconnected in many ways [261], it is crucial for the understanding of characteristics to understand a place’s contextual information (i.e., its connection to other places). These connections link a set of places to a network, which indicates the predefined geographic contexts for the places [262], combining the CAS thinking and the graph theory, as presented in section 2.1. In the complex urban ER (see Figure 3), the places are modelled as city units of a city. The **connections** between the **networks** are of **focus for spatial assessments**. Those connecting networks between the city units and the ERS buildings are made with the road network (**hierarchical approach**). Therefore, the **untangling of a complex system** can be achieved. The network theory (graph theory) enables the untangling of the complexity of the road network with analyses on the network’s topology to its nodes and links, providing alternative measures of link importance applied on transport networks worldwide [150, 263]. According to [104], the topology issue implies a focus on the network configuration and its properties (such as connectivity, centrality, clustering) for analysing the related impact on the behavioural dynamics of the network itself (such as timely ER). Therefore, it is argued in the thesis that the **location of the ERS** plays a vital factor for emergency management, for example, for the **location planning of fire brigades** [188] and allocation of ambulances [185]; for reviews on the subject, see [264, 265]. However, the location of ERS, i.e. **topology of the ERS** system, is **dependent** on the **network topology** and its **performance** in regards to **flood-impacted citywide accessibility**. **ER** is tightly associated with **accessibility**, a distinguishing factor of ERR, serving as an indicator in many resilience frameworks, such as urban resilience, community resilience, neighbourhood resilience, transport network resilience, and **traffic resilience**.

Accessibility, therefore, is associated with the rapidity of the response of the emergency responders in case of an incident (crisis, disaster, car accident, fire). The road networks in complex urban areas underpin mobility. They are crucially important during emergencies since their reliability (constant functioning provision) is tightly related to the resilience of communities, which rely upon fast connection to shelters, CI blue light services [266]. For Germany, this can be relevant for the so-called ‘lighthouses’, which are suitable shelters or locations providing the minimum emergency supplies for the everyday continuation of living, for example, in case of long-lasting blackouts. Within the framework of the German research project “Catastrophe-protection lighthouses” (Katastophenschutz-Leuchttürmen), a concept was developed for contact points for the population in case of a crisis. As stated in the project description, such lighthouses are *“... public buildings, such as schools or public service office buildings, which remain supplied with electricity even during long-term blackouts. As glowing islands in the dark, they give people hope that there are water, warmth and help”* [267]. Therefore, for flood risk reduction for humans (regarding access - safety), the building themselves (CIP-security) and the interdependent roads, resilience assessments are relevant and must be considered in the assessments. A crucial concern for emergency activities towards timely responses is the logistics of operations, which is highly relevant with the lighthouses and the road network accessibility after flood occurrence [171, 268, 269].

As demonstrated, the importance of the road network to the ER is high. When regarding floods, identifying areas more likely to be cut off in case of a hazard is fundamental for FRM and preparedness [270]. For this purpose, as demonstrated in section 2.1, when assessing risk, the following identifiers are considered,

- **the hazard** - one of the key metrics being the flood depth and flow velocities,
- **the exposure** - associated with spatial information in regards to the extent of the hazard
- **vulnerability/reliability** - such as the widely used damage-loss functions [271-273], also including **resilience** as a reciprocal of reliability.

This articulated consideration of **risk** is functional in research, such as the research conducted in this thesis, that **accounts for natural** (floods) **and built environment characteristics** (transportation perspectives previously displayed). For this purpose, **accessibility** is a **primary factor in transport network resilience**, e.g. road network. The road network in an urban ER system is higher in the hierarchy of networks (see Table 2). Therefore, the thesis proposes that the operationalisation assessments should first focus on the road network system since perturbations occurring on this system trigger the snowball effect of cascading flood risks. Lastly, answering the **RQ1**, for the reasons mentioned, accessibility is selected as a suitable driver also for ERR, and the thesis suggests that strengthened preparedness for response is achieved through a “satisfactory design of an urban ER system”, considering its CAS properties, for timely ER provision under any flood condition.

3. The Composite Multi-criteria Risk-based Time-dependent Accessibility Indicator (RITAI) of ERR to Floods

An urban ER system is a system in constant flux, and its optimal design is a difficult achievement due to the complexity of its networks. Nevertheless, as discussed in the thesis (see section 2.1), the resilience thinking in the developed resilience framework of ERR is shifting the focus from simple ‘damage loss functions’ to integrative ones with a combination of results from the assessment of various cascading impacts on different levels and scales of the system. For this purpose, the **methodological ERR operationalisation framework** (Figure 10) introduces the quantitative indicator of the ERR to riverine floods and flash floods, which is **a composite multi-criteria Risk-based Time-dependent Accessibility Indicator (RITAI) for the support of decision-making**. The RITAI is a combination of top-down scenario-based (commonly used for identification of cascading impacts, CI and hazard-related resilience assessments) and place-based approaches introduced from [137] (used in risk and resilience assessments), with a suggested spatial (bottom-up) upscaling analyses (see Figure 10). The indicator allows for identifying first-, second-, and third-order impacts of floods of various intensities on a road network level, with a spatial upscaling analysis for the efficiency/serviceability assessment of the entire urban ER system, presented in classified hexagonal spatial matrixes (city network).

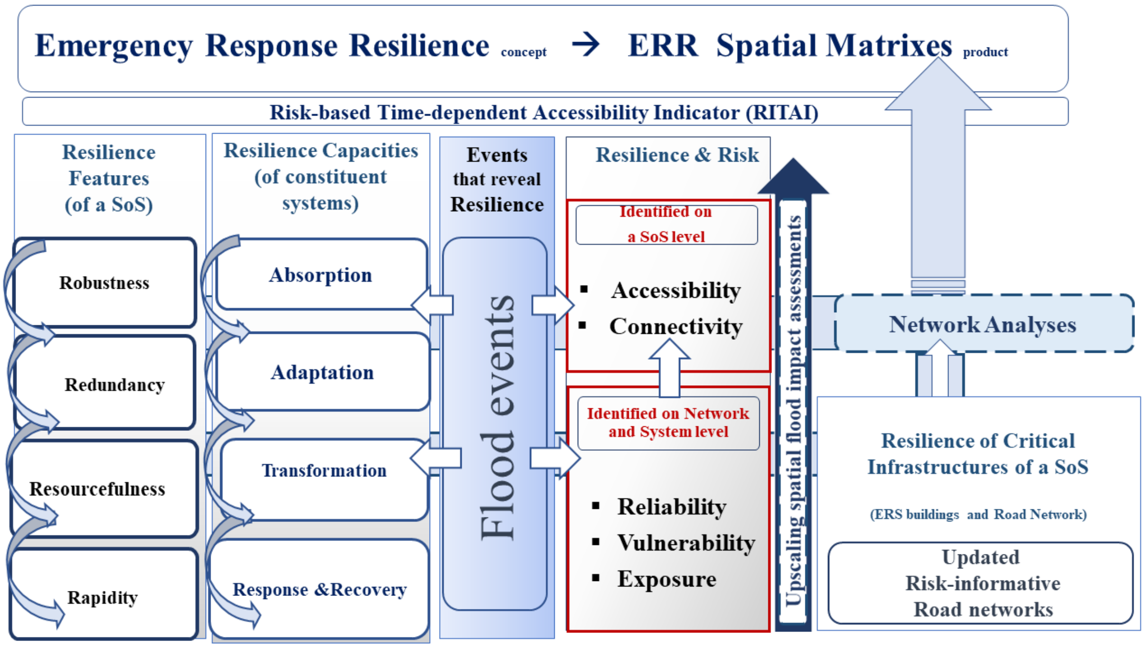


Figure 10: The Risk-based Time-dependent Accessibility Indicator (RITAI) of the urban ERR - based on the framework in Figure 6

In Figure 10, the concept of the urban ERR is presented in an operational form and is composed of the resilience of the urban ER system (SoS), the resilience of the CI (emergency rescue buildings and road network), and it interrelates with risk, such as flood events.

It is suggested, according to Figure 6 (i.e. conceptualization framework of the resilience of a SoS), that ERR is operationalised with the Risk-based Time-dependent Accessibility Indicator (RITAI) under the stressor of floods, supporting decision-making, with a combination of a top-down approach and a bottom-up GIS-based (scenario- and placed-based) spatial upscaling analysis approach. Hence, it is argued that the identification of risks in different scales combined with the interdependent constituent systems' resiliencies and their resilience capacities enable the resilience assessment of the entire SoS, which is further visualised in spatial resilience informative matrixes.

Categorically, the **RITAI's performance** reflects on the **rapidity of the response of the urban ER system under flooded conditions**, that is, reflection on the **time-dependent accessibility** on pre-defined response time thresholds from the ERS considering flood impacts on the ER **road network's capacities for timely ER**.

The indicator's performance relies on the performances of the sub-indicators (robustness, redundancy and resourcefulness) endogenously and exogenously, i.e. interdependent resiliencies of systems and CI. The sub-indicators of the RITAI for operationalisation of the urban ERR to floods focus on the transportation characteristics (as mentioned above) of an ER road network, i.e., traffic, mobility, connectivity and accessibility, and consider the hierarchy of the urban ER system. **The performance sub-indicators are assessed with applied geoinformatics conducted in GIS, with bottom-up (upscaling) spatial assessments of a top-down methodological approach.** Upscaling, or bottom-up approaches for quantifying the information from larger to smaller scales, commonly use point measurements upscaled to areal coverages while utilising thematic maps or remote sensing products [274].

Such approaches are most commonly used in spatial ecological models that rely on spatial data layers, at appropriate scales for the ecological process, analysing scale, resolution and patterns [275]. The issue of scale mainly deals with the decrease of the uncertainties occurring from the aggregation of information. Such issues have motivated further research overcoming such issues occurring of the commonly used spatial-aggregation methods (random rule, majority rule, nearest-neighbour rule and spatial scan statistic as in [276]), resulting in the production of multi-dimensional grid-point scaling algorithms addressing the quantitative spatial upscaling of categorical information with minimum loss of information [277].

The thesis further proposes that exposure assessments (direct flood damages) reflecting on the robustness of the system should start with a focus on the road segment level (large-scale of first analyses), proceeding to the entire road network and urban ER system, with the aggregation of information through geovisualisation techniques. According to the exposure levels reflecting the absorption capacity of the constituent systems, disruptions of the safe driving mobility are assessed on this scale of analysis, considering changes in the speed flows, reflecting the vulnerability of the ER road network and its adaptation for transformation capacity levels. Additionally, on the scale of analysis, it is also suggested that the assessments of the travel time reflected on their TTR reveal the impact of the flood risk on a network level for further degraded rapidity of response of the entire ER road network. Vulnerability is considered a flood risk identifier, and reliability an interdependent identifier of the flood impact on a network level, assisting the resilience assessment on a system level. That is, this combination of risk and resilience identified on road segments (network and constituent systems' level) impacts the connectivity of the entire road network and the entire urban ER system, i.e. risk identified on a SoS level (zoom-in and zoom-out ability of the suggested upscaling spatial assessment methodological approach).

Consequently, the connectivity of the SoS is impacting the accessibility of the urban ER system, assessed on the scale of city units, proceeding with the further aggregation of information with minimum losses, occurring from uncertainties conveyed from the data used. This thesis also presents that accessibility assessments, dependent on the system's connectivity on a network level, reveal the resilience levels on a SoS level. The accessibility resilience identifier assesses the degradation or impairment of the urban ER system (i.e. SoS with CAS properties) reflected in the response times (accessibility time) and its rapidity feature (response capacity). Precisely, the upscaling operationalisation methodological approach consists of the following metrics, reflecting on different resilience capacities of a SoS, dependent on the constituent systems' resilience capacities (interdependent resiliencies):

- **Exposure → absorption capacity** - reflected in the robustness of the **ER road segments** (road segment total amount) for ER route planning,

- **ER road network mobility capacity (RNMC) → adaptation and transformation levels (risk on a network level)** - considering safe driving mobility of emergency responders - reflected on the active and passive redundancies of the ER **road segments** built for timely ER provision,
- **Travel time reliability (TTR) of the ER road network → resilience on a network level** considering safe driving mobility of emergency responders - reflected on the resourcefulness of the **ER road segments** for timely ER provision (interdependency with the endogenous redundancies of the system), and
- **Citywide accessibility → rapidity for response/serviceability capacity (resilience on a SoS level)** of the urban ER system under various flooded conditions that results from scenario-based simulations with network analytics and reveals **risk on a SoS level** - reflected on the rapidity of response aggregated to a **city unit level** of the emergency responders according to the entire ER road **network's connectivity** for timely ER provision.

The suggested **hazard-, scenario-based resilience analysis** aims to provide insights of a CAS engineering towards resilient ER for the enhancement of the safety of the population, while also considering the safety of the emergency responders, i.e. safe driving mobility capacity of the emergency rescue vehicles, in case of riverine floods and flash floods, supporting fast decision-making. Therefore, the RITAI is developed to assess a citywide ERR to floods and is based on the functionalities of the urban ER system's network systems (capacities) at various scales. That is, the RITAI assesses changes in the system on a micro-scale (e.g. road network system) and their impacts on a macro-level (e.g. ERS system, city system).

Each ERS system uses different route planning speeds according to the road types for route plan preparedness and operational route planning (route planning in case of an incident/crisis event) for timely ER provision. Such emergency route planning speeds (ERPS) result from empirical speed tests around the areas of service or official speeds from guidelines used universally over the years. From my own experience on the issue, unfortunately, not all the ERS have the financial nor the staffing ability to use modern technologies such as GIS so to accelerate the process, and some, even if they do, refuse to utilise them because "*I am used to using my methods*" - short-sighted approaches due to years of experience. Years of experience, from an emergency responder to a civil protection officer, is another risk factor that must be considered in future strategies considering the safety of the emergency responders since these individuals are the ones that are most likely to drive through flooded waters [99] and are the ones that are not open to an adaptation of new approaches. Nevertheless, this risk factor will not be included in the operationalisation methodology suggested in this thesis.

The ERPS of an ERS (fire brigades, EMS, etc.) integrated into road network databases form the ER road networks. As suggested in this thesis, the ERR assessment is based on the ER road network of the ERS of fire brigades (covered in section 5.2). The flood impacts are assessed considering the risk factor of FD. As mentioned in previous sections, the FD is a significant risk factor affecting many levels and scales of the urban ER system. Flood impacts, according to FD, the benchmarking process of the system's functionality, that is, timely ER provision – the safety of the population - and safe driving mobility of the emergency responders according to the rescue vehicle's flood driving capacity. Additionally, the scope of the **RITAI is to provide the resources and knowledge for a base understanding of ERR** for further:

- combination with qualitative analyses towards the transformation of the cities [80] and

- communication between various stakeholders, fostering their cooperation by identifying critical socio-technical interdependencies for long-term adaptation plans.

The scientific community already recognises the vital importance of transport networks to emergency response. Resilient, i.e. reliable/uninterrupted transport networks, are vital for maintaining social networks [278] for protection, in case of extreme riverine flood events, of the vulnerable population of refugees in an urban area foreign to their culture, beliefs and language [226]. They are also vital for the provision of timely emergency services under flooded conditions [279, 280], including evacuations of hospitals and refugee shelters [226] and backup plans in case of compound events of extreme riverine floods and blackouts [234]. However, the more complex the environment under study is, the more difficult the ERR quantification/operationalisation becomes. Therefore, this thesis suggests that **urban complexity** and its impact on various ERR levels are **addressed by compartmentalising** each case study area, i.e., spatial matrixes.

Compartmentalisation of **CI networks and systems** allows the production of detailed **risk informative matrixes**, enabling the **gradation of information** provided from a **local level** (large-scale) to a **regional**, giving a detailed overview of the impact of the stressor on the under-study system. The **gathering** and **classified representation of information** for each **matrix cell/city unit** of the case study area become easier and manageable, with the geovisualisation techniques resulting in **in-depth cascading risk assessments revealing the resilience of the SoS in** various **scales** (upscaling approach) and **levels**. The reveal of resilience in various scales and levels, furthermore, enables **integrative decision-making** of different end-users and a more fundamental understanding and overview of cascading risks, potentially occurring on a local and regional level, which therefore builds the basis for further collaborative actions towards enhancement of the safety of the population. End-users can be emergency rescue planners, traffic planners, urban planners, and energy providers, (e.g. electricity, water, gas). The suggested **spatial upscaling methodology** is used in a similar form **in decision-making**, where decision-makers are involved in the decision scaling process, which originated in response to issues arising regarding the best approaches for processing and utilising climate change projections for adaptation planning [281]. Decision scaling has the same general problem formulation and structure of frameworks for decision analysis [282]. The decision scaling process, according to [281], includes the i) decision framing, ii) estimation of EWE-informed risks and iii) climate stress test. As also mentioned in [281], traditional frameworks of decision analysis initiate with the retrieval and gathering of information on the decision in structured ways, using four categories:

- choices - e.g., to adapt or not; plan A vs plan B,
- uncertainties - e.g., future climate extremes, future population densities,
- consequences - e.g., net benefits, damages, resilience capacities,
- connections - e.g., system diagram, system model.

Those above are integrated into the conceptualisation of an urban ER system and its representation as a graph (system model – see Figure 3). The graph reveals the connections between the constituent systems and the ERR, as applied to the urban ER in case of floods.

Specifically, the operationalisation methodology of the ERR with the RITAI, which is explicitly designed to integrate all of those mentioned above, is:

- revealing risks on a system, network and agent level (system model), enabling the identification, after

- "climate stress testing" with its implementation on various flood scenarios (uncertainties), after
- testing the constituent systems' flexibility for absorption, adaptation and transformation, revealing their resilience capacities (consequences), resulting in
- the identification of the entire system's risk revelation depending on the constituent systems' connectivity and
- providing the opportunity to adapt through the accessibility assessments (choices of ER route plans), aggregated and classified in spatial ERR matrixes, providing additional choices for advancement through adaptation and transformation, fostering integrative and adaptive management.

Complex information (such as those mentioned above) integrated into the decision-making can lead to wrong decisions taken during **crises**. Therefore, **simplifying information is critical** for several officials because they have to deal with emergencies, requiring a proper preparation phase through situational analysis of complex environments and a time-efficient response for enhanced recovery times. Additionally, the suggested **flood-impact bottom-up (upscaling) spatial dependency curves, combined with the top-down approach suggested before, aim** to **capture global/overall interactions among the several sub-systems**, providing a means for **operationalising** the complex adaptive SoS**,** i.e., **the urban ER system.** It is argued throughout the thesis that complex SoS needs untangling for the identification and even forecasting of potential cascading risks, considering the extreme flood events of various types, towards adaptive and collaborative disaster risk mitigation actions, enhancing the community resilience of an urban population. In the era of unpredictable EWE occurrence, where extremes will be the norm and not the exception, experts have already identified that transformational thinking and actions must be a prerequisite for facing future challenges towards enhancing community resilience [283] and neighbourhood resilience [230].

Undisrupted ER provision of emergency services under flooded conditions, which is a vital resilience identifying component in the resilience mentioned concepts, needs reliable road networks, along with the production of depth-disruption curves for safe driving of emergency vehicles [280], towards the quantification of the climate change impact on the disruption to the road network, is insufficiently studied [128]. Therefore, it is further argued that the zoom-in and zoom-out effect of the aggregation of information from larger to small scales and vice versa when assessing the resilience of SoS with CAS properties, i.e. interdependent resilience features of interdependent complex adaptive systems that the interdependent resiliencies concept (see Figure 6) is essential. More specifically, it is suggested in the thesis that for a deepened understanding of the flood risk and its relation with the resiliencies assessed on many levels and scales, the large-scale spatial assessments of urban robustness, redundancy, resourcefulness and rapidity of response to riverine floods and flash floods of frequent and rare probability of occurrence, are necessary. It is further suggested that it is also necessary to utilise the frequent scenarios (regular), depicting the present situations and the "potential extreme futures" to forecast the futures and strengthen the preparedness for response in urban areas.

3.1 Robustness, Absorption Capacity & Large-Scale Exposure Assessments

The difficulty of meeting the needs identified above to quantify climate change impacts on the road network, increases. The increase results from the complexity of the cities and their interfaced CI, such as the road network, which is vital for the ER provision. In general, the impact analyses of various hazards on the transport network initiate with exposure assessments since the flood risk in urban areas is inherently spatial. Exposure depends on the likelihood and intensity of the selected hazards. Intensity is defined as a discrepancy from frequent (regular events) [10], and for this reason, high intensities characterise extreme events. Therefore, focusing on the intensity shifts the emphasis of extreme event analysis to the impact estimation rather than determining the probability of occurrence [212]. Flood impact estimation is essential for large-scale intraurban assessments for further encapsulation of potential futures, in present risk mitigation methodologies, towards enhancing the resilience of urban SoS.

For this reason, the choice of different flood scenarios is a necessity for forecasting flood impacts. Forecasting such impacts in complex urban areas entails large-scale flood impact assessments. In this way, the efficiency of the urban ER system can be analysed adequately, providing insights into current and future potential situations. In this thesis, the quantified flood impact analysis of the transport network used for ER is considering the safe driving mobility of emergency vehicles under flooded conditions, based on benchmarking the functionality of the urban ER system. The benchmarking is conducted with the defined hypotheses and thresholds (see sections 4 and 6.3), set, according to the road type and the FD impact on safe driving through floodwaters; additional impedance costs and flood-impacted travel times, which are expected to cause delays or incapacitation to the ER provision. For a comprehensive overview of the flood impacts, direct flood impact assessments are the first step and include FD spatial information (geolocated FD values). The spatial analyses for ER purposes are the situational analyses conducted at the first step of an emergency management cycle for time-effective ER, mainly in the preparedness phase. Situational analyses are indicative of the damage extent of hazardous events, such as floods. In particular, the exposure assessments result in the value of the exposed elements, i.e. objects potentially impacted by a defined hazard scenario for a specific environment [284], which in our case are the road segments. The impacts on the transport network need to be addressed with various climate models enabling simulation ability for current and future events [165]. The impact analyses include the additional in-depth analyses essential for identifying vulnerabilities and risks to increase the effectiveness of emergency plans, specifically at a local scale [167, 168]. Provision of emergency services under flooded conditions needs resilient and reliable road networks and the production of depth-disruption curves for safe driving of emergency vehicles [280] to quantify the climate change impact on the disruption to the road network, which is insufficiently studied [128]. For the flood-impacted system under research for selected flood scenarios, the exposure assessments indicate vulnerability/robustness; thus, they indicate the potential loss of nodes and links (presence of infrastructure) that can affect the ERR negatively. Therefore, the first measure of the flood impact on the transport network is the proportional loss of the total length of road segments that have been affected by the various FDs.

The suggested graph model of the urban ER system assists the process, allowing for further operationalisation steps. As mentioned in previous sections, the term robustness is chosen because the time dimension is not included [256] at this step of the analysis. Generally, the robustness of ERR is operationalised through the exposure assessments, resulting in values on the potentially affected road segments with FD information (direct flood damage), which can be valuable for ER purposes but also for civil protection authorities, humanitarian responses traffic and urban planners, CIP strategies, and insurance and investment planning. Regarding floods, it has been proven that the exact location of people and assets are critical factors for the accurate evaluation of the associated risks [12]. Therefore, direct damages geographically located, i.e. proportional losses in infrastructure, which in this thesis is the total length (in kilometres) of roads that have been affected, are the first measure of the impact of flooding on the transportation network. Specifically, the main focus of the applied methodology is the quantification of the impact of the flood on the road network on a large scale and the driving ability of rescue vehicles to operationalise ERR in complex urban environments.

From a CAS engineering perspective, robustness is considered in this thesis as *the level of exposure of the ER road network to different riverine and flash flood depths, allowing for effortless driving or changes that do not affect the functionality (i.e. ER provision).*

Starting from large-scale robustness assessments via exposure assessments of the road network to different FDs of selected riverine scenarios, an exploration of the robustness of the system of ER follows, towards operationalisation of ERR, considering safe drivability and potential ER time delays. In this way, the absorption capacity of the urban ER system is assessed with the aggregation of information, indicating the extent of the selected riverine flood model. Riverine floods are extended around a river, with the extent to be dependent on the phenomenon's intensity. The potential coverage (probabilistic/forecasting models) of the flood determines the exposure of the road network to riverine floods and the direct damage of the infrastructure. On the other hand, exposure assessments of the ERS buildings, such as the fire departments to floods, could also be valuable for the ERS system to increase the robustness of their urban ER system to these potential hazards. Apart from the service area coverage (SOC) of each fire department, for assurance of timely ER, the cooperation of the fire departments' collective forces must remain undisrupted. For example, different types of rescue vehicles are located in different departments and may not be available for ER purposes due to high flood exposure of the geographically dependent road network.

Furthermore, studies have proven that roads may be closed even if they are not inundated due to the status of the neighbouring road links [179]; that is, floods indirectly impact road links due to geographical proximity. This particular flood risk of the transport network was introduced by [285], and it is argued that easy interpretation of such indirect impacts is achieved through geovisualisation techniques (classification, visualisation) and GIS spatial assessments. The concept applies to the sudden EWE, which also aggravate flash floods, resulting from the projected increase in the probability of extreme rainfall across most of Europe and the mean precipitation intensity [286]. Therefore, the need to analyse the impacts of hydrometeorological phenomena in major urban centres becomes highly essential. Nevertheless, flash floods are not a common hazard scenario for impact analysis on the transportation network for emergency preparedness, but primarily for traffic disruptions [85, 165, 287], while many impact studies focus on the impact of riverine flood exposure and usually examine the impacts with one extreme flood scenario of the 100-year probability of return. Flash flood models have been used for flood risk preparedness enhancement via early warning systems [176, 288-293], urban resilience strategies and traffic disruption, but the impact on the transport network for a large-scale (city scale and road segment scale) taking into consideration safety of driving (mobility factors) and functionality loss for ER purposes, lacks attention from the scientific community.

The reasons for this may lay between the lack of information regarding flash flood intensities and frequencies on the local level and either due to the lack of tools for advanced and detailed spatial analyses. Despite the increased demand for a better understanding of the urban road network risk to flash floods (pluvial flash floods), until 2005, very few studies have attempted to systematically examine the potential impacts of these flood events on a large scale of urban road systems.

The reason is the lack of adequate data and observations that concern road flooding, the difficulty in numerically modelling the flash flood dynamics and the complexity of cascading effects of flooding on transportation systems, in general, [294] and specifically, on roads [143, 295]. Of the existing studies, a number is often conducted for flood emergency evacuations [296], logistics [13], accessibility losses [297] or traffic delays [298], moreover, in a study of a local regional-scale model, designed for the identification of the interruption of a road network due to a hazardous event from a multiscale perspective [299]. The previous studies mainly focus on regional (basin) scales and intercity levels, considering poorly the flash floods at the intraurban level. Therefore, the results of a study conducted in Shanghai, utilising flash floods as the primary flood scenario for several years of occurrence probability, have been used for risk analysis of the intraurban road network of the city [179]. The results of this study from [179] prove that the pluvial/flash flood is found to lead to a proportionate, but nonlinear impact, on intraurban road flood risk.

The algorithm suggested in the study mentioned above uses a risk factor, the road blockage with an FD threshold of 0.3 m and gave results regarding the time duration of road closures for each flash flood scenario. Also, in [287], a different approach was introduced, where they proposed an FD-speed reduction function. After carrying out video analysis and with a GIS-based origin-destination matrix method, they found critical road links in Newcastle, UK, by measuring traffic counter data before and after flash flood scenarios. However, it is not clearly stated whether the roads were blocked or the drivers chose to delay their journeys. The actual FD from the event was not recorded, and therefore, the study could not validate the proposed function with actual data. The same approach was followed for the same under-research area using a 200-year riverine flood scenario [165], extracting risk matrixes for potential traffic disruption due to flooding.

Following the needs mentioned above, it is proposed from the thesis that the large-scale spatial assessments of ERR to floods must consider riverine and flash floods of different probabilities of return (regular and extreme). Furthermore, as suggested from the RITAI, the normalisation of the road network, that is, segmentation of the road network to one-meter segments, assists further large-scale flood impacts in speeds and travel times (second-order flood impacts/indirect). In this thesis, the ERR concept integrates aspects from the spatial resilience concept of socio-ecological systems [300] and the transport network resilience [151] towards efficiency assessments of the urban ER system to floods, from cascading local vulnerabilities to regional resilience assessments. For further enhancement of the preparedness phase, it is also proposed that comparative analyses of the results between the same flood types of different intensities, presented in flood impact curves, are providing a first overview of the flood risk impacts. The flood impact curves have a goal also to raise awareness for the overall absorption capacity of the urban ER (to selected flood types), which reflects the robustness of the system in case of compound and escalating events.

3.2 Redundancy, Adaptation Capacity & Large-Scale FFS Assessments

Road networks are becoming increasingly vulnerable due to unforeseen extreme, escalating or even compound scenarios such as disasters, accidents, and other emergencies, which cause disruptions. Disruptions are not only related to direct damages identified through exposure assessments, as presented in the previous section 3.1 but they are also related to several aspects of the road network, i.e. traffic flow and network connectivity and accessibility. However, the recovery from such disruptions becomes more challenging over time due to the diverse network flow demands that can directly affect the connectivity of the entire network [301], impacting the accessibility of the network itself and its interdependent ones.

For the integration of such flow disruptions in the ERR operationalisation methodology, the speed and the travel time (see section 3.3) are the only traffic properties considered for further assessments. As mentioned earlier in the thesis, the integration of flow disruptions is enabled after considering the road network as a weighted graph [162], which combines the graph theory and the network science and enables data structure. The flow disruptions integrated into the road network also enable further handling of real-world information and the capability to incorporate various dynamics of the road traffic [163] for further network analyses of intraurban roads [161] (see Figure 4).

The traffic volume, the traffic demand, congestions or queuing, due to the inundated road network are factors that will not be considered, but it is suggested that these factors could easily be integrated into the proposed methodology and assessed. Usually, in ER planning, these traffic properties are not considered since it is expected that the drivers will assist free-flowing driving of the rescue vehicles in cases of emergencies (*author's outcome from interviewing fire brigade officials*). For this reason, **ERPS** in the **ERR concept** proposed in this thesis **is considered the FFS** following the term used in traffic flow theory, *" the speed when there are no constraints placed on a driver by other vehicles on the road"* [302].

In general, weather conditions (rain, snow, wind speed and visibility loss) have an impact on three predominant traffic-related areas that and these are i) the traffic demand (density of vehicles), ii) traffic safety, and iii) traffic operations and flow [250, 303]. The suggested methodology and the RITAI are considering the safe driving of the rescue vehicles through flooded road segments and the traffic flow (changes in FFS and TTR) for timely ER operations. Several definitions are used for the FFS [252]. In the United States Highway Capacity Manual [304], FFS is defined as the theoretical speed when the density (of vehicles) and flow rate on the study segments are zero. Diversely, in the definition of FFS, the Transportation Research Board considers the environmental factor: *"the speed of vehicle travel at which drivers feel comfortable travelling under the physical, environmental and traffic control condition on an uncongested section of multilane highways"* [206]. Therefore, the physical conditions (status of the road network), the environmental conditions (weather conditions) and traffic (traffic volumes) have an impact on the FFS, giving motivation for further investigations on the matter. For example, studies in different regions such as Greece [305], Vienna [306] and Spain [307] estimated changes in traffic characteristics, such as reductions in FFS and speed-at-capacity (referring to speeds proportional to vehicle density) increase as the rain and snow intensities increase. Several studies focus on post-disaster traffic control management for the emergency management domain and specifically on the impacts of a potential hazard. In [308], it is suggested a model for post-disaster traffic control management (PD-TCM model), which is tested in-situ taking into consideration the urban transport network's FFS changes and a temporary traffic control strategy that can help to meet the demands of the emergency rescue time and minimize the negative impact on society. A literature review on the topic is also demonstrated, which mostly indicates that research focuses on post-disaster traffic regulation actions to be taken before and after earthquakes and landslides. One article is focusing on the setting methods of the regular rainfall for traffic regulations during strong rainfall to initiate and to remove traffic regulation based on rainfall predictions [309] and traffic light density-based control management [310], so to assist the timely ER.

Further to the suggestions for post-disaster traffic control management, according to the author's knowledge, there is no study demonstrating urban case-based methodological achievements for large-scale spatial impact analyses of riverine and flash floods to the FFS, according to the Road Network's Mobility Capacity **(**RNMC), for timely ER. From a CAS engineering perspective (network design), ***RNMC / adaptation and transformation capacity*** is introduced as the speed-flow capacity of the road network for safe driving mobility and as the metric for the redundancy of the road segments and the road network for timely ER under flooded and safe driving conditions. The definition is formed after taking into consideration several studies conducted in the field of transport and traffic in an attempt to capture both purely static topological indicators (from the conducted exposure assessments) and the impact of traffic conditions (FFS reductions according to safe mobility in flooded waters), for quantification purposes of the redundancy sub-indicator of the ERR. Redundancy in the technological fields of engineering, system design, and computer science is well established, with the definition to focus on the ability of a system to self-organize, *"... a process whereby internal structure and functions re-adjust along with changing circumstances"* [311].

Thus, for the systems' engineering, **redundancy** could be defined as *the extent of degradation that a system can suffer without losing some particularised elements of its functionality* [312].

Additionally, in a network context, redundancy refers to the degree of **spare capacity in the network** and is defined as the *existence of more than one means to accomplish a given function* [313]. From a CIP protection perspective and, expressly, from a reconstruction of network connectivity perspective, in [313], it is stated that there is an increasing need to achieve the network connectivity promptly, after the network's damage from a disaster. Low connectivity of the road transport network affects the redundancy, which is also defined *as the availability of different paths for each set of Origin-Destination (OD) pairs in the road transport network*. According to the latter definition, in [314], redundancy is differentiated into two types: the active and the passive. **Active redundancy** is the alternative number of routes preserved under natural conditions by speed adjustments (connectivity and accessibility analysis). The **passive redundancy** is the one that could be used to represent backup options that are only used in case of disruptions (ER planning under flooded conditions). In this context, in [301], the importance of redundancy is underlined since the lack of it in a network might be catastrophic because of delays, especially during emergencies, and the degradation of services. The term has also been used, focusing on the **redundancy importance of a link** based on **flow-based traffic factors** such as flow-based efficiency importance (vehicles/hour) and impact-based efficiency importance (vehicles/hour) [145].

Towards resiliency, in [315], it is suggested that the redundancy of the road transport network is one of the resilience indicators. In addition to damaging consequences (in case of rapid evacuations), it is explicitly suggested that insufficiency of the redundancy can have significant, consequential impacts on the level of service of the road transport network [313]. Therefore, in [316], it is argued that redundancy has a significant impact on the resilience of road transport networks since it represents the spare capacity of the road transport networks under different hazard/ stressful scenarios. Moreover, in [317], it is reported that distributed redundancy improves the resilience of a complex system. Under this notion, in [318], it is also identified that for the quantification of redundancy, the **"node to node"** (instead of "zone to zone") **combination of both traffic flow variations and network topology** is necessary. Redundancy, in the transport network resilience domain, is considered as a measure of efficiency importance (level of service) of a road network in case of disruptions/closures after loop-calculations on smaller-scale road segments (road links), mostly in-situ, not using real-world disaster impacts, "zone to zone" (instead of "node to node") and for local and social traffic purposes (not ER).

There are efforts from the impact studies domain to consider the effects of EWE on the road network's speed flow, combining both traffic flow variations and network topology for assessment of the impacts. The RNMC introduced in this thesis as a metric for the quantification of the "**road segment redundancy**", that is, **large scale, "node to node" flood impact assessments**, towards operationalisation of the ERR, is taking from the flood impact assessment concept used in transport network resilience concepts, towards criticality assessments of the transport networks (road and rail). Furthermore, few studies consider safe driving mobility under flooded waters for ER purposes; however, they are conducted on a smaller scale for analysis, i.e. road link [165, 319]. Additionally, these studies are conducted for civil purposes and are not providing information for ERS. For this purpose, the suggested operationalisation methodology is conducted on a large-scale, i.e. predefined road segments of an urban ER system, which allow for improvements of the complex systems' resilience (interdependent resiliencies between the systems and networks). Therefore, it is argued that predefined road segments allow the minimization of uncertainties from information aggregation to smaller scales due to the detailed geospatial analyses.

Nevertheless, uncertainties cannot be omitted in the conducted large-scale second-order flood-impact assessments (as suggested for the RITAI) since they are conveyed through the inherent uncertainties of the flood models. For example, if an area is identified, through the data used and first exposure assessments conducted (see section 3.1), as highly flooded (according to the choice of the critical threshold), the second-order flood impact assessments, in regards to RNMC, will return results as non-linear but analogous to the FD exposure. Therefore, the probabilistic flood models used for flood-impacted mobility assessments must be either up-to-date and high resolution or should occur from high-coverage of interest area, hourly-updated early warning systems, providing near real-time flood inundation depths.

Several studies underline the importance of a reliable and resilient road network from a mobility impact assessments perspective [85, 280]. However, they have a silo thinking, focusing on a specific catchment area considering one scenario of flood intensity (e.g. 100-year flood occurrence probability) affecting part of the road network (centre of the case study area) and focusing on risk-accessibility assessments to one CI, the hospitals. Nevertheless, they constitute examples of the importance of GIS and spatial assessments, which can provide, through geovisualisations, information on the scale of a road link in easily interpretable GIS maps.

Additionally, to the need identified from the impact assessments for identifying reliable road networks, in [320], the quantitative demonstration of the reliability is enabled by designing the systems for high reliability. From a system's perspective, it is argued that the *redundancy in technical systems should be understood as a design paradigm* [320]. According to this notion, it is argued that redundancy not only enables designers to design for high reliability, but it also allows for the quantitative demonstration of the reliability, following the suggestion of the engineering of a network system, *that redundancy should be used as an indicator for reliability.*

Therefore, from a design of the road structure engineering perspective, RITAI is suggesting the pre-design (rebuild) of redundant and reliable road network databases enabling timely ER, with considerations of large-scale flood impacts on the RNMC for safe driving under flooded conditions, for the ERR assessment to floods, wth large-scale flood impact assessments. Levels of the RNMC on a local level reveal the passive redundancy of the ER system to provide timely ER, which affects the active redundancy of an urban ER system Redundancy identified in different scales in a system of a SoS with CAS properties can be used as resilience indicator. Therefore, in the thesis, it is argued that enhanced redundancy in a system of a SoS with CAS properties, such as the urban ER system, results in enhanced resilience, identifying risks exogenously and endogenously. Thus, if the ER road network, after the shock of a flood causing disruptions, is assessed as highly redundant, then the entire urban ER system is characterised as redundant since the RNMC (passive redundancy) is undisrupted and the ER provision is possible with the utilisation of various route paths (active redundancies). Therefore, the thesis proposes that after adaptation and transformation of an urban ER system, self-organisation is quicker when operating on a redundant ER road network, enhancing the ERR to respective hazard scenarios. A redundant ER road network is also reliable for providing safe driving mobility to the emergency responders and timely ER for the population's safety.

3.3 Resourcefulness, Transformation Capacity & Large-Scale TTR Assessments

System approaches to the safety of complex systems, from a reliability engineering perspective, focus on the unintentional changes resulting from endogenous forces, such as random component failures [321]. In contrast, system robustness strives to prevent, mitigate and recover from unintended changes caused by exogenous forces [320], such as riverine floods and flash floods. Identifying unintended changes in the urban ER system and encapsulating endogenous and exogenous changes in the system will result in delayed or even impaired ER provision. It is suggested that the road segmentation also enables further large-scale, node to node vulnerability assessments. The vulnerability represents a network's susceptibility or a link to failure [322], where "*failure expresses a considerable deviation from the normal functioning state of the link or network*".

Therefore, a non-functioning or ill-functioning road or road component (node or segment) will appoint costs on the user (in our case, the ERS) in terms of time losses, additional operation costs (higher costs of fuel consumption) or other costs as a result of delays and diversions (e.g. life losses). Any threat to the reliability of the transport network constitutes a vulnerable spot, a weakness [261, 322]. Vulnerability is the probability of susceptibility of a system's element to potential disruption (on different levels). Hence the vulnerability can also be considered as a two-component concept. The concept in which probability and consequence are the two main attributes of study is, as mentioned in [146, 323], the probability of susceptibility with consequences for the serviceability. So far, in the ERR concept, vulnerability is also considered as a two-component concept as also suggested from [146, 322, 324], in which probability and consequence are the two main attributes, where the probability of susceptibility (RNMC) has a consequence on the serviceability (timely ER). According to this notion, the definition of **reliability** of the road network is as follows: *the probability that one or more of its links does not fail to function* [322]; therefore, it can *maintain satisfactory functionality at any given time* [148, 325].

In various studies in the network domain, network vulnerability is referred to as the decrease of performance due to disturbances [145, 326] and specifically for the road network, the vulnerability refers to as the *"susceptibility to incidents that can result in considerable reductions in roadway network serviceability"* [327]. If associating the term "reliable" with the term "operable" and therefore associating the term "vulnerable" with the "non-operable", then reliability means *"non-vulnerability or exhibits a high degree of operability under any circumstances"* [322]. In other words, the concept of **vulnerability** can be considered as the **reciprocating** one for **robustness** [328, 329]. Additionally, the **reliability** (at the flipside of vulnerability) can be considered the metric revealing the system's resilience on a network level. Therefore, in the **ERR** concept, the **reliability of an ER road network** for timely ER under flooded conditions is defined *as the probability that a high number of its components (road segments) will provide the means for ER under flooded conditions depending on the RNMC (passive redundancy) levels.* As previously stated, redundancy quantifications carry the vulnerability factor in the context of the degradation of serviceability of the road segment for timely ER due to decreased RNMC (serviceability), i.e. passive redundancy. Taking from the engineering of networks [320], where it is affirmed that the redundancy should be used as an indicator of reliability (see section 3.2), the RITAI is also suggesting the integration of the **reliability,** as the indicator of the relation between **the risk and the resilience** of the ER road system. The engineering of networks is utilised towards the design of reliable road network databases for reliable accessibility routes in the face of floods. Reliability depicts **the resourcefulness** towards timely ER provision, and the resourcefulness of a road network is quantified with the metric of the travel time reliability **- TTR** (see section 2.1). Therefore, in the ERR concept, a **resourceful road segment** is defined as a *redundant and travel-time reliable road segment, providing timely ER and active redundancies (exogenous / road segment reuse in ER route planning for alternative routes), depending on passive ones (endogenous), in the face of floods.*

The impact of flood events on the road network in complex urban areas, causing changes in the FFS (levels of redundancy), indicates the vulnerable road segments and will result in changes in the travel time of every road segment that is the TTR, defined in this thesis as, **Urban Flood Travel Time Reliability** (**UFTTR**). UFTTR considers the active and passive redundancy of the ER road network for timely ER, adding the risk factor in the analyses. Risk is translated in delays of the ER, occurring from changes in the travel time of the road segments that depend on their transformation levels in the course of a flood type and intensity. Therefore, in the **ERR** concept, the **reliability, i.e. resourcefulness** of a transport network, can be defined as *the probability that a road segment will provide timely ER under flooded conditions, according to the RNMC levels (redundancy).* The timely ER is achieved with ER delivery within defined time thresholds used for ER plans and can vary between the ERS and the region. Therefore, according to FD, benchmarking and the definition of thresholds (see previous sections 2.1 and 3) is essential for the ERR assessments.

In this way, the concept of the RITAI towards operationalisation of ERR to floods suggests that the timely ER (rapidity feature of urban ER systems) after floods is achieved with ER delivery within defined time thresholds from each ERS and is dependent on the mobility status of the ER road network for safe driving (robustness) and its impact on the FFS (redundancy). According to the author's knowledge, few studies exist, specifically from the impact studies domain, that consider TTR calculations for emergency response purposes under the impact of floods, used for the "forecasting" of timely ER delivery in complex urban systems. For example, in [280], information is provided on mobility preparedness in case of floods, but only for the centre of the case study, for one CI (the hospitals) and with the use of one flood scenario (100-year flood). However, they are using several human safety and mobility functions for risk assessments, including hazard and impact analysis, to provide an understanding of risks to people during a flood emergency. Additionally, GIS studies are conducting OD-matrixes to optimise the respective systems under several impacts [182, 187, 330].

These studies provide information on the travel time of a direct and linear route and not of the actual road links, which could add further travel costs due to the infrastructural morphology (e.g. roundabout, turn, one-way road, bridge) and the geomorphology of the area (e.g. curved road causing accumulation of rainwater). The concept of resourcefulness during disasters is introduced in emergency management, mainly emphasising human factors. In the ERR concept, the satisfactory functionality of the road segment, that is, the provision of ER delivery under flooded conditions, is analogous to the reliability of the road segment itself.

This relation can also be verified from other studies oriented to the quantification of disaster resilience. Specifically, in [222], it is argued that resourcefulness and redundancy are strongly interrelated to create redundancies, which did not exist before the occurrence of the stressor to the system. The example used for presenting this strong interrelation is the strong dependence of technology use from emergency managers, rendering it critical [227] for the emergency response delivery; if technology fails or is destroyed, the response is affected [226]. Concerning the ERR and taking from the disaster resilience, changes in resourcefulness and redundancy will affect the shape and the slope of the recovery curve and time, affecting the rapidity (see section 2.1) and robustness of the ER system.

The rapidity and the robustness of an entire system can be improved with redundancy and resourcefulness enhancements, leading to resiliency [222]. Therefore, in the ERR concept, it is argued that *timely ER (reflecting on the rapidity feature) is achieved using a robust, redundant and resourceful road network,* as defined in this thesis (see section 2.2). It is also argued that built ER road network databases using forecasting probabilistic flood models of various types and intensities strengthen the preparedness for response and decrease ER times through i) pre-planned ER routing and ii) operational routing considering flood risk information towards safe driving mobility. Moreover, a practical GIS-based methodological workflow and a developed GIS-Toolkit is demonstrated in section 4.2, semi-automating the process of large-scale flood impact assessments on robustness, redundancy and resourcefulness. It is also demonstrated how geovisualisation and fuzzification (assignment of fuzzy variables) processes utilise the fuzzy set theory, which will assist the aggregation of information to the entire ER road network, as the RITAI suggests, adding to the redundancies and resourcefulness of the urban ER system, towards timely ER reflected on the enhancement of rapidity. Geovisualisation regards techniques used for import, handling and classification of data for easily interpretable visualisations in maps and fuzzy variables and are qualitative considerations regarding the information on the capacities of the systems of the urban ER system on several scales. Considering the resilience capacities of the systems of the urban ER system, the RITAI suggests that ERR is operationalised with assessments on citywide accessibility of a selected ERS, considering the resilience mentioned above features of the urban ER system and reflected on its rapidity of response.

3.4 Rapidity of Response, Response Capacity &Accessibility Assessments

The thesis proposes that the rapidity of the response of an urban ER system is enhanced with reduced accessibility times, thus timely ER, dependent on the TTR (risk levels) of the road network and consequently of the connectivity of the urban ER system after occurrence of selected flood scenarios. Therefore, accessibility is an increasingly important risk factor, and, as also mentioned earlier, it is proposed as a driver for resilience, specifically in complex urban environments. Population growth in urban areas is directly analogous to increased emergency response demand due to the increasing needs of prehospital emergency medical care (emergency transit) needed by the population [331, 332]. EWE [245] and floods [86] severely impact various CI and particularly on the road network. The road network is an essential CI for fire and rescue services and the backbone for delivery of timely ground ER, transport of goods and the population. Transport is also the critical component in sustaining national productivity through the movement of people in *"large commuting catchments and goods in the ever-increasingly complex and time-sensitive supply chains"* [333].

Therefore, research has associated transport networks with accessibility measurements serving as a socio-economic growth indicator [334]. Therefore, it is essential to use road network analytics [246] by adopting vulnerability and criticality assessments with a geographic context [147] for risk-based accessibility assessments. For the case of floods, geolocated information on the UFTTR, as suggested in section 3.3, provides a detailed overview of the possible level of degradation of the ER efficiency regarding timely accessibility in predefined response times, considering vulnerability assessments. The response times [335] of several ERS (fire brigades, medical services) are crucial for the emergency response planning, and particularly in regards to accessibility, the emergency response route planning [242, 279, 336].

Therefore, timely ER must be provided between specific time thresholds, which are identified as sufficient worldwide; approximately eight minutes (plus/minus 2 minutes) is the most commonly used time threshold, also for Germany [28, 242, 243, 337-339]. Response times are the metric of accessibility. Several definitions have been given to accessibility, starting back from the 1920s [340]. A review of the different definitions and their measurements, with applications on the German commuting network, can be found in [104, 334].

Accessibility, in emergency management, is commonly used as a response time-based efficiency factor for the evaluation of the performance of the ER of several ERSs in terms of timely ER provision, in the predisaster phase for planning but also during and after various disaster/crises, to shelters [341], vulnerable populations, evacuation and location optimisation for emergency humanitarian logistics [188, 342-346]. In this thesis, the **RITAI for operationalisation of ERR quantifies the impact of the floods on the response times by considering the redundancy and resourcefulness of the road network regarding timely ER provision and safe mobility capacity through driving under flooded conditions**. Road networks underpin mobility, and since accessibility according to [347] refers to the *'properties of the configuration of opportunities for spatial interaction'*, it can be argued that the measurements of the accessibility are indicative of the high spatial dependence on the status of the road network (physical and geographical interdependency) with the serviceability level that is under study (timely ER provision). The road network status regarding free mobility provision to travellers can be hindered by the EWE's impact on the road network. The main concern and focus for emergency activities are the logistics of operations and road accessibility [348]. The leading indicator towards the operationalisation of ERR suggested in this thesis is accessibility, which is a risk-based indicator.

Accessibility, in the ERR concept, is defined as *the time of response of the ERS to the nearest city units that can be reached under any flood event.* It is dependent on the impact of the flood on the road-type dependent FFS (redundancy) and, consequently, the urban flood travel time (reliability) of the ER road network segments (UTTR). As suggested in this thesis, the large-scale impact assessments are enabled using graph theory and network science (see section 2.1), identifying the connectivity and accessibility levels of the urban ER system under the stressor of floods. In [104], it is argued that it is helpful to analyse the related type of stable/unstable evolution and the leading conditions to the system's resilience in the presence of shock or perturbations.

In [165], this theory is acknowledged for improved impact modelling of the climate extremes and their implications in transport.

The conceptualisation and the operationalisation methodology of ERR to floods are also formed around this theory. Specifically, the focus shifts on the untangling of the complexity of the urban ER system, from resilience analyses on its interdependent CI, with a particular focus on the road network (for reasons mentioned above). As suggested, **the urban ER system also consists of a complex beehive of city units**. The compartmentalisation of the urban area in components of similar size will further aid the accessibility and connectivity analyses of the urban ER system, reflecting on the response capacity of the systems after the shock of disasters (floods).

For comparison analyses for various states, the accessibility measurements consider the flood impacts on the travel times of the interconnecting road segments between the ERS buildings and the closest city units. The identification of flood risks in different systems and various scales is therefore enabled. This outcome shows that the methodology also provides results of the centrality of the road segments; tested performance for timely ER considering safe driving through flooded waters. Centrality measures are used generally to measure the degree of importance of specific nodes/links in a street network [334].

These measures aim to quantify the influence capacity of the node, either to be influenced or to influence other system elements under its connection topology [349-352]. For example, the measure of “betweenness centrality” has been used in strategies towards reducing the impacts of EWE to the infrastructure networks [287], indicating critical road network links potentially profoundly impacted by floods in regards to safe driving through flooded waters. The betweenness centrality reflects the extent to which a node lies between pairs or groups of other nodes of the graph, indicating the extent that a node is an intermediate in the communication over the entire network. In general, network analyses conducted with GIS have been proven effective for such centrality measurements in network concept generation methods [159]. The thesis discusses that betweenness centrality conducted with GIS and applied on scenarios of local flooding indicates areas affected by the impact of floods that are not physically nor geographically interdependent [353], which has also been identified through the application of the methodology. This identification is possible after weighing each city unit centroids with comparison accessibility analysis results between flood events and non-flood events. After classification, according to accessibility thresholds of the ERS (benchmarking of timely ER) under research, the visualisation of the flood impacts to the urban ER in the form of ERR matrixes is possible. The RITAI with its features, sub-indicators, metrics and expected outcomes are in Table 3.

Table 3: RITAI for the Emergency Response Resilience (ERR) operationalisation - ERR features, sub-indicators, metrics and outcomes

Emergency Response Resilience (ERR) to flood events in urban areas

Risk-based Time-dependent Accessibility Indicator (RITAI)

Features	Sub-Indicators	Metrics	Outcomes
Robustness	**Absorption capacity** ERS and ER Road Network exposure	Extent of exposure to the hazard per road segment and network length in kilometres	▪ Exposure assessment of the entire ER road network and ERS buildings through FD information (per scale of analysis – 1m road segments) ▪ Definition of critical thresholds (critical FD) ▪ Geovisualisation of information, after classification, on the entire road network ▪ Flood intensity impact curves of the entire road network and analysis after fuzzification regarding the safe driving mobility under flooded conditions
Redundancy	**Adaptation for transformation capacity –** ***Risk identifier on network and system level*** ERS and ER Road Network Capacity	FFS change and speed flow-based impact according to ERS capacity on rescue vehicles (height of rescue vehicles)	▪ Calculation of impacted FFS according to critical thresholds (per scale of analysis) ▪ Comparison analysis of FFS (per scale of analysis) ▪ Geovisualisation of information, after classification, on the entire road network ▪ Flood intensity impact curves of the whole ER road network and analysis after fuzzification regarding the safe driving mobility of emergency responders
Resourcefulness	**Transformation capacity -** ***Resilience identifier on network and system level*** Road Network and ERS Travel Time Reliability	Travel time change and impacted travel time reflecting on the travel time reliability (TTR) of the road segments	▪ Calculation of impacted travel time (per scale of analysis) ▪ Comparison analysis of TTR (per scale of analysis) ▪ Geovisualisation of information on the entire road network(maps) ▪ Flood intensity impact curves of the whole network and analysis after fuzzification regarding the road network's safe driving mobility for ER rescue vehicles
Rapidity	**Response/Serviceability capacity –** ***Resilience identifier on a SoS level*** Efficiency of ERS according to performance levels/efficiency of the road network for timely ER	Routing paths and calculations of response times for the closest city units, before and after flood events **' closest' refers to the fastest reachable city unit from an ERS building and is defined according to the regulations of the ERS*	▪ Connectivity (risk identifier on a SoS level) and Accessibility analysis (resilience identifier on a SoS level) based on flood-impacted ER road networks ⬇ ▪ Network Analysis, before and after a flood, for ERS of choice, covering the entire case study area ▪ Geovisualisation of information, after classification, on the entire road network ▪ Comparison analysis of accessibility ▪ Geovisualisation of information, after classification, on the entire case study area – ERR matrix ▪ Flood intensity impact curves for the entire case study and analysis after fuzzification regarding the road network's safe driving mobility for ER rescue vehicles

4. Applied Geoinformatics with GIS for Operationalisation Purposes

The RITAI is spatially assessing from large scales to smaller (see Figure 11 - general operationalisation concept), with the aggregation of information indicated with the blue arrows and the combination of a top-down (interdependent resilience features reflected in the interdependent resilience capacities) and upscaling spatial approach. The flood impacts are on a road segment level as aggregated to the entire road network and the city units (bottom-up dependencies and upscaling assessment approaches). Robust, therefore, is an urban ER system with characteristics (identity-critical functionality) that are not exposed to floods, and the safe driving ability is not affected. The intact identity of an urban ER system is related to unaffected critical functionality from the floods, which are stressing the system's (in the sub-systems and the entire system), traffic, mobility, connectivity, and accessibility characteristics. With the suggested set of a critical FD that extends the absorption capacity, it is supported in the thesis that the urban ER system will enhance its adaptation, transformation and response capacity after enhancement of the same capacities of the CI of which it consists, tested for their flexibility under the stressor of selected flood scenarios.

Thus, the redundancy (active and passive) is enhanced by enhancing the adaptation capacity of the urban ER system for timely ER according to the rescue vehicle's safe driving mobility capacity, considering the safety of the emergency responders. According to [314], redundancy is differentiated into two types: the active and the passive. Active redundancy is the number of alternative routes that could be preserved under natural conditions by various measures such as speed adjustments (FFS_{change}), and the passive one could be used to represent backup options that are only used in case of disruptions. In the case of floods, the passive redundancy is referring to the FFS_{change} impacted from the FD. These road segments or flooded roads still allow for safe driving mobility of rescue vehicles for ER provision, but with added delays, i.e. the active redundancies are also enhanced – more alternative ER routing paths (see section 3.4).

Furthermore, the urban ER system's resourcefulness focuses on the UFTTR of the ER road network since the critical function of the urban ER system is highly related to the travel times. TTR is dependent on the transformation capacity of the urban ER system up to levels that ER provision is still possible, reflecting on the potential risks (delay or incapacity). Finally, the response capacity of the system is reflecting on the rapidity feature of the ERR. Network analytics and graph theory, combined with GIS tools, are utilised for further connectivity and accessibility analyses. As the last step towards operationalising the ERR assessment, accessibility is used as a metric of the response capacity. It is argued that the response capacity is highly dependent on the connectivity of the system and is assessed with network analytics. After rebuilding the flood-impacted urban ER road network with the updated characteristics mentioned above (flood-impacted FFS and travel times), connectivity is assessed. During the network analysis process, only robust, redundant and resourceful roads that will be used for timely ER provision will participate and will be benchmarked as suggested. Visualisation of the city units participating in the network analyses provides a first overview of the connectivity of the urban ER system. It further raises awareness for future safety issues of the population settled in city units that are highly flood-impacted (blocked city units for ER provision). After the flood-impacted network analyses resulting in redundant closest routes for each ERS station, accessibility times are used as a weighting factor of the city units. Accessibility patterns serve as a first overview of the response capacity of the urban ER system after floods.

Comparison results of the accessibility times (before and after a flood event) indicate the response capacity of the respective ERS stations to floods integrating safety and security aspects. With accessibility assessments, the flood impact on the service of cover (SOC) of each ERS station, as well as each city unit's evacuation or resource/medical transit capacity, is also assessed.

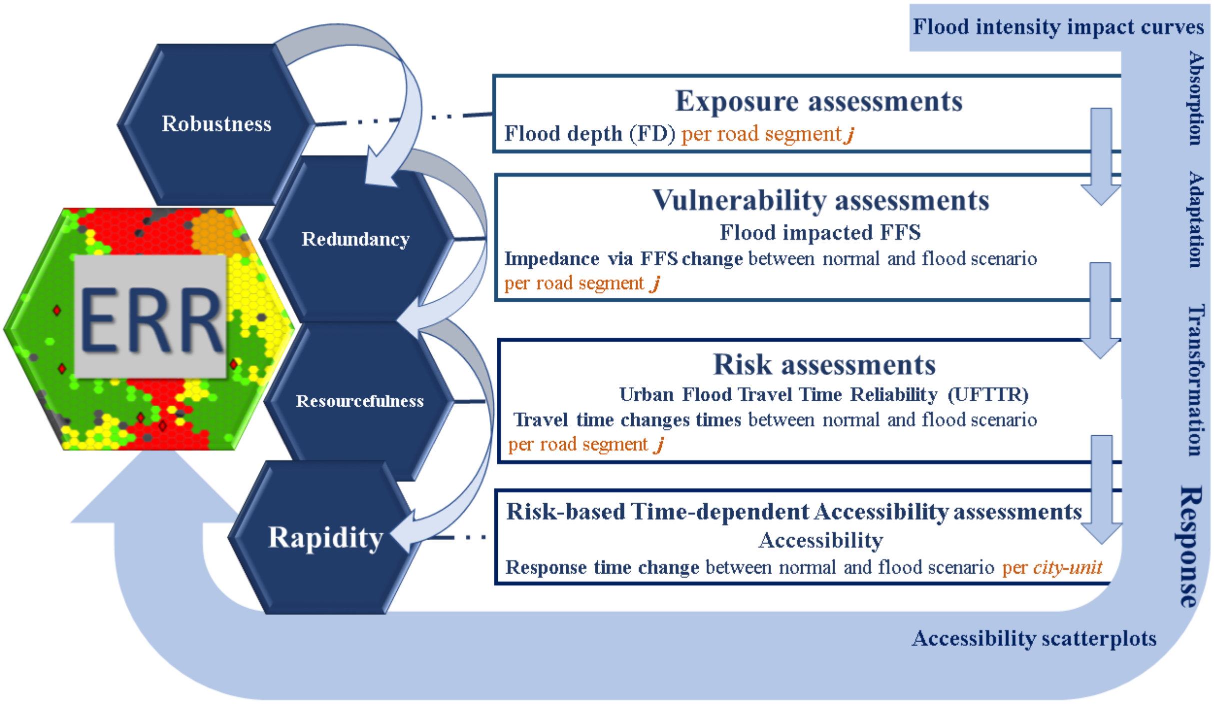


Figure 11: RITAI - Emergency Response Resilience operationalisation concept

4.1 RITAI's Benchmarking According to Safety, Security & Spatial Aspects

For a practical application of the RITAI towards the operationalisation of ERR, the concept behind ERR is described step-by-step with an explanation of the different functions used. The RITAI is presented on a general level. Benchmarking the ER's critical functionality (timely ER provision) is provided with selecting the appropriate critical FD. As mentioned earlier in the thesis, benchmarking allows for the revelation of cascading impacts. For the ER system, i.e. SoS with CAS properties, the cascading impacts of floods are assessed with the RITAI, enabling information flow from large to smaller scales and various levels (agent, network and system) through large-scale risk analyses (see section 3).

The characteristic value of the RITAI is the difference between the time accessibility of all city units during a flood event and the accessibility in the normal state. It, therefore, applies as:

$$RITAI = A_{AF} - A_{BF} \qquad (1)$$

The RITAI (function 1) indicates the ERR levels of the city units of an urban case study area. RITAI is the result of the difference between A_{AF} (the total accessibility after a flood event (riverine of a flash flood) and A_{BF} (total impacted accessibility in minutes after a riverine or a flash flood), from the closest ERS to the surrounding city units before a flood event.

Time-dependent accessibility plays a fundamental role in the transport network and specifically in emergency response operations. Firstly, it relates to all the nodes in the network. Secondly, it is a crucial instrument for exploring both slow network dynamics - characteristic of the network supply side (infrastructure development) - and fast network dynamics - typical of the demand side (mobility/collaboration of operations increase). The assessment of the accessibility used is conducted with a travel-cost approach, widely used for impact assessments related to transportation. The measure of accessibility can be interpreted as the level of connectivity of the nodes and the functionality (timely ER) of the urban ER system. The total time of accessibility A *(function 2)* is calculated as the sum of the individual travel times from the nearest fire station to the respective "closest city unit" i. It is essential for the case study area and the ERS under research to define the threshold of response, which is the one that will define the "closest city unit" and the fastest routes.

$$A = \sum_i^n T_i \qquad (2)$$

where T_i is the travel time from the start of the response (ERS buildings) to the nearest place of action i , i.e., "closest city unit" following the fastest routes.

The travel time T_i *(function 3)* is calculated from the summarisation (SUM) of the times needed to cross each road segment of the fastest route, from the ERS building to the city unit (place of action/incident area). In the following function, the time required to pass a route (/road segments) refers to its impedance (time costs) I. It applies to the travel time:

$$T_i = \sum_j^m I_j \qquad (3)$$

Risks jeopardising timely ER are identified in this level of analysis and for the system of the ER road network. They are dependent on the impedance, which is the travel costs added in the urban ER system. These travel costs are occurring after the adaptation and transformation of the road-type dependent free-flow speeds (FFS), per segment, according to FD or else road-type dependent route planning speed (ERPS).

The impedance I *(function 4)* in the thesis is a simple model used, which calculates the impedance from the segment length divided by the assigned ERPS of the segment, used for each ERS for ER route planning.

$$I_j = \frac{S_j}{K_j} \qquad (4)$$

where I_j is the impedance, S_j the length of the segment j and K_j the maximum driving speed of each segment j.

The segment length is normalised to one meter (1 m), and in this way, the analysis is local, integrating the geography perspective in the ERR concept, including large-scale intraurban speed change analyses. The driving speed depends on the ER road type-dependent maximum assigned driving speed for the road type of the segment j (N_j) before a flood event and after a flood event, dependent on the flood depth (FD_j) of the segment j and its impact on the emergency route planning speed - ERPS. The impedance, after calculation, is assigned to each road segment j before the flood events and after. The impact analysis of the different types of floods to the traffic flow (speed change) of each segment is also essential for the various hypotheses, which are configured according to the mobility capacities of each emergency rescue service (ERS), considering safety issues such as flood-depth disruption to rescue vehicle mobility. For a case-specific application of the methodology, the configuration is based on the assignment of maximum driving speeds (free-flow speeds - FFS) to each road segment for route planning purposes from each rescue service. Therefore, an update of the road network with specific information on maximum road type-dependent speeds, used for route planning of the ERS, is essential for each case study area, resulting in ER road networks.

To quantify flood impacts in FFS and travel time, according to FD and considering safety issues of the emergency responders and security of the rescue vehicles, the road network of a selected case study area is updated after each flood scenario (riverine floods and flash floods). The update regards information on the impact of the flood to the maximum driving speeds, i.e., endogenous redundancy and the travel time reliability, i.e. resourcefulness and the status of the road network in general for timely ER provision, reflecting on potential delays or blockage of emergency response (rapidity of response). The update of the flood impact on the route planning speeds is performed in a road network database in GIS, using various flood scenarios to capture an image of potential futures. The ER road network's capacity for timely ER, i.e., the passive or else endogenous redundancy of the system, is enhanced by providing one more redundancy to the urban ER system, by extending its connectivity and accessibility, with the use of the flooded roads that allow for safety of the population, the emergency responders and for the security of their assets. Concerning transport network resilience, it has been demonstrated that rapidity can be increased by adding just one more redundancy [203]. Following this notion and considering the need for the population's safety via timely ER, the following hypotheses are suggested to quantify the impact of floods on the ERPS on each j. The benchmarking considers the FD and the different capacities of each ERS in the heights of rescue vehicles.

These hypotheses are formed for modelling, automation of calculations and assessments of the exposure (FD per segment) and vulnerability (ERPS/FFS per segment) of the ER road network after the stressor of various flood types and intensities. The absorption and adaptation levels of the urban ER system are therefore reassigned to each road segment (scale of analysis) by i) extending the endogenous redundancy of the system in regards to safe driving mobility through flooded waters, according to ERS rescue vehicle capacity and ii) transforming the ER road networks, for fast accessibility/timely ER provision. The calculations of the flood-impacted ERPS/FFS per road segment and the reassignment to each road segment are conducted according to the following three hypotheses:

Hypothesis 1: If the flood depth is 0 (zero), which means an unaffected ER road network (i.e. not exposed to FD), then the network keeps its identity (characteristics). The road type-dependent ERPS K_j used from each ERS for ER route planning towards timely ER provision, remains the same and is assigned for each road segment. ***If not,*** the FD is greater than 0 (zero), the K_j is calculated using the following depth-disruption function [253],

$$\text{PR} = 0.0009 * FD_j^2 - 0.5529 * FD_j + 86.9448 \quad (5)$$

where the speed PR is the maximum acceptable velocity, which ensures safe control of the driving vehicle given the depth of water; in our case, the rescue vehicles**. In this way, the safe-driving mobility of the rescue vehicles is considered and, consequently, the safety of the emergency responders**. The depth-disruption function PR results from the combination of experimental data, observational and modelling studies reviewed in [253], leading to a curve developed to indicate the FD impact on the vehicle road speed (Figure 12). Precisely, a depth damage function, such as PR, is a function that results in providing information for what fraction of total value at risk is damaged at different inundation depths [354]. The results for each flood scenario will give an overview of the reliability of the road network segments for timely ER provision.

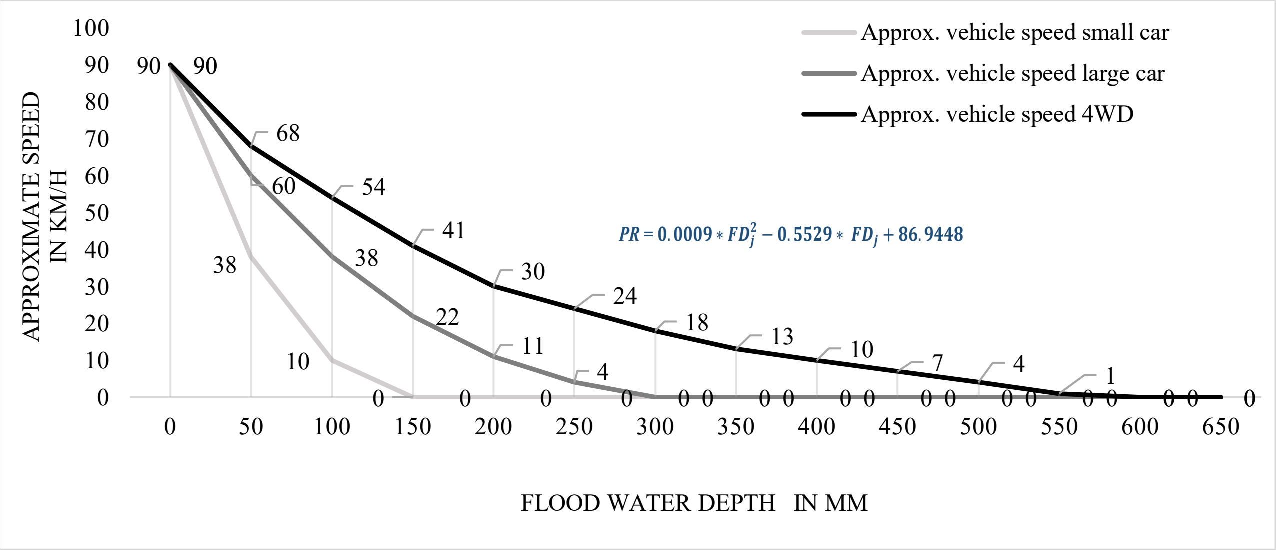


Figure 12: Depth-disruption function/Flood safety function, relating the flood depth with vehicle speed. Adapted from [253][3]

Hypothesis 2: If the maximum flood-impacted ERPS, resulting from the previous calculations from the PR function, is higher than the ERPS used from the ERS for timely ER, then it is assigned to the road segment to provide timely ER. ***If not***, then the maximum ERPS assigned to the road segment remains the same.

For the application of the hypothesis, it is a prerequisite the definition of the maximum allowed FD thresholds for safe driving through flooded roads. Through the curve (Figure 12), each ERS can configure the thresholds and, therefore, the hypotheses analogously with their capacities in equipment and area of service. For example, the fire brigade departments are equipped with fire trucks, which they deploy due to their ability to drive through flooded roads (4-wheel drive - 4WD cars) up to 0.6 m (see Figure 12). This FD value is estimated from experimental and observational values in a literature review conducted in [185, 253, 355-357]. Therefore, it is suggested that the value of FD equal to 0.6 m or 0.75 m can be a threshold of choice for fire brigades equipped with 4WD fire trucks for applying the methodology.

In the road network database, the hypothesis aims to configure the calculations to return to each road segment the K_j , when the road segment is not flooded and to assign the new calculated PR speed according to each FD_j. The resulting PR road type-dependent speeds are expected to have lower values than the K_j because of the flood impact. In this way, the urban ER system is adapted to the

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[3] Right axis: Speed reduction due to rainfall. Bottom axis: Floating floodwater depth from experimental studies on parked cars.

flooded conditions, and extending the ERR curve, i.e., slower rapidity feature but with remaining functionality.

