Risk Propagation Simulator for Assessing Urban Risk

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Declaration

I hereby declare that the work presented in this thesis is the result of my research and has been conducted by me. I affirm that this thesis has not been submitted, either in whole or in part, to any other institute or university to obtain a degree, diploma, or any other certification. All sources of information and assistance used in this work have been fully acknowledged.

Abbreviations

ABM	Agent-Based Modelling
AHP	Analytical Hierarchical Process
BN	Bayesian Network
CDF	Cumulative Distribution Function
CLT	Central Limit Theorem
COVID-19	Coronavirus Disease 2019
CVM	Contingent Valuation Method
CVM	Contingent Valuation Method
DEM	Digital Elevation Model
DM	Disaster Management
DRA	Disaster Risk Assessment
DSD	Divisional Secretariat Division
EU-CIRCLE	European Collaboration for Innovation in Resilience and Climate Adaptation
EV	The Expectancy Valence
FEMA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects, and Criticality Analysis
FTA	Failure Tree Analysis
G20	Group of Twenty
GIS	Geographic Information System
GN	Grama Niladari
HAZOP	Hazard and Operability Study
IoT	Internet of Things
IPCC	The Intergovernmental Panel on Climate Change
ISM	Interpretive Structure Modelling
ISO	The International Organization for Standardization
IT	The Information Technology
LDE	Direct Economic Loss
LHMP	Landslide Hazard Zonation Mapping Programme
LVSL	Loss of Value of Statistical Life
MCS	Monte Carlo Simulation
MIV	Motivation Intention Volition Model
NA	Network Analysis
NASA	National Aeronautics and Space Administration
NBRO	National Building Research Organisation
NGO	Non-Governmental Organisation
NRR	The National Risk Register
NUA	UN-Habitat’s New Urban Agenda
OECD	The Organisation for Economic Co-operation and Development

PDMA	Protective Action Decision Model
PMT	Project Motivation Theory
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCSA	Risk, Coping, and Social Appraisal
RISP	Risk Information Seeking and Processing Model
SD	System Dynamics
SDG	Sustainable Development Goals
SMS	Short Message Service
TC	Technical Committee
UN	United Nations
UNDRR	The United Nations office for Disaster Risk Reduction
UNECE	United Nations Economic Commission for Europe
UNISDR	The United Nations International Strategy for Disaster Reduction
VSL	Value of Statistical Life

Abstract

The Intergovernmental Panel on Climate Change (IPCC) report on "Climate Change and Land" (2020) underscores how climate change intensifies disaster risks such as floods, landslides, heatwaves, wildfires, and storm surges, significantly impacting economies, infrastructure, and food and water security. In response, robust approaches to understanding and mitigating local risks from climate change are essential. Sound risk assessment methods enable stakeholders to pinpoint and implement targeted interventions, thereby preventing the erosion of hard-earned economic gains and enhancing climate resilience. This proactive approach is endorsed by reports from the IPCC, UNDRR, World Bank, and OECD, highlighting the critical importance of early interventions in risk reduction for safeguarding economic progress and fostering resilient, sustainable communities.

There have been numerous efforts to develop frameworks for assessing risks, such as the ISO 31000 risk management framework and Sendai Framework for Disaster Risk Reduction. These frameworks utilise various quantitative and qualitative methods. However, these frameworks often fail to address the complex interdependencies of risks, mainly how risks propagate and intensify due to the risk behaviour and perception of a local community. As a result, the cascading impacts due to socio-technical interdependencies remain underexplored due to their complexity and the extensive data requirements.

Hence, considering the community risk principles, there is a critical need to develop a risk assessment model that captures these complex interdependencies and cascading risks. This research, therefore, investigates a risk assessment model that deploys the system dynamics techniques to identify and model how various community risk principles interact with each other to influence the overall risk state of a given community. The resulting model allows the decision-makers to conduct "what-if" scenarios, using the proposed risk model, to explore how local climate risks can be reduced by addressing various community characteristics such as risk perception, risk knowledge, risk understanding, risk communication to reduce overall local risks and hence build community resilience.

The research deploys the design science approach to develop the interactive risk model following the guiding seven design science principles. The development of the risk model

commenced with an exhaustive literature survey to identify common risk elements utilised in risk assessment models, including those pertinent to communities. Subsequently, another comprehensive literature review was undertaken to pinpoint the principles of risk propagation and methodologies for their modelling. These risk elements were carefully analysed, and their interconnections were delineated and modelled using System Dynamics (SD). The SD model aimed to encapsulate socio-technical risk interdependencies, thereby establishing a comprehensive risk model. This holistic modelling approach not only facilitated the identification of multiple risk reduction pathways crucial for stakeholders collaborating with communities to mitigate local risks but also enabled sensitivity analysis to comprehend the influence of each risk variable on the overall risk status of a given community.

The System Dynamics (SD) model developed in this study offers a tool for unravelling the intricate interdependencies among diverse risk elements and their propagation dynamics. This research uncovered fourteen distinct risk reduction pathways through system analysis and outlined four pivotal risk propagation principles. Leveraging the capabilities of AnyLogic software, this research operationalised the SD model to simulate risk propagation within a local community and explore various "what-if" scenarios. The SD approach was found to foster a nuanced understanding of how individual risk elements interact with each other and offer a tool to evaluate the potential cascading impact of risks, providing invaluable insights to the decision-makers to devise effective risk mitigation strategies. Before validating the SD model with the users, the representation of the causal loop diagrams was verified with the support of two SD experts. The mathematical constructs used to model the SD model for each loop were then verified by two mathematicians. This verification ensured the validity of the SD model for simulating the cascading impact of risks.

The evaluation of the SD model was conducted with twelve experts using two proposed development programs in Kalutara: one focused on risk communication improvement and the other on drainage improvement to fortify resistance. User evaluation was carried out to assess the ability of the System Dynamics model to aid decision-makers in comprehending the impact of their interventions on community resilience.

All experts agreed that the model effectively captures the relationships between key risk principles. Additionally, they found the model valuable for exploring how various interventions impact community resilience over time. The model's utility in the planning process was widely recognized, as it helped stakeholders understand how different interventions contribute to building resilient environments. Based on stakeholder feedback, future improvements have been suggested, and the researcher plans to extend the study by addressing these emerging requirements.

Chapter 1: Introduction

1.1 Research Context

According to the United Nations Report of the World Urbanisation Prospects, the existing urban population in 2018 was approximately 55%, and it is projected to be 68% by 2050 (United Nations, 2019). This increase in urban population is due to migration from rural to urban areas, driven by better infrastructure and socioeconomic facilities (Pandit, Lu, & Crittenden, 2015). This migration is forcing improvements to the existing urban forms to meet the urban services required by the new immigrants (Pandit et al., 2015). In urban environments, critical infrastructure services such as the water supply, electricity, communication, and transportation provide essential services to the settlements, and they act as pillars for everyday processes such as production, community services, and so on (Karakoc, Almoghathawi, Barker, González, & Mohebbi, 2019). However, such urban services should be effective, efficient, and resilient to external influences such as disasters while continuously meeting the basic needs of city dwellers (N. Bugert & R. Lasch, 2018).

Various internationally recognised tools exist to foster interdisciplinary collaboration among government agencies in promoting sustainable cities and communities, as emphasised by initiatives like Sustainable Development Goal 11 (United Nations, 2015b). These Sustainable Development Goals (SDGs) advocate for integrating disaster risk reduction strategies to enhance the safety and liveability of urban environments for communities (United Nations, 2015b). Furthermore, UN-Habitat's New Urban Agenda (NUA) similarly advocates the creation of sustainable environments (Nations, 2016). Various disaster risk reduction frameworks and action plans have been introduced in pursuit of sustainability. These international frameworks continuously urged local governments to promote disaster risk reduction activities, particularly in response to emerging climate-induced hazards.

The UNDRR highlighted the historical evaluation of risk assessment frameworks and new approaches, such as systemic risk lens and risk-informed sustainable development, which are implemented in many regions (Figure 1-1).

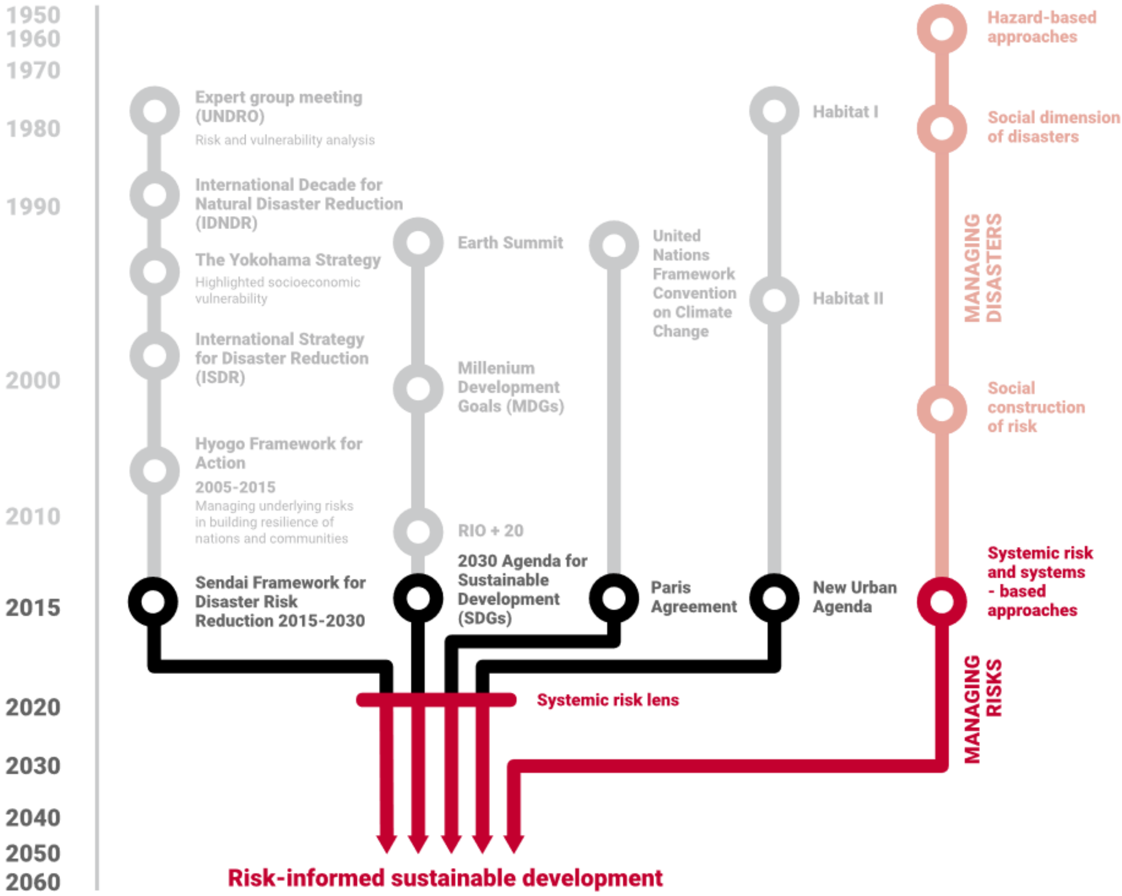

Figure 1-1Evolution of global policy agenda on DRR (UNDRR, 2019, p. 25)

Furthermore, the recent Intergovernmental Panel on Climate Change (IPCC) report on "Climate Change and Land" in 2020 underscores how climate change will intensify disaster risks such as floods, landslides, heatwaves, wildfires, and storm surges in the future, significantly impacting economies, infrastructure, and food and water security. In response, robust approaches to understanding and mitigating local risks from climate change are considered essential. In this context, the Sendai Framework clearly states that it is necessary to strengthen the technical and scientific capacities to develop or apply the methodologies and models to assess disaster risks, vulnerabilities, and hazard exposure (United Nations, 2015a). This requirement demands a holistic risk assessment framework that can comprehensively capture urban risks and allow decision-makers to understand and reduce climate risks for building sustainable urban environments for their citizens. This research aims to address this call for a comprehensive and holistic risk assessment framework.

Institutes and governments have considered various risk assessment methods and principles to understand existing and future risks. Examples of such frameworks include the ISO 31000 risk management framework (2009) (Standardization, 2009), Tropos Goal Risk Framework (Deng et al., 2018; Deng, Yang, Zhang, Li, & Lu, 2019), CORAS risk framework, IRM framework, Defect Detection and Prevention, Enterprise Risk Management Framework (Giorgini, 2009), FTA, FEMA/FMECA, HAZOP (Zhou, Zhai, Shi, & Lu, 2020) and KR-RRA (Ronco et al., 2014). These Risk Management frameworks have been categorised by Pedro Basabe (2018) into four types: Generic Principles, Guidelines, and Methods (e.g., ISO 31000), Applied Principles to governmental organisations (e.g., OECD), Intergovernmental frameworks (e.g., UNISDR), and National Institutionalised frameworks (e.g., EU-CIRCLE). These risk assessment frameworks deploy quantitative and qualitative methods and are primarily based on theories, such as Possibility theory, Fuzzy set, Probability theory, and Evidence Theory (Giorgini, 2009). However, several limitations of these risk management frameworks have been identified by researchers such as the lack of standard definitions for multi-hazard risk, the absence of a common approach for integrating different hazards within a unified framework, the confinement of risk assessments within disciplinary boundaries, the inability to capture cascading impacts of risks due to complex interconnections within a city and the overlooking of risk characteristics of communities when considering local risks (Aksha, Resler, Juran, & Carstensen, 2020; Munasinghe, Fernando, Keraminiyage, & Karunawardena, 2023).

As mentioned in Pandit et al. (2015), cities can be considered complex systems due to their intricate interdependencies and the interactions among urban services such as water, energy, heating/cooling, and transportation and socioeconomic needs such as jobs, business, neighbourhood, and housing. While these interconnections enable the diversification of outputs and improve the efficiency of cities to sustain social and economic stability, they increase the complexity of cities (Yang, Zhang, Ye, & Wang, 2019). As a result, a disruption or perturbation to a particular infrastructure network could lead to a catastrophic effect on another infrastructure network through a series of cascading failures (Karakoc et al., 2019). For instance, increased vehicles on the road due to economic growth can lead to traffic congestion, resulting in longer travel times, environmental pollution, health implications, and economic losses (W. Hao et al., 2020). As another example, any catastrophic impact on the water source or network could profoundly disrupt various aspects of a city and its environment, including economic development and ecological balance (Wang et al., 2011). A notable case is the shrinking of the world's fourth-largest lake, 'The Aral Sea,' which highlights how short-term water planning policies, implemented by state officials, resulted in disastrous outcomes (Wang et al., 2011). In the 1960s, farmers and state officers in Uzbekistan, Kazakhstan, and Central Asian states diverted the water stream of the Aral Lake to irrigate rice and cotton fields. This diversion led to an annual loss of fifty cubic kilometres of freshwater, causing an increase in the lake's salt and mineral content. These changes had a detrimental impact on the fish species in the lake, resulting in the loss of 60,000 jobs in the fishing industry.

Consequently, the area of the Aral Sea began to diminish, exposing the salty riverbed to the environment. As a result, strong winds frequently carried and deposited saline soil particles onto farmlands, leading to decreased crop yields (NASA, 2000). Literature suggests that city governors and administrators poorly understand the interdependencies of urban systems and how a failure of one connection could catastrophically impact the entire system (Pandit et al., 2015). Therefore, there is a need to consider the complex interdependencies of cities and how they can lead to cascading risks within risk assessment models. However, as identified Aksha et al. (2020), such cascading impacts are not adequately researched at present. Therefore, considering complex interdependencies, this research investigates how cascading impacts can be incorporated into a risk assessment model.

Furthermore, a city is a liveable space composed of heterogeneous people, and their behaviour in these complex interdependencies is inherently dynamic (Giardini & Vilone, 2021). This dynamic behaviour becomes particularly challenging during an emergency and is linked to their awareness of the potential consequences and preparedness state (Giardini & Vilone, 2021). Furthermore, the community's actions regarding the risk judgement during the emergency are based on the risk perception status, which is discussed as risk interpretation, similar previous experiences, and risk sensitivity (Giardini & Vilone, 2021). Consequently, understanding the risk and the risk propagation behaviour from the human perspective must be systematically modelled (Giardini & Vilone, 2021). As a result, the risk assessment should help minimise the underestimated or exaggerated plausible risk in the community and be discussed from the human perspective. Therefore, this research should consider to emphasise the risks inherent within communities and their inter-relationship in modelling the overall disaster risks.

Risk management agencies and communities are both critical actors in the decision-making process. While risk management agencies base their decisions on risk evaluations, often guided by established risk assessment models, implementing most risk-reduction actions takes place within the community. Crucially, the community's perception of risk management plays a pivotal role in identifying and analysing the existing gaps within settlements, which in turn drives sustainability efforts (Kruse et al., 2017). However, current risk models are static and do not allow decision-makers to understand the cascading impact of risks due to system interdependencies. This limits their ability to explore and understand the impact of various urban development interventions on reducing overall urban risks and, ultimately, creating sustainable urban environments. Therefore, this research should contribute to developing an interactive risk propagation simulator.

Accordingly, there is a research gap in understanding risk propagation across urban environments, which is essential for implementing a holistic approach to mitigating the consequences of hazards while recognising the community as a key actor in disaster risk reduction to build resilient environments. Therefore, this research is aimed at answering "How can an interactive urban risk simulator be developed to effectively model risk propagation through interdependent elements, incorporating community risk characteristics to enhance decision-making and management of urban risks?"

1.2 Aims and Objectives

This research aims to develop an interactive urban risk simulator for decision-makers that can model risk propagation through interdependent risk elements, emphasising incorporating community risk characteristics as a critical component to assess the overall risk of a local environment. This simulator will enable decision-makers to assess and manage urban risks more effectively by accounting for the interconnected nature of different risk elements and the community risk perceptions, knowledge, and behaviours. It will also help the decision-makers understand their interventions' impact on the overall risk level.

1.3 Objectives

The above research aim will be achieved through the following objectives:

1. Conceptualise a risk assessment model that encompasses a range of risk elements, including human risk characteristics and their interconnections.
2. Identify a detailed risk assessment model capable of simulating risk propagation across interconnected urban and human risk elements, and exploring the impact of interventions on the urban environment.
3. Implement an interactive simulator for decision-makers to assess urban risks using an appropriate state-of-the-art risk propagation modelling technique, informed by the risk assessment model developed in Objective 2.
4. Demonstrate the application of the urban risk simulator for evaluating the impact of various interventions on overall urban risks.
5. Validate the risk propagation simulator involving decision-makers to assess its usefulness for evaluating the impacts of various interventions on overall urban resilience.

1.4 Research Scope

The research focuses on modelling the propagation of risks stemming from the interactions between various risk factors associated with rain-induced landslides. Other disaster risks, such as floods and droughts, are excluded from this study. The systems thinking approach is considered for developing the model, emphasising the risks inherent within communities and their interrelationships in modelling the overall disaster risks. The validation of the model is limited to the Kalutara District in Sri Lanka due to data availability, but the overall concept is generic enough to be extended and applied to similar contexts outside Sri Lanka.

1.5 Research Questions

This research aims to answer the following research questions:

RQ1: What risk elements must be considered when defining landslide disaster risks in an urban environment?

Various disciplines interpret disaster risk from different perspectives and measure it differently. Therefore, this research question aims to harmonise the literature's risk definitions and establish clear guidance for measuring them. A literature review will be conducted to identify various risk elements, including those inherent within people.

RQ2: How can the interdependencies among risk elements be modelled to develop a model-based risk assessment framework using appropriate modelling techniques to assess the risks of a local urban environment?

This research question aims to explore the relationships among various risk elements and develop a model that can be used to simulate the overall risk in an urban environment. It is anticipated that such a model can be used to measure the overall risk level in an urban environment and to understand how the risk treatment on one element can propagate through other risk elements to impact the overall risk level of an urban environment.

Furthermore, this research question aims to identify the most suitable approach for modelling the risk cascading across urban environments to identify appropriate risk reduction measures. A thorough literature survey will be conducted to compare and contrast current approaches and identify the best modelling technique for urban risk management.

RQ3: How can an interactive risk simulator be established to enable decision-makers to assess the impact of cascading risks on the overall urban risks?

This research question seeks to explore how the proposed risk assessment model in this research can be implemented using an existing system modelling platform to provide an interactive and intuitive risk exploration environment for decision-makers.

RQ4: How useful is the interactive risk simulator for the decision-makers for making informed decisions for building resilient urban environments

This research assumes that an interactive simulator will enable decision-makers to implement more effective interventions for reducing urban risks. This research question aims to validate this assumption by evaluating the urban risk simulator with stakeholder involvement. The research will explore how the simulator can be utilised to assess the impact of various interventions aimed at reducing urban risks. This capability is essential for decision-makers to understand the effectiveness of their investment in risk reduction and to build resilience against climate-induced hazards.

Figure 1-2 illustrates the overall research process and the interrelationship between the research objectives (Obj1-5) and the research questions (RQ1-4).

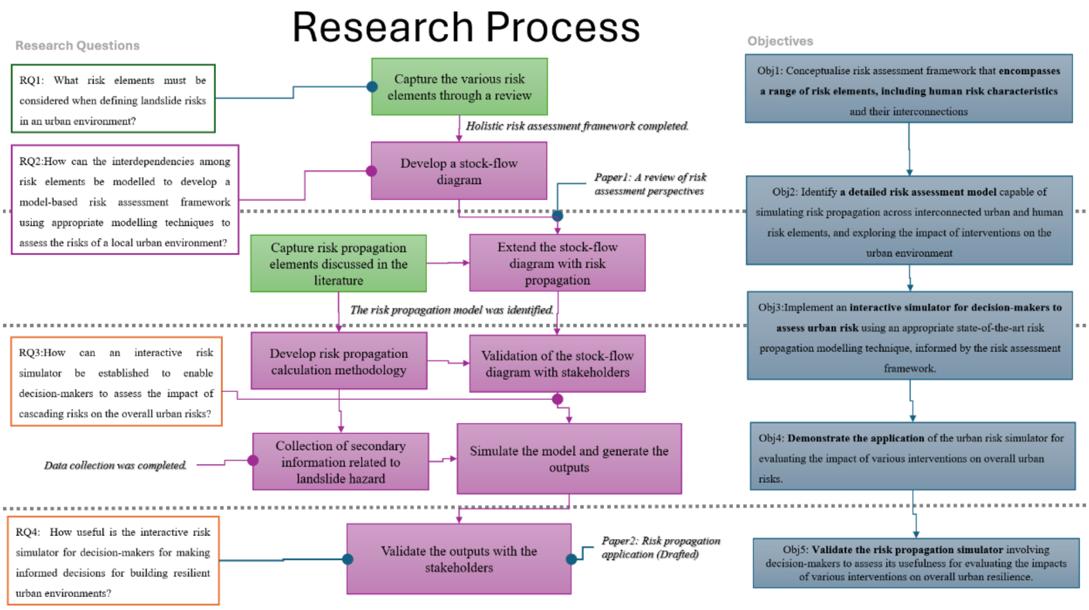

Figure 1-2: Research process

Two literature reviews were conducted in the research, represented by green-coloured boxes in the research process. Seven key steps, marked as purple-coloured boxes, were established as essential tasks to achieve the research aim.

The first literature review was conducted to explore various risk principles within the domain by examining multiple risk assessment frameworks, models, and approaches. Based on these insights, a stock-flow model was developed by integrating the identified risk principles, which addressed the second research question.

The second literature review focused on understanding risk propagation modelling approaches. The findings were incorporated into the stock-flow model, leading to the development of an extended stock-flow model with risk propagation calculations. This extended model was then validated by practitioners, ensuring the accuracy of both the model and the available implementation data.

Subsequently, the collected data was used to simulate the model for the case study area, and the model outputs were validated in the final stage of the research process. Through this structured approach, the research process effectively integrated all research questions and objectives, ultimately achieving the intended research aim.

1.6 Study Area

This research has chosen a district called Kalutara in Sri Lanka as the urban laboratory to deploy and validate the proposed model. Kalutara is a coastal city located forty kilometres from Colombo, Sri Lanka. Kalutara District covers 1,598 sq km and is divided into fourteen Divisional Secretariat Divisions (DSDs). The urban characteristics of the district in 2018 include 3% urban, 17% rural, 57% agricultural, and 23% natural areas, and therefore it has an agricultural-based economy. The district has a population of 1.2 million and three hundred thousand housing units.

As mentioned in the research scope, the model is applied to rain-induced landslides. Landslides are one of the catastrophic natural events in Sri Lanka, and Kalutara is one of the districts that experience major landslides. For instance, in 2017, a significant number of landslides occurred in the district, destroying around 350 lives and 4.9 billion US$ worth of properties. Therefore, Kalutara provides a good study area for this research due to its urban characteristics and hazardous nature.

Furthermore, the National Building Research Organisation (NBRO), which has the mandate for managing landslides, has collected a significant amount of hazard information, exposure, and vulnerability data, which is readily available to the researcher since he is an employee of NBRO. Furthermore, NBRO works closely with the local stakeholders in Kalutara to reduce the impact of landslides on their environment and hence has an interest in exploiting the outcome of this research for building a resilient Kalutara.

Furthermore, as a part of the GCRF TRANSCEND project and a World Bank-funded project, the researcher has been instrumental in establishing Kalutara Living Lab to bring all the local stakeholders to work together to understand the local risks and explore interventions to build local resilience. Therefore, Kalutara provides an ideal test location for developing and validating the proposed risk models with local stakeholders.

1.7 Structure of the Thesis

The thesis is structured into seven chapters, each building upon the previous to develop a comprehensive understanding of the research. Chapter One lays the foundation by presenting the rationale behind the research, along with the aims and objectives, research questions, and the selection of the case study location. This sets the context of the research.

Chapter Two explores the state of the art in risk characteristics and risk propagation modelling through two systematic literature surveys. This chapter identifies existing knowledge and gaps in the field, providing the essential foundation for establishing a model for interconnected risks.

Chapter Three provides a detailed explanation of the research methodology adopted in this study, including discussions on the research philosophy, design, and validation process. This chapter is crucial for understanding the systematic approach employed in the research.

Chapter Four builds on the insights gathered from the literature by analysing the risk elements identified in Chapter Two. It establishes a comprehensive risk assessment model, highlighting the interconnections among these elements. This model forms a pivotal foundation for developing effective strategies in risk management and resilience-building within communities.

Chapter Five introduces an innovative urban risk simulator environment, developed based on the risk assessment model from Chapter Four. This simulator is an essential tool for modelling and testing risk scenarios, providing valuable insights for urban planners and policymakers.

Chapter Six applies the urban risk simulator to a real-world scenario, focusing on the Kalutara District in Sri Lanka. This chapter includes a user validation process involving twelve experts, assessing the simulator's effectiveness in supporting decision-making processes aimed at reducing climate-induced risks.

Finally, Chapter Seven concludes the thesis by summarising the research outcomes and discussing directions for future research. This chapter reflects on the contributions made and suggests further exploration paths to enhance understanding and management of disaster risks.

Chapter 2: Literature Review on Risk Frameworks, Risk Perspectives and Risk Propagation

2.1 Introduction

This chapter presents the outcome of literature review activities conducted to gather state-of-the-art knowledge in risk assessment and propagation approaches. It begins by presenting the results of a general literature survey to identify the most widespread disaster risk management frameworks. The outcome of this research is presented in Section 2.2. Following this, two comprehensive literature surveys were conducted.

The first review sought to answer two key research questions: What risk perspectives must be considered when defining disaster risks and their propagation in an urban environment?; What key risk characteristics are inherent within communities that influence their resilience to disasters? The outcome of this review is presented in Section 2.3.

Following a detailed analysis of the approaches for modelling risk propagation, the second review focused on answering the research question: What models and methods are employed in System Dynamics and systems thinking to analyse risk propagation and resilience? The outcome of this review is presented in Section 2.5.

2.2 Disaster Risk Management Frameworks

A risk management framework guides users through a structured approach to understanding risk management principles and the systematic application of policies and practices developed by various institutions (Pedro Basabe, 2018). Pedro Basabe (2018) has classified these frameworks into four main clusters:

1. **Generic Principles, Guidelines, and Methods**: This category encompasses theoretical frameworks such as ISO 31000 and the International Risk Governance Council (IRGC), which provide foundational risk management principles and guidelines.

2. **Applied Principles for Governmental Organizations**: This group focuses on specific disciplines, illustrated by risk assessment frameworks from organizations like OECD

and UNECE. For instance, the OECD methodology, developed by G20 countries, specifically addresses financial risks (OECD, 2012).

3. **Intergovernmental Framework**: This framework is established through agreements between multiple governments. An example is the Sendai Framework introduced by UNISDR, which details seven targets and four priorities aimed at mitigating both existing and emerging disaster threats (UNDRR, 2015)

4. **National Institutionalized Framework**: This category includes frameworks adopted by individual governments. An example is EU-CIRCLE (2018), which outlines the UK government's national risk reduction strategies.

The following section discusses each of these risk framework categories in detail with examples.

2.2.1 Generic Principle: ISO 31000 Risk Assessment Framework

The International Organization for Standardisation (ISO) is a worldwide organisation that develops standards across various disciplines through technical committees (ISO-31000, 2019). ISO31000:2018, created by the technical committee (ISO/TC 262), offers a systematic and holistic approach to managing all types of risk within an organisation.

The principles of ISO 31000 emphasise creating and safeguarding organisational values to enhance performance, foster innovation, and achieve the organisation's objectives. These principles emphasise elements such as integration, structure, comprehensiveness, customisation, inclusivity, dynamism, utilisation of the best available information, consideration of human cultural factors, and continual improvement. The framework integrates risk management activities into significant activities and functions and consists of several components: leadership and commitment, integration, design, implementation, evaluation, and improvement. The risk assessment process outlines the systematic application of policies, procedures, and practices to effectively communicate, consult, and establish a risk management process (ISO-31000, 2019).

Figure 2-1 illustrates the guideline process which encompasses scope and context analysis, risk assessment, risk treatment, monitoring & review, communication & consultation, and recording & reporting. The risk assessment is further categorised into risk identification, analysis, and evaluation (ISO-31000, 2019).