Hypothesis 3: If the flood depth is higher than 300 mm (or else $FD_j > 0.3$ m), then the maximum ERPS/FFS to the road segment value assigned is 2.0748 km/h, which is close to the walking speed; this value is correspondent of the 300 mm of FD_j resulting from the PR formula. For more information, see [253].

At this step, expansion of adaptation capacity is performed with the modelled configuration of the FFS, according to the rescue vehicle's capacity and safe driving characteristics, for the fire brigade system of an urban area with a dense road network, where ER must be time-efficient under any weather condition. *Function 5* of the hypothesis demonstrates drivable flooded road segments after the assignment of the minimum and maximum thresholds of FD_j. The hypothesis aims to return information on the safe driving mobility (drivability) through flooded road segments for specific FD thresholds, transforming the particular road segments to walking paths (maximum allowed driving speed is close to the walking speed, i.e., 2.0748 km/h). This allows for adaptation and transformation (redundancy) and risk (resourcefulness) threshold extensions towards timely ER (rapidity) and enhancement of ERR.

As presented above, the methodology for the configuration of the input information according to the demands and needs of each case study area and analyses conducted in different scales is essential. Most fire brigades are deployed with rescue vehicles, which can still drive through flooded road networks. However, even if *function 5* loses its validity for $FD_j > 0.3$ m, it is assumed that the most used vehicles of the fire brigades have a driving ability to the height of approximately $FD_j = 0.5$ m. Therefore, in this thesis, the minimum value of speed for *function 5* is considered the one corresponding to a $FD_j = 0.3$ m and the maximum to $FD_j = 0.5$ m. For $FD_j > 0.5$ m the value is set to zero, and the flooded road segments of $FD_j \geq 0.5$ m are set as blocked and impassable. However, in this case, and if possible, different routes can be selected for ER route planning; otherwise, a destination cannot be reached (inaccessible/zero ER delivery).

Identification of blocked destinations is indicative of the need for measures taken, either for protection of the spatially related number of population (geographical interdependence), buildings and different CI, for the enhancement of response times and of the specific impacted road segment for the increase of recovery time, thus rapidity.

$$K_j(N_j, FD_j) = \begin{cases} N_j \;\; for \;\; FD_j = 0 \; or \; (\, FD_j > 0 \;\; and \;\; N_j < PR) \\ PR \;\; for \;\; FD_j > 0 \qquad and \, PR < N_j \\ 2.0748 \;\; for \;\; FD_j > 0.3 \qquad and \, FD_j < 0.5 \\ 0 \; (blocked) \qquad for \;\; FD_j > 0.5 \end{cases} \tag{6}$$

Function 6 aims to assign each road segment (scale of analysis) the updated maximum allowed road type-dependent speed (RPS) K_j after integrating the impact of the FD on the driving behaviour of the fire brigade vehicles for emergency rescue routing plans. Therefore, it transforms the traffic characteristics of the road segments. In this way, the transformation of each segment is achieved.

On the one hand, it adds delays to the ER time, but on the other hand, it enhances the redundancy and resourcefulness of the urban ER system. In this way, the ER, even if delayed, is still a possibility and extends the connectivity of the urban ER system.

While no adaptation and transformation has taken place, the resilience of the urban ER system is expected to be lower. For example, without the extension of the passive redundancy in the system, considering the RNMC for safe driving under flooded waters, the blocked functionality margin will expand, lowering the ER curve depicted in the rapidity feature.

The walking speed, even if delaying the ER, still enhances the response capacity. When rescue vehicles operate under flooded conditions, there are occasions (up to the rescue vehicle's safe driving mobility capacity) that they need to reach destinations by driving through flooded waters.

In this case, the danger of floating objects transferred from the flood velocities (gully tops, garbage, stones), which can damage the engine, can hinder or even entirely block the emergency response delivery or reduce driving speeds close to walking speeds. When driving through deeper flooded roads, until the flood depth (FD) that is possible (mostly till $FD_j = 0.5$ m or maximum till $FD_j = 0.75$ m), it is essential for the emergency rescue drivers to know if floating obstacles will damage the fire truck. To avoid damages and further accidents, a rescuer walks through flooded roads ahead of the fire truck and clears the way. The driving speed of the fire truck is then close to the walking speed, following the pace of the firefighter. In the case of Germany, this has been verified by fire brigade officials and volunteers of Cologne's fire brigades, which is the case study used for ERR assessments (see section 5).

4.2 GIS-based Spatial Upscaling Operationalisation Approach

> *"The fundamental mission of emergency management is to propose an operable, accurate, and cost-effective plan to cope with different unforeseen events" [237]*

According to FD, the benchmarking of the urban ER system, considering safe driving mobility of emergency rescue vehicles, **extends the redundancy** (passive and active) while consequently enhancing the resourcefulness of the system for ER provision. When disasters occur, even with considerably minor added delays (see section 5.3 - accessibility thresholds) in the provision of rescue and humanitarian relief, in the delivery of rescue equipment (rescue boats, ladders), and the transit of patients or doctors, this extension of redundancy and resourcefulness of the urban ER system is of value. It is argued that in urban areas, large-scale geolocated and visualised knowledge of FD with the information on the cascading flood impacts on the road network system can enable the identification of risks (flood impacts) on different scales and levels. Consequently, ERR can be enhanced with risk-informed and adaptive ER road network databases for adaptive ER route pre-planning, indicating the accessible areas in a city (city units).

In the preparedness phase, many roads can be impassable (non-drivable/blocked) due to high FD $\geq$ 0.5 m, and some others can still be drivable due to lower FD [0.01, 0.3) meters. The status of the ER road network regarding the level of a flood (direct flood loss) impacts the safe drivability/mobility capacity of the roads from rescue vehicles, which is dependent on the mobility capacity of different rescue vehicles (various heights and types) of each ERS. This issue can be tackled with the provision of risk informative databases and maps.

The developed methodology results in providing updated road networks with information on drivable and travel time reliable road segments for timely ER, which will enhance the efficiency of ER delivery in case of floods with ER route pre-planning, according to information in regards to the geolocated safe driving mobility capacity and citywide accessibility. The update occurs from the assignment of the new state of the ER free-flow speed (ERPS - traffic characteristic), which is the impacted FFS according to flood depths. Comparison analysis between the two states (normal and flooded) is visualised, providing exact geolocated information on degraded traffic characteristics.

Geovisualisation of the level of change indicates which road segments are travel-time reliable for use in ER route planning and the ones that are expected to add delays to the operations and should be avoided. Therefore, the opportunity is given to the ER route planners to either omit them from ER route planning or raise awareness for the vulnerability of the identified road segments for future ER operations under flooded conditions. Based on the updated ER FFS, travel times of each road segment are re-calculated, and the travel time reliability (TTR) of each road segment is assessed after comparison analysis before and after the occurrence of floods. The results visualised are providing a detailed overview of the urban flood travel time reliability (UFTTR). Different levels of UFTTR provided for each road segment provide further geolocalised information on the impacts of the floods to the main critical functionality of the ER road network, that is, timely ER provision.

Additionally, connectivity analyses are conducted with network analytics for each updated ER road network with information on the cascading impacts of the floods on their traffic characteristics. Consequently, accessibility analyses can be conducted using the updated ER road networks and the time difference of the accessibility before and after the type-based flood risk occurrence of different intensities. These values are assigned to each city unit, providing information on the ERS efficiency and the RNMC for safe driving through flooded waters and operationalising the ERR in urban environments. The outcomes of the methodology are visualised in ERR matrixes, after classification, indicating the level of resilience of the city units of action regarding the risk-based and time-dependent accessibility, aiming to enhance the rapidity feature of ERR to riverine floods and flash floods. It is argued that resilience assessments on different levels in a system combined with GIS tools, methodologies and geovisualisation techniques enhance the robustness, redundancies, resourcefulness and rapidity of the response of the urban ER system.

Specifically, the scenario-based GIS methodological framework of the operationalisation of the ERR is presented in Figure 13. The figure displays information aggregation from components to the constituent systems, the networks, and the SoS with CAS properties, i.e. the urban ER system. The system is presented as a network graph model of its sub-systems/components (road segments and centroids of city units). Flood models are used as external factors stressing and affecting the urban ER SoS, its systems and networks, leading to system distortion (delayed or impaired ER provision to the city units) and consequently to population safety reduction, potential vehicle-flood fatalities and an increase in operating costs.

In a GIS environment, the urban ER model is created by the abstraction of its components as nodes (emergency rescue buildings and centroids of city units), links (road network), road segments (after spatial separation and normalisation) and the base-layer (case study area/beehive of city units). In the suggested model, each component is defined by its quantitative attributes, which have been identified to have a significant impact on the ERR to riverine floods and flash floods and are reflected in each feature of the ERR; safe driving mobility of the emergency responders, travel time and accessibility response times, according to FD thresholds.

With semi-automated calculations through a developed GIS-Toolkit (see next section 4.3), the road network is normalised to one-meter road segments, and this is the scale of analysis for exposure, vulnerability and risk assessments depicted accordingly on the robustness, redundancy and resourcefulness of the ER road network for timely ER provision.

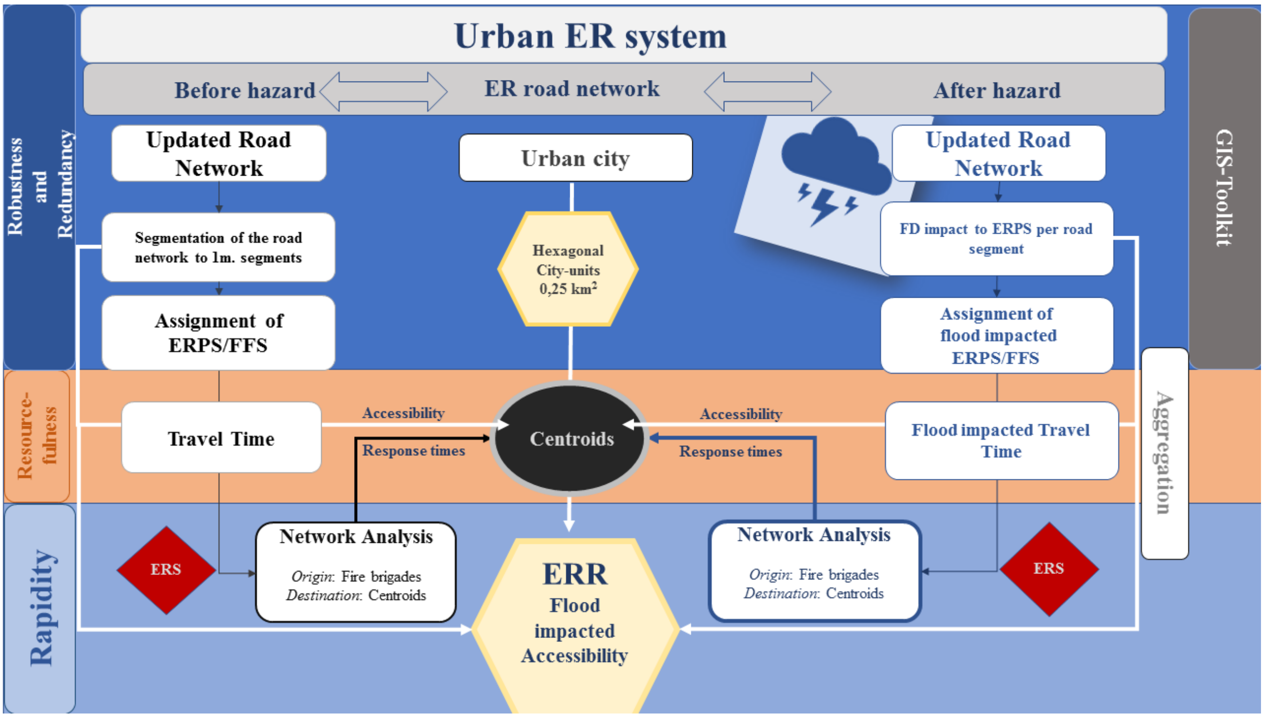

Figure 13: ERR upscaling spatial assessment GIS-based workflow indicating the aggregation of information to different scales (white arrows)

The normalisation enables the focus of the ERR assessments on local scales (large scales). Assessments as exposure assessments of the FD on an ER road network indicate the absorption and damage levels of the floods to the network and the entire urban ER road system due to high interdependence and interconnectedness. Vulnerability assessments are indicative of the transformation of the traffic system's characteristic ERPS/FFS, which lead to flood-impacted travel times, indicative of the adaptation capacity of the urban ER system. Risk assessments are depicted on the newly calculated flood-impacted travel times, which are indicative of the transformation capacity levels of the urban ER system, i.e. reliability. All of the information above is integrated into updated flood-impacted ER road network databases.

Furthermore, the urban ER system properties, such as network connectivity between its systems and accessibility, are analysed with graph theory combined with network science (network analytics). That is the reconstruction of ER road networks with risk attributes and search of the closest surrounding city units using GIS tools such as the Network Builder and Closest Facility (accordingly), reflecting on the resourcefulness and the rapidity features of the ERR. For citywide efficiency assessment of the urban ER under flooded conditions, these simulations are carried out from the emergency rescue buildings to the closest city units, followed by comparing the system functionality before and after the flood events based on the sub-systems'/components' level of functionality. Levels of functionality are used as weights.

According to the defined thresholds, the ER road network's segments (node and link components) are weighted with flood-impacted travel times, which reflect on the impedances that are the potential delays or even blockages of ER provision.

The centroids of the city units (city network's nodes) are weighted with accessibility response times from the closest ERS building. High-resolution geovisualisation of distortions caused to the road network system and, consequently, to the urban ER system as a whole, by riverine floods and flash floods, demonstrates the usefulness of GIS for modelling and geovisualisation techniques for the presentation of the results in regards to urban ERR.

Geovisualisation implies the adaptation of scientific visualisation to maps, as formerly called "geographic visualisation" and then, for simplification, renamed "geovisualisation" [358]. Geovisualisation is *"the set of visualisation tools, allowing interactive explorations of geolocated data in order to build and provide knowledge without a priori assumptions"* [358], and it includes fields such as scientific visualization, mapping, image processing, knowledge extraction and GIS [255]. Geovisualisation techniques, combined with ERR assessments, result in the identification of local ERR on several levels. Through such complex scientific information visualised in easy interpretable ways, the scope is to open a dialogue around the concept and integrate local (but not only) stakeholders into clarifying the concept. Moreover, to provide easier access to this concept based on i) semi-automated data analyses with the provision of the GIS-Toolkit and ii) processing and visualisation with the design of maps, as it has been presented for various other forms of resilience in different contexts [81, 234, 255, 315, 359, 360].

4.3 GIS-Toolkit

The exposure assessments result in the value of the exposed elements, i.e. objects potentially impacted by a defined hazard scenario for a specific environment [284]. The GIS-Toolkit enables semi-automatic large-scale flood exposure assessments of the ER road network (per j road segment - the scale of analysis). It is built to capture the exact flood extent with decimal precision (exposure of the ER road network to floods), i.e. FD values integrating this information in the ER road network database, per scale of analysis, i.e. FD_j assisting further the vulnerability assessment of the road network to different flood events in great detail. As previously mentioned, vulnerability is the information on the FD per road segment (FD_j), a direct exposure assessment (physical flood damage), and, therefore, a robustness assessment of the road network to the four selected flood scenarios. The GIS-Toolkit provides the ability to capture the exact flood extent with decimal precision and integrate it into the road network database, assisting further vulnerability assessment of the road network to different flood events in great detail. The combination of this information results in risk assessments of the road network to floods in complex environments through updated road networks that provide information on the impact of the FD to the FFS towards a comprehensive assessment of ERR (as aforementioned) with network analyses conducted in a GIS environment. ERR to riverine floods and flash floods for an urban ER system is operationalised utilising flood scenarios - models. These types of flood data are always provided in raster form and are used as a basis for FD extraction in GIS-based exposure assessments. The flood models are usually in a raster form. The extraction of raster values to line vectors is an issue that can be overcome with the GIS-Toolkit.

The updated, risk-informative ER road networks are resulting from the suggested GIS-Toolkit (Figure 14). The GIS-Toolkit is a semi-automation tool of:

- automatic compartmentalisation/segmentation of the road network in the case study area to 1 m segments (normalisation) - large-scale analysis,
- import the FD information to each segment (from raster to vector lines) and
- absorption of the impact of the FD to the maximum allowed ERPS using the *PR* function *(function 5)* and the *K* function *(function 6),* after consideration of the hypotheses of the methodology, resulting in flood risk-updated road networks for ER purposes after each selected scenario.

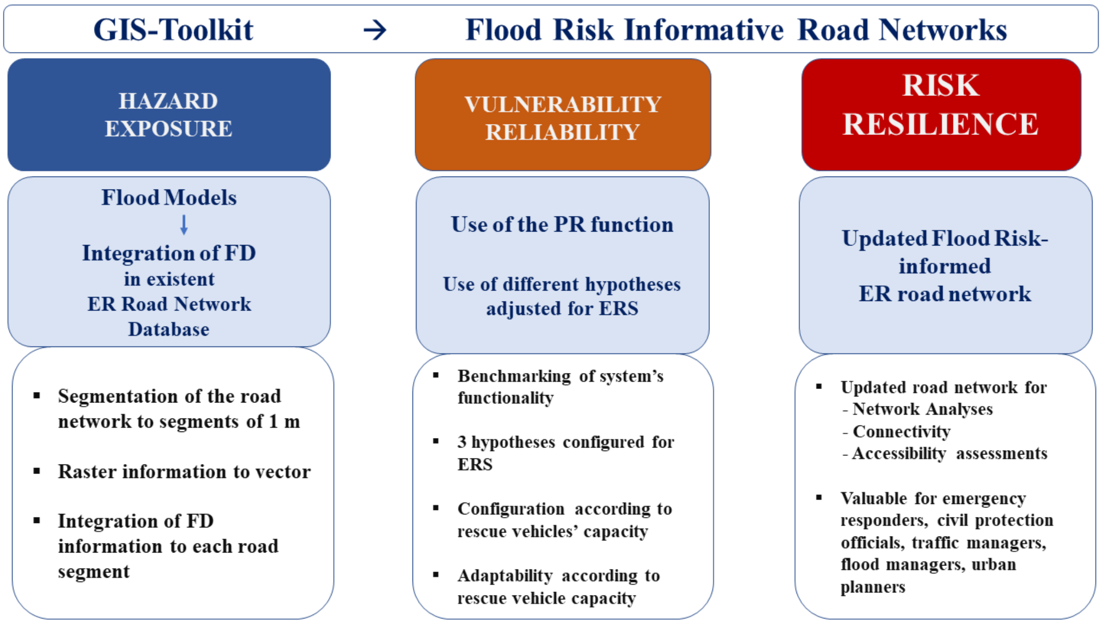

Figure 14: GIS-Toolkit: Semi-automated upscaling large-scale spatial assessments for flood risk-informed ER road networks

The RITAI in GIS suggests the building of ER road databases, resulting from the GIS-Toolkit. These databases provide on the scale of analysis (one-meter road segments) flood depth (FD) information revealing the geolocated road network's flood exposure and its geolocated vulnerability, reflected on the free flow speeds (maximum allowed ERPS) that are used for timely emergency response planning. These ER risk-informative road databases serve as the basis for further travel time reliability, connectivity and accessibility assessments (multi-scale risk and resilience) under flood conditions. Safety and security aspects are integrated through the different hypotheses suggested for the configuration of the GIS-Toolkit and the adaptability of the approach, according to the rescue vehicles' capacity that is dependent on the FD.

In this way, further multi-scale flood risk information flow for flood risk and resilience assessments are enabled with aggregated flood-risk and cascading flood-impact information in complex environments towards a comprehensive assessment of the urban ERR.

The GIS-based methodological workflow implemented with the GIS-Toolkit in a GIS environment (ArcMap) is presented in Figure 15. Specifically, it is portrayed the first part of the application of the RITAI in GIS, that is, the procedure for the aggregation of FD information from a raster data type (flood model) to a line vector (road network) and flood-impacted emergency route planning speeds (ERPS) according to defined benchmarks.

According to the three hypotheses, the implementation of the PR function (function 5) benchmarks the safe driving ability of the rescue vehicles through flooded waters and returns flood-impacted ERPS. The three hypotheses are assisting the calculation and assignment of the ERPS per scale of analysis, with the K_j *(function 6)* that incorporates the safety and security aspects into road network databases (emergency responders' safety and of rescue vehicles), for further ERR assessments in the case of floods.

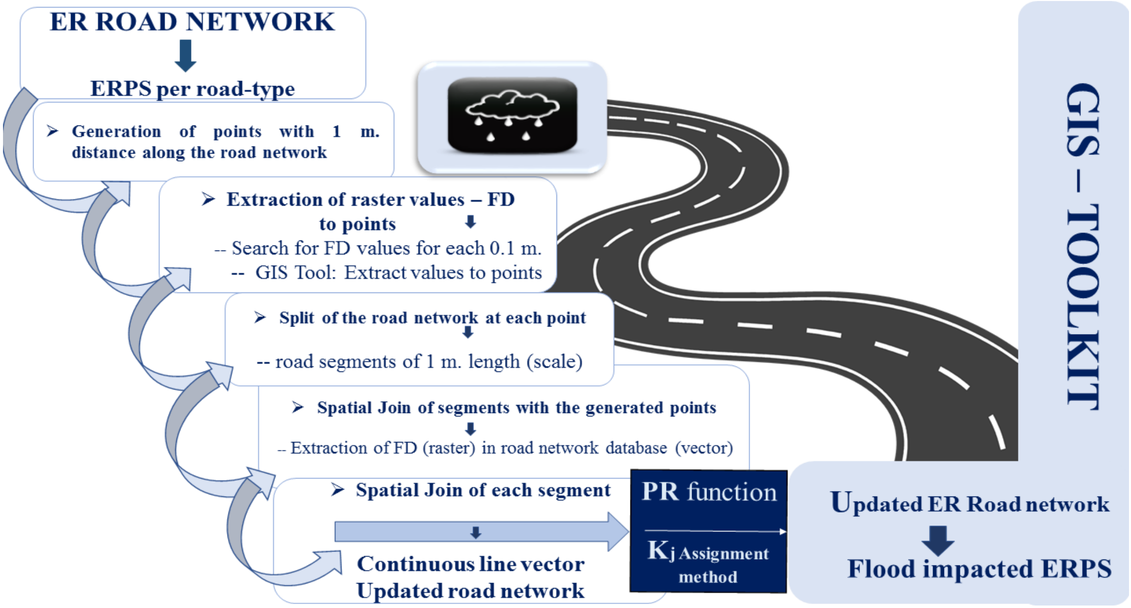

Figure 15: GIS-Toolkit – RITAI methodological workflow in GIS resulting in flood risk-informative ER road networks

The *PR* function is, therefore, configured after the definition of the FD thresholds for the case study area and the ERS of research, which are characterizing the respective flooded road segments with safe drivability levels for ER purposes as:

- **effortlessly drivable** with the maximum safe drivable FFS for values of **FD class 1 - zero exposure (FD = 0 m)**
- **drivable** - with low-impaired FFS for values of the **FD class 2: FD [0.01, 0.3) m**
- **drivable with additional delays** – with the minimum FFS for values of **FD class 3: FD [0.3, 0.5) m**
- **not drivable (blocked)** for values of the **FD class 4: FD ≥ 0.5 m.**

This fuzzification process of classified FD information aims to simplify the results' interpretation, supporting the decision-making and potential end-users.

Additionally, regarding the technical specifics, the GIS-Toolkit is built with the software of ArcMap version 10.6.1 and the use of the tool 'Model Builder'. The Model Builder allows for semi-automation and full automation of procedures in ArcMap and ArcGIS Pro. It also provides the opportunity for easy configuration of the model, respectively, with the vehicle capacities of each ERS, the ERPS and the flood-type. The workflow described above (Figure 15) is modelled in the Model Builder with input data (raster and vector), providing the opportunity to integrate values from one data type to another.

According to ESRI, the models are workflows, which order sequences of geoprocessing tools and feed the output of one tool into other tools as an input, and the tools' layout and variables are combined in a model diagram.

The modelling of the GIS-Toolkit is conducted with the programming language Python, with a combination of programming language Visual Basic (VB). The main goal of the GIS-Toolkit is to provide updated ER road network vector data (lines) with information on the FD_j (extracted from raster flood models) and the flood-impacted ERPS, on the scale of the road segment, in the database, after application of the three hypotheses (see *function 6*). The hypotheses for the calculation of flood-impacted ERPS are programmed using the VB language (Figure 16). For the application of the methodology (Figure 15), it is used a scale of 1 m for city-scale detailed flood-impact information, which is necessary for high resolution and accuracy.

Furthermore, the normalisation provided from this segmentation allows for large-scale intraurban flood impact-based assessments. The GIS-Toolkit (Figure 16) uses the flood models of raster form (manual input) as input aiming to combine static flood models with traffic flow values of an ER road network (manual input). The procedure aims to a large-scale, detailed, and, as comprehensive as possible, overview of the impacts of each flood scenario selected to the transport network characteristics and finally to the ERR. In Figure 16, the inputs are in dark blue, in light blue are the coding processes, in yellow are the standard procedures, and in green are the intermediate data and outcomes.

As discussed earlier, the toolkit provides the opportunity for exposure and vulnerability assessments of the ER road network. It is a standalone GIS-Toolkit, integrating into the road network database information on the FD per road segment (FD_j), a direct high-resolution exposure assessment (direct flood impact). Thus, it can also be used 'divided' since the first part of the toolkit allows for high-resolution urban flood exposure assessments of different scales with different types of vector line data (railway network and public transport, i.e. bus-line network, and tramline network). Therefore, it enables the robustness assessment of transportation networks, which do not include the temporal aspect. For a detailed presentation of the procedure and the Python script, please see Appendix C.

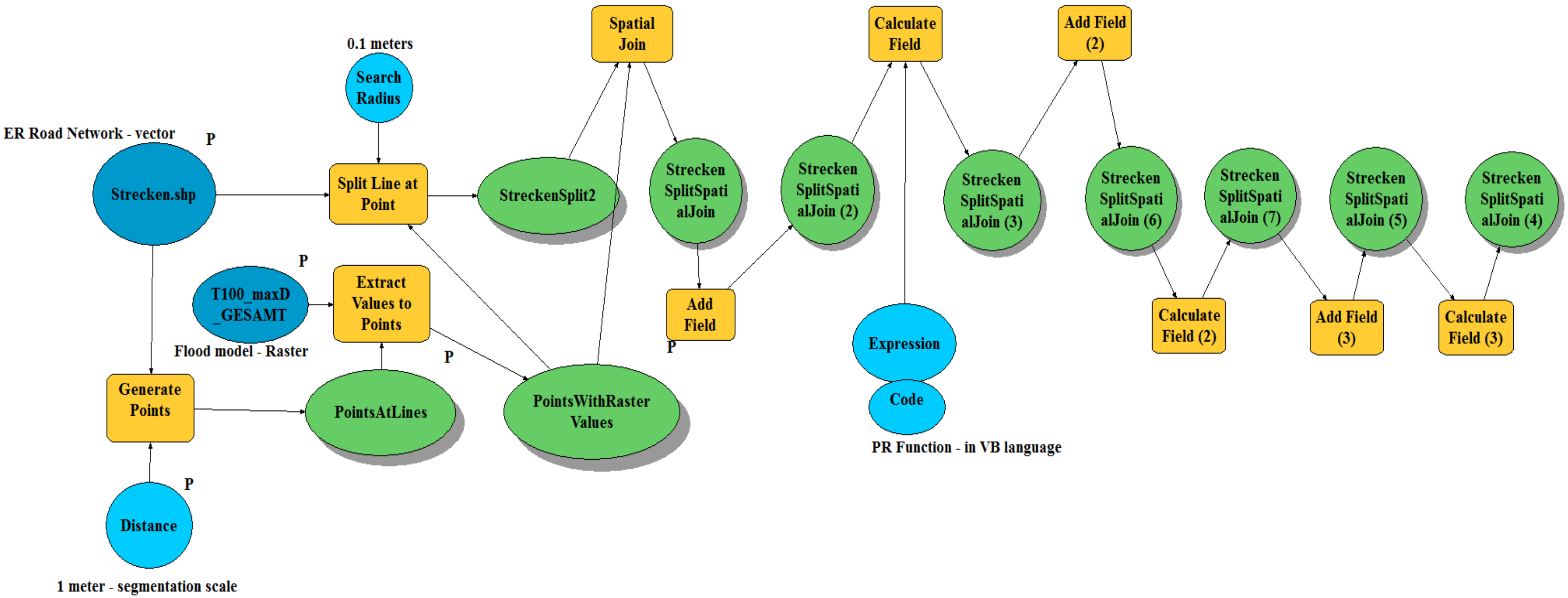

Figure 16: The GIS-Toolkit in the Model Builder of the ArcMap 10.6.1. - workflow model diagram

4.3.1 Advantages and limitations

The GIS-Toolkit is created in the ModelBuilder, and it automates the calculation processes presented in the previous section, creating geodatabases for different flood scenarios. The automation of the calculation processes makes the GIS-Toolkit ideal for transfer and use from different end-users, such as emergency responders (fire brigades, hospitals), civil protection officials, urban planners, traffic planners and researchers working in various scientific fields. It is easily configurable, and thus it can be applied for different case studies, i.e. other cities, different scales, such as entire road links, different lengths of road segments than that of the 1m, suggested in this thesis, on a national scale and for different line vector types, i.e. railway network, public transport networks.

Through the GIS-Toolkit, is given the opportunity to the users to isolate specific calculation processes and limit to, for, e.g., the exposure assessment of transport networks (line vectors) to floods (rasters). The GIS-Toolkit can add information to polylines from rasters through the automated process of the exposure assessment to floods. The flood depth information of the rasters is added to the line vectors in detail for the specified from the user unit scale. Even if ArcGIS Pro 2.3.2 provides a tool for using raster data as input, it must be of correct cell size greater than zero, and it should also be an integer raster dataset. These prerequisites limit the application of this specific tool, and it is not useful for applying the methodology suggested in this thesis since it is essential to have information on the FD with a decimal resolution for comparable real-life results.

There are attempts from different scientists to solve the issue by the provision of GIS methodological approaches. For example, in [280], the zonal statistics approach in GIS is used, and it is intended for emergency response preparedness to floods. They proceeded with the classification of each road segment according to flood depth using the maximum water depth; in zonal statistics, this is translated as selecting the highest value of all cells in the value raster, which belong to the same zone the output cell. The zonal tools allow performing analyses where the output results from computations performed on all the cells that belong to each input zone, defined by raster or feature datasets. In [280], the road segment is the zone definition dataset, which is the road from one intersection to another (node-to-node road link). Therefore, the classification of the road network and the information provided to emergency responders are aggregated to the entire road link, excluding detailed knowledge on the exposure of the different road segments of a whole road or else road link.

Since no tool exists in ArcMap and ArcGIS Pro to automatically extract raster information to polylines in spatial resolution of 1 m, with decimal precision, the GIS-Toolkit suggests a methodological approach for the integration of information from a raster to a polyline, in high resolution, for risk assessments of the road network and of ER route planning after flood events. In this way, the synthesis of highly detailed information for the FD of the road network is achieved according to the specified unit scale, avoiding data aggregation loss. The GIS-Toolkit, on the other hand, is providing exact and precise information with decimal precision, also allowing the emergency responders to know the FD of different road segments of an entire road. This information gives the emergency responders the advantage of including the flooded road segments (up to 0.5 m FD) in the route planning, with information on the exact travel time needed.

Furthermore, with the detailed and high-resolution results on the exposure of the road segments (1m scale of analysis), emergency responders can decide on potential sites of placement of the emergency boats in case of highly flooded roads, assisting a timely, effective response, and also on the exclusion of specific road segments from the emergency route planning. In this way, the impact of the stressor of floods is absorbed in the emergency system, enabling its potential transformation through alternative means of emergency response service (using aerial emergency rescue, use of alternative routing paths etc.), towards its resilience through the enhancement of the active redundancy. Another high-resolution tool called FLIAT [361] exists and is built for flood impacts on a socio-economic level, applied in GIS, which returns a road network converted to the same unstructured mesh form of the flood model, dividing the road network into unregulated segments.

The final result is not an integrated road network such as the road networks resulting from applying the GIS-Toolkit suggested in this thesis, which can be understandable and accessible for various end-users. The GIS-Toolkit also provides information for the FFS before and after each of the selected flood scenarios on a road segment scale. It, therefore, enables further calculations of the travel times before and after a flood event occurs and analyses on the FFS change (vulnerability indicator) and TTR change (risk indicator) of the road network, depicting potential futures of the emergency response performance of the selected ERS under flooded conditions of different types (riverine or flash floods). Flood risk identification on this large-scale can assist in further identifying potential cascading impacts and interdependencies between various CI, which is information that can also be utilised to enhance the safety of the population (also through self-protection enhancement) and many more analyses (see Table 2).

While applying the GIS-Toolkit on line vector data and raster data, the occurring limitations result from the size of the input data and the intermediate data, which are produced (point data along the line vectors, extraction of segments using the point data), making the GIS-Toolkit time costly in its application. The first part of the GIS-Toolkit (see Figure 16) is where most computation effort occurs. The calculation process does not return all segments with the same length of precisely one meter, but the lengths vary from 0.99996 – 1 meter. The issue can be overcome by recalculating the segment length in the road network database, setting the road segment length to one meter, simplifying the calculations, and flood-focused impact-based assessments.

Another limitation of the GIS-Toolkit is that exposure analyses may return *Null* information in the road network databases regarding FD_j for the road segments that are not affected by the floods (e.g., for application with riverine floods). These limitations can be overcome with calculations in the field by replacing the null information with the value zero (see Appendix C). Concluding with a summary of the advantages and limitations presented for the GIS-Toolkit:

- the GIS-Toolkit is easily transferable from end-user to end-user because it provides the results in the form of ArcGIS geodatabases[4] which are a collection of geographic datasets of various types held in a standard file system folder
- it allows automation of processes
- it is easily configurable, i.e., it can also be transferred from a larger scale to a smaller one (from a city-level to a national and country level), and it can also be used with different input data, i.e., different polylines (railway network, public transport) and raster data (heatmaps, snow coverage maps) for different detailed analyses where decimal precision is essential, i.e., flood depth and snow depth
- it adds to the redundancies and resources of an urban ER system by providing spatial assessment tools easily configured respectively to the needs of each end-user
- it is time-consuming when the analyses are conducted on a large scale and produces some errors, i.e. unintegrated unit scale of road segment length, which both are limitations that can be overcome with quick and straightforward in-field calculations.

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[4] http://desktop.arcgis.com/en/arcmap/10.3/manage-data/geodatabases/what-is-a-geodatabase.htm Accessed 02.2019

4.4 Aggregation & Simplification of Information with Classification & Fuzzification Methods

After the semi-automation of the flood impacts on $\mathrm{FFS_j}$, according to safe driving mobility based on the rescue vehicle capacity, the assessments of the $\mathrm{FFS_{j\ change}}$ and the $\mathrm{UFTTR_j}$ for aggregation of information to the entire network follows geovisualisation techniques. In this way, second-order flood impacts are visualised and can provide a first overview of the extent of delays expected in the ER provision.

The flood-impacted $\mathrm{FFS_j}$ (occurring from the implementation of function 5 - PR function) consequently affects the serviceability performance depicted from flood-impacted travel times and the $\mathrm{UFTTR_j}$,

The UFTTR is one of the sub-indicators of the RITAI for risk-based resilience assessments of the road network and reflects on the ability for ER provision, intended for adaptive ER route planning to each selected flood scenario, and connectivity and accessibility assessments of the urban ER system under flooded conditions. A sub-indicator is used to operationalise the ER road network resourcefulness for timely ER, measuring the flood-impacted TTR after each selected flood scenario. The quantification processes of the $\mathrm{FFS_j}$ changes and the $\mathrm{UFTTR_j}$ are taking place in the ArcGIS environment and particularly in the updated ER road network geodatabases. Changes of the FFS (function 7), on a road segment-scale, are observed after the impact of the flood events:

$$\mathrm{FFSj\ change} = \mathrm{ERPS_{j(BF)}} - \mathrm{ERPS_{j(AF)}} \qquad (7)$$

where $\mathrm{ERPS_{j(BF)}}$ is the empirical road-type dependent route planning speed that the respective ERS is using for ER route planning before any urban flood event and $\mathrm{ERPS_{j(AF)}}$ are the flood-impacted road-type dependent ERPS occurring after measurement of the impact of the $\mathrm{FD_j}$ to the $\mathrm{ERPS_{j(BF)}}$. Additionally, the $\mathrm{UFTTR_j}$ (function 8) of the road segments for ER route planning is calculated as follows:

$$\mathrm{UFTTRj} = \mathrm{TravelTime_{j(BF)}} - \mathrm{TravelTime_{j(AF)}} \quad (8)$$

where the $\mathrm{TravelTime_{j(BF)}}$ is the total travel time that it takes to a rescue vehicle to drive through each predefined road segment j before any urban flood events, and $\mathrm{TravelTime_{j(AF)}}$ is the total travel time that it takes for a rescue vehicle to travel through each road segment j up to the $\mathrm{FD_j}$ allowing for safe driving, after integration of the impact of the $\mathrm{FD_j}$ to the $\mathrm{ERPS_{j(BF)}}$.

Classification of results from (function 7) and (function 8) occurs according to the safe driving mobility, which depends on the rescue vehicle's capacities of the respective ERS. The reasons have been demonstrated throughout sections 6.2 and 6.3. The adaptation capacity of an urban ER road network reflects on the robustness of the urban ER system. It is assigned fuzzy variables regarding driveability (qualitative consideration of safe driving ability), which indicate the exposure of the ER road network to $\mathrm{FD_j}$.

Consequently, the transformation capacity is assigned variables concerning the transformation that a flood-impacted road segment undergoes analogously to the impact of $\mathrm{FD_j}$ on its driving mobility capacity. Finally, the TTR_j is analogous to the impact of FD_j and is assigned fuzzy variables depicting the $UFTTR_j$ levels (resourcefulness).

The visual and numerical presentation of the results is in a classified form, where each class is assigned a fuzzy value (linguistic variable), following a simple fuzzification method. Fuzzification is the process of the conversion of a "crisp" input value to a fuzzy value corresponding to a fuzzy subset or a membership function [143, 362-364], that is, precise values onto linguistic variables [365]. In this thesis, each linguistic variable, used for the description of the impact of selected flood scenarios to the road network and the ERS under research, is defined by a qualitative term set (e.g. [high; rather high; low; not impacted] or [reliable; medium reliable; not reliable]) with a defined number of members (see Table 4). The fuzzification in this thesis aims to present the classified results of the different functions implemented in a complex urban system. The goal is to provide an understandable overview of the results for further analyses and implementation of the methodology. The results mainly aim for ER purposes, civil protection decision making, traffic and urban planning, and critical infrastructure protection (CIP) analyses in complex urban environments. Therefore, it is argued that the potential impacts of a hazard on complex urban environments need untangling with easily understandable inputs. These inputs regard the potential impacts of the hazard on their interdependent systems (nexus of different population groups affected, complex road networks, different interdependent CI), feeding information to down to top DRM and FRM methods (see section 2.1).

Table 4: Sub-indicators classified - Impact of the flood depth (FD) on the road segments' status used for ground-based ERS.

Flood Depth – FD_j	**Status of road segment in case of urban flood scenarios (Absorption)** – $FFS_{j\ AF}$	**Transformation in case of urban floods** – Impact on the FFS_j	**Impact on Travel Time in case of urban floods** – $UFTTR_j$
≤ 0.3 m	Drivable as planned and Drivable with low impedance → insignificant delays	**No transformation**	**Reliable**
0.3 m – 0.5 m	Medium Drivable with high impedance → use of the speed at minimum FFS / walking speed	**Transformed into a walking path**	**Medium Reliable**
≥ 0.5 m	Blocked → incapacitation of ER	**Transformed to impassable**	**Not Reliable**

Apart from the compartmentalisation/segmentation of the ER road network, for several reasons mentioned above, the urban ER model suggests the compartmentalisation of the case study area for further risk-based time-dependent accessibility assessments of the urban ER system, using the updated ER road network databases to floods (see section 6.3.3).

5. Operationalisation of the ERR to Floods for Cologne's Fire Brigades

5.1 Cologne: Case Study, Climatic Characteristics & Flood Scenarios

For timely ER provision and quantification of a range of flood impacts, as stated in [272], it is essential to identify **risk sources and obtain scenarios** representing the risk situation. Hence, i) **flooding**, a typical example for Germany is selected as a risk scenario, and ii) the **case study** area selected is **Cologne (Köln) since river floods and flash floods are frequent**. Cologne's choice as a study area is reasoned as follows.

Similar to many European cities that expand on both sides of a river, Cologne expands on both sides of the river Rhine. In combination with the human settlement (alongside), this city planning narrowed down the natural riverbed considerably over recent decades and has increased the flood risk for the population and the geographically interdependent CI.

It is discussed in [366] that due to the exposed location of Cologne at the River Rhine, the flood risk is prevailing, despite the extensive efforts in flood protection and in [367], it is further mentioned that Cologne is Europe's most flood-prone metropolis, with increasing frequent flood events. Cologne is also the fourth most populated city in Germany after Berlin, Hamburg, and Munich and the largest city of Germany's most populated federal state of North Rhine-Westphalia (NRW). With over a million inhabitants (1.08 million), Cologne is the largest city on the Rhine river and the most populous city of the Rhine-Ruhr Metropolitan Region, Germany's largest and one of Europe's major metropolitan areas[5].

Riverine floods are measured with distributed gauges along the rivers all around Germany. Similarly, gauges are distributed at the river Rhine around the area of Cologne. Measurements of the gauges (1900 - 2002) around the Rhine catchment for Cologne and Bonn [368] have indicated significant upward flood trends in magnitude and frequency. It is further suggested in [367] that the gauge of Cologne is mainly dominated by winter floods and slowly rising water levels, which is typical for most gauges in the Rhine. For Cologne and the period 1951 - 2002, upward trends in the annual maximum flood in the Rhine and Weser basins are attributed to trends in the winter season. Comparing the yearly streamflow maxima with the seasonal streamflow maxima shows that the annual maximum streamflow is determined by floods occurring in the winter season, with the summer riverine floods being significantly smaller. In **2018 for the Rhine area and Cologne**, the local flood control centre mentioned that in January, the **riverine flood reached 9 m of flood depth** (FD).

On the other hand, the EWE occurrence increases significantly with a similar analogous increase of intensity [48], even on a regional scale. It is estimated that by the year 2050, the temperature of the **coldest month in the city of Cologne will have increased by 2.6 degrees Celsius,** and the temperature of the **warmest month will have increased by 5.7 degrees Celsius** (see Figure 17). An increase in temperatures leads to heavy precipitation and, therefore, heavy rainfalls, which can cause **flash floods**.

Flash floods in urban environments are regional events (depending on different factors, such as geomorphology, land use), and due to the density of CI and the dependent population can have significant impacts leading to domino cascading effects from CI to CI (e.g. transportation, electricity, water distribution network) impacting the spatially related community.

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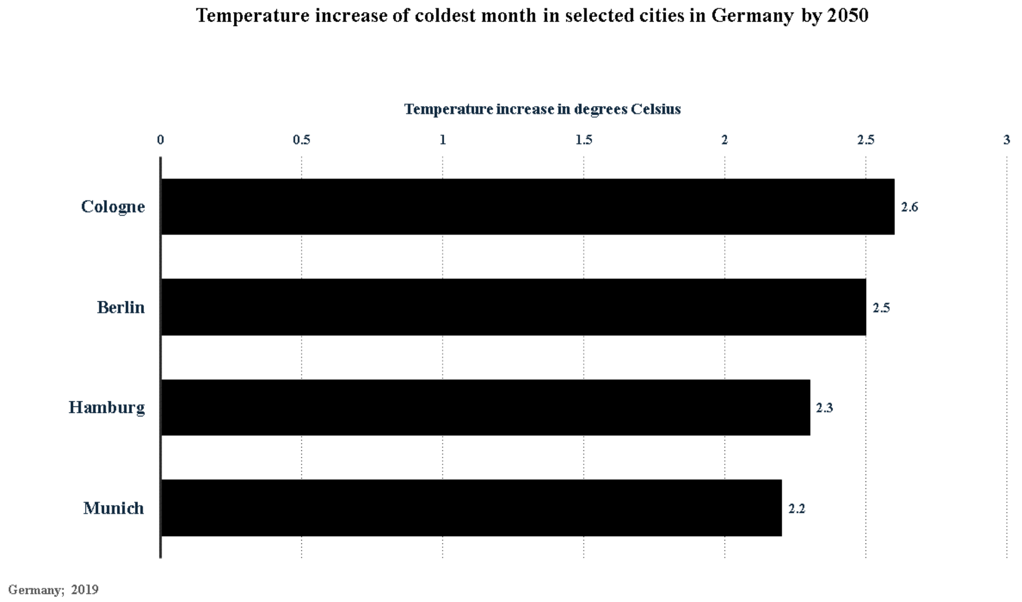
[5] Source: http://worldpopulationreview.com/world-cities/cologne-population/. Accessed 06.2019



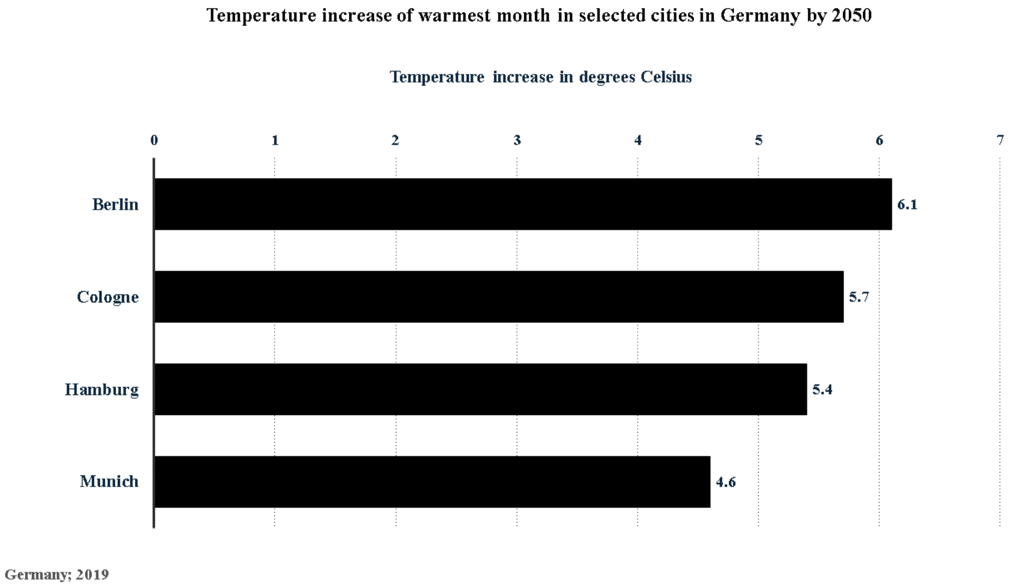


Figure 17: Estimated temperature increase of the coldest (above) and the warmest (below) month of German cities, including Cologne, by 2050 (in degrees Celsius) [6]

The increase in temperature and climate change have started to show their adverse effects in recent years. **Cologne is the second city in Germany with the highest recorded number of rainy days,** according to Eurostat (Urban Audit - see Figure 18.). The number of rainy days of German cities is presented in Figure 18, where Cologne (Köln) has 263, measured in 2004.

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[6] Original source theme - Cities of the future: visualising climate change to inspire action. Source: PLOS ONE. Published by Crowther Lab. Adapted from https://www.statista.com/statistics. Accessed 06.2019

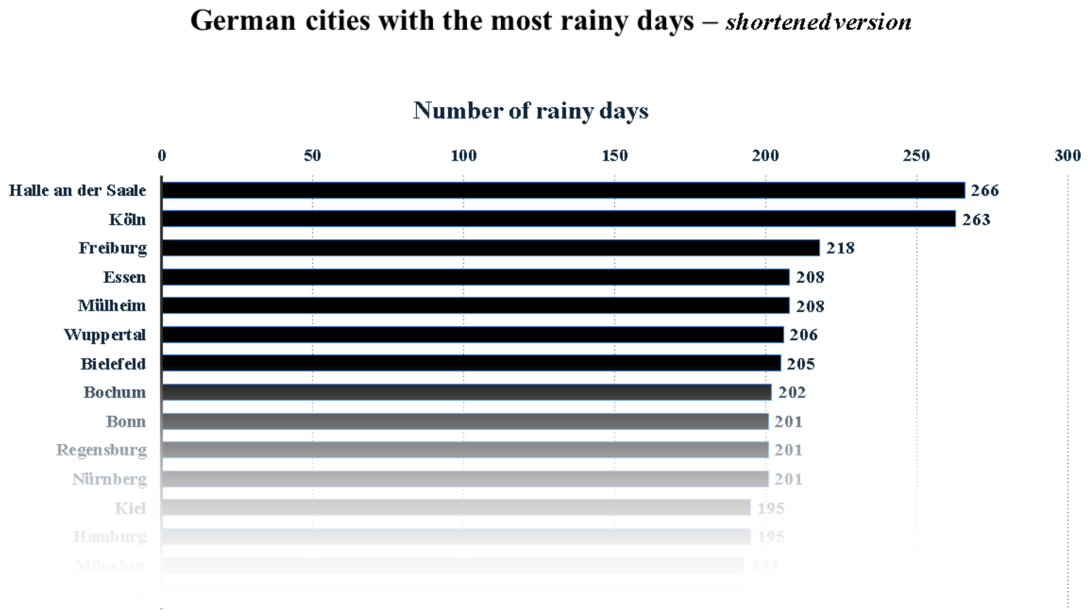

Figure 18: German cities with the rainiest days where Cologne (Köln) is the second[7]

As mentioned earlier, the precipitation is higher in the summer months, increasing the risk of flash floods. For this reason, in the summer months of the year 2017, Cologne faced some severely heavy rainfalls resulting to flash floods, impairing the daily traffic flow of commuters using the road network and the public transport means, i.e. trams and buses. More specifically, on July 19 of the same year, the population's commute was profoundly affected by the heavy rainfall on the road and rail infrastructure. **Partially flooded roads (locality of the phenomenon)** caused **chaos in traffic and transportation** in general, resulting in **significant delays** and even **isolation of specific areas**. The **storm** was by far the **strongest in the last 72 years** of intense rainfalls in Germany, with the massive rain event **spatially restricted to the area of Cologne**[8] with the amount of precipitation up to 95 l/m².

The German Meteorological Service (DWD – Deutsche Wetterdienst) declared July 2017 the rainiest month Germany has seen since measurements that began in 1881. Such extremes are strong evidence that climate change is affecting everyday life. The following year in 2018, Cologne was also affected by intense heavy rainfalls. As presented in Table 5, the higher temperatures are observed for the summer months of June, July and August and are related analogously with the higher observed precipitations up to 83 mm. For a year, the precipitation totals 774 mm and in February, the average rainfall is the lowest expected. Compared to June, with the highest rainfall, where the difference is 31 mm. In February, the precipitation falls on average at 52 mm, and on the contrary, June is the rainiest month of the year with 83 mm of rainfall.

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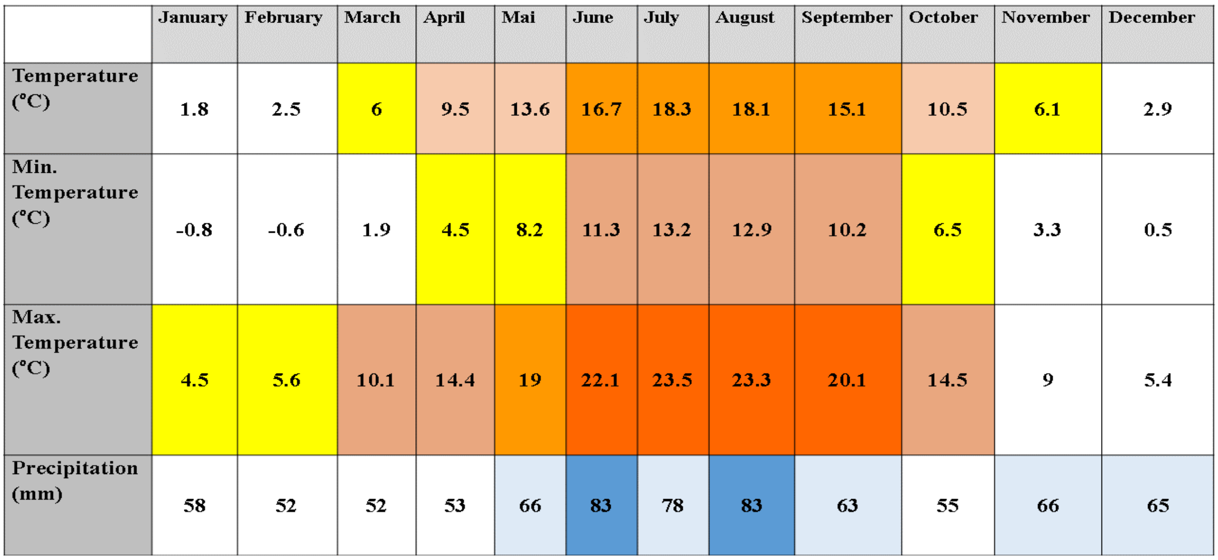
[7] Source Eurostat, Urban Audit - publication date 22.09.2008: Shortened version. Accessed 06.2019. Adapted from https://www.statista.com/statistics. Accessed 06.2019

[8] Information on this particular heavy rainfall for Cologne in: www.dwd.de and https://www.wetterkontor.de/. Accessed 06.2019

Table 5: Temperatures (with a colour classification from yellow to dark orange) and precipitation (with a colour classification from light to dark blue for Cologne). [9]



	January	February	March	April	Mai	June	July	August	September	October	November	December
Temperature (°C)	1.8	2.5	6	9.5	13.6	16.7	18.3	18.1	15.1	10.5	6.1	2.9
Min. Temperature (°C)	-0.8	-0.6	1.9	4.5	8.2	11.3	13.2	12.9	10.2	6.5	3.3	0.5
Max. Temperature (°C)	4.5	5.6	10.1	14.4	19	22.1	23.5	23.3	20.1	14.5	9	5.4
Precipitation (mm)	58	52	52	53	66	83	78	83	63	55	66	65

According to all the information provided in the chapter regarding Cologne's climate and population/city settlement alongside both Rhine river's banks, Cologne is a case study area that best fits the application of the methodology proposed in the chapter **thesis**.

5.2 Fire Brigade: ERS for Simulation and Operationalisation Purposes

> *"If a model simulates those aspects of interest to the degree necessary for the study at hand, the simulation is valid" [369]*

In the report published by the German Federal Highway Research Institute (Bundesanstalt für Straßenwesen), it is stated that between the years of 2016 and 2017, rescue vehicles were deployed 16.4 million times. For approximately 99% of these times, the dispatched rescue vehicle was ground-based, while only less than 1% of the deployments were air-based (helicopter) [370]. Specifically, for the fire brigades, the ratio between the usages of ground-based vehicles to air-based ones might even be higher.

In regards to all ERS (fire brigades and emergency medical services – EMS), according to [370]," *out of the approximately 13.9 million requests for assistance from the ERS received by emergency control centres throughout Germany, around 6.6 million (47.5%) relate to patient transportation. Approximately 2.6 million of these patient transportation requests are classified as requests that can be planned."* This outcome from the performance analysis of the German ERS services indicates that the pre-planning phase, i.e. preparedness phase, is of high priority. Furthermore, the speed and the time of response for assistance were important factors in the performance analysis.

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[9] Colour classified from low to higher values for the years 1982 - 2012. Adopted from https://de.climate-data.org. Accessed 06.2019

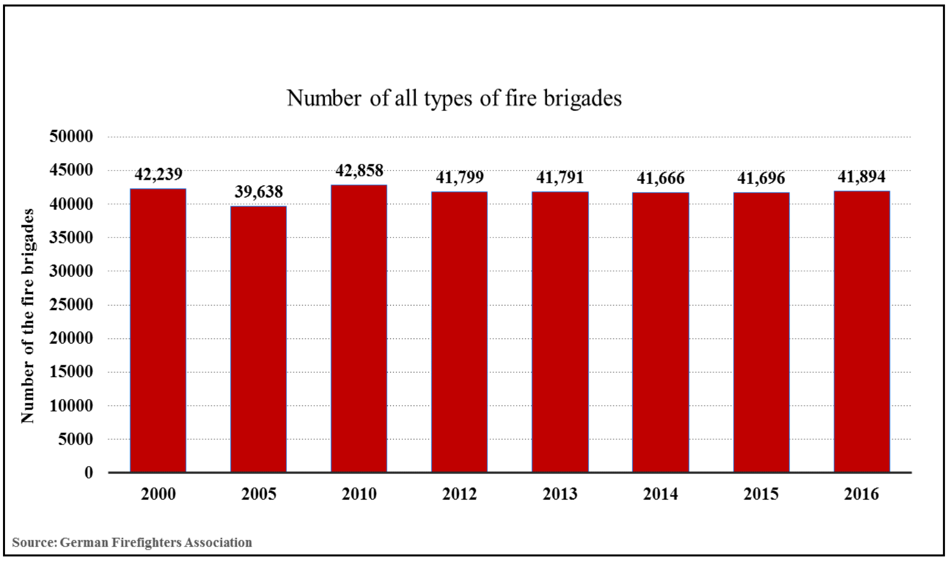
Notably, in [370], it is also stated, *"...the key measurement criterion in this regard, is the assistance period, i.e. the time from receipt of the report by the responsible control centre until the rescue facility arrives at the scene of the emergency. The assistance period is calculated based on the first suitable rescue facility that arrives at the scene of the emergency".* The outcome indicates that the timely arrival of the closest rescue facility to the emergency place is another critical factor that needs to be integrated into performance assessments through the RITAI and network analytics for citywide performance/serviceability analysis. The study also revealed that for Germany, an average assistance period is 9.0 minutes, with 95% of the emergencies being responded with a suitable rescue facility arriving on the scene within 17.7 minutes.

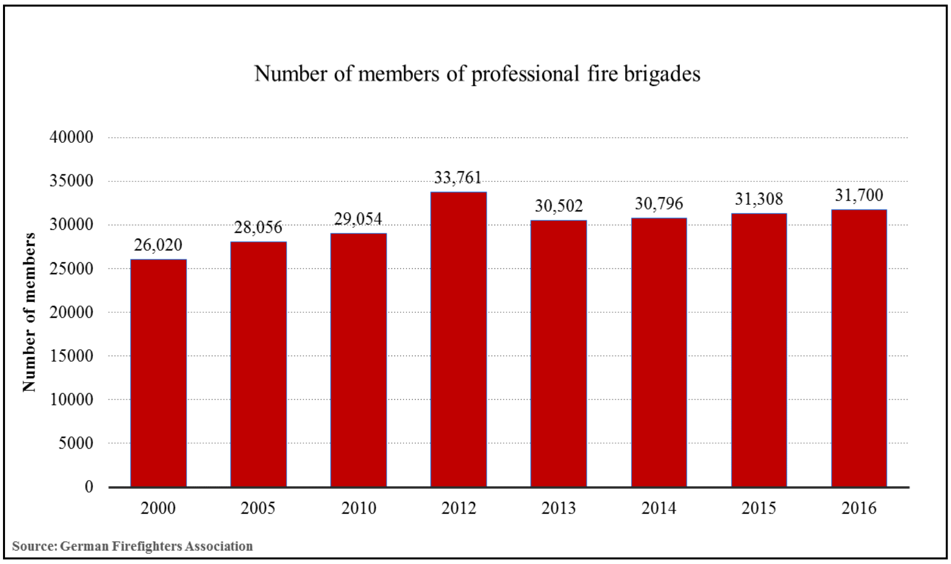
Additionally, the arrival time of doctors through ground-based transportation is 13.9 minutes on average, with 95% of the emergency doctors arriving within 30.5 minutes. The performance analysis on the response times nationwide for Germany revealed that the assistance period had deteriorated again compared to the performance analyses for the years 2004/2005 [370]. Therefore, speed changes of assistance, i.e. response times of the ERS, are an essential factor that must be integrated into performance and ERR assessments to disasters (floods), proving the correctness of direction of the methodological approach suggested. Moreover, the analyses revealed that approximately 56% of road traffic accidents are in built-up areas.

These numbers outweigh road traffic accidents occurring outside built-up areas stating that *if the road category breaks down the locations, we can see that the highest number of road traffic accident victims by far is recorded on municipal roads in built-up areas, with 66 road traffic accident victims* [370]. Therefore, ERR assessments must include factors leading to the deterioration of such statistics.

From the performance analysis conducted, the safe driving mobility of the emergency responders is excluded, and statistics regarding rescue vehicle-related accidents or fatalities. The RITAI aims to fill this gap considering the critical factors for serviceability assessments of the ERS (mentioned earlier in section 3) under flooded conditions.

In Germany (see Figure 19), the fire brigades, according to the German Firefighters Association (Deutscher Feuerwehrverband), are measuring up to 42,000 (forty-two thousand), and they consist of the official fire brigades (Berufsfeuerwehren) and the voluntary fire brigades (Freiwillige Feuerwhren). The number of professional fire brigades (Berufsfeuerwehren) is 105 (one-hundred and five) national, with the members of the official fire brigades counting up to approximately 32,000 (thirty-two thousand).





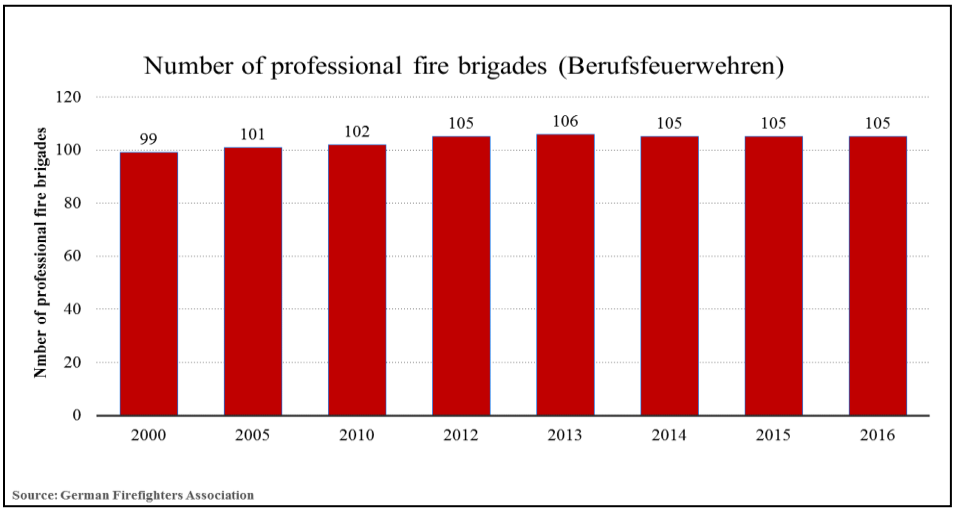


Figure 19: Total number of all types of fire brigades (above), of members of professional fire brigades (middle) and professional fire brigades (below), in Germany from 2000 to 2016 [10]

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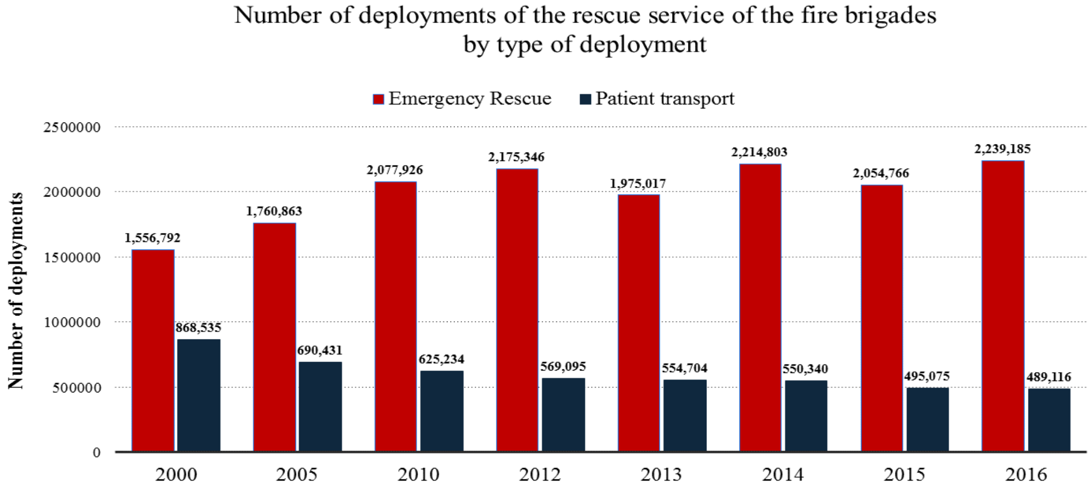
[10] Source: PLOS ONE. Adapted from - https://www.statista.com/statisticsSource: PLOS ONE. Adapted from - https://www.statista.com/statistics. Accessed 04.2020.

The official fire brigades are chosen since they often provide basic medical assistance (Figure) in case they are the first to arrive at the scene of the accident, and in case of floods, they are the first to respond for relief and rescue. Therefore, emergency rescue operations in a timely manner under any weather condition are relevant for ERR assessments. In Figure 19, the numbers reveal the high demand for deployments of the fire brigades.



Source: German Firefighters Association

Figure 19: Total number of fire brigade deployments limited to the emergency rescue and patient transport in Germany from 2000 to 2016 [11]

Specifically, for Cologne, the annual number of incidents that demand deployments were approximately between 200,000 and 242,000 for the years

- 2016 (1.1.2016 - 31.12.2016)
- 2017 (1.1.2017 - 31.12.2017)
- 2018 (1.1.2018 - 1.1.2019)

The incident numbers are official annual incident counts retrieved from the Cologne fire brigade during the collaboration of the author with fire brigade officials of the area in the project CIRmin[12], for analyses purposes conducted in the working package (WP) III - "Critical Infrastructure Resilience Analysis". More results from quantitative approaches can be found in [78].

Emergency responses co-occur with crises when also flood events occur, resulting in a compound of hazard and crises events. As mentioned in the previous section, in Cologne and for July of 2017, the strongest storm of the last seventy-two years occurred, causing partially flooded roads causing traffic chaos and transportation congestion, resulting in significant delays and isolation of specific areas. The fire brigades are the first responders who are called to act promptly during and after EWE events, despite the intense efforts that are verified by the vast amounts of the annual incidents of the fire brigade of Cologne, which are analogous to the high density of the urban population and various interdependent CI.

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[11] Source: PLOS ONE. Adapted from - https://www.statista.com/statistics. Accessed 04.2020.

[12] https://kirmin.web.th-koeln.de/?lang=en Accessed 03.2020

Additionally, more than 430 emergency personnel worked to repair the damage [371], which means that a high number of vehicles were deployed (rescue, damage and repair, civil protection). In Cologne, the fire brigade counted about 50 (fifty) operations until the morning of the next day - 20.7.2017.

Consequently, these rescue operations took place under EWE conditions. Therefore, timely ER provision under any weather condition (heavy rain, heatwave, snow) in a time-effective manner between specific time thresholds is of relevance and ERR assessments of the Cologne fire brigade system, in combination with its climate characteristics, displaying the significant climate change impact, is the best fit for a practical application of the RITAI.

5.3 RITAI's Benchmarking for Cologne's Fire Brigades

> *"We often fail to realize how little we know about a thing until we attempt to simulate it on a computer" [372]*

For the decision of the maximum allowed FD for safe driving of the fire trucks of Cologne's fire brigades, several guided interviews with fire brigade officials have taken place. The information retrieved in regards to safe driving through flooded roads, according to vehicle capacity, is that Cologne's fire brigades are equipped with rescue vehicles of varying heights and therefore, driving under flooded conditions is possible for FD between 0.118 m and 0.750 m. This information regarding the variation of heights of the fire trucks is also mentioned in an official fire brigade document, *"Operations of the fire brigade and the Rescue service in flooded areas".* Nevertheless, fire trucks with maximum FD driving ability up to 0.750 m are not available in all the fire brigade departments. Therefore, according to information extracted from the interviews and in combination with literature results (see section 4.1), the maximum height of safe FD for ER route planning chosen for applying the methodology is 0.5 m. The safe driving ability of rescue vehicles of lower heights through flooded road networks is also covered through the set of the suggested thresholds. The RITAI is benchmarked according to the hypotheses and the choice of thresholds (in section 4.1) for large-scale robustness, passive redundancy and resourcefulness assessments.

Proceeding to the benchmark of the RITAI for further connectivity and accessibility assessments, with network analyses in GIS, official information retrieved from the fire brigade of Cologne, indicates the time threshold of 8 (eight) minutes as critical. The German ERS (fire brigades, ambulances) have laws around the different German states, which dictate in which timeframe - starting with receiving the message of the incident - first emergency response units of sufficient qualifications and numbers must arrive at the place of the incident [370, 373, 374]. Internationally, various fire brigade departments in different case study areas have set different time thresholds for emergency response according to the needs of the area they serve (see section accessibility). The response threshold of 8 (eight) minutes is used more commonly and widely, similar to Cologne's fire brigades, for emergency response, routing plans and service area analyses based on this time threshold. Therefore, the specific time threshold is also used in this methodology as a maximum allowance for benchmarking and classifying time-dependent accessibility assessments and later the ERR to riverine floods and flash floods of Cologne.

Beyond this threshold of 8 (eight) minutes, the resilience of the urban ER system to floods is considered deteriorated, based on the time-dependent rescue provision (service area thresholds) of the fire brigades to access several city units of the case study area. Cologne’s fire brigades use the time threshold of 8 minutes, but they also generate service areas of 10 minutes (a maximum ER response time) indicative of the service of coverage (SOC) of the fire brigades under normal conditions, i.e. before flood events. The SOC of the Cologne fire brigade system has been analysed under extreme flood conditions in [226], and results indicated that the positioning of the fire brigade departments is sufficient for timely ER served in 8 min. before and after extreme flood conditions. However, is this true? In this article, [226], the FD_j was not taken into consideration for ER route planning and NA analyses (service areas extraction). The FD_j and its potential impact (second-order risk) on the travel time was integrated with a probabilistic form by using scale cost barriers (flood polygon of extreme scenario, flood probability occurrence >500 years), adding probable delays. NA was performed using the impedance factor 3.0 for flooded roads, which integrates into the system significant probable delays; the travel time will take three times longer than expected. This impedance (travel cost) factor was used in the article due to a lack of data regarding FD. It first served to identify the exposure extent of the people and CI (focused on fire brigade departments, hospitals and road network) to flood risk and suggested the possibility of integration of travel time delays in ER route planning calculations. The destinations of the NA were the hospitals located in the flooded area, and the starting points were Cologne’s fire brigades. In section 7.4, there is a demonstration of results, aiming to underline the significance of the FD information on a large scale for NA and ER route planning (as suggested in this thesis) to tackle issues arising from a flood-impacted ER road network and quantifications of efficiencies of urban ER systems.

6. Application of the RITAI in GIS for Cologne’s Fire Brigades

> *“If you do not know enough about a system, a good way to find out more is to try to simulate it” [369]*

The difficulty of describing and predicting the complex dynamic systems’ behaviour with analytical approaches, especially for the large scale emergency simulation, which is an application domain of interactions between humans and their proximate environment [375], is recognized in the scientific community. To address such issues, the application of the methodology takes place in a GIS environment. The usefulness of GIS in emergency response purposes has been presented thoroughly in sections 3 and 5. In general, the use of GIS to apply the methodology aims to provide:

- the ability of different ERS to process large amounts of data and
- visualise the results for the phase of preparedness. As previously argued, pre-route planning with the flood-impacted response times (accessibility) is essential for timely ER provision considering safe driving mobility.

The goal of the GIS-based methodological approach presented in Figure 13 is the application of geoinformatics in GIS, with the GIS-based operationalisation methodological workflow presented in section 4.2, including the development of a tool for GIS-based flood impact assessments of the ER road network, fuzzification and geovisualisation, for further adaptive flood-impacted ER route planning purposes considering:

- delays and blockages, different levels of safe driving mobility and transformation of traffic characteristics caused by different levels of FD_j
- several flood scenarios of riverine flood and flash flood using frequent and extreme models of the probability of occurrence, for near real-world simulations of ER response
- simple operation and interoperability of primary data (official and open-source),
- simple representations of the results through geovisualisation and fuzzification processes,
- calculation time as short as possible, given the resolution of the analysis.

The suggested GIS-based, scenario-based and place-based operationalisation methodology is related to the scientific community, emergency -, urban- and flood risk management, fire brigades and safety/rescue services applicable for different scales and various case studies and networks. Besides, it is suggested that for ER purposes, GIS are suitable tools because they provide tools for network analyses (NA) for connectivity and accessibility assessments of the urban ER system, applying the graph theory on an urban ER road network and enable:

- the production of semi-automated and automated tools (such as the GIS-Toolkit), adding value to the redundancies, the resourcefulness and rapidity of the urban ER system under research.
- the fast applications of methodologies, as suggested in this thesis,
- enable the easy adjustment of routing plans (for strengthened preparedness and enhanced response times) to case-specific flood scenarios and
- the transferability of the methodology for different case study areas and analyses scales, without significant adjustments.

6.1 Data Sources, Handling and Transformation for Interoperability

Data gathering started with the enrolment of the author as a project researcher and lead of the Working Package III in the CIRmin project, after the establishment of good relations with different stakeholders, including fire brigades and civil protection authorities from various case study areas within Cologne.

The combination of spatial and non-spatial information can lead to a holistic overview of the vulnerability, exposure, risk, and finally, resilience emergency response assessments of Cologne's urban, complex and dense road network, primarily based on the road network exposed to specific risks. In this study, different data sources have been used to develop the database of the ER road network and spatial resilience assessments of the urban ER system to riverine floods and flash floods. Specifically, open-source (OS) geodata are utilised from available online databases such as OpenStreetMap, provided and maintained by the community of Geofabrik[13] under the Open Data Commons Database License (OdbL) and the city of Cologne[14].

The OS data, combined with data from different stakeholders such as the Cologne fire brigade and the Water Management Planning Department, from the Cologne Municipal Sewerage Company, AöR (STEB Köln), allow a comprehensive build-up of databases.

Therefore, the methodology is applied with additional data and information that local stakeholders use. The data used, their source, their type and the transformation for interoperability reasons are

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[13] https://www.geofabrik.de/en/ Accessed 03.2020

[14] http://www.offenedaten-koeln.de/dataset Accessed 03 2020

presented in Table 6. For example, the walking paths were deleted from the road network database since they are not used for ER purposes.

Table 6: Data used for this study, source of data, type of data and transformation for further use in an ArcGIS environment

Data	**Source**	**Type**	**Transformation**
Fire brigades	**OSM/Geofabrik dataset**	Point shapefile - vector	Volunteered fire brigades excluded
Road network	**OSM/Geofabrik dataset/Fire brigade Cologne**	Line shapefile - vector	▪ Adjusted/cleaned - deleted walking paths ▪ Crossings/junctions inserted ▪ Retrieval of speed information according to road type from Cologne's fire brigades and insert in database ▪ Speeds calculation for every road and inserted - Free Flow Speed (FFS) ▪ Integration of the flood depth information Adjustment of FFS according to flood depth using the *function 5*
Flash flood data	**STEB Köln**	Raster of 2x2 m resolution	▪ Provided in raster form Probability of occurrence of 20 years (T20) and 100 years (T100 - extreme scenario)
Riverine data	**STEB Köln**	Raster of 2x2 m resolution	▪ Provided in raster form Probability of occurrence of 10 years (HQ10) and 500 years (HQ500 - extreme scenario)
Tessellation of the city	***own***	Polygon shapefile - vector	Creation of a shapefile - hexagonal tiles of 0.25 sq. km
Centroids of tessels (city units)	***own***	Point shapefile - vector	Transformation of the tessels to a point shapefile.

6.2 Flood Models for Scenario-Based Operationalisation of the ERR

From the probabilistic zonation of the online flood map and for further ERR assessments, focusing on the centre and the broader area of Cologne, additional data are used based on their flood zonation maps derived from freely available LIDAR data and provided by the city of Cologne. The Flood Directive 2007/60/EC [56] suggests the inclusion of floods with the following probabilities for integration into flood hazard maps and FRM approaches:

- **Low probability**
  - **Riverine flood:** extreme event scenarios- HQ500 scenario, which corresponds to a statistical flood recurrence interval of more than 500 years,
  - **Flash flood:** extreme event scenario - T100 scenario, which corresponds to statistical flash flood recurrence interval of 100 years
- **Medium probability**
  - **Riverine flood:** HQ100 scenario, which corresponds to a statistical flood recurrence interval of 100 years
  - **Flash flood:** T50 scenario, which corresponds to statistical flash flood recurrence interval of 50 years
- **High probability**
  - **Riverine flood:** HQ10 scenario - more often scenarios corresponding to statistical flash flood recurrence interval of 20 years
  - **Flash flood:** T20 scenario, which corresponds to statistical flash flood recurrence interval of 20 years.

The flood scenarios of riverine and flash flooding events chosen for simulation and operationalisation purposes are of different intensities. The intensity of the different scenarios is defined via physical parameters, i.e., the spatial extent of the flooded area, flood depth, flood duration or flow velocity. The intensity is usually related to defined discharge value with an associated return period (e.g. HQ 10 - 10-year flood, T20 - 20-year flash flood) [376]. A typical and more realistic scenario can be characterised as a flood with a high probability of recurrence [377] with few years of probability of return from 10 to 20 years); that is, the phenomenon is observed to occur more often. Low-probability floods (occurring in return periods of 100 to >500 years) are characterised as extreme due to the intensity of the phenomenon followed by higher water depths, longer flood durations and larger flood extents with increased severity of consequences to the population and various CI. A common misunderstanding is that a 100-year flood is more likely to occur only once in 100 years. There is a 63.4% chance of one or more 100-year floods occurring in any 100 years [376]. For example, on the Danube River at Passau, Germany, the actual intervals between 100-year floods from 1501 to 2013 vary from 37 to 192 years [377]. There is an abundance of research focusing on the conduction of probabilistic flood models on an international and regional level. Nevertheless, in this study, the subject will not be discussed in detail. The magnification to the aforementioned specific information provided serves as a justification for integrating the extreme scenarios into emergency rescue planning.

The scenarios are selected for ER simulating purposes according to their intensity. Frequent riverine and flash flood scenarios are most probable and closer to present reality. On the other hand, extreme ones can reveal probable flood risks and their impacts, which can be unknown when simulated. Modelling the potential impacts of the future, specifically with the increasing climate change that makes them more probable, adds value to the emergency management's preparedness levels towards timely emergency response, enhancing the ERR. Furthermore, emergency managers can deal with five to six scenarios [378, 379]. The focus on one natural hazard makes the process even more easily understandable since the scenario can be considered one scenario but of highly varying intensities, allowing for comparative analyses. Scenarios, then, can be used for coping with highly varying situations [380]. Visualizing the different flood scenarios enables further collaboration of the different decision-makers, even if they are geographically dispersed [381].

The selected food scenarios result from flood models used for Cologne, based on digital terrain models with a 2 x 2-meter grid based on a laser scan overflight in 2010 and existing water levels of the German Federal Institute of Hydrology (BfG), as of 2012.

The water levels are from different return periods of riverine floods and flash floods of Cologne. The visualised flood maps were produced on behalf of the district government of Cologne as part of the implementation of the European Flood Risk Management Directive in 2013 [56]. The flood data were provided from the Cologne Municipal Sewerage Company, AöR (STEB Köln), by Mr Stephan Monreal, responsible for GIS applications and Mr Ingo Schwedorf responsible for Water Management Planning. Every model contains inherent uncertainties from the methodology extracted based on various precipitation databases. In Figure 20, the raster models of the flash floods with a probability of recurrence of flood in 20 years (T20 - typical scenario) and 100 years (T100 - extreme scenario) are visualised in GIS with the author's created colour palette.

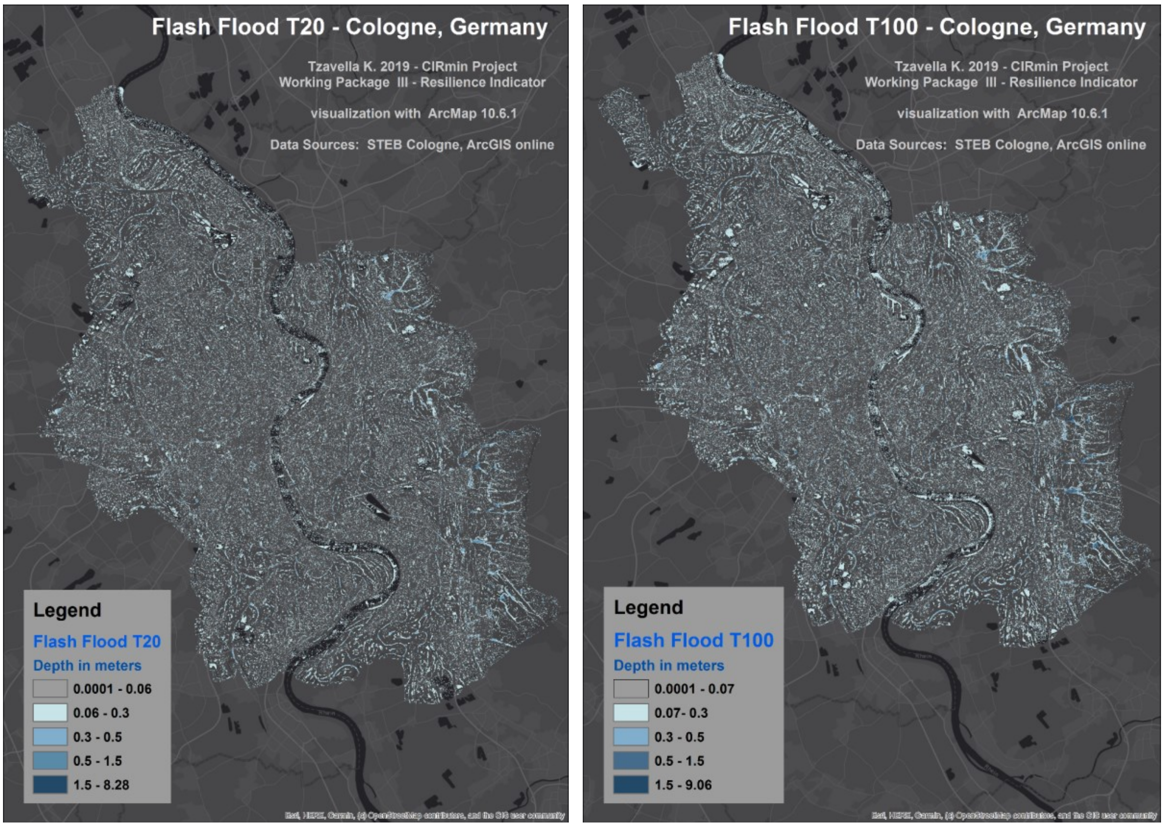

Figure 20: Raster of the flash flood T20 (frequent scenario - left) and the flash flood T100 (extreme scenario- right) - see enlarged in APPENDIX A

Due to the high-resolution FD information, a colour palette creation with colours that could depict the extent of the flood events on the map and geolocated information on flood depth (zone analysis) is created. In Figure 21, to the left, the raster of the frequent flash flood scenario T20 is a probabilistic flood scenario with 20-years of flood occurrence probability. To the right, the raster is an extreme probabilistic flash flood scenario with 100-years of flood occurrence probability.

The riverine flood scenarios are represented in GIS and ArcMap 10.6.1 (Figure 21) by two models in raster forms. These rasters display the FDs for areas without technical flood protection at HQ10 (Cologne gauge: maximum FD 9.85 m level, frequent/regular event) with a 10-year flood occurrence probability and one of a more than 500-year flood occurrence probability (HQ500) with maximum FD 12.75 m (Cologne gauge: 12.75 m level, extreme event).

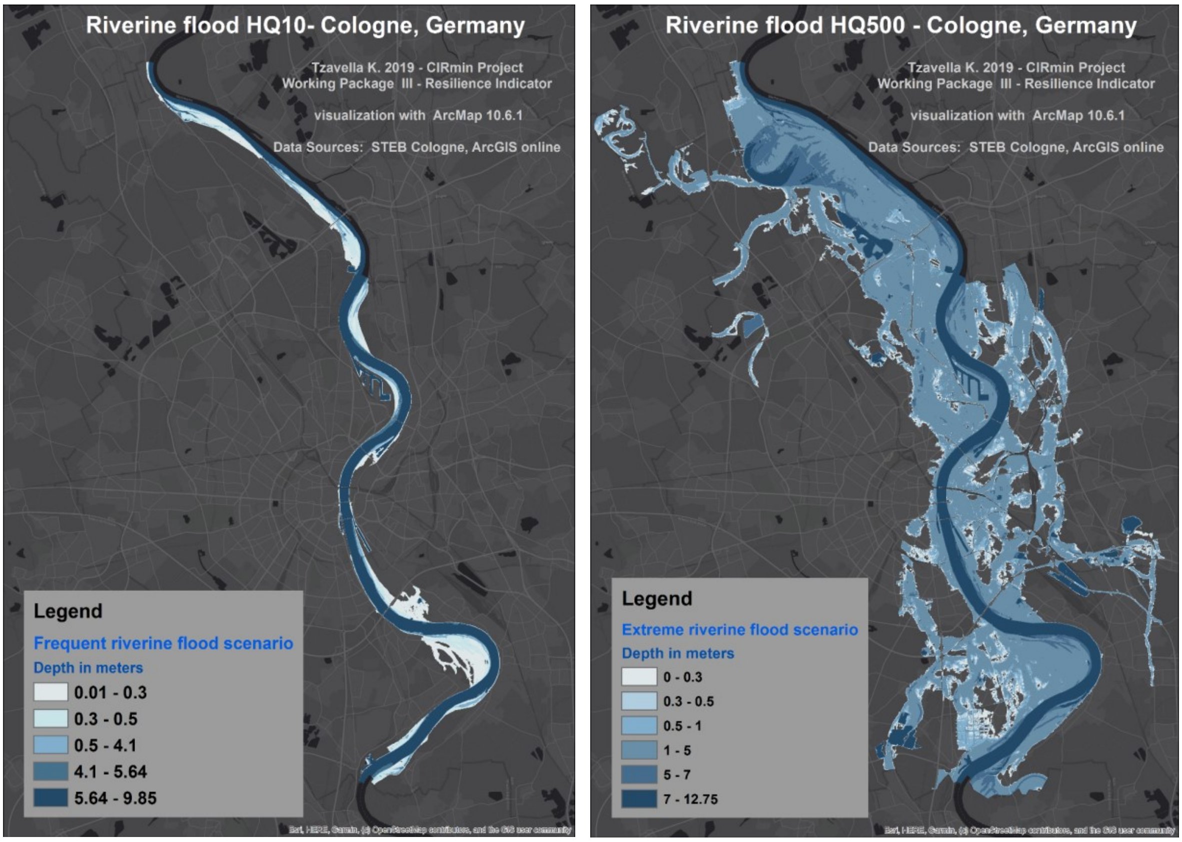

Figure 21: Raster of the riverine flood HQ10 (frequent scenario - left) and the HQ500 (extreme scenario-right) - see enlarged in APPENDIX A

To the left, the raster of the frequent riverine flood scenario H10 is a probabilistic flood scenario with 10-years of flood occurrence probability. To the right, the raster is an extreme probabilistic riverine flood scenario with > 500-years of flood occurrence probability.

6.3 GIS-based ERR Operationalisation Framework for Cologne’s Fire Brigades

6.3.1 Update of the OSM road network with official road type-dependent ERPS

For implementing the methodology in GIS, the software ArcMap 10.6.1 and ArcGIS Pro 2.2.3 are used. The road network of Cologne downloaded from OSM is of an incomplete database and, therefore, can be characterised by low quality. Speed information is missing for most of the roads. Thus, the road network database update is necessary and results from integrating information regarding the ERPS used by the fire brigade of Cologne. Additionally, the maximum allowed driving speeds (FFS) used from the fire brigades for ER route planning have been provided by Dr Martin Wesolowski, a planner at the central fire brigade office of fire protection, the Department of Emergency Services and Civil Protection. The ERPS used so far for route planning via Excel files are presented in Table 7. The Cologne fire brigade carries out the emergency response plans according to the methodology of [382] and based on corresponding "own experienced" planning speeds (empirical data retrieved after driving in a typical day, from the morning until the afternoon).

Table 7: The road type-dependent ER route planning speeds (ERPS) of Cologne's fire brigades, Source: Cologne Fire Brigade

ER Route Planning Speeds (ERPS)	Km/h
Passage road (2-Lane)	50.4
Passage road (1-Lane)	45.9
In-city connection road	45.9
Residential street	34.7
Motorway	85.5
Federal highway	66.1
National road	62.9
District road	67.5

Cologne's road network segmentation into segments of 1 m enables the detailed analysis of the FFS changes and thus vulnerability, travel time reliability and risk-based road network and urban ER system resilience assessments in terms of accessibility. Accessibility assessments occur in ArcMap and accurately with a developed GIS-Toolkit presented in section 4.3 (see Figure 15). After the segmentation of the road network, each segment is assigned with the respective road-type dependent speed considering the segment's length by i) adding a numeric field in the database and ii) calculating the speed for each segment. The calculations' results from *function 4* (the impedance of the network analysis) are performed later.

6.3.2 Compartmentalisation & Hexagonal Matrixes

> *"Design is the conscious and intuitive effort to impose a meaningful order. [...] Our delight in the order we find in frost flowers on a windowpane, in the hexagonal perfection of a honeycomb, in leaves, or the architecture of a rose reflects man's preoccupation with a pattern" [383]*

The compartmentalisation of the area into city units enables detailed situational analysis of the service area coverage (SOC) of Cologne's fire brigades through network analysis (NA) and building on the

ERR to riverine floods and flash floods of Cologne. Detailed situational analysis, i.e. serviceability assessments, is achieved by the separate accessibility assessments of the different city units.

NA performed for accessibility assessments patterns the ER capacity and efficiency of Cologne's ER urban complex system under flood conditions. This patterning resulting from the tessellation, with its strengths and weaknesses as a method, offers a holistic overview of the ERR after implementing the suggested methodology.

More specifically, in a GIS environment, compartmentalisation of the case study area is translated into tessellation, resulting in tiles/tessels of user-defined shapes (hexagonal, circular, and rectangular) and sizes (city units). Tessellation prepares data representations by creating partitions using one or more geometric shapes to fit each other without any overlap or gap on each side [384].

A tessellation is divided into two types: regular tessellation and irregular tessellation, based on the variation of the shapes and sizes. A regular tessellation is a tessellation that uses a uniform shape and size of a geometry cell, such as triangles, squares, and hexagons, to present data. Tessellation for observational purposes has been often applied to modelling, simulating, and even studying ecosystems. The geometry with the same pattern is an efficient way of surveying, sampling, and experimenting [385]. Tessellation is also useful for thematic mapping as it can represent different types of information and data within units of equal size and shape in an orderly and patterned way. Additional data can be spatially aggregated into the layer and readily normalised by the existing attributes, enabling secure handling of datasets, interoperability and transfer of analyses to different case study areas and resolution. For the implementation of the methodology, the regular hexagonal tesselation is chosen since the assessments of the ERR are based on static data. The representation of ERR through the proper size of tiles, which assists ERS officials with a more fundamental understanding of the resulting map, is also essential. Using ArcGIS, this polygon layer of tiles is extracted using the ¨Generate Tessellation¨ tool, which creates a grid of hexagons overlapping the study area. The aggregation of information into hexagons is supported in different spatial analysis studies [149, 385]. Hexagons are polygons with the highest symmetry and are the most circular of all regular polygons that tile the plane [386]. The fact that the horizontal, vertical and diagonal diametric lines of the hexagon are of the same length give the advantage for a uniform and complete coverage of the study area without gaps. The size of each tessellation feature is calculated by specifying a value to represent the area for each tile in square units or by determining a distance value. The distance is calculated as in Figure 22, where ***d*** is the value of the distance parameter.

The tiles are generated in a custom area, preserving a projected coordinate system using the specified size dimensions to ensure equal sizes and appropriateness for the area of interest[15].

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[15] Information in https://doc.arcgis.com/en/arcgis-online/analyze/generate-tessellations.htm Accessed 04.2019

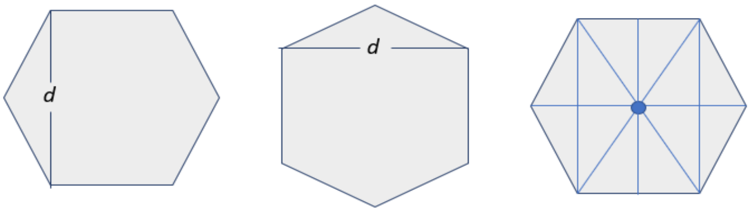

Figure 22: Distance measurement in hexagons, where d is the value of the distance parameter with the geometric centre (centroid) to the right

Furthermore, hexagons are appropriate for the display of ER related information on various levels since they have the following advantages:

- Hexagons reduce the sampling bias due to edge effects of the grid shape related to the low ratio of the perimeter to the area of the shape of the hexagon. It is observed that square cells are distracting, as opposed to hexagons, to map readers and thus make the determination and identification of the spatial pattern of a phenomenon [387] difficult.

  On the other hand, a circle has the lowest ratio but cannot tessellate to form a continuous grid. Hexagons are the most circular-shaped polygons (Figure 23) that can be tessellated to create an evenly spaced grid, which results in an integrated representation of aggregated information.

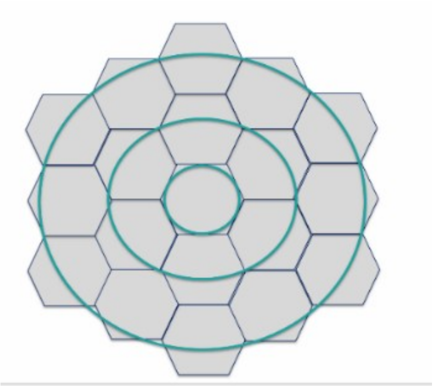

Figure 23: Circularity of hexagons

- The circularity of a hexagon grid allows it to represent curves in the patterns of the analysed data in a natural way than square grids, which is necessary for the visualisation of the emergency routing paths with exact directions (connectivity and movement paths). NA analyses conducted in a later stage are extracting routing paths following the road network. Therefore, their natural, close to reality representation is necessary, and hexagons assist this visual representation due to their circularity characteristic.

> *"From the basic circle and the hexagonal arrangement of a group of tangential circles of the same radius surrounding it, the three primary shapes emerge the triangle, the hexagon, and the square. These three shapes are explored in detail to reveal their inherent structure, subdivision, proportional ratios and interrelatedness. From this last, we can be called the 'sociability' of the polygons " [149, 386, 388]*

- The more similar to a circle the polygons of equal areas are, the closer to the centroid the points near the border are (especially points near the vertices). Therefore, due to the circularity of the hexagon, any point inside the hexagon is closer to the centroid of the hexagon than any given point in an equal-area square or triangle would be; this is due to the more acute angles of the square and triangle versus the hexagon. This attribute characterises the hexagonal tessellation as ideal for an accurate representation of the city units of the selected case study area used as destinations in the conducted NA analyses and for all the features/attributes classified in each hexagon (city unit).
- Hexagons tend to break up the lines allowing more precise and easy visibility of the curvature of the patterns in the data. This break-off of artificial linear patterns also diminishes any orientation bias that can be perceived in fishnet grids. They are also ideal for analyses on large areas because a hexagon grid suffers less distortion due to the earth's curvature than the shape of a fishnet grid. This attribute makes them an ideal fit for the applied methodology since the hexagonal tiles represent groups of road networks and access paths and times.
- According to [386, 389], hexagons have higher representational accuracy, and their boundaries are shared with six (6) neighbours rather than with four (4), as it would happen with squares, is making the process of finding neighbours more straightforward, avoiding the connectivity inefficiency of the rectangular grid. The edges, or the length of contact of a hexagon, are the same on every side. The centroid of each neighbour is equidistant, and because the distance between the centroids is the same in all six directions with hexagons if a distance band is used to find neighbours, more neighbours will be included in the calculations for each feature. Through NA, these attributes can assist ERS to identify accessible neighbours to inaccessible areas in an attempt for a time-efficient ER. Accessing a specific centroid (city unit/place of action) near an inaccessible one is still adequate for efficient ER due to the equidistance. On the other hand, if no neighbouring centroids are accessible, after various reasons of the blocked road network, i.e. hazard occurrence, accidents, destruction, then the awareness for alternative measures to be taken (air- and water-based emergency response), rises. Therefore, this is another way to assess the criticality of the respective city units, assigning and transferring the criticality level to the included and grouped geographically interdependent CI in the individual hexagons.
- Hexagonal representation of data has been widely used for big data in the form of points. Points are also geotagged tweets after Hurricane Sandy [390] due to their secure handling of cell/tile size, allowing more natural cartographic representation of the different amount of data and the discern of contours even if negating the "smoothness" of non-smooth data [390].

Hexagons have also been used in different games, such as the first German multi-player boarding game designed by Klaus Teuber and published in 1995 in Germany by the publisher Franckh-

Kosmos), which became famous out of the borders of Germany named the Settlers of Catan[16]. The players in the game represent settlers, establishing colonies on the island of Catan, composed of hexagonal tiles (hexes) of different land types, by building settlements, cities, and roads to connect them as they settle on the island. More recently, the gaming crowdsourcing platform Cerberus [391], used by the Dutch company BlackShore, generates maps of hexes on satellite images representing different characteristics of the population with the help of different gamers. The founder of "BlackShore", Hans van't Woud, in personal communication with the author, mentioned that the data were represented at first in square grids, but they have finally selected the hexagonal representation. More precisely, he mentioned, *"...because we rely on public input in a game, we use hexagons, which are more interesting and 'fun' to interact with as being the units of analysis". Going to the geospatial part, we do project the hexagons on the surface, drawing the map.*

However, my customers sometimes need more precision, and we do the mathematical trick here to combine three groups playing, each working on a 50% horizontal or vertical shifted grid, allowing us to triangulate results. Triple the effort, six times the resolution."

Hence, due to their morphologic features, hexagons allow the depiction of results, in great detail, of different sub-groups of a community, which are geographically dependent and spatially bind. The triangulation of the hexagons has been patented by the US and the Netherlands [392].

This attribute of hexagons can be valuable for detailed social vulnerability assessments, civil protection purposes, prioritisation of ER, CIP purposes (grouping of various geographically interdependent CI), interdependency analyses between different CI and the urban communities, as explained in section 1 and section 2.

> *"It is incorrect [...] to think that maps [...] prove the reality of the zoom effect: when one shifts from a map on a scale of 1 cm to 1 km or one from 1 cm to 10 km - the latter does not contain the same information as the former: it contains other information that might (or might not) coincide with what appears in the former" [393]*

The characteristic of the manageable configurable size of tiles allows for a zoom-in and zoom-out effect to different scale levels, but data loss must be considered when attempting this scale stretching.

The effect can assist, for example, comparison analyses by implementing the same methodology (gradation of information from a large scale to a smaller scale - local to regional), as well as for addressing the potential effect of the Modifiable Areal Unit Problem, as it is discussed in detail in [394]. Additionally, the hexagonal grids quantise the plane with a minor average error and provide high angular resolution. They are also preferred by statisticians involved with developing survey sample designs and geostatistical methods [395]. Accordingly, a hexagonal tessellation has the following properties [396]:

- Optimisation of space
- Normalisation of link direction,
- Normalisation of distances,
- Reduction of overlapping,
- Infinite tessellation and

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[16] Source: https://www.catan.de/ueber-uns/catan-gmbh Accessed 06.2019

- Collectiveness.

Configuration and transfer to different scales might be misleading or lead to data loss due to mistakes regarding false indexing of tiles representing the content information. Therefore, assigning a linear code or index to each tessel/city unit is often helpful. In [397], it is mentioned that the most valuable indexes are the hierarchical prefix codes. In these indexes, the cell is considered a specific resolution in a multi-resolution structure, and each digit in the index corresponds to a location at a single resolution relative to a hierarchical parent's index. Such indexing defines both a locality-preserving overall ordering of the pixels and a pyramid data structure, enabling efficient hierarchical algorithms [397]. The hierarchical prefix location codes naturally encode precision and direction and provide an algorithm for generalising features through address truncation [398]. The Node-Gosper space-filling curve based on the Gosper fractal proposed from [399] in [400, 401] is used on hexagonal grids and row encoding illustration of the target region.

The thesis suggests that such indexing could assist ERS and civil protection end-users keep their service area in a coded form, simplifying delegation of ER actions (humanitarian response regarding logistics and service, resources location-allocation - see sections 3.1, 3.4 and 5). This characteristic of hexagonal grids is another critical advantage verifying that their choice to represent the results in ERR matrixes is an optimal fit. In the methodology, the indexing of the grid cells is taking place in a GIS environment, and the tiles (city units) are indexed by their feature identification number (FID) in the database, assigned after the extraction of the hexagonal tessellation layer.

In this thesis and operationalisation purposes, each city unit is given the size of 0.25 km^2. The smaller the size of the city unit, the higher the increase of the processing time of the application of the methodology. Nevertheless, for an urban complex area, such as Cologne, the chosen size is appropriate for balancing between calculation times of the different data handling processes and tools. The specific format will also provide detailed information regarding risk assessments and ERR for the area of Cologne. Hexagonal tiles represent these city units of the case study area, and these tiles are represented by their geometric centres or else centroids, extracted in ArcMap with the tool "Find Centroids", which extracts the geometric centre of each hexagonal tile. Cologne's tessellation to city units and extraction of centroids is presented in Figure 25. Each centroid has its FID, assisting further to identification and calculation processes. The tessellation (compartmentalisation) of the case study area creates a detailed matrix for a later presentation of the operationalisation of ERR to different flooding events in the form of matrixes (see section 6.3.4). Additionally, the centroids will serve as destinations for the NA conducted at a later scale (see section 6.3.3), before and after the chosen flood events, towards operationalising the ERR in Cologne. The representation of an area by its geometric centre assists the deterioration of calculation times, weighting processes towards prioritisation of emergency response and can facilitate focused analyses such as exposure, vulnerability, risk, resilience and interdependency.

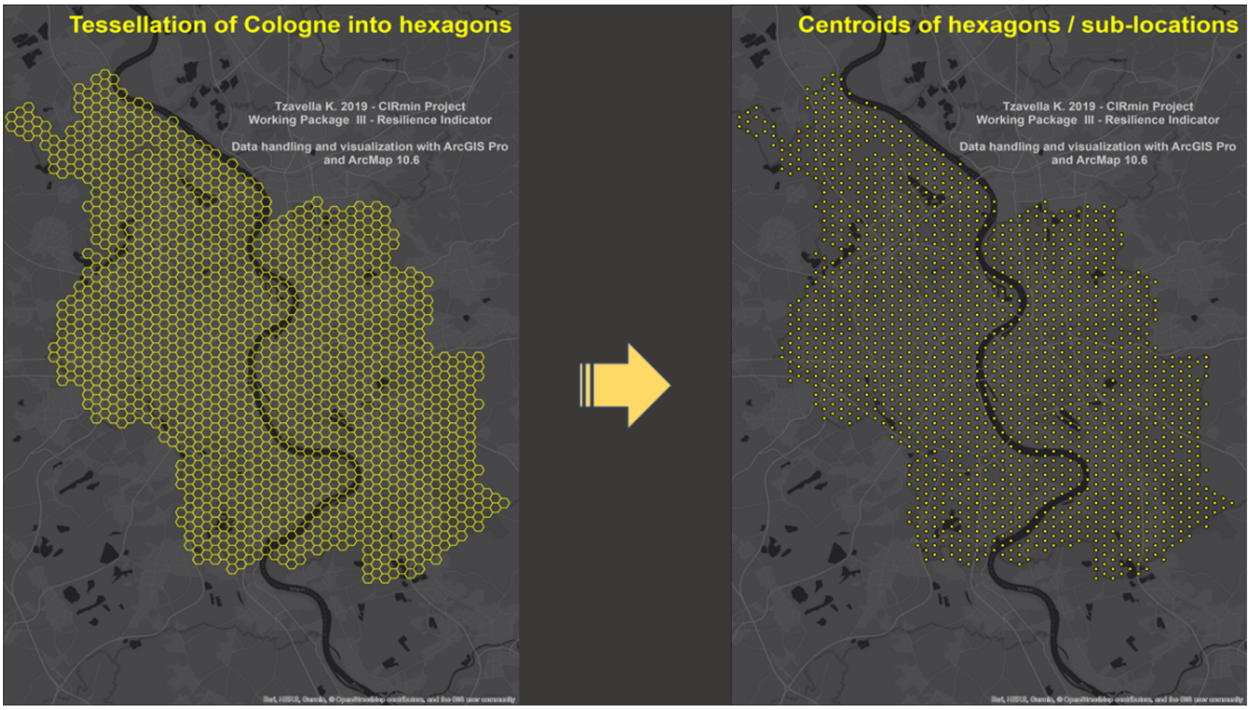

Figure 24: Cologne's tesselation in hexagonal city units of 0.25 km^2 (left) and transformation of the hexagons to centroids (right) serving as destinations for NA analysis for ER purposes

6.3.3 Network Analysis

Network Analysis (NA) in ArcGIS is performed with the Network Analyst tool in ArcGIS Pro after the build of the network in ArcMap (transformation of the road network to a graph), with the tool "Build of Network" from the Network Analyst's tools. Network analyst enables network-based (distance and time) spatial analyses, including routing, travel directions, closest facility, and service area analysis. ArcGIS Network Analyst is composed of an easily configurable environment, enabling users to dynamically parameterise the model's realistic network conditions with U-turn (180^0 degrees), one-way road restrictions, speed limits, traffic conditions at different times of the day and height restrictions.

The ArcGIS Network Analyst allows modelling for solving common network problems, such as finding the best route across a city, finding the closest emergency fire truck or facility, identifying a service area around a location, servicing a set of orders with a fleet of vehicles, or choosing the best facilities to be open or closed. For the NA conducted in this study and finding the shortest paths, Dijkstra's algorithm is used. Dijkstra's algorithm is a graph search algorithm, which solves the single-source shortest path problem [402] for a specified graph with nonnegative edge path costs, producing the shortest-path tree between one node and every other (see Figure 4).

Therefore, the road network is a weighted graph where each road link/segment can be weighted with different costs. In this study, through the suggested RITAI, the travel time costs will be calculated according to travel time calculations in minutes (Travel Time Impedance/Cost) before and after flood events, which are distance-based costs due to the relation between the FFS and the length of each road segment *(function 9).* Furthermore, normalisation of the procedure occurs with the compartmentalisation of the road segment to 1 m segments for detailed impact assessments of the

ER, for example, Travel Time calculation based on the length of road segments *(function 4 - translated in graph-based calculations)*.

$$\text{Travel Time Impedance} = \frac{1\text{ m } (\text{Length of road segment in meters})}{\text{Speed in km/h}} * \frac{60}{1000} \quad (9)$$

Therefore, network connectivity is assessed with ArcGIS 10.6.1 after converting and checking the road network topologies, of the different flood scenarios, into a non-directed graph for turn-by-turn analysis (rebuild of the ER flood risk informative road network datasets). The overall method is presented in Figure 25.

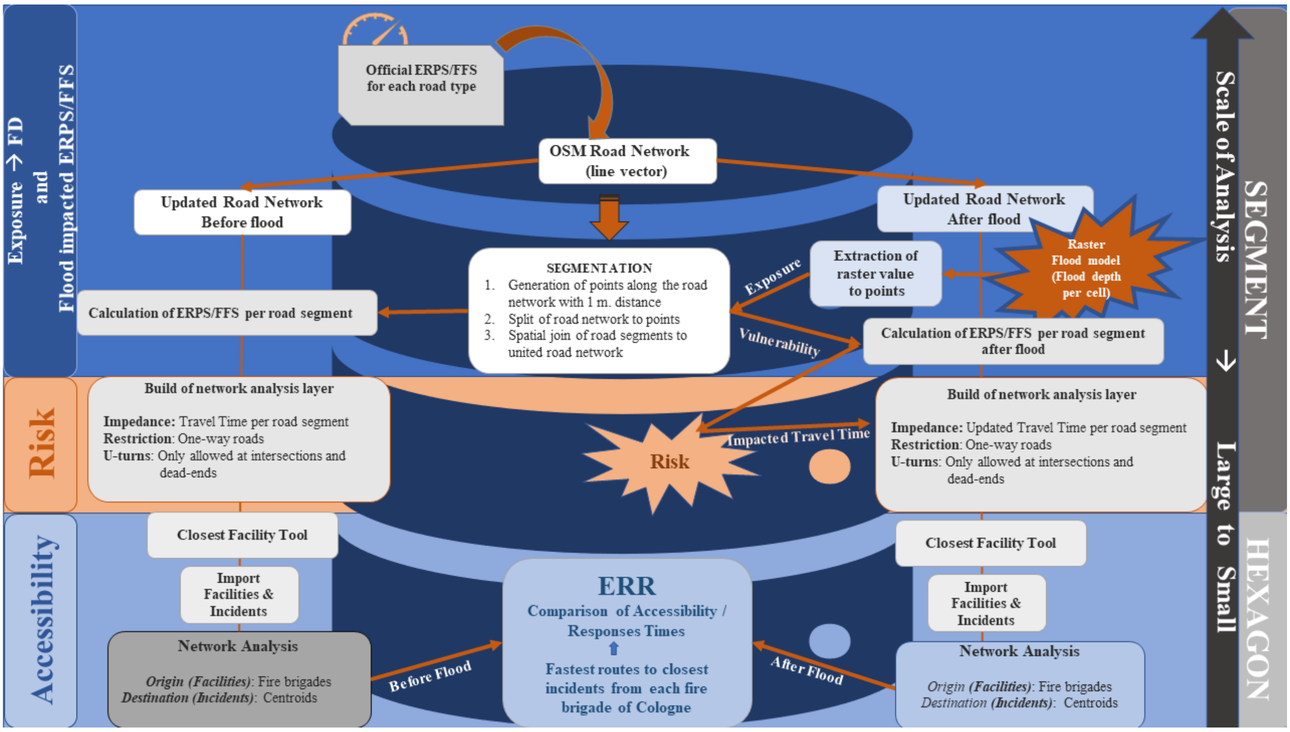

Figure 25: Operationalisation methodology of ERR to floods with a GIS-based upscaling spatial assessment workflow - see enlarged in APPENDIX A

The black arrow in Figure 25 indicates the aggregation of information throughout the implementation of the methodology in the GIS environment. The performed NA for each selected flood scenario is based on these resulting flood-impacted ER road networks.

They are the basis for searching the closest city units to Cologne's fire brigades and calculating their routing paths, before and after each selected flood scenario, towards ERR assessment (RITAI). The routing calculations mentioned above conducted in this thesis consider the fire brigades as the origin/starting points translated in the GIS environment as "Facilities" and as "Incidents" the centroids of each city unit (tile) to which the closest fire brigade should respond.

Routing calculations are performed with the use of the tool "Closest Facility"[17]. The tool provides a configurable algorithm through an interface enabling the set of the travel mode parameters. In general,

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[17] https://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/closest-facility.htm Accessed 04.2019

a travel mode is a collection of network dataset settings defining actions allowed on the network and how these can be performed. Such data settings can be the assignment of edge weights, i.e. restrictions and impedances on which the analysis is based, U-turn licencing (allowing the 180^0 degrees of a turn of a vehicle to different cases, i.e. as dead-ends and intersections) and hierarchies (use of the longer roads instead of smaller ones) taking place. The travel mode is presented in Figure 26. Each travel mode before and after each flood scenario is configured for emergency response routing calculations and takes into consideration the following:

- cost of the travel time taken for each fire brigade (facility) to travel each road segment till the destination point (incident) - avoiding routes passing through highly flooded road segments and choosing optimal routes for a timely enhanced response.
- the U-turns under specific conditions - fire trucks cannot perform U-turns throughout the entire road network in the urban area of Cologne, which can result in traffic congestion of even accidents
- the restriction of the one-way roads - avoidance of one-way streets for routing calculations can save a substantial amount of time.

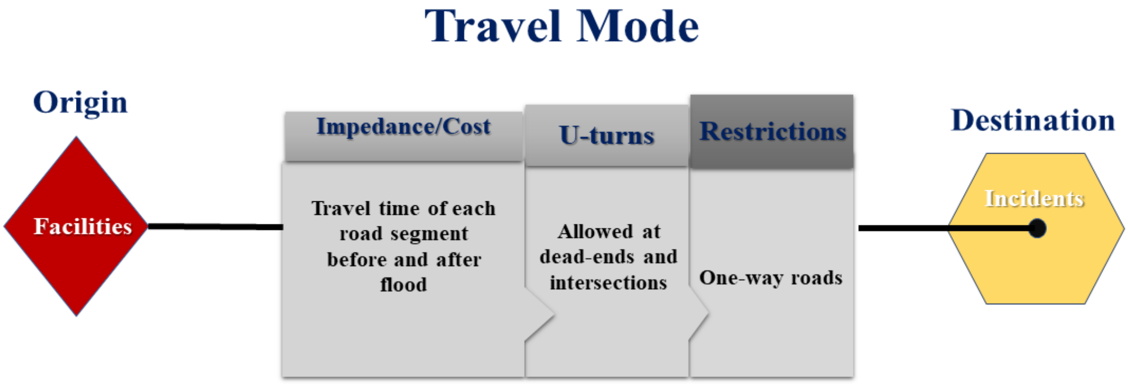


Figure 26: Configuration of the Closest Facility algorithm for emergency routing calculations. Facilities (left): Cologne’s fire brigades and Incidents (right): centroids of city units

The results of the performed algorithm can also serve as a detailed indirect SOC analysis of the area of each fire department of Cologne due to the particularity and locality of the updated ER road network datasets, that is, digitised graphical networks (see section 7.4). Each fire brigade is provided with different routing paths, with exact drive time and length, to the closest locations before a flood event and under flood conditions. The routes extracted can indicate the flood-impacted serviceability of each fire brigade in Cologne, assessed with the different selected flood models.

With the geovisualisation techniques of classification, this information provides aggregated information on Cologne's entire ER road network.

Furthermore, the suggested methodology in the thesis aims to provide a holistic overview of the accessibility coverage of the case study area on a city scale, reflecting on the active redundancy of Cologne’s fire brigades and the rapidity of the response of each fire brigade and the resulting pre-planned ER routes. Classification of the risk-based accessibility routes takes place according to the official fire brigade time thresholds of eight minutes. Additionally, since each route is the total response time from the closest fire brigade to the respective city unit (centroid), each centroid (incident) is weighted by it, serving as a basis for further comparative accessibility analyses (ERR assessments to floods), visualised in hexagonal ERR matrixes (see section 7.5).

6.3.4 Emergency Response Resilience (ERR) to Floods for Cologne's Fire Brigades

Following the suggested methodology, the scope provides ERR matrixes through the RITAI, the risk-based and time-dependent indicator of accessibility towards ERR to riverine floods and flash floods. As previously discussed, each destination is weighted with the total time of response. In this thesis, and for each selected scenario, the destinations are weighted accordingly. The ERR of each city unit, represented from the destinations (incidents/centroids), is calculated with *function 1*, i.e. the NA is performed before and after a flood scenario, using the updated road networks, where each incident is assigned an individual ID (identity number), named IncidentID, assisting identification and calculation processes. As explained in Figure 26, before any flood scenario, the updated road network used is the one updated with the FFS of ER used by Cologne's fire brigades and after each flood scenario, the NAs performed are based on the updated road networks with the new FFS impacted from the FD. The shortest paths are searched and found from the fire brigades to the respective closest city units, and each city unit (incident) is weighted with the total accessibility (response time) before flood (A_{BF}) and accessibility after flood (A_{AF}).

ERR *(function 1)* is then calculated by subtracting from the total accessibility time, calculated after a flood scenario, the accessibility time calculated before any flood scenario for each city unit. As a last step, the risk-based time-dependent accessibility times (response times) are presented as classified in ERR hexagonal matrixes of the area of Cologne, forming classified beehives of city units created in ArcMap 10.6.1. The process of data handling and visualisation in matrixes followed in the GIS environment is presented in Figure 27.

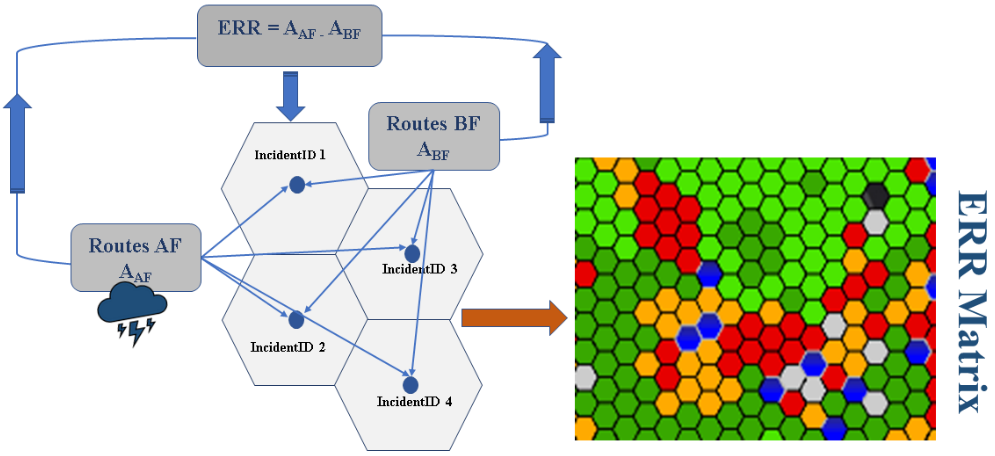


Figure 27: ERR hexagonal spatial matrixes - weighting of each city unit of Cologne with ERR to riverine floods and flash floods, with the application of function 1 in GIS

By presenting the results of the RITAI, the ERS can assess their ER serviceability, dependent on their rescue vehicle capacity and the road network's mobility capacity for safe driving under flooded conditions. For example, under specific flood conditions, some of the emergency rescue services can no longer be available, thus blocked, due to the spatially related unavailable road network (flooded with $FD_j > 0.5$ m) or their physical exposure to flood. Furthermore, the hexagonal matrixes provide aggregated information from the scale of the road segment to the city unit. Flood impacts on a road segment level are depicted on a city unit and city level through the hexagonal matrixes. The quantification of ERR is conducted, as presented in Figure 25, and the results from the calculations take place in each geodatabase.

Each city unit (hexagon) is assigned with the calculation results from *function 1* and is classified accordingly in different colours for a quicker derivation of situational assessments for ER purposes (preparedness, ER route planning, prioritization planning, location-allocation humanitarian assistance planning after different types of floods). The ERR is quantified and classified, as presented in Table 8. ER for Cologne has a time threshold of 8 minutes, as mentioned in section 5.2. Since each ER minute is valuable, specifically in a complex urban environment such as Cologne, the classification considers the increase of accessibility in minutes, where each minute increase indicates the ERR deficiency.

Table 8: Classification of ERR in hexagonal matrixes for ER purposes.

Accessibility Time Increase (in minutes)	Resilience level	Colour of classification after BBK (risk matrix) as in [403]
0	**Highly Resilient**	🟩
>= 1	**Resilient**	🟩
1 >= 2	**Medium**	🟧
2 >= max. increase	**Not resilient**	🟥

7. Results and Discussions

This section consists of presentations and discussions of the results answering the RQs, which form the spine of the thesis. The following is a general overview of the main issues covered throughout the thesis, along with the respective RQs:

RQ1	How can urban emergency response resilience (ERR) to riverine floods and flash floods be conceptualised towards operationalisation using graph and CAS theory?
RQ2	What is an urban ER system, and how does CAS theory identify its operational properties?
RQ3	How can the urban ERR of a fire brigade system, to riverine floods and flash floods, be operationalised, considering interdependent cascading and emerging risks on several scales, with GIS?
RQ4	How can spatial assessments be utilised to operationalise the robustness, redundancy, resourcefulness, and rapidity of ERR on several scales?

RQ5	How can large-scale exposure, vulnerability and risk be assessed with applied geoinformatics, GIS tools and graph theory?
RQ6	How GIS and network science enable identifying system-wide connectivity on various scales and levels, enabling citywide accessibility performance analysis with accessibility patterns and ER route pre-planning?
RQ7	How can GIS, graph theory, network science, fuzzification, geovisualisation and resilience matrixes accelerate the processes, raise awareness and form a basis for further collaboration between civil protection, CI operators and emergency managers?

This thesis's main objective is to develop a concept to apply resilience for urban ERR to floods and, secondly, to apply it in a case study (Cologne) for a specific emergency rescue service (fire brigade system). The first part of the thesis is devoted to conceptual development and the discussions of the concept. The conceptual development and the discussions regarding the ERR concept, its definition and features, are examined in sections 2 and 3. They are also covered briefly below to highlight the main contributions of the several theories to the concept towards its operationalisation. Specifically, in section 1 of the thesis, there is an introduction of identified problems related to the issue risen from climate change, which increases the intensity and frequency of the EWE, causing an increase in the intensity and frequency of floods.

Due to the increasing flood events, the section demonstrates the identified need, from the international DRR frameworks (i.e. SFDRR) for adaptive management, addressing risk explicitly, with a deepened understanding of their impacts on a range of scales, to inform the decision-making, for a strengthened preparedness for response. Emergency response in complex industrialised countries of high densities of population and clustering of interdependent critical infrastructures, such as Germany, is challenged by degradation occurring from the increased flood impacts.

Therefore, to answer the **first part of the RQ1**, in regards to the conceptualisation and utilisation of graph and CAS theory, this thesis proposes that the concept of CAS, as applied to DRM/FRM approaches for the mitigation of the impacts to the population and the critical infrastructures, assist with their advancement, away from their silo-thinking character.

The main strategic goal of emergency management, i.e. the timely ER provision for enhancing the population's safety, is advanced with integrative and adaptive management strategies applied with geoinformatics, aiming to identify and integrate the interdependencies between complex adaptive systems (CAS). Such systems are considered the urban ER systems, as presented in the next section. Therefore, it is suggested that such strategies should at first identify and address emergent risks occurring from a wide range of flood types and intensities spatially. Secondly, they should integrate safety aspects of the emergency responders, which are interdependent with the security aspects of the CI that they operate, the road network, and the rescue buildings and equipment, providing the means for resilience-based decision making aiming to enhance the safety of the population.

In order to answer the RQ1 completely, the RQ2 needs to be answered. Section 2 demonstrates the conceptualisation of the ER system of an urban area, introduced as a SoS, using CAS and graph theory. It specifically demonstrates how graph theory assists with the untangling of the complexity of a SoS and how CAS theory assists with identifying its operational properties for integration in DRR towards its resilience. After identifying its operational properties, CAS theory enabled identifying potential cascading risks, enhancing its resilience with their integration in DRR approaches. Additionally, CAS thinking in the conceptualisation of the urban ER system enables applying the model in the resilience concept and is suggested in the thesis that it is crucial for in-depth resilience assessments, specifically in complex urban environments.

Furthermore, combined CAS and graph theory are valuable in untangling the complexity of urban SoS with CAS properties (urban ER system) by identifying the road network as the higher in the systems' hierarchy.

Therefore, it is suggested in this thesis that it is reasonable to initiate resilience assessments from a road network level. The resilience concept to hazards such as floods, as applied to an urban ER system, is, therefore, as presented in section 2, characterised by the undisrupted timely ER provision and is conceptualised with a combination of graph theory and CAS thinking. The goal is to include the whole range of cascading risks in the resilience assessments, occurring in several levels and scales of the system, also the emerging risks to a technical and operational level, as well as to its environment, i.e. city, for a deepened understanding of the climate change impacts.

For this reason, and for answering the **second part of the RQ1** regarding the operationalisation, the ERR concept is introduced and defined, while the 4R resilience model (robustness, redundancy, resourcefulness, rapidity of response) is adopted for framing its features, operationally reflecting the flood impacts and their cascading risks to the entire urban ER system. It is suggested in section 2 that strengthened preparedness for ER, in the era of increased frequency of EWEs, is achieved with connectivity analysis of the urban ER road network, adaptive ER route plans and flood risk-based, place-based and time-dependent accessibility assessments. Furthermore, this thesis argues that the flood impacts can be further assessed with large-scale spatial assessments. The results depict the absorption and adaption for transformation capacities of the systems, reflected in the robustness and redundancy features of the overall SoS. The levels of these capacities affect the levels of risk regarding the degradation of the system's functionality reflected in the resourcefulness of the system for timely ER provision. Resourcefulness is, therefore, associated with the travel time reliability of the ER road network of an urban ER system, dependent on the absorption capacity levels of the system and its adaptation and transformation capacity towards reliability (undisrupted ER provision).

After identification of the operational properties of the urban ER system, as presented above, its resilience properties/features to EWE-triggered events (floods) is linked with risk identifiers after definition and characterisation through its 4R properties, the RQ3, RQ4, RQ5, RQ6 and RQ7 are answered, through the **operationalisation** methodological framework. As suggested in this thesis, the identifiers of flood risk towards enhancing resilience can be assessed with applied geoinformatics in GIS (**RQ3**).

In combination with the graph theory and network science, these flood risk identifiers can be utilised to operationalise the 4R features of ERR to riverine floods and flash floods, enabling the operationalisation of the concept applied to an urban ER system. In section 3, the multi-criteria indicator (resilient system), i.e. the risk-time-dependent accessibility indicator (RITAI), is conceptually introduced, reflecting on the rapidity of the response feature of ERR. The RITAI suggests the operationalisation of each of the 4R features of ERR, in different scales, with a combination of a top-down methodological approach and bottom-up scaling spatial assessments, conducted with GIS and assisted with CAS thinking, resulting in informative resilience matrixes. With the bottom-up scaling spatial assessment, the scenario-based resilience analysis suggested in this thesis (Figure 10) aims to provide insights into CAS engineering towards resilient ER. The goal is to enhance the safety of the population while also considering the safety of the emergency responders, i.e. safe driving mobility capacity of the emergency rescue vehicles, in case of riverine floods and flash floods. It is therefore demonstrated in the thesis that preparedness for response is strengthened and advanced with large-scale spatial exposure assessments reflecting on the robustness of the system (see section 3.1), after segmentation of the road network, on the road segment level (scale of first analyses) and to the entire road network and the entire urban ER system (see section 4). According to exposure levels, the safe driving mobility disruptions are assessed on the scale of analysis, considering changes in the FFS (see section 3.2 and section 4), reflected on the redundancy of the ER road network and on the travel time (see section 3.3), reflected on the resourcefulness of the ER road network. The latter is the flood risk identifier for degradation of the functionality of timely ER provision, as mentioned above.

This risk, identified on a road segment level, affects the connectivity of the entire road network and the urban ER system (zoom-in and zoom-out ability of the methodological approach) and is integrated into further risk-based and time-dependent accessibility assessments reflected on the rapidity of response feature of ERR. The procedure enables the operationalisation of the ERR after untangling the complexity of the urban ER system while it considers its complex environment (city). Respectively, and when answering the **RQ4**, the RITAI (see Table 3 in section 4) is designed so to address the urban complexity and the impact that can have on the levels of ERR with the compartmentalisation of each under research case study area into city units, forming polygon (of choice) matrixes. Hence, the thesis proposes that CAS thinking is integrated into the resilience assessment process, with the segmentation of the CI networks and the systems, which form risk informative matrixes. These matrixes further enable the gradation of information provided from a local level (large-scale) to a regional (small-scale), giving a detailed overview of the impact of the stressor on the urban ER system. The RITAI is developed to assess the citywide ERR to floods based on the functionalities of the networks of the urban ER system. Specifically, the citywide ERR assessment combines changes in the system on a micro-scale and their impacts on a macro-level. After identification of the need for:

- large-scale urban robustness assessments conducted with exposure assessments on a road segment scale, reflecting the safe drivability according to FD levels (section 3.1),
- large-scale redundancy assessments conducted with FFS assessments on a road segment level reflecting the RNMC of the ER road network according to FD levels (section 3.2),
- large-scale resourcefulness assessments conducted with travel time assessments, reflecting the UFTTR (i.e. risk) of the ER road network, according to FD levels (section 3.3)
- city-scale rapidity of response assessments conducted with risk-based and time-dependent accessibility assessments, reflecting the citywide ER efficiency under flooded conditions (section 3.4)

the RITAI is assessed with selected flood scenarios of two different types of floods (riverine and flash floods) and two different intensities (regular and extreme scenarios) in the case of Cologne and the fire brigade system (see section 5). A limitation of the suggested indicator is that it conveys the probabilistic uncertainties of the selected flood models (see Figure 20 and Figure 21). Therefore, the results will depend on the quality and resolution of the flood probabilistic models. Nevertheless, the RITAI, through the suggested methodology, in section 4 (see Figure 11), aims to provide the resources, adding redundancies for an integrative and adaptive ERR management for comparative evaluations of cross-system alternatives designed to enhance the ability of the urban ER system to:

- plan for various intensities of flood events,
- absorb the stress technically and operationally
- transform so to recover rapidly
- predict and prepare for future flood events in order to adapt to their potential flood impacts.

Hence, the urban ER system is advanced by implementing the RITAI that results in those mentioned above. The RITAI is implemented utilising geoinformatics in an operationalisation methodological framework conceptualised in section 4, with a GIS-based methodological workflow. Further, the GIS-based operationalisation approach provides additional resources and redundancies for enhanced ERR to riverine floods and flash floods, through

- the fast applications of methodologies,
- the easy adjustment of routing plans (for strengthened preparedness and enhanced response times) to case-specific flood scenarios and
- the transferability of the methodology for different case study areas and analyses scales, without significant adjustments.

The methodological workflow for quantitative assessment of ERR (Figure 13) aims to provide, for selected flood scenarios, risk-informed road network databases that will enable information aggregation from a road segment scale to the entire network. For this reason, and to answer the **RQ5**, in section 4.2, the GIS-based methodological framework and the developed GIS-Toolkit in section 4.3 is introduced. The GIS-Toolkit, in a semi-automatic way, conducts exposure assessments of an urban ER system, integrating, after segmentation of the entire ER road network, to one-meter segments, the FD information retrieved from a raster file and integrated into a line vector shapefile. The development of a tool for GIS-based flood impact assessments of the ER road network for further adaptive flood-impacted ER route planning purposes is designed for

- calculating the delays and blockages, the different levels of safe driving mobility
- the transformation of traffic characteristics, caused by different levels of FD_j
- easy implementation using several flood scenarios of riverine flood and flash flood (frequent and extreme) models of the probability of occurrence, for near real-world simulations of ER response
- simple operation and interoperability of primary data (official and open-source),
- simple representations of the results through geovisualisation and fuzzification processes,
- calculation time as short as possible, given the resolution of the analysis.

For the implementation of the RITAI and operationalisation of the 4R features of ERR, the benchmarking of the indicator is proposed for near-real life simulations with GIS, in regards to accessibility assessments, considering the safety of the emergency responders through the security of the emergency vehicles, when operating under flooded conditions. According to FD and for further flood impact assessments on the traffic characteristic of the road network, the road-type dependent FFS of each road segment is recalculated, according to the RITAI and the *PR function 5*, reflecting the absorption capacity of the ER road network to the selected flood, revealing its robustness levels. For the assignment of each flood-impacted FFS, in the road segments, the *Kj function 6* is suggested, which, after benchmarking, considers the safe driving of rescue vehicles up to 0.5 m, but with a reduction of speed to walking speed for flooded roads for FD between 0.3 m and 0.5 m.

The Kj function, in the GIS-Toolkit programmed in VB language, assigns according to the FD, the adapted FFS, transforming each road segment, fostering the transformation of the entire ER road network and urban ER system towards enhanced rapidity of response (timely ER/accessibility). The updated ER road network databases are furthermore enriched with travel time calculations, providing large-scale TTR analysis. To identify the flood impact (changes in the FFS and the travel times), *function 7 and function 8* are applied accordingly. Furthermore, when implemented, these functions allow for redundancy and resourcefulness assessments on a road segment level, which with geovisualisation techniques, are aggregated to the entire road network.

The operationalisation methodological framework (Figure 25), according to the GIS-based methodological workflow (Figure 13), suggests the connectivity analysis of the selected fire brigade system for further accessibility assessments and citywide ERR operationalisation on the city unit scale (**RQ6**). These assessments result in risk-based time-dependent accessibility assessments of the Cologne fire brigade system, which is compartmentalised to city units of 0.25 $km^{2,}$ for a holistic overview of the fire brigade system ERR levels to each of the selected flood scenarios. As presented in section 6, graph theory and network science allow for connectivity network analysis amongst the various networks of a SoS. As presented in section 2.3, GIS provide the tools for such analyses, which are proven essential for a strengthened preparedness phase towards ERR to floods. GIS are ideal for the operational/response phase, specifically for service analyses (network analyses) in the face of a flood. Service analyses, conducted with NA, result in flood-impacted service ranges of the emergency response for each of the fire brigade stations, with identification of the fastest routing paths, i.e. identification of the least-cost paths (in regards to distance or time), to the incident area (city unit), based on flood-risk informed road networks (section 4.2 - Figure 15).

These networks serve as the basis for searching and finding the closest city units to Cologne's fire brigades and calculating their routing paths, before and after (input) each selected flood scenario, towards citywide ERR assessments (RITAI). Rebuild of the ER road network is performed after implementation of the "Network Builder", which is rebuilding each ER road network database, providing connections through the road network between the fire brigade stations and the centroids of each city unit, according to the travel time impedance (see *function 4* - risk reflected on the ER road network's TTR). Moreover, the routing calculations as mentioned earlier conducted in this thesis consider the fire brigades as the origin/starting points, translated in the GIS environment as "Facilities" and the centroids of each city unit (Figure 25) as "Incident", to which the closest fire brigade should respond.

As mentioned in section 6.3.1, routing calculations are performed with the use of the tool "Closest Facility", which offers the configuration of the travel mode used, simulating the travel of a rescue vehicle (fire truck) with the following restrictions:

- avoiding routes passing through highly flooded road segments by choosing optimal routes for a timely enhanced response,
- restricting the U-turns throughout the entire road network in the urban area of Cologne avoiding the probability to cause traffic chaos or even accidents - due to the size of the fire trucks in an urban area, U-turns might also not be possible in most of the cases,
- avoiding the one-way streets for routing calculations saving a substantial amount of time (consideration of travel time impedance).

Thereby, each centroid is weighted with accessibility/response times. The path resulting from the weighted graphs of the ER road networks (flood-risk informative databases with information on flood-impacted travel times) leads to the weighted ERR hexagonal matrixes, as described in section 6.3.4. Resilience-based informative matrixes regarding the citywide flood-impacted ER efficiency of the Cologne fire brigade system result after implementing *function 1* (see section 4) to each hexagonal city unit, contributing to accessibility assessments.

Moreover, when answering the **RQ7**, the thesis suggests aggregation of information methods for advanced analyses with geovisualisation techniques suggested in the GIS-based methodological framework. The goal is the deepened understanding of the flood impacts at a range of flood types and intensities and the escalation of the intensities to identify global/overall interactions among the several sub-systems. These escalations of floods from regular to extreme, which are under-researched Grey Rhino scenarios, need further addressing, and for this reason, in this thesis, they are addressed with flood impact curves and statistics. In case of compound and/or escalating flood events, the flood impact curves provide information regarding the ER road network's robustness, redundancy, and resourcefulness "stretched" to its maximum, therefore testing its flexibility. These techniques in a GIS environment represent complex information regarding each cell of the spatial matrix (city unit) of the compartmentalised case study area. Therefore, the complex information becomes effortless and manageable for a more fundamental understanding and overview of cascading risks that could occur on a local and regional level.

The information enables the large-scale resilience/vulnerability/reliability assessments for integrative emergency management and decision-making of different end-users, as suggested from the RITAI, enhancing the redundancy and resourcefulness of the urban ER system towards consequent enhancement of resilience. End-users can be emergency rescue planners, traffic planners, urban planners, and energy providers (e.g., electricity, water, gas). The simplification of information, which was discussed throughout the thesis and specifically and further throughout this section, is critical for the several officials since they must deal with emergencies, which need a proper preparation phase through situational analysis of complex environments and a time-efficient response for enhanced recovery times. This need is also identified through the qualitative assessment with interviews conducted with European scientists and emergency response, and civil protection officials (see section 7.4.1).

As mentioned earlier, the main objective of this thesis is to develop a concept to apply resilience for urban ERR and, secondly, to apply it in an urban case study (Cologne) for a specific emergency rescue service (fire brigade system). The development and discussion of the concept are treated in sections 2 and 3 and are outlined in the text above, recalling the contributions of the theories throughout the following sections.

Therefore, it follows the logical concept as displayed in Figure 28; addressing the components of the ERR; that is, robustness in section 7.1, redundancy in section 7.2, resourcefulness in section 7.3 and rapidity of response in section 7.4, summarising the classified outcomes in ERR spatial matrixes as presented in section 7.5. The results from the GIS-based upscaling (bottom-up) operationalisation methodology are discussed in detail in the following sections.

The results are a detailed presentation of each methodological step and present the aggregation of information from a large scale to a smaller scale, identifying the risk in a SoS with CAS properties demands (see section 2). The multi-scale and multi-level identification of flood risks in a SoS with CAS properties such as the suggested urban ER system results from applying suggested geovisualisation techniques and the flood impact curves (upscaling method); a deepened understanding of hazard-related impacts.

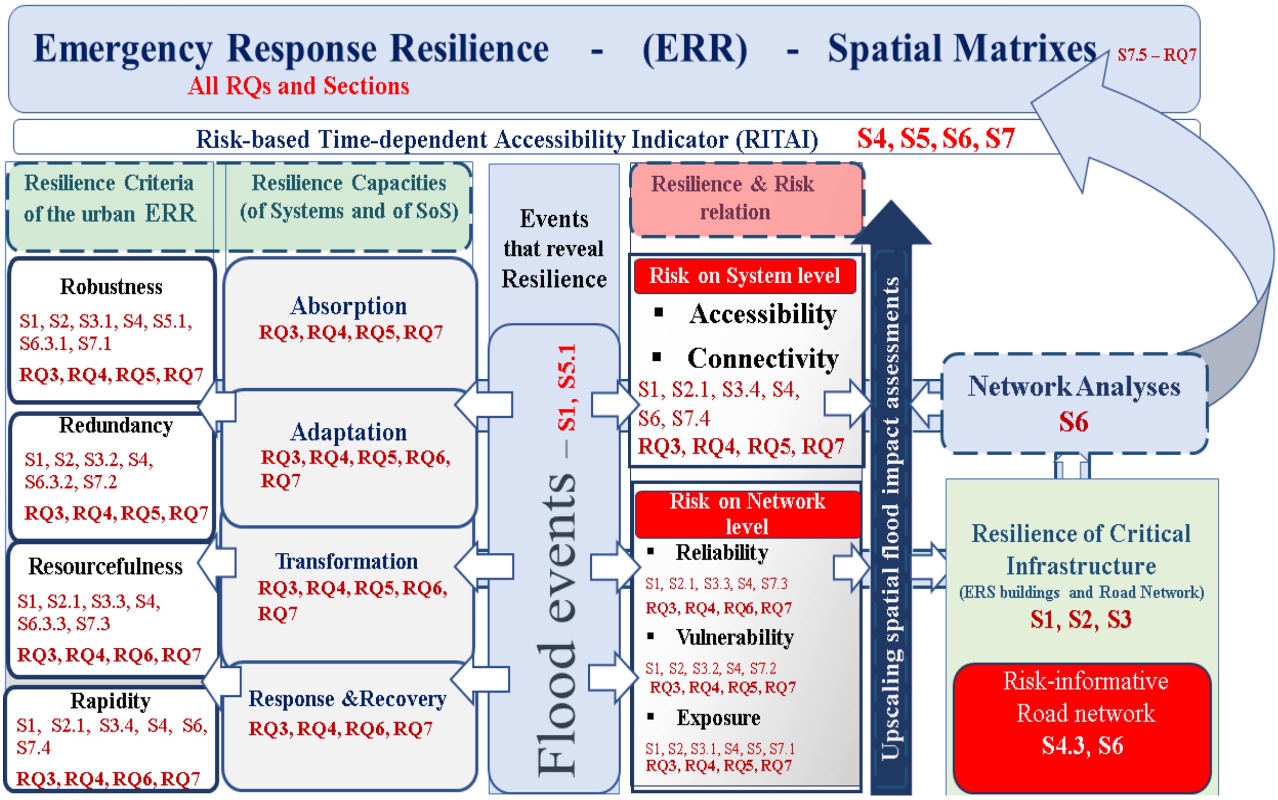


Figure 28: The Emergency Response Resilience (ERR) concept in abstraction with related sections (S) and research questions (RQ)

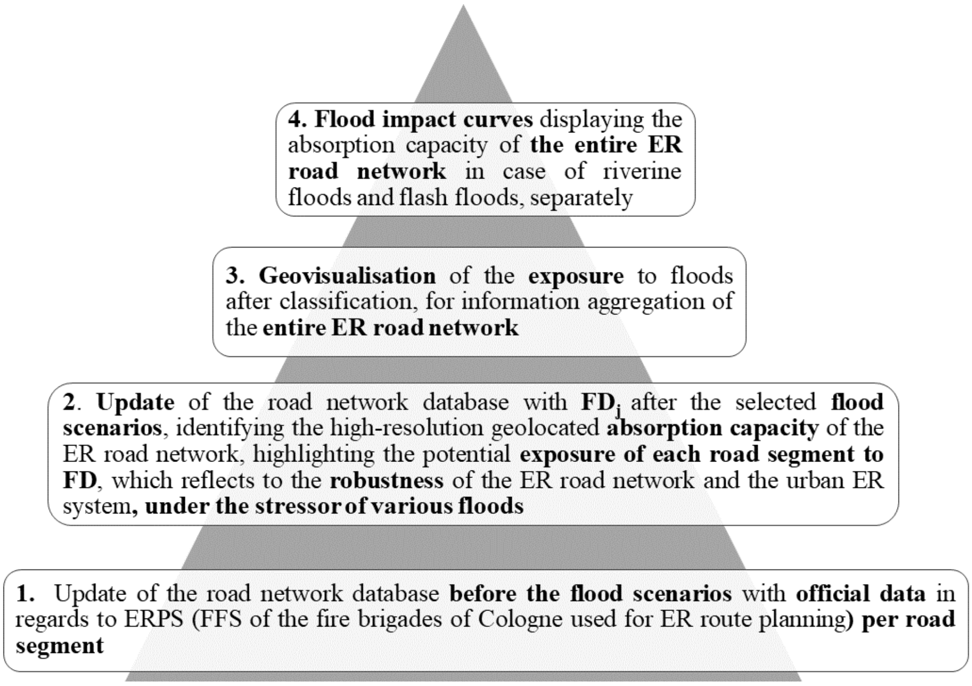
7.1 Robustness Under Flood Conditions

The operationalisation of the suggested ERR (Figure 10 and Figure 11) (also presented in previous sections) is conducted with the GIS-Toolkit (Figure 14), and the first step is spatial exposure assessments of the ER road network to the different flood scenarios selected for Cologne. Exposure of the ER road network to the floods reflects the robustness of the ER road network, serving as the basis for the next operationalisation steps (see Table 9).