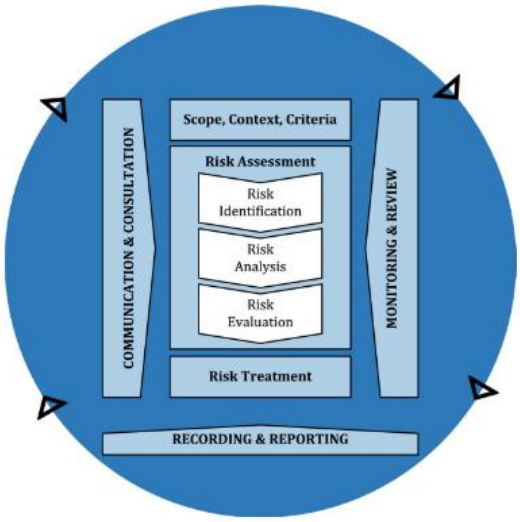

Figure 2-1: ISO 31000 Risk Management Process (ISO-31000, 2019)

2.2.2 Applied Principle for Risk Reduction: G20/OECD Framework

This framework was developed by the Organization for Economic Co-operation and Development (OCED) at the request of G20 Finance Ministers, Central Bank Governors, and G20 leaders in recognition of the importance and priorities of disaster risk management strategies (OECD, 2012). Risk financing was the focus of this framework for achieving financial resilience, which is considered a critical component of effective disaster risk management. Therefore, this framework has strong interconnections between disaster risk assessment, risk reduction, and financial management. Figure 2-2 shows the methodological framework developed by the OECD.

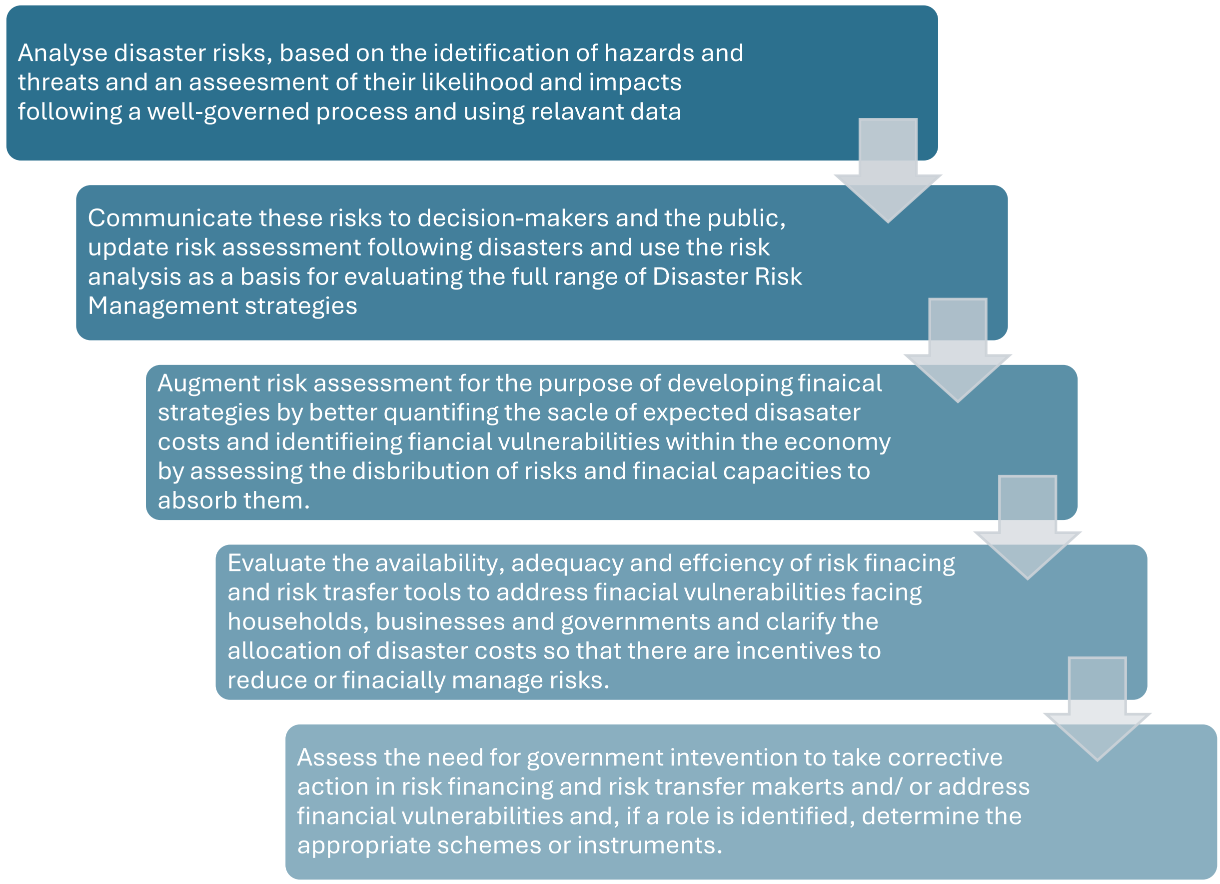

Figure 2-2: Risk assessment steps G20/OECD (OECD, 2012, p. 5)

Here, two significant pathways drive this OECD framework: risk assessment and financing. The risk assessment consists of governance, risk analysis, risk communication & awareness, post-disaster impact analysis, and policy implications of risk assessment. Risk financing includes risk exposure & risk-bearing capacity, risk financing & risk transfer, and institutional financial arrangements (OECD, 2012).

2.2.3 Intergovernmental Framework: Sendai Framework (2015-2030)

The Sendai framework was adopted at the Third UN World Conference in Sendai, Japan, as the successor instrument to the Hyogo Framework for Action. This framework emphasises the importance of enhancing understanding of disaster risk across all aspects, including exposure, vulnerability, and hazard characteristics. It highlights the necessity of strengthening disaster risk governance through national platforms, fostering accountability in disaster risk management, and promoting preparedness for 'Building Back Better'. Additionally, it recognises the roles of various stakeholders, encourages risk-sensitive investment to prevent new risks, underscores the resilience of health infrastructure, cultural heritage, and workplaces, advocates for enhanced international cooperation and global partnerships, and calls for risk-informed donor policies and programs, including financial support and loans from international financial institutions (UNDRR, 2015).

Sendai Framework proposes seven targets to achieve its goal of “preventing new and reducing existing disaster risk through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political, and institutional measures” (UNDRR, 2015, p. 15). These measures aim to lessen hazard exposure and vulnerability to disasters, enhance preparedness for response and recovery, and ultimately strengthen (UNDRR, 2015). Furthermore, four priorities are proposed for the implementation of the actions. Figure 2-3 shows the targets and priority action areas of the Sendai Framework.

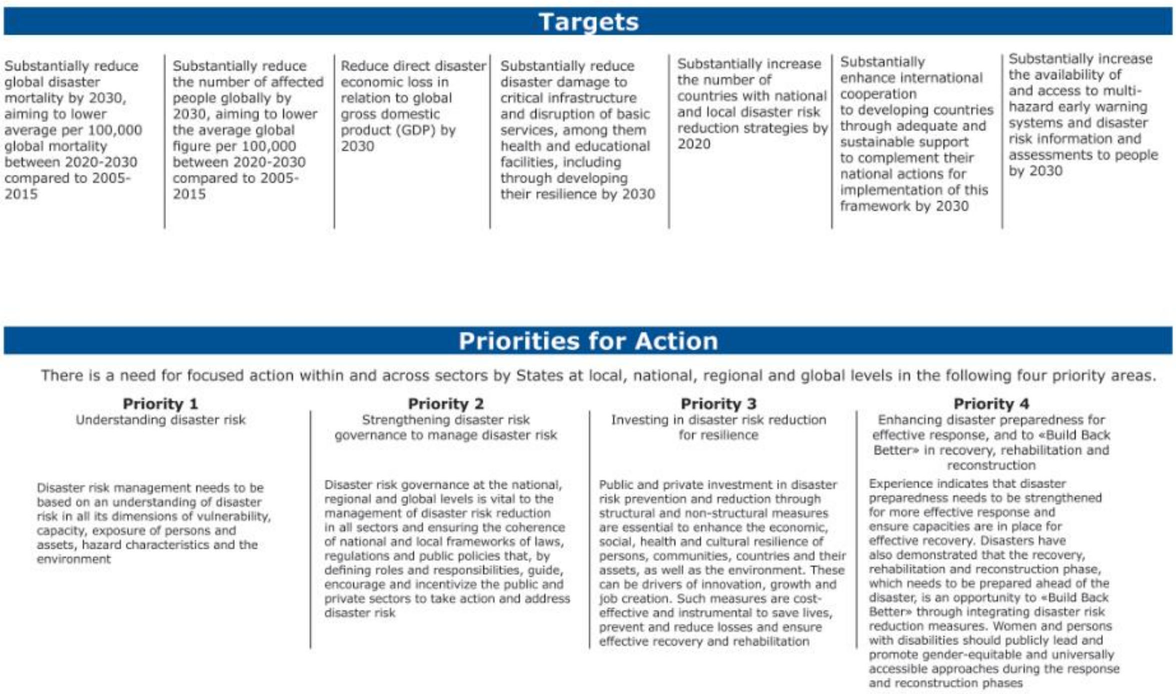

Figure 2-3: Target and priority action areas of the Sendai Framework (UNDRR, 2015, p. 36)

The progress of the Sendai Framework is assessed using thirty-eight indicators, categorised according to their respective targets, with each target comprising three to eight specific indicators. While the first four targets primarily focus on reducing disaster risk and improving resilience, the last three emphasise enhancing sustainability and resilience in recovery efforts. Consequently, the indicators reflect the factors that pose risks to sustainability and those that promote sustainable practices.

2.2.4 National Institutionalised Framework

The National Risk Register (NRR) of the United Kingdom serves as a vital resource that provides detailed insights into potential risks that could materialise within the next two years and have significant implications for society at large (Cabinet-Office-UK, 2020). In essence, risks are meticulously examined and characterised as 'reasonable worst-case scenarios,' representing the most severe and plausible manifestation of each risk. This approach allows relevant authorities to proactively engage in contingency planning efforts to mitigate potential adverse impacts.

Within the NRR 2020, a total of thirty-five distinct risks were identified and subsequently assessed, with a focus on prioritisation using a risk matrix framework. This prioritisation highlights the criticality and urgency of each risk, aiding in the allocation of resources and strategic interventions. The impact assessment of these risks encapsulates seven overarching dimensions: human welfare, behavioural consequences, effects on essential services, economic ramifications, environmental implications, security considerations, and international repercussions. By comprehensively analysing risks across these dimensions, authorities gain a holistic understanding of potential vulnerabilities and can tailor response strategies accordingly.

Moreover, the NRR emphasises the importance of public preparedness initiatives aimed at enhancing societal resilience and response capabilities in the face of plausible hazards. By fostering awareness, education, and readiness among the general populace, these preparedness activities play a crucial role in mitigating the effects of potential risks and building a more resilient society. Through a robust framework that integrates risk assessment, prioritisation, and public engagement, the NRR serves as a cornerstone for enhancing national resilience and fostering proactive risk management practices across various sectors.

Similarly, other countries have implemented their own risk registers to address national risks and enhance preparedness. Australia's National Risk Assessment and its associated National Risk Register provide insights into risks that could impact the nation, specifically focusing on strategies to bolster resilience against natural disasters and public health emergencies (Australian Government, 2020). In New Zealand, the National Disaster Resilience Strategy outlines risk management frameworks that include a comprehensive risk register, targeting hazards such as earthquakes, floods, and pandemics, emphasising community engagement and coordinated response planning (New Zealand Government, 2019). Meanwhile, the United States employs the National Preparedness Goal and the National Preparedness System, which includes the National Planning Frameworks that outline systematic approaches for assessing and managing risks across a range of threats (Federal Emergency Management Agency, 2015). Each of these frameworks reflects a commitment to understanding risks in the context of national security, crisis management, and public safety, thereby fostering a more resilient society through proactive planning and coordinated responses.

2.2.5 Summary

While the aforementioned risk frameworks may vary in their specific approaches, they share common attributes as they centre around the analysis of risks, vulnerabilities, and their underlying causes and effects. Emphasising factors such as hazards, developmental interrelations, risk governance, and regulatory frameworks (Pedro Basabe, 2018), these frameworks underscore the importance of comprehensively assessing risks. Hence, it is vital to grasp the shared characteristics and terminologies of risk assessment to formulate a cohesive and all-encompassing approach to risk evaluation (Hasani, El-Haddadeh, & Aktas, 2014)

2.3 Disaster Risk Assessment

Disaster Risk Assessment (DRA) is an important step for understanding local risks, enabling the implementation of suitable interventions for risk reduction and the development of resilient urban environments. Risk assessment needs to be carried out taking a systemic view by considering the interdependencies of various subsystems to recognise the cascading impact of hazards across different subsystems and domains (Hasani, El-Haddadeh, & Aktas, 2014). Given the complex relationships among risk assessment variables, researchers have investigated various risk assessment approaches to assess the risks. (Huang, Li, Guo, Zheng, & Qi, 2020; Khazai, Kunz-Plapp, Büscher, & Wegner, 2014; Munasinghe & Wijegunarathne, 2015; Torre, Cruz, Jose, Gatdula, & Blanco, 2019; Yeganeh & Sabri, 2014; Zlatanova, Ghawana, Kaur, & Neuvel, 2014). However, according to previous research, there is a lack of standard definitions for multi-hazard risk, and the current risk assessment processes are not taking a holistic view in assessing urban risks considering cascading impact (Aksha et al. (2020). Therefore, a systemised literature survey was conducted to identify the state-of-the-art in addressing the following research questions: What risk perspectives must be considered when defining disaster risks and their propagation in an urban environment?

"What key risk characteristics are inherent within communities that influence their resilience to disasters?. The following section outlines the outcome of the literature review conducted to answer these two research questions.

2.3.1 Literature Review Procedure

Initially, a literature search string was developed based on the keywords identified in the research question to facilitate the identification of pertinent literature. Following this, synonymous terms were gathered and organised to create a final search string.
Next, the keywords were connected using "AND" and "OR" operators. The "OR" operator was utilised to link terms within the same group, while the "AND" operator was employed to connect different groups of keywords. The following search string was subsequently used to locate research papers that correspond with the keywords, abstracts, and titles in the Scopus and Web of Science databases:

Literature search statement: ('Urban' OR 'Urban Infrastructure' OR 'Urban Development' OR 'Urban design*' OR 'Urban Environment*' OR City OR Town) AND (Hazard OR Risk OR Risk Perspectives OR Risk Characteristics OR Community Risks OR 'Cascading effect' OR Propagation OR 'Cascading failure OR 'Chain Reaction' OR interdependence*) AND (Resilience OR Impact OR Disaster OR Perturbation OR Damage OR Failure).

This literature search resulted in 2406 research papers. Further, eight reports were collected from intergovernmental organisational websites. The systemised literature survey employed specific exclusion and inclusion criteria for paper selection. Figure 2-4 illustrates the utilisation of the PRISMA method to screen literature records for the study. The inclusion criteria aimed to identify papers most relevant for risk propagation modelling. These criteria included considering research papers published in English after 1999, focusing on key subject areas such as Engineering, Environmental Science, Physics, Mathematics, and Social Science that align closely with the research scope. Following this process, 123 papers were initially selected for further review. Subsequently, after abstract assessment, 119 research papers proceeded to the full paper review stage.

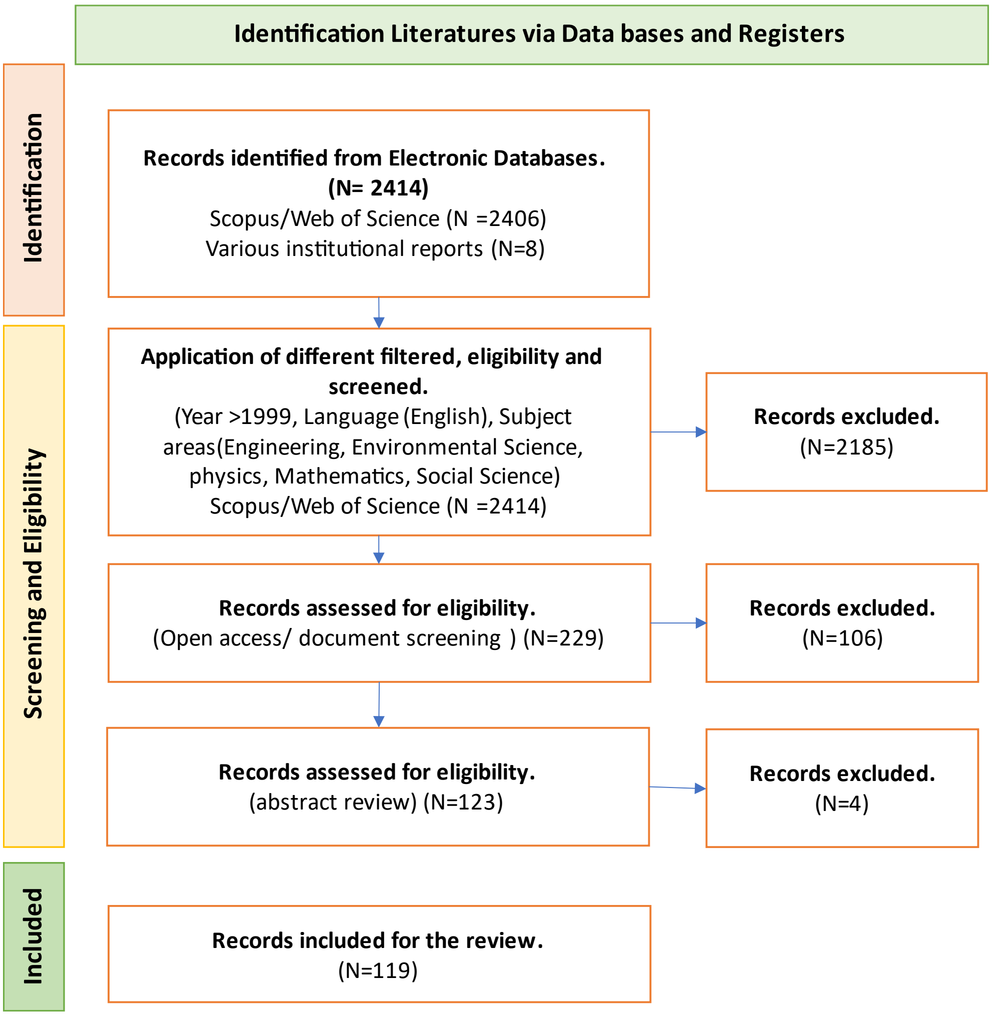

Figure 2-4: Stages in PRISMA review as carried out in the study

2.3.2 Summary Analysis of the Risk Perspectives

A systematic or mapping review approach (Grant & Booth, 2009) was chosen to map the existing characteristics onto a network diagram. Each research paper was carefully examined to identify risk assessment principles and to represent them in a network diagram. The analysis of the literature review was conducted using Nvivo12 Pro software (Sweet, 2014), and cases/nodes were created for each risk character. Figure 2-5 shows identified risk perspectives from the research papers.

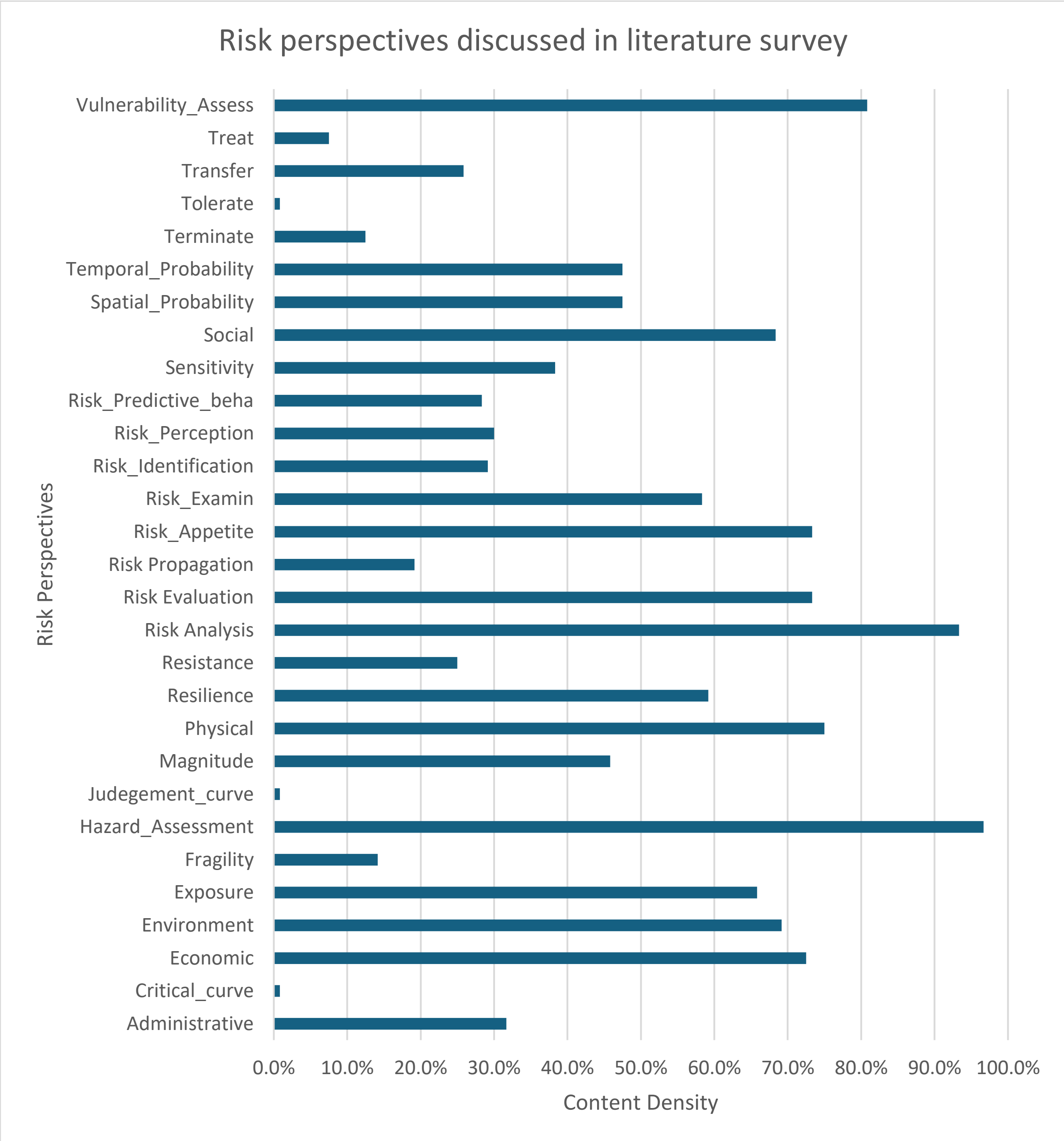

Figure 2-5: Risk Perspectives found in the literature

The review revealed that 94% of the research papers examined various approaches to risk analysis, with particular emphasis on hazard assessments (97%), vulnerability assessments (82%), exposures (66%), risk propagation (19%), and risk perception (30%). While risk appetite was mentioned in 74% of the papers, this aspect was not thoroughly explored. Specifically, critical elements of risk appetite, such as risk thresholds, risk tolerance, and judgment values, were referenced in only 1% of the studies reviewed. The following section summarizes the key perspectives on risk and the approaches to modelling risk propagation identified through the literature survey.

The subsections below summarise various risk perspectives found in the literature.

2.3.3 Hazard

Hazard is considered a source of potential harm (ISO-Guide73, 2009) or an external threat to the neighbourhood, which can create perturbation in the natural and built environment at different scales (Gallopín, 2006). While the initiation area of the hazard may not directly affect the neighbourhood, the runout zone or the propagated secondary hazard can impact the natural and built environment. Therefore, the hazard assessment is concerned with both susceptibility and triggering factors. The susceptibility factors investigate both potential initiation areas (initiation probability) and potential runout areas (reach probability) (Corominas et al., 2013). Here, the spatial and temporal probability of hazard occurrence in both initiation and runout areas is determined by its properties, such as propagation, size, and intensity (Corominas et al., 2013). Some hazard characteristics share common attributes that establish connections between them. For instance, susceptibility is linked with spatial and temporal probability, while triggering factors are associated with both magnitude and temporal probability (Corominas et al., 2013). Therefore, understanding these connections is useful to make a holistic risk assessment approach.

Another essential hazard assessment characteristic is the resistance factor, encompassing parameters that influence weak shear strength or heightened shear stress, thereby triggering hazards (Aksha et al., 2020). In their work, Wheeler, Register, and Mathias (2017) explored diverse energy fragmentation methodologies, ultimately advocating for the fragmented-cloud model approach as a pragmatic technique for hazard assessment. Aksha et al. (2020) conducted a geospatial study that combined multiple hazard types and identified various parameters contributing to landslide occurrences. For instance, evaluating landslide hazards involves considerations such as slope angle, elevation, slope aspect, surface curvature, soil liquefaction, and groundwater fluctuation (Aksha et al., 2020). Therefore, grasping resistance parameters or fragmentation mechanisms can aid in determining which factors exacerbate the severity of the hazard.

Therefore, the outcome of the hazard assessment is determined by the spatial and temporal probability of hazard events in the area along with the hazard type, magnitude, and resistance capacities (Aksha et al., 2020; Corominas et al., 2013; Gallopín, 2006; Huang et al., 2020; Izquierdo-Horna & Kahhat, 2018; Tran, Dobrovnik, & Kummer, 2018; Wheeler et al., 2017; Zhou et al., 2020; Zlatanova et al., 2014).

The hazard assessment can be represented as follows.

$$Hazard = f(P_S, P_T, M, R)$$

Where;

P_s - Spatial probability of an event

$P_{.T.}$ - Temporal probability of an event

M - Magnitude of the hazard event

R - Resistance of the hazard event, which comes as intrinsic properties of hazard or external environmental forces

2.3.4 Vulnerability

Vulnerability is defined in various ways in the literature. ISO-Guide73 (2009) defined vulnerability as intrinsic properties resulting in susceptibility to a risk source that can lead to an event with a consequence. International Strategy for Disaster Reduction (ISDR) has considered vulnerability a process or condition governed by external and internal factors that increase a community's propensity to be affected by natural events (Izquierdo-Horna & Kahhat, 2018). Therefore, in general, vulnerability refers to internal factors of elements that external or internal threats can impact.

Vulnerability has been defined in diverse ways by researchers, showcasing varying dimensions in their assessments. Corominas et al. (2013) emphasise physical, social, economic, and environmental dimensions as integral to vulnerability considerations. Sarwar, Ramachandran, and Hosseinian Far (2017) adopt the PESTLE framework, encompassing political, economic, social, technological, legal, and environmental dimensions for vulnerability analysis. The application of the Disaster Crunch model unveils delicate, driving, and fluctuating factors within settlements to effectively address vulnerability (Munasinghe & Wijegunarathne, 2015; Musacchio et al., 2016)

In contrast, Munasinghe and Wijegunarathne (2015) view vulnerability as a multifaceted construct incorporating Societal Analysis, Economic Analysis, Environmental Analysis, Critical Facility Analysis, and Mitigation Opportunity Analysis. Gao, Yuan, Qi, and Liu (2014) highlight population-related vulnerable factors tied to psychological, social, and spatial considerations, while economic vulnerability factors include economic scale, density, susceptibility, and importance of various industrial sectors. In a study by Izquierdo-Horna and Kahhat (2018), vulnerability is categorised into two primary dimensions: physical and social, with health factors specifically falling under the social dimension as 'Vulnerabilities due to demographic conditions'. As a result, this research incorporates five key dimensions for vulnerability assessment: physical, social, economic, environmental, and governance.

Various research activities have attempted to define the characteristics of vulnerability. Gallopín (2006) has conceptualised vulnerability as being constituted by components that include exposure to perturbations or external stresses, sensitivity to perturbation, and the capacity to adapt. Some studies used fragility measurement to define vulnerability and assess coping capacities (Bibi, Nawaz, Abdul Rahman, Azahari Razak, & Latif, 2018a; Bosetti, Ivanovic, & Munshey, 2016a). Weichselgartner and Kelman (2015) have also pointed out that vulnerability is a function of resilience, resistance, and susceptibility. However, the degree and exact characteristics and their interrelationship depend on the context and are a matter of perception (Weichselgartner & Kelman, 2015). Vulnerability, similar to resilience, is generally viewed as specific to perturbations that impinge on the system. This means a system can be vulnerable to certain disturbances and not others (Gallopín, 2006). Izquierdo-Horna and Kahhat (2018) propose that vulnerability could be elaborated considering a multifactored structure, including exposure, sensitivity, susceptibility, coping capacity, adaptation, and response.

Therefore, according to the literature survey, vulnerability could be discussed from a broader perspective as the functions of resilience, fragility, and sensitivity. This vulnerability assessment becomes a pivotal analysis to develop measures and pathways to a risk-reducing thorough understanding of critical factors to monitor the vulnerability over time (Khazai et al., 2014).

Researchers represent vulnerability as a function of other factors as follows (Bosetti, Ivanovic, & Munshey, 2016b; Corominas et al., 2013; Khazai et al., 2014; Munasinghe & Wijegunarathne, 2015; Torre et al., 2019):

$$Vulnerability = f\ \{F_p \quad F_s \quad F_{ec} \quad F_{en} \quad F_g | R \quad S \quad F\}$$

where,

F_p – Physical Aspect of vulnerability

F_s- Social Aspect of vulnerability

F_{ec}- Economic Aspect of vulnerability

F_{en} – Environmental Aspect of vulnerability

F_g- Governance of vulnerability

R – Resilience (intrinsic properties)

S- Sensitivity (intrinsic properties)

F- Fragility (intrinsic properties)

The following subsections discussed the definition and characterisation of resilience, fragility, and sensitivity.

2.3.5 Resilience

Resilience is a fundamental aspect of vulnerability. According to ISO Guide 73 (2009), resilience is defined as an organization's ability to adapt in a complex and changing environment. UNISDRR defines resilience as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" (UNISDR, 2013, p. 24). Additionally, the EU-CIRCLE (2018) enhances the understanding of resilience by identifying different types of capacities: anticipatory, absorptive, and restorative. Their approach is based on the resilience triangle (Cimellaro, Reinhorn, & Bruneau, 2010), which illustrates how resilience is expressed as a function of these three capacities. Collectively, they contribute to the adaptive capacity of the system, thereby depicting resilience. This comprehensive perspective underscores the multifaceted nature of resilience and its significance in understanding vulnerability.

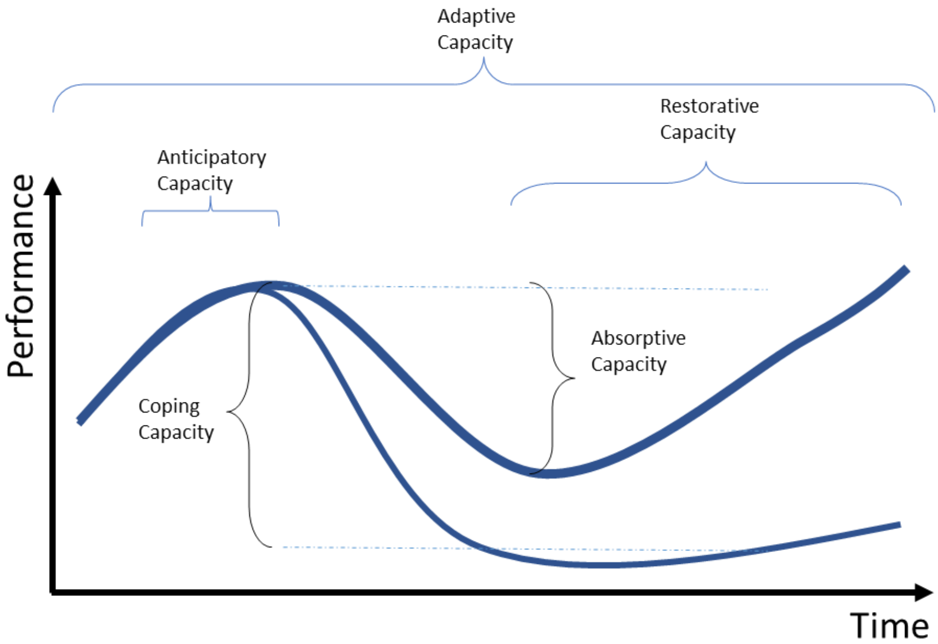

Figure 2-6: Types of resilience capacities

In EU-CIRCLE (2018), anticipatory capacity is defined as the ability of a system to foresee and mitigate the impacts of climate variability and extremes through effective preparedness and planning. A survey conducted by Tariq, Pathirage, and Fernando (2021) identifies indicators for measuring anticipatory capacity, which include the degree to which a country or region is implementing its mitigation, adaptation, preparedness, awareness, and risk communication strategies. Similarly, absorptive capacity is characterized as the system's ability to buffer, endure, and withstand the immediate impacts of climate extremes without collapsing (EU-CIRCLE, 2018). Indicators for assessing absorptive capacity focus on reduced vulnerability, the presence of responsive systems, and the establishment of social structures that can withstand shocks (Tariq et al., 2021). In this context, coping capacity refers to the maximum level at which a system can recover from a shock and return to functionality. When this threshold is surpassed, the system's ability to recover can be diminished significantly. Additionally, restorative capacity is defined as the system's ability to be quickly and efficiently return to its original state or improved state, in alignment with the principles of "Building Back Better". Together, these capacities provide a comprehensive framework for understanding resilience in the face of climate change and extreme events.

2.3.6 Sensitivity

The Intergovernmental Panel on Climate Change (IPCC) describes sensitivity as "the degree to which a system is adversely or beneficially affected by climate-related impacts" (IPCC, as cited by Torre et al. (2019, p. 174)). Torre et al. (2019) further emphasize that sensitivity is influenced by both the internal characteristics of a system and its degree of exposure to hazards. The calculation of sensitivity values involves assessing input-output variations within a specific environment (Francesca Pianosi et al., 2016). To compute these sensitivity values, various modelling approaches can be used in four key steps: (1) define the model, including input and output parameters; (2) assign probability models to facilitate value calculations; (3) generate an input matrix; and (4) assess the influences and relative importance of the input-output relationships (Francesca Pianosi et al., 2016). The choice of analytical techniques depends on the complexity of the system being studied. Systems can generally be categorized into simple systems, characterized by single directed connections, and complex systems, which exhibit multiple interconnected relationships (Francesca Pianosi et al., 2016).

In simple systems, sensitivity values are often calculated using differential equations, which provide a straightforward mathematical framework (Francesca Pianosi et al., 2016). In contrast, complex systems necessitate advanced calculation methods, such as Fourier analysis and Green's functions, to accurately determine sensitivity values due to their intricacies. By understanding sensitivity in this multifaceted manner, stakeholders can better assess how different systems respond to climate-related changes and enhance overall disaster resilience.

2.3.7 Fragility

Fragility is another attribute of vulnerability. Corominas et al. (2013) have identified that the vulnerability of an element can be quantified by using either vulnerability indices or fragility curves. These fragility curves estimate the probability of damage for given physical features, such as peak building response over a particular hazard represented as spectral acceleration or displacement at the performance point (Choi, Park, & Kim, 2019). Izquierdo-Horna and Kahhat (2018) have argued that many social variables are challenging to measure, such as the level of exposure, fragility suffered by human groups, their degree of preparation, the response of people to natural disasters, and other social characteristics of affected communities. Bosetti et al. (2016b) have also argued that there is no set definition of a 'fragile state,' and the standard approach is to assess the ability and willingness to carry out core functions that meet the needs and expectations of society.

Further, several researchers identify the dimensions of fragility as legitimacy, effectiveness (capacity), security, authority, social cohesion, welfare, degree & duration of fragility (Bosetti et al., 2016b). Nilsson and Grelsson (1995) have described that the species, ecosystems, or communities damaged mainly by human intervention may be called fragile, sensitive, or vulnerable. For example, poor villages (less capable of coping with disasters) need to strengthen their social ecosystem construction from the perspective of community development (Zhao, He, & Zhao, 2020). Therefore, fragility can be illustrated as the inverse of the stability of a system (Nilsson & Grelsson, 1995).

Similar to sensitivity, various methods are available for modelling fragility, and the most common method is the fragility function (Shinozuka, Feng, Lee, & Naganuma, 2000). Four main steps can be identified in these methods: (1) Background concept, (2) Systematised concept, (3) Selection of measurement of indicators, and (4) Calculation of index scores (Shinozuka et al., 2000).

2.3.8 Exposure

UNISDR defines exposure as "People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses."(UNISDR, 2009, p. 15). However, the detailed exposure analysis is subjective to the specific hazard condition. The expected exposure of a disaster consists of 1) non-economic loss (loss of human lives, injuries and other socio-cultural aspects), and 2) economic loss, which is further divided into a direct economic loss (mainly the value of property loss) and indirect economic loss (or long-term economic effects) (Zhou et al., 2020). Different exposures can be estimated through diverse evaluation methods, such as property evaluation models, input-output models, computational general equilibrium models, and environment evaluation models (Zhou et al., 2020). The evaluation models could be selected by referring to the risk assessment scope, and this research is only focused on understanding the holistic approach and characteristics of risk assessment.

2.3.9 Risk Assessment Process

Risk assessment is a vital component of risk management, aimed at evaluating the risk status of the community. According to Zlatanova et al. (2014), risk management comprises four major phases; 1) risk identification, 2) risk evaluation, 3) choice and implementation of risk reduction measures and instruments, and 4) monitoring and maintenance of acceptable risk. Risk identification and evaluation are considered two important parts of the risk assessment process in risk management. However, various approaches are being practised to assess the risks. For instance, ISO-Guide73 (2009) has defined risk assessment activities as understanding risk, risk- analysis, and risk evaluation.

In contrast, Corominas et al. (2013) identified risk understanding, analysis and evaluation as the key phases in risk assessment. The critical activities involved in risk analysis include hazard identification, hazard assessment, inventorying elements at risk and their exposure, vulnerability assessment, and risk estimation. Within this phase, hazard identification serves as the initial step for understanding any threats, uncertainties, vulnerabilities, and unexpected events that may act as sources or triggers for risk to materialise (Tran et al., 2018). Risk evaluation is the stage where values and judgments influence the decision-making process, either explicitly or implicitly.

This involves assessing the significance of the estimated risks and their related social, environmental, and economic consequences to recognized various strategies for risk management (Corominas et al., 2013). Risk evaluation is regarded as a vital step in the risk assessment process, facilitating enhancements to the current system to effectively address future risks. In this phase, values and judgments play a significant role in the decision-making process, either explicitly or implicitly, by evaluating the severity of the estimated risks along with their associated social, environmental, and economic consequences. This assessment aids in identifying a variety of alternatives for effective risk management (Corominas et al., 2013).

2.3.9.1 Risk Analysis

The definition of risk varies from discipline to discipline (Aksha et al., 2020; Stock & Wentworth, 2019). According to the generic principles, risk analysis is a process of understanding and estimating the nature of risk and allowing users to make decisions on the risk treatment by considering the risk evaluation (ISO-Guide73, 2009). Hazard, vulnerability, and exposure are the three variables in the risk analysis (Bibi, Nawaz, Abdul Rahman, Azahari Razak, & Latif, 2018b; Gallopín, 2006; Huang et al., 2020; Zhou et al., 2020).

According to the review, the risk analysis materializes with several attributes, such as consequences, probability of occurrence, hazard, exposure, vulnerability, capacity, triggering factors, cycle incubations, perturbation, range of alternatives, uncertainty, unexpected events, threat and perception (Corominas et al., 2013; Gallopín, 2006; Huang et al., 2020; Izquierdo-Horna & Kahhat, 2018; Tran et al., 2018; Zhou et al., 2020; Zlatanova et al., 2014). The subsequent subsections provide a detailed discussion of the relationships among the risk analysis variables.

2.3.9.2 Risk Analysis Methods

Various risk assessment formulas are utilised in different risk contexts, with risk generally viewed as a function of hazard, vulnerability, and exposure. The following paragraphs examine how these risk values are represented to facilitate decision-making. Corominas et al. (2013, p. 210) developed a formula for landslide risk assessment by subcategorizing hazards according to their characteristics of magnitude, spatial probability, and temporal probability. Their formula and expression can be outlined as follows.

$$R=P(M_i).\ P(X_j|M_i).P(T|X_j).\ V_{ij}.\ C$$

Where R is the risk due to the occurrence of a landslide of magnitude M_i on an element at risk located at a distance X from the landslide source, the variables are defined as follows (Corominas et al., 2013, p. 210):

- $P(M_i)$ is the probability of occurrence of a landslide of magnitude Mi.
- $P(X_j|M_i)$ is the probability of the landslide reaching a point located at a distance X from the landslide source with an intensity j.
- $P(T|X_j)$ is the probability of the element being at the point X at the time of occurrence of the landslide.
- V_{ij} is the vulnerability of the element to a landslide of magnitude i and intensity j.
- C is the monetary value of the element at risk.

Various theories and approaches are employed for different hazard analyses. The most common methodologies for assessing disaster risk include mathematical and statistical analysis, quantitative methods, Multi-Criteria Decision Analysis, system dynamics methods, and uncertainty methods (Yeganeh & Sabri, 2014). These theories and approaches can be categorized into four types (Yeganeh & Sabri, 2014):

1. **Stochastic programming approach**, where variables are treated as random variables with defined probability distributions;
2. **Fuzzy programming approach**, which treats variables as fuzzy numbers;
3. **Stochastic dynamic programming**, which considers random variables distributed across all areas of multi-stage decision-making;
4. **Robust optimization**, which aims to find the optimal result for a given set of input data in a real-world scenario.

Furthermore, Yeganeh and Sabri (2014) identified four common techniques for developing weights for each variable: the ranking method, the rating method, the pairwise comparison method, and the trade-off analysis and comparison method.

Most risk assessments have primarily focused on the physical elements of settlements. However, some studies also address the valuation of human life within the context of risk assessments. For instance, Zhou et al. (2020) have considered the 'Value of Statistical Life (VSL)', which is defined as the additional cost that an individual willingness to get for reducing the potential consequences, and calculated risk using the following equation.

$$Risk(I) = Probability(I) \times Loss(I)$$
$$Loss(I) = LDE(I) + LVSL(I)$$

Here, direct loss (Loss(I)) is calculated by using direct economic loss (LDE (I)) and the Loss of Value of Statistical Life (LVSL(I)). The evaluation method of VSL calculates risk using either a human capital approach or a willingness-to-pay approach. To determine the additional cost required to enhance community resilience, one would need to assess the investments necessary for infrastructure improvements, disaster preparedness programs, and community education initiatives, along with ongoing maintenance costs. This would involve estimating the financial resources needed to implement these measures effectively, considering both direct and indirect costs associated with resilience-building efforts (Zhou et al., 2020).

2.3.9.3 Presentation of Risk Values

Lee, Chen, Pai, and Wu (2015) suggested that risk values should be classified into zero (0) to one (1) range for easy classification purposes. Alternatively, unique names can be assigned to different risk classes based on their probabilities and levels of perturbation. For instance, the following names can be assigned based on the risk condition: Medusa, Cassandra, Pandora, Pythia, Cyclops, and Damocles (Stock & Wentworth, 2019).

A risk matrix is a commonly used method for representing risk values in most risk assessments (Corominas et al., 2013; Hopkin, 2010). In this method, a plot is created by assessing expected losses against the probability of occurrence of natural hazards for each element. These individual risk matrices can then be integrated to form a comprehensive total risk matrix for a specific area. Figure 2-7 illustrates the risk matrix diagram, which is a graphical representation that considers two dimensions: impact and likelihood.

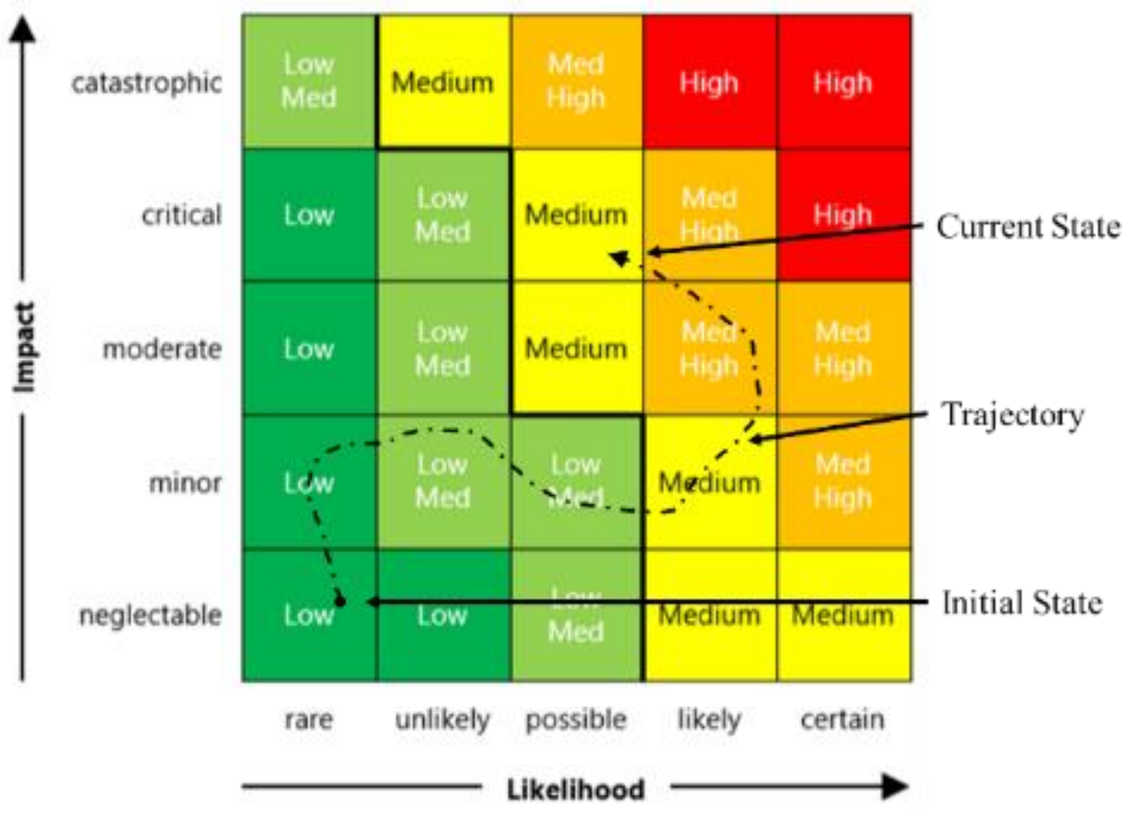

Figure 2-7: Risk matrix and trajectory curve

Trajectory trend curves can be applied to evaluate risk values by referring to various criteria, and they can be overlaid on the risk matrix to visualize the variations in risk values concerning the identified variables. Gallopín (2006) used this approach to evaluate social resilience values, reflecting the ability of groups or communities to cope with external stresses and disturbances due to social, political, and environmental change. Figure 2-7 illustrates the trajectory trend curve, depicting the initial state, trajectories, and current state, along with its connection to the risk matrix.

2.3.9.4 Risk Evaluation Methods

Risk evaluation is a significant step in risk assessment and is discussed within various risk management frameworks. According to the ISO-Guide73 (2009, p. 8), risk evaluation is defined as the “process of comparing risk analysis results with risk criteria” to determine risk appetite. This risk evaluation provides necessary instruction to define the risk treatment measures. For instance, the stakeholders' perceptions of risk status can be a form of evaluation. Kellens, Terpstra, and De Maeyer (2013) have described risk perception as a subjective risk assessment that can gauge attendees' perceptions of risk status concerning an identified perturbation. Similarly, D. Xu, Zhuang, Deng, Qing, and Yong (2020) found that new communication media systems enhance community understanding of risks, including their magnitude and frequency. Therefore, reviewing the literature on risk perception methods that could be utilized in risk assessments is essential.

2.3.10 Risk Perception

Human perception of risk reduction is a crucial factor in effective risk management, highlighting the importance of implementing risk reduction strategies to create a sustainable and resilient built environment over the long term. Risk perception is a complex process that involves both cognitive factors (e.g., likelihood and knowledge) and affective factors (e.g., emotions and perceived control) (Kellens et al., 2013). Many research papers have examined the characteristics of risk perception at various scales, with risk knowledge and resilience being the most frequently discussed aspects. In contrast, topics such as data collection from multiple sources, verification of risk status, and assessments of original risk status were addressed less frequently compared to others.

Moreover, the perception of risk across different sectors and hazards has been explored. For instance, Bajracharya et al. (2021) noted that community perceptions regarding the actions taken by institutions during disasters improved following the implementation of community-based disaster training programmes. Initially, the broader community had higher expectations for support from institutions. However, through community-based disaster risk reduction initiatives, the community came to understand that they could manage several components independently. This underscores the need for communities to grasp the roles and responsibilities of various institutions in risk reduction, emphasizing that communities should take a proactive role in risk management (Bajracharya et al., 2021).

Community perception and understanding of both existing and future risks are critical components of effective risk management. Communities have the capability to recognise potential hazards in their surroundings and possess the knowledge necessary to identify their associated impacts. To enhance this understanding, it is essential for communities to engage in continuous knowledge improvement programmes and conduct regular observations of their environment (Bajracharya et al., 2021). Consequently, risk assessment methods play a vital role in evaluating the community's level of risk perception.

Moreover, risk perception is deeply influenced by previous experiences, which can be transformed into risk knowledge (Bajracharya et al., 2021; Kellens et al., 2013). This historical context is vital for improving local expertise on risks during community engagement workshops. For instance, Bajracharya et al. (2021) found that over 90% of community members acknowledged the adverse impacts of risks on their markets, infrastructure, and livelihoods during community-based disaster risk reduction programmes. This highlights the importance of integrating past experiences into current risk management practices to foster greater resilience.

The Psychometric Paradigm and the heuristics approach are two types of risk perception analysis methods (Kellens et al., 2013; Kellens, Zaalberg, Neutens, Vanneuville, & De Maeyer, 2011). The psychometric paradigm is a prominent and widely used theoretical framework in risk perception that aims to quantify individuals' risk perceptions and attitudes through structured questionnaires. Heuristics, which are simple and efficient rules of thumb, are often employed to simplify complex problems and facilitate decision-making without requiring extensive cognitive resources.

The foremost approaches for examining risk perceptions include the Expectancy-Valence (EV) approach and the application of Contingent Valuation Methods (CVM).

2.3.10.1 Expectancy Valence Approaches (EV)

This framework emphasizes the explanation of people's adaptive behaviour, which can be predicted by examining their valences for different outcomes, such as the desire to protect themselves, the instrumentalities associated with their actions (e.g., installing flood barriers), and their experiences of previous successful risk reduction efforts. The concepts are grounded in psychological theories, and several other methods are associated with the Expected Value (EV), which can be described as follows:

- Protection Motivation Theory (PMT): This tool assists in analyzing an individual's threat and coping appraisal regarding their perception. Three constructs are defined as mechanisms to predict coping appraisal: response efficacy, self-efficacy, and response cost (Kellens et al., 2013). Two constants for predicting the threat appraisal are perceived probability and perceived consequence (Bubeck, Botzen, & Aerts, 2012). Bubeck et al. (2012) discussed the applicability of the Protection Motivation Theory (PMT) in flood risk management, emphasizing that these aspects should be given greater consideration in risk communication policies.
- The RCSA Model (Risk, Coping, and Social Appraisal) This framework incorporates three types of appraisals: Risk Appraisal, which includes perceptions of severity and probability; Coping Appraisal, which encompasses self-efficacy and response efficacy; and Social Appraisal, which involves community identification and perceived norms. This tool is utilized to understand farmers' drought adaptation practices and has been demonstrated to be a more effective predictor of adaptation intentions than a purely demographic model (Truelove, Carrico, & Thabrew, 2015).
- Protective Action Decision Model (PADM): This tool is similar to the PMT and is mainly applied for earthquake hazards. Here, efficiency attributes are protecting people, protecting property, and protecting utilities.
- Motivation Intention Volition Model (MIV): Motivation stems from perceived risk but can be hindered by a lack of perceived personal responsibility and tendencies to avoid or suppress the perceived threat. An individual's intention to adopt hazard adjustments is further influenced by their perceived response efficacy and self-efficacy. The intentions formed during the violation phase translate into actions based on the situational barriers encountered (Kellens et al., 2013).
- Risk Information Seeking and Processing Model (RISP): This tool represents the construct of insufficient information, defined as the gap between an individual's current knowledge and their knowledge threshold.

2.3.10.2 Applications of Contingent Valuation Methods (CVM)

This economic approach assesses individuals' perceptions by focusing on their willingness to pay (Kellens et al., 2013). The technique has been used to analyse earthquake disasters in Taiwan by Chen, Chao, and Cheng (2020). The study indicates that individuals tend to have heightened risk perceptions of future hazards while showing less willingness to pay for retrofitting their homes after experiencing a severe disaster. Conversely, those with higher education and better occupational status may be more inclined to invest in adopting adaptive behaviours compared to others.

In addition to theoretical frameworks, there are cognitive approaches for examining risk perceptions based on the following key areas:

1. **Awareness**: For example, “Are you aware that you live in a flood-prone area?”
2. **Affect**: For instance, “Do you feel personally endangered by a flood?”
3. **Likelihood**: Such as, “What do you think are the chances of a flood occurring in your neighborhood within the next ten years?”
4. **Impact**: For example, “Rate the following statement: A flood will have fatal consequences for my family and me.”
5. **Cause**: For instance, “Can you indicate the cause of the flood risk in your neighborhood?” (Kellens et al., 2013, p. 38).

A perception study conducted in Japan’s Toki-Shonai River basin assessed the acceptability of flood risk. This study revealed that perceptions of loss related to public facilities and services due to floods increase the public’s acceptability of flood risk (Zhai & Ikeda, 2008).

2.3.10.3 Risk Predictive Behaviour

Understanding the current risk and predicting its behaviour is crucial for identifying effective risk reduction approaches (Jemec Auflič, Kumelj, Peternel, & Jež, 2018). Therefore, understanding the probability of hazard occurrence during the hazard assessment stage is significant and involves engaging stakeholders and the community to identify potential hazards (Jemec Auflič et al., 2018).

Frequent training and knowledge-sharing sessions are essential to enhance the community and stakeholders’ understanding of hazard impacts. For instance, the Learning-by-Doing approach has been shown to be particularly effective for community awareness around landslide risks, improving participation and understanding in community awareness programs (Jemec Auflič et al., 2018). However, the effectiveness of community awareness activities depends on social classes, past experiences with impacts, and the duration of residence in hazardous areas (Kellens et al., 2013).

2.3.11 Risk Communication

Risk communication plays a crucial role in disaster risk reduction, providing significant benefits throughout all stages of the risk management process. Proactive measures for potential events are essential, and effective risk communication offers clear guidance to minimise impacts, thereby reducing loss of life, damage to property, and threats to critical infrastructure (Bajracharya et al., 2021). To achieve this, hazard-related early warnings must effectively convey the potential impacts to communities. Warning messages should be categorised according to impact probabilities and the corresponding level of preparedness. For instance, several levels of hazard warnings can be established: Level 1 (Watch Alert) indicates that no precautionary actions are required; Level 2 (Preparation Level) signifies potential hazards and calls for the protection of vulnerable individuals; and Level 3 (Evacuation) warns of significant impacts and advises immediate relocation to safer areas (Bajracharya et al., 2021).

The medium of risk communication is paramount in disseminating crucial information to communities. Various communication channels, including mass media and user-specific applications, are commonly employed. Traditional methods such as television, print media, radio, SMS, and web-based information are widely used (Bajracharya et al., 2021). However, access to mass media may be limited in certain areas, prompting the development of specific applications to effectively communicate risks to targeted communities (Pierson, Wood, & Driedger, 2014). In these situations, both automated and manual risk communication approaches are implemented.

Additionally, sensor networks that monitor event threshold limits can greatly enhance risk communication efforts. Pierson et al. (2014) highlight various Internet of Things (IoT) technologies, which range from high-cost to low-cost solutions for tracking hazard initiation and flow paths. These sensors serve as early warning systems, and the information they gather should be complemented by actionable prevention measures. For example, human observation is often necessary to assess the cumulative impacts of low-tech instruments

(Pierson et al., 2014). Understanding sensor data and observations requires adequate knowledge and experience within the community. Therefore, stakeholders must ensure that relevant training and drills are provided to empower communities to effectively respond to hazard risk information (Bajracharya et al., 2021; Pierson et al., 2014).

2.3.11.1 Communication based on previous experiences

Showcasing success stories can help improve the community's risk perception. Similar hazards may occur in different geographic regions, and various risk reduction techniques have been tested to reduce hazard impacts in many locations. Sharing these lessons with targeted communities can serve as a valuable trust-building tool. For example, Bajracharya et al. (2021) discussed implementing community-based disaster risk management activities in a few countries before conducting community programmes. Further, the impact of these studies is also mentioned to understand the level of success of activities. Bajracharya et al. (2021) have mentioned that the community-based disaster risk management program significantly increases the preparedness level of communities. The results showed that the percentage of unprepared communities reduced from 75% to 45% after implementing community-based risk management programs.

Transforming a high-risk community into a low-risk one is a complex journey that involves passing through several key milestones. Success stories from various communities can provide valuable insights into how these milestones are achieved. To measure community resilience along this journey, several researchers have employed frameworks such as emBRACE (Bajracharya et al., 2021; Kruse et al., 2017). These measurements are essential for assessing the current status of a community in its risk management efforts, as the concept of resilience encompasses the community's ability to absorb risks, its anticipatory state, tolerance levels, and options for recovery (Kruse et al., 2017).

Additionally, researchers have linked international risk management frameworks, including the Yokohama Strategy, the Hyogo Framework, the Sendai Framework, and the Sustainable Development Goals (SDG), with community development outcomes (Kruse et al., 2017). By aligning these frameworks with local experiences and conveying the results effectively, researchers aim to build trust in risk reduction programs. This alignment not only enhances community confidence but also reinforces the reliability of the proposed human-centric approaches to risk reduction.

2.3.12 Risk Reduction Approaches

Risk perception is closely linked to the outputs of risk reduction strategies. The effectiveness of each risk reduction strategy relies on thorough technical knowledge and analysis. Consequently, researchers have employed various models, scenarios, surveys, and applications to assess these impacts (Bajracharya et al., 2021). Such hypotheses or scenarios are essential for investigating community risk by manipulating different variables (D. Xu et al., 2020). Following this, potential damage assessments are conducted based on hypothetical events and their impacts on properties (D. Xu et al., 2020). The findings from these assessments inform discussions around risk acceptance, which is evaluated through cost-benefit analyses or the consequences of the damage assessments (Stock & Wentworth, 2019; Zhai & Ikeda, 2008).

After conducting multiple scenarios, priority actions can be identified and subsequently validated in consultation with stakeholders. Stock and Wentworth (2019) note that emergency planning activities are informed by these risk acceptance priorities. Both worst-case and most probable scenarios play critical roles in shaping emergency planning efforts (Stock & Wentworth, 2019). Governments are encouraged to communicate the most probable scenarios to the public, while community engagement can help validate these scenario outputs by gathering geographic and physical data (Stock & Wentworth, 2019). Although a reasonable worst-case scenario can pose challenges for the community, it may not be directly informative for businesses and the general public; nevertheless, it should still be integrated into the risk assessment process (Stock & Wentworth, 2019).

2.3.13 Risk Appetite

Risk appetite plays a critical role in informing decision-making and prioritising risk mitigation strategies. As climate-related risks become increasingly complex and impactful, understanding an organisation's or community's risk appetite is essential for effective disaster risk reduction and building resilience.

Risk appetite reflects the level of risk that an entity is willing to accept in pursuit of its risk reduction objectives. It provides a framework for evaluating risk capacities and potential responses to climate threats, allowing stakeholders to balance the need for proactive measures against the inherent uncertainties of climate impacts. (Hopkin, 2010) explores various dimensions of risk appetite, categorizing responses into four primary strategies: Risk Accept, Risk Adapt, Risk Avoid, and Risk Transfer. Each of these strategies indicates a distinct approach to managing climate-related risks, depend on the level of risk assessed.

Current research emphasises the importance of tailoring risk appetite definitions to specific contexts, especially in the face of climate disasters. Several studies have suggested that organisations should engage in collaborative risk assessments that incorporate diverse stakeholder perspectives, including vulnerable communities, policymakers, and private sector actors (Sim, Dominelli, & Lau, 2017; Zhao et al., 2020). This collaborative approach enhances the understanding of acceptable risk levels and helps to establish clearer thresholds for decision-making.

The use of a risk matrix, a tool highlighted by Hopkin (2010), remains fundamental in this process, where risk levels are plotted against the probability and impact of climate-related events. The judgment line signifies the balance between an entity's comfort and cautious zones. In the comfort zone, where risks are deemed acceptable, the primary response is often to risk tolerate, allowing for limited investment in mitigation strategies. Conversely, within the cautious zone, characterized by heightened awareness of potential adverse consequences, stakeholders may tend toward risk transfer, such as through insurance contracts, or risk treat, where active measures are taken to reduce exposure and vulnerability to climate impacts. The concerned zone further underscores the potential for severe impacts, encouraging organisations to adopt a risk-terminating approach, which entails the avoidance of certain high-risk activities altogether.