Table 9: Large-scale robustness operationalisation for the ERR of Cologne's fire brigade system, to floods

Features	Sub-Indicators	Metric	Outcome
Robustness	**Absorption capacity** ERS and ER Road Network exposure	Extent of exposure to the hazard per road segment and network length in kilometres	▪ Exposure assessment of the entire ER road network and ERS buildings through FD information (per scale of analysis - 1m road segments) ▪ Definition of critical thresholds (critical FD) ▪ Geovisualisation of information, after classification, on the entire road network ▪ Flood intensity impact curves of the whole network and analysis after fuzzification regarding the safe driving mobility under flooded conditions

The GIS-Toolkit enables the high-resolution exposure assessments of the ER road network and the ERS buildings. In this way, the exposure of the urban ER system is spatially analysed on a large scale after each of the selected flood scenarios. Therefore, the large-scale spatial extent of the flood scenarios is modelled with the assignment of FD_j values (on the scale of analysis) in the road network database after each selected flood scenario and after normalisation of the ER road network (segmentation of the ER road network to one-meter segments). The exposure assessment of the urban ER system to floods is enriched with flood impact curves reflected on the robustness levels, indicative of its absorption capacity in case of compound riverine and flash flood events. The results from the operationalisation methodology of the urban ER system's robustness to floods focuses on the normalised large-scale assessments of the ER road network due to the identified hierarchy, which places it first, and the need for a bottom-up scaling approach for a deepened understanding of the flood impacts on several levels. The operationalisation process of robustness in GIS is displayed in Figure 29.



4. Flood impact curves displaying the absorption capacity of **the entire ER road network** in case of riverine floods and flash floods, separately

3. Geovisualisation of the **exposure** to floods after classification, for information aggregation of the **entire ER road network**

2. **Update** of the road network database with **FD_j** after the selected **flood scenarios**, identifying the high-resolution geolocated **absorption capacity** of the ER road network, highlighting the potential **exposure of each road segment to FD**, which reflects to the **robustness** of the ER road network and the urban ER system**, under the stressor of various floods**

1. Update of the road network database **before the flood scenarios** with **official data** in regards to ERPS (FFS of the fire brigades of Cologne used for ER route planning**) per road segment**

Figure 29: GIS-based upscaling operationalisation process of the robustness of Cologne's fire brigade system, dependent on the absorption capacity of the ER road network

The results from the exposure assessment of the road network to the riverine floods of HQ10 and HQ500 are geovisualised and presented in maps after classification according to the identified critical FD for safe driving mobility (see Figure 30). The incorporated information on FD_j in the ER road network databases enables the classification for visualisation and aggregation of information from a road segment level to the level of the entire road network. These classifications enable further analyses from a CIP lens of the citywide ERR to enhance the population's safety. The maps are created in ArcMap10.6.1 and provide a detailed and high-resolution understanding of the robustness of the ER road network for ER purposes (route planning and timely ER provision) and the ERS system of the fire brigades for each of the selected flood scenarios.

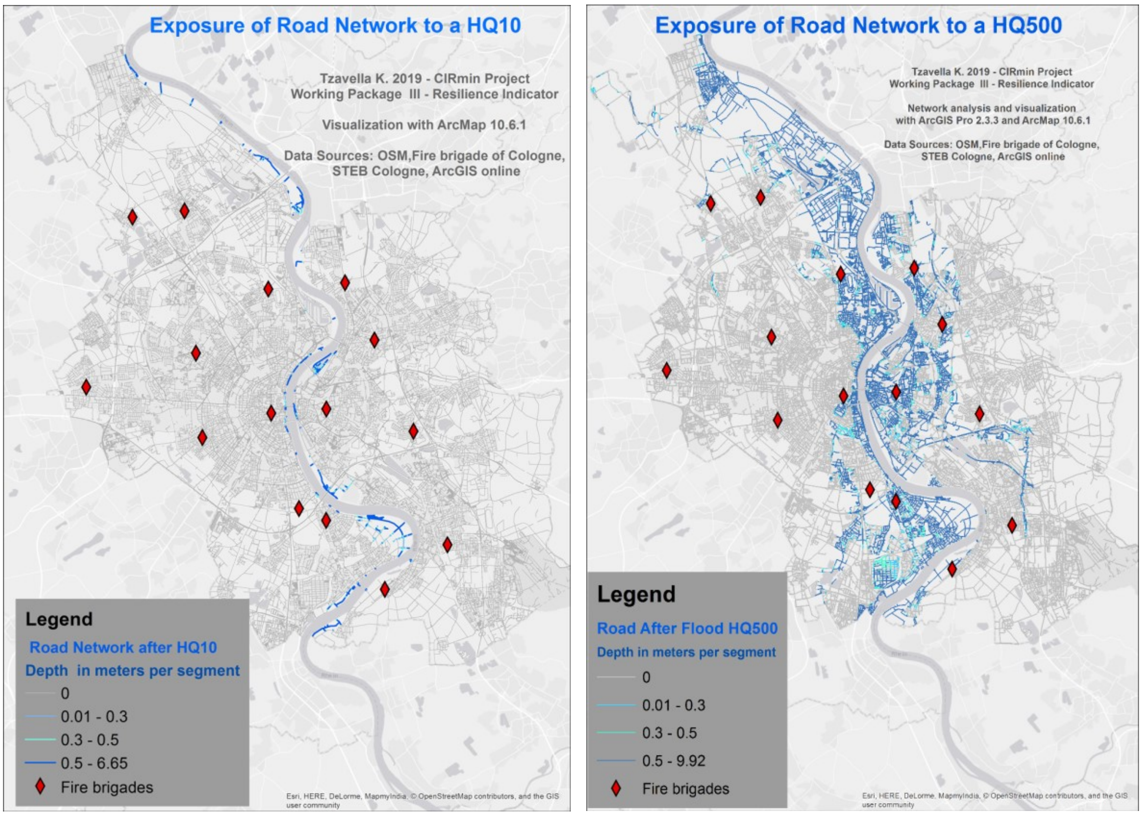


Figure 30: Geolocated exposure of the ER road network to the HQ10 (left) and the HQ500 (right) with classified FD considering the safe driving mobility of the fire trucks (see enlarged in APPENDIX B)

The flood depth levels per road segments (FD_j) are classified considering the safety of the population (timely ER provision with a potential extension of connectivity) and the safe driving mobility under flooded waters of the emergency responders, according to rescue vehicle capacity, integrating the safety lens perspective into the ERR assessment. When aiming to answer the RQ7, the road segments' classification indicates the spatial exposure of the urban ER road network, in kilometres, with information on the total value of exposed road segments. Additionally, the road segments ***exposed to 0 m of FD*** are characterised as ***robust*** to the respective riverine flood. They are categorised to ***FD class 1***. That is, the exposure *to 0 meters of FD* has a positive effect on the robustness of the ER road network and the fire brigades due to their tight interdependency (physical and geographical). After fuzzification, according to Table 4, the flood impact analysis follows. Robust ER road segments are assigned the fuzzy variable ***drivable as planned*** for a more straightforward interpretation of the results since the analysis is conducted with official ERPS from the fire brigade of Cologne, used for ER route planning. The ER road segments exposed to ***[0.01, 0.3) m***, according to the methodology, are assigned to the ***FD class 2*** and allow for safe driving of the rescue vehicles with expected insignificant delays to the ER provision. Therefore they are assigned the fuzzy variable ***drivable***. The expansion of the absorption capacity of the urban ER system of the fire brigades is achieved with the consideration of the ER road segments, exposed to the ***FD class 3*** of ***[0.3, 0.5) m***, as ***medium drivable***. Medium drivable characterise the ER road segments that remain drivable, but they are expected to cause significant delays if used for ER provision purposes. This expansion of the absorption capacity of the fire brigade system is argued that enhances its response capacity, enhancing the safety of the urban population.

Furthermore, the ER road segments exposed to FD≥ ***0.5 m*** (0.5 m to $FD_{maximum}$ m) are considered ***blocked/not robust*** since they block the ER provision and ara assigned to the ***FD class 4.*** The ***total amount*** of the ***road segments*** is indicative of the levels of the ***robustness of different levels of the entire road network***, which is expected to analogously affect the robustness of the fire brigade system, causing a deep low in the different flood impact curves. The flood impact curves for each of the riverine flood intensities (HQ10 and HQ500) depicts the absorption capacity of the entire ER road network of Cologne for timely ER. Specifically, in Figure 31, there are flood impact curves on the safe drivability levels of the ER road network. Safe drivability information is classified per FD class, according to the benchmarking process of the RITAI, which considers the safe drivability of the fire trucks under flood conditions, while it also considers the safety of the population with timely ER. Safe drivability and aggregated exposure assessments from a road segment to a road network level reveal the robustness of the ER road network and, consequently, the fire brigade system to the riverine floods.

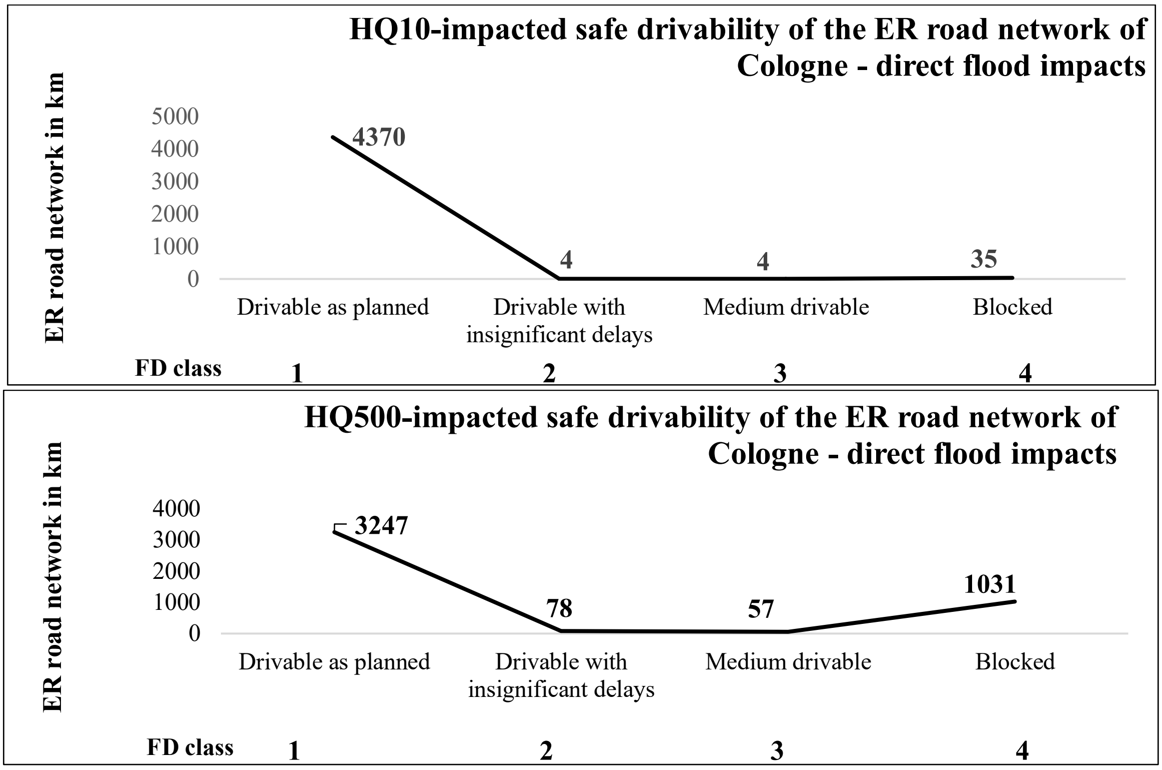


Figure 31: Safe drivability levels of the ER road network per FD exposure class in case of a HQ10 (above) and a HQ500 (below)

Each probabilistic model of the riverine flood (in GIS - raster data) has a different maximum FD. For the riverine flood of HQ10 (regular scenario), the ER road network is exposed to $FD_{maximum}$, up to 6.65 meters and for the riverine flood of HQ500 (extreme scenario), 9.92 meters. The intensities of the two selected riverine floods are reflected in their maximum value of FD that represents two different flood states that the urban ER system needs to absorb.

In Figure 32, the length of the road segments is summarised in kilometres, with calculations made with summarisation tools of ArcMap in each flood risk-informed road network database resulting from the GIS-Toolkit. The exposed road segments are classified and summarised.

The percentage increase of exposure indicates the absorption capacity of the ER road network, analogously affecting the robustness of the urban ER system in case of compound events, which is not an unusual scenario in this era of increasing frequency and intensity of exposure EWE. The absorption capacity is calculated (%increase/decrease = Increase/Decrease ÷ Original Number × 100) as follows:

- road segments exposed to **zero FD** for the HQ10 are of 4370 km length and for the HQ500 of 3247 km length - 26% decrease of exposure from the HQ10 to the HQ500
- road segments exposed to FD **up to 0.3 m** are for the HQ10 of 4 km length and the HQ500 of 78.45 km. - 1813% increase of exposure
- road segments exposed to FD **ranging from 0.3 m to 0.5 m** are for the HQ10 of 4 km length, and the HQ500 of 57 km length - 1419% increase of exposure
- road segments exposed to FD **ranging from 0.5 m** to **FD$_{maximum}$ m** are for the HQ10 of 35 km length and the HQ500 of 1031 km length – 2873.5% increase of exposure or else 996 km.

Riverine flood exposure of the road network of Cologne from regular to extreme scenarios is analysed. The difference between the exposed road segments to the extreme riverine flood scenario HQ500 and the regular riverine flood scenario HQ10 is a direct indicator of the road network's locational vulnerability to riverine floods on a 1 m segment scale.

In a risk-based operationalisation approach of the ERR, robustness to the riverine flood stressor of the researched interdependent systems (road network and ER) is considered the exposure of the systems. Simply, robustness, as defined in the ERR concept, does not consider the time variable. Therefore, Figure 32 provides insights on the increase and decrease of the number of the exposed road segments to the selected regular and extreme riverine floods, aggregated to the ER road network length (in km). The increase and decrease of the exposed road segments analyzed in the different exposure classes are expected to negatively affect the road network's resilience for timely ER since they indicate a less robust system to riverine flooding. For example, a decrease of exposure to zero FDs indicates an increase to higher FDs; more road segments are exposed to FDs higher than zero meters.

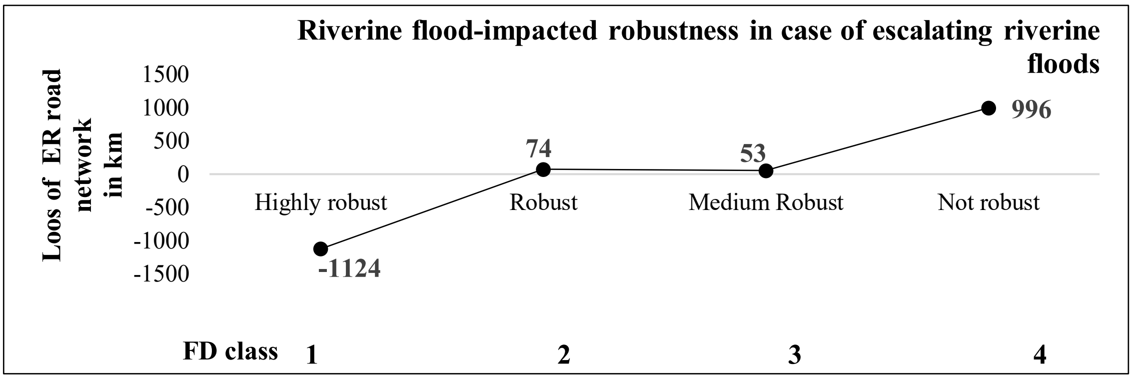


Figure 32: Loss of robustness levels for safe driving of the ER road network in km, according to FD exposure class in case of escalating riverine floods from a HQ10 to a HQ500

At a road segment level, exposure assessments are also conducted for Cologne with selected flash flood scenarios for different return periods, indicative of the regular (20-year return period - T20) and the extreme scenario (100-year return period - T100). The visualised results in ArcMap 10.6.1 are presented in Figure 33. The rasters of the different probabilistic scenarios of flash floods for Cologne (see Figure 20), as expected due to the type of the phenomenon, provide information on the FD for the entire extent of Cologne.

The classification procedure followed is the same as the one used for riverine floods, with the FD's maxima to differ between the two flash flood scenarios. For the T20 (regular flash flood scenario), the $\text{FD}_{\text{maximum}}$ is expected to be 6.219 meters, and for the T100 (extreme flash flood scenario), 6.45 meters. The $\text{FD}_{\text{maximum}}$ does not differ much between the two scenarios, which indicates that the near same (in type and amount) road segments are exposed to these flash flood scenarios. It is expected that the extreme flash flood scenario T100 would affect more road segments, and therefore the robustness of the road network is expected to be lower than after exposure to the regular flash flood scenario T20. Further, the visual interpretation of the results verifies the assumption that more road segments are exposed to flood depth (FD) of more than 0.5 meters.

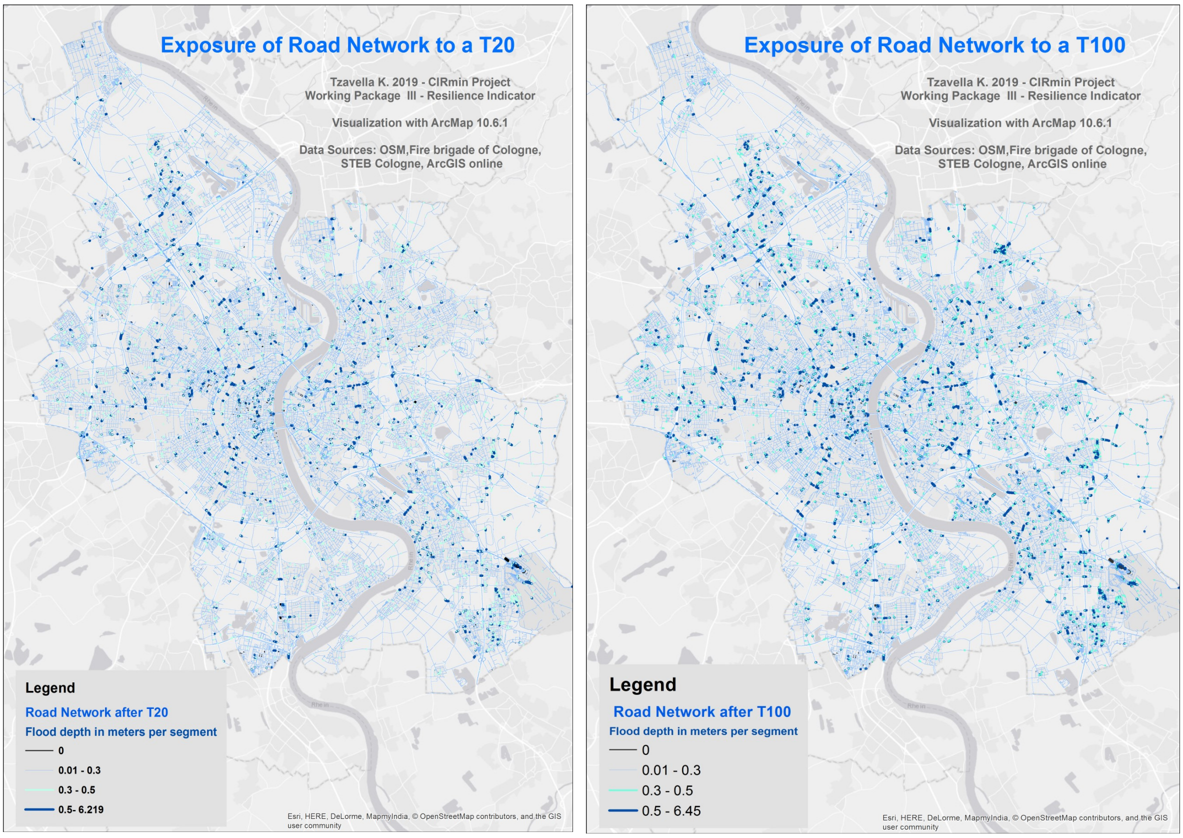


Figure 33: Geolocated exposure of the ER road network to the T20 (left) and the T100 (right) with classified FD considering the safe driving mobility of the fire trucks (see enlarged in APPENDIX B)

For a numeric verification and provision of information regarding the different lengths of the ER road network of Cologne, exposed to the different flash flood scenarios, calculations took place in ArcMap 10.6.1, and the recorded numbers are presented in an Excel graph in Figure 34. The length of the road segments is summarised with the algebraic sum in kilometres, with calculations made with

summarisation tools of ArcMap in the flood-risk informed ER road network database that resulted from the GIS-Toolkit, for the selected flash flood scenarios of Cologne.
Each set FD class has been chosen considering the safety of the population and the emergency responders for operations in the course of EWE.

The road segments exposed are classified and summarised as follows:

- for the T20 and the T100, road segments exposed to **zero FD** are of 15.5 km length - 0% increase/decrease of exposure from the T20 to the T100
- road segments exposed to FD **up to 0.3 m** are for the T20 4285 km length and the T100 4225 length. - 1% decrease of exposure
- road segments exposed to FD ranging **from 0.3 m to 0.5 m** are for the T20 of 76 km length and the T100 of 114 km length – 49% increase of exposure
- road segments exposed to FD ranging **from 0.5 m to FD$_{\text{maximum}}$ m** are for the T20 of 35 km length and the T100 of 58 km length - 65% increase of exposure.

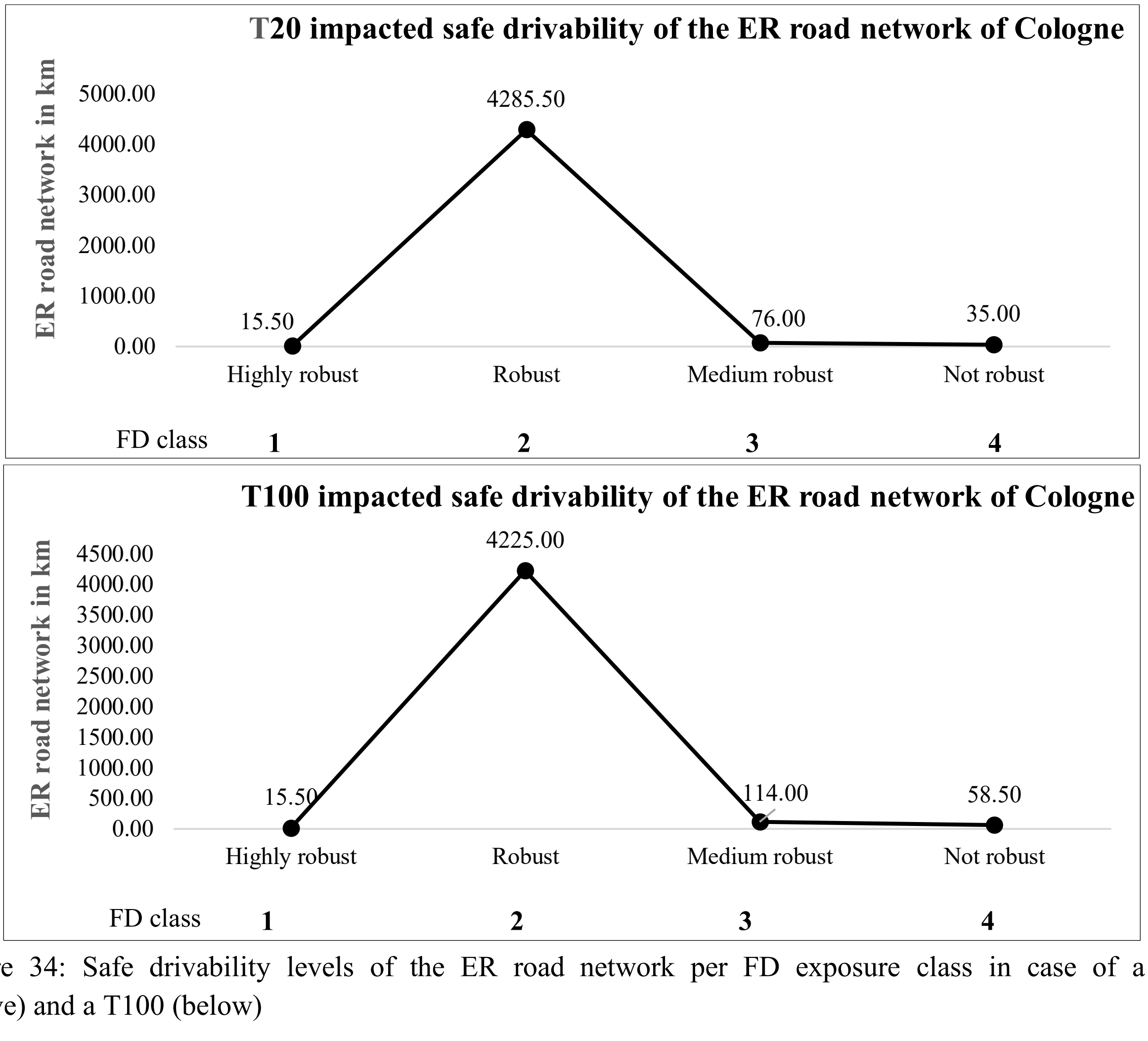


Figure 34: Safe drivability levels of the ER road network per FD exposure class in case of a T20 (above) and a T100 (below)

The robustness of the high in the hierarchy system ER road network to flash floods is operationalised with results from comparing the exposure levels between the number of the exposed road segments to the different FDs from the extreme scenario to the regular (T100 - T20). Considering the flash flood scenarios of Cologne, the following graph presents the impact (negative or positive) that the exposure to different flash flood FDs has on the system of the ER road network.

This flood impact is reflected in the robustness of the ER road network to the selected, regular and extreme flash flood scenarios. The percentage calculation of the ER road network's robustness to flash floods indicates its absorption capacity in case of compound events. As has been demonstrated throughout the entire text, the scenario of escalating and compound events are not a Black Swan but rather Grey Rhinos, which need more attention from the scientific community and the practitioners, particularly in city-scale studies. The Grey Rhino scenario of the flash flood impacts on the ER road network of Cologne indicates the percentage trend of the exposure (absorption capacity) of the road network from the regular (T20) to the extreme (T100) flash flood scenario (Figure 35).

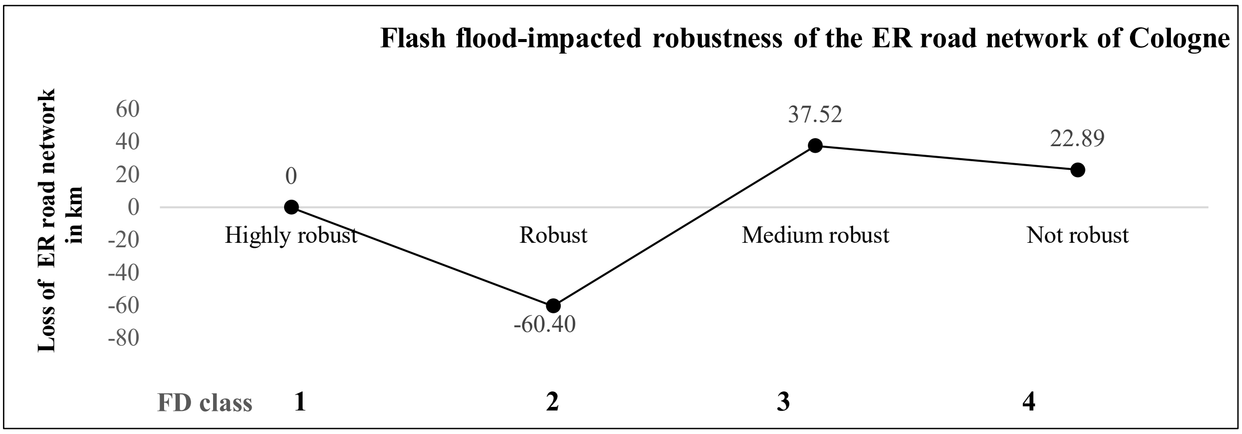


Figure 35: Loss of robustness levels for safe driving of the ER road network in km according to FD exposure class, in case of escalating riverine floods from a T20 to a T100

7.1.1 Discussions of the Robustness

Flood impacts of various intensities and probabilities of occurrence need to be analysed on the different levels of an urban ER system. In the era of increasing frequency and intensity of EWE, DRM approaches need advancement. DRM approaches in the case of urban complex adaptive SoS, as demonstrated in section 1, are advanced with the conceptualisation of the ERR concept, since there is a need for strengthened preparedness for response, as mentioned in the SFDRR [31], explicitly focusing on cascading risks, EWE- triggered, from the tight interconnectedness and interdependence of interface CI, applied to fire brigade systems. Answering RQ3, the suggested operationalisation methodology of the ERR with GIS focuses on the Cologne fire brigade system with a combined top-down and bottom-up scaling approach (see Figure 10). As demonstrated in section 3.1.1, in-depth impact analyses of various hazards on the transport network initiate large-scale intraurban exposure assessments, essential for intraurban high-resolution ERR spatial assessments, as suggested in this thesis. The official fire brigade system in Germany, as presented in section 5.2, is chosen due to its high annual demand for deployments, which need to be time-effective under any weather condition. Cologne is categorised as one of the rainiest cities in Germany (see Figure 18), making the necessity for in-depth flood impact analysis even higher.

EWE's high impact on the transport system of Cologne (see section 4.4) enhances the need for additional action taken from the fire brigade system towards the safety of the population. It is argued that the high amounts of the fire brigade system in Cologne annually, in combination with the climatic characteristics of the city, that they are about to develop, increase the need for strengthened preparedness. In regards to RQ2, considering the complexity of the fire brigade system in an urban area and the need for preparedness for timely and undisrupted ER, the urban ER system is viewed as a SoS with CAS properties, which will need constant feedback loops from disruptions occurring in different levels of its interdependent systems. Graph theory with network science enables the high-resolution flood impact analyses essential in city scales enabling spatial resilience assessments on different levels. They facilitate untangling the complexity of an urban ER system with CAS properties (see Figure 3), assisting with identifying the hierarchy between the urban road network and its interdependent CI systems (RQ3). The urban road network can be viewed as a weighted graph with quantifiable attributes, such as distance, length and time. Such compartmentalisation of the urban road network to its components (nodes and edges) advances flood impact analyses by providing the opportunity for node-to-node in-depth assessments (RQ4). The focus on the components of the urban road network, which with additional information provided from the Cologne fire brigade regarding the ERPS used for ER route planning, transforms the ER system and advances the DRR methodologies with high-resolution (large-scale) flood impact assessments (RQ4). With the application of GIS spatial analyses, suggested from the composite risk-based time-dependent indicator RITAI (Figure 10), the flood impacts on the Cologne fire brigade system are analysed on many levels (RQ5). In the urban ER system with CAS properties, the ER road network is higher in the hierarchy, serving the lower in the hierarchy interdependent CI (RQ3, RQ4). With a need to escape the siloing in the current DRM approaches, the ERR concept also proposes the integration of flood impacts to the environment of the fire brigade system, that is, the safety of the population, exposed to various flood types and intensities, as well as the safety of the emergency responders, of the rescue vehicles and the ERS buildings (RQ3).

The exposure depends on the likelihood and intensity of the selected hazards. As discussed throughout the text, the intensity is a discrepancy from the frequent events [10]. The higher the discrepancy, the higher the intensity of a hazard, which is identified as extreme. The four different selected flood scenarios are chosen because there is a need to focus on the impact estimation, shifting away from determining the probability of occurrence [212]. In this way, the analysis on many scales, which is essential in resilience assessments of CAS, such as the urban ER system, is enabled to assess exposure across a range of riverine flood and flash flood intensities and likelihoods (RQ4). When answering the RQ5, the exposure assessments in this thesis are conducted with spatial analyses of high resolution applied with geoinformatics and GIS tools, such as the developed GIS-Toolkit (see Figure 16). With the GIS-Toolkit, the high-resolution compartmentalisation of the ER road network of Cologne to its nodes and links is enabled. Its nodes and links are integrated into the primary ER road network creating the scale of analysis (1 m road segment) and defining the local road area of the road network, for further large-scale spatial resilience assessments.

The spatial analyses for ER purposes are the situational analyses conducted at the first step of an emergency management cycle for time-effective ER, mainly in the preparedness phase. Situational analyses are indicative of the damage extent of hazardous events.

Therefore, in this thesis, the exposure assessments are the basis for further resilience analyses through impact assessments of the selected flood scenarios to the ER road network and the ER efficiency in the urban complex environment of Cologne (RQ3, RQ4, RQ5). Considering the safety of the population, that is, timely ER provision and the security of the emergency responders operating under flooded conditions, the RITAI suggested the classification of the FD (see section 4.1) according to the rescue vehicle capacity for safe driving through flooded waters. To answer RQ5, the exposure assessments indicate vulnerability or robustness; thus, they indicate the potential loss of nodes and links (infrastructure), which can negatively affect the ERR after the impact of specific flood scenarios. Therefore, the first measure of the flood impacts on the transport network is the proportional loss of the total length of road segments that have been exposed to a range of FD. As suggested in this thesis (see section 3.1), the robustness of ERR is operationalised through the exposure assessments, resulting in values on the potentially affected road segments with FD information (direct flood damage), which can be valuable for ER purposes but also for civil protection authorities, humanitarian response, traffic and urban planners, CIP strategies and insurance and investment planning (RQ5, RQ7).

Furthermore, continuing to answer the RQ5, in regards to flooding, it has been scientifically proven that the exact location, i.e. geolocation, of people and assets matters significantly for the accurate evaluation of the associated risks [12]. Therefore, direct damages geographically located, i.e. proportional losses in infrastructure, which in this thesis is the total length (in kilometres) of roads that have been affected, are the first measure of the impact of flooding on the transportation network (RQ4, RQ5).

However, the main focus of the applied methodology is the quantification of the impact of the flood on the road network on a large scale and the driving ability of rescue vehicles to operationalise ERR in complex urban environments. Answering the RQ3 and RQ4, in order to tackle the urban complexity of the city of Cologne, the normalisation of the ER road network aims to provide detailed information in regards to the robustness of the road network to flooded situations (different types and recurrence times) for timely ER, towards operationalisation of ERR. Aiming to address issues arising from the complexity and to answer the RQ7, calculations conducted in GIS revealed that high-resolution exposure assessments to riverine floods of different intensities and probabilities of occurrence with the classification of the road segments according to the assigned FD values (visualised in maps) result in not only a geolocated (local) in-depth robustness assessment of the road network but also in an overview of the whole transportation infrastructure system.

As defined in this thesis, robustness, from a resilience CAS engineering perspective, is considered the level of exposure of the road network to different riverine and flash flood depths, which jeopardises the critical functionality of the ER road network (timely ER provision) and the safety of the emergency responders, in case of deployment. Answering the RQ5, large-scale robustness assessments via exposure assessments of the road network to different FDs of the selected riverine scenarios enable an exploration and identification of the robustness of the system of ER follows, towards operationalisation of the ERR, considering safe drivability and potential ER time delays. Riverine floods are extended around a river, with the extent to be dependent on the phenomenon's intensity. The flood's potential coverage determines the road network's exposure to riverine floods and the direct damage to the infrastructure.

Additionally, exposure assessments of the fire departments to floods could also be valuable for an urban fire brigade system to increase the ER system's robustness to these potential hazards. Apart from the service area coverage (SOC) of each fire department, the undisrupted cooperation of the fire departments' collective forces (RQ3, RQ4) is crucial for the assurance of timely ER. For example, different types of rescue vehicles are located in different departments and may not be available for ER purposes due to high flood exposure of the geographically dependent road network.

However, as presented in the results in section 7.1 and from a visual interpretation of the results in Figure 30, it is evident that the regular riverine flood of HQ10 is likely to affect few road segments of Cologne along the river Rhein. On the contrary, the extreme riverine flood HQ500 is expected to affect the geographical interdependent road segments, to a greater extent, due to higher intensity, that is, the more extensive coverage area of the probabilistic flood zonation (RQ5, RQ7).

The results of calculations conducted in the geodatabases of the created road networks for ER purposes revealed that there is a 26% decrease of exposure of the road to zero flood depths (robust); that is, an additional 1124 km of the road network are exposed to higher FD values (less robust). Exposure to zero FD is a positive factor for increasing the ERR curve, indicating the high absorption capacity of specific road segments to the under research flood type and intensity. Accordingly, an 1813% increase of exposure of the road network to FDs between 0.01 m to 0.3 m from the regular (HQ10) to the extreme scenario (HQ500) of riverine floods is observed. This amount of exposed road network affects the robustness level of the road network negatively and the amount of exposed road network for FDs between 0.3 m to 0.5 m, where there is an increase of exposure of 1419%. Furthermore, more road segments are flooded with water levels higher than 0.5 m (996 km of road). The decreasing trend of the road network's robustness vs the increasing trend of the exposure of the road network between the two selected riverine scenarios (Graph 2) is expected due to the different intensities. (RQ7). Correctly, in calculations conducted in the flood-risk informed ER road network databases, it is observed that there are:

- +30% more exposed road network to FD between the 0.01 m - 0.3 m, which are still allowing safe drivability of the rescue vehicles, according to the thresholds chosen in the thesis,
- +23% more exposed road network to FD between the 0.3 m - 0.5 m, which are allowing delayed safe drivability of the rescue vehicles and
- +47% more blocked road network due to exposure to FD higher than 0.5 m.

The classification suggested from the RITAI aims to expand the FD thresholds while consequently aiming to enhance the redundancy, resourcefulness and rapidity of the response of the fire brigade system. As stated in section 3.1, it is proved that roads may be closed even if not inundated due to the status of the neighbouring road links [285]. Moreover, it is argued that large-scale spatial exposure assessments with GIS and geovisualisation techniques provide such information in a numeric and visual form (maps). Analyzing the impacts of hydrometeorological phenomena in major urban centres becomes highly essential, specifically within the projected increase in the mean precipitation intensity and the probability of extreme rainfall across most of Europe [286]. Therefore, the methodology proposes using a range of flash flood models of different intensities for a more holistic overview of their impacts on the urban road network of Cologne for ER purposes. The exposure assessments are also conducted with the regular and extreme flash flood scenarios in a GIS environment since the impact of flash floods on the road network and the ER in the city environment needs analysis.

The resulting road networks from the GIS-Toolkit provide information per 1 m road segment regarding the selected FD levels towards safe drivability of the rescue vehicles of Cologne and operationalisation of the ERR (RQ 7). As presented in section 3.1, flash floods are not a common hazard scenario for impact analysis on the transportation network for emergency preparedness due to the highly detailed information needed and lack of tools for high-resolution extraction of information regarding the exposure, specifically for intraurban roads.

Moreover, this is due to the massive demand for understanding flood risks occurring from intraurban road network disruptions or losses [179], leading to connectivity and accessibility impairment or even loss, enhancing the risk for the population's lives. The methodology in this thesis aims to overcome the limitations identified so far, filling the identified gap for an in-depth understanding of the potential cascading EWE-triggered flash floods resulting in temporary flooding on urban road networks systems with large-scale identifications, with untangling techniques and applied theories considering the complexity of the issue and the system researched (RQ3, RQ5).

Consequently, the suggested application of the GIS-Toolkit (RQ4), using as input data the flood models of regular flash floods of a 20-year probability of occurrence and the extreme flash floods with a return probability of 100 years, returned results that verify the fact that the flash flood damage on the infrastructure of the road network depends on its infrastructural morphology, further dependent on the geomorphology of Cologne. The normalised large-scale exposure assessment enabled with the application of the GIS-Toolkit can enhance the identification of critical areas intraurban roads while enabling further analyses of the robustness of the ER road network of Cologne, used from the fire brigades. Additionally, the high-resolution geolocated results can raise awareness for future actions that need to be taken to improve the infrastructure (pavement of the roads) or prioritise response through alternative pre-planned routes. With the scenario of flash floods, in particular, the GIS-Toolkit has proven to be a valuable tool in the situational analysis, even if applied with static flash flood models, since it can reveal geolocated damage on the complex intraurban transport network of Cologne with information on FD and extent (Figure 36). Furthermore, this information provides a basis for other risk-based approaches, i.e. quantification of the indirect impacts on the road network's characteristics (FFS change-section 3.2, UFTTR- section 3.3, ER accessibility according to the connectivity of the ER road network after floods - section 5).

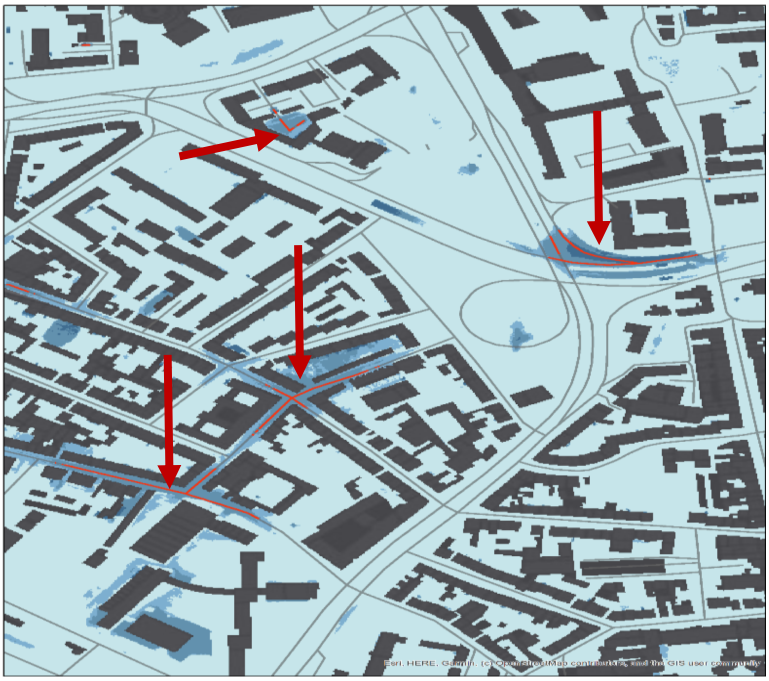


Figure 36: Geolocated FD levels per 1 m road segment indicate the intensity of the T20 (light to dark blue and red the blocked road segments) and its direct impact on Cologne’s intraurban ER road network

Regarding this matter, the results spatially showed that the unaffected road segments from the flash floods of both intensities, hence robust, remain the same (15.5 km). According to the models used, spatial analyses proved that even though intense rainfalls can be unexpected, due to the increasing climate change, the occurrence of a flash flood regarding location could be predictable, with uncertainties carried from the flash flood (and riverine flood) models themselves. With the geolocated exposure of the road network to the two selected flash flood scenarios, it is observed (Figure 33) that the flash flood extents did not vary much. Therefore, the road segments exposed to regular flash floods with the road segments exposed to the extreme ones present a geographical locality. That is, road segments exposed to FDs between 0.3 m - 0.5 m in a regular (T20) flash flood scenario are more likely to be blocked (exposed to > 0.5 m) on an extreme scenario (T100), and this is also dependent on the status of the exposure of the neighbouring road segments. Moreover, the spatial analyses revealed that even though the maxima FDs for the two flash flood models are not varying much ($FD_{maximum}$ for the T20 is 6.219 m and for the T100 is 6.45 m), there is a decrease of exposure to flood depths between 0.01 m - 0.3 m and an increase of exposure to higher FDs (see Figure 34). This verifies the increasing trend of exposure (and thus impact) of the selected intensities of flash floods and, therefore, the decreasing trend of the robustness of the road network (system of analysis).

From the flood impact curves for each of the selected flood scenarios, the absorption capacity of the ER road network, considering not only the direct impact (timely ER provision) but also the safety of the emergency responders and their assets, in case of deployments under extreme weather conditions, is identified. The comparison analyses also provide a general overview of the levels of the absorption capacity, i.e. the robustness of the ER road network to floods, in case of compound effects.

As demonstrated throughout the entire text, the scenario of compound events is not a Black Swan, but rather Grey Rhinos, which need more attention from the scientific community and the practitioners, particularly in city-scale studies.

These Grey Rhino scenarios are considered to strengthen the preparedness for response, specifically under EWE-triggered flood conditions. In Figure 32 and Figure 34, the riverine and flash flood impact trends from the regular scenarios to the extreme ones, for each flood type, on Cologne's entire ER road network are presented. The two flash flood models (see Figure 33) do not vary much in intensity (FD maximum), but their escalation could potentially impact highly the ER provision (Figure 35 - 56% not robust road segments), increasing the need for inclusion of extreme scenarios in preparedness response plans and training.

Furthermore, the medium drivable road network, that is, ER road network of low absorption capacity, still drivable but with expected delays in the ER provision, for the riverine floods is 23% and for flash floods 43%. The results indicate the high direct impact of the flash floods in an intraurban road network and, more specifically, in an urban ER road network, vital for timely ER provision. The reasons are that the different type of floods, e.g. flash floods caused by EWE, have a greater extent than a riverine flood limited to a radius (even if high in case of extreme events) around the river basin. Additionally, the results reveal that the Grey Rhino scenario of escalating flash floods must be considered for further actions towards reconstructing the road network or enhancing preparedness for the areas where their probability of occurrence is high.

The proposed operationalisation methodology, with applied geoinformatics and GIS-Tools, provides the opportunity to the emergency managers, the civil protection officials and the CI operators to utilise detailed information on the geolocation of floods (riverine or flash floods) in a complex urban environment, with high-resolution information regarding their intensity (FD) and extent (impact on the road network). Such information can be used for further establishment of live surveillance of early warning systems and flood information [176, 292, 404-406], which could be integrated into emergency plans, economic flash flood risk assessments [298] and socio-economic assessments [9, 38, 293], emergency responders [279, 280] civil protection authorities [407], and urban resilience strategies from a CIP perspective [234, 287, 295, 407-415]. Specifically for complex urban environments, localised knowledge for the FD of the road segments, on a large scale, enhances the chances for an increase of time-effective ER, through i) the prioritisation of the ER via network analytics (route analysis) avoiding the highly flooded road segments and ii) through the provision of the exact flood extent for the transfer and positioning of heavy rescuing equipment such as emergency boats.

Additionally, as it will be analysed and displayed in the subsequent sections, exposure assessments/robustness analyses to specific flood scenarios serve as the basis for measurements of redundancy through the road network's mobility capacity, road network reliability and finally, the efficiency of ER to floods, towards operationalisation of the ERR for Cologne.

7.2 Redundancy Under Flood Conditions

This section will present the results of the vulnerability assessments of the ER road network of Cologne to the different selected scenarios of floods, for ER purposes, in order to answer the research questions RQ3, RQ4, RQ5 and RQ7, while applying the assessment steps, suggested from the RITAI (Table 10).

Table 10 demonstrates the suggested methodology for identifying the adaptation and transformation capacity of the ER road network system with large-scale vulnerability assessments towards operationalisation of the passive redundancy of the system, as explained in section 3.2 (RQ3). Identification of the passive redundancy is the basis for further indirect flood impact identification, depicted on the risk for delayed or blocked RNMC, consequently revealing potential risks for degradation of the fire brigade system's response capacity. From a transport resilience perspective, which overlays metrics and definitions from the vulnerability concept, RNMC for ER purposes is considered the indicator of redundancy towards operationalisation of ER in the case study area. In the ERR concept and for a road segment level, redundancy characterises those road segments which have absorbed the stressor of the floods and have been transformed to a level that they can provide timely ER (not impacted or low impacted). The results indicate the impact of the FD on the RNMC, as defined in section 3.2.

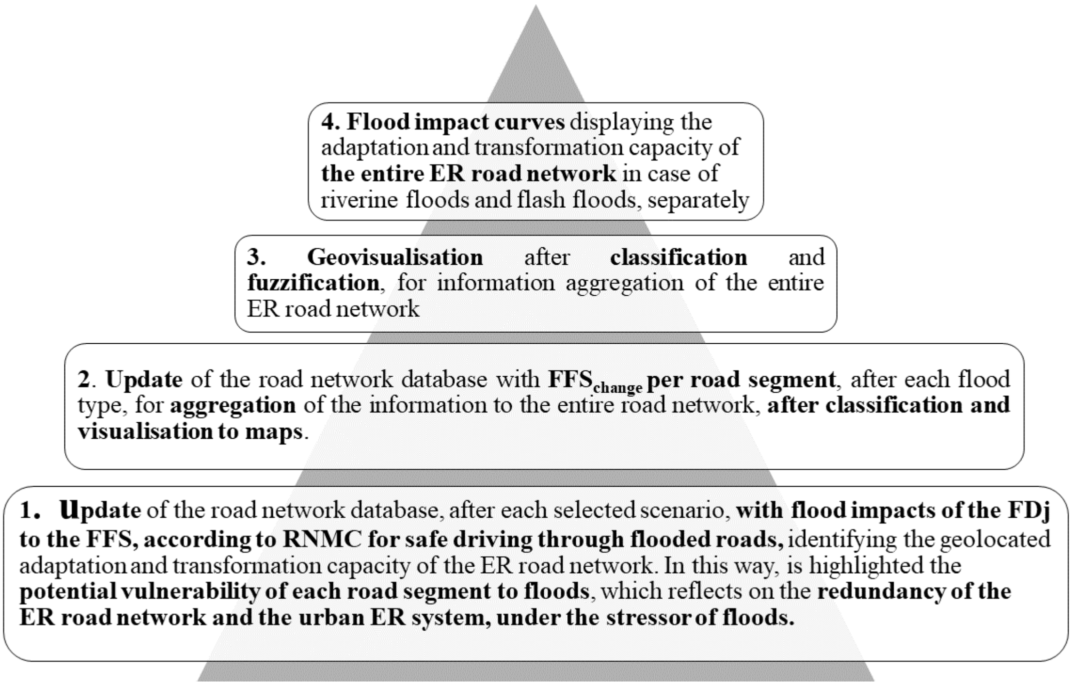
Additionally, the impact is quantified, providing an overview of the redundancy of the Cologne fire brigade system. The RNMC is dependent on the ERS capacity in rescue vehicles able to drive through flooded waters (various heights), e.g. the fire brigades in Cologne are equipped with high-wheeled trucks able to drive through 0.75 m (see section 4.4). On a second level, the fire brigade system capacity is impacted due to the neighbouring and tight interdependent relation of the fire brigade stations with the ER road network. That is, the conduction of calculations and assignment of the associated flood impacts on the traffic characteristic of FFS is associated with speed reductions of the respective road segments used for ER provision; thus, vulnerable road segments impacting the response capacity of the fire brigade system across the entire city of Cologne.

The second level's flow-based impact measurement (active redundancy) of the fire brigade system is incorporated later in the accessibility measurements.

Table 10: Large-scale redundancy operationalisation for the ERR of Cologne's fire brigade system, to floods

Features	Sub-Indicators	Metric	Outcome
Redundancy	**Adaptation for transformation capacity** ERS and ER Road Network Capacity	FFS change and speed flow-based impact according to ERS capacity of rescue vehicles (height of rescue vehicles)	▪ Calculation of impacted FFS according to critical thresholds (per scale of analysis) ▪ Comparison analysis of FFS (per scale of analysis) ▪ Geovisualisation of information, after classification, on the entire road network ▪ Flood intensity impact curves of the whole ER road network and analysis after fuzzification regarding the safe driving mobility of emergency responders

The impact of the FD_j on the FFS of the ER road network is the vulnerability indicator of the road network used for ER route planning for ER provision. The FFS after each flood scenario depicts the adaptation of the system's capacity for timely ER provision after absorption of the direct impact and transformation for the enhancement of the ERR curve. Flood impact measurements, conducted with applied geoinformatics and GIS tools (RQ4), on the traffic characteristic of the FFS for operational ER route planning, aim to provide spatially geolocated vulnerable ER road segments (RQ5) and statistical analyses (separately and in combination) for a strengthened preparedness for response, also in case of escalating flood events (RQ7). Hence, the application of *function 7* ($FFS_{j\ change}$) provides detailed information on the redundancy of each road segment, indicative of the level of the resilience of the road network for timely ER provision. The results are a product of the GIS-Toolkit (section 4.3) and are gathered in the geodatabases of each updated flood-risk informed road network database. For the update of the ER road network after each selected flood scenario, *function 5* (*PR*) is implemented in ArcMap 10.6.1, calculating the flood-impacted FFS per road segment, which are later transformed according to *function 6*, reassigning the adjusted FFS (K_j), resulting to geolocated redundancy levels. The bottom-up scaling approach for the operationalisation procedure of the redundancy with GIS, geovisualisation techniques and flood impact curves are presented in Figure 37.



4. Flood impact curves displaying the adaptation and transformation capacity of **the entire ER road network** in case of riverine floods and flash floods, separately

3. Geovisualisation after **classification** and **fuzzification**, for information aggregation of the entire ER road network

2. Update of the road network database with **$\text{FFS}_{\text{change}}$ per road segment**, after each flood type, for **aggregation** of the information to the entire road network, **after classification and visualisation to maps**.

1. Update of the road network database, after each selected scenario, **with flood impacts of the FD_j to the FFS, according to RNMC for safe driving through flooded roads,** identifying the geolocated adaptation and transformation capacity of the ER road network. In this way, is highlighted the **potential vulnerability of each road segment to floods**, which reflects on the **redundancy of the ER road network and the urban ER system, under the stressor of floods.**

Figure 37: GIS-based upscaling operationalisation process of the robustness of Cologne's fire brigade system, dependent on the absorption capacity of the ER road network analogous to the FD exposure

With an aim to answer the RQ7 and for visualisation and analyses purposes, $\text{FFS}_{\text{j change}}$ is classified into four classes, from zero change to the maximum, which is the maximum ERPS of each updated road network according to the impact each flood scenario has on the FFS of the ER road network of Cologne. The ERPS classification indicates the road networks' redundancy level for ER purposes after each selected flood scenario. The first class (***zero change***) represents the ***unaffected*** road segments (***not impacted - from floods***), and the last one represents the profoundly impacted road segments. Each class is indicative of the level of impact and is visualised with different colours and assigned with a different linguistic variable. Where the FFS is

- ***not impacted*** (highly redundant ER road segments) FFS is presented with the ***grey colour***,
- the ***low impacted*** FFS (redundant ER road segments) is represented by the ***green colour***,
- the ***rather high impacted*** FFS (medium redundant ER road segments) with ***orange*** and
- the ***high impacted*** FFS with ***red*** (highest impact of the FD_j to the FFS-blocked mobility).

The visualisation of the different levels of the $\text{FFS}_{\text{j change}}$ provides detailed information on the RNMC, which analogously affects the ER capacity of the ERS; if the ERS stations are situated in proximal areas to profoundly affected FFS_j (or else ERPS). Specifically, for the riverine floods of HQ10 and HQ500, the visualised results are in Figure 38. The classification results depict the impact level on traffic mobility under flood conditions (potential transport disruptions). Specifically, the results reveal the maximum $\text{FFS}_{\text{j change}}$ of each riverine flood scenario, which is another indicator for the extent of this indirect flood impact to the system's mobility capacity that reflects the adaptation and transformation capacity of the ER road network and the response capacity of the fire brigade system. Therefore, the maps created after each flood scenario are the visualisations of the transformed road segments after absorption of the impact of the FD of various floods.

Specifically, the road-type dependent FFS's transformation per road segment indicates the redundancy of the system for ER route planning and timely ER. The methodology returns results, not only for the local vulnerability of the road network, which is analysed and visualised, indicating potential critical road segments for timely ER but also for the risk factor that is integrated through the transformation into the road network system (delayed or incapacitated ER) for further risk-based assessments towards operationalisation of the ERR.

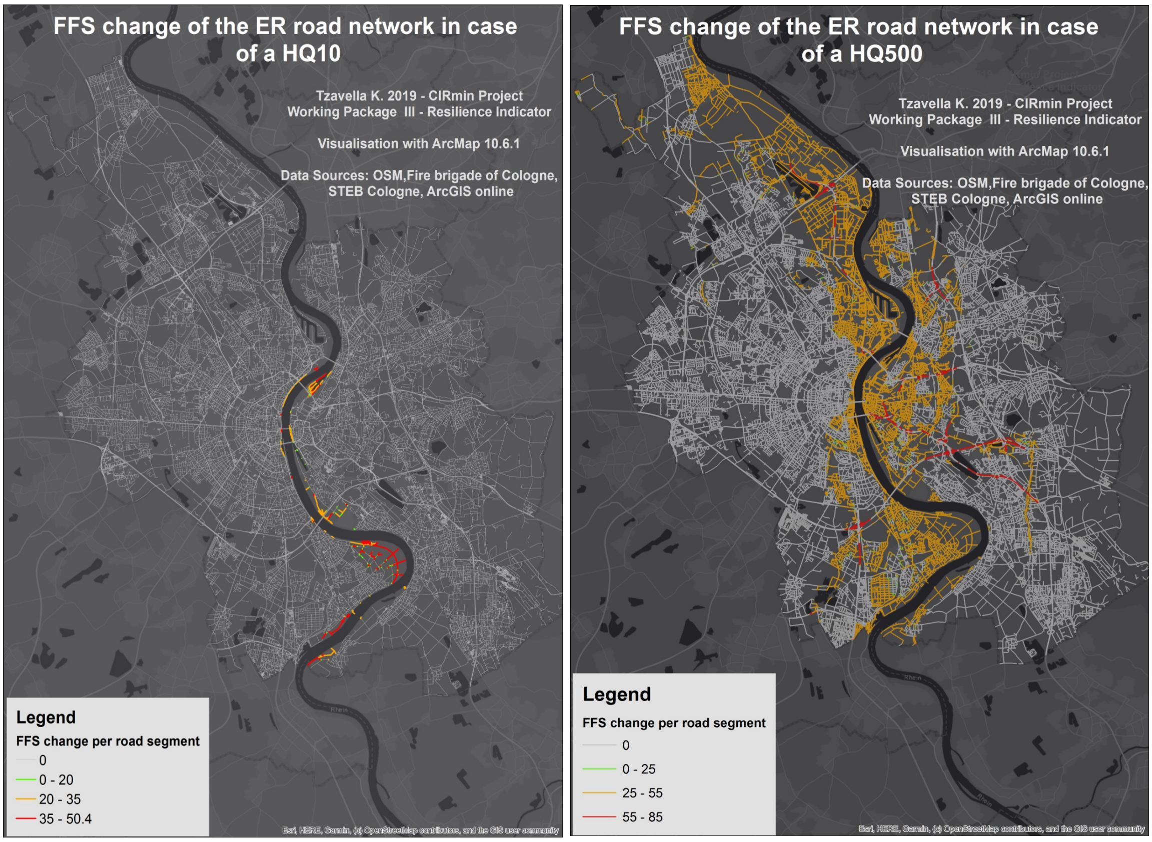


Figure 38: Geolocated vulnerability (classified FFS_{change} in km/h) of the road network to a HQ10 (left) and a HQ500 (right) for timely ER provision in Cologne (see enlarged in APPENDIX B)

To answer RQ5 and numerical analysis, the classified results are summarised in the geodatabase and transferred in Excel files where graphs are created. In Figure 39, the sub-indicator of the road network mobility capacity (RNMC) is assessed per FD class for each riverine scenario, and the levels of the redundancy of the ER road network are classified. In this way, the free flow speed (FFS) changes according to the flood depth (FD) impact indicate the endogenous redundancy of the road transport system. Aggregation of information from a road segment to the road network is achieved by calculating the road network length in km that is flood-impacted on its traffic characteristics, i.e. the speeds (second-order riverine flood impacts on the road network).

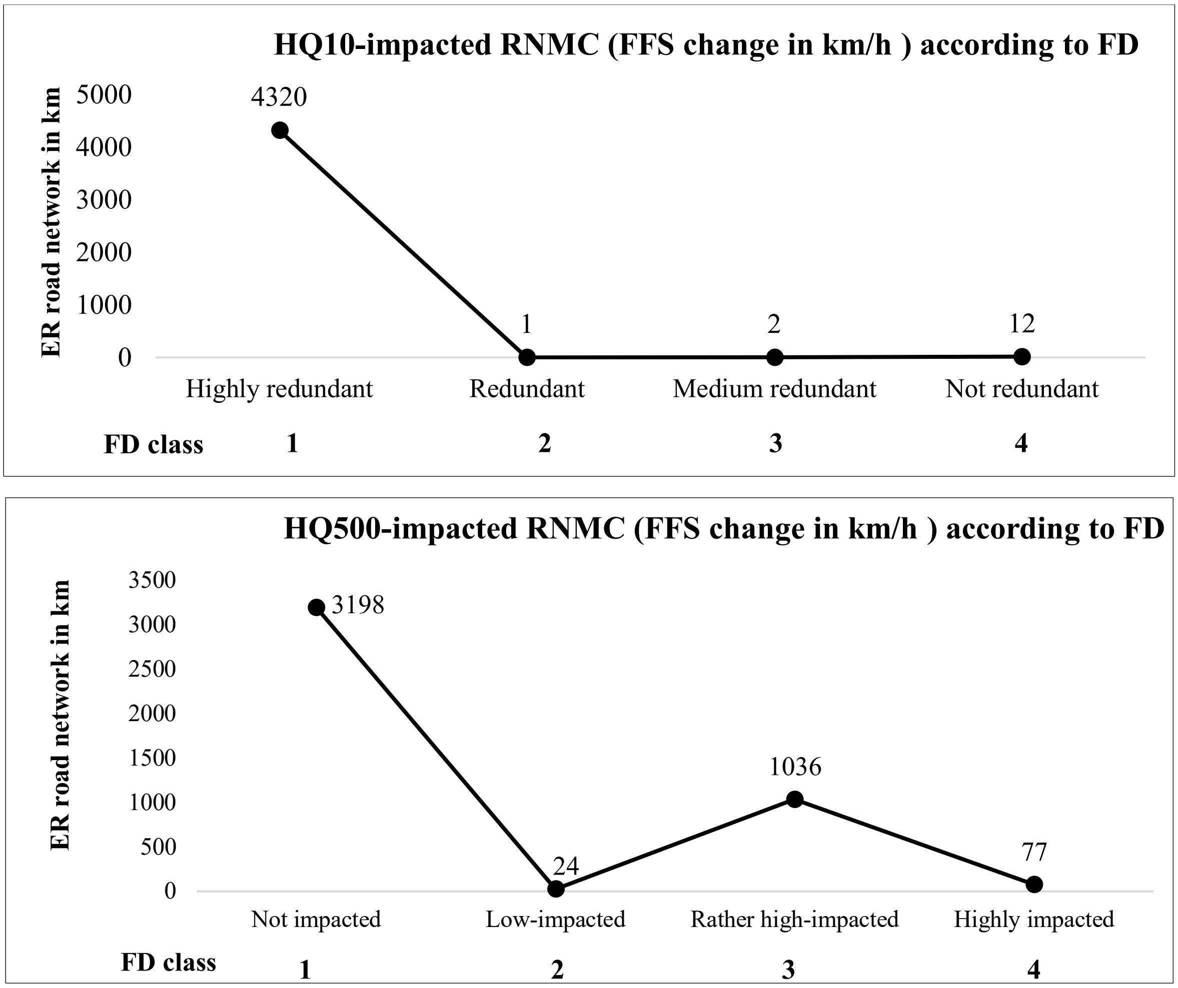


Figure 39: RNMC levels of the ER road network per FD class (classified FFS_{change} in km/h) in case of a HQ10 (above) and a HQ500 (below), reflecting its endogenous redundancy

The road network mobility capacity (RNMC) that is ***unaffected/not impacted*** by the riverine floods is identified in the case of the HQ10 for 4320.10 km and the HQ500 for 3198 km; a decrease of 26% of unaffected ER road network length from the HQ10 to the HQ500. The ***unaffected/not impacted road network***, according to the fuzzification suggested in Table 4, is characterised as ***drivable, and no transformation*** takes place for ER purposes; therefore, it keeps the ER road-type dependent speed attributes before the floods (ERPS of Cologne's fire brigades) and is characterised, as ***highly redundant*** for timely ER provision (zero FFS_{change}).

The ***low impact*** of the riverine floods to the FFS of the road network ranging from 0-20 km/h in the case of the HQ10 is identified for 1 km, and the HQ500 from 0-25 km/h for 24 km, with an increase of 4% of more road segments with $FFS_{j\ change}$.
Low-impacted road segments are still ***drivable with expected delays (low impedance)*** since the transformations after the absorption of the impact of the FDs is at a low level and not expected to affect the times of ER with significant delays higher than 1 minute; therefore, these road segments are characterised as ***redundant*** for timely ER provision. The ***rather high*** $FFS_{j\ change}$ is observed for the HQ10 and 2.38 km of the road network and the HQ500 for 1036 km, with 43% road network $FFS_{j\ change}$. Rather high impacted mobility of the road network means that the absorption of the FD has led to the ***transformation of the road segments to walking paths***.

That is, the drivability of the rescue vehicles through these road segments is still possible but with the minimum FFS (walking speed 2.0748 km/h according to PR) and therefore, these road segments are characterised as ***medium redundant*** (FFS_{change} 25 km/h - 52 km/h). The ***higher*** impacted $FFS_{j\ change}$ is identified for the HQ10 for 12.23 km road length and the HQ500 for 77 km road length with a significant increase (as expected from the increasing trend of exposure analysed in the previous section) of 530% of more road segments with the highest $FFS_{j\ change}$. These road segments are characterised as ***blocked***, hindering the ER; therefore, they are ***not redundant*** for ER purposes.

Moving further for the redundancy operationalisation of the road networks after the selected low- and high-intensity riverine floods, the ***percentage change of FFS*** for ER provision (percentage increase and decrease) is presented in Figure 40, resulting from the ***impact*** of the riverine floods of Cologne on the ***RNMC***, reflected on ***the redundancy levels***. The results and the relation between the sub-indicator of the RNMC and the ***redundancy*** are discussed in section 3.2.

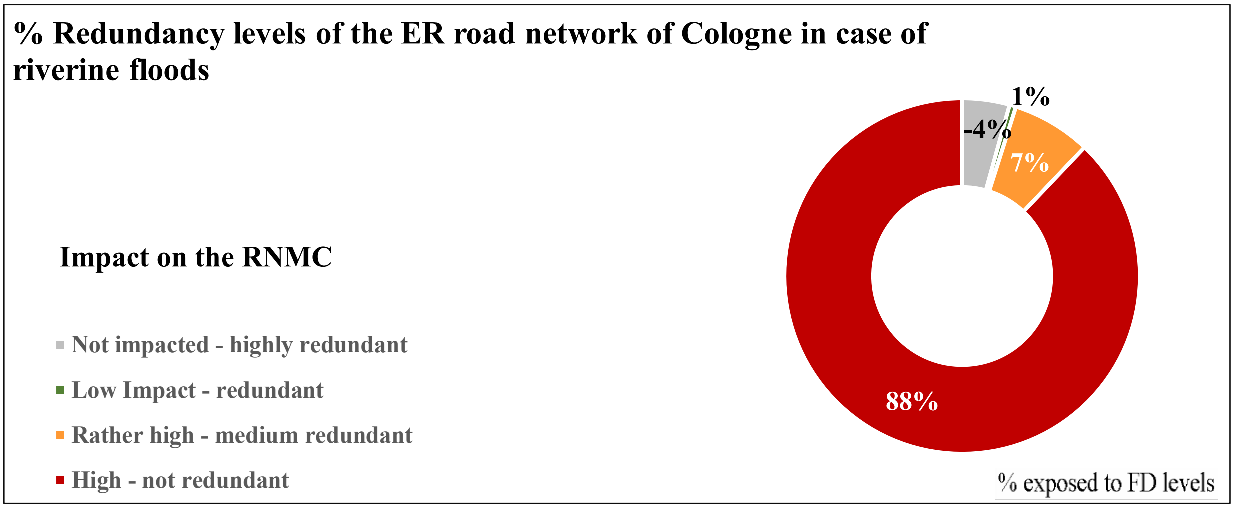


Figure 40: Percentage redundancy levels, according to the RNMC levels per FD class, for timely ER in case of escalating riverine floods from a HQ10 to a HQ500

Proceeding with the implementation of the methodology to the regular scenario of flash floods T20 and the extreme scenario of flash floods T100, the results are presented in Figure 41. The scenarios of flash floods are flood models (rasters) providing information on FD for the entire case study, due to the phenomenon of flash floods, which results from intense rainfall, expected to affect the entire road network's FFS and thus its mobility capacity for safe and timely ER provision in different levels. With GIS, the visualisation of the results with the classification of the different levels of the impact of the FD to the FFS in four classes in the geodatabase of each occurring flash flood road network in ArcMap 10.6.1 is possible.

The results are visualisations of the transformed road segments for timely ER, indicating the potential criticality of road segments for network disruptions decreasing the performance of ER (RQ7). The ***not impacted*** FFS_j that is $FFS_{j\ change}$ equal to zero is presented with a *grey colour*, with *green colour* is the $FFS_{j\ change}$ of ***low*** level, and *orange* and *red* are the two different classes, representing the $FFS_{j\ change}$ of ***high*** levels, named ***rather high*** and ***high*** accordingly.

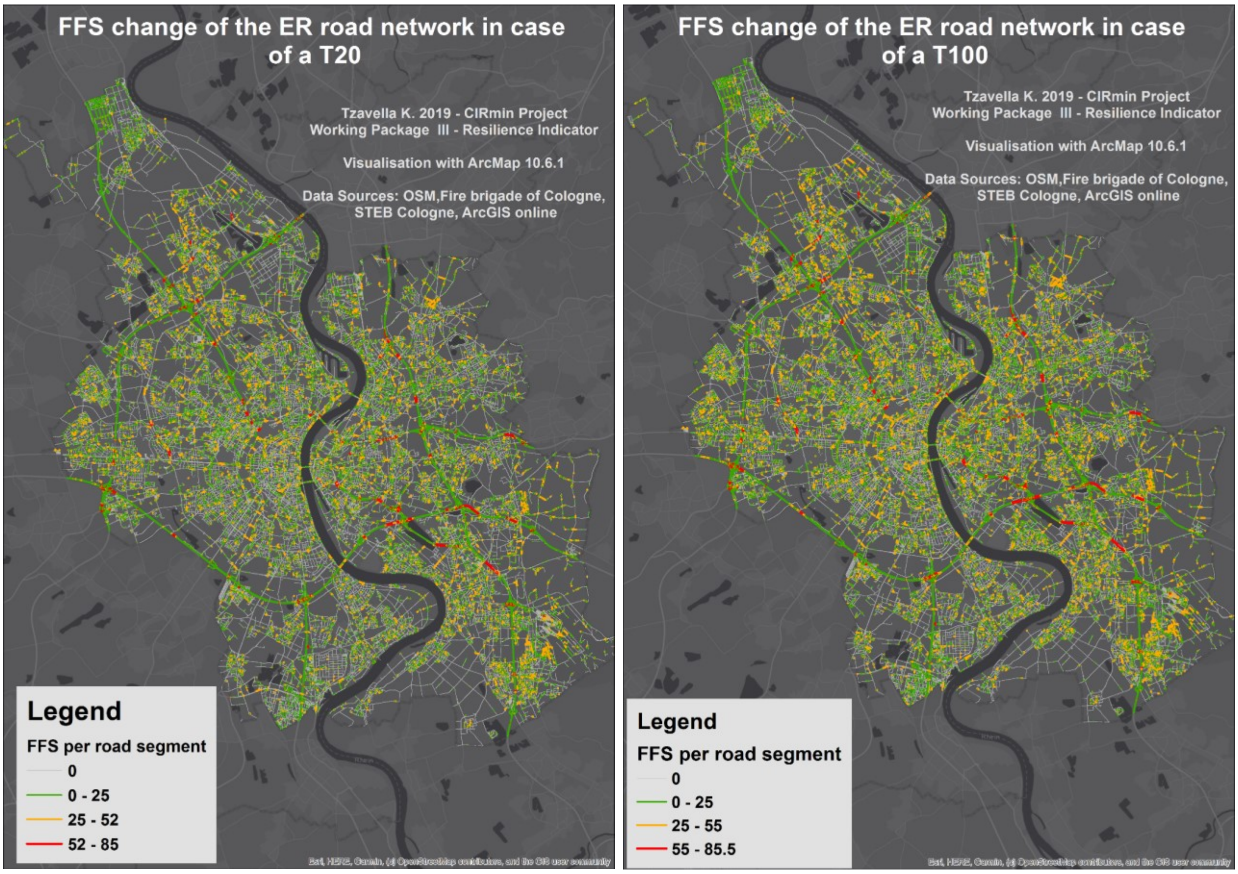


Figure 41: Geolocated vulnerability (classified $\mathrm{FFS}_{\mathrm{change}}$ in km/h) of the road network to a T20 (left) and a T100 (right) for delayed or incapacitated ER provision in Cologne (see enlarged in APPENDIX B)

For an overall overview of the RNMC levels of the entire road network, the changes in the FFS per road segment are summarised in the geodatabase of each flash flood risk-informative road network, with the GIS-Toolkit. The results are transferred into Microsoft Excel to produce graphs and information aggregation from a road segment level to a road network level. Specifically, the graphs provide additional information for a clearer understanding of the indirect impact of the FD of various intensities of flash floods on the FFS of the road network, on a large-scale (network level), towards safe driving of rescue vehicles (RNMC for ER). As mentioned in section 3.2, the vulnerability of the road network to flood disruptions in its traffic characteristics is assessed with the geolocated flood-impacted FFS. In Figure 42, there are representations of the $\mathrm{FFS}_{\mathrm{j\ change}}$ and the level of the RNMC for ER purposes in the case of each selected flash flood scenario. The two flash flood scenarios have the same maxima of impacted FFS (approx.85 km/h), which indicates that the two flash flood scenarios, even though they are of two different intensities (regular and extreme), can both have the same impact on specific road segments, i.e. high impact on the FFS towards blockage of ER provision.

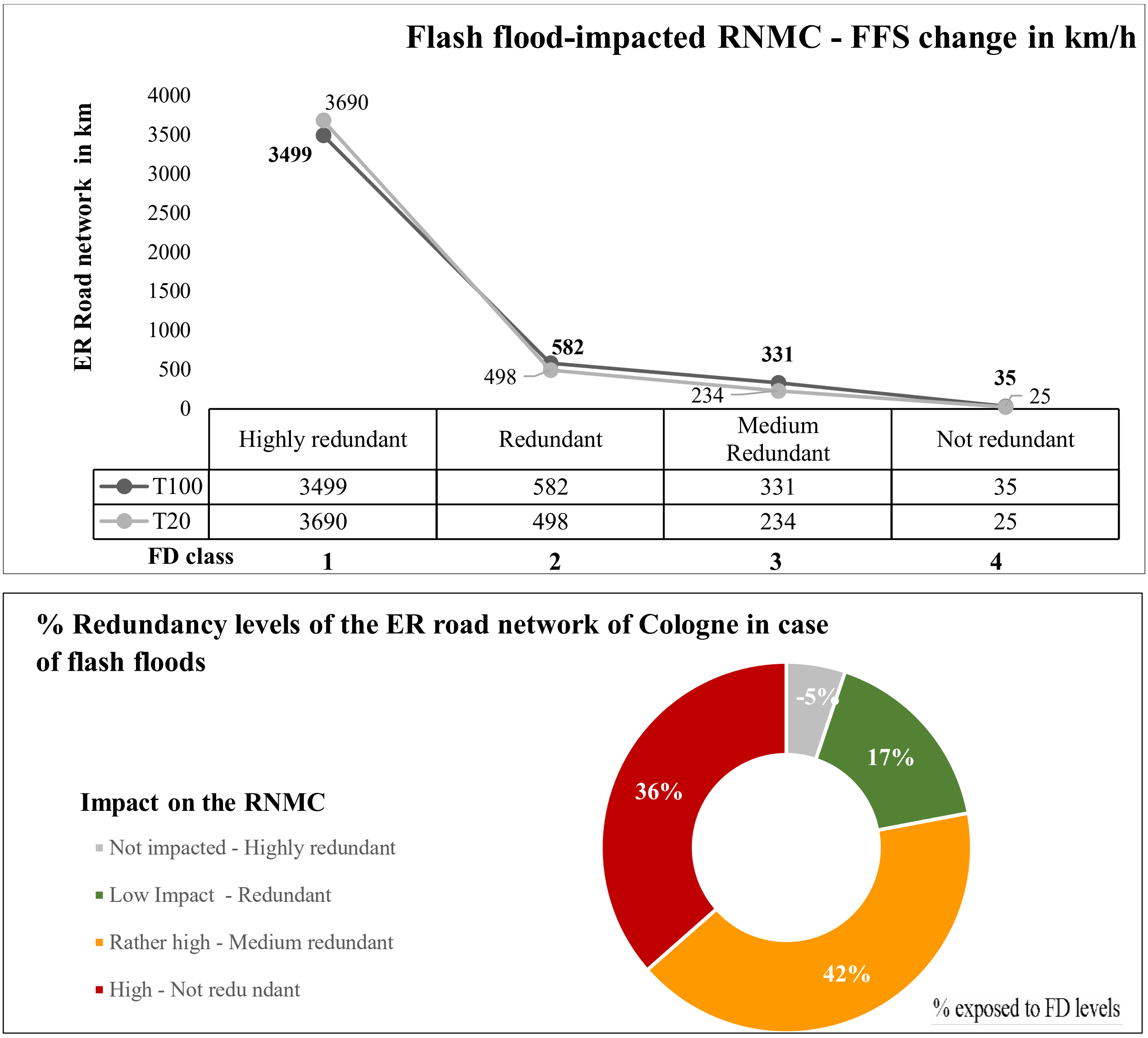


Figure 42: RNMC levels of the ER road network, in km, per FD class (classified FFS_{change} in km/h) in case of a T20 and a T100, reflecting its redundancy for timely ER (above), and % redundancy in case of escalating floods from a T20 to a T100 (below)

In Figure 42, the length of the road segments is summarised in kilometres, with summarization tools of ArcMap 10.6.1 in the geodatabases of each updated road network after exposure to each of the selected flash flood scenarios. According to the fuzzification suggested in Table 4, the $FFS_{j\ change}$ is classified and summarised.

Specifically, ***drivable*** road segments, that is, road segments with no FFS impact (***unaffected-not impacted***) in case of the T20 are of 3690 km length and the T100 of 3499 km length, with an observed 5% decrease in the ***high redundancy***.

Still ***drivable*** but expected to ***affect the ER with insignificant delays*** are the ***low-impacted*** road segments up to 25 km/h, 498 km length for the T20 and 582 km length for the T100;17% ***redundancy*** increase.

Rather high impacted FFS is identified for road segments in case of the T20 in 234 km of road and the T100 in 331 km of road length that is 41.66% more road segments, which are transformed and characterised as ***drivable with the minimum speed*** (walking speed 2.0748 km/h according to PR).

This transformation further adapts the FFS in ranges between 25 km/h and 55 km/hare ***medium redundant***.

High impact on FFS is identified in the case of the T20 for 25 km of road and the T100 for 35 km, that is a 36 % increase of road segments with the highest $FFS_{j\ change}$ (55-85 km/h) for road segments which are ***blocked*** and therefore, characterised as ***not redundant***.

7.2.1 Discussions of the Redundancy

The road networks are becoming increasingly vulnerable to various unforeseen scenarios such as EWE-triggered disasters and other emergencies, which cause disruptions that affect directly several aspects of the road network, i.e. traffic flow and network connectivity (see Figure 7). Recovering from such disruptions becomes more complex over time due to changing demands in the network flows on a large scale, which can directly affect the connectivity of the entire network (see section 3.2). For an answer to the RQ3, the suggested RITAI indicator (Figure 11), from a safety and security engineering perspective towards ERR to adverse weather events (floods) and as applied to the Cologne fire brigade system, combines methods used in the transport network resilience and CI protection domains, for the assessment and operationalisation of their impacts to the ER road network, utilising the traffic and graph theory together with the network science. In particular, speed (section 3.2) and travel time (section 3.3) are the traffic properties considered. Other traffic properties, such as traffic volume, traffic demand, and congestions, are usually not considered in ER planning since it is expected that the drivers will assist free-flow driving of the rescue vehicles in case of emergencies (*result from interviewing fire brigade officials*). Answering the RQ4 and from a system engineering perspective (network design), the suggested methodology introduces the RNMC as a metric for the redundancy of the road segments and the road network for timely ER under flooded conditions (see definition in section 3.2). The suggested measure of the sub-indicator of the road network's redundancy in case of floods, measured on a road segment level, indicates the adaptation and transformation capacity of the road segments, after absorption of the direct flood impact, towards timely ER. To answer RQ5, the FFS changes in the ER road network are calculated and assigned to each predefined road segment in the geodatabases of each updated ER road network in case of each understudy flood scenario - transformed road network for ER purposes under flooded conditions. As displayed in Figure 37, GIS applications allow for detailed calculations and visualisations of the change of the FFS (Figure 38 - riverine floods, Figure 41 - flash floods), and indirect damage of floods to the network for:

- the identification of the critical (more vulnerable) segments of the road for ER delivery through calculations conducted on predefined road segments,
- the quantification of the RNMC for timely ER provision
- the large-scale visualisations providing geolocated road network mobility capacity for ER planning and
- the quantification of the road segment redundancy in the case of floods allows for further analyses towards the operationalisation of the urban ERR.

When answering the RQ4 and from an indirect impact assessment perspective, the methodology proposes ***redundancy operationalisation via vulnerability assessments of the ER road network*** by measuring the impact of different flood scenarios of different types and intensities in the urban complex environment Cologne. The application of the methodology results in the quantification of the redundancy of the ER road network between the selected riverine floods of HQ10 (regular) and

HQ500 (extreme), revealing the redundancy trend occurring from the calculated changes in RNMC between the two impacted ER road networks. The trend reveals the various levels of the ER road network's redundancies for timely ER under different intensities of riverine floods.

Therefore, as shown in Figure 42, there is a 4% decrease of high redundancy between the two selected scenarios for the riverine floods. That is, 4% less of the road network of Cologne that will allow timely ER with undisrupted driving mobility in case of riverine floods. The ***rather high*** redundancy levels are increased by 1%, which means an increase in the RNMC, but with expected low-impact delays in the ER.

Furthermore, a 7% increase in the low redundant road network length is observed, which still allows for safe mobility of the rescue vehicles under flooded conditions, but it is expected to add high delays in the ER provision. Lastly, an 88% increase of the length (in kilometres) of the not redundant ER road network after the occurrence of the riverine floods is 88% more of the road that does not allow safe driving mobility under flooded conditions. A blocked and not redundant road ER road network is the ER road network not reliable for participation in the ER route planning in case of deployments in the face of floods.

For the scenario of the flash floods (Figure 44), the quantification of the redundancy of the ER road network to flash floods per road segment revealed that between the two selected scenarios of regular (T20) and extreme (T100), there is a 5% decrease of ***high redundant road segments*** for ER route planning and timely ER. On the other hand, there is a 17% increase of the ***rather high*** redundant road segments; that is, there is an increase to the road segments that will still allow for undisrupted and mobile stable and safe driving under flash flood conditions but with the addition of minimum delays (< 1 minute). Furthermore, there is a 42% increase of ***low redundant road segments,*** which still allow safe driving mobility after transformation to walking paths (see Table 4), but on the other hand, they are adding significant delays to the ER delivery. Finally, there is a 36% increase of blocked ER road network, which is ***not redundant*** for timely ER under flash flood conditions.

A non-linear analogous relation between the RNMC (vulnerability) changes, the redundancy of the road network, and the FD (exposure) is observed. The higher the urban RNMC under flooded conditions, the higher the redundancy of the urban ER road network for timely ER under flooded conditions, as presented in Figure 42 and Figure 44. Identification of redundant roads segments to floods would be helpful in the reduction of travel costs and also serve as a guide for prioritization of measures to be taken during and in the case of floods (e.g. choice of redundant road segments for provision of timely ER, timely transfer of equipment such as rescue boats for evacuation purposes and medical ER provision to vulnerable groups of the population). As previously mentioned, in the design of the technical systems, such as the design of ER road networks for timely ER towards operationalisation of the ERR in the urban complex city of Cologne, the quantification of the redundancy can serve as a reliability indicator [320].

According to this notion, in the next session, reliability quantifications will occur, considering the quantifications of the redundancy metric, the RNMC. Since the ER road networks in case of floods are designed for timely ER, the quantification factor of the reliability will be travel, calculating the travel costs of each road segment to the ER. When answering the RQ7, geovisualisation techniques with the statistical analytics for each flood scenario and compound events resulting in maps of high-resolution information and flood impact curves strengthen the preparedness for response and enhance the resilience of the urban ER system. For this reason, the updated risk-informed ER road network databases can not only provide a deepened understanding of the indirect flood impacts on the traffic characteristics of the urban ER system in many scales and levels but can also enable route planning through redundant and reliable road segments for timely ER provision. In this way, critical areas that need further attention from the civil protection authorities are revealed, and awareness of the population is enhanced, boosting community resilience.

7.3 Resourcefulness Under Flood Conditions

This section aims to answer the RQ questions RQ3, RQ4, RQ5, RQ7, with a presentation of the results of the urban flood travel-time reliability (UFTTR) assessments of the ER road network of Cologne to the different selected scenarios of floods, for timely ER, towards operationalisation of the ERR of the fire brigade system. With the selected stressor of floods to the fire brigade system and large-scale exposure and vulnerability assessments on the traffic characteristic of FFS, the goal is also to identify their impact on the travel time of the ER road network (mobility characteristic). More specifically, the RITAI indicator (Figure 11) suggests a further large-scale identification of the ER road network's adaptability levels, through local vulnerability assessments, based on the identification of the flood impacts on the mobility characteristic of the travel time, dependent on the network redundancy (adaptation and transformation) assessments, presented in section 7.2. Impacts on the travel time reflect the resourcefulness levels of the ER road network, depicted on the levels of risk for delayed or blocked ER provision (see section 3.3). Table 11 is a part of the RITAI indicator (Table 3), presenting the ERR features, sub-indicators, metrics, and expected outcomes from the suggested operationalisation process with GIS (Figure 13).

Table 11: Large-scale resourcefulness operationalisation for the ERR of Cologne's fire brigade system, to floods

Features	Sub-Indicators	Metric	Outcome
Resourcefulness	**Transformation capacity** Road Network and ERS Travel Time Reliability	Travel time change and impacted travel time reflecting on the travel time reliability (TTR) of the road segments	▪ Calculation of impacted travel-time (per scale of analysis) ▪ Comparison analysis of TTR (per scale of analysis) ▪ Geovisualisation of information on the entire road network(maps) ▪ Flood intensity impact curves of the whole network and analysis after fuzzification regarding the road network's safe driving mobility for ER rescue vehicles

Answering the RQ3, in the ERR concept, which incorporates CAS thinking in the resilience assessment, the study under research is the ER road network, which is segmented into 1 m segments (normalisation), as suggested from the RITAI indicator (see section 4.1) and the operationalisation methodology in GIS (Figure 13). Therefore, satisfactory functionality of the road segment, i.e. the timely provision of ER under flooded conditions, is analogous to the reliability of the road segment itself regarding the undisrupted travel throughout the segment. More specifically, undisrupted travel occurs when there is no travel time impedance under the stressor of floods (see section 4.1).

Travel time impedances, i.e. additional travel time costs *(function 9)* due to perturbations of floods, are assigned to each road segment in the road network segments after consideration of the flood-impacted FFS (see section 3.2). So to answer the RQ4, the timely ER is achieved with ER delivery within defined time thresholds from each ERS and therefore, it is argued that travel time reliable road segments enhance the resourcefulness of the ER road network by providing the means/resources for alternatives (active redundancy) towards rapidity of response (timely ER - accessibility).

It is further argued that the TTR of the road segments determines the resourcefulness levels of the ER road networks impacted by the selected floods (for the definition of resourceful road segments, see section 3.3). The resourcefulness of a road network is quantified with the metric of the TTR, taking into consideration the redundancy of the ER road network for timely ER, adding the risk factor in the analyses. In the ERR concept, the reliability of an ER road network can be defined as the probability that a road segment will provide timely ER under flooded conditions, according to the redundancy (see section 3.3). Redundancy quantifications carry the factor of vulnerability in the context of degradation of serviceability of the road segment for timely ER due to a decrease of the RNMC (see section 3.2). Additionally, and to answer the RQ5, the methodology also suggests the UFTTR, as defined in section 3.3, as a sub-indicator providing results on a network level (zoom-out effect from a large-scale). The UFTTR is indicative of the travel-time reliability of the road segments and resourcefulness of the ER road network for the provision of timely ER, integrating the risk factor in the analyses, towards operationalisation of the ERR of the fire brigade system, under the stressor of floods.

The measurements result after implementing *function 8*, where the travel time of each road segment is calculated by subtracting the $\text{TravelTime}_{j\,(AF)}$ from the $\text{TravelTime}_{j\,(BF)}$. So, to answer the RQ7, the calculations take place in the road network databases, resulting in updated road segments with flood-impacted travel times, for further risk-based time-dependent accessibility assessments towards ERR operationalisation in the next section. For the presentation of results, when $\text{TravelTime}_{j\,(AF)}$ is higher or equal to $\text{TravelTime}_{j\,(BF)}$, the resulting values are **lower than zero and equal to zero accordingly; therefore, fuzzification is essential**. The distinction between zero, as the indicative value of non-reliable road segments and reliable ones is needed. For example, after the negative impact of the selected floods on the FFS_j for some road segments, the $\text{FFS}_{j\,AF}$ and the UFTTR are equal to zero. Where the negative impact of the high FDs to the FFS_j, has transformed the road segments to non-drivable/blocked/not redundant, there is no value for calculations for the $\text{TTR}_{j\,AF}$ (*analogous relation between redundancy and reliability of the road network*), indicative of the resourcefulness of the road network in case of floods.

The value of **zero can also indicate the high travel time reliability** of the road network segments for the selected flood scenarios. Therefore, to avoid confusion, and for further analysis purposes, **zero** for the reliable road segments **is replaced with the value 100** (one hundred).

Table 12: Urban Flood Travel Time Reliability per road segment (UFTTR$_j$) fuzzification enabling decision-making - Adapted according to Table 4.

Flood Depth FD$_j$	**Drivability of the road segments in case of floods (Absorption) –** FFS$_{j\ AF}$	**Numerical classification of changes in the travel time (per hour)** UFTTR$_j$	**Linguistic classification of** UFTTR$_j$ **&** **the impact on ER**
≤ 0.3 m	Drivable	100	***Reliable*** **(+ positive impact - timely ER)**
0.3 m – 0.5 m	Drivable with impedance at minimum FFS$_j$ (walking speed)	0 – 0.028 minutes/per 1 m	***Medium Reliable*** **(- negative impact - delayed ER)**
≥ 0.5 m	Blocked	0	***Not Reliable*** **(- - negative impact - no ER)**

After adding a new field for integrating values of the UFTTR and the classification in three classes followed with ArcMap's classification tools, the calculations took place in the updated road network databases, considering the FD$_j$. The visualised results for the urban flood travel time reliability per road segment (UFTTR$_j$) of Cologne for each flood scenario are presented in Figure 43.

For a numerical comparison of the Urban Flood Travel Time Reliability per road segment (UFTTR$_j$) considering the two riverine flood scenarios of HQ10 and HQ500 and the two flash flood scenarios, fuzzification is conducted. Specifically, the **linguistic variables *not reliable (red colour), medium reliable (yellow colour), reliable (green colour)*** are assigned for the three numerical classes, delimited according to the FD$_j$ as presented in Table 12. For example, ***medium reliable*** are characterised road segments that are ***still drivable***, but their FFS is transformed to walking speed (medium redundant), and therefore, their TTR is hindered to the reliability of a walking path; ***still drivable but expected to add significant drive time impedance (an increase of travel cost)***. Walking paths are usually not selected for ER route planning, but under flood situations, the drivability through flooded road networks may be essential for the accessibility of the population or different CI (hospitals, schools, elderly homes, etc.).

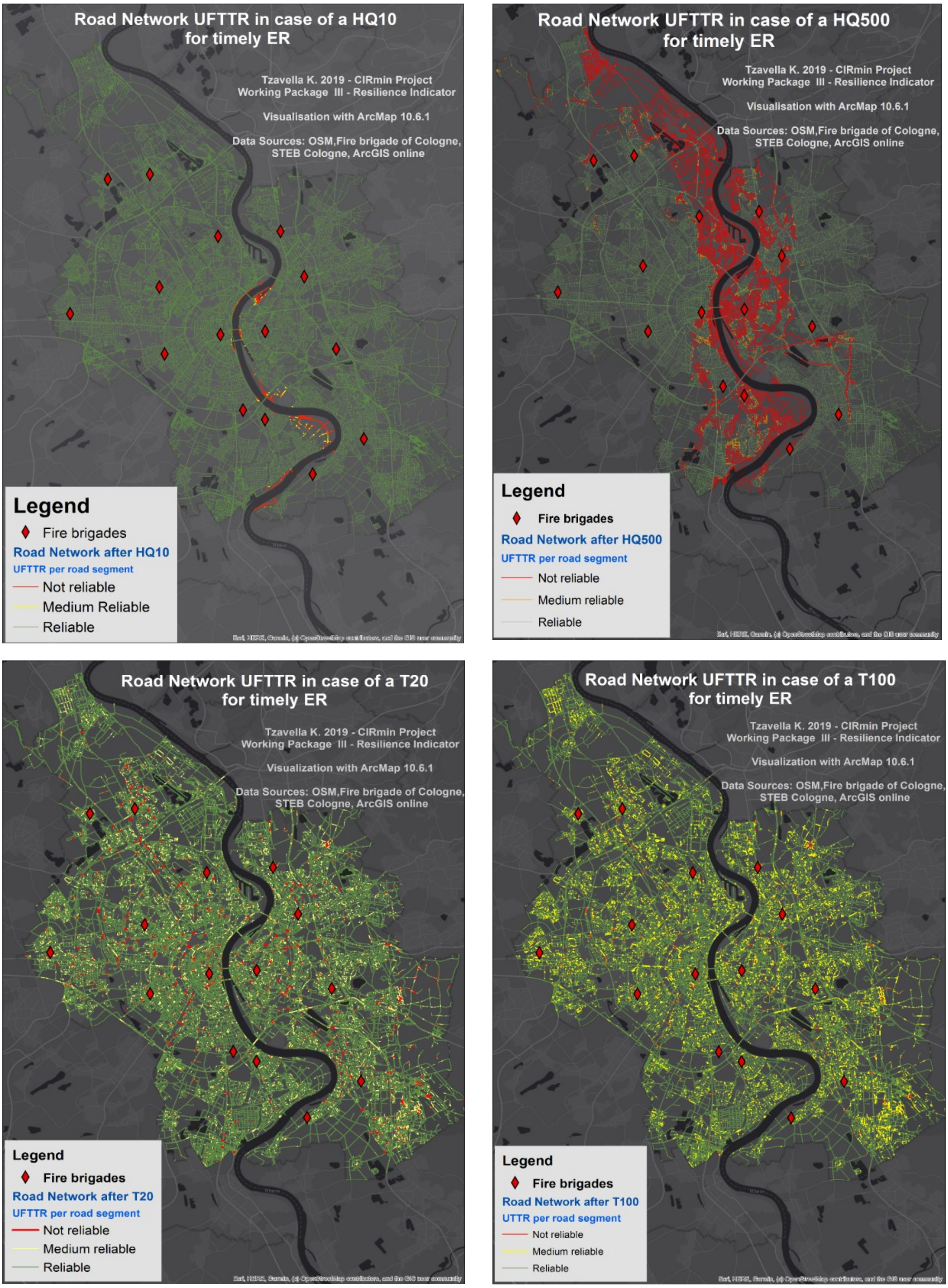
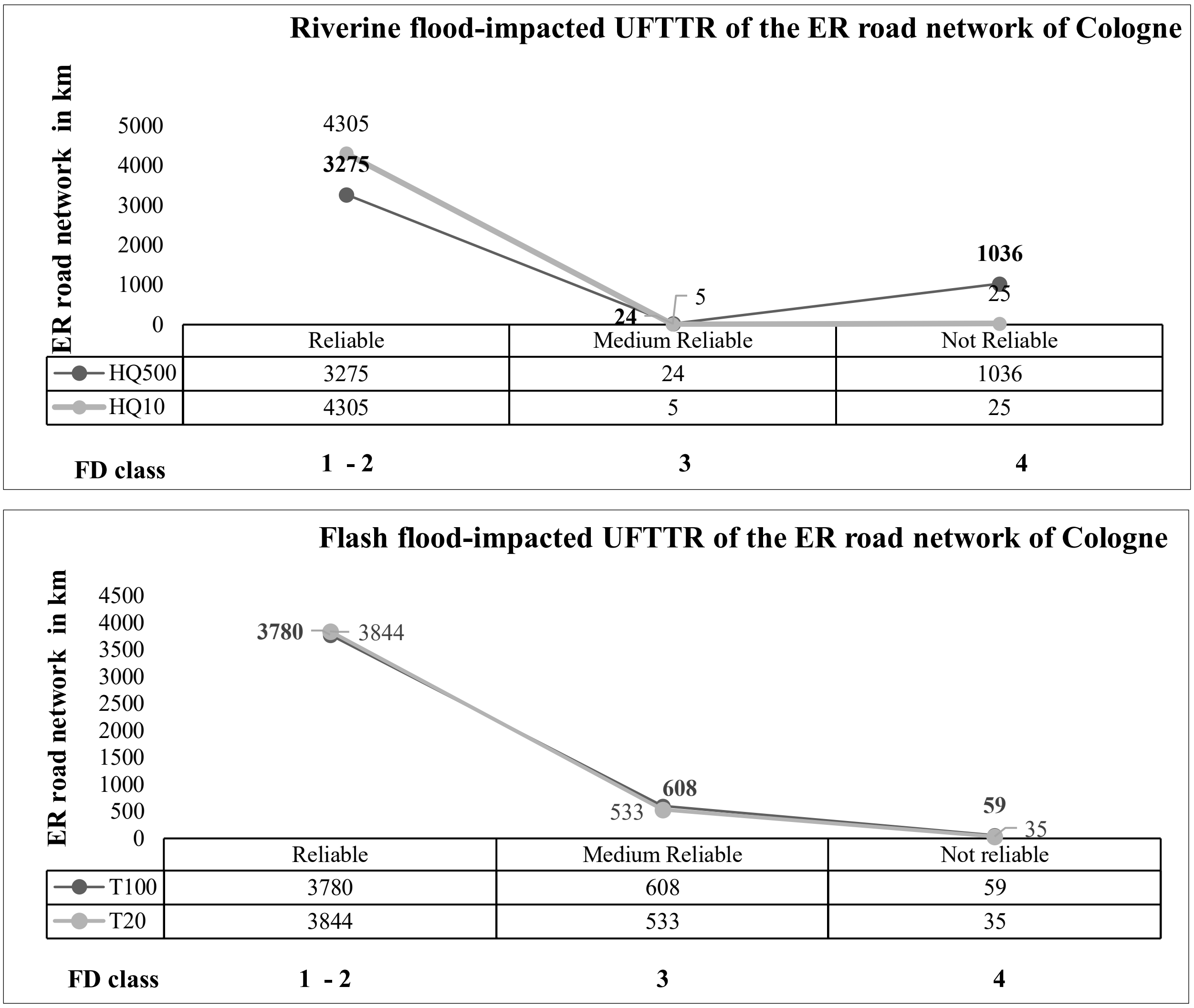


Figure 43: Geolocated classified UFTTR$_j$ of Cologne's ER road network in case of a HQ10 (upper left), a HQ500 (upper right), a T20 (bottom left) and a T100 (bottom right) (see enlarged in APPENDIX B)

With the provision of the information through databases and maps, the respective ERS can include these road segments in their ER route planning, considering additional travel costs or exclude them.

Nevertheless, the visualised results also provide a tool for quick identification of the degradation of serviceability of the ER road transport system (critical ER road segments) for timely ER provision, which allows for prioritisation of the ER delivery through alternate route paths.

The use of GIS and the configuration of the GIS-Toolkit (Figure 15) enables the integration of traffic characteristics to different (configurable) scales, in combination with the flood impact information on the RNMC for timely ER (Figure 14). The UFTTR$_j$ is calculated in the geodatabase of each flood-risk informed updated road network for each flood scenario. The results are transferred to Microsoft Excel for the production of Figure 44. The aim is to provide additional information for an overview of the impact of the FD of the riverine and flash floods on the FFS of the road network and the UFTTR$_j$ (free-flow-based TTR measurement of each road segment). Figure 44 presents a comparison of the UFTTR$_j$ after the potential occurrence of each selected riverine and flash flood scenario, considering the two selected intensities (regular and extreme).


Riverine flood-impacted UFTTR of the ER road network of Cologne

	Reliable	Medium Reliable	Not Reliable
HQ500	3275	24	1036
HQ10	4305	5	25

Flash flood-impacted UFTTR of the ER road network of Cologne

	Reliable	Medium Reliable	Not reliable
T100	3780	608	59
T20	3844	533	35

Figure 44: Aggregated flood-impacted UFTTR levels for the ER road network in km per FD class in the case of the HQ10 and the HQ500 (above) and the T20 and T100 (below)

In Figure 44, the length of the road segments is summarised in kilometres, with summarization tools from ArcMap 10.6.1 in the flood risk-informative ER road network databases for each of the selected flood scenarios. The results reflect the resourcefulness of the ER road network for travel time reliable ER routes for timely ER provision.

The aggregated information on the flood-impacted intraurban UFTTR is classified and summarised as follows:

- ***Reliable*** road network length in kilometres for ER purposes, ***with no travel time impact*** in case of the riverine flood scenarios HQ10 and HQ500, is identified with a decrease of 24%. Between the flash flood scenario of T20 and the flash flood of T100, there is a 2% decrease in reliable road network length. As defined in this thesis, a reliable road network is the road network that a high number of its components (i.e. road segments) will provide the means for ER under flooded conditions depending on the RNMC (passive redundancy) levels. For this reason, the ER road network is also characterised as ***resourceful*** since, due to *its* **high redundancy, it will provide more resources to the fire brigade of the system in regards to alternatives for timely ER (enhanced rapidity of response).**
- ***Medium reliable*** road network length between the riverine flood scenarios HQ10 and HQ500 is identified with a significant increase of 395%. As expected, in the extreme flood of HQ500, more of the road network (summed in km) is transformed into ***walking paths***, ***adding significant travel costs to the ER delivery***. For the flash flood scenarios, the medium reliable road length is increased by 14% between T20 and T100 (extreme flash flood scenarios). The ***medium resourceful*** ER road network is the road network that still allows for safe drivability but enhances the travel costs (high impedance in the response operations). It is argued that medium redundant and medium resourceful road segments, i.e. road network, even though it is enhancing the response time and degrading the serviceability of the fire brigade system, it extends its response capacity, accepting that the system is working under sub-optimal conditions and 'in the edge of risk'. This addition of redundancy and resourcefulness is valuable for emergency rescue operations since it expands the ERR curve, leaving space for improvement towards high levels of ERR.
- ***Not reliable*** road network length that is ***blocked and not drivabl***e is identified with an enormous increase of 3999% between the two riverine flood scenarios. This increase of not reliable road length is expected, since, in the case of the regular scenario of HQ10, the exposure of the road network to high FDs is very low, increasing the results of the subtraction and thus the percentage of the increase of the value of the road length in kilometres. In the case of flash floods, the increase of the not reliable/blocked road network for timely ER is 67%. These road network lengths are characterised as not reliable, are ***not resourceful*** and **should be avoided for ER provision.**

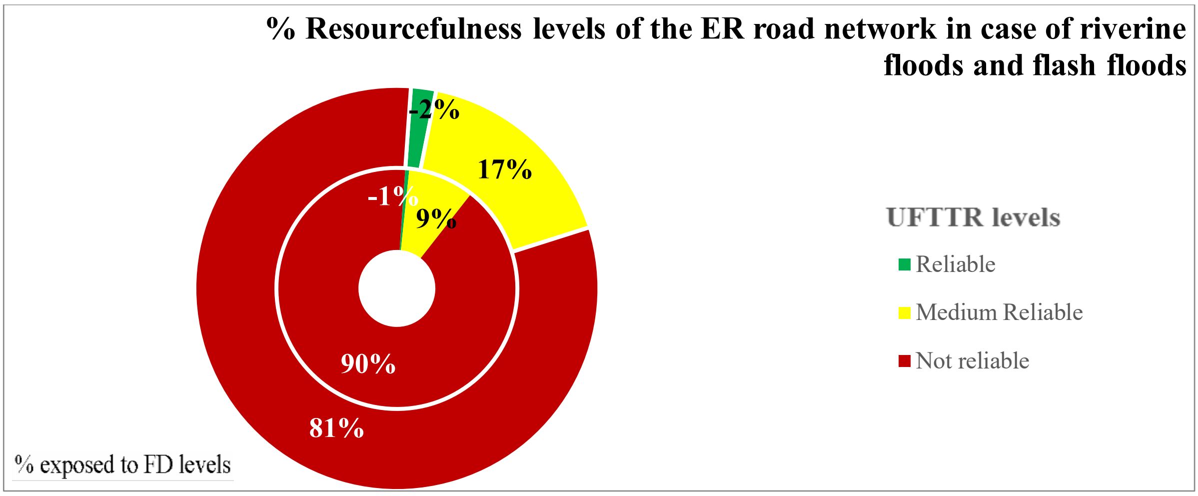


Figure 45: Percentage levels of flash flood-impacted (outer doughnut) and riverine flood-impacted (inner doughnut) resourcefulness of the ER road network according to UFTTR levels in case of escalating flood events

In Figure 45, the percentage levels of resourcefulness according to UFTTR in case of escalation of the selected riverine and flash floods of different intensities are displayed. That is, the ER road network databases are updated on a large scale, with information on the levels of risk for delayed or blocked ER (disruptions) reflected on the UFTTR levels in case of compound or escalating flood events.

7.3.1 Discussions of the Resourcefulness

As presented in section 3.3, from a network perspective, it is argued that vulnerability is a factor for the susceptibility of a network or a system's element for failures, i.e. considerable deviations from their normal functioning state [322], on several levels. The vulnerability can also be considered the probability of susceptibility for non-serviceability [146, 323, 324] or the probability of incidents causing disruptions [327]. As applied to the Cologne fire brigade system in the ERR concept, non-serviceability occurs from rescue operations with unreliable and not resourceful ER road networks/segments. As presented in section 3.3, reliability is a commonly used term and a "*desired function to an acceptable level of performance for some given period*" [141]. In the ERR concept, the desired function is the undisrupted critical functionality of an ER road network, and a desirable state is the ER provision and undisrupted serviceability aiming to a timely ER. So to answer the RQ3, an ill-functioning road segment will appoint costs on the emergency rescue deployments in terms of loss of time, higher costs of fuel consumption (in case of rerouting due to road failures), or other costs as a result of delays and diversions.

Identifying ill-functioning or non-functioning ER road segments, with the suggested methodology in GIS, and answering the RQ4, leads to vulnerability assessments of the ER road network under the stressor of floods, bringing the risk for degraded or blocked ER provision to the forefront. As presented in section 3.2 and 3.3, in the ERR concept, vulnerability is also considered as a two-component concept, in which probability and consequences are the two main attributes, where the probability of susceptibility (reflected on the RNMC - redundancy levels) has a consequence on the serviceability (time reliable road networks - resourcefulness levels). In section 3.3, the reliable road network is defined, considering the literature around the vulnerability of networks and specifically, road networks, where the reliability of an ER road network refers to the functionality levels (i.e. undisrupted travel time) of its components (road segments), under flood conditions. The combinatory node between the term vulnerability and reliability of networks has been suggested from [322]. Reliability is referred to as non-vulnerability (when framed regarding the operability) and, therefore, as reciprocal of the robustness [328, 329]. In the ERR concept, this notion is verified by analysing the results (section 7.1, section 7.2, section 7.3). The results from the exposure assessments depicting the robustness levels of the road segments (Figure 33 and Figure 36) are analogous and directly comparable with the results of the resourcefulness levels according to the UFTTR, which depends on the redundancy levels (RNMC).

From a visual interpretation, it is observed that the road segments, which are characterised as highly robust for safe driving with undisrupted mobility (drivable), are those, which are characterised as reliable, providing the means for timely ER. The characterised road segments are deemed reliable and have unaffected/not impacted FFS from the impact of floods and high RNMC levels, which means redundant road segments for timely ER delivery. In the ERR concept (section 2.1), the satisfactory functionality of the road segment, that is, the provision of ER delivery under flooded conditions, is analogous to the reliability of the road segment itself. This relation can also be verified from other studies oriented to the quantification of disaster resilience. As already proven scientifically, in [222], resourcefulness and redundancy are strongly interrelated in ways that could create more redundancies, which did not exist previously to the occurrence of the stressor to the system. For example, if the fire brigade system needs to operate under flood conditions, for achieving its primary strategic goal, timely ER towards the safety of the population needs to operate with resourceful road segments that provide the resources in regards to reliability for undisrupted (decreased travel time) or, at least, higher travel time (still operable roads).

When answering the RQ4, the operationalisation methodology of the ERR (Figure 13) to floods of the Cologne fire brigade system suggests the utilisation of the graph theory and the network science with applied geoinformatics (section 4). With the developed GIS-Toolkit (Figure 14 and Figure 15), the suggested methodology provides high-resolution large-scale robustness, redundancy, and resourcefulness assessments of the fire brigade system's ER road network and results in flood-risk informed road network databases for each of the selected flood scenarios. The redundancies added from GIS databases are valuable for the enhancement of the rapidity of response feature, but on the other hand, the strong dependence of the use of technology from emergency managers is rendering it as critical [227] for the emergency response delivery; if technology fails or is not secure (hacked). To overcome this and to answer the RQ7, through the suggested methodology, the redundancies added can be critical in case of terrorist attacks or blackouts, which can enhance the resourcefulness of the fire brigade system with the provision of created maps, enhancing their geospatial preparedness, with flood-risk informative maps, towards timely ER provision (see section 3.3). Answering the RQ5, the timely ER (reflected on the rapidity feature of ERR) is achieved with ER delivery within defined time thresholds from each ERS and is dependent on the status of the ER road network (robustness) and its impact on the FFS (redundancy).

Additionally, as stated in section 3.2, the quantification of the redundancy can serve as a reliability indicator when designing a system [320], and therefore, the flood-impacted travel time reliability is calculated according to the flood-impacted FFS. As the RITAI indicator suggests (see section 4.1), taking from the transport network science, where TTR is vital for assessing the performance of an ER road network under the influence of EWE. The concept of resourcefulness during disasters is introduced in emergency management, mainly emphasising on human factors. However, in this thesis, it is argued that the resourcefulness of the fire brigade system can be identified on many different scales and levels of the SoS (i.e. urban ER system). To answer the RQ5, the RITAI suggested for implementation in a GIS environment for the enhancement of the ERR to floods, enables automated calculations of the flood-impacted TTR, through the simple configuration of the GIS-Toolkit (Figure 14), implementing *function 6* and *function 7*, for every selected flood scenario, per road segment, in maps (Figure 40 and Figure 41). The UFTTR is calculated with *function 8* and reveals the geolocated resourcefulness levels of each road segment for timely ER and allows for aggregation of the information for the entire ER road network. Answering the RQ3, together with the visualisations of the quantified robustness and redundancy (sections 8.2 and 8.3), the maps of UFTTR provide the basis for risk-based performance assessments of the serviceability of the ER road network of Cologne under flooded conditions, as presented in this section, towards mitigation of the potential cascading and emerging risks, identified in section 1. This identification of the cascading risks is enabled with large-scale spatial assessments of the ER road network of the Cologne fire brigade system, which is tightly interfaced and interdependent and could enhance its vulnerability. Towards enhancement of its ERR to floods and mitigation of cascading risks occurring under the stressor of floods, consideration and integration of indirect flood impact interdependent features such as the traffic and mobility characteristics of a road network is a necessity.

Robustness, redundancy and resourcefulness of the ER road network, as spatially analysed in a semi-automatic way (GIS-Toolkit) for the selected flood scenarios, are the interdependent ERR features that affect the rapidity of response. Therefore, their assessment as a whole (interdependent resilience features – see Figure 11) through the RITAI is suggested. The robustness levels affect the redundancy levels and resourcefulness levels (in a non-linear way). Accurately, the resourcefulness levels of the road segments for timely ER are derived from measurements of the UFTTR per road segment and are dependent on measurements of the flood-impacted FFS (redundancy - section 7.2).

Stressing the ER road network system with compound escalating flood events, the ***high resourcefulness*** of the road segments for timely ER is decreased (between the regular HQ10 and the HQ500) by 1% due to the high intensity and extent of the HQ500. In the case of the flash floods (T20 and T100) stressor to the ER road network, the ***high resourcefulness*** of the road segments for timely ER is also decreased by 2%. ***Medium resourcefulness*** according to the levels of UFTTR, as discussed, characterises the road segments, which are ***adding high travel costs to the ER (impedance)*** but are ***still drivable*** (depending on the ER capacity on vehicle equipment, see section 2.1). The medium resourcefulness increases by 9% for the riverine floods, which means that 9% more of the ER road network is flood-impacted, but to a level that still allows safe drivability (even if slow - walking speed). The medium resourceful road segments are increased by 17% for the case of flash floods, with 17% more impaired kilometres of the ER road network, adding high travel costs in the ER provision. ***In the ERR concept, as blocked are characterised the road segments that are not resourceful*** due to the impact of high FD (higher than 0.5 m - not robust/not drivable). These road segments are ***not redundant for providing timely ER,*** and it is suggested that these road segments should not participate in ER route planning [26, 240, 246, 416]. The increase of UFTTR, that is, the decrease of the travel time from node to node for each road segment, is high for both flood types. It is expected that the riverine floods, in case they escalate from regular to extreme, will highly impact the travel times of the ER road network by 90% more and 81% more in case of flash flood events escalating from the T20 to the T100 (extreme scenario). This means that the calculated flood impacts on the travel times for each scenario are almost doubled in case of flood intensity escalation. These are the so-called Grey Rhino scenarios, which, it is argued, should raise awareness for further actions taken from all the participating agents in the urban ER system (see Table 2).

When answering the RQ7, as implemented in previous analyses, fuzzification for discussing the results is necessary. Notably, because fuzzification makes the measurements of the sub-indicators of ERR succinct, it is intended indicatively for:

i) praxis-oriented purposes

- implementation of the methodology for timely ER planning with prioritisation of the route planning with robust, redundant and resourceful road segments under several flooded conditions
- identification of critical areas on a road segment level for positioning of real-time awareness sensors monitoring the intensities of the flash flood levels, for timely evacuations and location-allocation (logistics) of ER equipment etc. [81, 133, 167, 174, 181, 188, 239, 269, 296, 404, 417]
- CIP - transport networks' protection and specifically the road network by identifying critical road segments of potential quicker pavement degradation and other geographically interdependent CI to avoid cascading effects [79, 140] resource planning (electrical grids) and more
- traffic control management regulations according to flood intensities [89, 303, 308, 309, 318, 331, 418-422] for mitigation of accidents
- bridge protection to floods towards timely ER provision and ERR, enhancing the reliability of the transport infrastructure integrated or adapted to resilience-based designs such as [423], as well as bridge cables, integrated into research frameworks such as [424], for the enhancement of the safety of the population, through the undisrupted provision of resources.

ii) for the scientific community and further possibilities for enrichment/improvement

- possibilities for further update of the methodology with additional traffic characteristics/risk identifiers, such as traffic density and traffic demand, with additional weather impact factors such as visibility and scanning of raindrop density, road slipperiness, and winter maintenance frequency [89, 174, 250, 302, 303, 308, 419, 421, 422]
- use of the methodology with different stressors to the system such as unintended disruptions through accidents (traffic domain) [89, 421],
- provision of weighing factors for further criticality, flood risk and climate change impact assessments on a large-scale of various interdependent CI [155, 179, 235, 408, 409, 425-429]
- provision of weighing factors for further local vulnerability and risk assessments (neighbourhood, community and network level) integrated with various approaches [195, 254, 298, 408, 412, 415, 427, 429-437]
- combined with other models [123, 249]
- combined with resilience indexes and assessment tools [149, 201, 230, 235, 293, 360, 401, 438, 439].

From the quantification measurements of the different features of the ERR towards operationalisation of the ERR to riverine floods and flash floods of different intensities, it is proven that geolocated information on the FD and its impact on the RNMC is essential. In the previous sections, through operationalisations of the different sub-indicators of the ERR, it is presented that:

- the higher the level of exposure of the ER road network (FD levels) to floods, the lower the level of the robustness for timely ER
- the higher the robustness level, the higher the RNMC in the case of floods - the lower the level of exposure -
- the higher the level of the RNMC, the higher the redundancy of the ER road network for timely ER towards ERR.

Absorption of the impact of the floods from the ER road network system, with analogous system transformation according to adaptation capacity, is expected to provide timely ER, analogous to the risk level. This notion will be examined in the next section, where the RITAI indicator is operationalised on a city unit level, considering the risk of degraded or blocked ER provision of a road segment, for connectivity analysis through the rebuild of the ER road network for each selected flood scenario (aggregation of information – see Figure 13).

7.4 Rapidity of Response Under Flood Conditions/Connectivity & Accessibility

This section intends to answer the main RQ3, RQ6 and RQ7 by quantifying the leading indicator of ERR, the RITAI (see section 4) in GIS, with the methodological suggested workflow in Figure 25. Answering the RQ3, the flood-risk informed ER road network databases on a large-scale (road segment level), with large-scale assessments of the robustness, the redundancy and the resourcefulness in a GIS environment, reveal potential CI losses on a road segment level. These updated road network databases are rebuilt in a GIS environment with the Network Analyst tool as suggested in section 6 for further network analyses regarding the connectivity of the ER road network (NA road network) and the entire Cologne fire brigade system. The rebuilding of the ER road network with information on the flood risk, in regards to flood-impacted travel times according to the various defined FD classes, is, concretely, the redesign of the entire fire brigade system (see Figure 4) after configuration (see Figure 26) with the ‘Closest Facility’ algorithm. The resulting rebuilt ER road network databases, with flood risk information for each flood scenario, are designed to provide information in regards to the connectivity of the ER road network, omitting the small road segments (smaller than one-meter length) and the ones that are considered unreliable, according to travel time (see section 4.1). In this way, the fire brigade stations are connected with the city units flood-impacted to a level that ER provision is available. Therefore, answering the RQ7, identified losses on a road network level under the stressor of floods are depicted on the participation of the city units in the network analysis after network analyses conducted in GIS, providing an aggregation of information in regards to flood risks reflected in the rapidity of the response feature of ERR. As suggested from the RITAI (Table 3), the rapidity of the response feature of the ERR is assessed with connectivity and accessibility assessments, with aggregated information from a road network level to a city unit level.

The suggested methodology (Figure 15) enables flood-risk information feedback loops between the different systems of the fire brigade system, with a zoom-in and zoom-out effect, which is needed to enhance the ERR to floods in complex urban environments. ER efficiency operationalisation under flooded situations, towards operationalisation of the ERR to riverine floods and flash floods, with the RITAI, also considers the risk of delayed ER. The risk is analogous to the impact of the selected floods on the RNMC and the UFTTR (see section 4.1). The operationalisation procedure of the RITAI with GIS (Figure 25) starts with network analytics on the ER road network before the occurrence of a flood event. In this way, the identification of the connectivity of the ER road network and the fire brigade system in normal conditions (typical “dry” days of deployments) is enabled. Answering the

RQ6, time is the primary risk identifier of degradation or impairment of the ER provision, i.e. the time needed to travel/drive through each road segment. In this way, the redesign of the ER road network databases is a reassignment of travel times to each road segment of the entire road network of Cologne, is weighted by its impedance cost (travel time), from node to node (road as a weighted graph – Figure 4). In the case of 'normal days' of ER provision, before any flood occurrence, the ERPS used from Cologne's fire brigades for ER route planning are used to calculate the travel times with *function 9*. The redesigned/updated ER road network database uses these travel times as weights for connectivity analysis of the entire fire brigade system (Figure 3), forming the NA networks. After the rebuild of the NA network (before a flood scenario), the citywide connectivity analysis of the entire Cologne fire brigade system with the 'Closest Facility' algorithm is enabled. As mentioned in section 5, each city unit of Cologne serves as a destination, which is transformed to its point of representation, the centroids (see Figure 24) for NA performed for each flood-risk updated ER road network database. As discussed in section 6, the algorithm is configured to use the 'Time Impedance' as a travel cost to identify the 'Closest Incident' (city unit) instead of the distance impedance. For the ER efficiency operationalisation of the fire brigade system, towards operationalisation of the ERR to floods, the "closest" city units to fire brigade stations are the city units that can be reached within specific time thresholds (see section 4.1 and 6.3). The Network Analyst tool, using the Closest Facility algorithm, assigns a unique ID number, named "IncidentID", after the build of each NA road network (see Figure 46). With GIS visualisation techniques, the IncidentID of the city units is displayed in the form of labels. Each city unit is a hexagonal sub-location of Cologne, forming the city's beehive, covering the entire area, enabling further accessibility assessments.

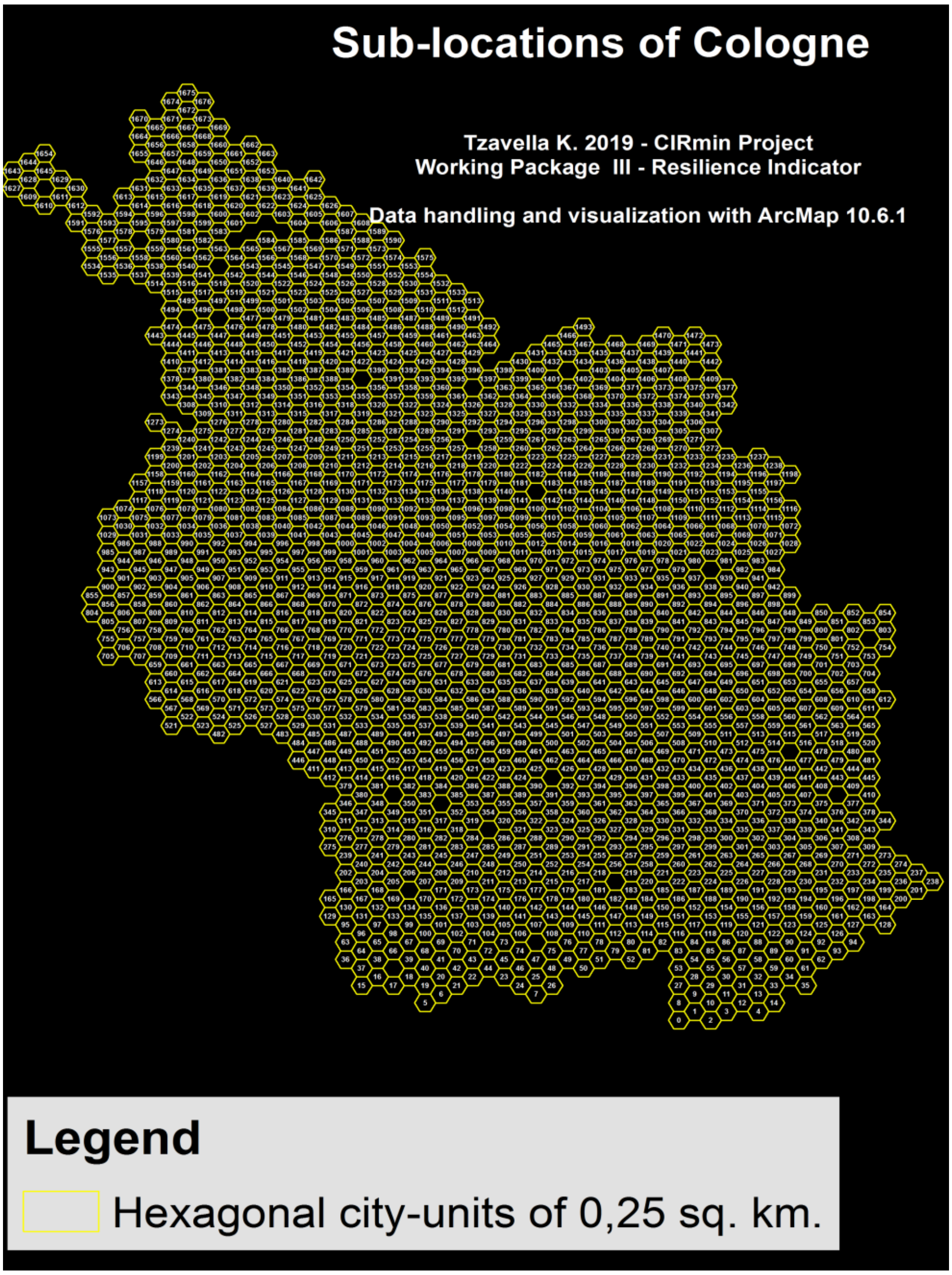


Figure 46: Hexagonal spatial matrix of city units of Cologne of 0.25km² serving as the destinations for the ER's simulation with network analysis

The hexagonal city units, covering the entire Cologne area, are 1677 in number. The enumeration and labelling of the centroids serving as incident points (destinations) for the NA are random and are conducted from the 'Tessellation tool' of ArcMap 10.6.1. For structured enumeration for ER and civil protection purposes, the different methods presented in section 6.3.2 are suggested. Before the occurrence of a flood, the connectivity analysis of the NA network revealed that 96 city units out of 1677 are not participating in the NA (Figure 47); therefore, the participating areas in the NA analyses are 1581 in number. These 96 areas will not participate in further accessibility analyses, indicating the ER efficiency in regular days (before any flood occurrence). After verification with a land-use map of Cologne, including water bodies and land use, the non-participating areas have been identified as areas of either water bodies (river area, lakes) or parks, which do not include any road segments. Their exclusion from the NA does not hinder the analysis process and are considered as 'NO DATA' city units/centroids.

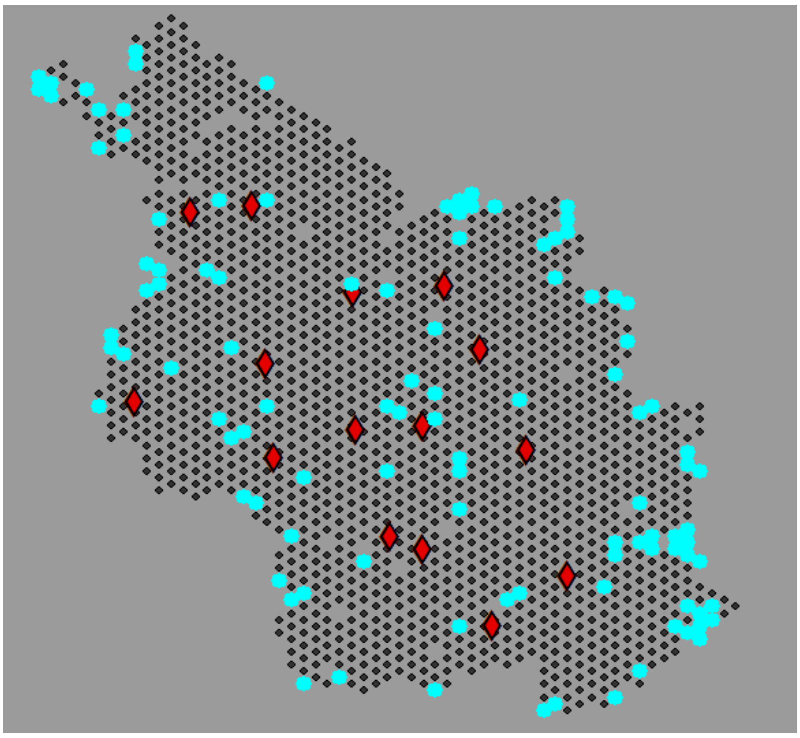
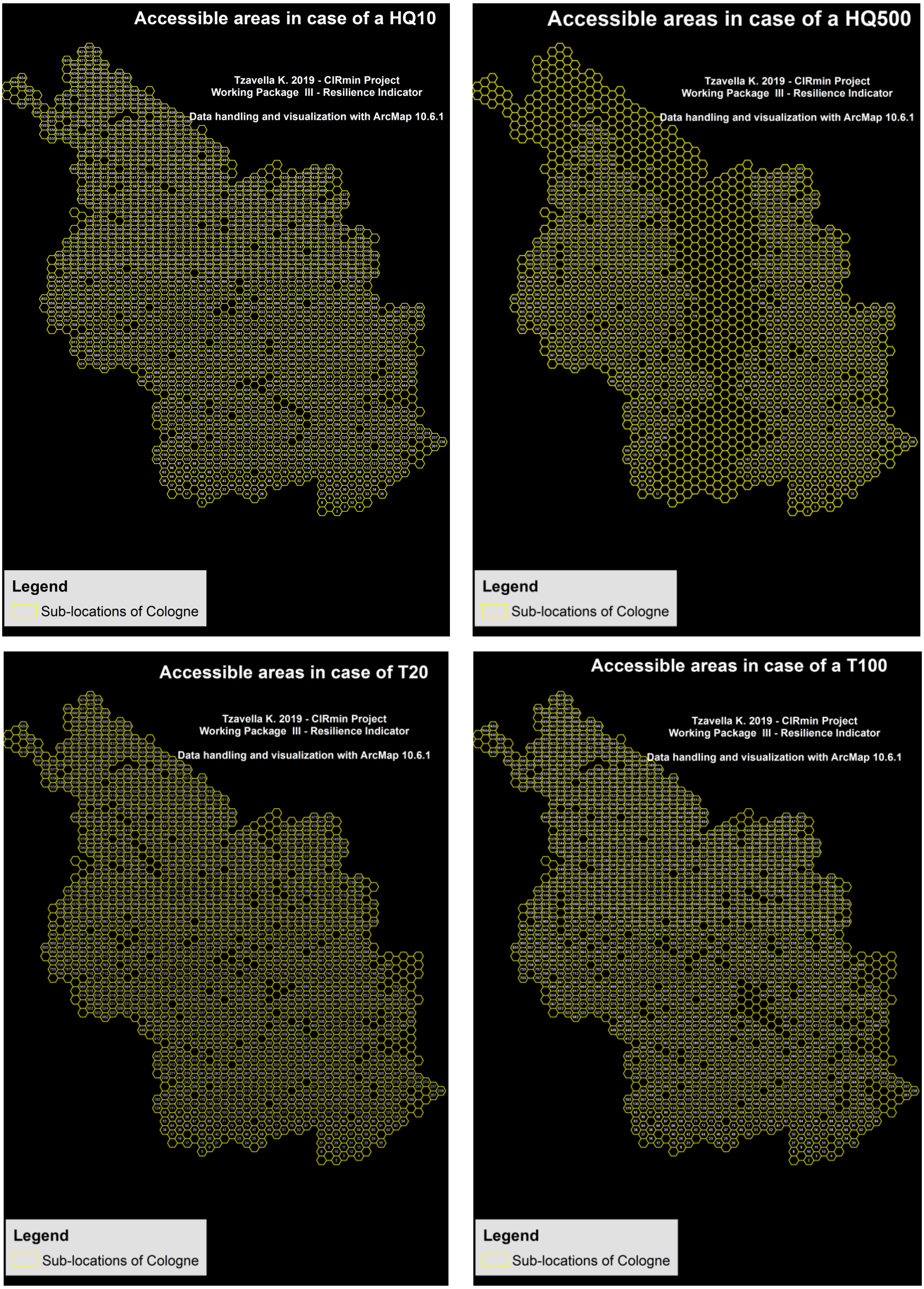


Figure 47: Not participating areas in the NA (blue dots) for connectivity and accessibility assessments. Cologne's fire brigades are the red rhombi, and the city units are represented by their centroids (black dots)

Since not all the city units/incidents are participating in the NA after the rebuild of the ER road networks, the visualisation of the participating ones provides complementary results to these from the exposure assessments on a local area level. To answer RQ7, the visualised participating city units in the NA can serve as a first situational analysis regarding the exposure and accessibility of the case study area under flooded conditions. The results are also i) depictive of the impact of the FD on the RNMC and UFTTR for ER purposes and ii) assisting the efficiency assessment (timely ER provision) of the fire brigade system under flooded conditions, leading to ERR assessments. After the rebuild of the flood-risk informed NA networks for each selected flood scenario, the connectivity analysis of the fire brigade system under flooded conditions is enabled. That is, the weighted road segments with highly impacted travel times (not reliable) that will not participate further in the accessibility assessments and therefore, the city units (incident/centroids), that were identified from the 'Çlosest Facility' algorithm as not reachable, are excluded, indicating highly flood-impacted areas.

Therefore, identifying the extent of each flood is enabled with the aggregation of information from a road segment level to a city unit, providing a deepened understanding of the whole range of flood impacts (direct and indirect). The neighbouring road segments failing to provide ER (participate in the accessibility assessments) due to their high weight (highly impacted travel times) on a road segment level. This first exclusion of the participating centroids provides a primary situational analysis valuable for the fire brigade system, raising awareness for critical areas that need further action towards enhancing ERR. The visualisation of the participating incidents (city units) in each NA implemented with updated NA networks in each selected flood scenario is presented in Figure 48. The information provided in such forms (spatial hexagonal encoded maps) enhance the redundancies and the resources (resourcefulness) of the ER towards ERR (see section 4.2).



Accessible areas in case of a HQ10

Tzavella K. 2019 - CIRmin Project
Working Package III - Resilience Indicator
Data handling and visualization with ArcMap 10.6.1

Accessible areas in case of a HQ500

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Working Package III - Resilience Indicator
Data handling and visualization with ArcMap 10.6.1

Accessible areas in case of T20

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Working Package III - Resilience Indicator
Data handling and visualization with ArcMap 10.6.1

Accessible areas in case of a T100

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Data handling and visualization with ArcMap 10.6.1

Figure 48: Hexagonal connectivity-informative spatial matrixes with encoded accessible city units of Cologne from the fire brigade stations, in case of the HQ10 (upper left), the HQ500 (upper right), the T20 (bottom-left) and the T100 (bottom-right) (see enlarged in APPENDIX B)

As presented in section 7.3, emergency operations' primary concern and focus are the logistics of operations (resource allocation – staff and rescue equipment) and the road status regarding connectivity and accessibility. Therefore, the suggested methodology is applied to the fire brigade system of a complex urban area for operationalising the ERR to floods, with the risk-based and time-dependent accessibility indicator, the RITAI (section 4.1). Accessibility in the ERR concept is defined in section 7.3 and considers the risk of delayed or blocked ER provision in deployments under flooded conditions.

Accessibility in the ERR concept is defined as *the time of response of the fire brigades to the nearest city units that can be reached in case of floods in a timely manner (within defined response time thresholds.* RITAI is, therefore, calculated with the abstraction of the flood-impacted accessibility time from the accessibility time that a fire brigade needs to respond/reach/access the closest city units. It considers the impact of the flood on the road-type dependent FFS and, therefore, the travel time (reliability) of the ER road network segments (TTR) so to provide the final accessibility time *(function 2)*. In GIS (see Figure 25), the risk-based indicator of the accessibility is measured through route-directed accessibility assessments, calculated in minutes from each of the fire brigade system to the nearest centroids before and in case of each of the selected flood scenarios *(function 1*). Accessibility assessments for the nearest locations through network analytics, which enable the calculations of the shortest route paths from the fire brigade stations, indicate the fire brigades' ER efficiency under flooded situations.

Therefore, it is argued that the fire brigades' ER efficiency (resiliency) to floods is dependent on the RNMC (redundancy) and the UFTTR reliability (resourcefulness) of the ER road network under flooded conditions. The implementation of the methodology suggests the absorption of the stressor (floods) to the selected ER system, with large-scale exposure assessments and the assignment of FD per road segment. The absorption capacity of each road segment is benchmarked as suggested in sections 6.2 and 6.3, according to each urban ER system's equipment capacity in rescue vehicles, for driving through flooded waters considering the safety of the emergency responders, their assets, but also the safety of the population, through the extension of the adaptation capacity through transformation. It is argued that ER efficiency assessments should consider the travel time delays that occur from the flood-impacted travel times assigned to the road network on the scale of analysis so that the route planning could be time-efficient. Time efficiency is further benchmarked according to each ERS response time thresholds. It is argued that response efficiency is enhanced by enriching the resourcefulness component of the ERR with suggestions on the fastest routes provided for each of the fire brigades, taking into consideration the offered ER RNMC for timely ER route planning. For an overview of the efficiency of the ER under different flood scenarios in a complex urban environment towards the operationalisation of ERR, network analyses are conducted on a compartmentalised case study area (Cologne) into the hexagonal city units.

The fastest routes are identified with directed route calculations (from facilities to closest centroids/city units), planned through resourceful and medium resourceful (travel time reliable and medium travel time reliable) road segments for ER provision, thus aiming to enhance the rapidity of response. The results are presented in the following Figure 49.

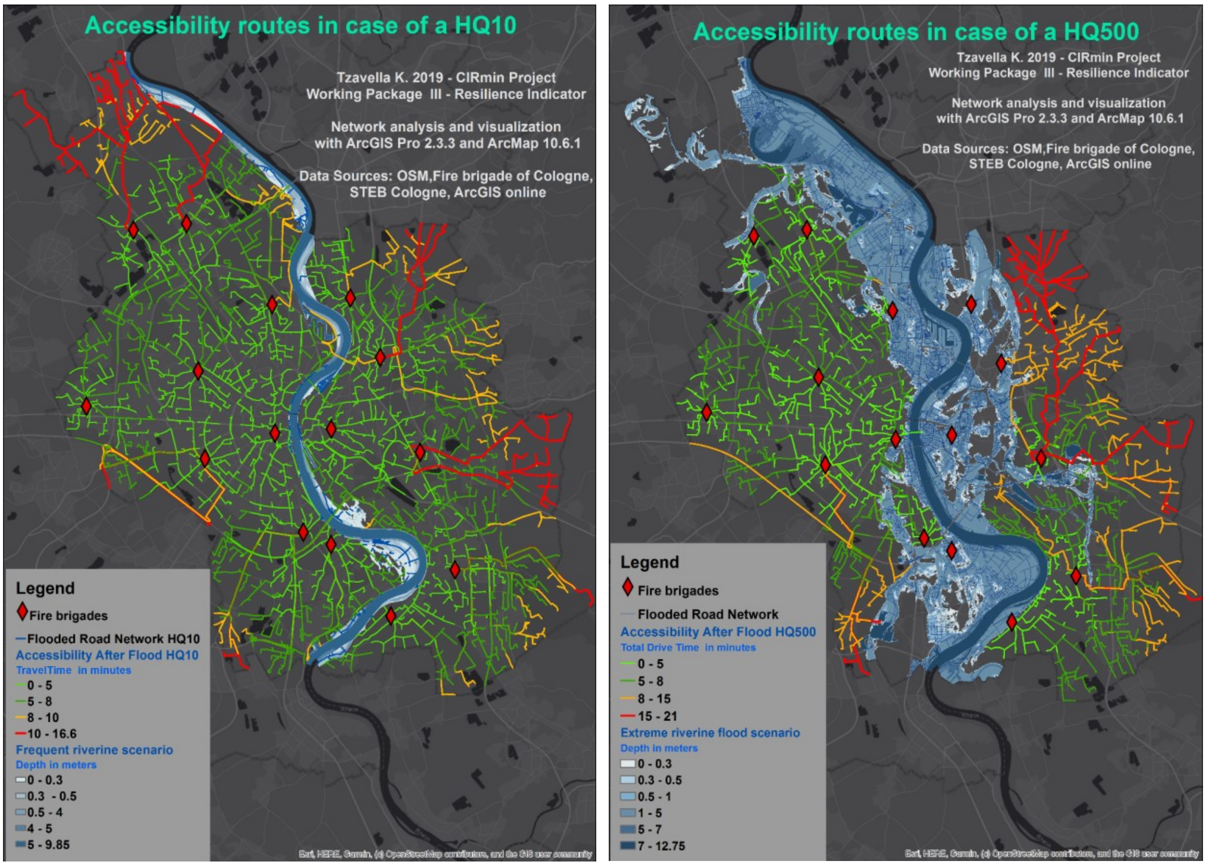
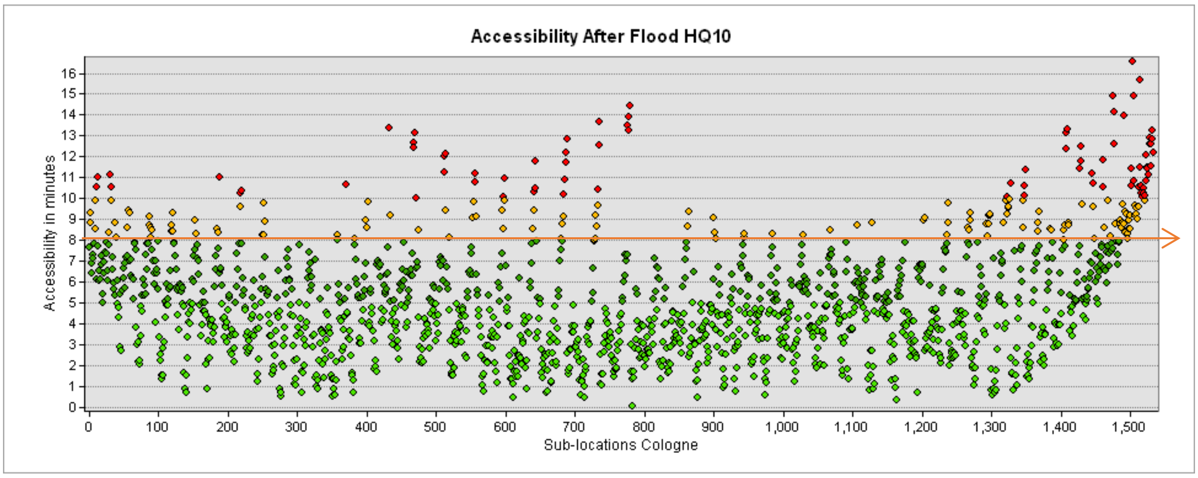


Figure 49: Risk-based time-dependent fastest accessibility routes of Cologne's fire brigades to the nearest city units in case of the HQ10 (left) and the HQ500 (right) (see enlarged in APPENDIX B)

The NA results for each flood scenario, i.e. flood-impacted accessibility assessments, differ due to the degradation of serviceability of the road network affected by each of the selected flood scenarios. According to the flood intensities, the degradation of service depicts the flood-impact levels on the redundancy and resourcefulness of the ER road network. The accessibility times, before and after the occurrence of the selected flood scenarios, are calculated with the configured 'Closest Facility' tool in ArcGIS Pro 2.3.2. The accessibility times are assigned to each centroid, and they serve as the weighting factor for further ERR assessments. The accessibility patterns (Figure 50) conducted in ArcMap add to the redundancy and resourcefulness of the fire brigade system for the enhancement of the ERR to floods. The plotted measurements are the results of the accessibility time, in minutes, of the city units of Cologne from the nearest fire brigades in case of the riverine floods of HQ10 and HQ500, as well as of the potential blocked areas (absence from NA results/not participating in NA) where ER cannot be provided. The place and the colour of the dots that follow the classification colouring scheme (green, orange, red) indicate the accessibility time of each sub-location from the closest fire brigade station and its variance from the official fire brigade response time threshold of Cologne.