2.4 Risk Propagation

The interdependencies and the interactions between urban infrastructure and services such as water, energy, heating/cooling, transportation, and socioeconomic needs such as jobs, business, neighbourhood, and housing are directly correlated to the complexity of cities

(Pandit et al., 2015). As cities expand and develop to meet their citizens' socioeconomic goals, these complexities grow faster and become more complex, all while striving to maintain social and economic stability (Yang et al., 2019).

The interconnectedness of various systems means that disruption to one infrastructure or service can trigger cascading failures across others, leading to catastrophic effects (Karakoc et al., 2019). These hazards can propagate across different domains, such as physical, social, ecological, and economic, due to their complex interconnections, potentially resulting in a widespread disaster within a city (Wei Hao et al., 2020; Karakoc et al., 2019). One example that illustrates such a cascading impact is Hurricane Katrina. Here, the failure of the levee system during the storm led to widespread flooding, which physically damaged infrastructure and homes while displacing thousands of residents and disrupting social networks. This disaster not only devastated local ecosystems by contaminating waters and habitats but also resulted in significant economic losses, crippling businesses and straining recovery efforts for years to come.

Therefore, future urban development necessitates a system thinking approach, wherein relevant stakeholders across all sectors collaborate to consider cities as complex systems. This perspective acknowledges that risks are an integral element of overall city planning (X.-j. Wang et al., 2010; Jiuping Xu & Lu, 2018). It is essential for local governments to adopt a robust risk assessment process that accounts for cascading risks, enabling them to understand and manage both existing and future challenges. By embracing this comprehensive approach, authorities can cultivate resilient environments that effectively respond to the multifaceted nature of urban risks (Kwesi-Buor, Menachof, & Talas, 2019; W. Xu, Xiang, & Proverbs, 2020).

Risk propagation refers to the process by which a risk or potential threat in one system or component of a system can spread or propagate to other parts of the system, leading to possible catastrophic consequences (Abhijeet Ghadge, Jena, Kamble, Misra, & Tiwari, 2020; Karakoc et al., 2019; Lasch, 2018). This risk propagation can occur through financial, economic, or physical connections, amplifying or exacerbating risks (Abhijeet Ghadge et al., 2020).

Several studies have emphasised the importance of considering risk propagation in sectoral risk assessments (Abhijeet Ghadge et al., 2020; P. Li, Cheng, & Tao, 2020; W. Li, Han, Wang, & Guan, 2019; Luo, Yang, & Sun, 2018). (Lasch, 2018) highlighted the limitations in existing quantitative risk propagation models for assessing the impacts of supply chain disruptions in urban settings. Researchers have also pointed out the significant advantages of analysing cascading propagation phenomena in financial assessments (Abhijeet Ghadge et al., 2020; P. Li et al., 2020).Furthermore, a study examining the interconnections between the tourism and transportation sectors emphasises the necessity of propagation assessments for effective contingency planning (W. Li et al., 2019).

2.4.1 Approaches for Risk Propagation Modelling

Risk propagation is the process by which risks spread through a system or network, affecting multiple components or subsystems (Karakoc et al., 2019). Various approaches exist for analyzing and managing risk propagation (Arosio, Martina, & Figueiredo, 2020; Kanj, Aly, & Kanj, 2022; Lasch, 2018; X. Liu, Lu, Cheng, Ma, & Osaba, 2021; Vitali, Battiston, & Gallegati, 2016; X.-j. Wang et al., 2010), including:

1. Bayesian Network (BN): This probabilistic graphical model facilitates reasoning under uncertainty and by propagating probability distributions of random variables and their conditional dependencies(Lasch, 2018; X. Liu et al., 2021).
2. Network Analysis (NA): This approach uses graph theory to analyse how risks propagate through a network of interconnected components or subsystems (Arosio et al., 2020).
3. This approach models the behaviour of systems over time, enabling analysts to understand how various factors and events can significantly influence the system in the long term and how risks can propagate throughout it (Kanj et al., 2022; Lasch, 2018; X.-j. Wang et al., 2010).
4. Agent-Based Modelling (ABM): In the context of risk propagation, an ABM can be used to simulate how different risks can spread through a network of agents, such as a supply chain, financial network, or social network (Kanj et al., 2022; Lasch, 2018; Vitali et al., 2016).

Although these models have been used for risk propagation assessments, each has its own different advantages and disadvantages. One key advantage of risk propagation models is their ability to identify and analyse interdependencies between different risks, helping organisations pinpoint areas where a minor issue in one location could have significant repercussions on overall risk levels (Deng et al., 2018). They can also help organisations prioritise which risks to address first and allocate resources more effectively (Lasch, 2018). Conversely, a major disadvantage of risk propagation models lies in their complexity; developing these models can be time-consuming and resource-intensive (Duan et al., 2019). Additionally, they often require a substantial amount of data, which can be difficult to obtain or unreliable (Qu et al., 2018). Additionally, the models may not accurately capture all the interactions and complexities of real-world risks, which could lead to inaccurate or incomplete results (Luo et al., 2018). Table 1 summarises the advantages and disadvantages of risk propagation approaches discussed by many researchers (Arosio et al., 2020; Lasch, 2018; X. Liu et al., 2021; Luo et al., 2018; Vitali et al., 2016).

Table 1: Advantages and disadvantages of risk propagation approaches

Propagation approach	**Advantage**	**Disadvantage**	**References**
Bayesian Network (BN)	Flexibility, Incorporation of prior knowledge, quantification of uncertainty through probabilistic reasoning, Handling missing data	Complexity, High computational demand, Assumption prior distributions, Limited applicability	(Lasch, 2018; X. Liu et al., 2021)
Network Analysis (NA)	Identification of nodes & linkages,	Complexity, Data requirement, Assumption on	(Arosio et al., 2020; Lasch, 2018)

	quantification of network properties,	network structure, Limited applicability	
System Dynamics (SD)	Holistic perspective, Dynamic modelling, Dynamic feedback loops, scenario analysis, long-term focus, Integration of quantitative and qualitative data.	Complexity in development, Data requirement, Simplification and assumptions of system behaviour, Sensitivity to initial conditions, Limited applicability	(Lasch, 2018; X.-j. Wang et al., 2010)
Agent-Based Model (ABM)	Micro-level modelling, Complex interactions, Flexibility, Emergence	Complexity, Data requirement, Assumption of agent behaviour, Limited Granularity, Limited applicability	(Kanj et al., 2022; Lasch, 2018; Vitali et al., 2016)

The critical review conducted by Niels Bugert and Rainer Lasch (2018) evaluated several modelling approaches, identifying the strengths and limitations of each (Figure 10). Their findings indicate that while Bayesian Networks (BNs) effectively assess risk propagation in a static context, they lack the dynamic capabilities crucial for understanding the evolving nature of risks over time. In contrast, the SD model excels in capturing the dynamic interactions and feedback loops that are integral to risk propagation processes.

SD models provide a systematic approach to analysing how risks propagate through interconnected components of a system, accommodating the complexities and interdependencies inherent in urban environments. By addressing internal feedback loops and time delays, the SD methodology aligns well with the nature of risk propagation, which often unfolds over extended periods. As highlighted by Reynolds & Holwell, 2010, understanding the behaviour of complex systems requires a dynamic perspective, something that the SD approach is fundamentally designed to provide. Moreover, by focusing on long-term system behaviour, SD models effectively capture the ongoing changes and developments that characterise risk conditions. This ability to model dynamic system changes enhances the reliability and applicability of the analysis in real-world scenarios (Adria Rubio-Martin, Manuel Pulido-Velazquez, Hector Macian-Sorribes, & Alberto Garcia-Prats, 2020).

Therefore, the System Dynamics model stands out as the most effective modelling approach for risk propagation in complex urban environments. Due to its capability to represent dynamic interactions, along with its comprehensive evaluation of feedback loops and temporal changes, SD was considered the best fit for comprehensively understanding risk propagation and interdependencies in this study. Therefore, a detailed literature review was conducted to assess the state of the art in system thinking and dynamic modelling approaches.

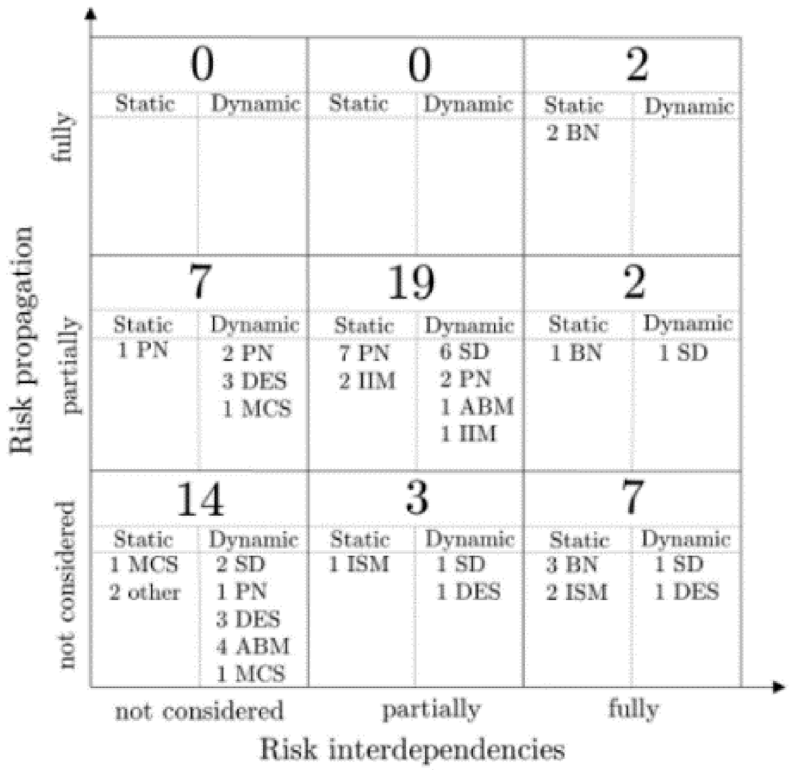

Figure 2-8: Analysis of complexity models

2.4.2 Literature Survey on System Dynamics

This section presents the outcome of the literature survey to answer the research question: What models and methods are employed in System Dynamics and systems thinking to analyse risk propagation and analyse resilience? The following search string was used to capture the relevant research papers.

(“risk propagation” or “ripple effect” or “cascading failure” or “chain reaction”) And (‘system thinking’ or ‘system dynamics’ or interdependanc*) AND (resilience or fragile or sensitive or disaster or risk or damage or exposure) and (model* or theor* or methods or formula or index or equation or approach or simulator)

The Scopus and Web of Science databases were utilised to gather relevant literature for this research, resulting in a total of 198 publications. Additionally, eight pertinent grey literature sources were incorporated, bringing the total to 206 publications. The following inclusion and exclusion criteria were applied to select the research articles:

- Language: Publications must be in English.
- Year: Publications must be from the year 2015 onward.
- Subject Discipline: Relevant disciplines included Engineering, Environmental Science, Physics, Mathematics, Computer Science, and Social Science.

Following these criteria, 122 papers were initially identified. A subsequent screening of titles and abstracts narrowed this down to 92 papers, which were then deemed suitable for a detailed review.

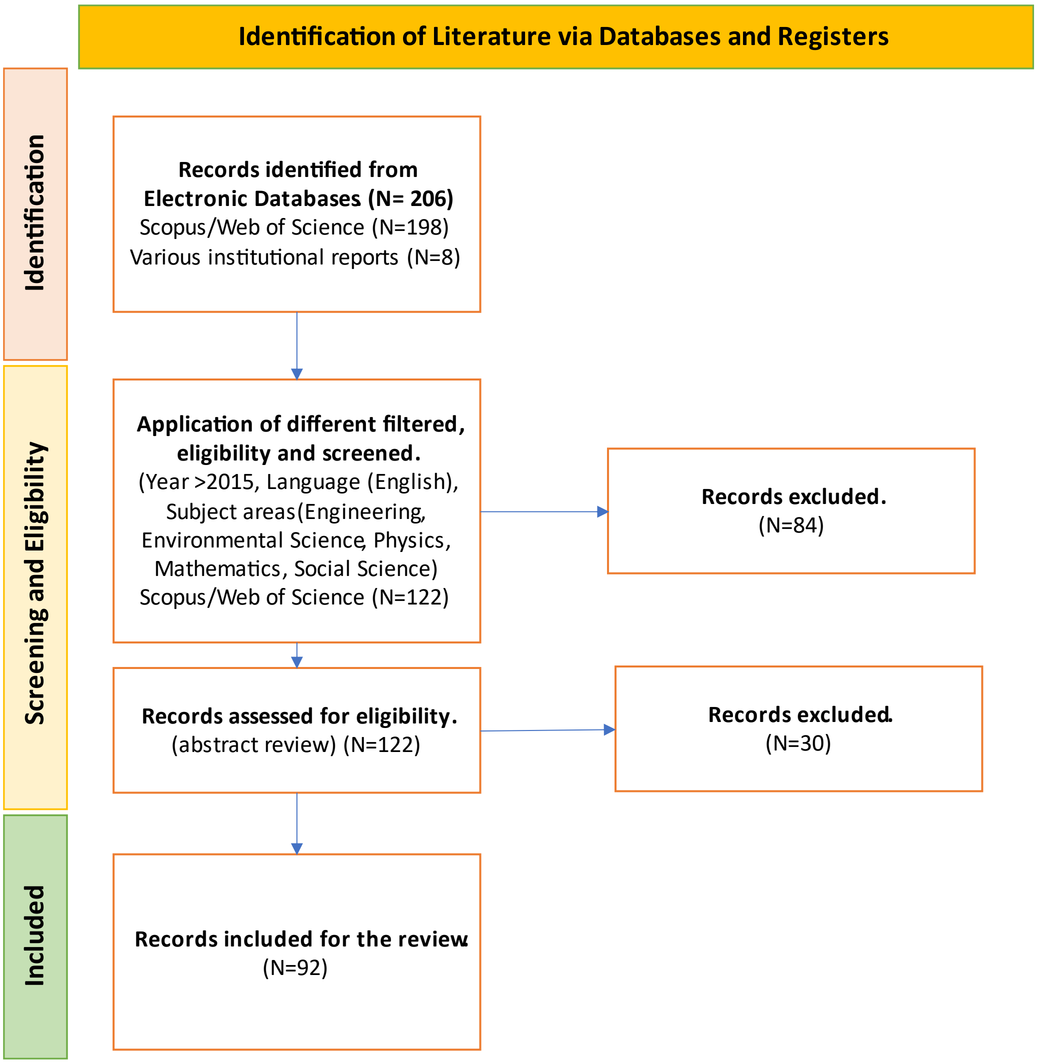

Figure 2-9: Literature for reviewing purposes

The literature survey identified various perspectives on risk propagation that must be considered for a comprehensive risk propagation analysis. Figure 2-10 illustrates the seventy-two characteristics identified through the literature review. These characteristics were clustered into six categories: System Connectivity, Complexity, System Status, System Reliability, Cascading Failure, and Threshold Value. The following sections discuss each category in detail.

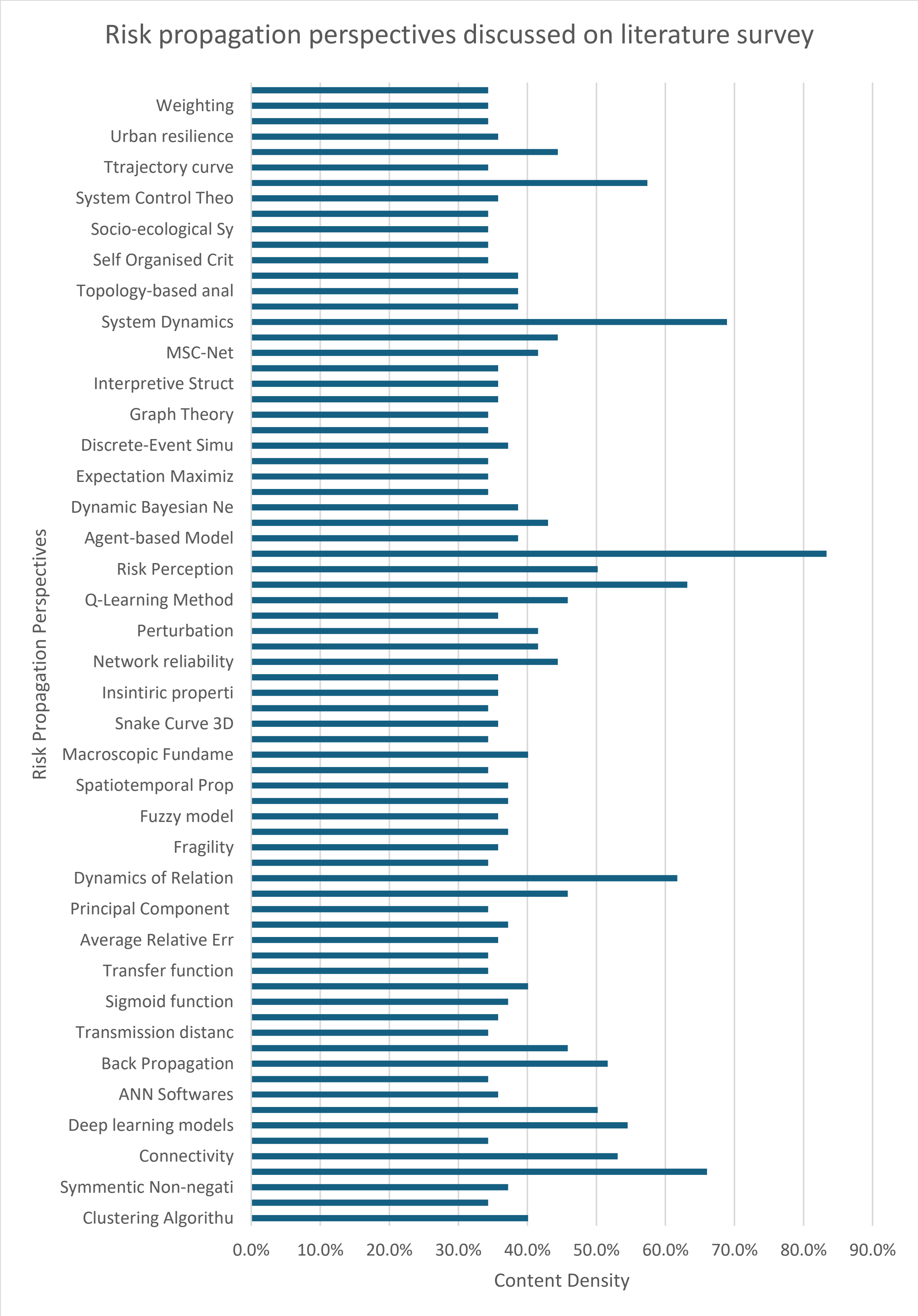

Figure 2-10: Risk propagation perspective discussed in the literature survey

2.4.3 Risk Propagation Perspectives

Risk propagation refers to the transmission of risk events through specific pathways within a system (Deng et al., 2018). It encompasses the processes of risk identification, description, evaluation, and response within that system (Deng et al., 2018). In this context, the risk can be defined as an event, a change in circumstances or consequences, along with the likelihood of occurrence(ISO-Guide73, 2009).

Understanding the integrated elements and their meanings in the dynamic system is a challenging task (Cumiskey, Priest, Klijn, & Juntti, 2019). For example, disturbances in critical infrastructure networks such as water, electricity, communication, and transportation may trigger chain reactions in the interconnected networks and society (Karakoc et al., 2019). Additionally, globalisation and technological advancements have led to the creation of increasingly frequent and complex interdependencies among these systems (Karakoc et al., 2019). While such interdependencies can enhance network efficiency, they also contribute to greater vulnerability to disruptions due to their intricate integration (Karakoc et al., 2019). Consequently, interdisciplinary and system-thinking approaches, such as System Dynamics, are essential for identifying and mitigating the impacts of disasters on complex networks (Jiuping Xu & Lu, 2018).

System Dynamics (SD) is a process and modelling technique used to analyse complex and dynamic systems (Niels Bugert & Rainer Lasch, 2018). It helps to understand how different parts of a system interact and how changes in one part can affect other parts (Niels Bugert & Rainer Lasch, 2018). Using SD, one can gain insight into how a system behaves over time and identify ways to improve the system's performance (Niels Bugert & Rainer Lasch, 2018). SD provides a holistic view of the system trends, patterns, and connections between different model variables (A. Rubio-Martin, M. Pulido-Velazquez, H. Macian-Sorribes, & A. Garcia-Prats, 2020).

In SD, the system behaviour refers to how the system changes over time in response to internal and external influences (Lasch, 2018). This includes the interactions and feedback loops between different system components and the overall patterns and trends in the system's behaviour(Lasch, 2018; Jian Xu & Kang, 2017). Understanding system behaviour aids in comprehending the complexity and connectivity within systems (Adria Rubio-Martin et al., 2020; X.-j. Wang et al., 2010).

2.4.4 System Connectivity

Researchers define system connectivity as the degree of interconnectedness and interdependence between different components or subsystems of a system (Arrighi, Pregnolato, & Castelli, 2021; Karakoc et al., 2019; Vitali et al., 2016). Usually, the node connectivity is computed by its degree in an unweighted graph (k_i) and by its weight in a weighted graph(s_i) (Gaur, Yadav, Soni, & Rathore, 2020), which could be computed as;

$$k_i = \sum_j l_{ij}$$

Here, l_{ij} represents the number of edges connecting the i and j nodes(Gaur et al., 2020).

$$s_i = \sum_j \omega_{ij}$$

Here, ω_{ij} represents the weight assigned to the edge of the vertex connecting node i and j(Gaur et al., 2020).

Connectivity is a measurement of how the different parts of a system are linked together reflecting both network robustness and the interactions among its components, known as network dependency (Dong, Esmalian, Farahmand, & Mostafavi, 2020; Karakoc et al., 2019). High connectivity in a system means many interactions and relationships between its components, making it more resilient and complex to manage. On the other hand, low connectivity means fewer interactions and relationships between its components, making the system more fragile and more straightforward to understand and manage (Vié & Morales, 2020; Vitali et al., 2016). In addition, the functional connectivity of the network is also required to assess because it enables the diversification of outputs and improves economic efficiency and complexity(Karakoc et al., 2019; Vié & Morales, 2020).

2.4.5 System Complexity

System behaviour helps to understand the system's complexity (Adria Rubio-Martin et al., 2020; X.-j. Wang et al., 2010). System complexity refers to the number of interacting components or elements and their relationships within a system (Dong et al., 2020). Therefore, a complex system has many interconnected parts or subsystems that discuss the overall system's behaviour (Adria Rubio-Martin et al., 2020; Vié & Morales, 2020). Consequently, complex systems can exhibit non-linear behaviour, meaning that small changes in one part of the system can significantly change the system's overall behaviour (Karakoc et al., 2019).

System complexity encompasses concepts of observability and controllability (Karaca, 2022). Here, system observability refers to the degree to which the internal states and behaviour of a system can be inferred through measurement and observation (Karaca, 2022). In other words, understanding the behaviour of a complex system requires comprehending how the behaviour of its individual parts collectively contributes to the overall system behaviour (Karaca, 2022). Therefore, a highly observable system allows its internal state and behaviour to be easily measured and monitored (Karaca, 2022). In contrast, a system that is not easily observable may pose significant challenges to understanding and predicting its behaviour (Karaca, 2022). Therefore, system observability is essential in system dynamics, as it aids in identifying and understanding the structure and behaviour of the system (Karaca, 2022; Adria Rubio-Martin et al., 2020).

System controllability refers to the ability to influence or regulate the behaviour of a system by manipulating its inputs or structure (Karaca, 2022). Therefore, there is a connection between system structure, function, and controllability (Karaca, 2022). Here, the system structure discusses how its components and subsystems are organised and interact with one another (X.-j. Wang et al., 2010). Essentially, the structure determines the relationships, connections, and interactions among various parts, which collectively influence the system's overall behavior (Lasch, 2018; Adria Rubio-Martin et al., 2020). Consequently, to effectively define and manage a complex system, it is essential to understand its nature, structure, evolution, and underlying principles (Karaca, 2022).

A network diagram or a graph could be used to define a complex system in an urban settlement (Arosio et al., 2020). However, unlike other approaches, SD introduces system-level thinking for modelling and analysing the problem behaviour by integrating cause-effect relationships, feedback loops, and delays (X.-j. Wang et al., 2010). Typically, SD modelling involves several steps: problem definition, system conceptualisation, model formulation, model evaluation, and implementation (X.-j. Wang et al., 2010). Therefore, as the initial step of SD modelling, it is essential to understand the positive and negative relationships between the variables, feedback loops, system archetypes, and delays(X.-j. Wang et al., 2010).

System archetypes discuss the typical patterns of behaviour and provide insights into underlying structures from which behaviour over time and discrete events (Braun, 2002). They help to diagnose the existing problems or assess the viability of proposals in the organisation (Braun, 2002). Braun (2002) has identified ten archetypes to reveal behaviour patterns in systems and suggest prescriptive actions to minimise their impact.

The “Fixes that Fail” archetype addresses situations where solutions lead to unintended consequences that exacerbate the original problem. For example, the emergence of landslide symptoms increases the need for landslide risk management activities in an area. These risk management activities subsequently reduce the landslide symptoms, creating a safer environment and potentially triggering urban sprawl. However, due to haphazard development, this urban sprawl can ultimately lead to an increase in landslide symptoms once again. This phenomenon illustrates the “Fixes that Fail” archetype, as shown in Figure 2-11.

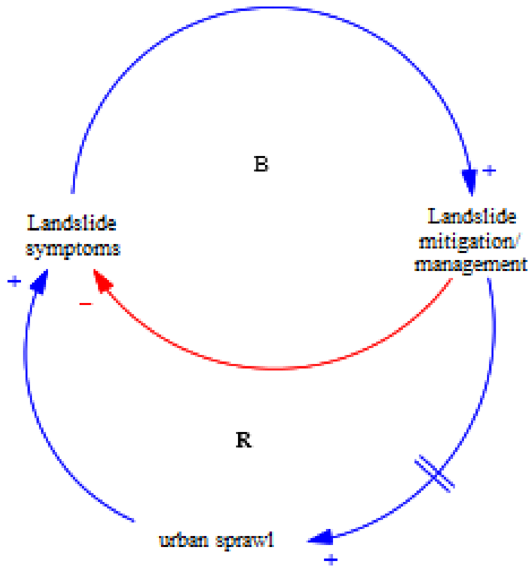

Figure 2-11: Fixes that Fail archetype

2.4.6 System Status

The resilience curve helps to monitor the system status of a complex system. Resilience is defined as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” (UNISDR, 2013, p. 24). Karakoc et al. (2019) have divided the resilience curve into five states; (1) original stable state, (2) system disruption, (3) disrupted state, (4) system recovery, and (5) recovered stable state. Additionally, Hopkin (2010) has divided the likelihood and potential impact zone, which is equal to the original stable state in the previous classification, into three categories; (1) comfort zone, (2) cautious zone, and (3) concerned zone. Consequently, seven system statuses could be identified, as shown in Figure 2-12. Table 2 provides a mathematical interpretation of each stage.

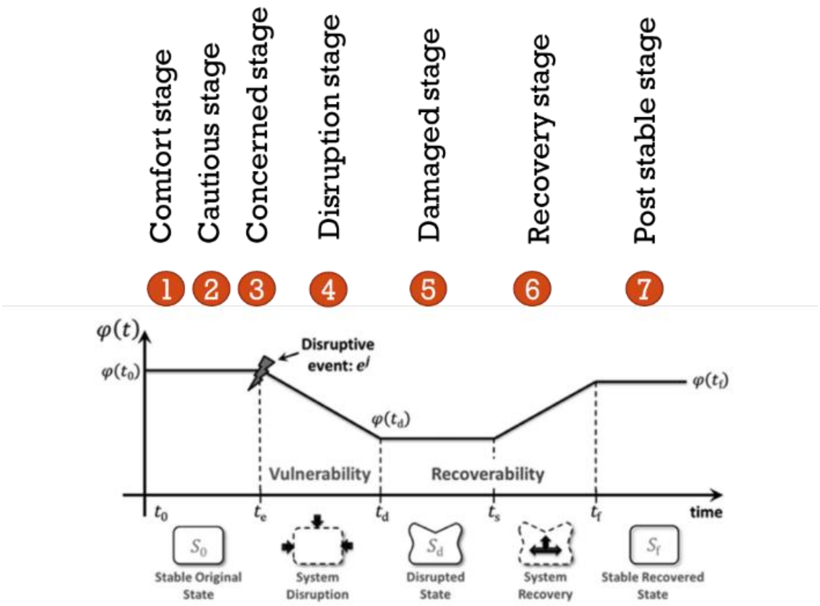

Figure 2-12: Resilience Stage of Node

Table 2: Description of resilience stages

Zone	Description
Comfort stage	The system capacity is more than its requirement. ($S_c>S_r$)
Caution stage	The system is functioning at its maximum level. ($S_c=S_r$)
Concerned stage	The system is functioning at its maximum capacity level ($S_c< S_r$) and expecting damage.
Disruption stage	The system is being disrupted, and its capacity is continuously decreasing. The system performance is getting decreased. ($S_c<$ w(t).S_r)
Damaged stage	The system is disrupted. ($S_{c\Delta i} = S_c - S_d$)
Recovery stage	The system is recovering by applying remedial measures. ($S_c<$ w(t).S_r)
Post stable stage	The final stage is after the system recovery. ($S_{c\Delta i} = S_c \pm S_d$)

Here,

- S_c denotes the maximum system capacity.
- S_r refers to the required capacity for providing the necessary services.
- $S_{c\Delta i}$ represents the system capacity at the Δi stage.
- S_d indicates the system capacity after a shock.
- A shock represents either a negative impact (e.g., disaster) or a positive impact (e.g., repair) on the system.

Mathematically, the system's current status discusses the state function by constructing the state space, which is divided into state discretisation and value evaluation (Wei Hao et al., 2020). In these two steps, the state position and velocity are identified and measured with the actions (Wei Hao et al., 2020). Wei Hao et al. (2020) defined the state function as (equation 1):

Equation 1: State Function

$$V_p(s) = \sum_{s'} p_{(s)}(s, s')(R_{p(s)}(s, s') + \gamma V_p(s'))$$

Here, $V_p(s)$ represents the degree of return according to the strategy p under state s. p(s,s') represents the state transition probability. R(s, s') represents the reward obtained from s-»s', and γ is a functional coefficient (Wei Hao et al., 2020).