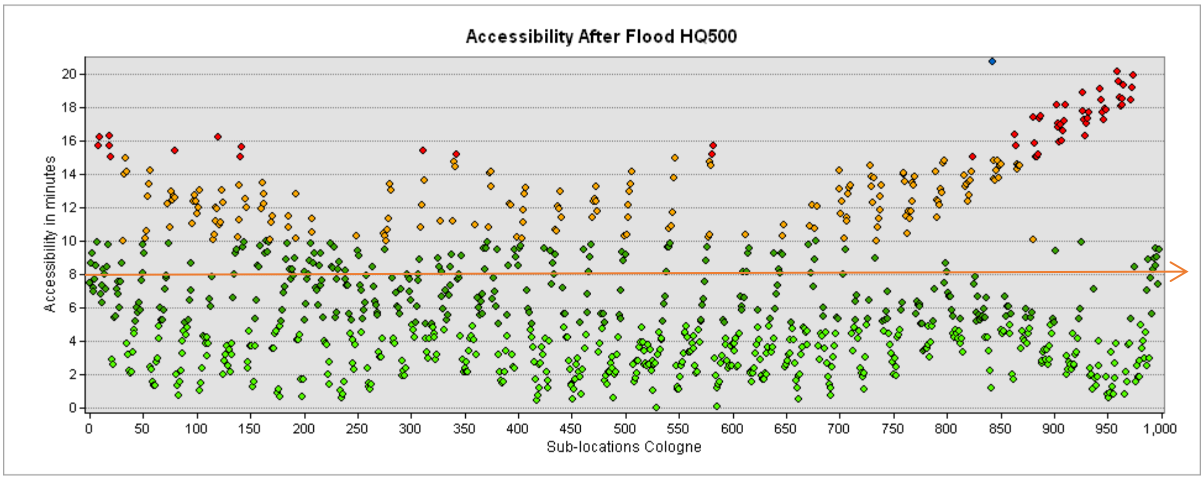


Figure 50: Accessibility patterns above and below the eight-minute response time threshold in case of the HQ10 (above) and the HQ500 (below) with the number of accessible sub-locations of Cologne

Apart from the riverine floods, the methodology also suggests implementing the two selected flash flood scenarios for the urban area of Cologne, aiming to provide insights and raise awareness about the reliability of the road network in case of each flash flood scenario. Thereby, information regarding the ER provision affecting the overall ER efficiency of the fire brigade system under flash flood situations is provided. The NA conducted with ArcGIS Pro 2.3.2 and the Network Analyst tool uses the updated ER road networks (built-in ArcMap 10.6.1 for NA) after the regular and extreme flash flood scenario. The results are presented in Figure 51.

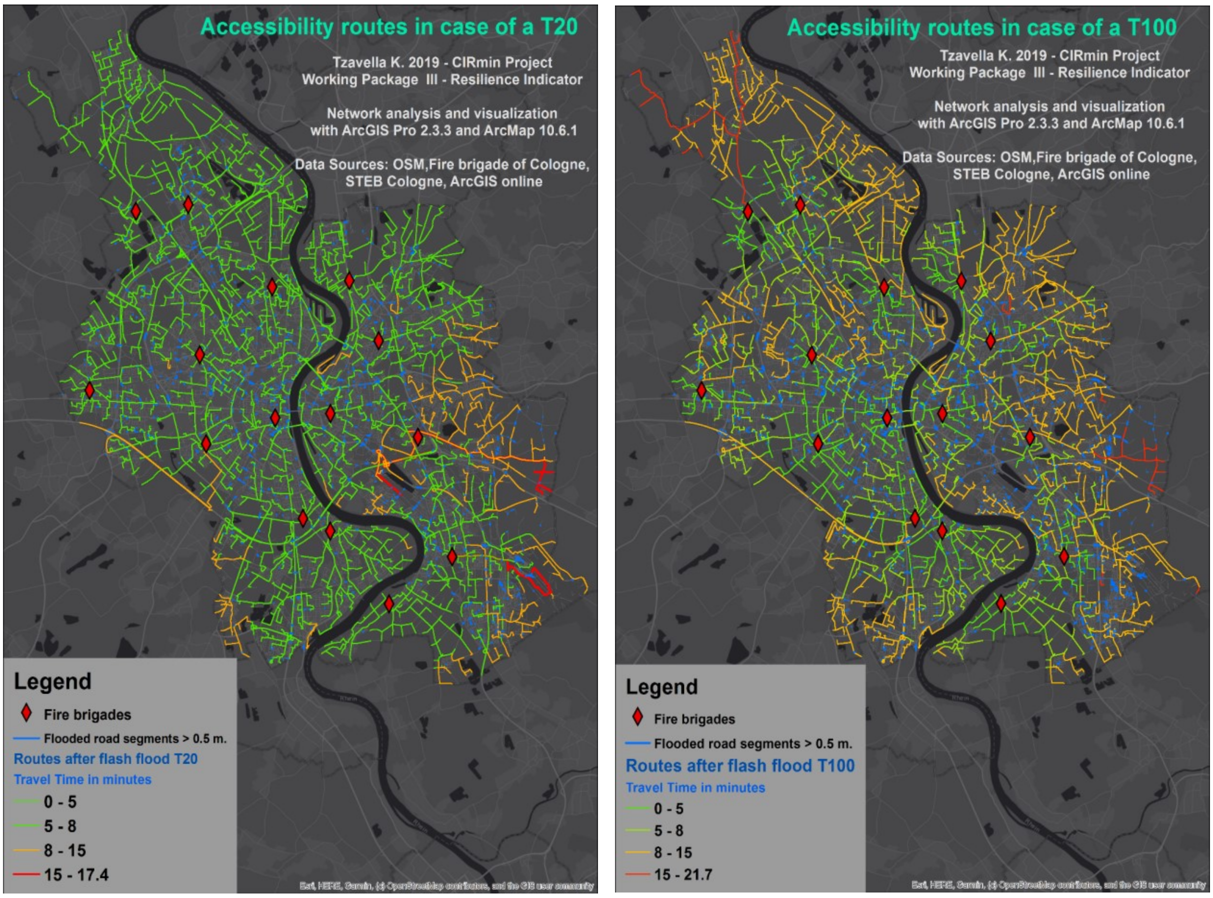


Figure 51: Risk-based time-dependent fastest accessibility routes of Cologne's fire brigades to the nearest city units in case of the T20 (left) and the T100 (right) (see enlarged in APPENDIX B)

After the accessibility routing calculations implemented for the regular and extreme flash flood scenario in Cologne, the accessibility patterns (Figure 52), created in ArcMap 10.6.1, are raising awareness in regards to the effects of the flash floods to the ER delivery and, in general, the efficiency of the ER operations.

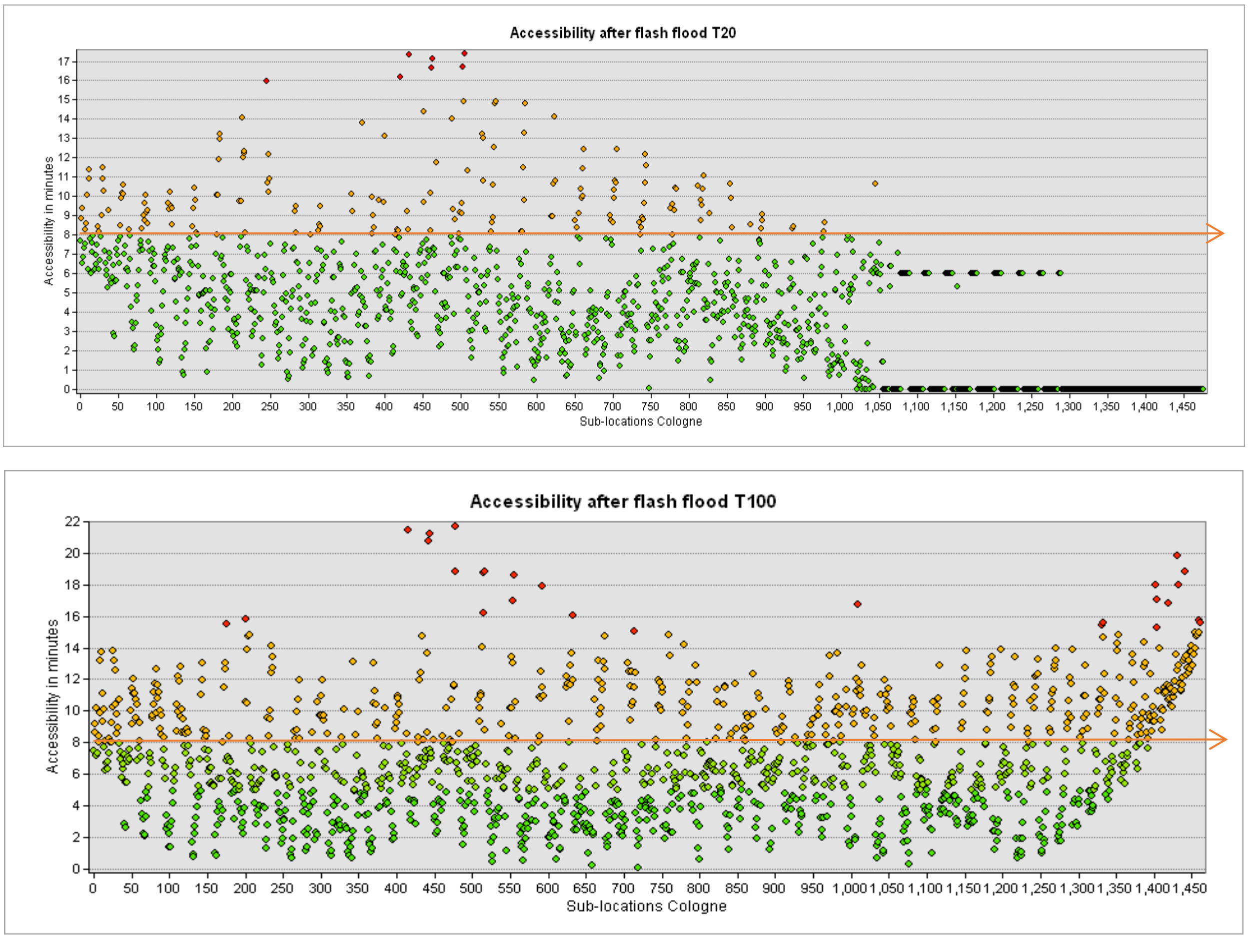


Figure 52: Accessibility patterns above and below the eight-minute response time threshold in case of the HQ10 (above) and the HQ500 (below) with number of accessible sub-locations of Cologne

7.4.1 Discussion of the Rapidity of Response

Answering the RQ7, the accessibility patterns (Figure 50 and Figure 52) of Cologne's fire brigades provide a first overview of the ER efficiency for the selected flood scenarios with observations regarding the density of the coloured dots. They also provide additional resources to the fire brigade system towards enhancement of the rapidity of response. The coloured time-weighted dots are representing the accessible city units, with information on their accessibility time. Their colour indicates the assigned risk-based accessibility time (weighted local areas with risk information regarding ER accessibility after the occurrence of floods). The density and deviation from the time threshold of 8 minutes indicate the ER road network efficiency. For example:

- the density of the dots is indicative of the density of the accessible city units from the fire brigades,
- the further they are above the threshold (*negative impact to the rapidity of response and ERR*), the higher their time of accessibility from the closest fire brigades,
- the further they are under the threshold (*positive impact to the rapidity of response and ERR),* the quicker they are accessible from the nearest fire brigades.

Additionally, through the accessibility patterns, the identification of the flood intensities of the different selected flood scenarios is enabled for the entire area of Cologne. Furthermore, to answer the RQ3, the suggested operationalisation methodology conducted in GIS (Figure 25) enables the identification of the snowball indirect flood impacts of the selected riverine and flash flood scenarios in several scales and levels. The large-scale risk assessments dependent on exposure and vulnerability assessments on a road segment level, conducted with the GIS-Toolkit (see Figure 14), provide large-scale risk information reflected on the levels of robustness, redundancy and resourcefulness of the ER road network for timely ER provision, considering the safety of the emergency responders, as well as the security of the rescue vehicles. Geovisualisation techniques combined with fuzzification enabled the classification of the impacts according to the FD classes, which benchmark the operationalisation assessments. The benchmarking of the assessments is additionally enabled with geovisualisation, which provides geolocated large-scale information, displaying critical areas of the ER road network and aggregates the information to the entire ER road network with a comprehensive overview of the entire city of Cologne, enabling further accessibility assessments of the ER road network, reflected on the entire fire brigade system. The accessibility assessments are, later on, conducted using network analytics and the flood-risk updated road databases resulting from the GIS-Toolkit, which are reconstructed after configuration (see section 6). The fastest routes of the fire brigades to the closest (in time) city units provide additional risk information, reflected on the rapidity of the response of each fire brigade station and the entire fire brigade system.

Geovisualisation techniques enable the classification process, for a more straightforward interpretation of the results, regarding levels of ER provision. From a visual interpretation from the results in Figure 50 and Figure 51, the right side of Cologne (east), as a reader sees the maps, seems to suffer more from the degradation of the fire brigade ER provision. Even with the regular riverine and flash flood scenarios, H10 and T20 respectively, this side of Cologne seems to have a road network that has reduced absorptive capacity of the flood impacts, with decreased adaptation and transformation capacity.

Therefore, these visualisations of such flood impact information raise awareness for further actions to be taken, either for improving the road network (CIP) or enhanced preparedness for response and joint forces between the fire brigade stations of the entire city with training for such flooded situations. In the training process, it is argued that the flood-impact curves conducted for each selected flood type, considering the scenario of escalating flood events, can add to the redundancy of all three agents of an urban ER system (see Table 2), fostering further collaboration, towards a strengthened preparedness for response. For example, it is argued that in case that the storages of rescue equipment of the fire brigade system are located on the right side of Cologne, without any backup location, there is an increased need to relocate the equipment to more than one storage unit for the enhancement of the ERR, in the face of floods. Furthermore, the visualised maps can enhance the resourcefulness of the fire brigade system with added redundancies such as the printed maps, specifically in case of black-outs, which can also be EWE-triggered.

The accessibility maps, resulting from the suggested methodology, offer detailed route pre-planning, considering potential disruptions to the ER road network in several flood scenarios. On the other hand, flood-impacted route plans convey the uncertainties of the flood models used, which could lead to biases, but on the other hand, they are raising awareness for the accessibility to city units that may cluster other CI i.e., hospitals, nursing homes and schools. In section 7.4, it is mentioned that emergency response route planning [242, 279, 336] is of vital importance. In the case of the ERS of Germany (section 6.3), as mentioned in the performance analysis for 2016-2017, many of the deployments could be pre-planned [370]. Pre-planning means that there was enough time between the time of response and the initiation of the response. EWE-triggered route pre-planning might seem far from reality in the case of floods since the assessments do not integrate any other traffic characteristics, such as traffic density or demand. Nevertheless, it is argued that it is appropriate for raising awareness and training purposes since it can cover various flood types and intensities while also providing information for potential escalations.

Additionally, the route-planners, traffic planners and urban planners can be informed in regards to geolocated and visualised large-scale information on the TTR, which provide a detailed overview of the possible level of degradation of the road network and the ER efficiency in regards to timely accessibility in predefined response times, considering direct and indirect flood impacts. As demonstrated in section 7.4, the response times [335] of several ERS, such as the fire brigades and the medical services, are crucial for emergency response planning, specifically regarding accessibility. So to answer RQ6 and as mentioned in section 7.4, emergency managers are using accessibility in general as a risk-identifier of the response efficiency.

Response efficiency is used for the evaluation of the performance of the ER of several ERS in terms of timely ER provision, in the predisaster phase but also during and after various disaster/crises for planning, shelter of the vulnerable population, evacuation and location optimization for emergency humanitarian logistics [188, 342-346]. As Weibull [347] stated in 1980, "*the accessibility refers to the properties of the configuration of opportunities for spatial interaction*". As it is presented in the thesis, through the application of the methodology, the accessibility route pre-plans provide these configurable opportunities for spatial interaction between the systems of the fire brigade system, with CAS properties (in Figure 3), for a strengthened preparedness of response and enhancement of the ERR floods. It can be argued that the measurements of the accessibility are indicative of the high spatial dependency on the status of the road network (physical and geographical interdependency) with the serviceability level that is under research, as critical functionality of the ER road network, revealing the high interdependence. So to answer the RQ3, the mentioned interdependencies are considered with the suggested methodology and the developed ERR indicator, the RITAI.

Moreover, in regards to the location of ERS for ERR under the impact of floods, visual interpretations of the results of the exposure assessments to riverine floods (Figure 30) indicated that some of the fire brigade stations are located around highly flooded road segments - indirect exposure assessment of the geographically interdependent CI. This observation could raise awareness towards the robustness of the fire brigade system itself (answering the RQ7) through department positioning analysis. Exposure of the fire brigades in Cologne, hospitals and refugee shelters and ER efficiency assessments have been already conducted via static exposures, but only with the use of the extent (no FD information) of the extreme flood scenario HQ500 [226, 234]. Specifically, they have been conducted in the context of civil protection, emergency response routing and service area analyses, including additional delays (impact) from driving through the flooded road network, towards vulnerability and resilience assessments of the ERS (fire brigades and hospitals). In [226], potential delays due to the absence of the actual information on FD levels were calculated by weighting the flooded road network with a delaying factor of 3.0 (triple tie increase of drive time) used for emergency routing analysis. The road network used at that time was an OS dataset of low-quality with missing information on the speeds of many roads around Cologne. The results provided potential alternate routing paths to be followed after an extreme flood occurrence for ER purposes, such as evacuations of the flooded hospitals and refugee shelters. In 2019 and for work conducted for the final workshop of the project CIRmin the methodology was applied with the same extreme flood scenario (HQ500) and for the same goal: accessibility assessments of the fire brigades to impacted flooded hospitals enriched with potential delays occurring from driving through flooded road segments (road network).

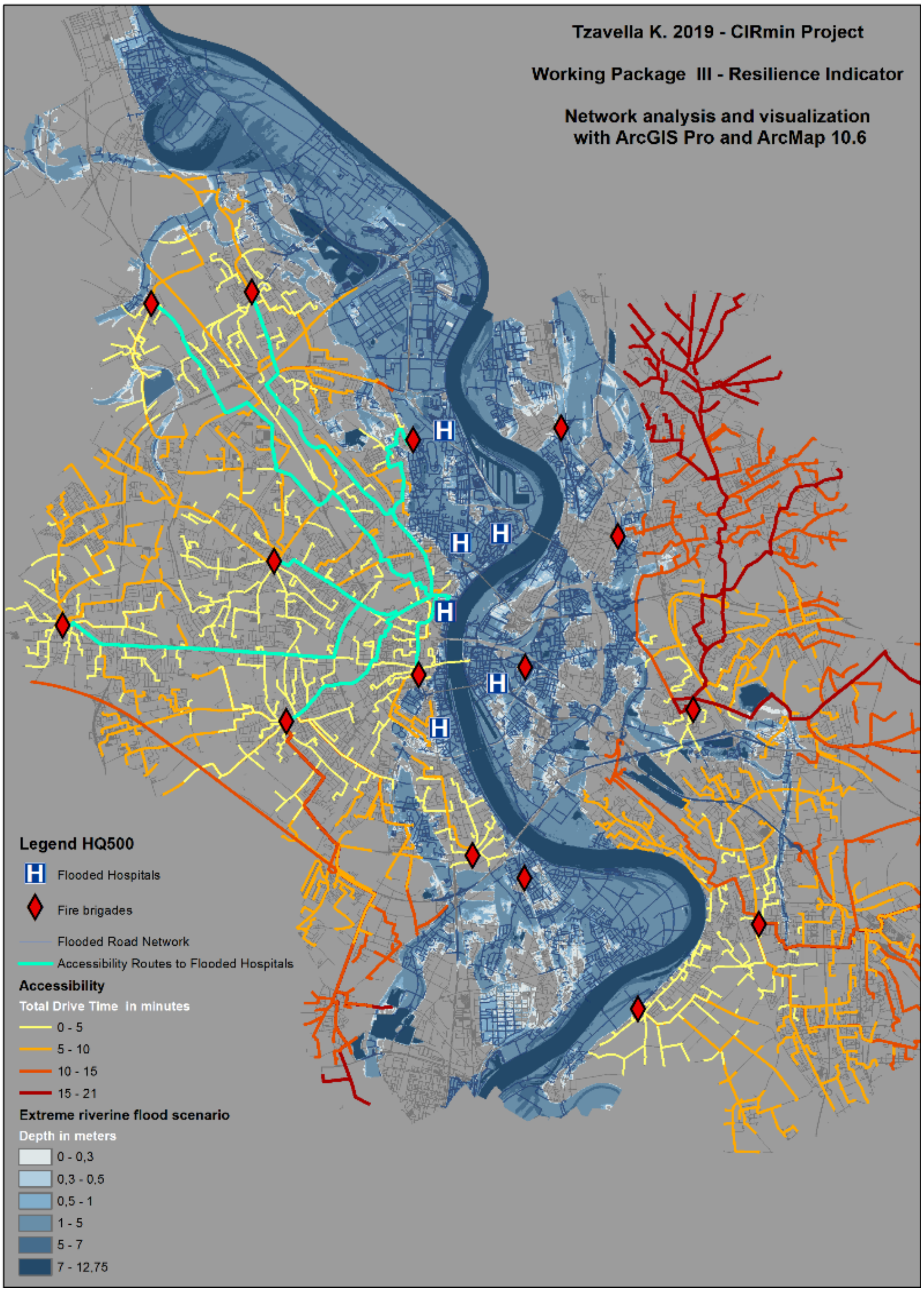


Figure 53: Fire brigade ER risk-based time-dependent accessibility assessments in case of the extreme riverine flood HQ500 [18]

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[18] Information on:

- the FD levels and their impact on the accessibility considering the flood impact on the RNMC according to the safe driving capacity of the fire truck through flooded road segments,
- the exposure of the fire brigades to the extreme riverine flood,
- the exposure of the hospitals and
- the ER efficiency (timely ER delivery) of the fire brigade system. Fastest accessibility routes through travel time reliable and medium travel time reliable road segments.

In: https://kirmin.web.th-koeln.de/wp-content/uploads/2019/05/Poster_Risikoanalyse-der-Bev%C3%B6lkerung-und-Infrastruktur-am-Szenario-Extremhochwasser.pdf

The results, as shown in Figure 53, differ extensively from the ones in [226]. The reasons are that detailed information of the impact of the FD levels of a HQ500 on the speeds and the update of the ER road network with empirical data on the speeds used for ER route planning from the Cologne fire brigade(pre-flood state) are essential for near reality accessibility assessments under potential floods. Officials from the Cologne fire brigade(external partners of the project and participants in the final workshop of the project CIRmin) expressed that i) they, of course, are aware of the results provided from the GIS analyses, but ii) on the other hand, they do recognize the value of GIS and its potentials in emergency management.

In discussions with civil protection officials, it was verified that GIS maps are easily interpretable compact visualisations of sophisticated analyses for praxis-oriented purposes.

In this section, to answer RQ6 in efforts to tackle the urban complexity of Cologne, considerations are made regarding the dynamic relations between the different concepts of the transport network (network topology), the traffic (speeds) and the given dynamic characteristics of complex networks. In [104], it is argued that it is helpful to analyse the related type of stable/unstable evolution and the leading conditions to the system's resilience in the presence of shock or perturbations. In [165], this theory is acknowledged for improved climate extremes impact modelling and their transport implications. The conceptualisation and the implementation of the methodology suggested in this thesis are formed around this theory, focusing on the untangling of the complexity of the urban ER system initiating the analyses on compartments of its interdependent CI, with particular focus on the road network (for reasons mentioned above). Towards this notion, the accessibility measurements are provided for the city units of the case study area, occuring from the process described in section 3.2.3, depicting citywide accessibility assessments for each selected flood scenario and reflecting the rapidity of response capacity of the fire brigade system in case of floods.

These outcomes indicate that the methodology also provides results of the centrality of the road segments; tested performance for timely ER considering safe driving through flooded waters. Centrality measures are used generally to measure the degree of importance of specific nodes/links in a street network [334] and aim to quantify a node's capacity to be influenced by or to influence other system elements under its connection topology [349-352]. For example, the measure of betweenness centrality has been used in strategies to reduce the impacts of EWE to the infrastructure networks [287], indicating critical road network links potentially profoundly impacted from floods in regards to safe driving through flooded waters. In general, network analyses conducted with GIS have been proven effective for centrality measurements in network concept generation methods [353]. When applied to scenarios of local flooding, centrality measurements indicate flood-impacted areas, which are not physically or geographically interdependent [159], as also has been identified through the application of the methodology (see Figure 48). Such information can raise awareness for further adaptive management of cities towards integrative and adaptive disaster-risk mitigation actions.

In the next section, the evaluation of the changes in the ER accessibility measurements for the selected flood scenarios represented in hexagonal matrixes takes place. These changes represent the impact of the selected flood scenarios on the ER road network, taking into account vulnerability assessments regarding reductions of the ER FFS through flooded waters and accessibility.

It is argued, in the thesis that the resilience informative resulting matrixes that enhance the redundancies and resourcefulness of the Cologne fire brigade enhance the rapidity of response and enable resilience-based decision making, which includes interdependent resilience information in regards to the participating systems of the SoS of the urban fire brigade of Cologne. It is suggested that the interpretation of such measures, combined with outcomes from complex methodological analyses presented in the thesis, becomes easier when classified in matrixes.

7.5 Emergency Response Resilience (ERR) to Floods for Cologne's Fire Brigades

The quantification of ERR is conducted, as presented in Figure 27. The results from the calculations take place in each flood-risk informative road network database. Each city unit (hexagon) is assigned with the calculation results from *function 1* and is accordingly classified in different colours for a quicker derivation of situational assessments for ER purposes (preparedness, ER route planning, prioritization planning, location-allocation planning of humanitarian assistance in case of different types of floods). The ERR is quantified and classified as presented in Figure 54.

ER for Cologne has a time threshold of 8 minutes, as mentioned in section 5.2. Since each ER minute is valuable, specifically in a complex urban environment such as Cologne, the classification considers the increase of accessibility in minutes, where each minute increase indicates the ERR deficiency.

The results in Figure 54 portray the ERR hexagonal matrixes in the selected regular and extreme scenarios of flash floods and riverine floods (Figure 20 and Figure 21). The hexagonal matrixes are classified according to the ERR level of the city units (hexagons) regarding the risk-based accessibility from the fire brigades under floods; the quantifying factor suggested in the thesis. The calculations conducted for each of the selected flood scenarios revealed different maxima of increase of the accessibility, which can also be an additional indicator of the impact of each of the flood scenarios on the ER efficiency. As blocked areas are described as areas inaccessible from any fire brigade stations, they vary between the different flood scenarios.

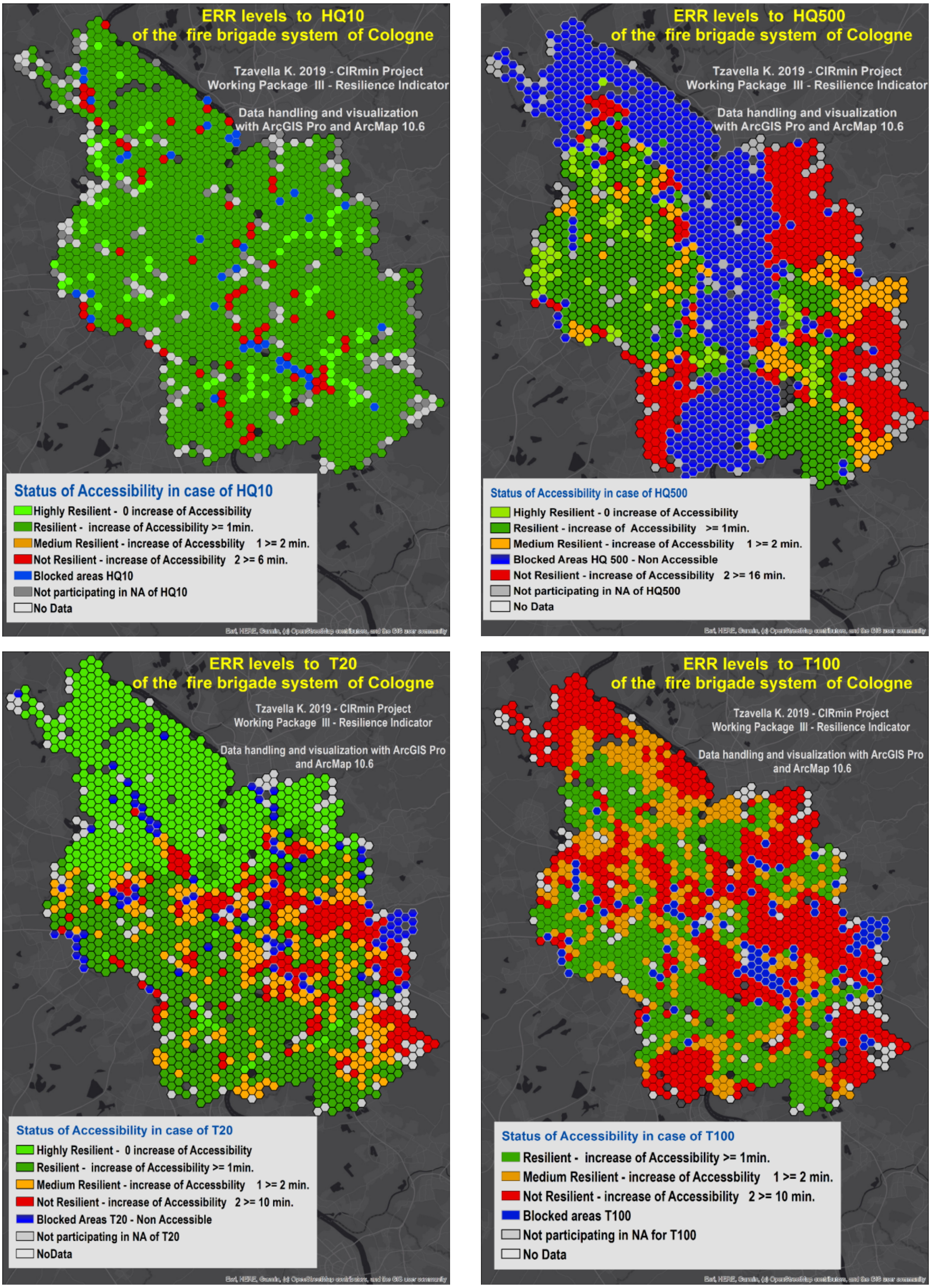


Figure 54: Hexagonal ERR-informative spatial matrixes with ERR levels per city unit of Cologne in case of the HQ10 (upper left), the HQ500 (upper right), the T20 (bottom left) and the T100 (bottom right) (see enlarged in APPENDIX B)

The ERR to the selected riverine floods and flash floods is summarised and analysed in Figure 55. After implementing function 1 in GIS, the total accessible city units with qualitative classifying variables are calculated for each class. Figure 55 summarises the potential fire brigade response efficiency in the selected riverine and flood scenarios. Potential is used as a word since, as stated earlier in the thesis, the calculations convey the uncertainties from the calculations of the selected flood models.

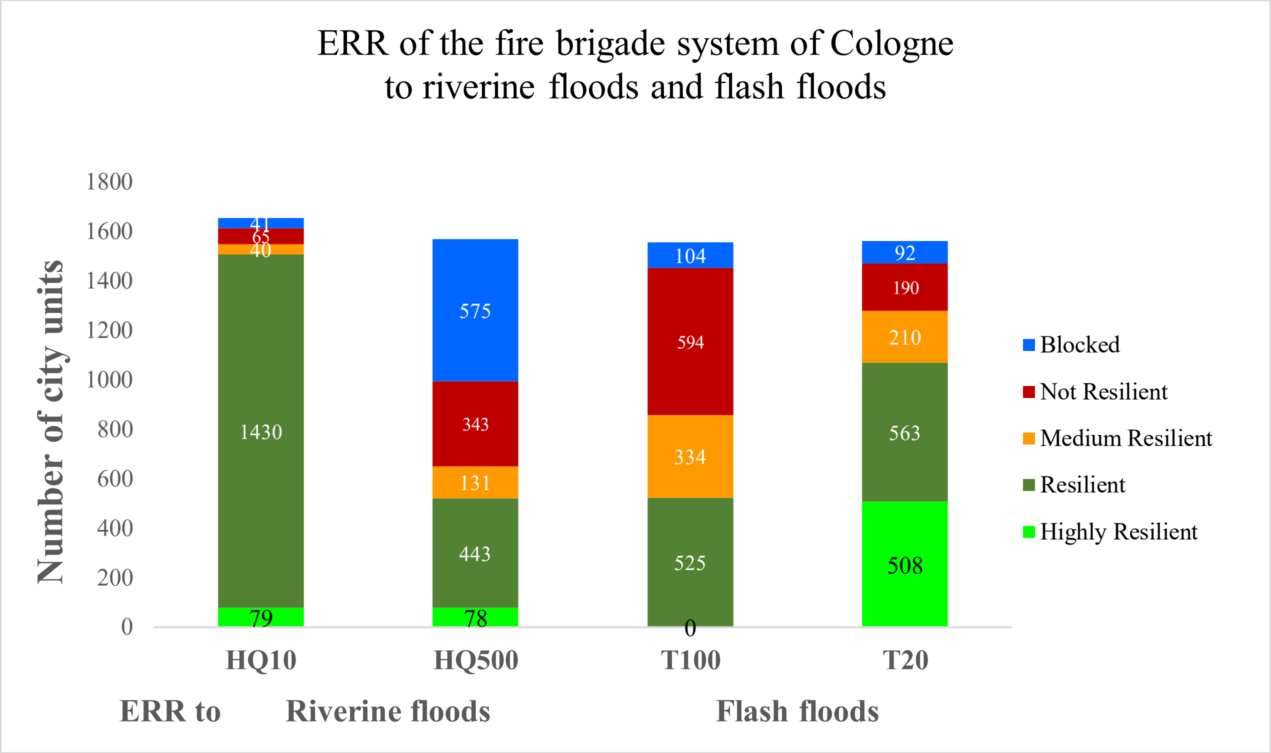


Figure 55: ERR levels of Cologne to the riverine floods HQ10 and HQ500, and the flash floods T20 and T100, with a qualitative classification of the ERR according to FD impacts to the accessibility times of each city unit

Individually, for each selected scenario, the percentage of ERR levels is presented in the following Figure 56. They individually reflect the percentage of ERR levels, in case of each selected scenario, i.e. percentage of flood-impacted accessibility time changes, providing a citywide overview of the ERR as applied to the Cologne fire brigade system (aggregation of information). The results serve as a cumulative overview of the percentage efficiency of the fire brigade response system of Cologne, according to the resilience capacities of the ER road network to the selected flood scenarios. Specifically, they present the percentage response efficiency levels of the Cologne fire brigade system, in case of floods, that is, the percentage of the accessibility time change of the city units from the closest fire brigades, according to the official ER time threshold of eight minutes.

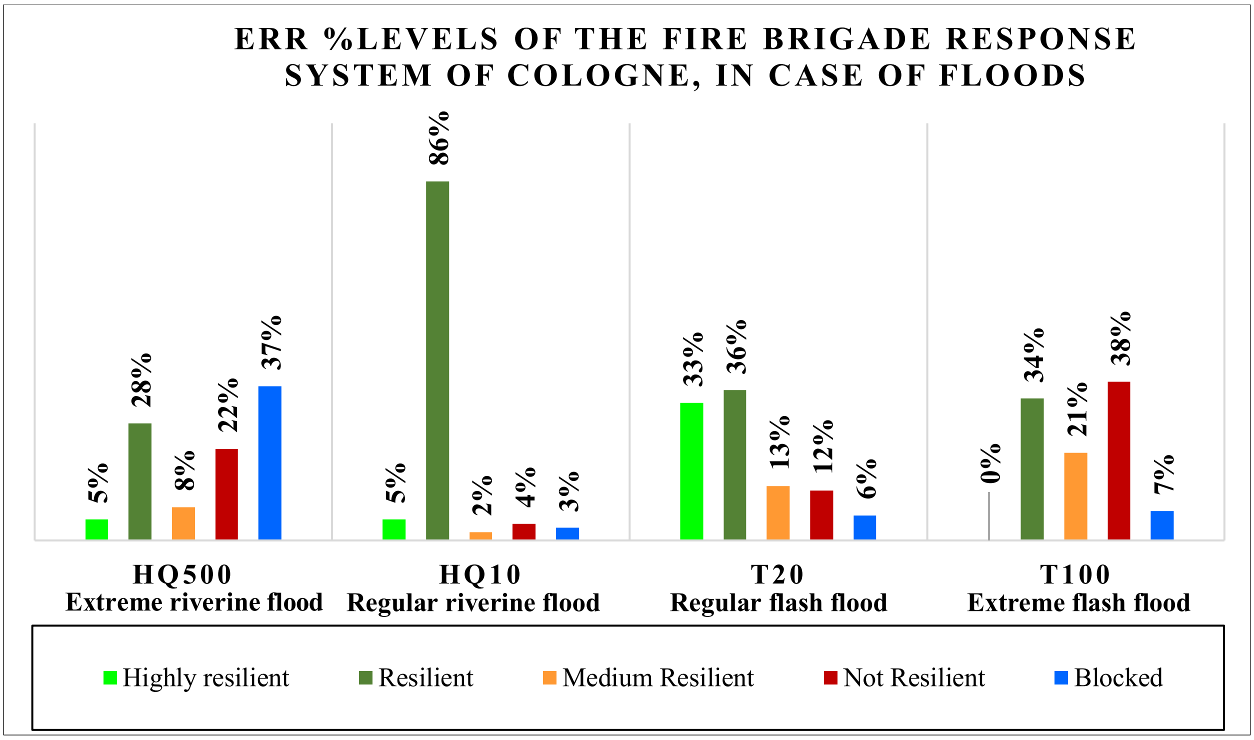


Figure 56: Percentage ERR levels for the riverine floods and flash floods of Cologne's fire brigade system (HQ500, the HQ10, the T20 and the T100)

7.5.1 Discussion of the ERR to Floods for Cologne's Fire Brigades

So to answer the RQ6, the compartmentalisation of the area with GIS tools into city units enables detailed situational analysis of the service area coverage (SOC) of Cologne's fire brigades through NA, building on the ERR to riverine floods and flash floods of Cologne. Detailed situational analysis is achieved by the separate accessibility assessments of the different city units. NA performed for accessibility assessments (see section 6.3.3), patterns the ER efficiency and structure of the urban complex system of Cologne. In combination with compartmentalisation, this patterning results in a holistic overview of the ERR with its strengths and weaknesses after implementing the methodology (see section 6.3.2).

In a GIS environment, the compartmentalisation of the case study area is a tessellation, resulting in hexagonal tessels/tiles, which are the city units, as suggested from the methodology in this thesis. As previously stated, tessellation is a process of preparing various data representations by creating partitions using one or more geometric shapes fitting each other without any overlap and gap on each side [384]. Nevertheless, this was not optional with the use of the 'Tessellation' tool in GIS. As observed in Figure 54, there are some missing areas; an error of the GIS tool used from the ArcMap 10.6.1 - library version.

The tessel (city unit) size is determined according to the scenario of analysis. Specifically, for the application of the methodology, for Cologne, a tile size of 0.25 km² is chosen. It is selected after considering the calculation times and the detailed analyses. For example, even though it would minimize the calculation costs (which are high due to the large-scale analysis), a larger size is not selected due to the large-scale analysis focus of the methodology.

After initial tests, larger tessels, up to 0.50 km², could also be ideal for implementing the methodology for other urban case study areas close to the size of Cologne, avoiding loss of information and biases. Even larger tessels than the 0.50 km², on a city scale, are not recommended.

Nevertheless, configurations of the methodology and easy adaptability to different scenarios and case studies of various scales is an advantage*. *The disadvantage is the high calculations costs (see section 4.2.1) ***stemming from the large-scale analysis on a road network level (1 m road segment).***

The results of the quantification of ERR to floods for Cologne are presented in Figure 54 with the different levels of ERR represented by the colouring scheme suggested, following the regulations of [403] for communication of risk and resilience, via matrixes. The advantages of the hexagons (section 3.2.3) and their ability for a uniform and complete coverage of the study area without gaps are considered, as they are fit for consistent communication of results of the methodology. In this way, decision-makers can proceed to collaborative training activities towards strengthened preparedness for response and adapt their management agendas accordingly to enhance urban resilience [440]. Explicitly, in this methodology, the areas are represented by their centroids, which are nodes of hexagons added to the analysis system and serve as incident areas for the NA conducted. The suggested RITAI weights these nodes with quantified ERR, and the ERR matrixes (see Figure 24) display the ERR levels.

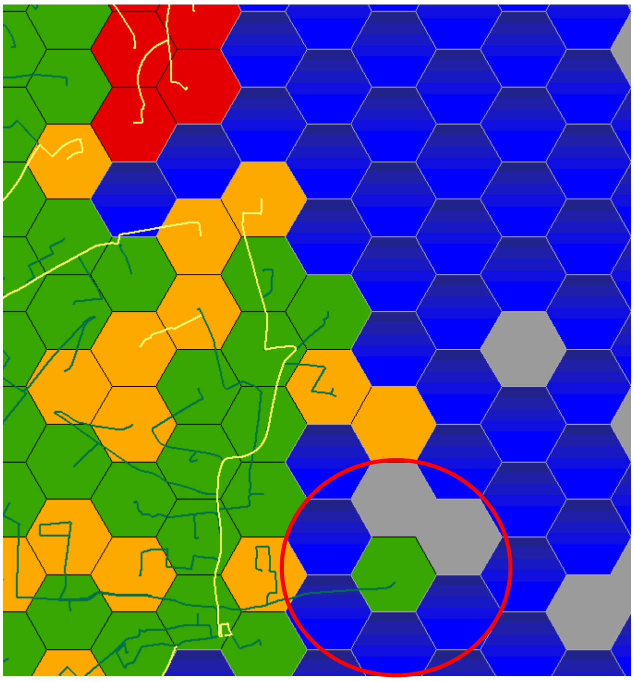


Figure 57: City units of different ERR levels and accessibility routes. In the red circle is a city unit with high ERR (green hexagon)

Taking a closer look at the ER road network's efficiency (see Figure 57) overlaid with the ER efficiency (i.e., ERR levels) reveals critical areas regarding the risk of untimely accessibility or inaccessibility. The results depend highly on the correctness of data, their resolution, the scale of analysis and benchmarking of the indicator (RITAI). For example, for further improvement of the methodology, the city units with high ERR and high accessibility, neighbouring more than one blocked city unit, could be weighted differently regarding ERR levels if the area has a high population and contains several CI, i.e., schools and hospitals.

These results could serve as additional weighting factors for a more comprehensive ERR analysis towards prioritised route planning for timely ER under flooded conditions.
The representation of different types of information (population, schools, hospitals) for further analyses is possible due to the high representational accuracy of the hexagons [386, 389].

Their boundaries are shared with six (6) neighbours rather than four (4), as would happen with squares. This attribute makes finding neighbours more straightforward, avoiding the connectivity inefficiency of the rectangular grid providing valuable information for further analysis, as mentioned earlier. The circularity of the hexagons gives the advantage for further impact analysis and weighting opportunities towards prioritisation of ER in case of floods, as presented in this thesis. They also reduce the sampling bias due to edge effects of the grid shape, which is related to the low perimeter-to-area ratio of the shape, providing the opportunity for a realistic integrated representation of aggregated information of various analyses suggested in previous sections. This characteristic also allows for the representation of curves in the patterns of the emergency route paths with exact directions (connectivity and movement paths); therefore, the hexagonal matrixes are best fit for analyses, including ER accessibility assessments.
Furthermore, any point inside a hexagon is closer to its centroid than any given point in an equal-area square or triangle; therefore, they are best fit for comparing polygons with equal areas. This attribute enables further improvement on the accessibility assessments, considering the closest and timely accessible point in a hexagon as a destination and not the centroid as suggested in the methodology. This idea can also be supported further due to the notion that: when more similar to a circle, the polygon, the closer to the centroid the points near the border are, and the comparison is then avoiding biases. Hexagons are also ideal for analyses on large areas because a hexagon grid suffers less distortion than the shape of a fishnet grid due to the curvature of the earth (risk matrixes used extensively in risk analysis).
Despite the occurring resulting errors from the GIS tools used, in general, the visualisations of complex information carried from the RITAI is sufficient for interpretation of the level of ERR in case of each selected flood scenario, according to the response time classification of choice.
The thesis also argued that the hexagonal matrixes are the best fit for representing risk information for ER, civil protection, and CIP purposes. For this purpose, future work could focus on the enrichment of the RITAI with the integration of information on different weighting factors such as:

- accessibility assessments under different potential hazards and benchmarked according to CI and systems' capacities integrated into various resilience indexes [230, 293, 439],
- real-world route representations updated from live flood and rainfall early warning systems, which provide actual FD using methodologies and tools as in [176, 288, 441] and [442] who also addresses the scale and resolution issue in urban flood modelling,
- traffic light density - as an additional delay factor of the ER, as also suggested from the author of the thesis in [79, 226] in case of compound events
- information on the density of the population after [147] enhancing the criticality level of the neighbouring road network and the city unit, towards prioritisation of response (see Figure 58),
- vulnerable groups of the population - also enabled through the triangulation capability of the hexagons, which enables their representation towards prioritisation of ER (see section 6.3.2)
- different groups of the population of one city unit - also enabled through the triangulation capability of the hexagons (see section 6.3.2) for further risk assessments.
- density of the various CI (Figure 58) which could serve as lighthouses [267], enhancing the criticality level of the city unit towards prioritisation of the distribution of aid, such as schools,

hospitals, nursing homes, refugee shelters. The indicator can be integrated with GIS-based assessments for ER purposes, such as in [341, 345, 346].

For this purpose, they must guarantee the information, communication and supply needs of the population for a long time after a crisis occurs, if necessary. Therefore, accessibility to buildings that can serve as potential lighthouses must be undisrupted and timely under any weather conditions. The density of such buildings (Figure 58) plays an essential role in enhancing the criticality of the area (tessels, as suggested in this thesis), providing awareness for focused civil protection actions to be taken towards urban flood resiliency at a local scale. The example is proposed for further investigation of emergency logistics' prioritisation and incorporation in urban resilience concepts. Furthermore, population density has been suggested already as an important factor affecting the vulnerability of a road network on large scales [145] negatively. In Figure 58, the population density is aggregated from 1 km^2 to 0.5 km^2, displaying the zoom-in and zoom-out possibilities of a hexagonal matrix on a city-scale, valuable for civil protection, CIP and emergency management purposes. Considering the population's safety, time-effective ER services must be incorporated as a risk factor in DRM/FRM approaches in urban areas, as suggested in this thesis. This is essential due to the dependence of lives on external rescue.

For the prioritization of emergency response purposes, the population's dependency levels can be qualitatively assessed and localised via GIS maps. More specifically, attempts for the assessment of the disaster/crisis preparedness of different groups of the population (elderly, young, migrants) in case of a long-lasting blackout and their dependency levels in regards to external rescue and information (social media, internet, radio, television), has been conducted in the frames of the project CIRmin [78, 226]. Unfortunately, they were not statistically significant to be used in the suggested operationalisation methodology, as weighting factors of the city units, towards prioritisation of rescue. Regarding logistics on resources, fuel consumption and population needs - the elderly, handicapped, migrants and the young generation have different needs and capacities. Nevertheless, it is argued throughout the thesis that the population density, geolocalised in the city units forming urban population beehives, can enhance the rapidity of the response of an urban ER system and strengthen the preparedness phase with advanced preparation, for fast resilience-based decision making, in regards to timely ER provision in case of riverine floods and flash floods, considering:

- relocation of ERS buildings,
- flood resilient lighthouses,
- community resilience through the enhancement of self-preparedness and flood insurance strategies
- CI resilience through the strengthening of the CIP against floods
- post-flood traffic regulations
- prioritisation resource plans
- scenario-based ER route pre-planning and printed maps
- training activities for compound and escalating events.

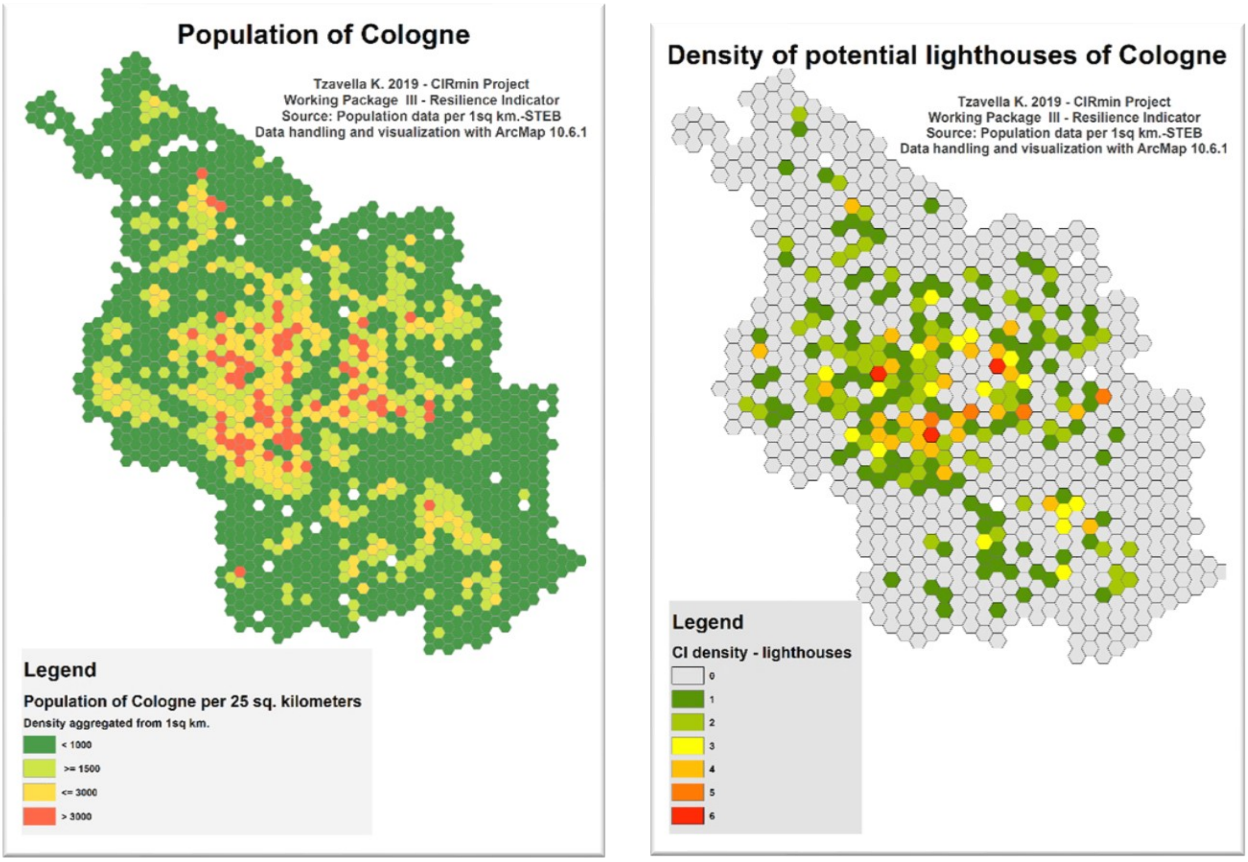


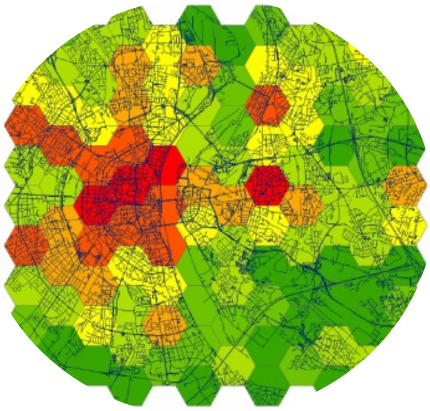
Figure 58: Hexagonal spatial matrix of Cologne's population density with hexagonal spatial units of 0.25 km^2 (left) and hexagonal spatial matrix of the density of different CI (potential lighthouses) and shelters with hexagonal spatial units of 0.5 km^2 (right) – *intentional lower resolution maps*

7.5.2 The intent of integration of the ERR Concept: Semi-structured Interviews & Qualitative analysis

In Madrid, Spain and specifically at the Spanish Civil Protection School (ENPC), the EU project ANYWHERE (6 - 7 March 2019) organised a hands-on training activity on new tools to support real-time response during weather-induced emergencies - platform A4EU. In such platforms, "meteorological data are translated to risk impact maps" for emergency response purposes in case of weather-induced events. The platforms are used for early warnings for energy providers, traffic planners, emergency managers etc. and can be used as self-protection tools (flood-prone campsites - impact on roads). They have been applied to several European case studies and have used hazard information and risk information (from sensors or forecasting models) integrated with vulnerability maps resulting in dynamic impact maps.

However, the impact of different intensities of floods has been assessed on a building/area and road cell (rectangular buffer) scale and none of the case studies presented have used road safe mobility capacity as a factor for further consideration. Therefore, the author, motivated by the risk scenario-based methodology implemented in this thesis, conducted semi-structured interviews with various European stakeholders, researchers, emergency response and civil protection officials participating in the training. The following questions were answered:

- **Q1**: Are you familiar with the concept of resilience?
- **Q2**: What could be ERR for you? How would you define ERR in simple words according to your background knowledge?
- **Q3**: Is the information on road network status after a risk occurs essential for timely, effective emergency response and why?
- **Q4**: Is flood depth information and drive time delays needed for timely-effective emergency response purposes? *If yes,* how would you integrate such information into emergency response plans?
- **Q5**: Would you integrate into emergency response plans drive time delays resulting from driving through flooded road networks?
- **Q6**: How would you read the following map?



- **Q7**: How could information provided in this form (pattern/matrix) assist emergency planners /stakeholders/you?

The semi-structured interviews aimed to gain some insights from the experts (practitioners and scientists from different EU countries) according to their knowledge background, in regards to:

- the level of familiarity with the subject of resilience - indicative of the level of understanding of the following questions (answer to **Q1**)
- the level of ERR definition capability, according to their knowledge background - indicative of the efficiency of communication of the thesis' subject (answer to **Q2**)
- the need for integration of drive-time delays caused by floods (for civil protection and emergency response purposes) from a practitioners' perspective, but also from different officials/scientists (familiar with the impact of weather-induced emergencies) - indicative of the usability of the methodology suggested and intent for further consideration in emergency/civil-protection/ CIP /evacuation planning and training (answers to **Q3, Q4, Q5**).
- the level of interpretation and understanding of colour-classified risk-based resilience matrixes, with little information provided (image of ERR hexagonal matrix) - indicative of the easy interpretability of such matrixes (answer to **Q6**)
- the level of intent for potential integration of the methodology to different planning for civil protection and emergency response activities and different platforms, such as the A4EU presented in this training activity (answer to **Q7**).

The results from the interviews are presented in a Table in Appendix C.

In general, the participants in the interview are familiar with the concept of resilience. According to their knowledge/experience background, they have also defined ERR successfully, close to the given definition in the thesis. The definitions provided lie in the emergency service adaptability, transformation, and continuation of the perturbations occurring due to EWEs or natural hazards of different intensities. Furthermore, the need for FD information (physical damage/loss of a flood) and its impact on the ERR is verified. The information on the actual FD, via real-time monitoring systems or flood preparedness maps, is recognised as an essential factor for the situational awareness of the ERS, traffic control management after flood occurrence, and criticality assessment of city areas. The participants also underlined the usefulness and the need of information in regards to FD impacted drive time and its integration in layers of data and maps for:

- emergency/civil protection response,
- safety of the population
- evacuation processes
- city-based criticality assessments
- accessibility of the population and geographically interdependent CI
- safe driving mobility of emergency vehicles
- emergency route planning
- shelter positioning
- reducing the risk of weather- and flood-caused fatalities
- identification of safety zones for the population (gather points)
- pre-location planning of teams involved in the emergency response
- impact analysis of the floods on the RNMC for emergency response purposes on a large scale
- connectivity assessment of critical assets (interdependency analysis is essential).

Nevertheless, few participants (3 out of 14) replied that drive-time delays are not needed or are impossible to integrate into emergency response route planning. In regards to the level of interpretability of ERR hexagonal matrixes, the results showed that 100% of the participants understand the risk-based colouring, utilising the fuzzy set theory and assigning fuzzy classifying variables (qualitative), such as high (red colour), medium (orange), operational (yellow), green (no impacts). The results verify that such resilience informative matrixes are the best fit for the visualisation of complex information.

Additionally, this colour scheme is recognisable in Europe, and it might differ in other continents (comment of a participant familiar with the subject). This comment of the participant raises awareness about the applicability of such methodologies in other continents, but on the other hand, the risk-based colour classification is easily configurable. In the end, the level of intent for potential integration to different planning for civil protection and emergency response activities, but also to different platforms bringing science to the end-users, is high. It is mentioned that impact assessment of floods to the road network is *"...affecting the accessibility of the different areas",* and *"...could be useful for real case studies"*, emphasizing the need for locational knowledge background for improved assessments and prioritisation processes. Another critical insight given was in regards to suggestions for *further usability* of such methodologies "*... in countries that do not face flood risk, for practical training of the responders regarding emergency preparedness and planning"*. Overall, 99% of the participants identified the usefulness of implementing such methodologies (impact assessments towards risk-based ERR assessments). Specifically, it is mentioned that "*the study on the resilience of an emergency response system can be a step forward for better emergency planning activities".* Additionally, the traffic density is identified as an additional factor for further consideration (as also suggested throughout the thesis), and it is emphasized that such maps can be used as "*…forecast maps of people's movements" for evacuation processes in case of need, and not only".*

General observations also indicate that for civil protection and emergency response purposes, there is a need for:

- assessment of the emergency response resilience of systems
- for simplification of information, on a national and accurately on a regional scale, regarding disseminating risk information.
- for tools assessing the impact of EWE-induced events (riverine floods and flash floods, of snow, of drought etc.) on CI using forecasting models etc. time effectively (primary CI of focus impact on the road network, schools and hospitals -a bit for rail network)
- there is a need for the enrichment of such platforms with more tools providing information for a timely, effective emergency response.

In this thesis, the ERR conceptual framework and the operationalisation methodology suggested, applied with GIS workflows and tools, aim to fulfil these needs by providing different large-scale maps (exposure, redundancy, resourcefulness and ERR matrixes) for ER purposes. These maps enhance the geospatial preparedness to such events, with high-resolution products, regarding in-depth impact (risk) analyses assessments considering both present and future extreme flood events. The analyses in the thesis regard flood impacts to the components of the road network and their traffic characteristics (RNMC and TTR) and the ER delivery (urban ER system efficiency). The aim is the quantification of the ERR considering safety and security aspects on a city-scale, based on risk-based and time-dependent accessibility assessments, in case of riverine floods and flash floods of different intensities, and the concept can be utilised further as mentioned in the discussion sections 7.1.1, 7.2.1, 7.3.1, 7.4.1, 7.5.1.

8. Conclusions

Since disasters continue mounting, with climate change playing a vital role in this increase, the international frameworks, such as the SFDRR, call for strengthened preparedness for response with adaptive management, which explicitly addresses the risk and a deepened understanding of hazard related impacts on societies and their environment, in a range of scales. Strengthening the preparedness and response to EWE-induced disasters, such as riverine floods and flash floods and the cascading impact they trigger, is a challenge for the scientific community, practitioners and decision-makers. Therefore, EWE-induced riverine floods and flash floods have been under the magnifying glass of the scientific community, either for the production of high-accuracy probabilistic models, for methodologies that assess their impacts, in efforts to enhance the resilience of communities and the interfaced CI, to their occurrence. Through the literature review conducted in the thesis, the need for inclusion of aspects, such as the safety of the population, safety of the emergency responders operating under sub-optimal flooded conditions and security of rescue assets (fire brigade buildings, rescue equipment storages, rescue vehicles), lack scientific attention is demonstrated. Additionally, there is an identified lack of connection to application fields such as the fire brigades, civil protection and critical infrastructure protection, which need to be made. Therefore, this thesis contributes to the overall goals of saving lives, a strategic goal of civil protection and emergency management, by reducing losses in CI functioning that is a strategic goal of CIP. This is achieved by providing more detailed risk analyses on large scales (intraurban), boosting community resilience by enabling emergency responders, civil protection officials, and critical infrastructure planners to utilise the suggested ERR concept and its operationalisation framework with applied geoinformatics.

Many scientists argue that it seems impossible to develop a single theory, model, or tool for solving EWE-related issues of increasing frequency and intensity due to their unpredictable nature. Such issues become even more complicated when they occur in the operation and management, in complex adaptive urban settings, with high densities of CI and population, specifically in emergencies.

Therefore, this thesis argues that it is feasible to strengthen the preparedness for operations in sub-optimal conditions by analysing the present (frequent flood events) and the "improbable" future extremes. Furthermore, it is argued that a deepened understanding of a range of flood events in complex urban environments is enabled with a further breakdown of the complex systems into simple components with further compartmentalisation to identical segments or units. With this compartmentalisation, this thesis suggests that the issues can be solved independently, on different levels, concerning traditional boundaries and conditions, after configuration according to the capacities and needs of the respective ERS systems, urban CI networks and urban areas. In the end, they can be combined to solve the issues of a single SoS and can be utilised for macro-level solutions in regards to enhancing their resilience to external disruptions. Moreover, for this isolation of issues, this thesis proposes the utilisation of applied geoinformatics, which intersect digital technologies and spatial sciences, enabling spatial analyses, handling, extracting and manipulating several forms of data (quantitative and qualitative). Therefore, issues occurring from flood-induced disruptions in urban complex adaptive systems enable the digitisation and compartmentalisation of an urban SoS, a deepened understanding of the flood impacts on large and small scales, as called from the international DRR frameworks (i.e. SFDRR). GIS, offer a high quantity of tools, which are most commonly used for applying geoinformatics, offering the possibility to develop new tools for complex problem-solving.

Regarding the resilience concept towards mitigation of flood impacts in complex urban environments, this thesis proposes an urban ER system conceptualised with graph theory, CAS thinking, and network science, enabling resilience thinking for advanced and integrative resilience approaches. In this way, the thesis suggests combining the flood, transport, urban and spatial resilience concepts applied to urban ER systems. Respectively, resilience and the indicator approach followed enable further compartmentalisation of the SoS (urban ER system) for in-depth operationalisation assessments and provision of solutions for every system, network level and agent of the urban ER system. Therefore, it is also suggested that CAS thinking enables the identification of operational properties of a SoS with CAS properties (urban ER system) through the identification of the hierarchy of the interconnected systems and paves the ground for further magnification, enabling the isolation mentioned above of the issues and large-scale operationalisation assessments. As it has been argued throughout the text, such operationalisation assessments are enriching the so far silo-thinking DRM approaches, which still lack spatial assessment tools that are combining cascading impacts (risks) of various intensities, enabling fast decision-making through strengthened preparedness. Therefore, through the conceptualisation of an urban ER system and its resilience framework, it is proposed that resilience, for an overall system of an urban area related to its ER, is a composition of interdependent resilient components of the systems they compose it. That is, the interdependency of resiliencies of the systems of a SoS is suggested as a core component of an ERR concept and is consisted of:

- the resilience of the ER in urban environments - named urban ERR,
- the resilience of the under research urban ER system (i.e. fire brigade system),
- the resilience of the critical infrastructures used (i.e. road network and ERS buildings),
- the interrelation of the urban ERR with risk when it comes to a disruptive event (flood) that reveals an adaptive resilience cycle; through its resilience main characteristics (4Rs) of the

urban ER system under the stressor of various flood intensities, providing opportunities for enhancement of the resilience capacities of the systems.

The flood events reveal how the urban ER system can cope with the flood due to these 4R features (robustness, redundancy, resourcefulness and rapidity of response). In the thesis, and with the utilisation of the CAS theory, the road network is identified as higher in the system's hierarchy. Therefore, following the conceptualisation of the suggested ERR framework, its resilience, i.e. TTR, for timely ER under the stressor of floods, is of focus and is considered the primary resilience identifier for the overall urban ER system resilience. In general, the revelation of the coping capacity of the timely urban ER under flooded conditions is in the ERR concept, the TTR of the ER road network. TTR is proposed as a resilience identifier on a network level, which serves as a combinatory node between the concept of risk and resilience. TTR's operationalisation reveals the complex behaviour of the ER road network regarding its ER efficiency provision and, consequently, the urban ER system. Specifically, TTR is assessed after exposure and vulnerability assessments, which are identifiers of the absorption capacity of the system and the adaptation and transformation capacity of the urban ER system under the stressor of floods.

Furthermore, for an application of the suggested ERR operationalization methodology to several case study areas and several urban ER systems (fire brigade systems, EMS) and CI networks, a multi-criteria indicator is suggested. The risk-based time-dependent accessibility indicator, the RITAI, is designed to spatially analyse the aforementioned interdependent resilience components of an urban ER system with applied geoinformatics, which include:

- a GIS-based methodological framework and a developed GIS-Toolkit for large-scale spatial assessments of the robustness, the redundancy of the road network, transferring information from raster to line vector data and automatically calculating the flood-impacted road-type dependent FFS, on a road segment level,
- risk-informed updated road network databases resulting from the developed GIS-Toolkit and GIS calculations of the flood-impacted travel times on a road segment level,
- spatial assessments of the robustness, redundancy and the resourcefulness of the ER road network for timely ER, with exposure and vulnerability assessments associated with FFS and TTR changes, on the scale of analysis,
- flood impact curves (statistical analyses) of the robustness, redundancy and resourcefulness, for detailed, in-depth analyses of the flood risk to the ER, *v)* network analyses for connectivity and risk-based time-dependent accessibility assessments revealing the impact of the flood risk to the performance of an urban ER system (i.e. fire brigade system) under ER,
- the aggregation of information with GIS-based calculations and geovisualisation techniques after simplifying information with fuzzy variables and classification.

Therefore, this thesis contributes to the overall goals of saving lives, as mentioned previously, which is a strategic goal of civil protection and emergency management by cutting down losses on CI functioning - a strategic goal of CIP -, with the provision of more detailed risk analyses in large-scales (intraurban). The aim is to enhance community resilience by enabling emergency responders, civil protection officials and critical infrastructure planners to utilise:

- an operationalisation adaptive resilience framework for SoS with CAS properties, which are furthermore fostering collaboration between end-users (agents of the urban ER system),
- large-scale spatial assessments explicitly assessing the 4Rs,

- adaptive and transformative pre-routing plans, according to rescue equipment capacities, strengthening the preparedness for rapid response through enhancement of the redundancy and resourcefulness of the urban ER system, in case of blackouts, enhancing their geospatial preparedness for such events, but also providing the possibility for operations under sub-optimal conditions,
- service area analyses, considering the status of the ER road network in regards to the resourcefulness levels for timely ER provision, revealing the risk to each fire brigade station,
- flood-impact curves for flexibility testing and identification of "no-recovery" thresholds of the urban ER system in case of floods,
- geovisualisation techniques for aggregation of information from large-scales to smaller and vice versa, fostering the exchange of information between the ERS system and CI operators, providing the means and tools for enhanced collaboration towards the safety of the population, the safety of the emergency responders and security of the interconnected CI in an urban ER system.

Categorically, the adaptive operationalisation spatial upscaling methodology suggesting the multi-criteria RITAI applied to the Cologne fire brigade system, after application of the GIS-Toolkit for the four selected flood scenarios of the city of Cologne, returned four updated ER road network databases with information per one-meter road segment in regards to the FD and the recalculated flood-impacted FFS. The benchmarking of the calculation process to four FD classes, including the zero FD, allows for the configuration of the operationalisation process according to the rescue vehicle capacity of Cologne's fire brigades. The classification of the FD levels per road segment of an urban ER system is easily configurable, especially with the developed GIS-Toolkit. It is suggested that they should be classified to consider the safety of the population (timely ER provision with a potential extension of connectivity) and the safe driving mobility by the emergency responders under flooded waters, which, according to the rescue vehicle capacity, integrates the decision-making and the ERR assessments the safety lens perspective. Accordingly, the detailed geolocated identification of critically flooded ER road network areas, specifically in urban areas, is vital for the operation and management, specifically in emergencies, may be possible.

The large-scale GIS-based upscaling suggested methodology and the toolkit developed aim to advance the traditional urban management, and emergency response approaches, providing the theories, methods and tools for a strengthened preparedness for response to riverine floods and flash floods, which in intraurban systems, are under-researched [179, 233, 254]. The large-scale methodological workflow suggested in the thesis can be utilised and enriched further in combination with various theories, apart from those combined in the thesis, graph and fuzzy set theories, for further information before or during emergencies. Such theories are indicatively: i) the 'decision tree', which handles non-linear relationships in complex systems [443], ii) the 'systems dynamics', which can be used in CI protection tools as suggested from [426], and provide feedback loops [112, 444], indicating connections and consequences between various CI, and iii) the ' high-level architecture', used for the modelling and simulation of complex distributed systems [445] and multi-agent systems for resource optimisation after strong earthquakes [446].

Additionally, as previously stated, it can also be utilised for agent-based modelling, producing dynamic interactions between real-world systems [447]. Specifically, is utilised for i) agent-based validation techniques for geospatial simulations [228], ii) risk-based flood incident management purposes [167], iii) integration with GIS for large scale emergency simulations [375], iv) urban flood risk management frameworks [448] and v) synergetic mechanism simulations in emergency response [106].

Throughout this thesis, it is also discussed that it is essential to understand the dynamics of the urban ER systems to enhance the urban safety of the dense population and the densely interfaced CI, considering safety aspects, including safe driving through flooded waters.

End-users, such as emergency managers, together with city managers, urban planners, traffic planners, CI planners and various decision-makers in urban settings, need to start cooperating and enhance their resilience, towards EWE-induced perturbations, through collaborative training activities that can be fostered or initiated with the concepts and methodologies that this thesis brings together. As mentioned throughout the thesis, exchange of information, i.e. cyber interdependency of the participating agents in an urban SoS, such as the urban ER system proposed, must be an iterative process (adaptive and transformative management) and overcome issues of sensitivity of data, which often degrades the efficiency of timely-response. Scientists have underlined the lack of information, even though it plays a significant role in the effectiveness of ER [449, 450]. Therefore, this thesis also provides the means to overcome the exchange of sensitive data, which most disaster managers and CI operators cannot or refuse to exchange. The thesis further suggests that with the provision of detailed quality time-critical aggregated information, as outlined throughout the application of the methodology and has been under the scientific focus too for years [449-451], the exchange of information is enabled towards faster resilience-based decision-making and enhanced response capacity.

Moreover, the spatial resilience-informative matrixes can be further enriched with ways presented throughout the discussion sections, fostering easier collaboration and exchange of sensitivity on the one hand but aggregated information on the other hand. Through the weighting processes suggested in the methodology for many scales and levels of an urban ER system applying geoinformatics, aggregation of information is asserted that it is not jeopardising data sensitivity issues that mostly come with geolocated information. Furthermore, the ERR concept as applied to the fire brigade system and outlined in the sections of the thesis propounds the further utilisation of the:

- *location theory* [264, 452] solving its main issues, such as the "service area covering" and the "location-allocation" [242, 269, 338, 417, 453], combined with the tool of the Analytic Hierarchy Processes [454] introduced by [455, 456] for the support of decision-making and has been so far used in accessibility indexes [344],
- *prioritisation of restoration concept* of individual systems and CI towards self-organisation and improvement of the urban ER system following the restoration interdependency mentioned in [457] and the *reconstruction* as a factor for redundancy analyses [301],
- *optimisation of the resources* through the handling of the uncertainties occurring in risk management strategies for urban SoS with adaptive, transformative and collaborative management [22] of the participating agents fostering,
- *optimal coordination of the agents* (organisations) through iterative communication and synchronisation of their operations towards time-effective management and response, as also suggested in [80].