2.4.7 System Reliability

System reliability measures the probability of performing its intended function for a specified period under certain conditions (Shuang, Liu, Tang, Liu, & Shuang, 2017). In other words, higher system reliability indicates that the system can provide its function for an extended period. Shuang et al. (2017) identified two aspects of system reliability: structural and operational. Structural reliability concerns the network topology and connectivity of the network for a given failure (Shuang et al., 2017). Operational reliability refers to the ability of the system to meet the current demand (Shuang et al., 2017). Further, Shuang et al. (2017) have mathematically defined the system's operational reliability using the following formula:

$$R_{sys} = \frac{\sum_{k=1}^{m} Q_{k,t,act}}{\sum_{k=1}^{m} Q_{k,req}}$$

Here, R_{sys} represents the system's operational reliability, and m represents the number of nodes in the network. $Q_{k,t,act}$ and $Q_{k,req}$ represent actual demand and required demand to the kth node at t-time.

2.4.8 Cascading Failure

A universal cascading failure of a network has been derived by considering a fraction of nodes that are perturbed within the network (Duan et al., 2019). It discusses in the following formula (Duan et al., 2019).

Equation 2: Universal Cascading Formula

$$\frac{dx_i}{dt} = W\big(x_i(t)\big) + \sum_{j=1}^{N} [A_{ij}.\, Q\left(x_i(t), x_j(t)\right)]$$

Here, $W(x_i)$ accounts for the evolution of x_i in the absence of network interactions, and $Q(x_i, x_j)$ discusses pairwise interactions. A_{ij} represents the adjacent matrix of a network.

Typically, a regression model is used to analyse the interaction between the scaled supervised data (PHILLIPS, 2019). However, the availability or unavailability of an operation can be represented as binary values. Therefore, the binomial theorem could be used for the analysis of the interaction of the network (E.Newman, 2003). Network reliability, on the other hand, measures the probability that a node is connected to another node. A similar methodology has been used to assess the system's reliability by D. Li, Zhang, Zio, Havlin, and Kang (2015).

$$R_s(t) = \sum_{i=[N*pc]+1}^{N} \binom{N}{i} R(t)^i (1 - R(t))^{N-i}$$

Here, R(t) is the reliability of a generic node, and N represents the number of nodes in the network. $\binom{N}{i}$ represents the binomial coefficient of the network, and Pc represents the percolation threshold of the network.

2.4.9 Threshold Value

In a complex system modelled using System Dynamics, the network initially operates at a stable position without perturbation (Duan et al., 2019; Qu et al., 2018). However, the system possesses a tolerance level beyond which the system function begins to decline. If this tolerance level is set to 0%, it indicates that a node is disconnected from the network (Duan et al., 2019). Consequently, the system has a maximum tolerance value that allows it to function without failure, referred to as the system threshold. Thus, it is an important requirement to determine thresholds for different connections to assess the risk status of a network(Qu et al., 2018).

Percolation theory serves as a method for estimating the numerical threshold of a network failure (D. Li et al., 2015). The theory involves removing network nodes and edges to evaluate the system's ability to maintain required services (Peng et al., 2021; Radicchi & Castellano, 2015). Therefore, the percolation theory quantifies the network's robustness by examining topological connectivity and the size of the largest connected component following perturbation (Dong et al., 2020). Two standard percolation modes are defined: bond percolation and site percolation (Peng et al., 2021). Bond percolation involves removing edges from the network to assess transitions, while site percolation involves removing nodes from the network. This leads to the estimation of different percolation thresholds across various lattices.

In a lattice, the probability of maintaining a top-to-bottom path in a network can be either bond or site percolation, denoted by p (Peng et al., 2021). The percolation threshold (p_c) is defined as the critical probability at which an infinite cluster appears for the first time in an lattice (Christensen, 2002). Probability theory can be used to calculate these percolation values (Christensen, 2002).

2.5 Summary

Chapter two provides a comprehensive overview of existing theoretical frameworks and approaches for disaster risk assessment and risk propagation, drawing upon two comprehensive literature reviews. The chapter identifies risk-defining characteristics (hazard, vulnerability, and exposure), risk assessment process characteristics (analysis, evaluation, perception, predictive behaviour, appetite, and propagation), and propagation-defining characteristics (system connectivity, system complexity, state, system reliability, failures, and threshold). The analysis emphasises the importance of understanding risk through a systemic lens, acknowledging the interconnectedness of different elements within urban environments. It further highlights the crucial role of human perception in shaping risk reduction strategies and emphasises the importance of community engagement in managing risks effectively.

The chapter concludes by advocating for a system-thinking approach to urban development, stressing the need for collaboration across sectors to foster resilience in the face of increasingly complex and interconnected risks. Furthermore, it elaborates on the mathematical constructs that can be deployed in modelling risk propagation using system dynamic modelling.

The findings of the review underscore the need for a more integrated approach to risk management, incorporating social and physical dimensions and acknowledging the dynamic nature of risk propagation.

Chapter 3: Research Methodology

3.1 Introduction

In this chapter, the research methodology is thoroughly explored, beginning with the research philosophy commonly used in social science research, which underlies the ontological, epistemological, and axiological assumptions. These foundational assumptions guide the approach to understanding and investigating social phenomena. Following this, the Design Science approach is introduced and proposed as the key methodology for this research. Design Science is particularly suited for developing artefacts, making it an ideal framework for this study, which aims to create a risk propagation simulator for assessing urban resilience. The chapter outlines how this methodology will be used to systematically develop and validate the simulator, ensuring it is both theoretically grounded and practically applicable.

3.2 Research Methodology

Research methodology is a process of systematically solving research problems (Kothari, 2004). Researchers use various methodologies, such as waterfall, Saunders's research onion, design science, and agile methods, based on their discipline. Research methodology refers to the overarching framework that guides the research process., It encompasses the research philosophy, research type, problem, objectives, and data collection (Bhattacherjee, 2012; Johannesson & Perjons, 2014; Kothari, 2004; Saunders, Lewis, & Thrunhill, 1997). Thus, it is essential to identify the positioning of the research study across these various dimensions.

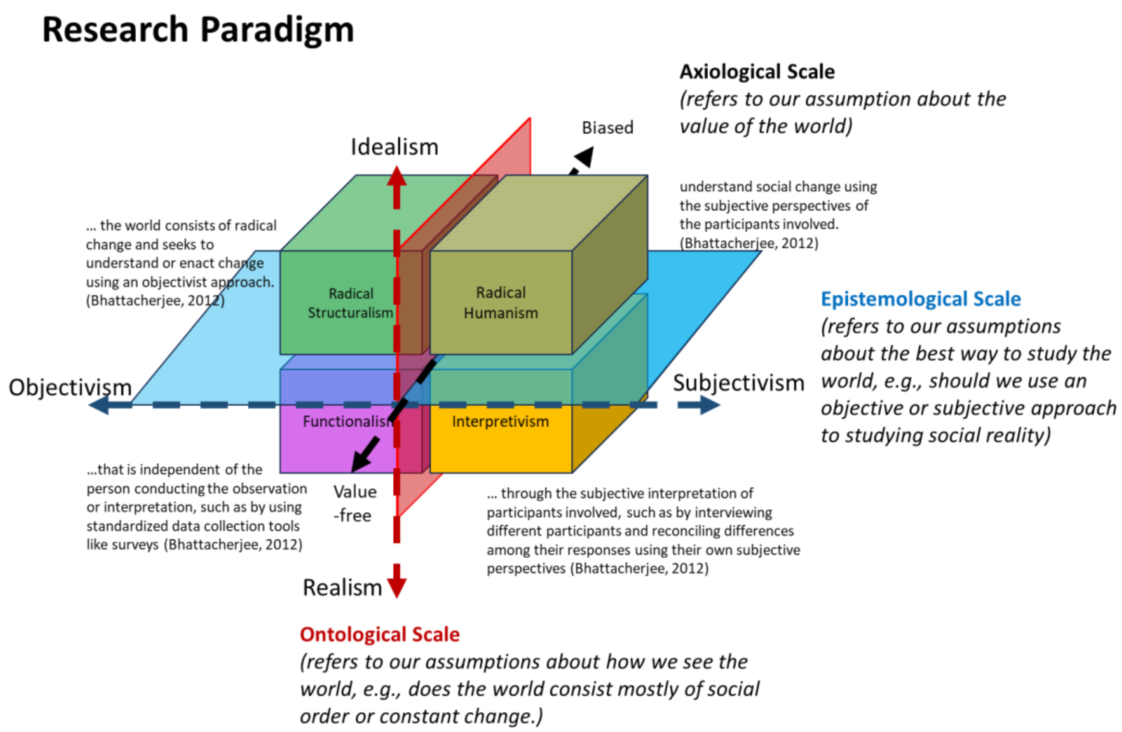

Figure 3-1: Research paradigm

The research philosophy underlies the researcher's ontological, epistemological, and axiological assumptions (Bhattacherjee, 2012; Johannesson & Perjons, 2014; Saunders et al., 1997). Figure 3-1 shows the graphical presentation of the research paradigm on ontological, epistemological, and axiological scales. Accordingly, several clusters have been identified by the researchers as structuralism, radical humanism, functionalism, and interpretivism. Functionalism describes that if any person is doing observation through scientific data collection or a standardised procedure, it is considered objective. Interpretivism describes subjective-based data collection through interviews and focus group discussions to interpret problem behaviour. Radical structuralism discusses social changes due to the objectivist approach, while radical humanism discusses social changes due to the subjectivist approach. (Bhattacherjee, 2012).

The Ontological assumption describes truth on social belief, scaled from idealism to realism. Idealism indicates an unknowable reality perceived by different individuals, and realism represents the commonly experienced external reality with a predetermined nature and structure (Bhattacherjee, 2012; Johannesson & Perjons, 2014; Saunders et al., 1997). This research focuses on addressing real-world problems, specifically exploring landslide risk reduction applications, and aims to simulate the situation based on theoretically developed mathematical models. The research then undergoes empirical validation through a case study in a known context, in this case, assessing the impact of landslide hazards in the urban environment. The simulated outputs, designed to capture the realistic nature of the problem, align with a realist ontology. Therefore, this research leans towards realism on the ontological scale.

Epistemological assumption describes knowledge as a social phenomenon scaled from subjective to objective (Bhattacherjee, 2012; Johannesson & Perjons, 2014; Saunders et al., 1997). This research aims to understand the current relationships and risk propagation by capturing theoretical knowledge and developing a model to assess the hazard impacts on the urban environment using mathematical expressions. The validation process involves gathering expert knowledge and testing the model's applicability to practical situations. Therefore, the research encompasses more objective knowledge. As a result, epistemologically, the research is positioned at objectivism.

Axiological assumptions address the role of values within research, ranging from value-free to bias. Value-free research seeks to remain objective and impartial, while biased research acknowledges the influence of personal or societal values (Bhattacherjee, 2012; Johannesson & Perjons, 2014; Saunders et al., 1997). This research incorporates a comprehensive literature survey to identify relevant risk assessment principles. The system dynamics concept is then employed to connect these principles into a model. However, the values assigned to various principles within this model are informed by societal values and judgements. Consequently, the model integrates both value-free and biased information. Therefore, this research can be positioned at the centre of the axiological scale, acknowledging the inherent complexity of incorporating values in research.

Therefore, the research adhered to functionalism by considering the research paradigm's ontological, epistemological, and axiological positions. Functionalist studies necessitate comprehensive information to model the existing problem accurately. Consequently, the researcher employed more participatory approaches, including discussions, interviews, document analysis, and narrative analysis, to gather pertinent information. Subsequently, the identified principles were used to construct and integrate a functional diagram, facilitating an understanding of the equilibrium of nature.

Accordingly, the researcher collected various research articles published in online open-access journals to understand the principles of risk assessment and propagation. Two primary literature surveys were conducted to gather the published information. This information was systematically mapped into a diagram to comprehend the risk assessment process and public perception of risk assessment. Twelve practitioners were consulted to verify the model connections. The practitioners were selected from diverse national, regional, and local strata.

In addition, two system dynamics experts and two mathematicians technically assessed the model.

This research aims to develop a simulation environment for building resilient urban environments, situating it within the field of information systems. Consequently, the design science approach is employed as the overarching research methodology.

3.3 Design Science Approach

The behaviour and design science approaches are two predominant paradigms in information system research (Hevner, March, Park, & Ram, 2004). The behaviour science paradigm studies developing or verifying theories that explain the behaviour of individuals or organisations and is grounded in natural science methodologies (Hevner et al., 2004). In contrast, the design science paradigm aims to extend the capabilities boundaries of individuals or organisations by creating new artefacts, drawing from engineering principles (Hevner et al., 2004).

The Information Technology (IT) sector has experienced rapid growth and expansion, generating new opportunities for developing new artefacts (Hevner et al., 2004). Consequently, IT artefacts can be designed to address complex problems and enhance organisational capabilities by providing advanced computational tools. However, creating new artefacts is challenging, mainly when existing theories do not address specific issues within the domain (Hevner et al., 2004).

The design science approach is structured around a comprehensive framework that includes essential components: Environment, knowledge base, artefact building, and evaluation, as shown in Figure 3-2. Here, the environment defines the problem space that is going to be addressed in the targeted research, drawing from inputs provided by people, organisations, and technologies. The knowledge base comprises existing theories and methodologies, which underpin the construction and evaluation of solutions. This approach focuses on designing artefacts to tackle "wicked" problems (complex issues) that are challenging to define and solve. Hevner et al. (2004) outline seven guidelines for this framework: (1) design as an artefact, emphasising the creation of constructs, models, methods, or instantiations; (2) problem relevance, ensuring research addresses impactful issues; (3) design evaluation, which rigorously assesses the efficacy of the artefacts; (4) research contribution, where outcomes advance both theoretical understanding and practical applications; (5) research regor, adhering to sound methodological principles; (6) research as a search, exploring the discovery or creation of new artefacts; and (7) Communication of research, effectively sharing findings and implications with broader audiences. By following these guidelines, the Design Science approach facilitates the development of innovative solutions to complex challenges while enhancing knowledge in the field. A detailed discussion of these guidelines is presented below.

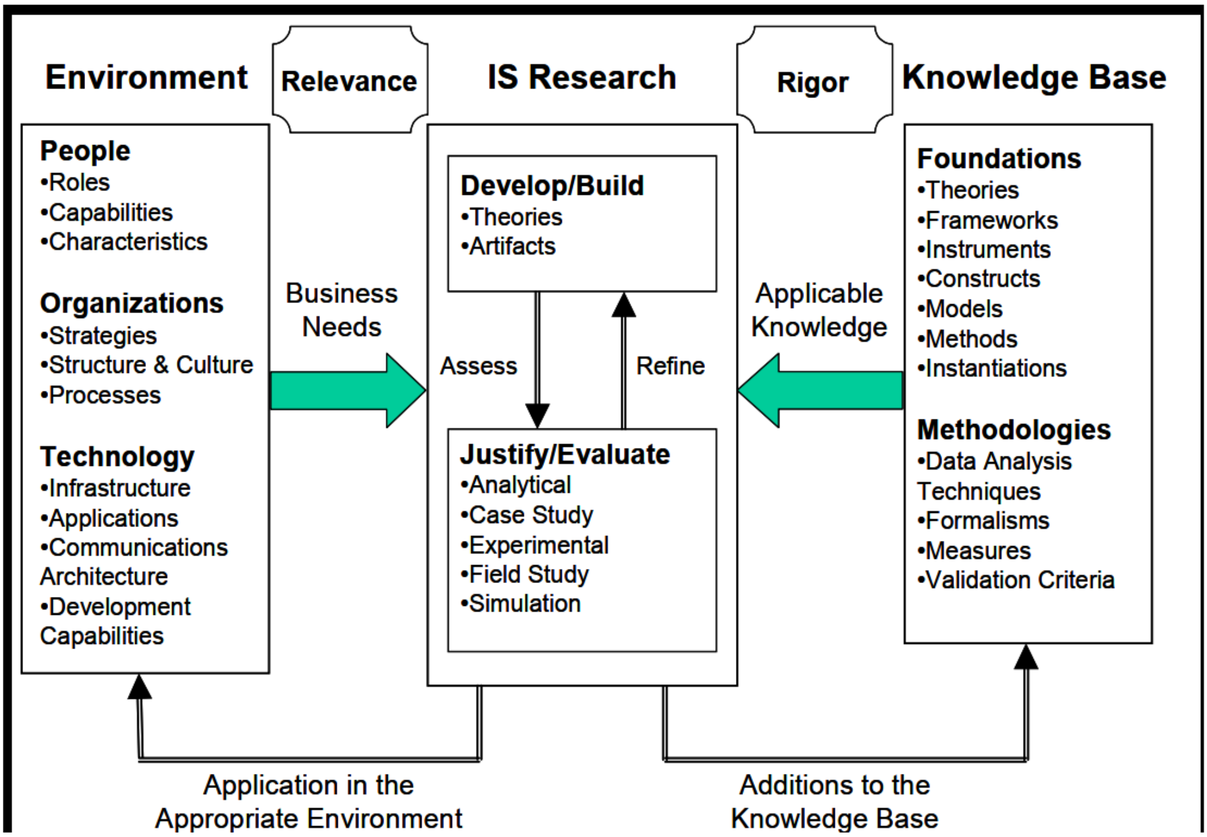

Figure 3-2: Design science framework (adopted from Hevner et al. (2004, p. 80))

3.4 Design as an Artefact

The design science approach is commonly used in Information Technology to solve practical problems (Johannesson & Perjons, 2014). However, some problems cannot be solved without comprehensive knowledge. Those problems are called wicked problems (Johannesson & Perjons, 2014). However, when the criteria for solving such wicked problems are somewhat known, they are called Tame problems (Johannesson & Perjons, 2014). Such Tame problems can be solved using various approaches. The research being addressed in this research can be considered a Tame problem, as the criteria for solving risk and propagation are known.

The “Design as an Artifact” principle in the Design Science approach emphasises the creation of innovative artefacts such as models, methods, constructs, or instantiations that provide solutions to identified problems. These artefacts are key outputs of the research process and serve to extend the capabilities of individuals and organisations in tackling specific issues. By focusing on designing tangible solutions, this phase aims to address practical challenges effectively while advancing both theory and practice.

Artefacts in the Design Science approach are characterised by intrinsic properties (internal and interface attributes) and extrinsic properties (external aspects) (Johannesson & Perjons, 2014). When designing artefacts, five factors are generally considered: four intrinsic properties (structure, behaviour, function, and effects) and one extrinsic property (environment) (Johannesson & Perjons, 2014).

- **Structure**: Refers to the internal attributes or components of the artefact, which may include intellectual elements.
- **Behaviour**: Represents the patterns, shapes, or performance levels exhibited by the artefact.
- **Function**: Encompasses the actions, roles, benefits, and support provided by the artefact to its users.
- **Effects**: Includes both intended and unintended environmental impacts, distinguishing between effects and side effects.
- **Environment**: Pertains to the external context surrounding the artefact's components.

This concept is illustrated in Figure 3-3. Although artefacts can be classified in various ways, they are commonly categorised into four types (Johannesson & Perjons, 2014), as follows :

1. **Constructs**: Represent terms, notations, definitions, and concepts necessary for formulating problems and potential solutions.
2. **Models**: Provide possible solutions to practical problems.
3. **Methods**: Convey prescriptive knowledge by defining guidelines and processes for solving problems and achieving goals.
4. **Instantiations**: Represent working systems that can be applied in practice.

Thus, an artefact must be developed and described within these categories to address specific issues in the Design Science approach effectively. This research will utilise all four aspects in creating a risk simulation environment.

First, this research identified key risk characteristics (constructs) that form part of the overall risk propagation model. These risk characteristics were used to define a system dynamics model that captures risk propagation. Subsequently, the key loops or pathways within the system dynamics model were analysed and explained to elucidate how various risks can propagate and influence the overall resilience of an urban environment. This knowledge will be used to provide guidelines for enhancing urban resilience (methods). Finally, the overall system dynamics model was applied to two case studies to demonstrate its practical application (instantiations).

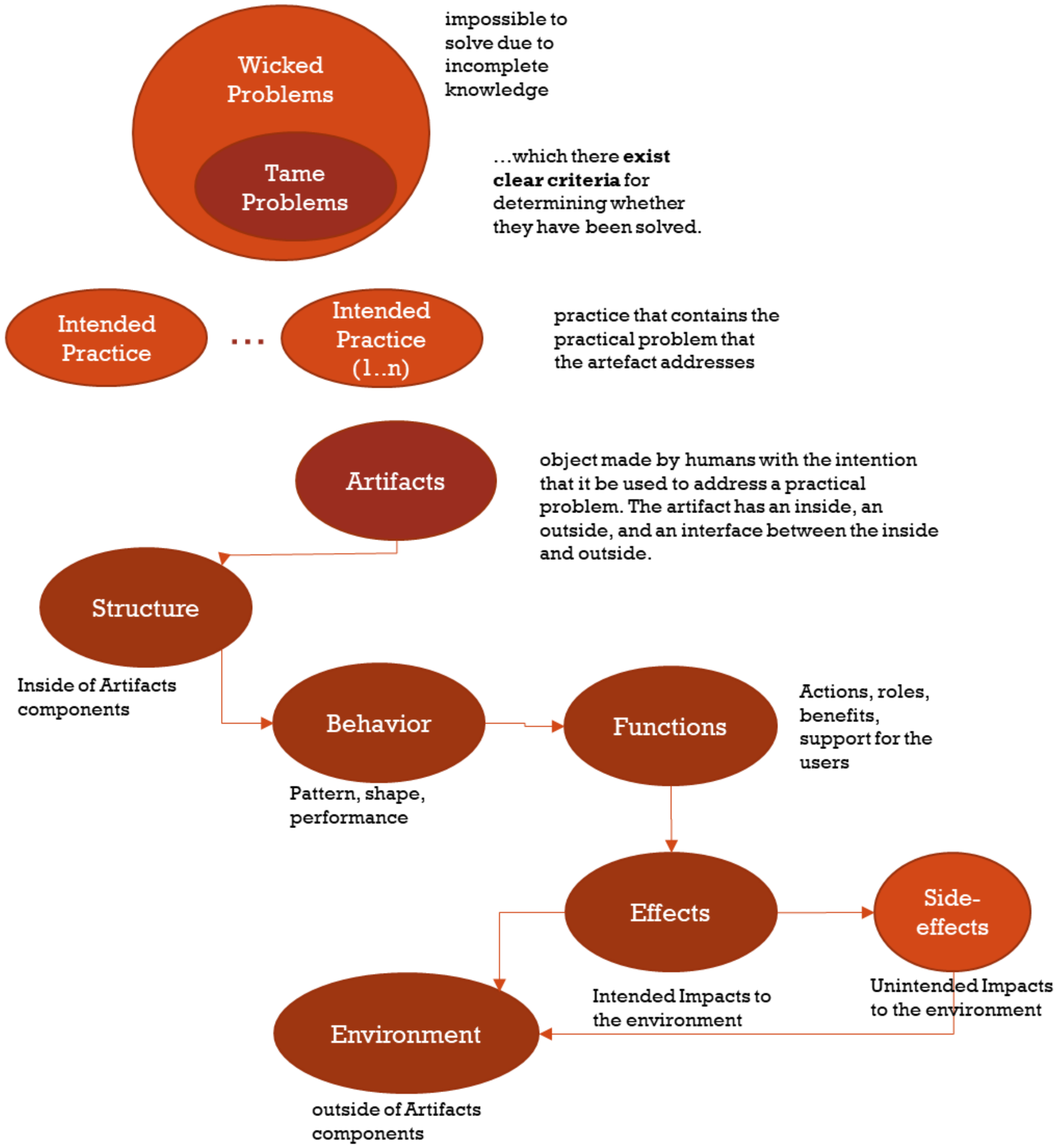

Figure 3-3: Design science artefacts

3.5 Problem Relevance

Risk assessments are common in many disaster risk reduction applications. However, existing practices often fall short in capturing the complex interplay of factors that contribute to risk propagation, ultimately hindering efforts to build resilient and sustainable urban communities. There exist a range of challenges in creating a comprehensive risk assessment such as :

1. **Inadequate Consideration of Cascading Effects:** Many development proposals fail to adequately consider the cascading effects of disaster risks due to a lack of technical knowledge(Shuang et al., 2017). This oversight undermines the ability to understand and manage the evolving resilience of settlements over time.
2. **Exclusion of Community Risk Perception:** While risk perception is acknowledged as a crucial factor in driving risk management activities (Bubeck, Botzen, & Aerts, 2012), existing practices often fail to account for the diverse and evolving risk perceptions within communities. Communities may have varying levels of risk awareness and understanding, leading to uneven participation in risk reduction initiatives and ultimately contributing to catastrophic events.
3. **Difficulty in Comparing Expected and Actual Outcomes:** Urban planning and development often struggle to align risk assessments with actual outcomes, creating discrepancies in risk estimation and hindering the ability to effectively compare predicted and actual results (Hevner et al., 2004). This discrepancy highlights the need for a more systematic approach to risk assessment and a deeper understanding of the complex relationships between risks.

Therefore, the research aims to develop a novel artefact that will:

- **Capture the complex interplay of risk characteristics:** This includes incorporating diverse elements like risk perception, risk understanding, and community engagement into a robust model of risk propagation.
- **Simulate risk propagation across urban systems:** The artefact will utilise system dynamics to simulate the interconnectedness of risks and how they spread through various sectors and components of the urban environment.
- **Identify potential risk reduction pathways:** The model will enable stakeholders to identify potential mitigation strategies and explore various interventions to enhance urban resilience.

By addressing these critical gaps in risk assessment and propagation, this research aims to contribute significantly to the development of more effective and robust risk management practices, ultimately supporting the creation of safer and more resilient urban environments.

3.6 Design Evaluation

The design evaluation is a critical stage in the research process and should be thoroughly discussed. The evaluation methodology is influenced by the theories available in the knowledge base (Hevner et al., 2004). Several approaches are available for evaluation purposes (Hevner et al., 2004):

- **Observational:** Case study, field study.
- **Analytical**: Static analysis, architecture analysis, optimisation, dynamic analysis.
- **Experimental**: Controlled experiment, simulation.
- **Testing:** Functional testing, structural testing.
- **Descriptive:** Informed argument, scenarios.

This research is focused on the experimental evaluation method, and the research validation is based on theoretical and empirical validation approaches (Pedersen, Emblemsvåg, Bailey, Allen, & Mistree, 2000). Pedersen et al. (2000) proposed a “validation square”, shown in Figure 3-4, to address the question, ‘What is scientific knowledge, and how is new knowledge confirmed?’. The effectiveness and efficiency of the model will be assessed through various combinations, including structural, performance, theoretical, and empirical evaluations, as represented in the validation square. Accordingly, theoretical structure, empirical structure, theoretical performance, and empirical performance were discussed to determine the model’s effectiveness and efficiency levels.

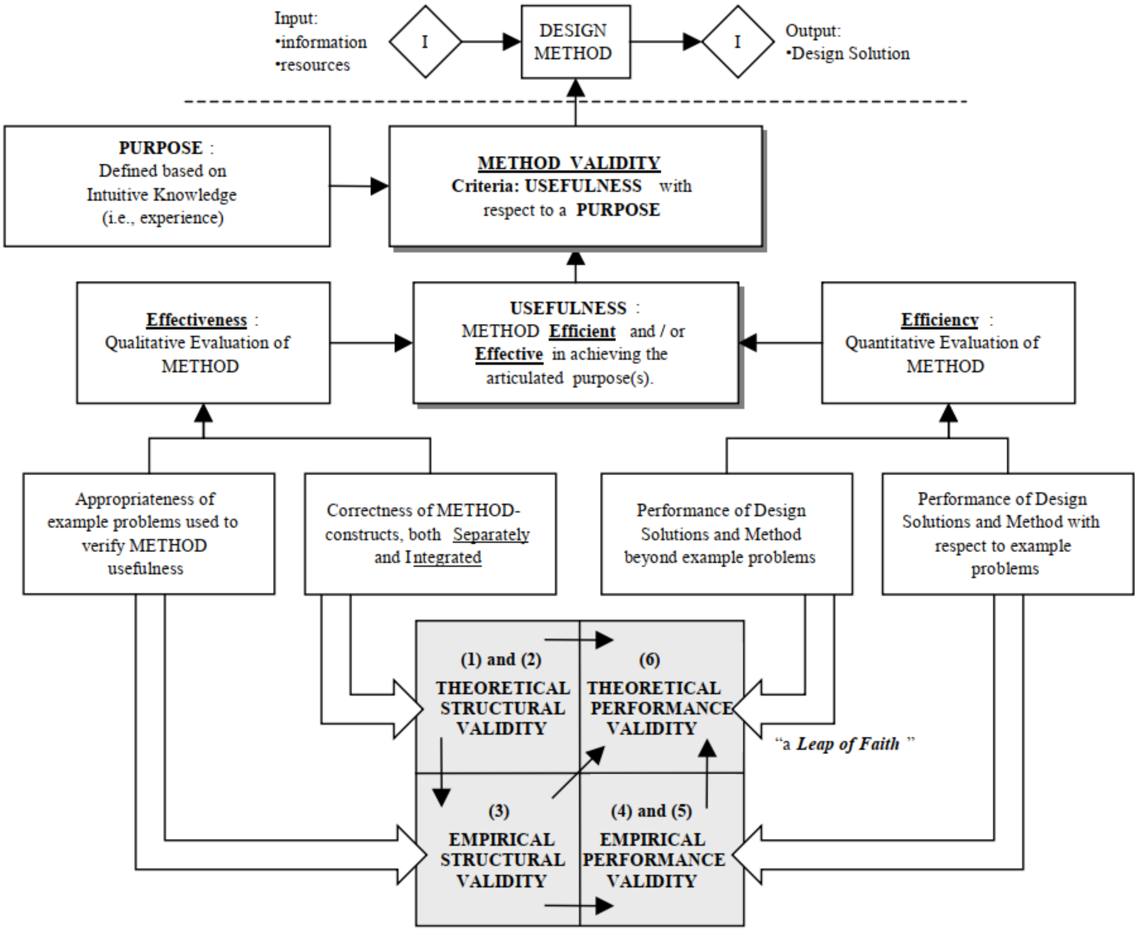

Figure 3-4: Validation Square (Pedersen et al. (2000))

3.6.1.1 Theoretical structural validity

This section explores the theoretical structural validity of the system dynamics model developed in this research. The initial step in model validation involves assessing the model's correctness, which requires two evaluations: acceptance of the contrast's validity and acceptance of method consistency.

Acceptance of the Contrast's Validity: The acceptance of the contrast's validity examines the quality of the literature used to construct the model. All research publications were sourced from open-access journals and documents published by international organisations such as the UNDRR. Initially, 119 research articles were reviewed to identify risk characteristics, which were then recorded for each paper. Saturation, where no new risk characteristics were added to the list, was achieved. The second review examined 95 research articles to understand risk propagation perspectives and the mathematical foundation for developing system dynamics models. In total, 214 research articles were considered to construct and detail the model.