Emergency management must shift the focus from simple risk-based decision-making to hazard-related resilience-based decision-making, considering its resilience for response to various hazards as a priority of focus for further advancement, strengthening and enhancement of safety, both of the population but of the emergency responders as well. Uncertainties in the operation phase, specifically in urban complex areas, stressing the decision-makers for quick responses must be part of further investigations towards a deepened understanding of the occurring and emerging risks for further enhancing the urban community resilience.

The conceptualisation of the resilience framework of a SoS in an operational way and specifically of the ERR as applied in a complex urban area and its fire brigade system is the first step towards enhancing the resilience of emergency rescue services to hazardous events e.g. floods. Flood impact assessment in urban areas on complex SoS, for a strengthened preparedness for response, as called from the SFDRR, needs high-resolution operationalisation methodologies and resilient architectural design to capture risks in all scales and levels, enhancing the interdependent resilience of its systems through constant adaptation and transformation. Furthermore, in this era of the increase in frequency and intensity of EWE, the management of the cities must consider and proceed with collaborative, adaptive and transformative management strategies. Such strategies, towards enhancing urban resilience, community resilience, and CI resilience, should have a mitigation focus rather than a focus on enhancing the preparedness for response to the extremes and known, until the capacity of prediction, futures. Therefore, it is argued that extreme, escalating, and compound events' scenarios must be the future of hazard-related resilience assessments, considering not only the safety of the population but also the operational safety of the emergency responders and the security of the interrelated critical infrastructures (CI), bringing the resilience thinking to the forefront as a priority. Exchange of information between the different disaster, emergency and urban management agents in urban areas can be supported with aggregating methods and applied geoinformatics, fostering future collaborations for enhanced preparedness to respond to escalating and compound events. Finally, the suggested conceptualised framework of ERR to floods as applied to emergency rescue services and its operationalisation methodology, utilising applied geoinformatics, offers an exchange of multi-scale, multi-level and multi-network information, can be either used compartmentalised or as a whole. This flexible and interdisciplinary character of the concept can be valuable for further applications to various emergency rescue services with various hazard scenarios in different urban districts, counties, and countries, where floods are not typical for enhanced emergency response and safety.

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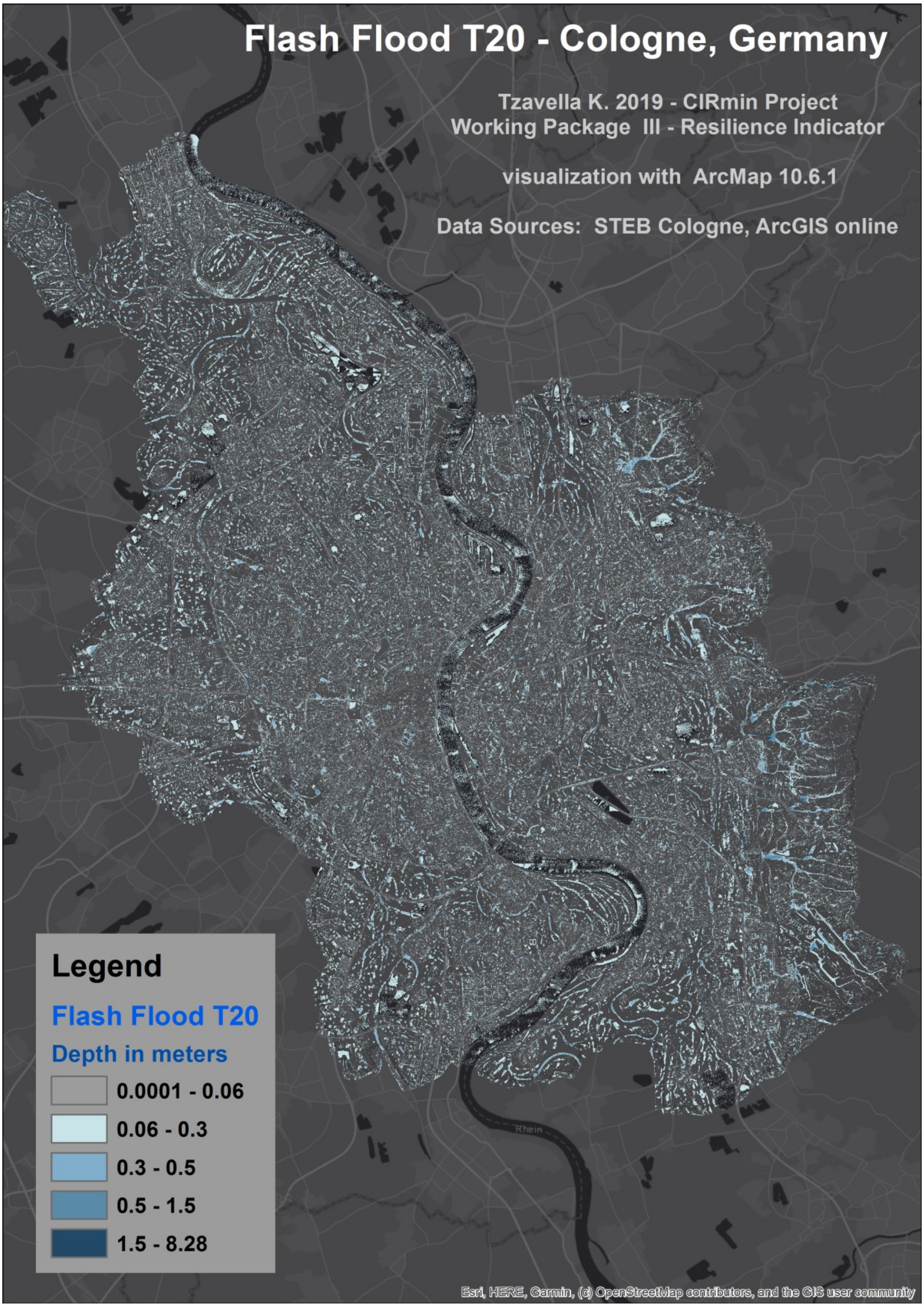
APPENDIX A – Data&GIS-based spatial upscaling workflow

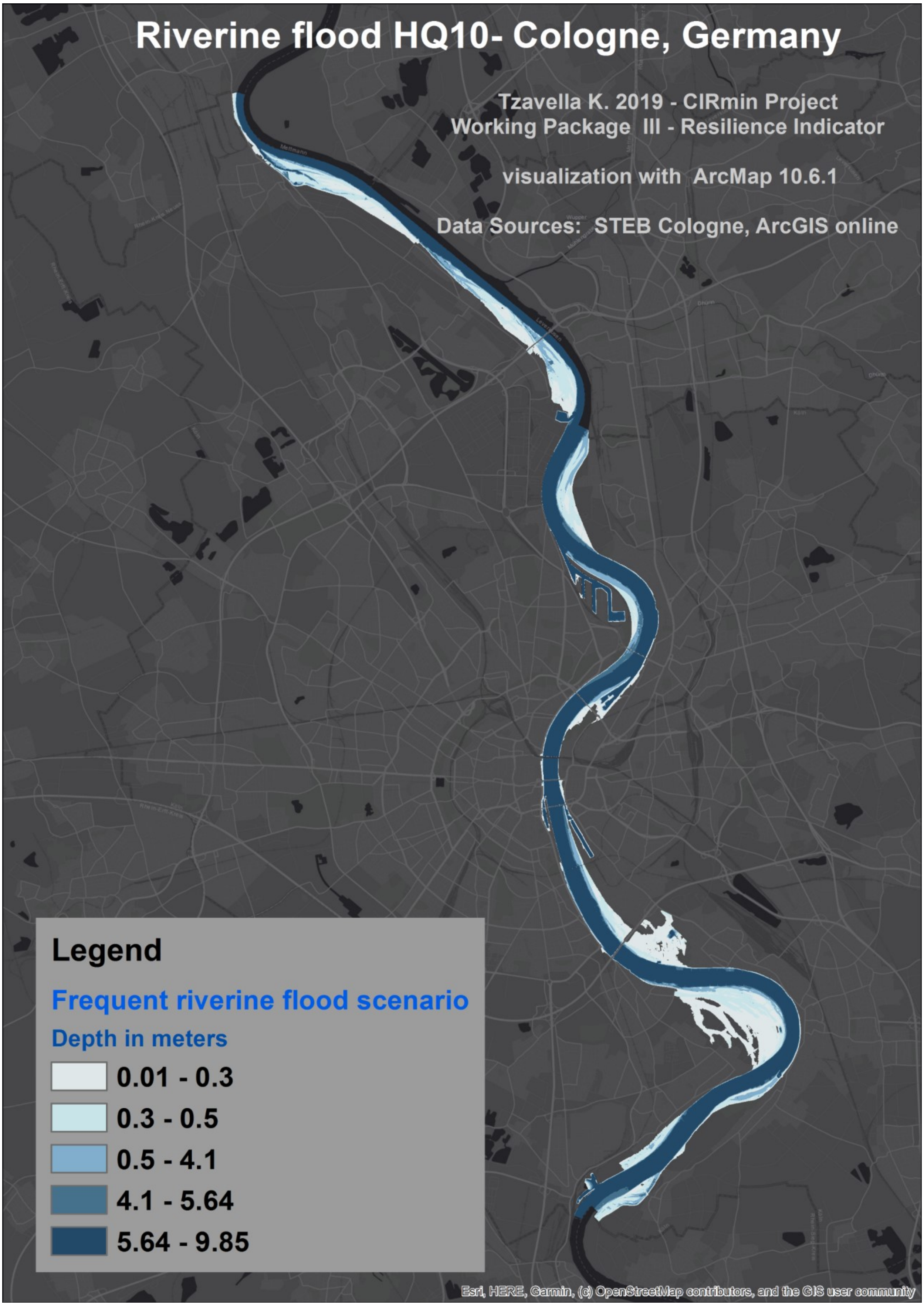
Rasters of the flood scenarios selected for the case study area of Cologne for simulation and “stress-test” purposes

Flash flood T20 (frequent scenario) – high resolution raster model

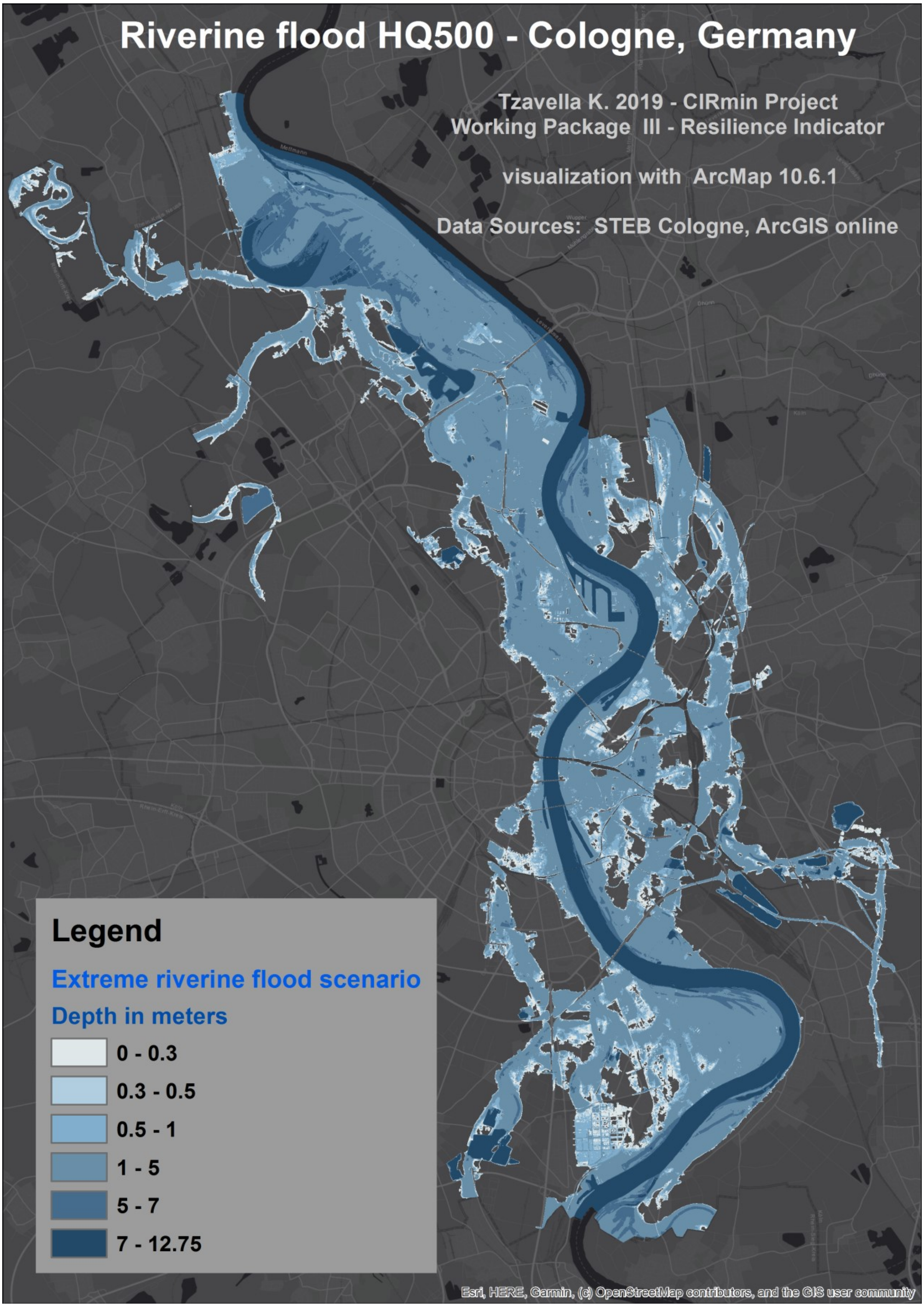


Flash flood T100 (rare scenario) - high resolution raster model

Frequent riverine flood scenario H10 with 10-years of flood occurrence probability (high-resolution raster model)

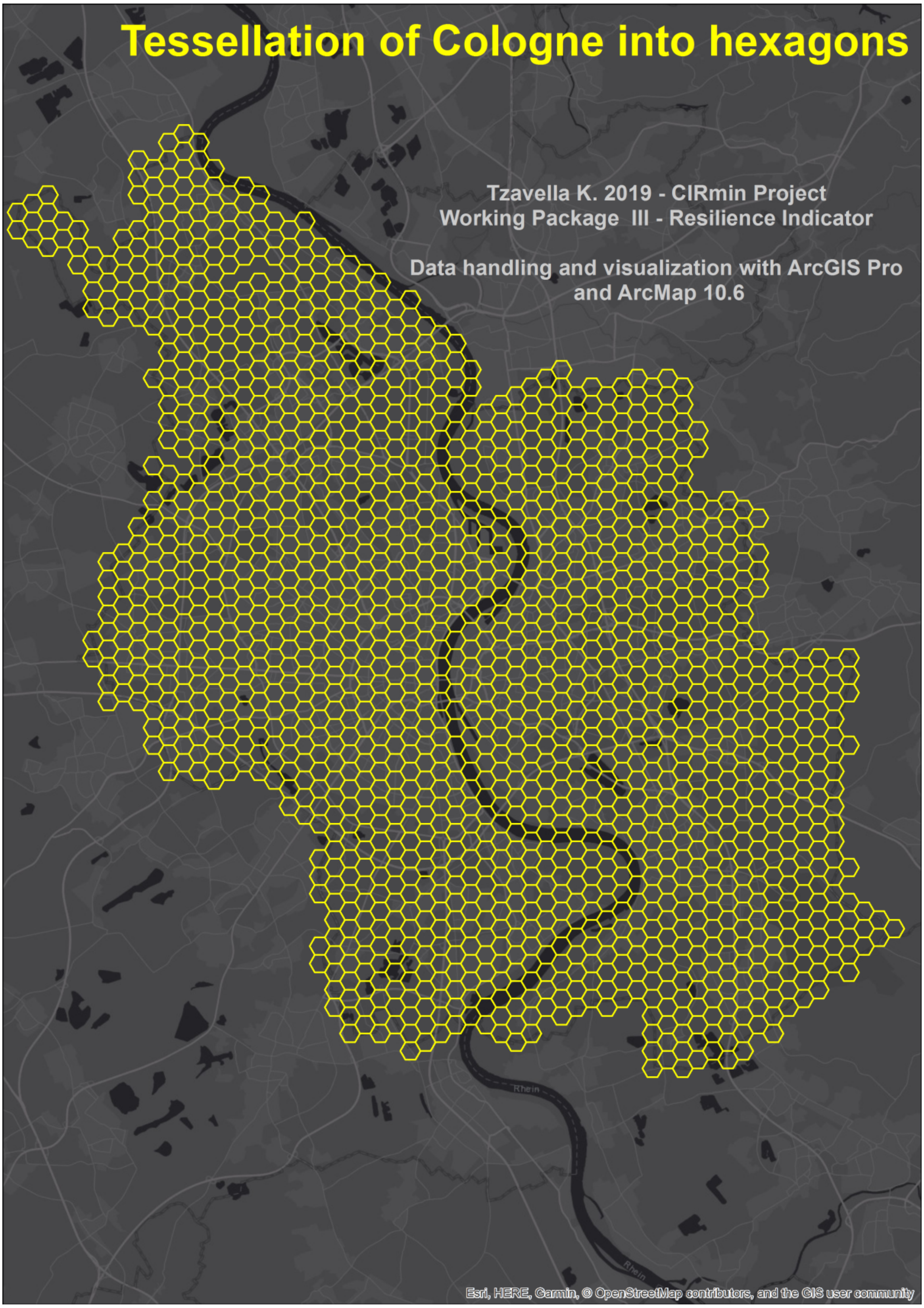


Extreme riverine flood scenario HQ500 with >500-years of flood occurrence probability (high resolution raster model)

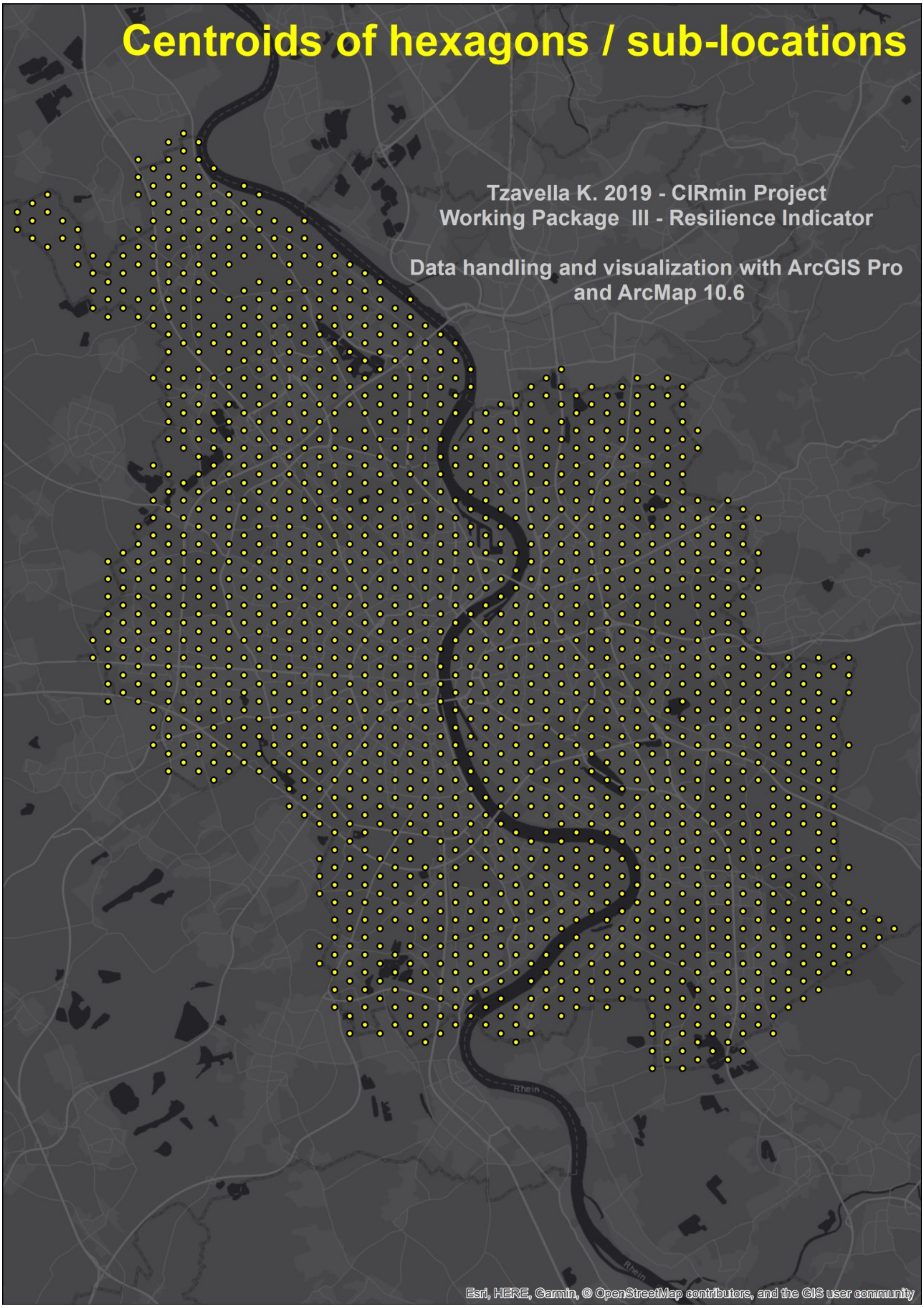


Tessellation and geometric representation of the city units of Cologne

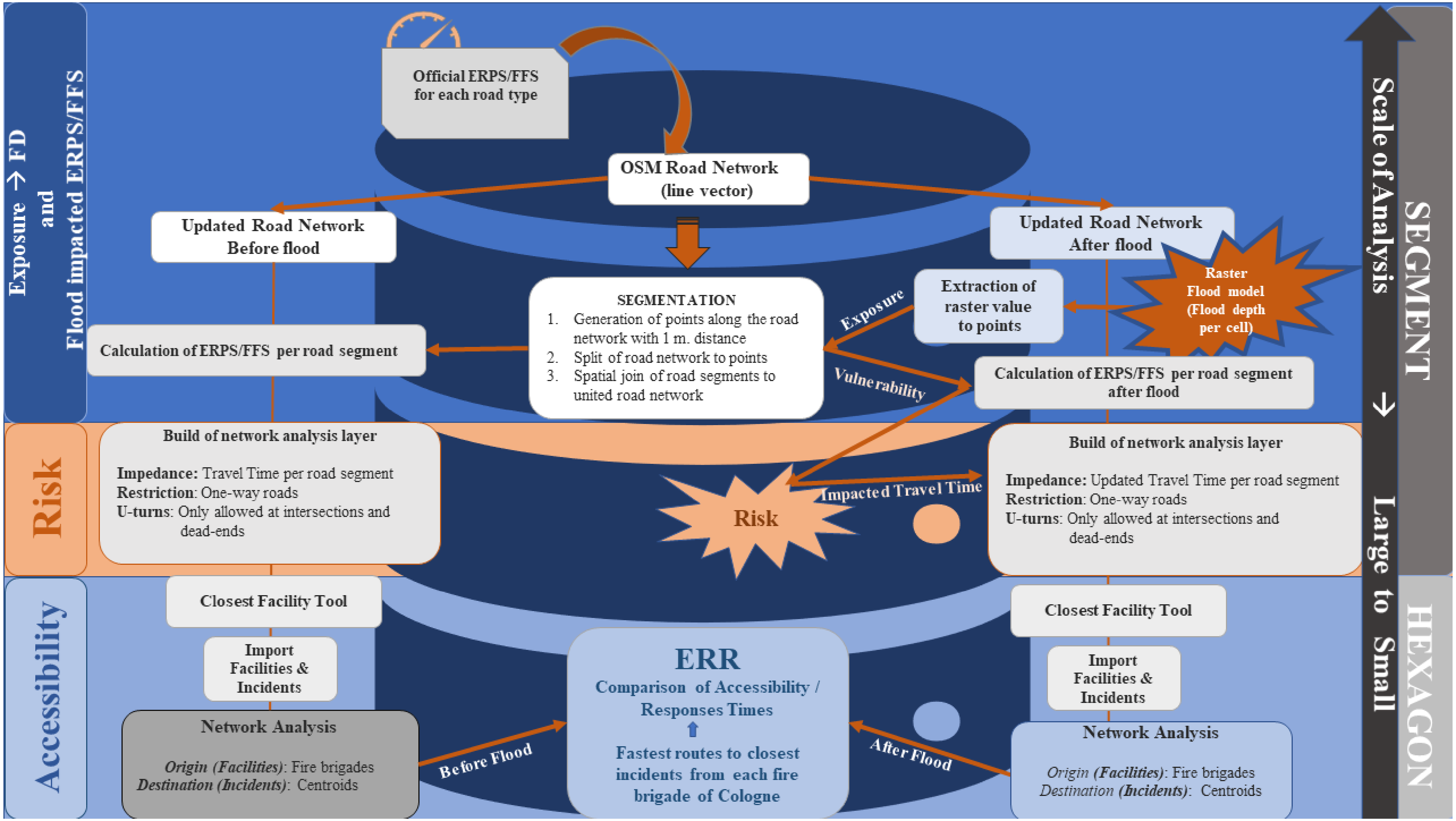
Hexagonal spatial matrix of Cologne (hexagonal city units in the form of hexagons of 0.25 km$^{2)}$



Transformation of the hexagons into their geometric representatives (centroids)



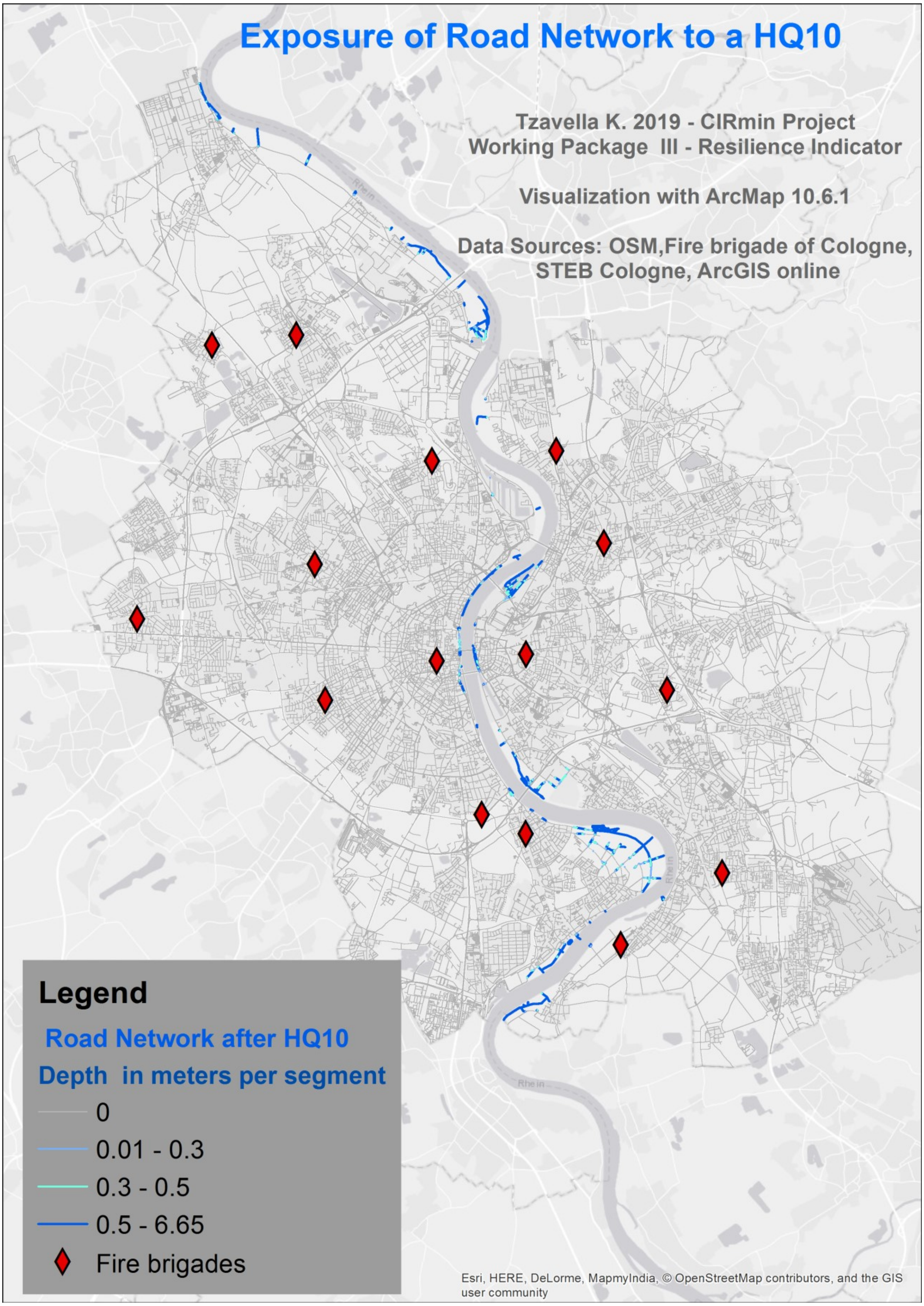
Operationalisation methodology of ERR to floods with a GIS-based upscaling spatial assessment workflow resulting in flood-risk informative ER road networks



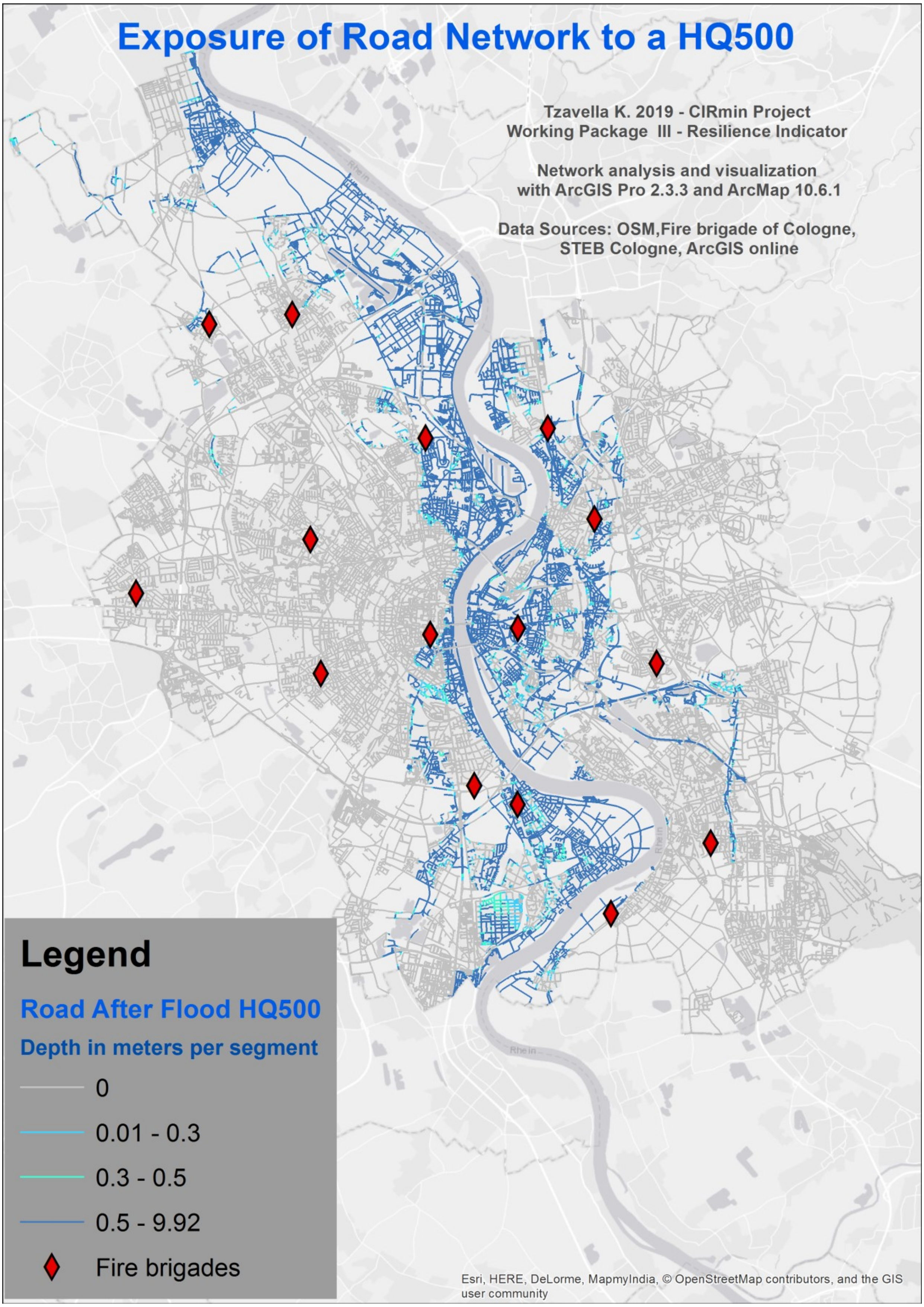
APPENDIX B - Results

Exposure of the road network to floods

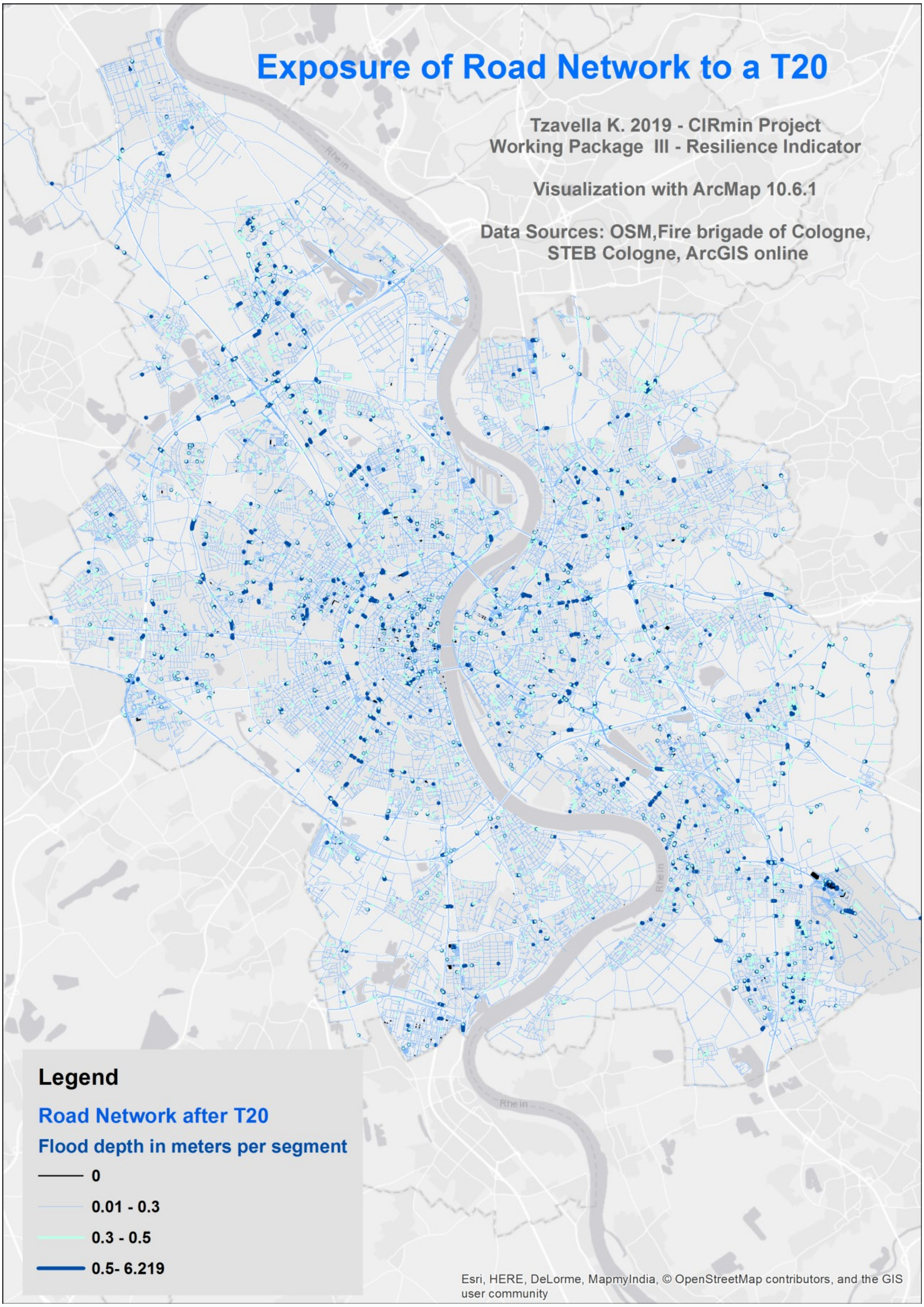
Exposure of the road network to the regular riverine flood HQ10



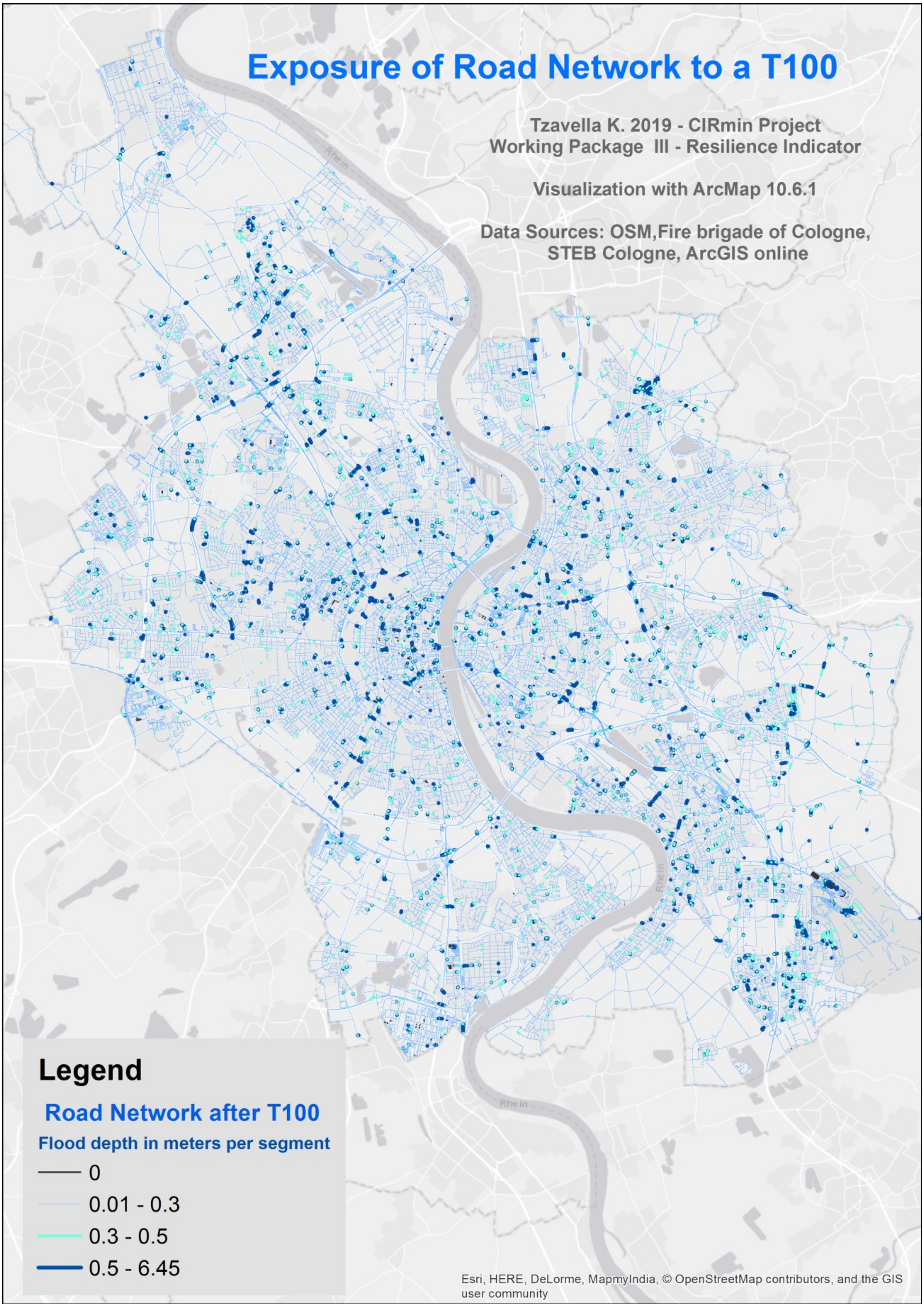
Exposure of the road network to the regular riverine flood HQ500



Exposure of the road network to the regular flash flood scenario T20

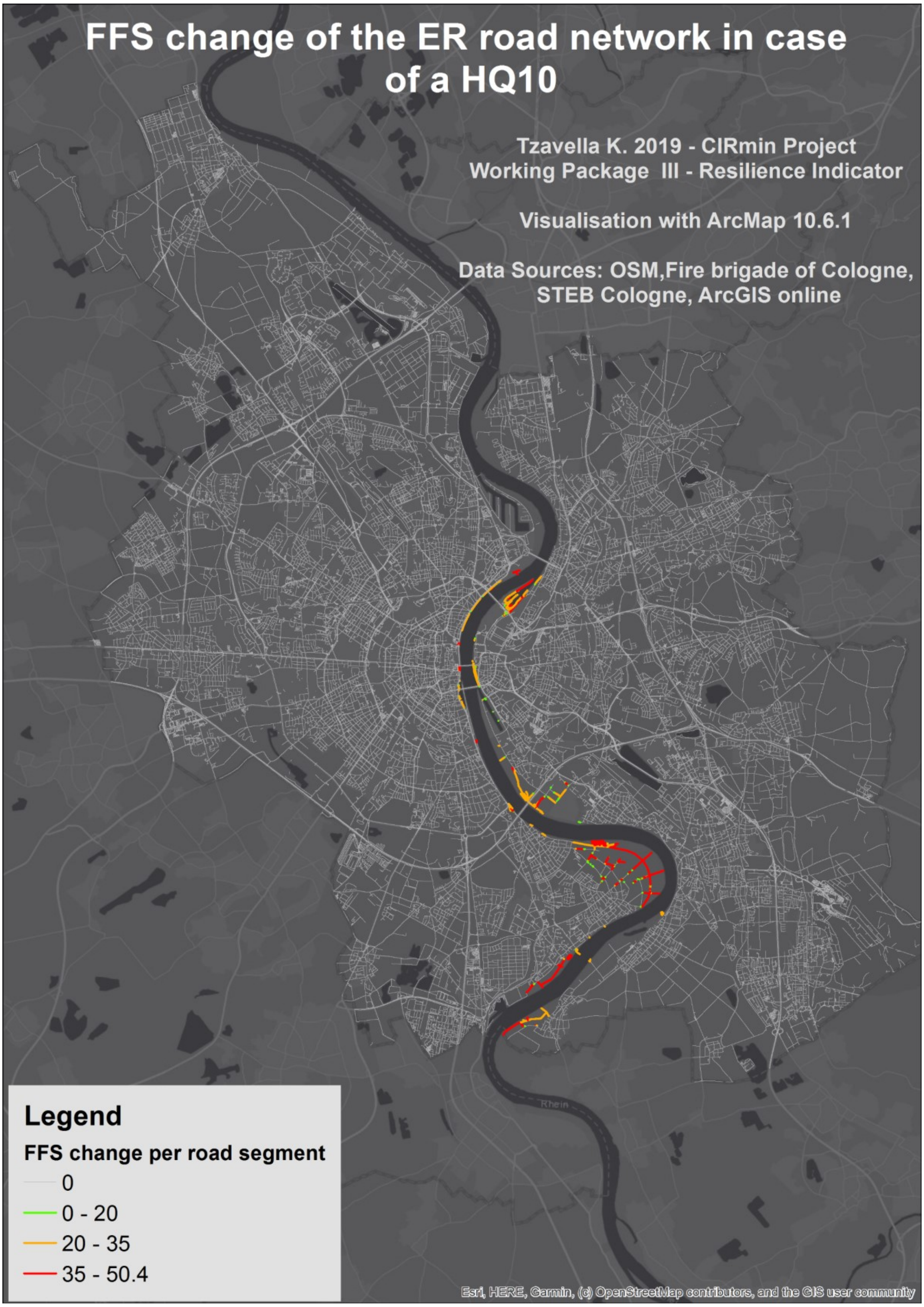


Exposure of the road network to the extreme flash flood scenario T100

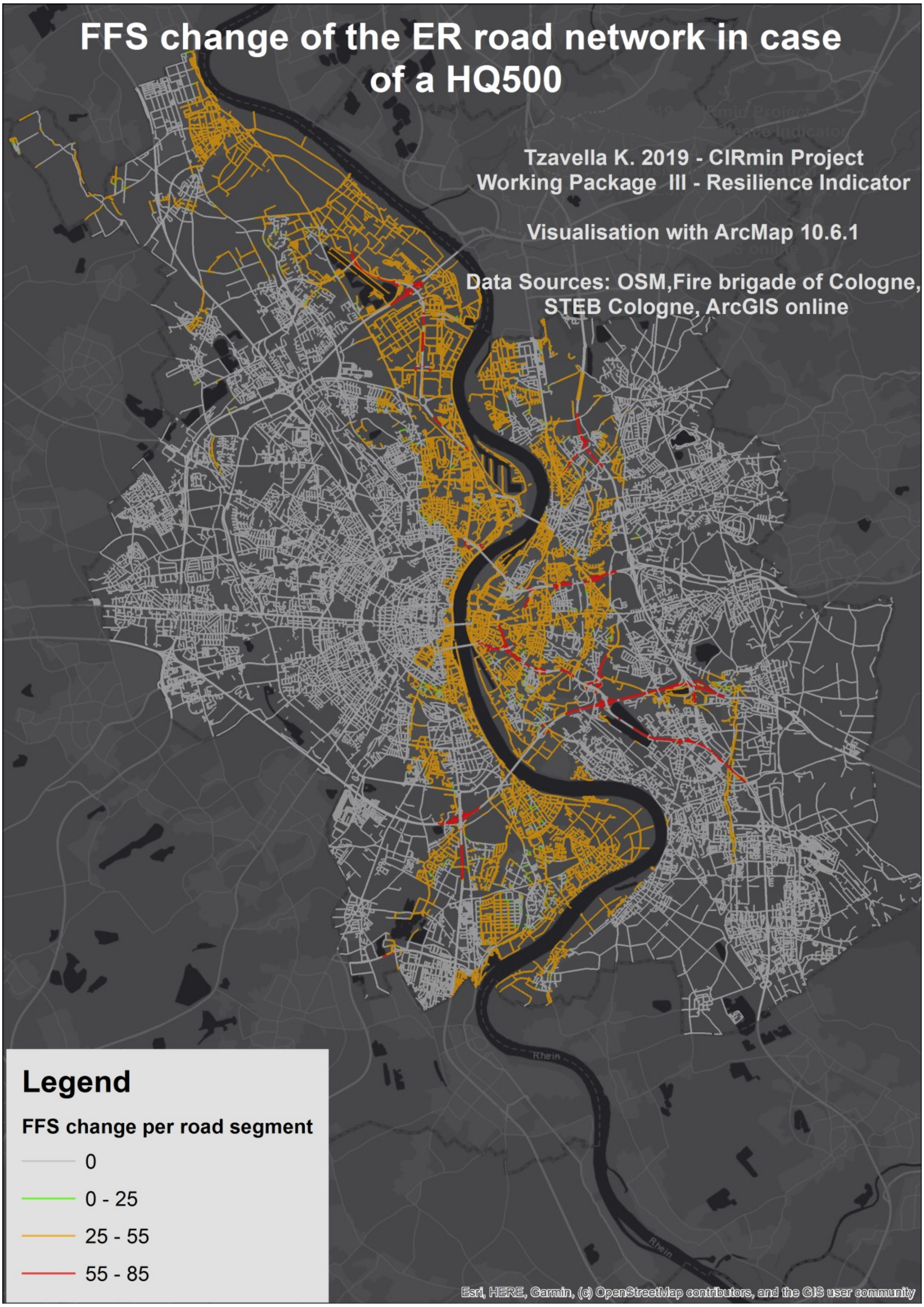


Classified $\text{FFS}_{\text{change}}$ of Cologne’s ER road network in case of the extreme flash flood of floods

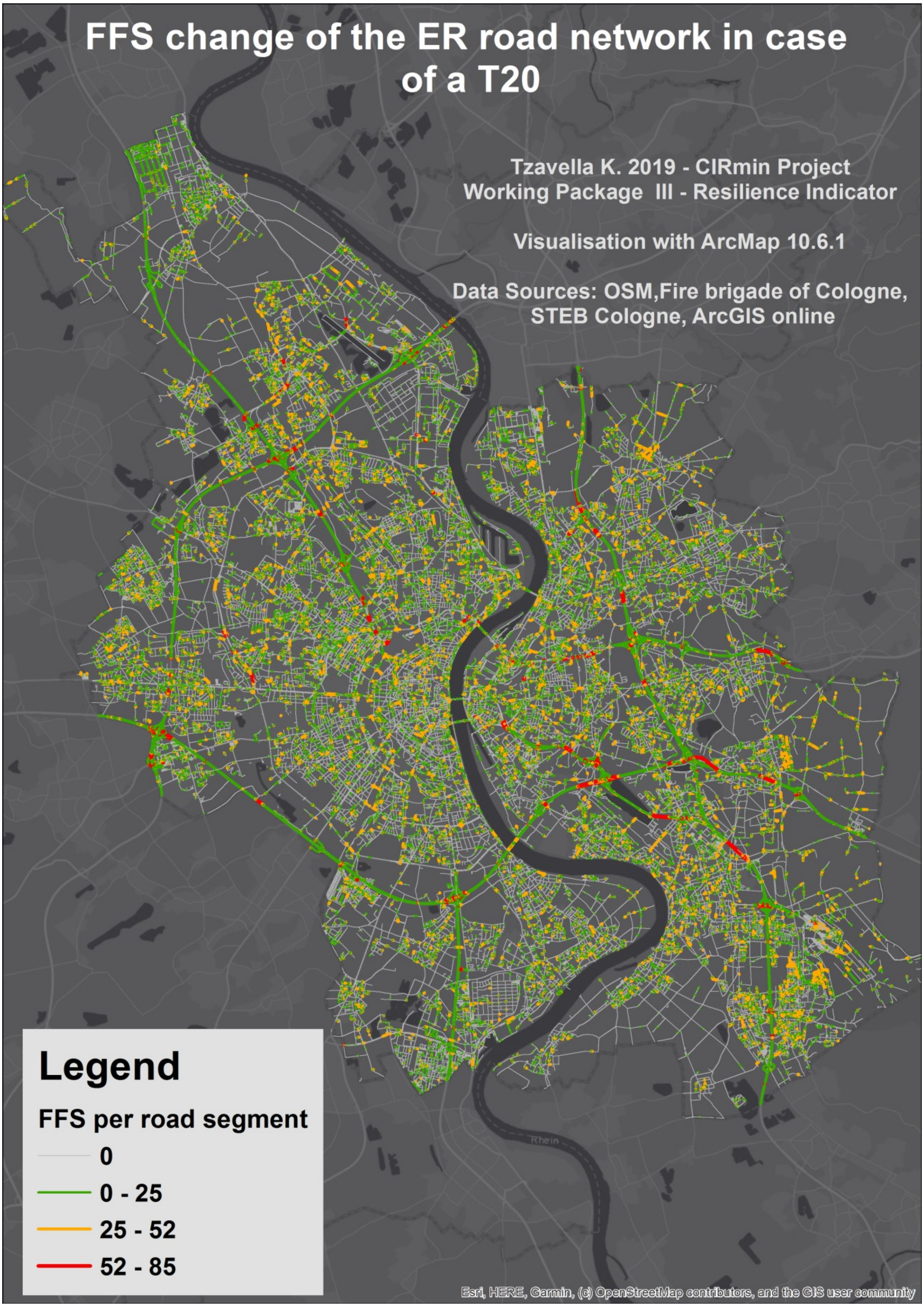
Classified $\text{FFS}_{\text{change}}$ of Cologne’s ER road network in case the regular riverine flood of HQ10



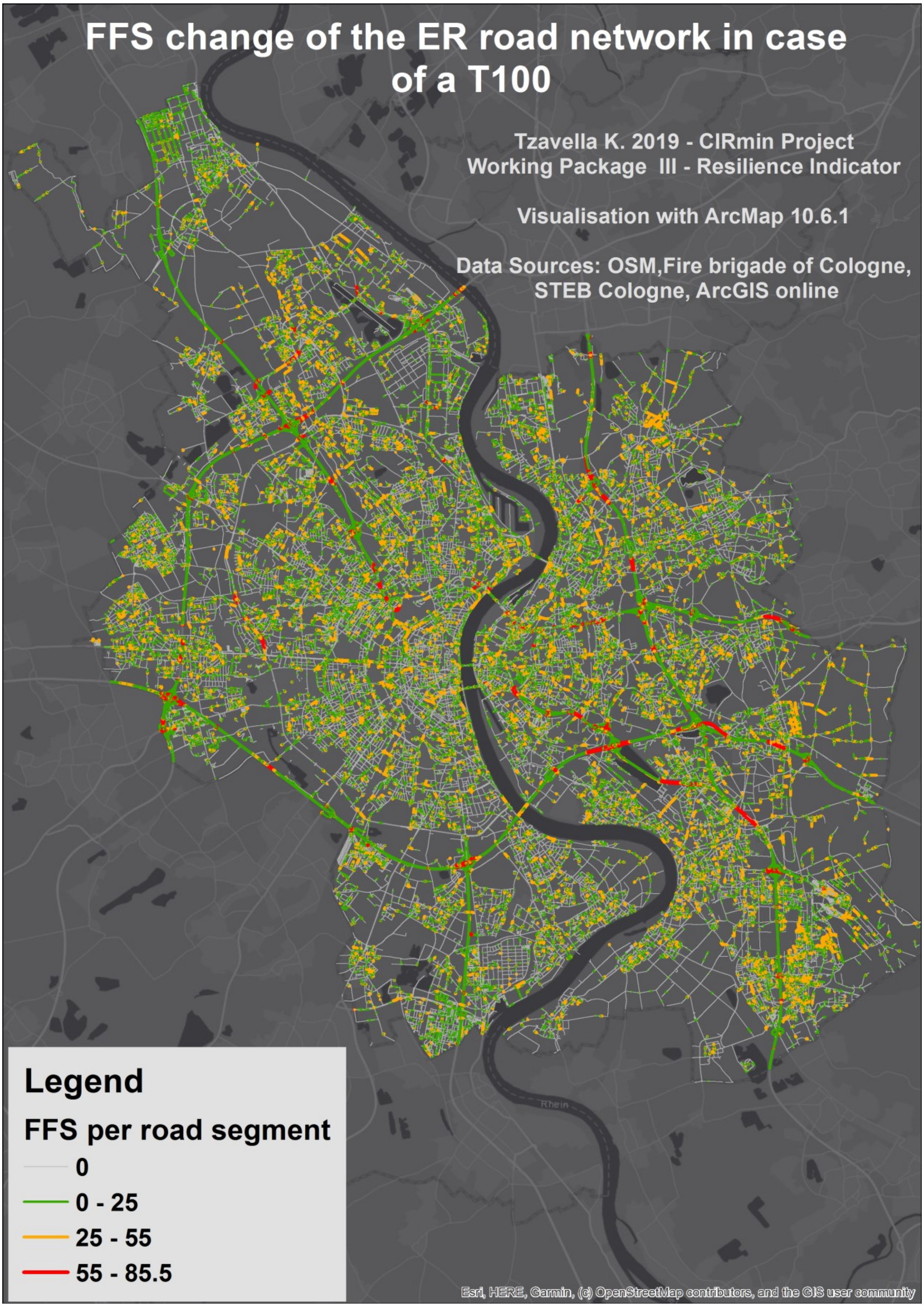
Classified $\text{FFS}_{\text{change}}$ of Cologne’s ER road network in case of the extreme riverine flood of HQ500



Classified FFS$_{change}$ of Cologne's ER road network in case of the regular flash flood of T20

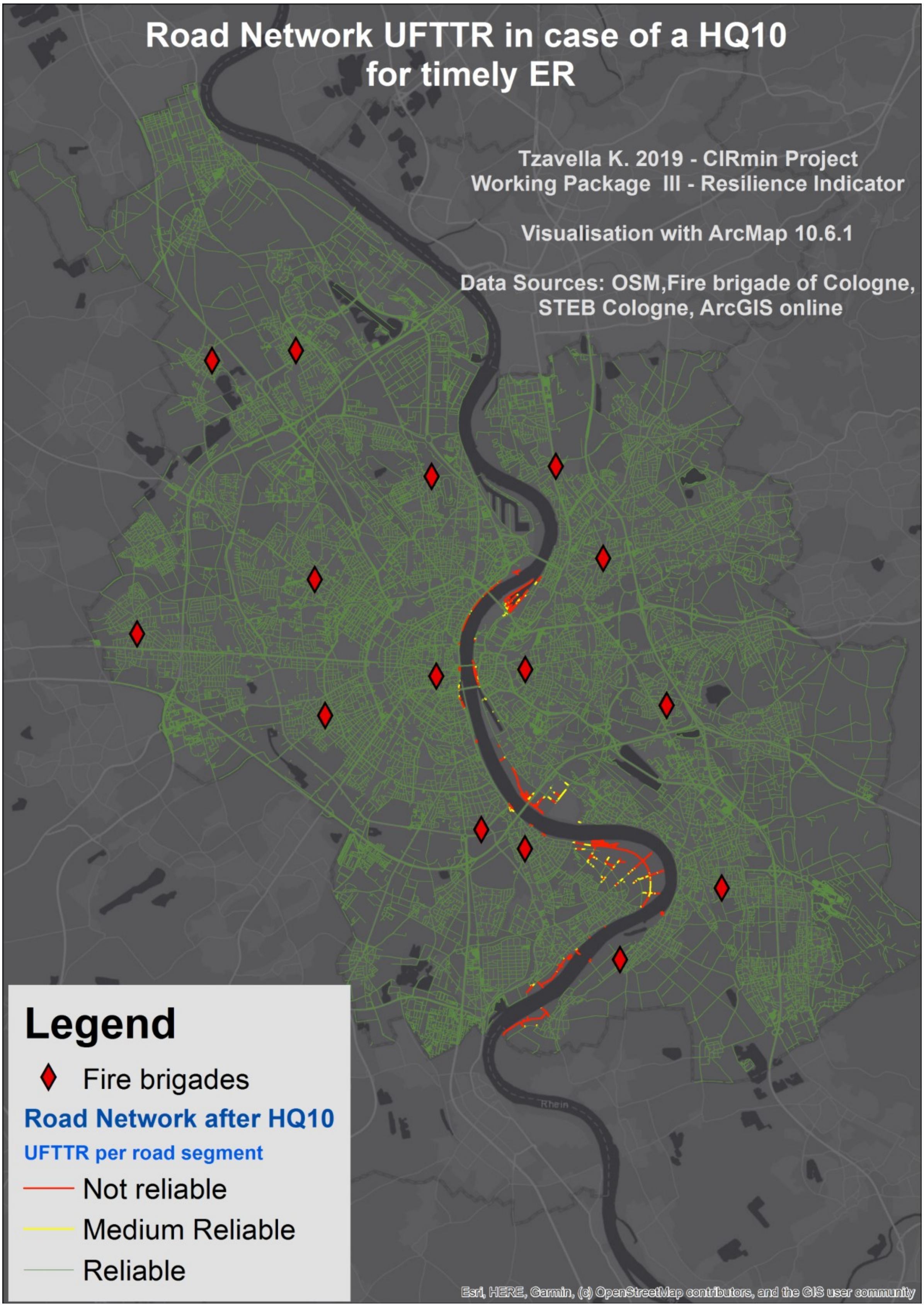


Classified FFS$_{change}$ of Cologne's ER road network in case of the extreme flash flood of T100

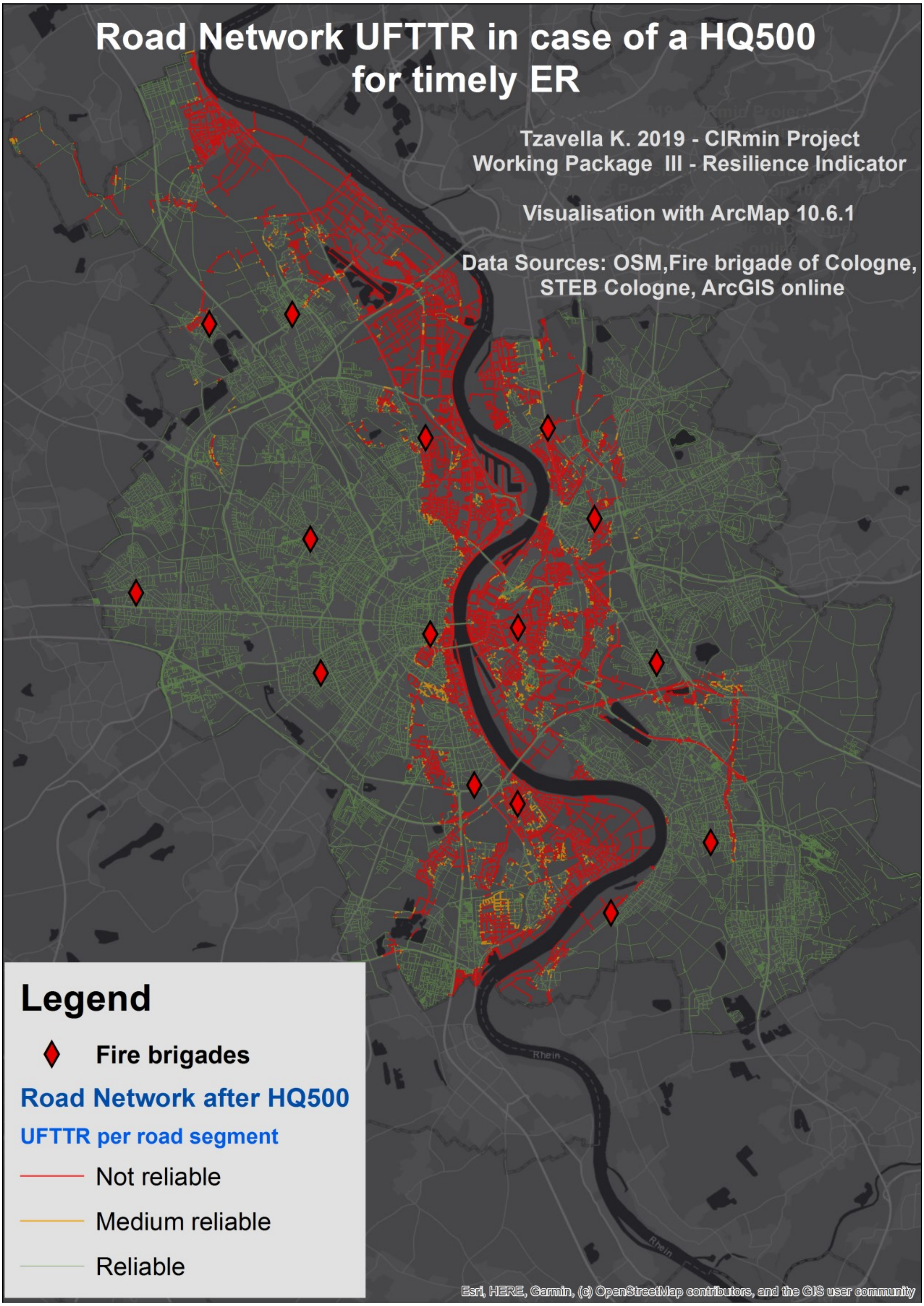


Classified Urban Flood Travel Time Reliability per segment (UFTTR$_j$) of Cologne's ER road network in case of floods

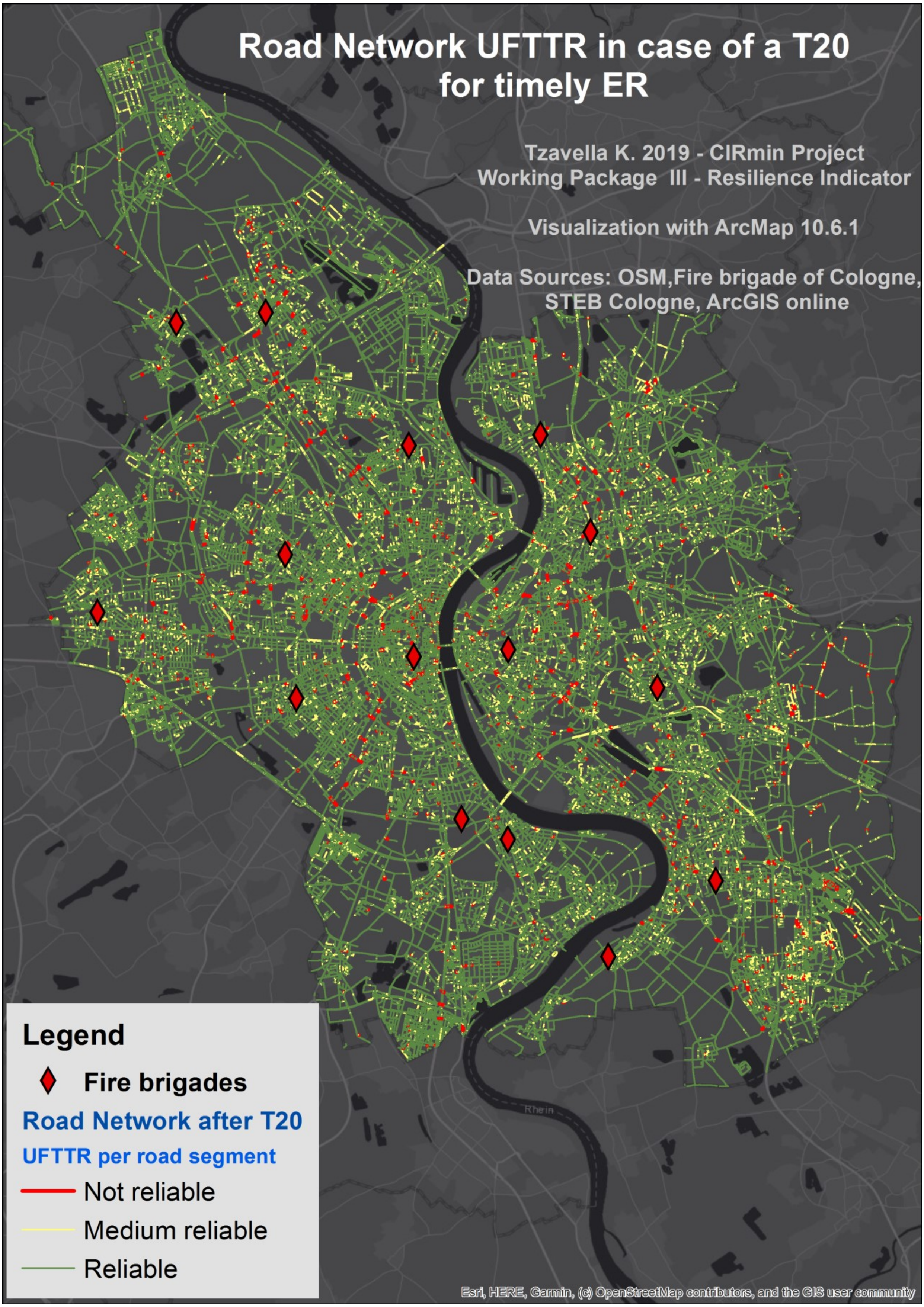
Classified UFTTR$_j$ of Cologne's ER road network after the regular riverine flood of HQ10



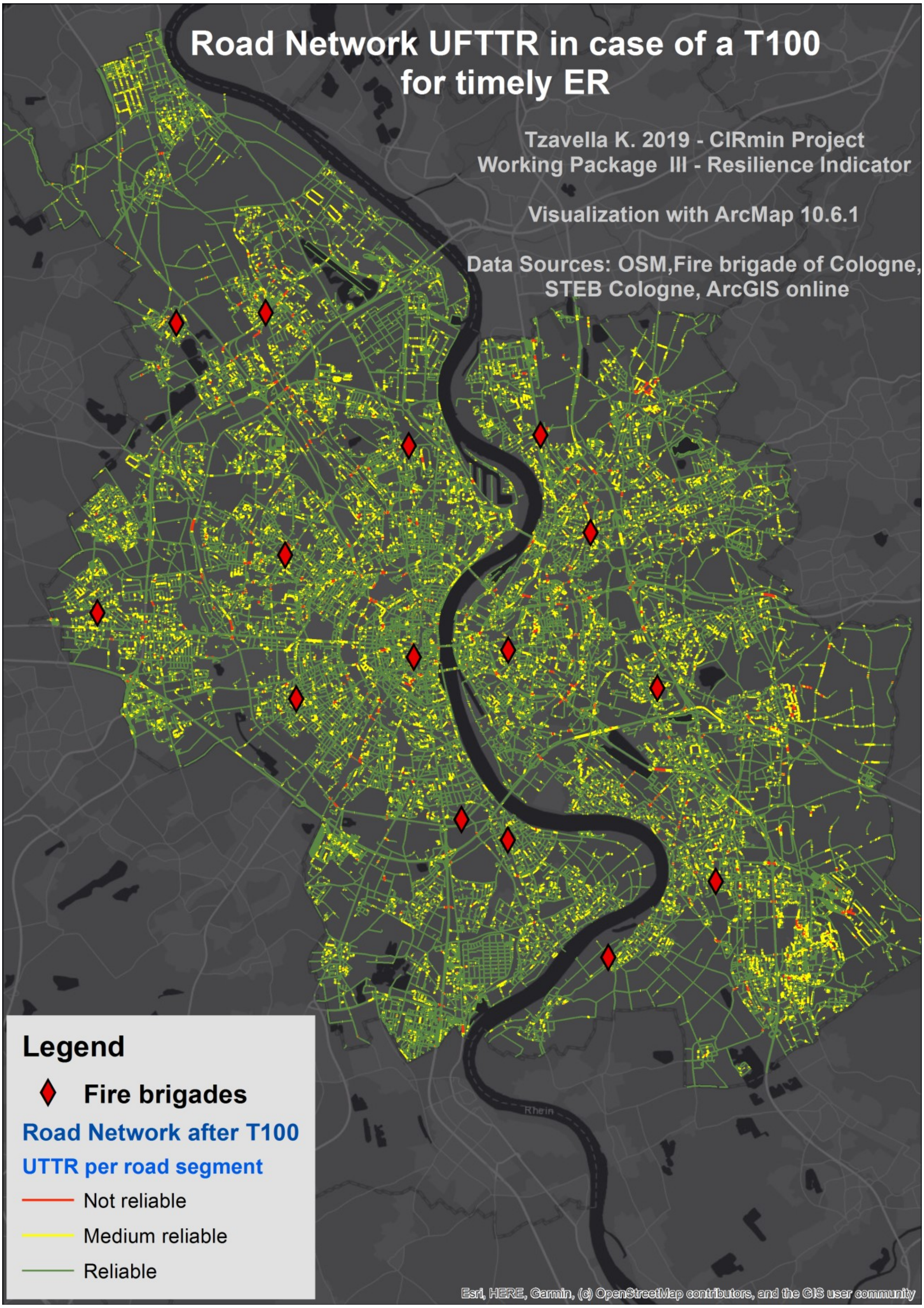
Classified UFTTR$_j$ of Cologne's ER road network after the extreme riverine flood HQ500