Acceptance of Method Consistency: The second assessment in the theoretical evaluation is the 'acceptance of method consistency', which examines data availability for the identified model parameters. To ensure effective application and simulation of the model, it is crucial to verify data availability. This involves validating both the model parameters and the data used to represent them.

The identified risk characteristics were reviewed to assess data availability at various scales. The National Building Research Organisation, the focal point for landslide risk management in Sri Lanka, provided data for the research. Notably, the Grama Niladari (GN) divisions, representing the lowest administrative boundaries in Sri Lanka, contained sufficient data to simulate the desired outputs. The table below shows the identified risk characteristics and household data that was available for the model validation in high-risk landslide communities.

Table 3: Risk characteristics and data availability

Risk Assessment characteristic	**Description of the data**
Hazard	Consider landslide hazards, mainly rain-induced landslides.
Spatial probability of landslide hazard	Landslide zonation maps (polygons), Possible impact locations, Special landslide investigation locations, (point layer, describing the level of probability in three categories: high, medium, and low.)
Temporal probability of landslide hazard	Rainfall (gird data, CHIRPS satellite facility), availability of surface water discharge system- drainage network (household level information gathered through questionnaire survey)

Magnitude	Cut-slope height (Household-level information gathered through a questionnaire survey)
Resistance	Terrain shape, and slope angle (derived from the digital elevation model (DEM))
Susceptibility	Four susceptibility zones were available: landslide not likely to be occurred, modest level landslide risk exists, High landslide risk exists, and landslides are tobe expected.
Triggering factors	Change in slope morophology during house construction : The landslides are triggered based on natural and man-made factors. NBRO data contained nearly 15,000 locations having landslide symptoms in these modified slope morphological areas.
Vulnerability	Inverse relationship with resilience.
Resilience	The following data was available for modelling resilience: Physical: type of house, year of construction, availability of water, availability of electricity, availability of telecommunication. Social: Household demographic information: age, gender, education, disability, number of families, number of members, religion, nationality. Economic: Household expenditure (foods, education, water, electricity, telecommunication, accommodation, health, travelling), household income (occupation, income, other income), livestock, Environment: availability of solid waste disposal. (Household-level information had been gathered through a questionnaire survey)

Risk appetite	Actions taken to reduce hazard impacts, or initiate risk reduction approaches.
Risk matrix	Engagement with disaster risk management activities, (Household level information gathered through a questionnaire survey)
Risk assessments	Special investigation locations: categorised the risk level into three: high, moderate, low. The information was gathered through various landslide investigation reports carried out by NBRO.
Risk education	Level of instructions to prepare for impact mitigation. (Household-level information gathered through a questionnaire survey)
Risk perception	Community perception on whether their houses are vulnerable to landslide hazards, and perception of possible damage to their houses (Household level information gathered through a questionnaire survey)
Risk identification	Availability of landslide symptoms in their houses and vicinity (Household-level information gathered through a questionnaire survey)
Risk communication	Receiving of early warning messages was considered. (Household-level information gathered through a questionnaire survey)
Disaster	Number of impacted communities from the landslides.

3.6.1.2 Empirical structural validity

The second validation approach in the validation square is empirical structural validity. This assessment focuses on accepting the example to be tested with the model. The model in this research considers landslide hazards and their mitigation measures.

Initially, the identified risk characteristics were discussed with practitioners, gathering their feedback on any missing principles. Based on their comments, adjustments were made to the model's connections, leading to the development of a final model incorporating these changes.

The case study, documented and reviewed with the practitioners, was then assessed for acceptability. Practitioners were selected based on their experience, subject knowledge, and performance levels at international, national, district, and divisional strata. The table below shows the identified practitioners involved in validating the case study.

Table 4:Practitioners for research validation

Stakeholder Identification	**Designation**	**Experience**
SID1	Former director of the National Building Research Organisation, Sri Lanka,	More than 30 years of experience in landslide risk management in Sri Lanka.
SID2	Former Director of Asian Disaster Preparedness Center, Thailand.	Over 30 years of experience in landslide risk management in Asian countries.
SID3	Disaster Risk Management Expert, World Vision.	Over 15 years of disaster risk management experience and community-based disaster risk management activities.
SID4	Disaster Management Expert, working on UN agencies as a DRR consultant/ expert.	Over 25 years of experience in landslide risk management, urban resilient planning, and international coordination between the country's risk management institutes.

SID5	District Officer, National Building Research Organisation.	More than 15 years of experience in landslide risk investigation, coordination, and management at the district level (regional level).
SID6	Disaster Risk Management in NGO, OPEN.	Over 15 years of experience in community-based disaster risk management activities and empowering communities to be resilient.
SID7	Community development expert in an NGO, Sevanatha.	Over 30 years of experience in community-based disaster risk management, planning, and community capacity development.
SID8	Divisional Secretary, Palindanuwara.	Over 20 years of experience in administrative setup at the district, divisional and institutional levels. Coordinating the divisional disaster management committee and governing the divisional secretariat area.
SID9	Urban planning consultant, a former Institute of Town Planners Sri Lanka president.	Over 35 years of experience in urban planning, creating resilient environments, urban regeneration, and waste management.
SID10	A former lecturer at the University of Moratuwa.	Over 15 years of experience in economic resilience, urban planning, and community engagement.

SID11	A director of Urban Development Authority.	20 years of experience in urban development, participatory planning, and governance planning.
SID12	A former director of the Land Use Policy Planning Department.	Over 30 years of experience in land use planning, geography, and management.

3.6.1.3 Empirical Performance Validity

The third level of validation was conducted using two assessments: evaluating the usefulness of the method and the model's usefulness. The method's usefulness was considered on two levels: industrial (focusing on outputs) and theoretical (focusing on new knowledge). The model's usefulness was evaluated by comparing previously developed risk reduction plans, and the model outputs.

To facilitate the empirical performance analysis, the method was transformed into a graphical interface, integrating several output graphs for ease of visualisation and quantification. Practitioners from various disciplines were involved, and the model was presented using clear and simple language with illustrative examples.

Two key questions were posed to assess the empirical performance validity:

- Do you agree that the defined strategies can be effectively applied to enhance landslide resilience?
- In what ways can the proposed system serve as a decision-making tool for building resilience, and how does it influence decision-making ?

The thoughts of industrial practitioners were captured and analysed through qualitative analysis. The case studies were evaluated to monitor the results, and interactive discussions were conducted with stakeholders. Feedback from several stakeholders in disaster management was considered to justify the new knowledge achieved through the research.

The model's applicability was also discussed with stakeholders, and their suggestions were taken into account to understand the model's outputs for their decisions.

3.6.1.4 Theoretical performance validity

The final step in the validation square involves examining the wider applicability of the method and model to various other cases. This step is undertaken after successfully completing the previous validation stages. The discussion centred around the question: 'How do you perceive the potential application of this model in other fields?'.

Stakeholders were invited to share their thoughts on the model's applicability to other sectors, and their requirements were carefully considered. Through this process, the model's applicability to a broader range of applications was confirmed.

3.6.2 Guideline 4: Research Contribution

In the research contribution phase of the Design Science approach, it is expected that research will deliver substantive advancements to both theoretical knowledge and practical applications. This phase involves producing new artefacts or improving existing ones, thereby contributing valuable insights into addressing complex problems. Contributions should enhance the body of knowledge by introducing innovative models, methods, frameworks, or tools that provide solutions to identified issues (Hevner et al., 2004).

This research makes several significant contributions to the field. First, it identifies and presents key risk characteristics that should be considered within a comprehensive risk assessment process. This knowledge is derived from a detailed literature survey of reputable academic journals. Secondly, the research introduces a novel system dynamics model that depicts the interrelationships among these risk characteristics using a causal loop diagram with balancing and reinforcing loops. By analysing various causal loops, this research provides new insights into how risks propagate through interconnected characteristics, thereby influencing the overall resilience of an environment. This knowledge emphasises the importance of considering communities as a crucial aspect of understanding and enhancing the resilience of urban environments.

Furthermore, the research develops holistic disaster risk reduction strategies based on the analysis of balancing and reinforcing loops within the system. Building upon this foundational knowledge, the research implements a system dynamics model employing several theories, including the Central Limit Theorem, Monte Carlo Simulation, and Percolation Theory. This results in the creation of a decision-making tool for urban resilience planning. The model illustrates how system thinking, system dynamics modelling, and the incorporation of human risk factors can be integrated into a simulation environment, guiding decision-makers in making informed decisions to build resilient environments.

3.7 Research Rigour

The Research Rigour phase of the Design Science methodology is critical for ensuring the trustworthiness and validity of the research outcomes. In this phase, it is essential to apply rigorous methods and techniques throughout the research process. This involves using well-established theories and frameworks as the foundation for the research, which helps to ensure that the study is grounded in existing knowledge. Rigour also requires meticulous data collection and analysis, employing appropriate methodologies to obtain reliable and valid results. This includes utilising robust statistical techniques, validated measurement instruments, and systematic analytical procedures.

Additionally, researchers must document their methods in detail, ensuring the study's transparency and reproducibility. Peer review and critical evaluation of the research design, procedures, and findings further contribute to the rigour of the study. By adhering to these stringent practices, the Research Rigour phase helps to produce high-quality, credible, and dependable research results that can withstand scrutiny and contribute effectively to the body of knowledge Hevner et al. (2004).

The sections below are discussed the establishment of the research rigor by discussing the acquisition of various knowledge, mathematical formulation, research strategy, research as a search, and research communication.

3.7.1 Knowledge

The design science approach classifies knowledge into two aspects: types and forms. The first type, the purpose of knowledge, is classified into five types. (1) Definitional knowledge consists of concepts, constructs, terminologies, vocabularies, definitions, taxonomies, classification, and other kinds of conceptual knowledge; (2) Descriptive knowledge describes and analyses existing or past reality without including predictions; (3) Explanatory knowledge provides answers as to how objects behave and why events occur; (4) Predictive knowledge represents how accurately make predictions without knowledge about the internal functions, considering it as a black-box; and (5) Prescriptive knowledge, consists of models and methods which developed through procedures and helps to solve the practical problems (Johannesson & Perjons, 2014).

Knowledge form can be divided into three categories: Explicit, Embodied, and Embeded Knowledge. Here, explicit knowledge discusses articulation, expression and recording of knowledge into media (text, manuals) which can easily converted into other sources. Embodied knowledge describes the ideas in people's minds which cannot be expressed explicitly. On the other hand, the knowledge associated with physical objects such as processes, procedures, routines, formulas, and structures can be explicitly presented, and described as embedded knowledge. The table below discusses the activities conducted to improve the knowledge.

Table 5: Knowledge Areas touch under the research

		Knowledge type				
		Definitional	Descriptive	Explanatory	Predictive	Prescriptive
Knowledge form	Explicit	A separate section was developed to understand the definition of each risk principle.	Literature reviews were conducted to understand the risk principles.	A system dynamic model was developed by understanding the connections	Several risk reduction pathway/ loops were identified through the system	Applied the model into real ground scenarios, and tested the applicability

				between the risk principles.	dynamic model, and understand the behaviour of its changes.	with stakeholders.
	Embodied	The research considered the community perception level to understand the risk.	A literature review was conducted to understand risk perception principles, and risk propagation behaviour in the system.	Risk perception estimation methods were gathered, and a System dynamics model was developed to explain the perception involve into the risk reduction process.		
	Embedded	The research was considered on landslide-impacted areas in urban environments. Therefore, the landslide phenomenon was studied.	Landslide impact was detail discussed in the literature review.	Landslide hazard properties were connected to the system dynamic model and discussed the contribution of each hazard assessment principles.		

This study focuses on developing a risk propagation simulator for urban environments. The research process employed a systematic approach to knowledge development, building upon four key types of knowledge:

- **Definitional knowledge:** A comprehensive literature review was conducted to capture a sufficient number of sources and establish a foundational understanding of risk principles.
- **Descriptive knowledge:** The literature was further reviewed to understand the links between variables, aiding in the creation of correlations between artefacts.
- **Explanatory knowledge:** System dynamics theories were applied to develop the artefacts, resulting in the creation of a system dynamics model designed to simulate the behaviour of the problem.
- **Predictive knowledge:** The various loops within the system dynamics model were analysed, with each loop offering a plausible risk reduction application. This understanding of the system's dynamics enabled predictions about how different interventions would influence the level of risk propagation.
- **Prescriptive knowledge:** The model was applied to real-world scenarios, and the model outputs were discussed with relevant stakeholders. This final stage focused on translating the model's insights into practical recommendations and actionable steps for addressing risk in the urban environment.

3.7.2 Mathematical Formalism

Initially, risk assessment principles were derived from a comprehensive literature review, identifying both positive and negative correlations. The system dynamics approach was subsequently utilised to develop a model integrating stocks, flows, and feedback loops.

The model's equations were formulated based on an extensive review of various research papers, employing generic equations for analysing risk propagation. The propagation of risk, specifically, the transmission of risk values to adjacent sectors, was mathematically articulated using concepts such as system fragility, sensitivity, and resilience. Furthermore, a method for standardising input data was implemented to ensure the generalisability of the model inputs.

The mathematical model was first tested using hypothetical data to explore all possibilities. Subsequently, it was tested with relevant field data to verify the applicability of existing data to the model. The model equations were validated with two mathematicians to ensure accuracy.

3.7.3 Research Strategy

Several research strategies are discussed within the design science approach, including experiments, surveys, case studies, ethnography, grounded theory, action research, phenomenology, simulations, and mathematical and logical proofing (Johannesson & Perjons, 2014). In this research, the approach was categorised under functionalism, with a focus on a structured data-gathering system. However, capturing risk variations over time using structured data collection is linked to the simulation of initial principles, and the model outputs were discussed with stakeholders. Consequently, the simulation research strategy was selected, considering the research paradigm.

This research utilised empirical data and published documents from peer-reviewed journals, as well as information provided by dissemination organisations, to simulate model outputs. As a result, the model was aligned with data structures established by authorised agencies. The model outputs were subsequently reviewed and discussed with selected stakeholders, and multiple in-person and online meetings were conducted to validate the research findings.

3.7.4 Research as a Search

The "Research as a Search" phase of the Design Science methodology emphasises the iterative and exploratory nature of research aimed at discovering innovative solutions to complex problems. This phase involves systematically seeking out and evaluating alternative solutions, refining artefacts, and improving methodologies to address the defined research problems effectively. By treating research as an ongoing search process, researchers can explore a wide range of potential solutions, iteratively testing and adjusting their approaches based on empirical evidence and theoretical insights (Hevner et al., 2004).

Initially, risk assessment principles were considered through literature. Then, the risk assessment principles were communicated with the stakeholders to verify the coverage of risk assessment principles on a risk assessment domain. Afterwards, the system dynamic model was developed, and again, the connections between the risk assessment principles were verified with stakeholders. Accordingly, a few connections were modified considering the applicability of the model. Then, the refined system dynamic model was tested with ground application, and the outputs were discussed.

To facilitate communication of the results to a wider audience, a graphical user interface was developed. Several existing system dynamics applications were initially considered to create a more user-friendly environment. Ultimately, an application was developed based on dynamic system principles, and its usability was discussed with stakeholders.

3.7.5 Communication of Research

The “Communication of Research” phase of the Design Science methodology is essential for disseminating research findings to both the academic community and practitioners in the field. Effective communication ensures that the coherence and significance of the work are understood, promoting its adoption and further development (Hevner et al., 2004). In this phase, research outputs are presented through various channels, such as academic publications, conferences, workshops, and direct interactions with practitioners.

Several publications are planned to highlight the novelty and contributions of this research. A paper detailing a holistic risk assessment perspective has already been presented at a conference on the 6th World Landslide Forum, 2023, in Italy (Casagli, Canuti, Sassa, & Tofani, 2024). An extension of this paper has already been submitted to a peer-reviewed journal (Progress in Landslide Research and Technology, (Munasinghe et al., 2023)), emphasising the theoretical advancements and practical implications derived from the study. Another research paper focusing on the risk propagation modelling approach has been drafted, showcasing the innovative methodological aspects and their potential applications. A further paper will discuss the outcomes of the case studies, providing empirical evidence of the model’s effectiveness and practical value in real-world scenarios. The findings of this work will be communicated to practitioners through workshops and a booklet.

This dissemination of knowledge through both academic channels and practitioner engagement ensures that the research achieves a broad impact, contributing to advancements in the field and offering tangible benefits to society.

3.8 Implementation Methodology

The 'Implementation Methodology' phase of the Design Science approach emphasises the practical application and deployment of developed artefacts in real-world contexts. This phase involves translating theoretical models, methods, and frameworks into operational tools and systems that practitioners can use to solve specific problems. By bridging the gap between research and practice, the 'Implementation Methodology' phase ensures that solutions developed through the Design Science approach have a tangible impact, enhancing the capabilities and performance of targeted systems. This phase not only validates the practical utility of the research but also provides valuable insights for further refinement and future research directions.

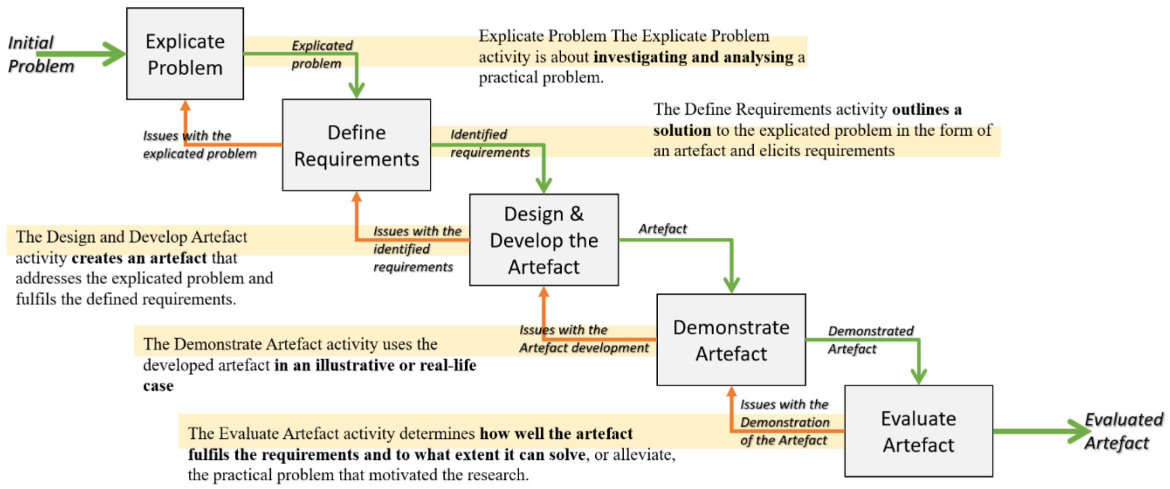

Figure 3-5: Design Science approach to design an artefact

Figure 3-5 illustrates the design science approach workflow, tracing the process from the initial problem statement to the final evaluation of the artefact at the implementation stage. This development follows five iterative steps: (1) Explicating the problem, (2) Defining requirements, (3) Designing and developing the artefact, (4) Demonstrating the artefact, and (5) Evaluating the artefact. Each step is examined in detail in Chapter 5.

The research focuses on rain-induced landslide risk reduction, with several risk mitigation measures implemented to address existing risks. These actions were identified through stakeholder discussions, and their impact was assessed using the new artefact. User feedback was gathered to verify the model's behaviour.

A comparison was made between existing risk assessment principles, leading to the identification of future research areas. The researcher found that several risk assessment principles have not been sufficiently explored or popularised within the field. Additionally, the research identified several reinforcing and balancing loops through system dynamic modelling. The artefact can calculate impact propagation through these loops, and future research is anticipated to focus on implementing these loops as a 'Key Performance Indicator' in disaster risk reduction.

3.9 Research Ethics

Ethical approval for this research was sought through the University of Salford's research ethics clearance process. The application (ID: 11375) was submitted to the ethical review panel, which approved on the 6th of September, 2023. (Annexure 01)

3.10 Summary

The research philosophy in social science encompasses the researcher's ontological, epistemological, and axiological assumptions, as explained by Bhattacherjee (2012), Johannesson and Perjons (2014), and Saunders et al. (1997). Ontology concerns the nature of reality and what can be known about it, epistemology involves the nature and scope of knowledge and how it can be acquired, and axiology addresses the role of values and ethics in research. These philosophical underpinnings guide researchers in understanding social phenomena and formulating their inquiries within the social science domain (Bhattacherjee, 2012; Johannesson & Perjons, 2014; Saunders et al., 1997).

Design Science, traditionally used in the Information Science discipline, also aligns well with the research philosophy in social science by addressing complex, real-world problems through the creation and evaluation of artefacts (Hevner et al., 2004). In the context of social science, Design Science emphasises the generation of innovative solutions (artefacts) that are grounded in rigorous theoretical foundations and practical applicability. This approach resonates with the epistemological stance of social science, which values knowledge gained through both theoretical insight and empirical validation (Hevner et al., 2004; Pedersen et al., 2000).

Ontology in Design Science is compatible with social science research as it recognises the constructed nature of reality and seeks to improve it through human-centred design and interventions (Hevner et al., 2004). This aligns with the social science perspective that social constructs shape reality and can be influenced through informed actions (Bhattacherjee, 2012). Epistemologically, Design Science contributes to the body of knowledge by creating new artefacts and frameworks, which are evaluated for their effectiveness and utility, thereby enhancing our understanding of how these solutions impact social systems (Hevner et al., 2004).

Moreover, Design Science's axiological focus on the practical relevance and applicability of research ensures that the solutions developed are not only theoretically sound but also ethically and socially responsible (Johannesson & Perjons, 2014). This aligns with the social science emphasis on research that addresses social issues, improves human conditions, and respects ethical considerations (Saunders et al., 1997).

In summary, Design Science complements the research philosophy in social science by integrating its ontological, epistemological, and axiological assumptions. It provides a structured approach to developing and validating solutions that address complex social problems, thereby contributing to both theoretical advancement and practical application in social sciences (Hevner et al., 2004; Bhattacherjee, 2012; Johannesson & Perjons, 2014; Saunders et al., 1997).

Chapter 4: Framework for Risk Assessment and Reduction

4.1 Introduction

This chapter analyses the risk elements identified in Chapter two and establishes a comprehensive network that represents the interconnections among these elements. This intricate network is transformed into a stock-flow diagram that incorporates both balancing and reinforcing loops, thereby creating a robust risk propagation model. A thorough examination of the main fourteen loops within this diagram provides insights into how risks propagate through various connections and highlights the critical role that the community plays in managing risks at the local level to foster resilience. This detailed analysis not only unveils the dynamics of risk transmission but also leads to the identification of fourteen actionable recommendations aimed at reducing risks and enhancing community resilience. Furthermore, the chapter presents the research conducted to explore key principles essential for operationalising this risk propagation model, facilitating a deeper understanding of risk behaviour as a systemic phenomenon. This chapter serves as a pivotal foundation for developing effective strategies in risk management and resilience-building within communities.

4.2 Disaster Risk Assessment Dynamic Connections

Chapter 2 provided a comprehensive examination of the risk elements discussed in the literature, along with the phases of the risk assessment process, which encompasses three primary activities: risk identification, analysis, and evaluation. Within risk analysis, careful attention is given to three major components: hazards, vulnerabilities, and exposure analysis (Bibi, Nawaz, Abdul Rahman, Azahari Razak, & Latif, 2018b; Gallopín, 2006; Huang et al., 2020; Zhou et al., 2020). According to Gallopín (2006), vulnerable elements represent the internal processes of human settlements, while hazards or perturbations refer to external processes. Additionally, hazard assessment includes four key elements: spatial probability, temporal probability, magnitude, and resistance. The vulnerability assessment further examines various factors, including physical, social, economic, environmental, governance, resilience, sensitivity, and fragility.

Moreover, risk evaluation is categorised into risk perception and risk appetite through the use of a risk matrix, which serves as a tool for decision-making regarding risk management strategies. In this context, risk perceptions gauge individuals' attitudes towards known hazards, encompassing two facets: risk examination and risk prediction behaviour. Furthermore, risk appetite defines how individuals perceive the limits and boundaries of risk exposure and includes various options for managing risk, such as risk tolerance, risk transfer, risk treatment, and risk termination, all shaped by risk judgment and critical curves. Understanding these interconnected elements is crucial for developing effective risk management strategies that address the complex dynamics of hazards and vulnerabilities within communities.

The figure below illustrates the initial connections for risk assessment identified through the literature survey. Stakeholder verification was conducted to assess the practical applicability of these connections within the risk assessment domain. In the figure, blue arrows represent positive relationships, while red arrows indicate negative relationships.

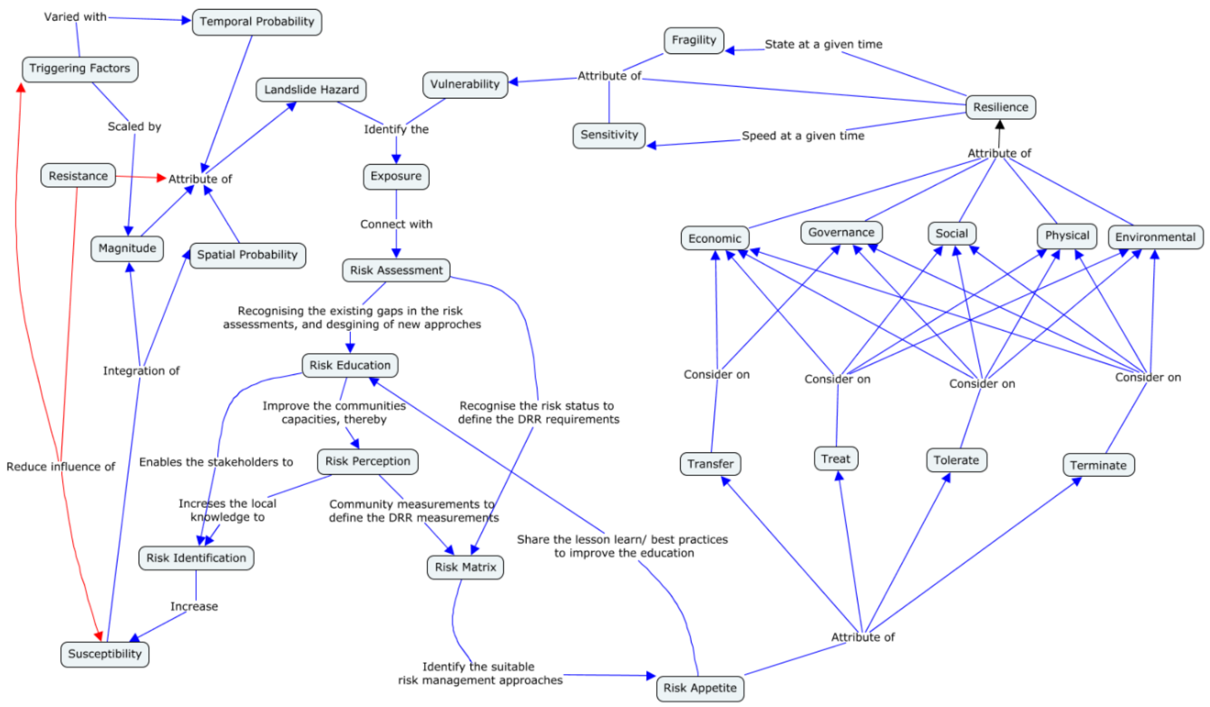

Figure 4-1: Initial connections for risk assessment

This initial concept was discussed with the stakeholders to get initial feedback on the model. This communication was the starting point of the model's validation. Accordingly, the stakeholders' feedback can be summarised as follows.

A network diagram is a complex structure that represents combinations of various interlinked nodes. However, the readability of such a diagram can be improved by reducing its complexity. As suggested by SID 1-4, the existing network was complicated, and it was recommended to cluster principles where additional detail was unnecessary. Additionally, the model provides clear guidance on which principles are linked to others, and these connections need to be clarified. Therefore in order to simplify and enhance clarity, some loops in the network were identified and clustered around the main principles, as discussed below.

Complexity Between Resilience and Risk Appetite: Five dimensions of resilience were identified: Physical, Social, Economic, Environmental, and Governance. Additionally, four risk appetite options were recognised: tolerate, treat, transfer, and terminate. These attributes were clustered under their respective parent principles to reduce the model's complexity.

Complexity Between Risk Matrix, Risk Perception, and Risk Education: The model identified two measurement levels to define risk status. The judgment curve represents the decision line between risk tolerance and risk treatment or between risk tolerance and risk transfer. This first-level decision involves recognising that current processes are inadequate and that some risk-reduction strategies are needed. The critical curve indicates when risk reduction activities are insufficient to manage the risk, making termination the only option, which involves removing hazard sources or exposures or elements at risk.

Risk examination is necessary to identify the existing risk status within the risk matrix. Consequently, the judgment curve and the critical curve were considered parameters of the risk matrix, and risk examination was integrated as part of the decision-making process. As a result, the nodes for risk examination, judgment curve, and critical curve were combined into the risk matrix node.

The connection between Risk communication and risk predictive behaviour: Risk communication involves educating communities about potential risks to help them understand the possible consequences. SID1-4 suggest that communication is key to fostering communities' ability to predict hazards. This process is already illustrated in a diagram that connects risk communication, risk identification, risk education, risk perception, and risk prediction behaviour. Accordingly, the risk predictive behaviour was absorbed into the risk communication and the direct link between risk communication and risk prediction behaviour was removed.

The connection between risk identification and susceptibility: Risk identification helps recognise more vulnerable locations. However, this process is also associated with various risk principles, as depicted in the diagram. Consequently, SID1- 4 recommended removing the link between risk identification and susceptibility to simplify the model.

Accordingly, the model was revised, considering the feedback of SID 1-4, and the new links of risk principles can be illustrated as follows.

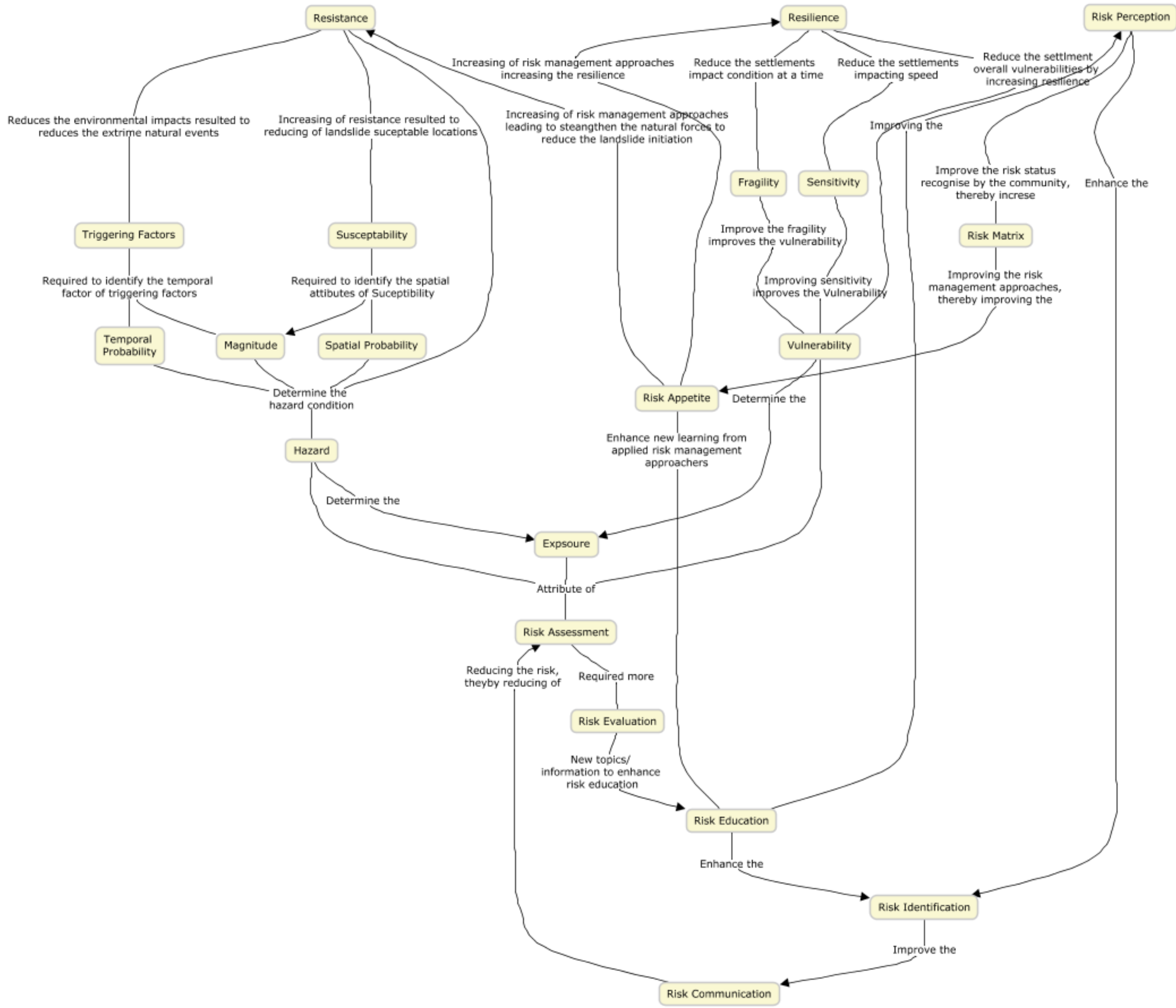

Figure 4-2: Revised causal loop diagramme

Table 6 below summarises the relationships among these risk characteristics with supporting references to the literature, while Figure 4-2 graphically illustrates these connections, highlighting their interdependencies and mutual influences. The mark ‘<>’ indicates connections between the identified principles, showing, for example, that principle A is connected to principle B. These connections are classified as either positive or negative. A positive connection indicates that the first principle positively influences or engages with the second principle, while a negative connection implies the opposite.

Table 6: Relationships between risk characteristics.

Connection	Connection type	Comment	Literature source
Spatial Probability <> Hazard	Positive	An increase in spatial probability will lead to an increase in hazard.	(Corominas et al., 2013; Zhou et al., 2020)
Temporal Probability <>Hazard	Positive	An increase in temporal probability will lead to an increase in hazard.	(Corominas et al., 2013; Zhou et al., 2020)
Magnitude <> Hazard	Positive	An increase in the magnitude of the source of hazard will lead to an increase in hazard.	(Hopkin, 2010; Zhou et al., 2020)
Resistance <> Hazard	Negative	An increase in resistance to hazard will decrease hazard.	(Shuang et al., 2017; Wheeler et al., 2017)
Susceptibility <> Spatial Probability	Positive	An increase in susceptibility to hazards in an area will lead to an increase in the spatial probability of a hazard.	(Corominas et al., 2013; Zhou et al., 2020)
Susceptibility <> Magnitude	Positive	An increase in susceptibility will lead to an increase in the magnitude of a hazard.	(Hopkin, 2010; Zhou et al., 2020)
Triggering Factors <> Temporal Probability	Positive	An increase in triggering factors will lead to an increase in the temporal probability of a hazard.	(Corominas et al., 2013; Zhou et al., 2020)
Triggering Factors <> Magnitude	Positive	An increase in triggering factors will lead to an increase in the magnitude of a hazard.	(Hopkin, 2010; Zhou et al., 2020)

Resistance <> Susceptibility	Negative	An increase in resistance to a hazard will decrease susceptibility to a hazard.	(Aksha et al., 2020; Wheeler et al., 2017)
Resistance <> Triggering Factors	Negative	An increase in resistance to a hazard will decrease triggering factors to the hazard.	(Aksha et al., 2020; Kruse et al., 2017; Wheeler et al., 2017)
Resistance <> hazard	Negative	An increase in resistance to a hazard will decrease the hazard.	(Aksha et al., 2020; Wheeler et al., 2017)
Resilience <> Vulnerability	Negative	An increase in resilience will decrease vulnerability	(Cimellaro, Reinhorn, & Bruneau, 2010; Gallopín, 2006; Izquierdo-Horna & Kahhat, 2018; Tariq et al., 2021; Weichselgartner & Kelman, 2015)
Fragility <> resilience	Negative	A decrease in fragility will increase resilience	(Bibi et al., 2018a; Bosetti et al., 2016a)
Sensitivity <> resilience	Negative	A decrease in sensitivity will increase resilience	(Izquierdo-Horna & Kahhat, 2018)
Fragility <> sensitivity	Positive	An increase in fragility will increase sensitivity.	(Bosetti et al., 2016b; Nilsson & Grelsson, 1995; Zhao et al., 2020)
Fragility <> Vulnerability	Positive	An increase in fragility will increase vulnerability	(Bosetti et al., 2016b; Izquierdo-Horna & Kahhat, 2018; Nilsson & Grelsson, 1995; Zhao et al., 2020)
Sensitivity <> Vulnerability	Positive	An increase in sensitivity will increase the vulnerability	(Gallopín, 2006; Torre et al., 2019)
Hazard <>	Positive	An increase in hazard	(Gallopín, 2006; Zhou et

Exposure		(extent) will increase exposure.	al., 2020)
Exposure <> Risk	Positive	An increase in exposure will increase the risk.	(Corominas et al., 2013; Gallopín, 2006; Huang et al., 2020; Zlatanova et al., 2014)
Vulnerability <> Risk	Positive	An increase in vulnerability will increase risk.	(Corominas et al., 2013; Gallopín, 2006; Huang et al., 2020; Tran et al., 2018; Zlatanova et al., 2014)
Hazard <> Risk	Positive	An increase in hazard will increase the risk.	(Corominas et al., 2013; Gallopín, 2006; Huang et al., 2020; Zlatanova et al., 2014)
Risk communication <> Risk	Negative	An increase in risk communication activities will decrease the risk.	(Lee et al., 2015; D. Xu et al., 2020)
Risk identification <> Risk communication	Positive	An increase in risk identification will lead to risk communication activities.	(D. Xu et al., 2020)
Susceptibility <> Risk identification	Positive	An increase in susceptibility will lead to risk identification activities.	(Corominas et al., 2013; Zhou et al., 2020)
Risk education <> Risk identification	Positive	An increase in risk education will lead to more risk identification activities.	(Jemec Auflič et al., 2018; Kellens et al., 2013)
Risk education <> Risk perception	Positive	An increase in risk education will lead to high-risk perception.	(Kellens et al., 2013; Kellens et al., 2011)

Risk <> Risk evaluation	Positive	An increase in risk will lead to higher risk evaluation activities.	(Corominas et al., 2013; Zlatanova et al., 2014)
Risk evaluation <> Risk perception	Positive	An increase in risk evaluation activities with communities will lead to higher risk perception.	(Kellens et al., 2013)
Risk perception <> Risk Examination	Positive	An increase in community risk perception will lead to higher risk examination activities.	(Kellens et al., 2013)
Risk Matrix <> Risk appetite	Positive	An increase in risk matrix assessment will lead to risk appetite for risk reduction activities.	(Corominas et al., 2013; Hopkin, 2010)

The network diagramme was converted into a stock-flow diagram, which is considered as the central concept of the system dynamics (Sterman, 2000). The stocks are the accumulations, which are estimated as the difference between inflows and outflows (Sterman, 2000). The stocks were considered as unit space and building. This unit space size could be changed with the infrastructures available on the ground. This unit space could be further explained by considering Figure 4-3 below.

Figure 4-3: A diagram of conceptual settlement

The figure above presents a conceptual settlement diagram, depicting features ranging from rural to urban areas. Understanding the unit space within this diagram requires considering the characteristics of each area as outlined in the table below:

Table 7: Description of the unit space

Area	**Unit space**
Built-up areas	This built-up land includes buildings, infrastructure, and service locations. The concept of unit space is defined by the building or the individual associated with it. For instance, in rural areas, a single building can often serve as the unit space because rural areas tend to have lower densities with larger, more self-contained dwellings. In contrast, urban areas consist of a large number of buildings concentrated to a small area.
Agricultural areas (e.g., rubber land, tea, other plantations)	In agricultural areas, such as rubber plantations, tea estates, or other cultivated land, the farmland unit is considered the "unit space" within the context of this

	risk assessment model. This means that a single plot of farmland, devoted to a specific agricultural activity, is treated as the fundamental unit for analysis.
Natural areas (e.g., forest lands, rock, waterbodies)	A tract of land encompassing natural elements such as forests, water bodies, and rocks is defined as the unit space. The specific size of the tract is less important than its measurability. For example, when a natural area is converted into agricultural land, the area must be clearly quantifiable.

Within the system dynamics model, the status of a tract of land with associated physical elements serves as the unit of flow, representing the movement of risk or vulnerability within the system. This concept is applied differently depending on the land's classification:

- **Natural Areas:** For tracts of land classified as natural (e.g., forests, water bodies, rock formations), the hazard status of the tract becomes the unit of flow. This signifies the potential for hazards to originate from these areas and potentially impact other parts of the system. For example, the probability of a landslide occurring in a particular forested area would be represented as a flow value.
- **Built-up and Agricultural Areas:** For built-up areas (e.g., settlements, infrastructure) and agricultural areas (e.g., farmland), the vulnerability status of the tract becomes the unit of flow. This signifies the susceptibility of these areas to various risks, considering their physical characteristics, human activity, and exposure. For example, the vulnerability of a densely populated urban area to landslides would be represented as a flow value.
- **Risk Conditions of Exposed Elements:** The risk conditions of elements within these areas (such as buildings, infrastructure, crops, and even the population) are also identified and assessed as units of flow. This captures the specific risks associated with each element and how they are affected by broader system dynamics.

This approach, guided by the system dynamics concept, models stocks and flows through interconnected relationships. Each flow is connected to the identified risk principles, such as risk perception, risk communication, and risk appetite, as outlined in the network diagram.

This connection reflects the influence of these risk principles on the flow of risks and vulnerabilities within the system.

The following steps were considered during the system dynamic model formulation.

1. At the outset, exposure was modelled as a stock, with perturbated units treated as a separate stock. These two stocks were interconnected through the risk level (Expsoure and Impacted). As the risk level increases, more exposure units transition into perturbated units, and conversely, as the risk decreases, perturbated units revert to exposure units. This dynamic interaction can be depicted within the framework of system dynamics as follows (Figure 4-4). Here, the square represents the stock, and the arrow with triangles represents the flow.

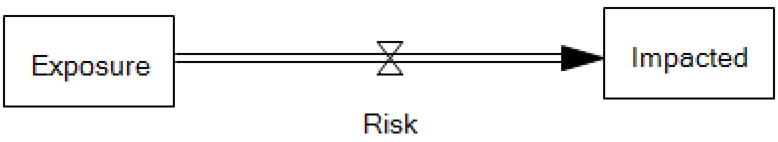

Figure 4-4: SD model - Initial step

2. In this model, the exposure refers to the physical element located on a tract of land. Accordingly, the two main components, physical elements and land, are in the exposure. The rain-induced landslide is focused on the research, and it occurred on the tract of land. The vulnerability is due to the intrinsic properties of the physical elements. Therefore, the exposure stock can be connected to safer units (integrated physical elements and tract of land) through two flows: hazard and vulnerability. Further, the exposure stock was converted to 'Element at Risk', due to both hazard and vulnerability. Exposure identifies the extent, but elements at risk include vulnerability and potential hazard zones (M. Papathoma-K¨ohle, B. Neuh¨auser, K. Ratzinger, H. Wenzel, & Dominey-Howes2, 2007). The improved model can be illustrated as follows (Figure 4-5):

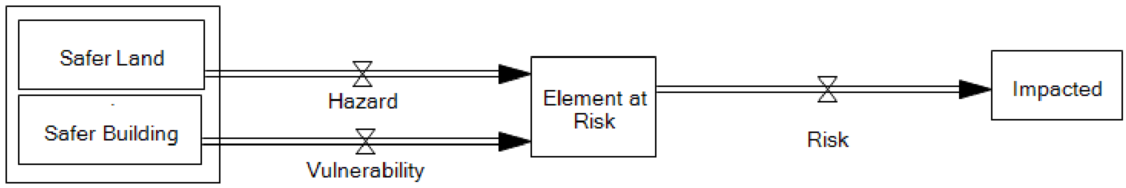

Figure 4-5: SD model: Continuing Steps- Stock improvement

3. The Causal loop output, shown in Figure 4-2, can be accommodated to the SD model, by connecting each flow with the risk assessment characteristics.
4. Thereafter, the reinforcing ("R") and balancing ("B") loops can be identified by referring to amplification or making equilibrium of variable values.

Accordingly, Figure 4-6 illustrates the stock-flow model derived from the literature and validated with stakeholders, demonstrating these interconnected relationships.

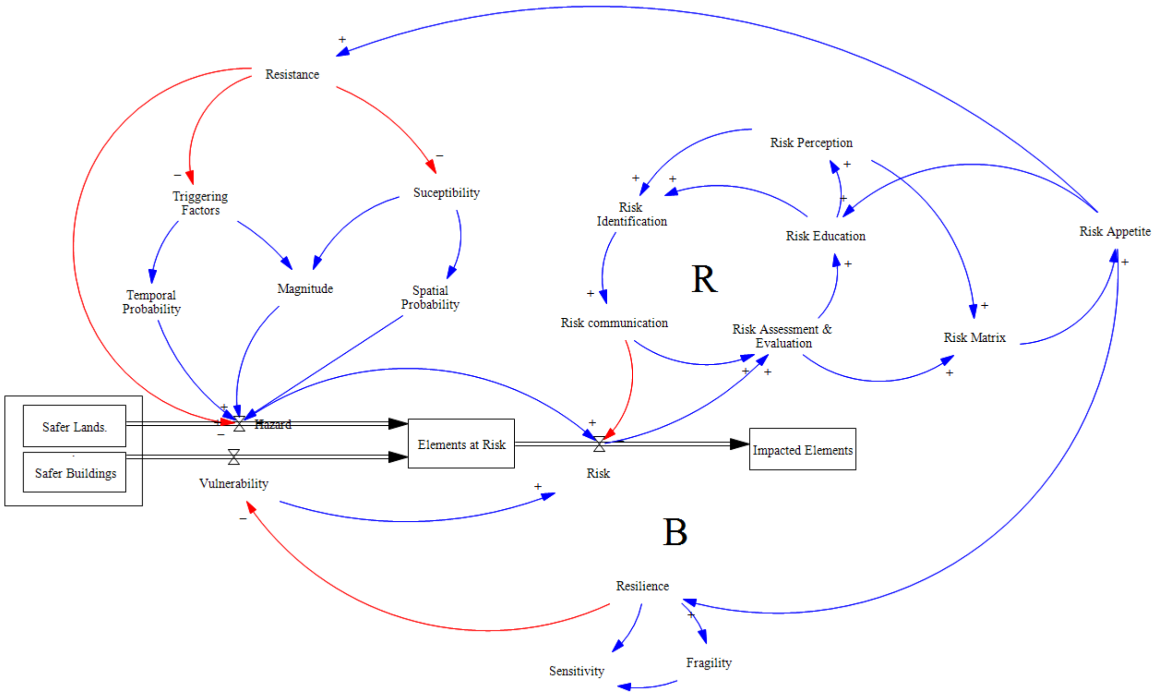

Figure 4-6: Verified stock-flow model

4.3 Risk Reduction Strategies

The risk perspective causal loop model shown in Figure 4-2 helps to understand the connections among characteristics identified through the literature review. However, since the stock-flow diagram helps to establish these relationships in a formal model, as well as risk reduction options, this risk perspective diagram was converted into a stock-flow diagram, as shown in Figure 4-6.

The primary objective of a standard risk assessment process is to understand the risk status of a human settlement and implement measures to reduce risks, thereby creating a safer environment for the community. To facilitate this, a stock-flow diagram was developed to illustrate the risk context of a human settlement, employing balancing and reinforced loops. In this model, the local area or the environment is considered a stock, with certain parts becoming exposed to one or more hazards. Similarly, the community is viewed as a stock, with a portion exposed to hazards. These exposed elements can be viewed as another stock whose resilience can be enhanced by applying risk reduction options.

Figure 4-2 shows the stock flow diagram developed by analysing the risk perspectives identified in Chapter 2, featuring negative (Red) and positive (Blue) connections. These loops provide deeper insights into how various risk elements influence each other and, as a result, impact the community's overall resilience. Consequently, this diagram can guide the formulation of risk-reduction strategies by highlighting the critical risk elements.

The system dynamic model was developed by considering the Vensim application, and loops were identified by selecting the characteristics of risk. That means any path that contains the risk element is regarded as a risk reduction measure. Accordingly, 16 loops were identified, and the applicability of each loop was discussed with the practitioners before defining the complete strategies. Accordingly, a few loops were combined by considering the stakeholder discussions.

Risk assessment before or after an incident: Proactive and reactive planning are essential strategies in hazard-prone areas to mitigate potential consequences. Proactive risk reduction activities focus on minimising potential damage from identified scenarios, while reactive planning is implemented in disaster-impacted regions to address and mitigate the effects of future hazards. However, Andersson-Sköld, Bergman, Johansson, Persson, and Nyberg (2013) highlights significant challenges in conducting proactive disaster risk reduction, particularly in accurately predicting the location of probable landslides. Similarly, SID 1-4 argues for the importance of conducting risk assessments in both proactive and reactive planning. Even after a landslide occurs, it remains crucial to estimate the likelihood of future events. Therefore, contextually, the risk assessment is the same before and after the incident. This ensures that risk reduction pathways remain the same, although the priority of various risk strategies may shift. For instance, in-situ mitigation or resilience improvement becomes a priority when an incident occurs in a specific area.

Combining susceptibility > magnitude and triggering factor > magnitude segments: Landslide magnitude significantly impact the exposure elements and is considered as the energy state of the event. For example, the landslide runout is determined by few factors, including the landslide volume (Corominas et al., 2013). The literature pointed out that the magnitude can be articulated by susceptibility and triggering factors. However, SID-1 and SID-2 mentioned that the solutions for reducing the magnitude have a combination effect. For instance, the occurrence of rain-induced landslides requires both susceptibility and triggering factors; no single factor makes an event.

Accordingly, fourteen balancing loops were identified by analysing the stock-flow diagram in Figure 4-6, and these loops were further examined to propose strategies aimed at reducing risk and enhancing community resilience. The following section proposes strategies that can be employed to mitigate risks by analysing the identified balancing loops.

1. **(Risk -> Risk Assessment -> Risk Education -> Risk Identification -> Risk Communication -> Risk)**

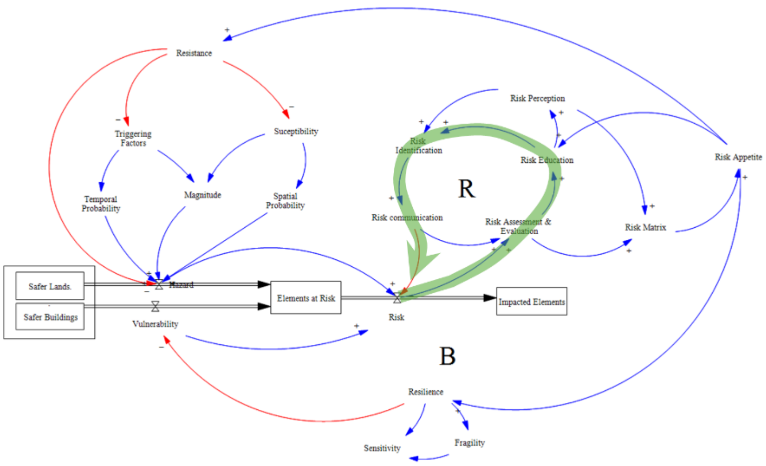

Figure 4-7: Loop 1: Risk-Risk Assessment-Risk Education- Risk Identification - Risk Communication - Risk

The presence of risk within a community triggers the necessity for thorough risk assessments. These assessments are critical as they quantify and provide a comprehensive understanding of the various threats faced by the community. The insights gained from these risk assessments then form the foundation for developing robust risk education programs. These programs are designed to convey substantial knowledge about potential risks to the community, ensuring that residents are well-informed and aware of the dangers they might encounter.

As community members become more knowledgeable through effective risk education, their capacity to identify risks early is significantly enhanced. An informed community is better equipped to recognise potential threats, which in turn leads to proactive risk identification. When individuals can identify risks accurately, it improves the overall risk communication within the community. Effective risk communication ensures that information about potential threats is shared widely and efficiently, enabling the community to take preventive measures promptly.

Improved risk communication within the community contributes directly to mitigating the overall risk levels. When risk information is disseminated effectively, it empowers community members to act on the knowledge, thereby reducing vulnerability and enhancing safety.

However, this positive feedback loop can face challenges over time. If the perceived level of risk decreases due to successful mitigation efforts, the urgency and frequency of ongoing risk assessments may diminish. When risk assessments are reduced or neglected, the information that feeds into the risk education programs becomes outdated. This results in less effective risk education, weakening the community's ability to identify new or emerging risks. Consequently, poor risk identification leads to ineffective risk communication, creating a false sense of security within the community. As vigilance wanes, the risk level begins to increase once again.

Recommendation: To sustain an effective risk management cycle, it is crucial to continuously update risk education programs with insights from the latest risk assessments and disaster evaluations. Keeping education programs relevant and current ensures that the community remains aware and capable of identifying threats. Additionally, maintaining regular, systematic risk assessments ensures that the understanding of risks is based on up-to-date information. Strengthening risk communication networks is equally important; developing robust channels for information dissemination encourages active participation and sharing of observations related to potential risks within the community.

By implementing these strategies, a community can maintain a resilient feedback loop where continuous education, assessment, and communication work together to sustain low levels of risk and enhance overall safety.

2. (**Risk -> Risk Assessment -> Risk Education -> Risk Perception -> Risk Identification -> Risk Communication -> Risk**) –

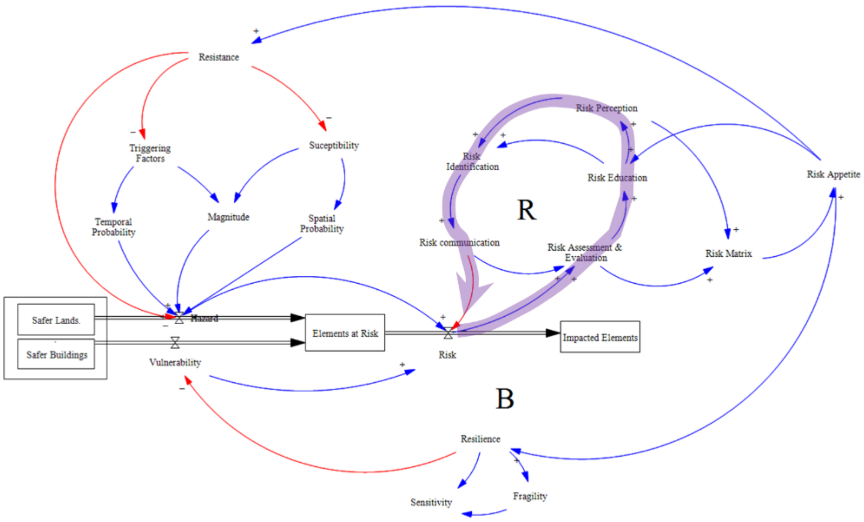

Figure 4-8: Loop 2: Risk - Risk Assessment - Risk Education - Risk Perception - Risk Identification - Risk Communication - Risk

The importance of risk assessment and risk education was explained in the previous loop. Risk education significantly influences the community's perception of risk. When individuals are educated about possible threats and the measures they can take, their awareness and understanding of risk levels improve. This heightened perception means that community members are more alert and cognisant of the risks surrounding them. Enhanced risk perception directly impacts risk identification. As people become more aware, they can better recognise and identify potential threats early on, contributing to a proactive community stance on risk management.

Effective risk identification leads to improved risk communication. When community members can recognise risks accurately, they share this information with others, creating robust communication networks within the community. As information about risks is disseminated broadly and efficiently, the community can take collective preventive measures, thereby mitigating the overall risk level. However, this positive feedback loop needs careful management to remain effective over time.

Incorporating risk perception into the loop underscores the importance of regularly assessing how the community views risk. If the perceived risk decreases due to effective risk reduction measures, there might be a diminished urgency for continuous risk assessments and education. Consequently, the flow of updated information into risk education programs may become sporadic, resulting in a less informed community. This can lead to poor risk identification and communication, ultimately increasing the overall risk level.

To maintain a sustainable and effective risk management cycle, it is essential to frequently measure the community's risk perception using various assessment tools. Understanding how the community perceives risk at any given time helps in tailoring risk education programs to address specific concerns and misconceptions. Introducing community activities that engage residents in understanding and addressing local risks can transform them into active stakeholders in the risk reduction process.

By fostering an environment where the community actively participates in risk identification and communication, the overall risk level can be significantly reduced. Continuous evaluation and enhancement of risk perception and education ensure that the community remains vigilant and proactive in mitigating risks.

Recommendation: Continuously measure community risk perception and introduce activities to ensure an accurate understanding of local risks within the community. These activities should aim to keep the risk perception aligned with actual risk levels, fostering a culture of awareness and proactive risk management.

3. **(Risk -> Risk Assessment -> Risk Matrix -> Risk Apatite -> Risk Education -> Risk Identification -> Risk communication -> Risk**)

The presence of risk within a community necessitates comprehensive risk assessments. These assessments aim to identify potential threats and quantify their impact, laying the groundwork for effective risk management. Moving beyond basic risk assessments, the incorporation of a risk matrix allows for a more meticulous evaluation of risks. The risk matrix is a powerful tool that facilitates the categorisation and prioritisation of risks based on their likelihood and impact. By plotting risks on the matrix, one can visualise and understand which risks require immediate attention.

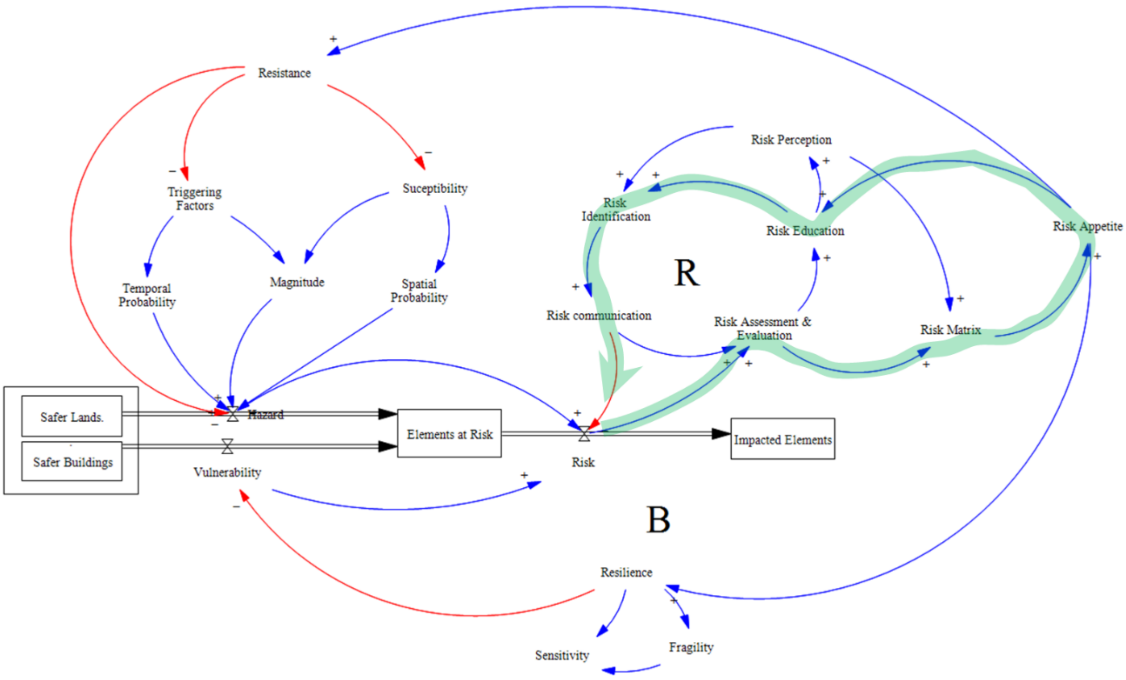

Figure 4-9: Loop 3: Risk - Risk Assessment - Risk Matrix - Risk Appetite- Risk Education - Risk Identification - Risk Communication - Risk

Building on the insights derived from the risk matrix, the concept of risk appetite comes into play. Risk appetite refers to the level of risk that an organisation or community is willing to accept in pursuit of its objectives. It serves as a guiding principle for making informed decisions about risk management. Depending on the positioning of risks on the critical and judgment curves within the risk matrix, communities can determine their optimal risk appetite, balancing the need for safety with the acceptance of some level of risk for growth and development.

Integrating the concepts of risk matrix and risk appetite into risk education programs ensures that the community and professional stakeholders are well-informed about local risks and the rationale behind risk management decisions. These programs can convey detailed information gathered through risk matrix analyses and explain how risk appetite shapes risk management strategies. This comprehensive approach not only enhances the community's understanding of risks but also strengthens their capacity for risk identification. When individuals are educated about why certain risks are prioritised and how decisions are made, their ability to recognise and communicate about risks improves.