Classified UFTTR$_j$ of Cologne’s ER road network after the regular flash flood scenario T20

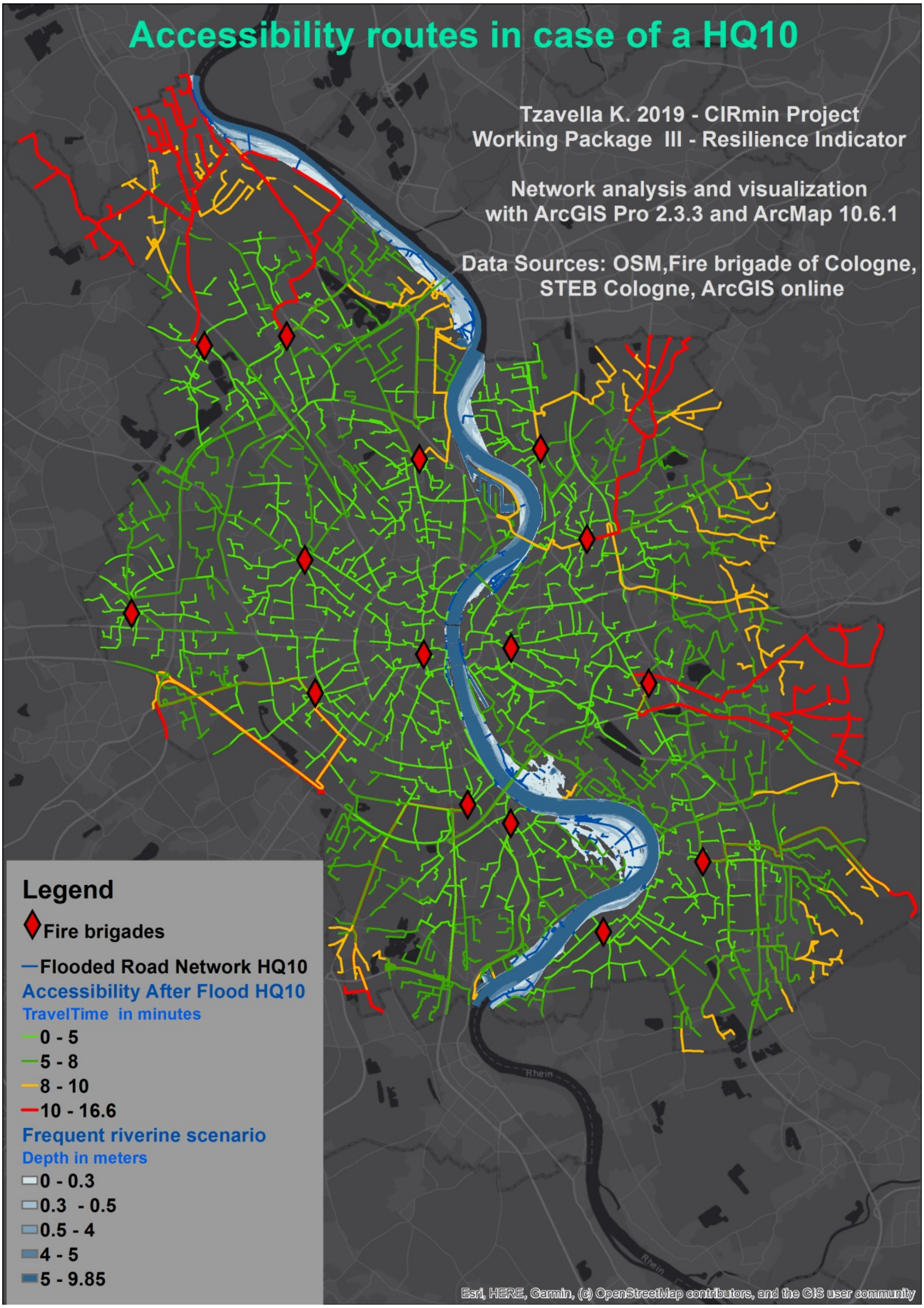


Classified UFTTR_j of Cologne's ER road network after the extreme flash flood scenario T100

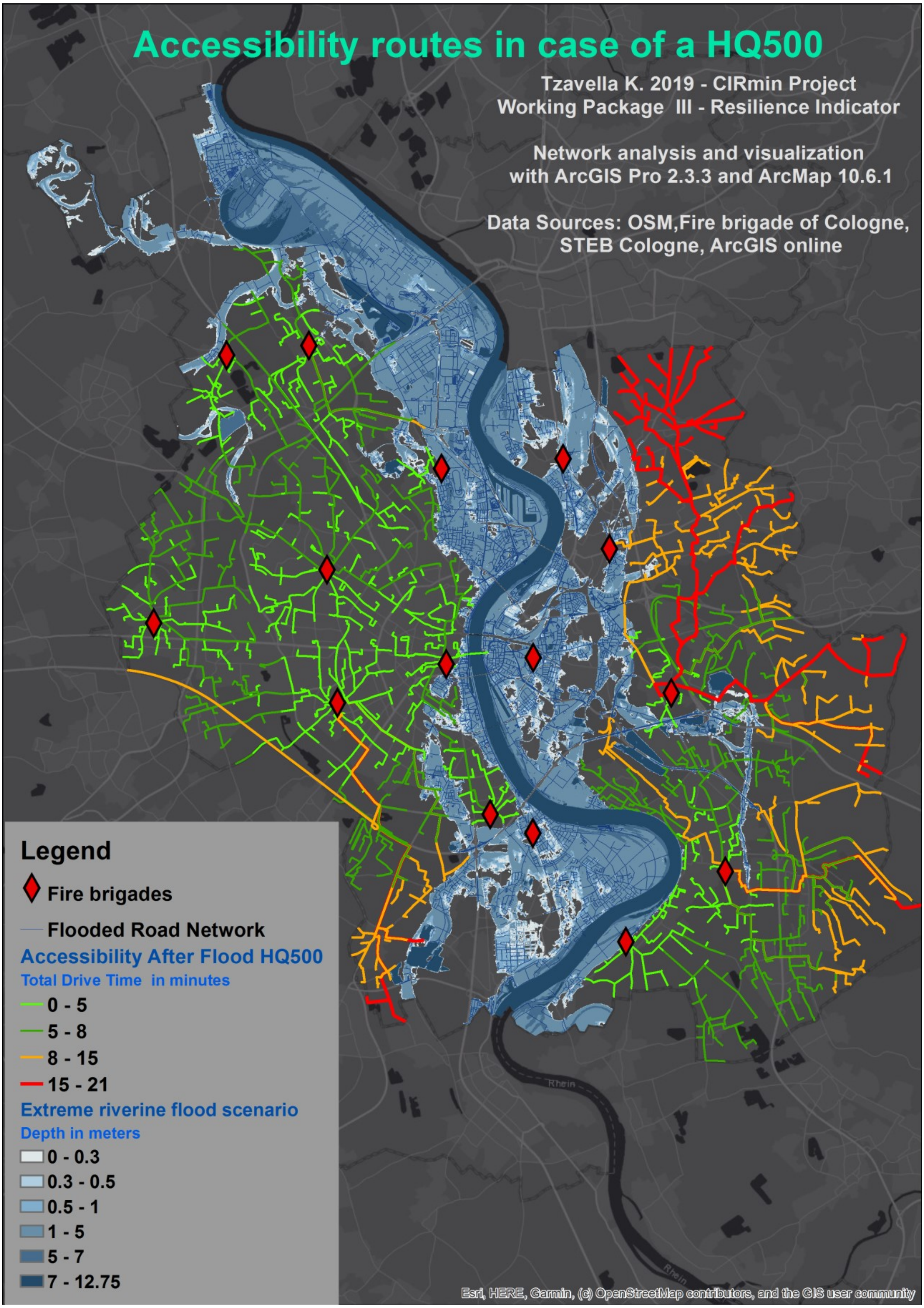


Risk-based time-dependent fastest accessibility routes for Cologne’s fire brigades to the nearest city units in case of floods

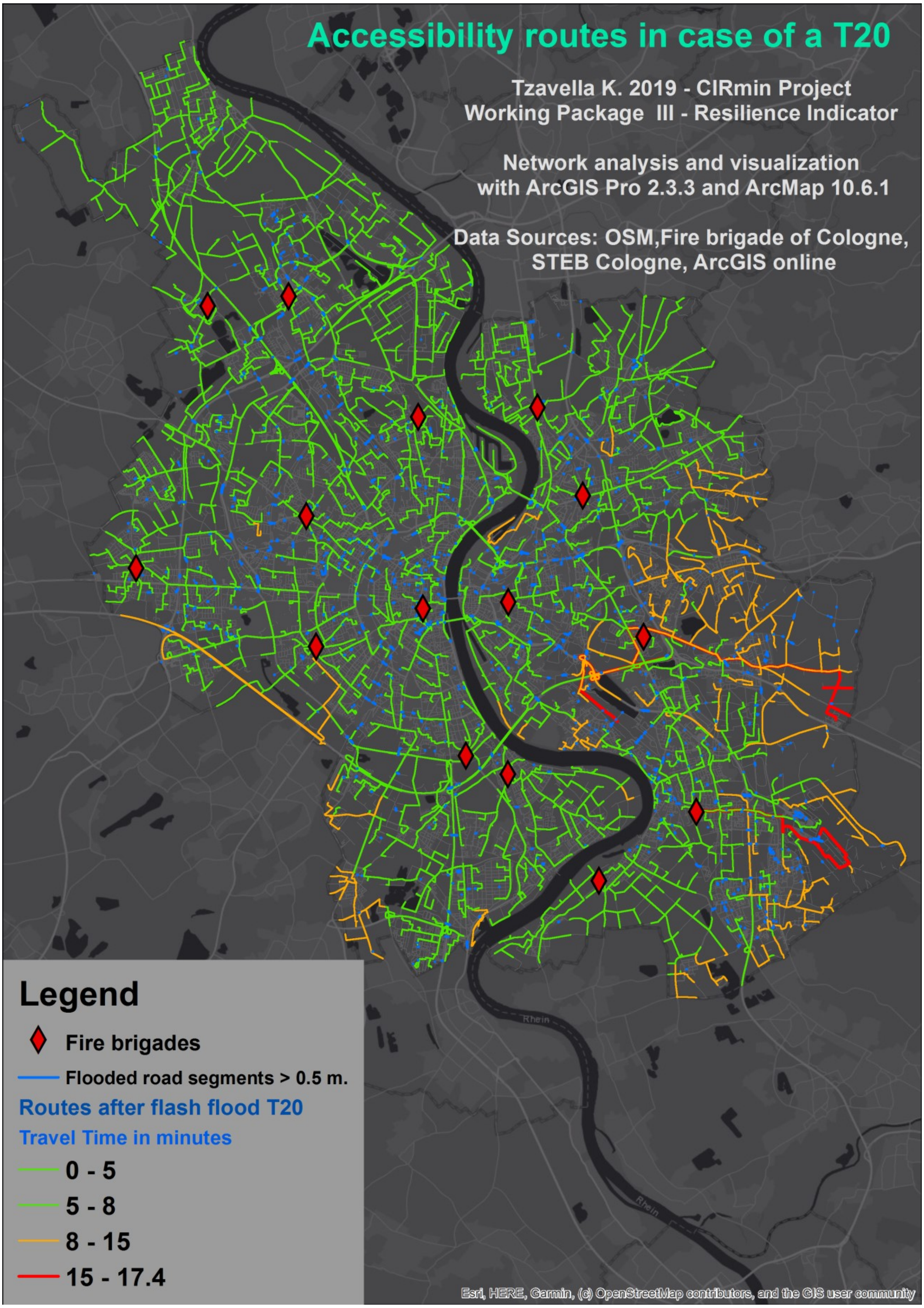
Risk-based time-dependent fastest accessibility routes of Cologne’s fire brigades to the nearest city units in case of the frequent riverine scenario HQ10



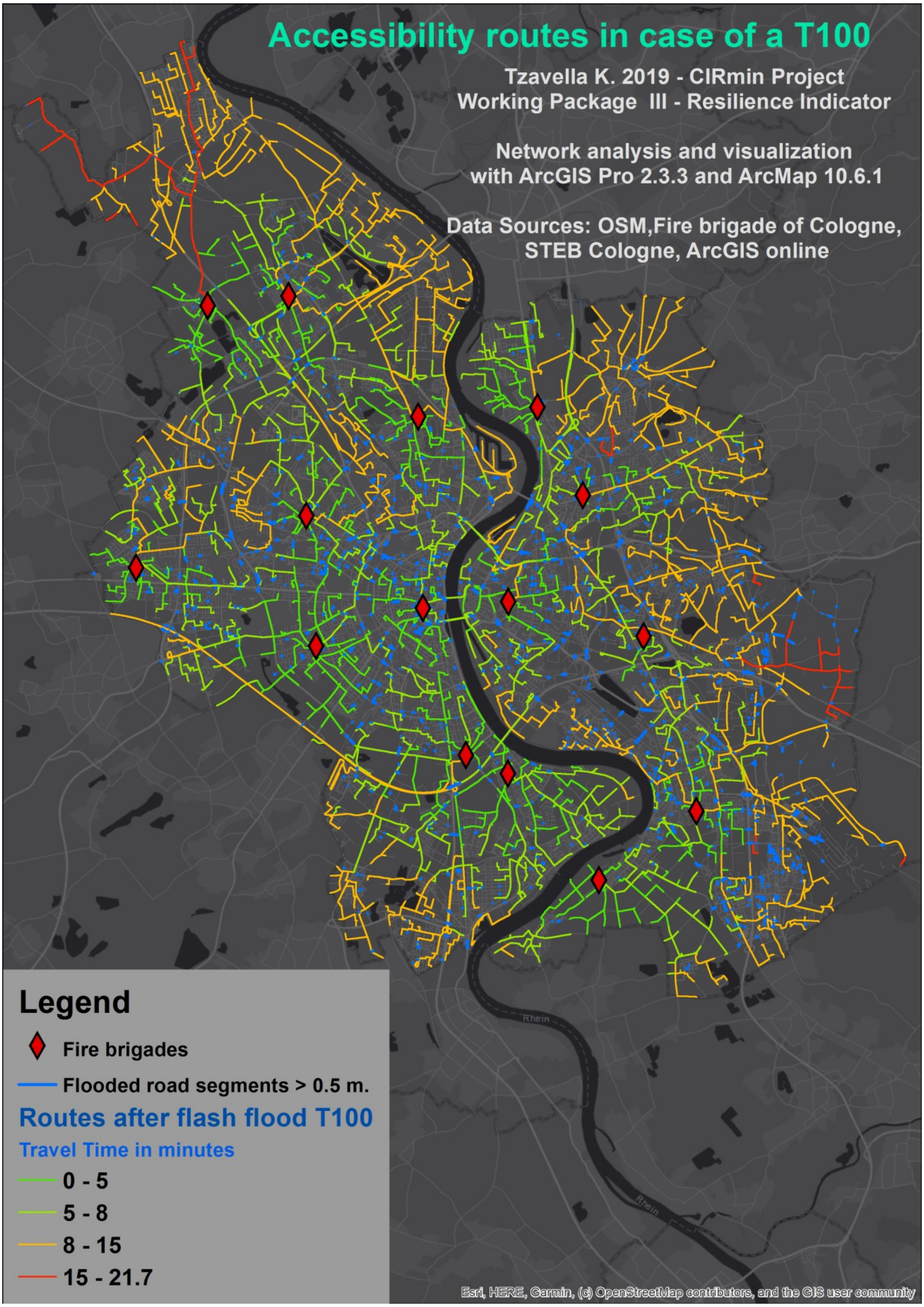
Risk-based time-dependent fastest accessibility routes of Cologne's fire brigades to the nearest city units in case of the extreme riverine scenario HQ500



Risk-based time-dependent fastest accessibility routes for Cologne’s fire brigades to the nearest city units in case of the frequent flash flood scenario T20

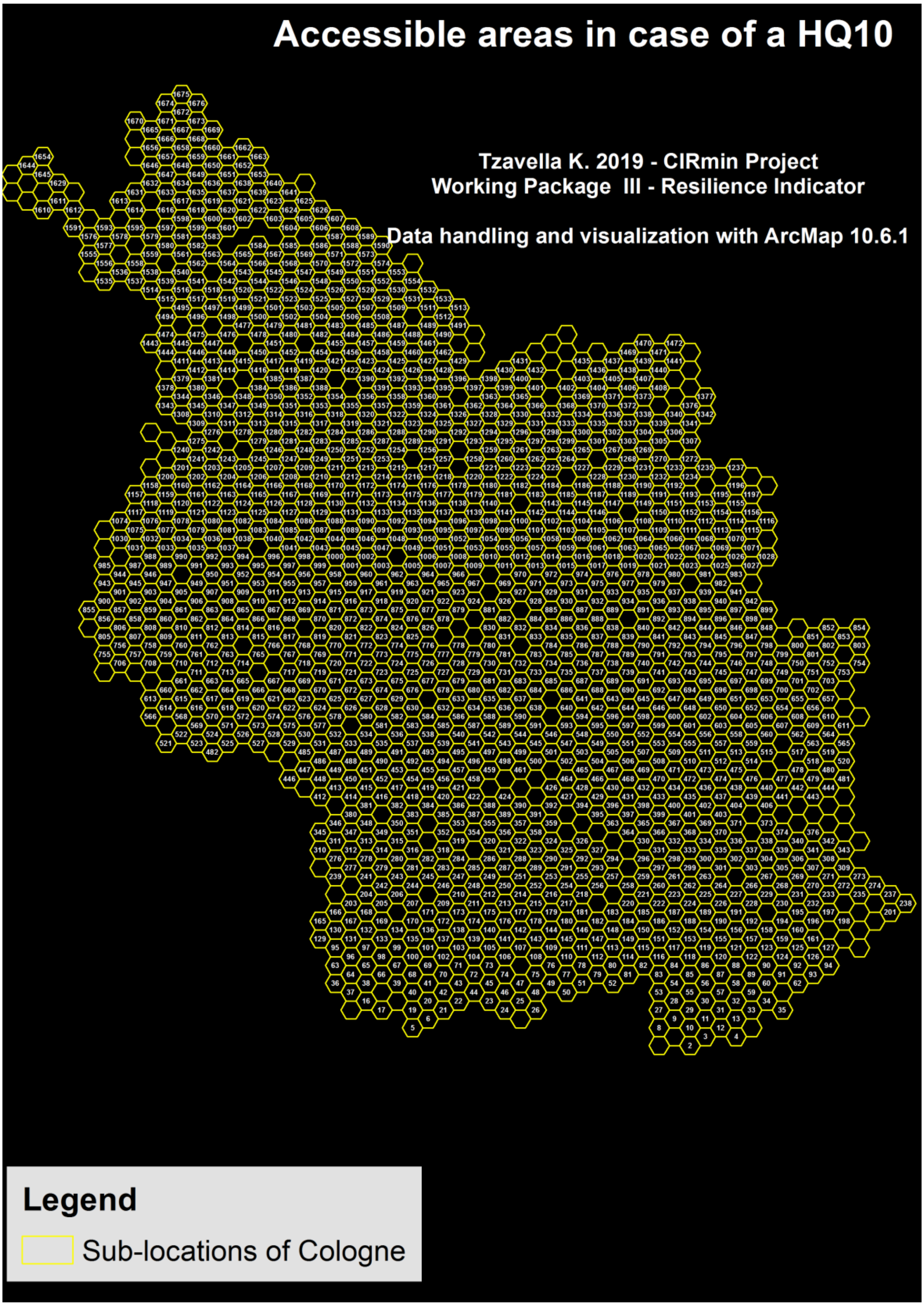


Risk-based time-dependent fastest accessibility routes for Cologne’s fire brigades to the nearest city units in case of the extreme flash flood scenario T100

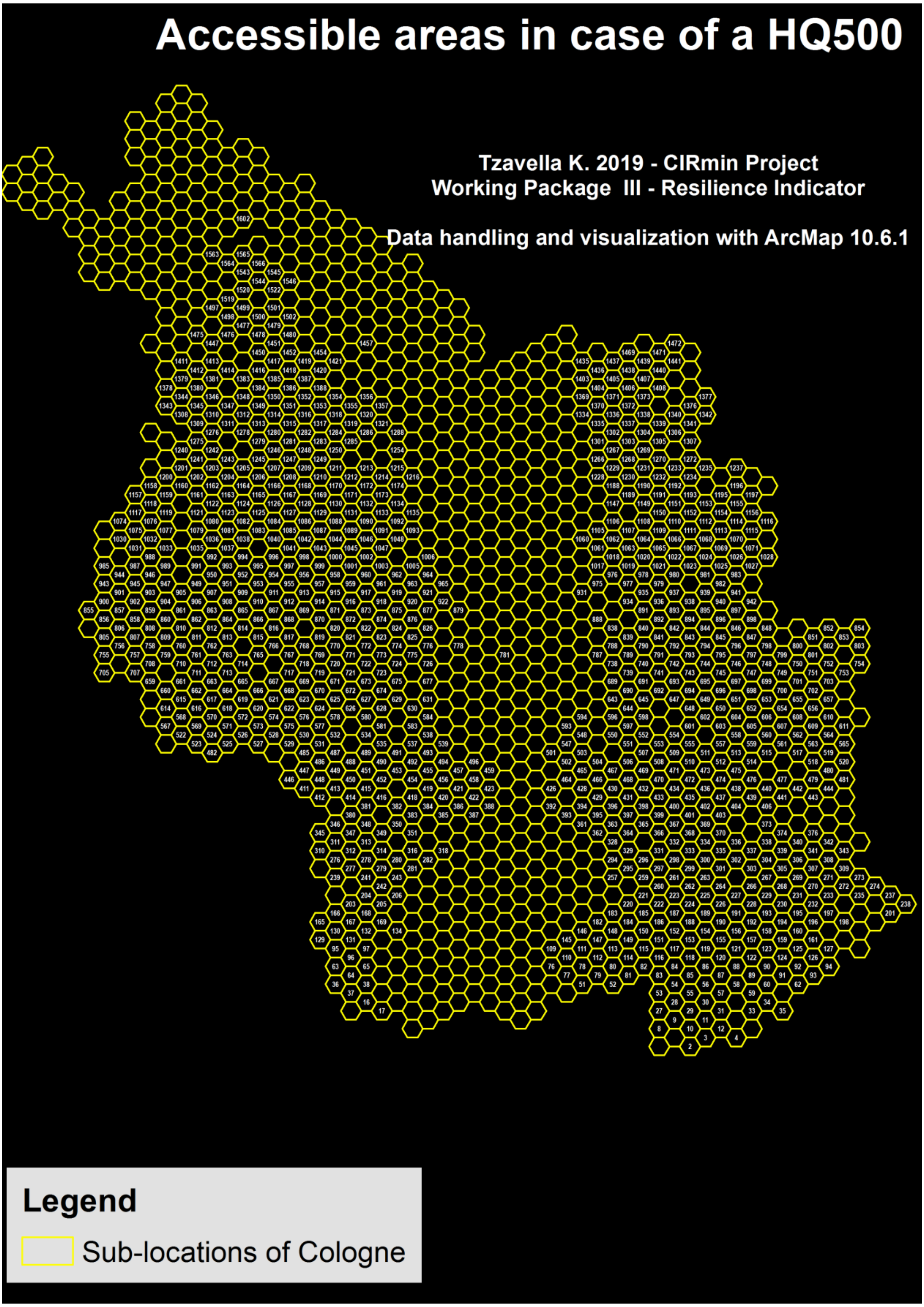


Connectivity-informative hexagonal spatial matrixes - Encoded accessible sub-locations of Cologne from the fire brigade stations in case of floods

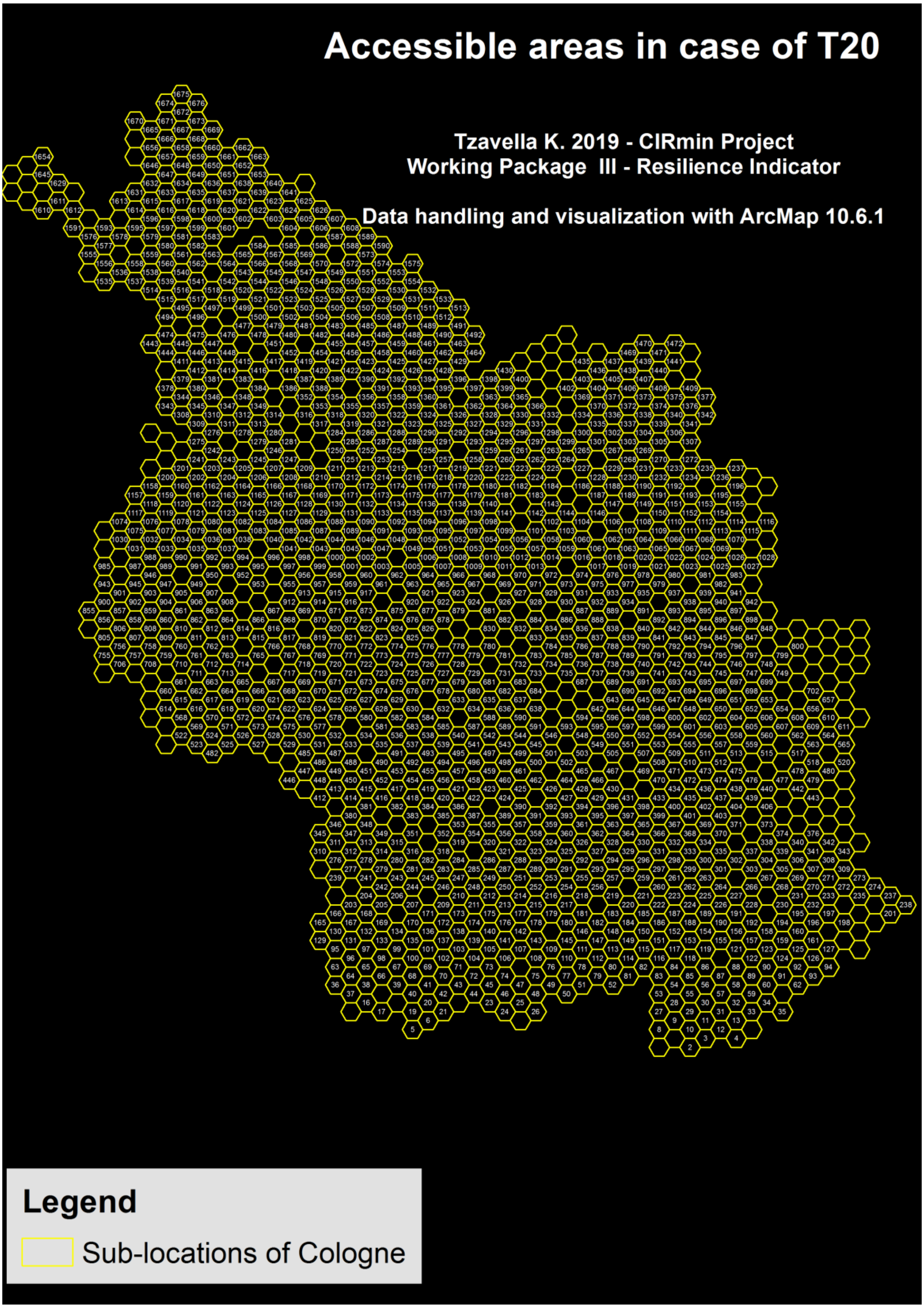
Cologne's accessible city units in case of the regular riverine flood scenario HQ10



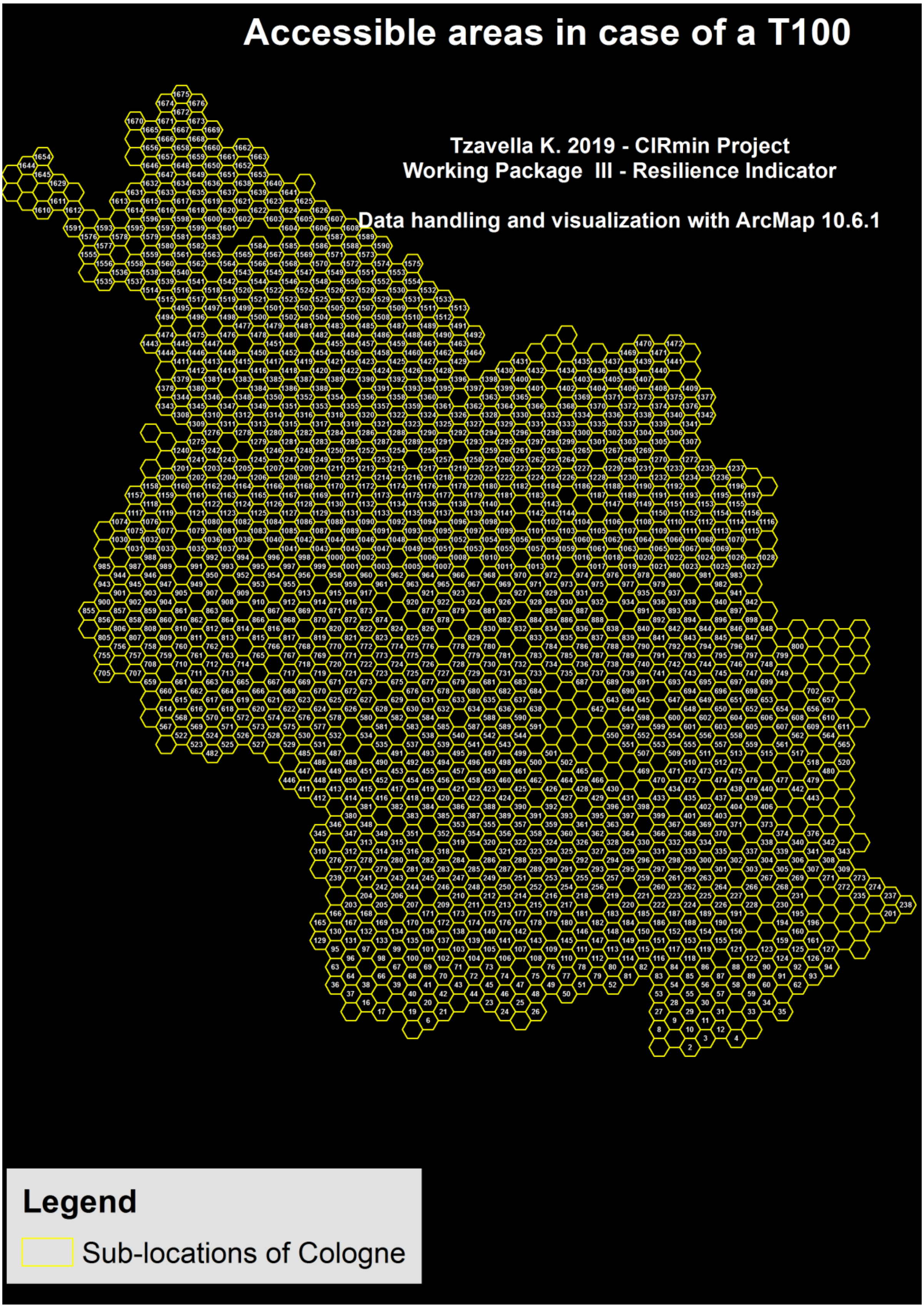
Cologne’s accessible city units in case of the extreme riverine flood scenario HQ500



Cologne’s accessible city units in case of the regular flash flood scenario T20



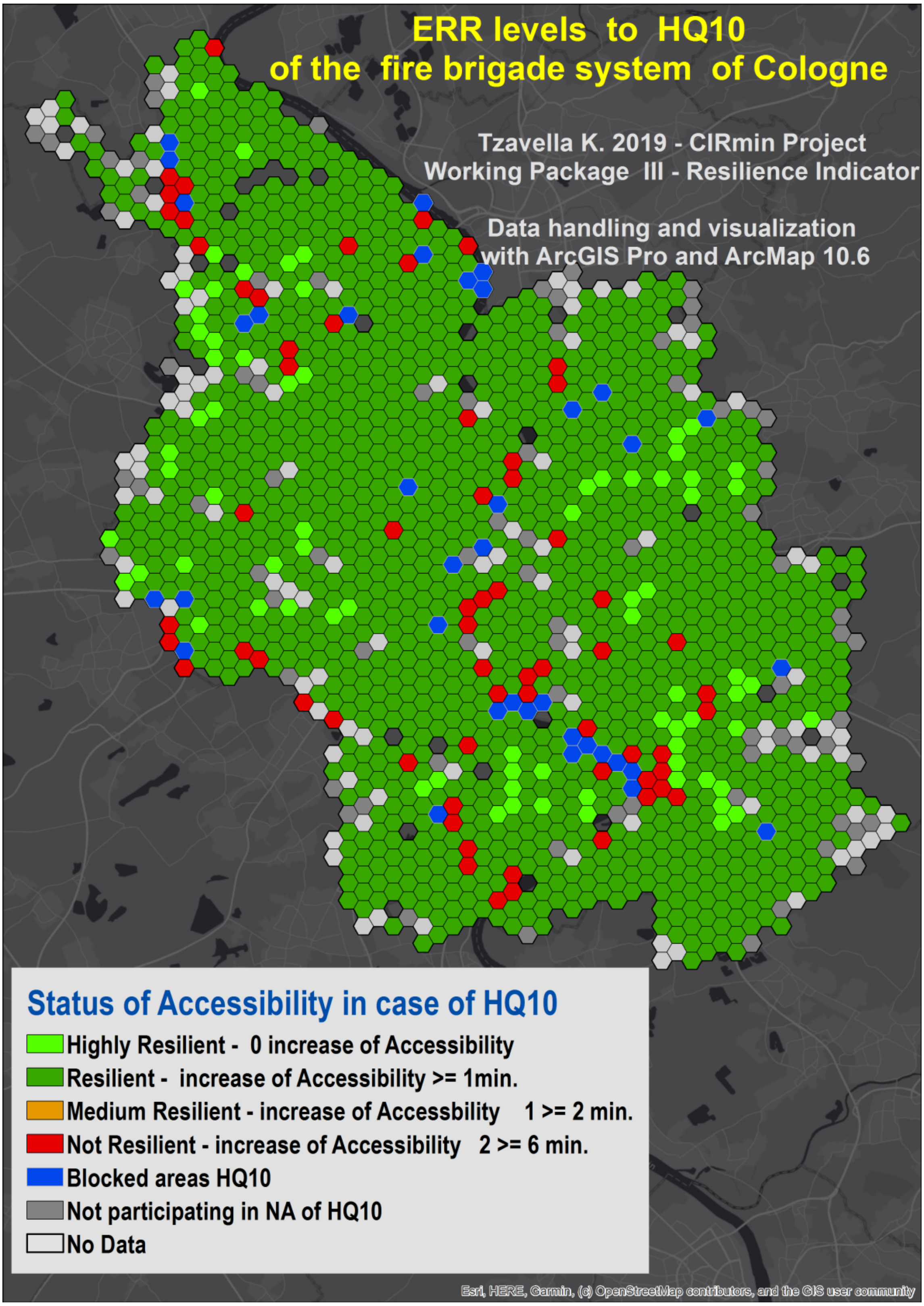
Cologne’s accessible city units after the extreme flash flood scenario T100



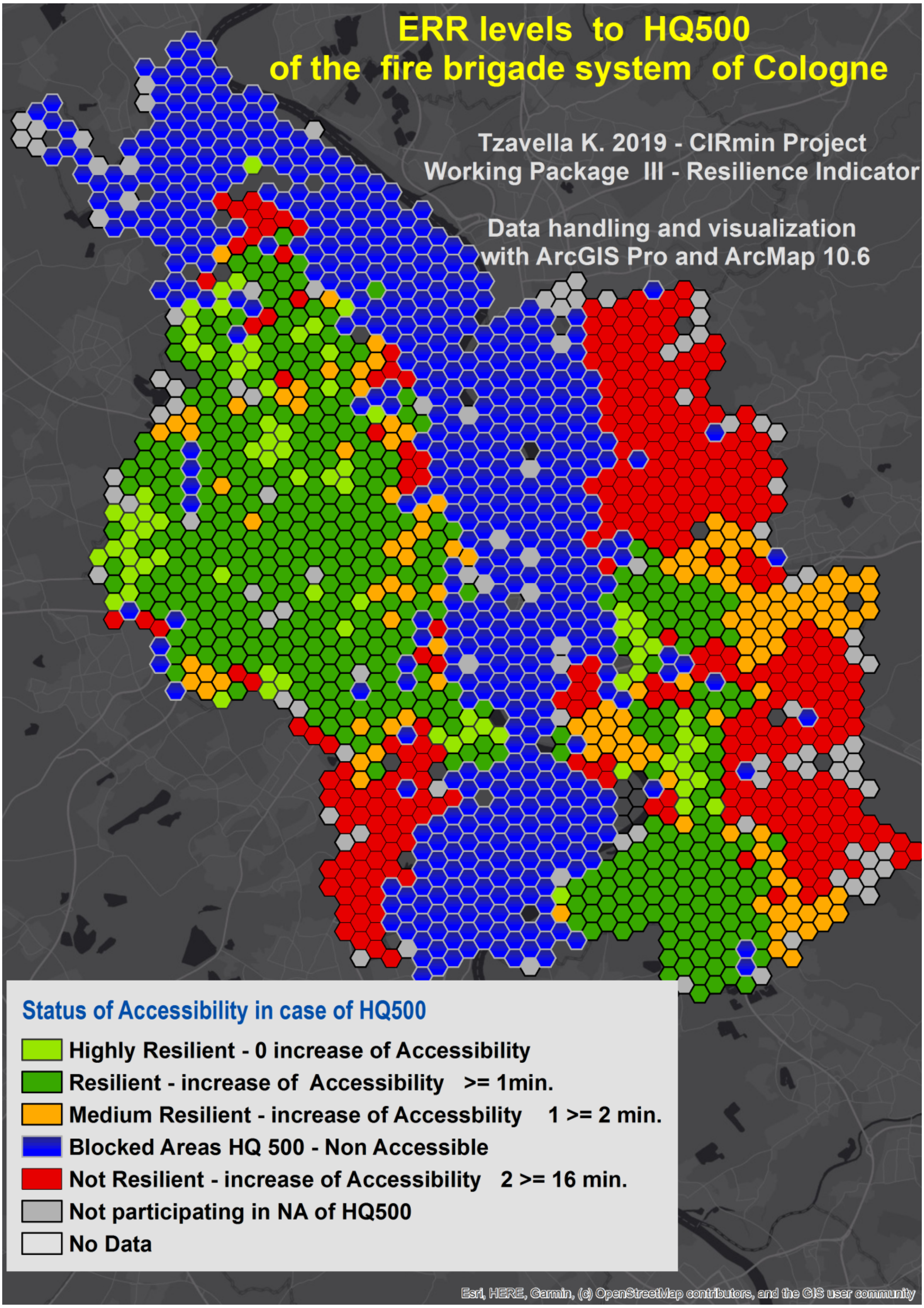
Hexagonal Spatial ERR-informative matrixes

per city unit of Cologne in case of floods

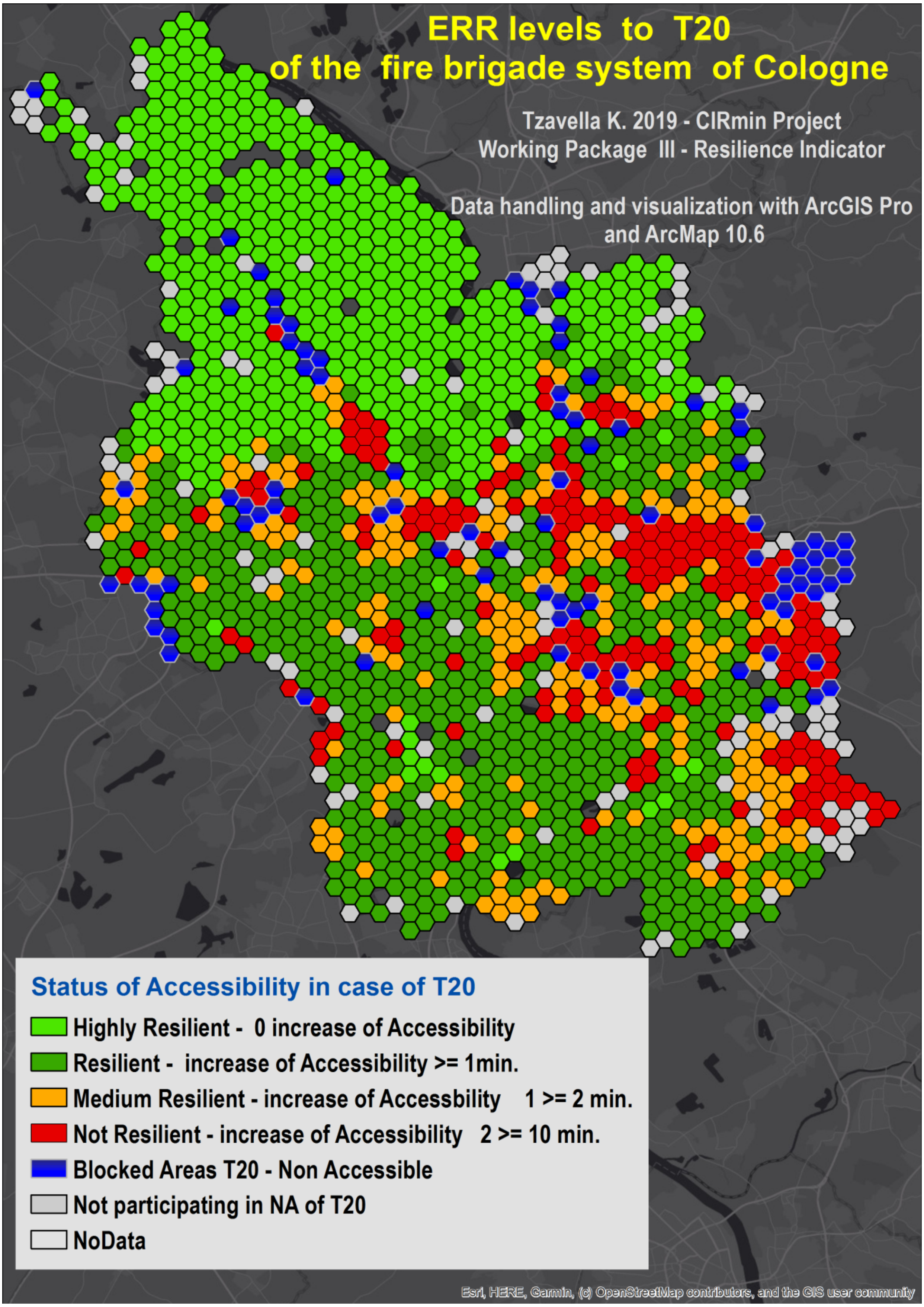
ERR levels of Cologne's fire brigade system in case of a regular riverine flood HQ10



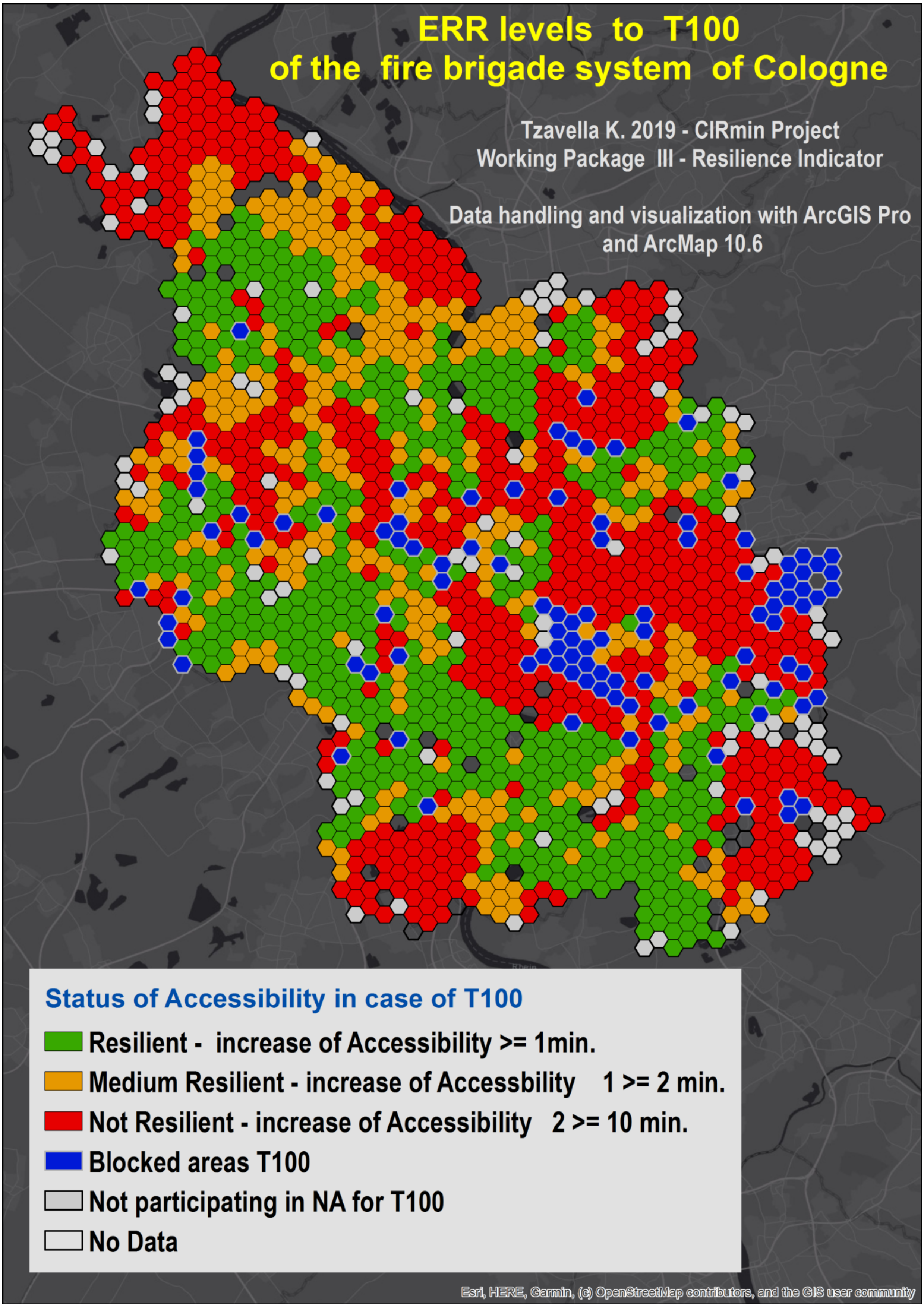
ERR levels of Cologne's fire brigade system in case of an extreme riverine flood HQ500



ERR levels of Cologne’s fire brigade system in case of a regular flash flood T20



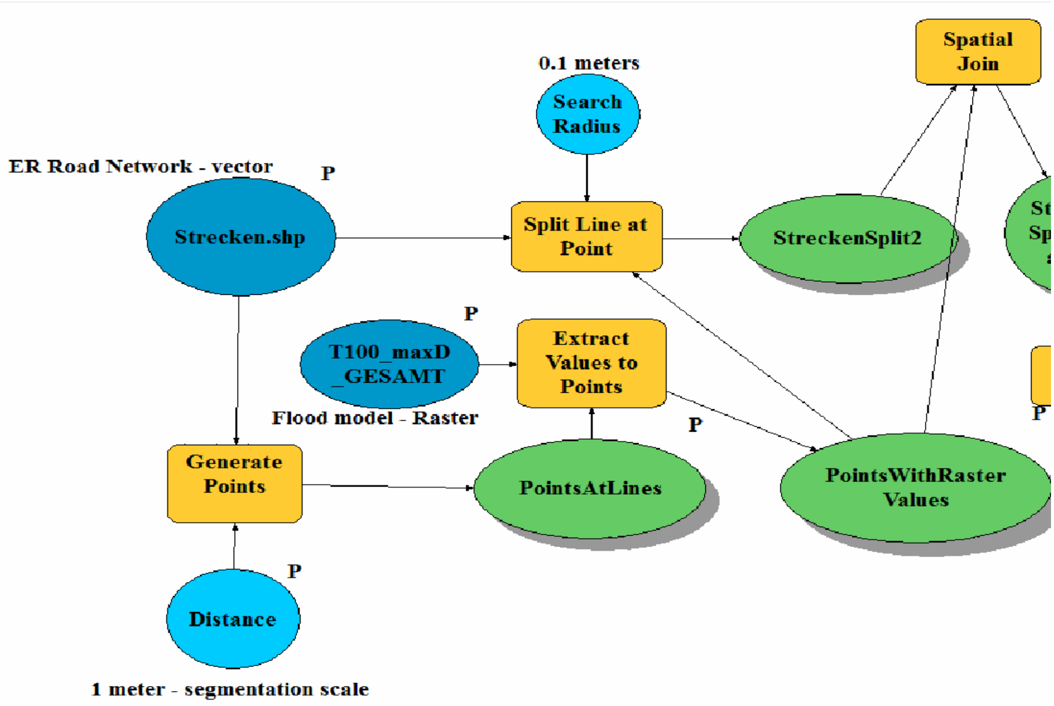
ERR levels of Cologne's fire brigade system in case of an extreme flash flood - T100



APPENDIX C - GIS-Toolkit

GIS-TOOLKIT - Detailed Methodology and Model

The first part of the GIS-Toolkit is presented in the figure below and is mainly built because the ArcMap toolkit library collection lacks a tool for the extraction of information from a raster file (flood scenarios) to a line vector. Therefore, detailed information of the FD cannot be extracted into the road network directly. Nevertheless, in the GIS Toolkit library, the tool “Extract values to points” can extract information from a raster file to points (vector), feeding information regarding the FD into the database.



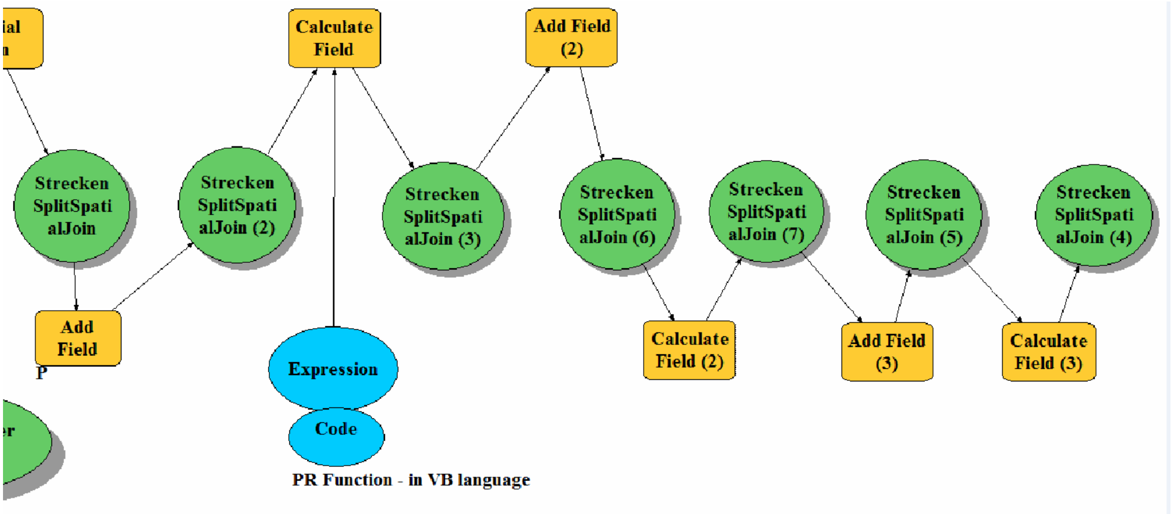
Zooming to the first part of the GIS-Toolkit. Tools stringed together in the ModelBuilder of ArcMap 10.6.1 to create road segments (unit scale of the methodology) and extraction of information of the FD to the unit of the scale used.

For applying the methodology suggested in section 4.2, it is used the scale of one meter (normalised) since it is applied on a city scale, and detailed information is necessary for high resolution results regarding resilience assessments. Furthermore, the normalisation provided from this segmentation allows for purely flood impact-based focused assessments, necessary for further detailed comparison analyses. Therefore, the creation of road segments of 1 m starts with a generation of points throughout the updated ER road network with official ERPS, with the tool named “Generate points”. The tool's output is a shapefile named “PointsAtLines”, with 4,382,013 points extracted along the road network of Cologne. This shapefile is one of the two inputs to the tool “Extract values to points”. The second input is the raster file of the flood scenarios through which the information of the FD is extracted and inserted in the road network database.

This information is then provided in the shapefile named “PointsWithRasterValues”. This shapefile is, later on, one of the inputs to the tool “Split Line at Point”, which is splitting the road network of Cologne (first input) into segments, having as a start and endpoint the extracted points with FD information, and is saving the results in the shapefile “road_networksplit2”. A search radius of 0.1 m is used to search for the maximum FD (in the flood raster models) around the segments and assigns the values.

Finally, the shapefiles of “PointsWithRasterValues” and “road_networksplit2” are spatially joined with the tool “Spatial Join”, resulting in an integrated line vector road network with information on FD per road segment, gathered in the database field named “RasterValue”. ***Information on the FD per road segment (FD_j) is a direct exposure assessment (physical flood damage), and therefore robustness assessments to the four selected flood scenarios of the road network are enabled (see section 3.1).***

In the second part of the model (see figure below) takes place the assignment of FFS per road segment and the updated FFS after each flood scenario, per road segment, based on the FD. Cologne's road network downloaded from OSM provides information on the FFS per road link and type, but not for all the road links. This lack of information is overcome with the manual update of the road network database with the official FFS used for ER purposes provided from the Cologne fire brigade per road. According to the road type, recalculations of the FFS per 1 m of the road on a later stage and per road segment occur. Furthermore, the travel time of each road segment before a flood scenario is calculated and saved in a new field, “DriveTimeBF”.



Zooming to the second part of the GIS-Toolkit: Tools stringed together in the ModelBuilder of ArcMap 10.6.1 to create an updated risk-informed road network database with information on FD, FFS and travel time before and after each input flood scenario for the scale unit (road segment).

For the quantification of the impact of the selected flood scenarios to the road network with vulnerability assessments (see section 3.2) **and therefore of the redundancy of the ERS** (the ability of ERS to absorb the impact of the stressor to the system and transform so to function towards timely ER), **new values of FFS per road segment** are assigned using *function 8*. The road network database is updated with information on the FFS/ERPS, used for ER purposes from the Cologne fire brigade in a new field on a road segment scale. The next step is the assignment of the flood-impacted FFS_{AF} calculated in case of each selected flood scenario in a new field. In this way, **the road network database contains information on the FFS before and after each flood scenario (FFS change - an indicator of vulnerability)**, further enabling detailed large scale vulnerability assessments. After a flood, the three hypotheses are used and applied with VB language in ArcGIS for the FFS assignment. The following VB script is indicative of the process. The *PR function (function 5)* is based on FD calculated in millimetres, but the rasters of each flood probability used in this thesis are in meters. Therefore, so to achieve the extraction of FD information on a large scale with a decimal definition, for each raster (flood scenario), the “RasterValue” field (FD in meters) is multiplied by 1000. The higher the resolution of a raster model is, the more detailed is the information retrieved.

Code block → Script written in Visual Basics (VB)

```
RasterValuemm = [RasterValue] * 1000
PR= 0.0009*( RasterValuemm* RasterValuemm)-0.5529*RasterValuemm+86.9448
If [RasterValue] > 0.5 Then
SpeedwithFlood = 0
ElseIF [RasterValue] > 0.3 Then
SpeedwithFlood = 2.0748
ElseIf SpeedPregnolato < [DriveTimeBF] Then
SpeedwithFlood =PR
Else
SpeedwithFlood = [DriveTimeBF]
End if
```

The three hypotheses (see section 4) are considered for automated benchmarking, calculation and assignment of **new FFS for the case of each flood scenario**, applied with the PR function (function 5) and K_j function (function 6), which are **taking into consideration the safe driving behaviour of a vehicle through flooded road segments** according to FD_j.

Safe driving is achieved by driving a specific vehicle within a range of FFS. Furthermore, flooded road segments with **FD_j > 0.5 m** are **transformed to impassable, and for FD [0.3, 0.5) m,** the road segments are **transformed to walking paths**, assigned with the FFS corresponding to a walking speed (see section 4.1). For the **road segments not impacted from floods** (not exposed to floods) with **intact FFS**, it is **assigned** to each of these road segments the FFS assigned before the flood; aforementioned first update of the road network with **official ERRPS from the fire brigade of Cologne.** The results of the calculation are saved in a new field, “SpeedwithFlood”. With flood-impacted FFS per road segment, this field is used for the accessibility assessments (see section 6), taking place at a later stage of applying the upscaling spatial assessment methodology towards operationalising the ERR to floods.

The new field on the database “SpeedwithFlood” is used for calculations, using function 8, on **the travel time needed to pass each of the road segments,** and the information is saved in a new field “DriveTimeAF”. The result is the TTR, which is calculated before and after each flood scenario per road segment, named in this thesis **UFTTR**, **indicating the potential risk of each flood scenario to the driving behaviour of the emergency vehicles for timely ER provision**. This information can be useful for the ERS, given the opportunity to include or exclude specific road segments from their emergency route planning.

Finally, **the GIS-Toolkit is** applied to the four selected flood scenarios **providing four different road network databases with detailed risk information per 1 m road segment for ER purposes.** These ER road network databases will serve as inputs for further risk and resilience assessments of the urban ER system, stress-testing its flexibility and resistance to the selected flood scenarios.

Python script of the GIS-Toolkit

```
# Python script MODEL.py
# Created on: 2019-01-7 12:29:34.00000
# (generated by ArcGIS/ModelBuilder)
# Usage: Python script MODEL <Distance> <PointsAtLines> <Strecken_shp> <Flood_raster> <PointsWithRasterValues>
# Description:
# Set the necessary product code
# import arcinfo
# Import arcpy module
import arcpy
# Script arguments
Distance = arcpy.GetParameterAsText(0)
if Distance == '#' or not Distance:
    Distance = "1 Meters" # provide a default value if unspecified
PointsAtLines = arcpy.GetParameterAsText(1)
if PointsAtLines == '#' or not PointsAtLines:
    PointsAtLines = "\... Flooddatabase.gdb\\PointsAtLines" # provide a default value if unspecified
ER_road Network.shp = arcpy.GetParameterAsText(2)
if ER_road Network.shp == '#' or not ER_road Network.shp:
    ER_road Network.shp = "….\\...\\ ER_road Network.shp" # provide a default value if unspecified
Flood_raster = arcpy.GetParameterAsText(3)
if Flood_raster == '#' or not Flood_raster:
    Flood_raster = "…..\\....l\\Flooddepths\\Flooddatabase.gdb\\T100_maxD_GESAMT" # provide a default value if unspecified
PointsWithRasterValues = arcpy.GetParameterAsText(4)
if PointsWithRasterValues == '#' or not PointsWithRasterValues:
    PointsWithRasterValues = "… …\\...l\\... \\Flooddatabase.gdb\\PointsWithRasterValues" # provide a default value if unspecified
# Local variables:
Search_Radius = "0,1 Meters"
StreckenSplit2 = "…\\... Flooddatabase.gdb\\road network_Split2"
ER_road_networkSplitSpatialJoin = "… ….\\Flooddatabase.gdb\\ER_road_networkSplitSpatialJoin"
ER_road_networkSplitSpatialJoin__2_ = ER_road_networkSplitSpatialJoin
ER_road_networkSplitSpatialJoin__3_ = ER_road_networkSplitSpatialJoin__2_
Expression = "Speedvari"
ER_road_networkSplitSpatialJoin__6_ = ER_road_networkSplitSpatialJoin__3_
ER_road_networkSplitSpatialJoin__7_ = ER_road_networkSplitSpatialJoin__6_
ER_road_networkSplitSpatialJoin__5_ = ER_road_networkSplitSpatialJoin__7_
ER_road_networkSplitSpatialJoin__4_ = ER_road_networkSplitSpatialJoin__5_
Code_Block
# Process: Generate Points Along Lines
arcpy.GeneratePointsAlongLines_management(ER_road_network_shp, PointsAtLines, "DISTANCE", Distance, "","")
# Process: Extract Values to Points
arcpy.gp.ExtractValuesToPoints_sa(PointsAtLines, Flood_raster, PointsWithRasterValues, "NONE", "VALUE_ONLY")
# Process: Split Line at Point
arcpy.SplitLineAtPoint_management(Strecken_shp, PointsWithRasterValues, ER_road_networkSplit2, Search_Radius)
```

```
# Process: Spatial Join
arcpy.SpatialJoin_analysis(ER_road_networkSplit2, PointsWithRasterValues,
ER_road_networkSplitSpatialJoin, "JOIN_ONE_TO_ONE", "KEEP_ALL", "Id \"Id\" true false 6 Long 0 6
,First,#,….\\Flooddatabase.gdb\\ER_road_networkSplit2,Id,-1,-1;DriveTimeBF \"DriveTimeBF\" true false
19 Double 0 0 ,First,#,….\\Flooddatabase.gdb\\ER_road_networkSplit2,DriveTimetBF,-1,-1;Shape_length
\"Shape_length\" true false 0 Double 0 0
,First,#,….\\Flooddatabase.gdb\\ER_road_networkSplit2,Shape_length,-1,-1", "INTERSECT", "", "")
# Process: Add Field
arcpy.AddField_management(ER_road_networkSplitSpatialJoin, "SpeedwithFlood", "FLOAT", "", "", "",
"", "NULLABLE", "NON_REQUIRED", "")
# Process: Calculate Field
arcpy.CalculateField_management(ER_road_networkSpatialJoin__2_, Code block_expression
# Process: Add Field (2)
arcpy.AddField_management(ER_road_networkSplitSpatialJoin__3_, "ShapeLengthCalc", "FLOAT", "",
"", "", "", "NULLABLE", "NON_REQUIRED", "")
# Process: Calculate Field (2)
arcpy.CalculateField_management(ER_road_networkSplitSpatialJoin__6_, "ShapeLengthCalc",
"!shape.length@kilometers!", "PYTHON", "")
# Process: Add Field (3)
arcpy.AddField_management(ER_road_networkSplitSpatialJoin__7_, "FloodImpactedTime", "FLOAT",
"", "", "", "", "NULLABLE", "NON_REQUIRED", "")
# Process: Calculate Field (3)
arcpy.CalculateField_management(ER_road_networkSplitSpatialJoin__5_, " FloodImpactedTime ",
"[ShapeLengthCalc]/ [SpeedwithFlood]*60", "VB", "")
```

APPENDIX D - Results of the Questionnaire in section 7.5.2

	ANSWERS TO QUESTIONS						
Interviewees	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**
Senior Specialist ***Ministry of the Interior, Department for Rescue Services, Finland***	Yes, some sort of knowledge. There are so many different definitions for the term resilience.	An emergency response resilience is one that works together to understand and manage the risks that it confronts, to reducing future risk by enhancing protection and building for recovery.	Yes, it is very important. The roadblocks has to be known in advance, otherwise the response time will grow and in a worst case-scenario, people will lose their lives.	Yes, but in a normal interventions you do not really use the emergency response plan. In Finland you can add road blocks etc. as a layer to our emergency management support tool (alarm list, maps and navigation) which every emergency vehicle has, but this information has to known and layers added before the intervention.	Yes, if the depth is measured constantly and the plan updated.	▪ Red (extreme) ▪ Orange (high) ▪ Yellow (substantial) ▪ Light green (moderate) ▪ Green (low or normal))	From this map, I can see which areas are accessible by vehicles.

Interviewees	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	▪ **Q7**
Project manager ***CEPRI - www.cepri.net, France***	I think I am	A response leading to the safety of people, reducing social disturbances, stress, psychological damages specially in case of massive evacuation	Essential for the action of first responders, the reducing of risk of fatality (in Mediterranean areas 50% of the deaths are due to the use of the cars), and for the evacuation plans	Yes, for the reasons above	Yes, essential to evaluate predicted time of an evacuation for example	Several options: ▪ The risk for users from dark green to red (most dangerous) ▪ The availability e.g.: red = forbidden, orange = first responders only, yellow = allowed but with cautious	▪ To identify alternative safe paths ▪ To close the dangerous roads ▪ To preposition law enforcers in strategic place in order to regulate traffic ▪ To preposition rescuers near the most dangerous roads in case of floods
Engineer ***PREDICT - http://www.predictservices.com/, France***	Yes, but focused on industrial sites	It is a way to relaunch traffic and activities in the short time possible and with less damage to people and goods	Yes it is important in order to afford a better understanding of the on-going situation probable deviations, safety/waiting zones	For time delays yes and they should be integrated on plans. As for the flood depth I am not sure because even small flood depths may hide damages on road that could impact cars and people	Yes	Road and traffic condition impacts due to runoff and floods from green (less impacted) to red (the most impacted)	The information provided could help decisors to better deploy its means and people

Interviewees	Q1	Q2	Q3	Q4	Q5	▪ Q6	Q7
Researcher ***Instituto Superior de Agronomia https://www.isa.ulisboa.pt/en, Portugal***	Yes	Fast response to mitigate the impact and help in a fast recovery	Yes - To be sure emergency vehicles can pass, the people can go to a safe place in safety	Yes - with evacuating routes	Yes	▪ Red- extreme river is the flood ▪ Orange - high " " ▪ Yellow - medium " " Green - low " "	▪ Create population awareness of the critical areas ▪ Anticipate for evacuation with critical areas Cut the population access of red areas
Chief of Civil Protection Unit ***Government Delegation in Aragon, Spain***	Yes	Is the capability to maintain flexibility actions despite the emergency (or in the middle)	Yes, the road status is a very important function in emergency response, if not one of the most important	Yes I need this data to give access routes for the vehicles and to decide other needs to help the population	Yes - after all we need a rapid reaction and response	▪ In the context we are talking about it's the accessibility for the emergency teams to different areas of a city	▪ We need this info to planify the routes and to prioritize the actions to be taken
Technician ***Civil Protection - Municipality of Mafra, Portugal***	Yes	-	Yes	Yes, emergency routes (safe ones)	-	Red ones have high water, are the flooded ones	Helps us to set the escape routes and distribute routes

Interviewees	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Business continuity ***EDP https://www.edp.pt/particulares/, Portugal***	Yes	ERR= To maintain the electricity for working To have comprehensive plans so we can cope with the flood	Yes, because our teams depend on the roads to arrive to affected assets	Yes – it will enable to preposition teams and to reconnect some assets	No	Red zones are the affected areas	In planning and response to extreme events
Employee ***German Council on Foreign Relations, Germany***	Yes	Crisis management / intervention in a critical situation in order to guarantee and sustain basic societal functions	Obviously. Among other informetrics in order to support common operational in order to support common operational pictures (- situational awareness)	Is for other ones	Yes	Classical risk colour coding	If it has the form of recommendations / guidelines

Interviewees	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Senior hydrologist technician ***Catalan Water Agency, Catalonia***	Yes	For me the Emergency Response Resilience is the way of thinking or prioritize how to deploy the emergency resource in the most efficient way knowing in advance the impact of the hazard. I would also understand the ERR as the manage of focusing the resource where the risk is higher no bothering where the hazard is in a non-risk area.	Totally agree. If we want to deploy the emergency response in an efficient way is totally necessary to know which roads are operative or will be close in next hours (fire, snow, flood…)	Roads for evacuation, roads for emergency services… it's a must in an emergency response plan to avoid a one path to arrive to a place, trying always to have a network of roads to arrive everywhere. And if a unique road is the only way to arrive to one place and this road is highly potential of be under a hazard, the place has to be ready to be confined against that hazard.	In few years all the cars will be driverless, so its ESTRICTLY necessary to add this layer of information in each city	Areas with high potential of road problems	Information in real time of density of cars and probability of impact of hazards next hours Forecast of the people's movements for the hazard. Ex: a city is in fire, so all the people will exit the city in all directions (but are the roads open and are safe for the next hours?)

Interviewees	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Scientist ***Stavanger Hospital University https://helse-stavanger.no/, Norway***	Yes, I am familiar with the concept of resilience. Resilience is the ability of a system, a community or an individual to deal with disturbances, damages, surprises and changes.	ERR is the ability of the emergency response system to deal with all the disturbances that can occur in case of an event, both extreme or not. Dealing with disturbance may not affect the performances of the emergency system and that's the ERR, it is of the emergency system the ability to deal with the unexpected without modify its performance.	Yes, in case of an extreme event the road situation is a crucial point especially if the area to reach are in the countryside or remote area. The emergency response system has to be ready to face and organize its emergency plan in order to help people in need; that means that without a good communication all the system might be affected by a wrong use of the resources.	Maybe yes and I would like that could be a good benefit in the emergency response plan.	-	There are different way to read the map above. Below my idea that could represent a mix of the different information I read: ▪ Red area: is the most affected area by the event and high difficulties to reach people in need. The emergency response team has to be there as soon as possible to proceed to the evacuation, if needed, and to secure the area; ▪ Orange area: effected by the event and difficulties to reach people in need. The emergency response team has to be there as soon as possible and secure the area and use it in case of evacuation of the red area; ▪ Yellow area: slightly affected by the event and the difficulties are fewer compared to the orange and the red area to reach people in need. The emergency response team can use the area to reach the orange and red area in order to provide help to the people affected; Green area: the area is not affected by the event and the emergency response team can fully use the area to reach the most affected area.	According to me, this kind of study is of crucial importance for the good of the population that can be affected by an extreme event. I think that the study of the resilience in the Emergency response system can be a step forward for better emergency planning activities.

Interviewees	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Fire Officer/ Officer in charge ***South-Savo Rescue Department, Finland***	In this context I believe it means an organisation’s (e.g. Rescue Department) ability to respond to a changing situation	As a field officer almost all accidents are more or less responding to changing surroundings. It can also be more than just single accident case. It can be e.g problems with communication network when you need to find out other ways to communicate between rescue units.	Yes it is very important to know which roads are available to use and which are not. It is also important to know other route options especially for those areas where leads only one or two roads. Sometimes if primary route is not able to use it may cause tens of minutes delay in reaching the accident site because rescue units may drive even “wrong way” at first and then forced to go back to find other route.	If the depth of the flood gives information, that is the road accessible or not it is very important. If roads are still able to use but there are many flood areas (especially in the urban area) then it is important to know how much all those floods delay driving time taken together because there might be dozens of smaller floods on the way.	Unfortunately, I do not quite understand the question. Maybe due to lack of my language skills	In this context I understand it that red areas are either high flood risk areas or there are already worst situation. Orange areas same but moderate risk or situation and so on. Green areas are fine. In other context it might mean population density or also it might mean risk areas based on actual accidents in each hexagon.	Specially in those areas where floods are rare must have plans how to react when situation strikes because there might not be chance to practice. And when situation strikes you have to count on good plans.
Fire inspector ***North Karelia Rescue Service - Lieksa Fire Station, Finland***	No, I am not	-	In Finland, it is not so important. In here we think that the road is in running condition or not. The weather can change fast so we have to estimate the vehicle we take on the scene. The condition of the roads can also change over the years so it is very hard to maintain data of it.	The flash flood risk is so low that the information is not needed. There is only a little risk in spring	-	Red = high risk Green = low risk	In some places it could be useful. In here we have so much other (more important) things to take in account so this may not be used

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