Effective risk identification and communication are crucial for reducing overall community risk. As previously discussed, informed community members can identify emerging threats more accurately and share this information widely, enabling prompt preventive measures. By ensuring that risk education programs are grounded in solid evidence from the risk matrix and risk appetite activities, it is possible to create a feedback loop that continuously informs and empowers the community.

Recommendation: To enhance risk management, ensure that risk education programs are informed by evidence gathered through risk matrix analyses and risk appetite assessments. This integration will provide a clear rationale for risk management decisions, improve risk identification, and strengthen risk communication within the community.

4. **(Risk -> Risk Assessment ->Risk Matrix -> Risk Apatite -> Risk Education -> Risk Perception -> Risk Identification -> Risk Communication -> Risk**)

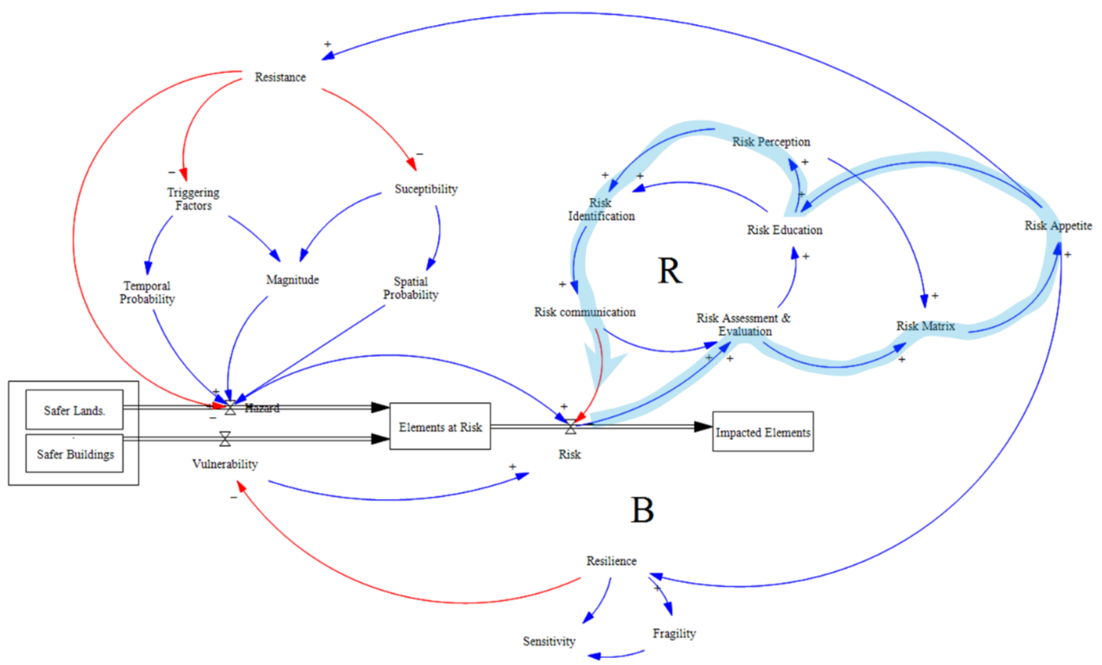

Figure 4-10: Loop 4: Risk - Risk Assessment - Risk Matrix - Risk Apatite - Risk Education - Risk Perception - Risk Identification - Risk Communication - Risk

While the previous risk propagation loop 3 highlighted the essential components of risk assessment, risk matrix, risk appetite, risk education, risk identification, and risk communication, the introduction of risk perception adds a nuanced but crucial element to the overall risk management process. Risk perception significantly influences how communities respond to identified risks. Even with well-defined risk assessments, matrix analyses, and tailored education programs, if the community's perception of risk does not align with the actual risks, the effectiveness of these efforts can be severely compromised. People might underestimate or overestimate certain risks, leading to either complacency or unnecessary alarm. Therefore, understanding and addressing risk perception is critical to ensuring that risk management strategies are both understood and accepted by the community.

Effective risk education must therefore go beyond simply conveying facts; it must also bridge the gap between technical risk assessments and public understanding. By aligning risk perception with the actual risk levels as identified through thorough assessments and the risk matrix, education programs can foster a more accurate and rational public response. When the community perceives risks accurately, it enhances their ability to identify and communicate about these risks effectively, thereby creating a more vigilant and proactive environment.

Moreover, accurate risk perception empowers individuals to take appropriate preventive measures. When people understand the rationale behind risk management decisions, shaped by the risk appetite and supported by evidence from the risk matrix, they are more likely to engage in proactive risk-reducing behaviours. This heightened awareness and corresponding action contribute to the community's overall resilience and capability to manage risks.

In summary, integrating risk perception into the risk management loop ensures that the community's subjective understanding aligns with objective assessments. This alignment can significantly enhance risk identification and communication efforts, leading to more effective mitigation strategies. As a result, the overall risk level within the community is reduced, demonstrating the critical importance of addressing risk perception in comprehensive risk management plans.

Recommendation: To enhance risk management, tailor risk education programs to address both factual information and risk perception, ensuring community understanding aligns with actual risks. Regularly assess and adjust the community's risk perception to maintain alignment with objective risk levels. Clearly communicate the rationale behind risk management decisions to build trust and cooperation.

5. **(Risk -> Risk Assessment -> Risk Matrix -> Risk Apatite -> Resilience -> Vulnerability -> Risk**)

This loop highlights how thorough risk assessment, utilising the risk matrix and understanding risk appetite, can lead to enhanced resilience and reduced vulnerability within a community.

Risk assessment begins the process by identifying and quantifying potential threats. Utilising the risk matrix, these risks can be categorised based on their likelihood and severity. This matrix helps prioritise which risks need immediate attention. Subsequently, these prioritised risks are analysed in the context of the community's risk appetite, which involves determining the level of risk that the community is willing to accept in pursuit of its goals.

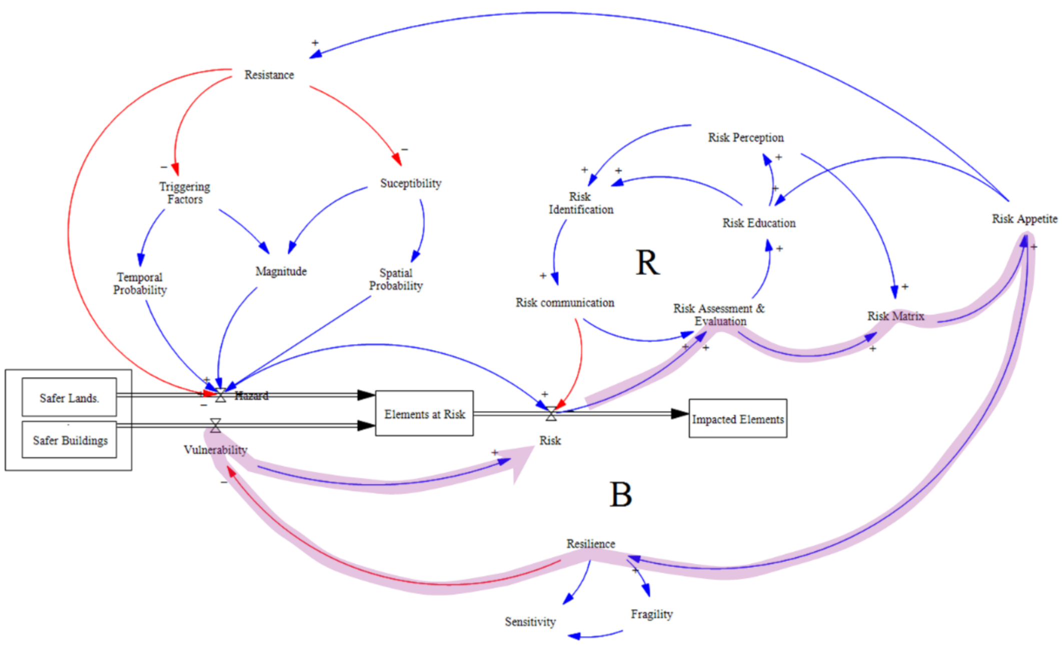

Figure 4-11: Loop 5: Risk - Risk Assessment- Risk matrix - Risk Appetite - Resilience - Vulnerability - Risk

When the community's risk management strategies are aligned with its risk appetite, targeted actions can be developed to enhance resilience. Resilience, in this context, encompasses the community's ability to anticipate, absorb, restore, and transform in the face of hazards. By knowing which risks are acceptable and which require mitigation, communities can implement resilience-building measures across various dimensions: physical, social, economic, environmental, and governance.

For instance, if the risk matrix identifies flooding as a high-priority risk, and the community's risk appetite dictates that flood risk should be reduced as much as possible, specific resilience-building measures could be taken. These might include improving flood defences, educating the public about flood preparedness, and developing rapid response plans. These measures contribute to the community's ability to anticipate, absorb, and restore from flooding.

Enhanced resilience directly translates to reduced vulnerability. A community that is well-prepared for risks, with robust systems in place to manage and recover from them, will have lower vulnerabilities. This, in turn, leads to a lower overall risk to the community as a whole.

Recommendation: To effectively reduce community risk, use risk assessments informed by risk matrix analyses and aligned with risk appetite to develop and implement targeted resilience-building measures. Focus on enhancing capacities in various dimensions (physical, social, economic, environmental, and governance) to lower vulnerabilities and strengthen the community's ability to manage risks effectively.

6. (**Risk -> Risk Assessment -> Risk Education -> Risk Perception -> Risk Matrix -> Risk Apatite -> Resilience -> Vulnerability -> Risk**)

This loop introduces two critical elements: risk education and risk perception. This loop highlights how these elements propagate through the system to enhance resilience and reduce vulnerability within the community.

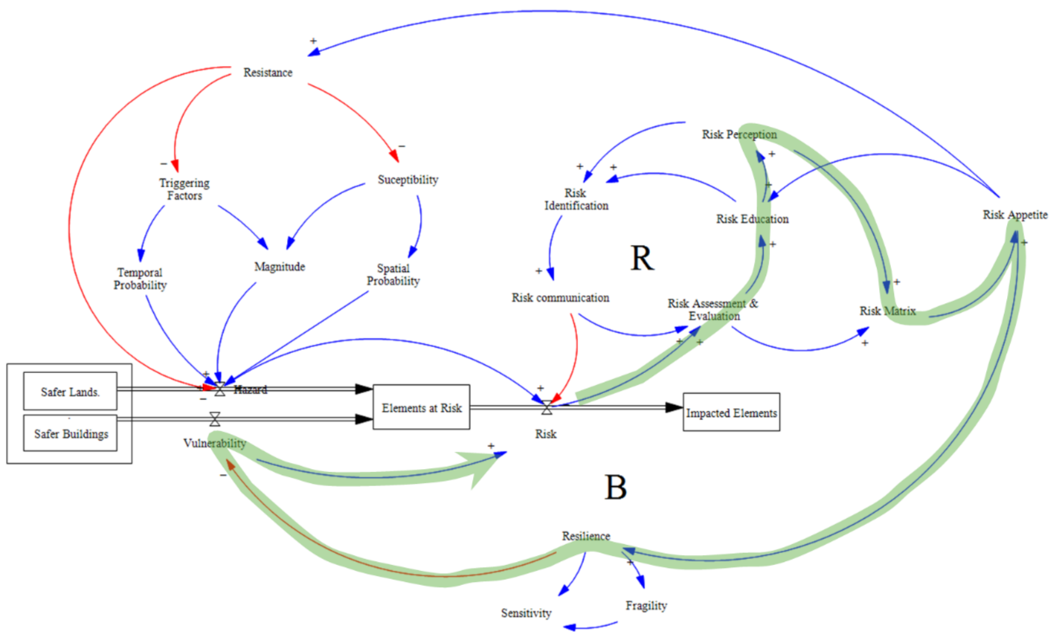

Figure 4-12: Loop 6: Risk - Risk Assessment - Risk Education - Risk Perception - Risk Matrix- Risk Apatite - Resilience - Vulnerability - Risk

Risk assessment begins this process by identifying and quantifying potential threats. The insights from these assessments then feed into risk education programs, which are designed to inform and educate the community about the identified risks. These educational initiatives aim to improve the community's understanding of the nature and extent of risks, as well as the importance of proactive risk management strategies.

Improved risk perception is a direct outcome of effective risk education. When community members are well-educated about the risks, their perception of these risks becomes more accurate and aligned with actual threat levels. This accurate risk perception influences the next steps of the risk management process significantly. The risk matrix then takes into account the community's improved risk perception to categorise and prioritise identified risks based on their likelihood and impact. With a clear and accurate understanding of risks, the community can make informed decisions about its risk appetite, defining which risks are acceptable and which require mitigation. Properly aligning risk perception with the risk matrix ensures that the community's risk appetite is realistic and based on well-understood threats.

These steps collectively contribute to enhancing resilience. With an informed and accurate perception of risks, the community can implement targeted resilience-building measures, such as adopting building codes, improving infrastructure, and developing emergency response plans. These measures enhance the community's capacities to anticipate, absorb, restore, and transform in the face of adversities.

As resilience increases, vulnerability decreases. The community becomes better prepared to manage and recover from risks, thereby reducing its overall vulnerability to future threats. This reduction in vulnerability further decreases the overall risk level within the community, completing the loop.

Recommendation: Deploy community-based approaches to defining and addressing resilience and vulnerabilities, ensuring that educational initiatives and risk perception align with practical risk management strategies.

7. **(Risk -> Risk Assessment -> Risk Matrix -> Risk Apatite -> Resistance -> Hazard -> Risk**)

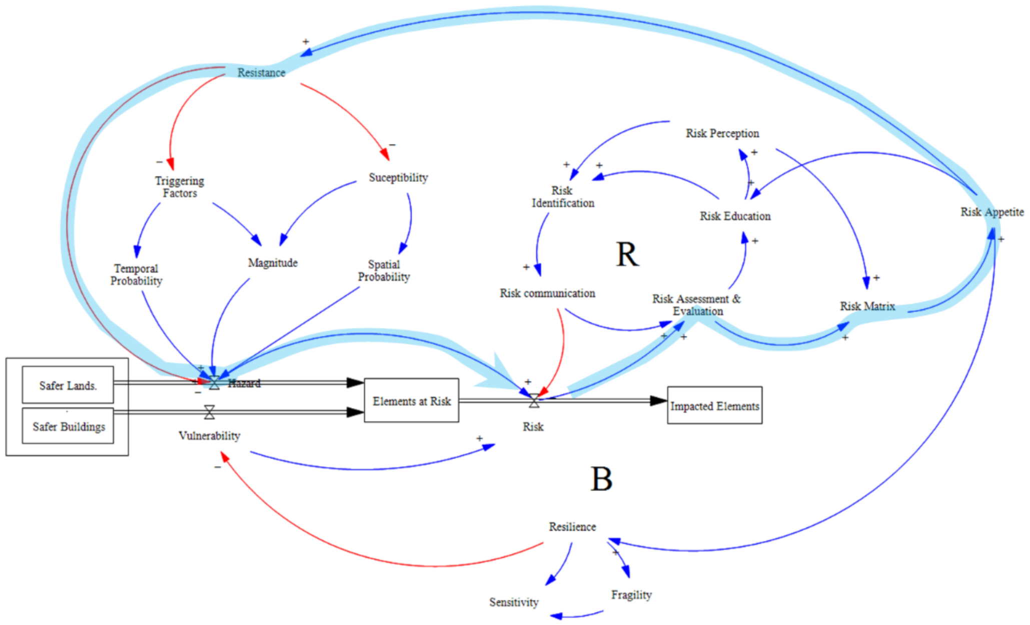

Figure 4-13: Loop 7: Risk - Risk Assessment - Risk Matrix- Risk Apatite - Resistance - Hazard-Ris

This loop illustrates how a structured approach to risk management can foster resistance to hazards, specifically leading to reduced hazards and, ultimately, reduced risks. The loop indicates that the risk matrix and the community's risk appetite play vital roles in shaping the strategies for building resistance against hazards.

By prioritising risks that exceed the community's appetite, actions can be taken to enhance resistance. This resistance may involve both structural and non-structural measures that aim to fortify the community against identified hazards such as landslides.

One effective approach includes ecosystem management, which recognises the natural factors that contribute to resistance against hazards. Specifically, the introduction of appropriate native plants serves as a nature-based solution. Native plants typically have extensive root systems that stabilise soil, reducing erosion and increasing slope stability. By selecting plant species that are well-suited to local conditions, communities can enhance the natural resilience of their landscapes, thus reducing the likelihood and severity of landslides.

As resistance built through these measures increases, the magnitude and frequency of hazards like landslides are diminished. Since hazards are directly linked to the overall risk, reducing hazard intensity leads to a corresponding decrease in community risk levels.

Recommendation: Promote ecosystem management approaches for reducing hazards. For example, the implementation of nature-based solutions can reduce the risk of landslides and contribute to overall community resilience.

8. **(Risk -> Risk Assessment -> Risk Education -> Risk Perception -> Risk Matrix -> Risk Apatite -> Resistance -> Hazard -> Risk**)

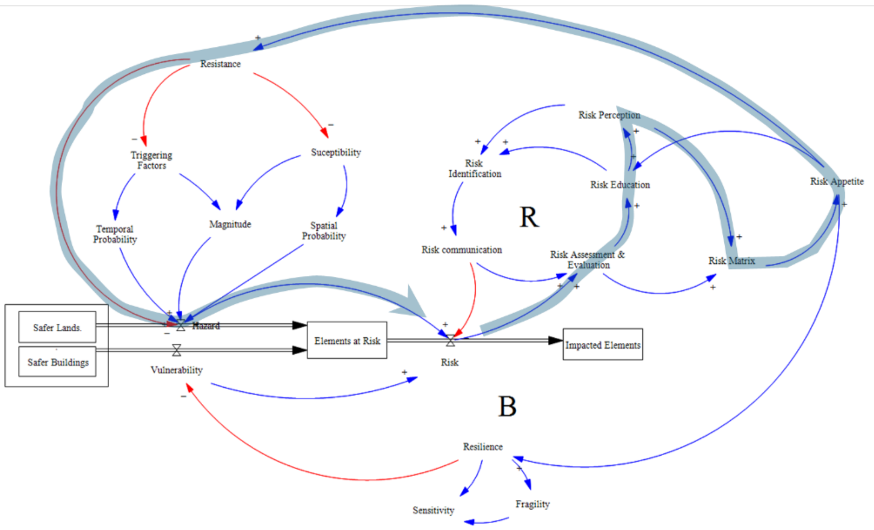

Figure 4-14: Loop 8: Risk - Risk Assessment - Risk Education - Risk Matrix- Risk Apatite - Resistance - Hazard- Risk

This loop emphasises the critical interconnections between risk education, risk perception, the risk matrix, and risk appetite in building resistance against hazards, ultimately leading to reduced risks. Risk education equips communities with the necessary knowledge to understand their local environments, ecosystem management, and the consequences of environmental degradation, such as how deforestation can increase the risk of landslides. An informed risk perception allows communities to accurately assess the hazards they face, guided by a well-defined risk matrix that prioritises risks according to their severity and likelihood. This structured understanding empowers communities to set appropriate risk appetite levels for interventions aimed at enhancing resistance, such as implementing sustainable land-use practices and promoting reforestation efforts. By fostering these elements, communities can effectively mitigate hazards, thereby reducing their overall risk and protecting their livelihoods.

Recommendation: Communicate the importance of ecosystem management in mitigating hazards by emphasising the role of risk education in helping communities understand their local environments. Encourage the transfer of knowledge regarding geomorphological conditions and sustainable practices to ensure local efforts actively contribute to hazard reduction and long-term resilience.

9. **(Risk -> Risk Assessment -> Risk Matrix -> Risk Apatite -> Resistance -> Susceptibility -> Spatial Probability -> Hazard -> Risk**)

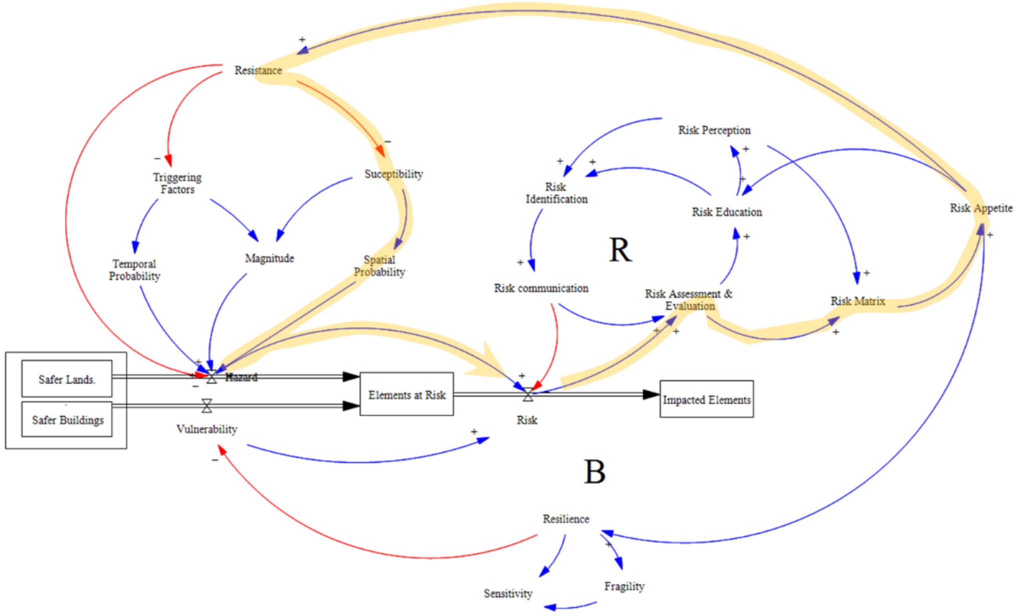

Figure 4-15: Loop 9: Risk - Risk Assessment - Risk Matrix - Risk Apatite - Resistance - Susceptibility - Spatial Probability - Hazard- Risk

This loop emphasises the critical role of resistance in reducing susceptibility and consequently influencing spatial probability, thereby minimising both hazards and overall risks. As resistance increases through measures such as sustainable land management, reforestation, and structural interventions like SABO dams, locations become less susceptible to triggering hazards. This heightened resilience reduces the spatial probability of hazards occurring, as areas prone to landslides or floods are reinforced against environmental triggers. By mitigating susceptibility, the likelihood of hazards manifesting decreases, which directly translates to a lower risk profile for the community. Consequently, integrating resistance strategies into hazard assessments allows for more accurate predictions of spatial probabilities and effective risk reduction options, ultimately enhancing community safety.

Recommendation: Promote ecosystem restoration programs at susceptible locations to enhance resistance against hazards and decrease their spatial probabilities. By focusing on nature-based solutions and structural interventions, communities can effectively minimise susceptibility, leading to a significant reduction in the likelihood and impact of future hazards.

10. **(Risk -> Risk Assessment -> Risk Education -> Risk Perception -> Risk Matrix -> Risk Apatite -> Resistance -> Susceptibility -> Spatial Probability-> Hazard)**

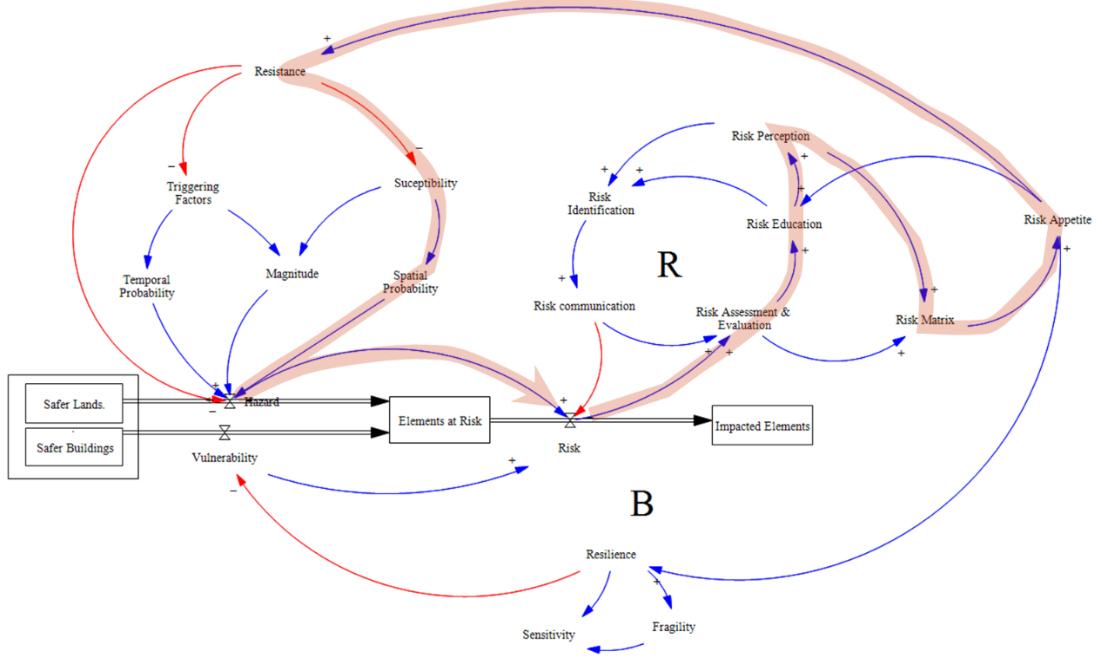

Figure 4-16: Loop 10: Risk - Risk Assessment - Risk Education - Risk Perception - Risk Matrix - Risk Apatite - Resistance - Susceptibility - Spatial Probability - Hazard- Risk

This loop highlights the critical interplay between community engagement through risk education, risk perception, the risk matrix, and risk appetite for enhancing resistance. By equipping communities with knowledge about hazards through educational programs, residents can better understand spatial probabilities and the specific locations at which hazards are most likely to occur. This knowledge fosters an informed risk perception that encourages community-driven action, enhancing resistance to potential hazards. As communities become more engaged in monitoring and maintaining the identified hazard-prone areas, their collective efforts can effectively lower susceptibility and reduce the spatial probability, leading to a significant decrease in the frequency and severity of hazards. Community engagement ensures that local voices are heard and contributes to the implementation of structural and non-structural mitigation solutions that manage hazards more effectively and protect future generations.

Recommendation: Implement community-led approaches to hazard mitigation at critical locations to enhance local capacity for risk reduction. By actively involving community members in the identification and management of hazard-prone areas, tailored solutions can be developed that effectively address local vulnerabilities and enhance overall resilience against hazards.

11. **(Risk -> Risk Assessment -> Risk Matrix -> Risk Apatite -> Resistance -> Susceptibility -> Magnitude -> Hazard)**

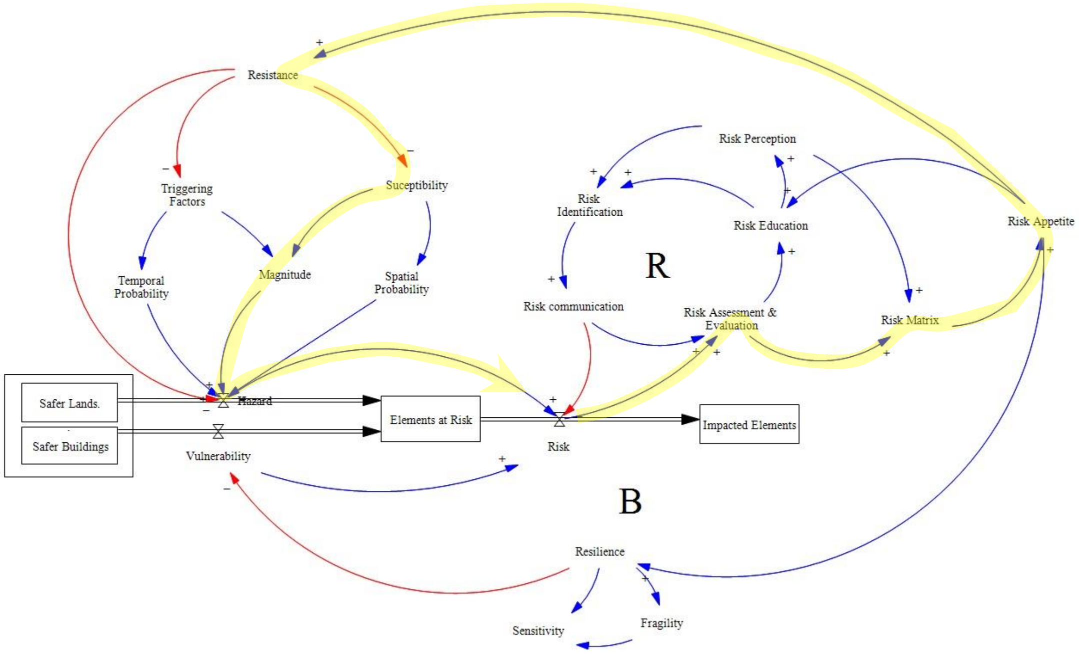

Figure 4-17: Loop 11: Risk - Risk Assessment - Risk Matrix- Risk Apatite - Resistance - Susceptibility/Triggering factors - Magnitude - Hazard - Risk

This loop emphasises the critical role of the risk matrix and risk appetite in enhancing resistance and reducing susceptibility, ultimately controlling the magnitude of hazards and minimising risks. Hazard magnitude is a crucial characteristic that requires careful management; thus, hazard assessments should estimate potential magnitudes using probability or scale values. These magnitudes can vary based on spatial or temporal factors, as seen during the failure of a dike or dam, where the potential for catastrophic flooding is closely linked to the structure's integrity and the environmental conditions surrounding it. By conducting thorough risk assessments and effectively utilising the risk matrix, communities can prioritise hazards based on their likelihood and potential impact, establishing an informed risk appetite. Setting appropriate risk appetite levels enables the adoption of targeted strategies to build resistance against identified hazards, thereby decreasing overall susceptibility. For instance, in landslide-prone areas, groundwater levels play a significant role in triggering landslides. By controlling these levels, communities can effectively lower the risk of high-magnitude hazards. One effective solution is the implementation of horizontal drains designed to remove excess water from slopes. These drains mitigate the saturation of the soil, thus reducing its weight and stability, and ultimately decreasing the potential for landslides. This proactive approach to managing the influences that contribute to high-magnitude hazards is essential for effective risk reduction.

Recommendations: Prioritise ecosystem-based solutions at locations prone to triggering high-magnitude hazards, such as implementing drainage systems and vegetation management, to enhance resilience and minimise risks. By integrating natural systems into risk management, communities can effectively control the underlying factors that contribute to hazard magnitudes, leading to safer environments and lower overall risks.

12. **(Risk -> Risk Assessment -> Risk Education -> Risk Perception -> Risk Matrix -> Risk Apatite -> Resistance -> Susceptibility -> Magnitude -> Hazard**)

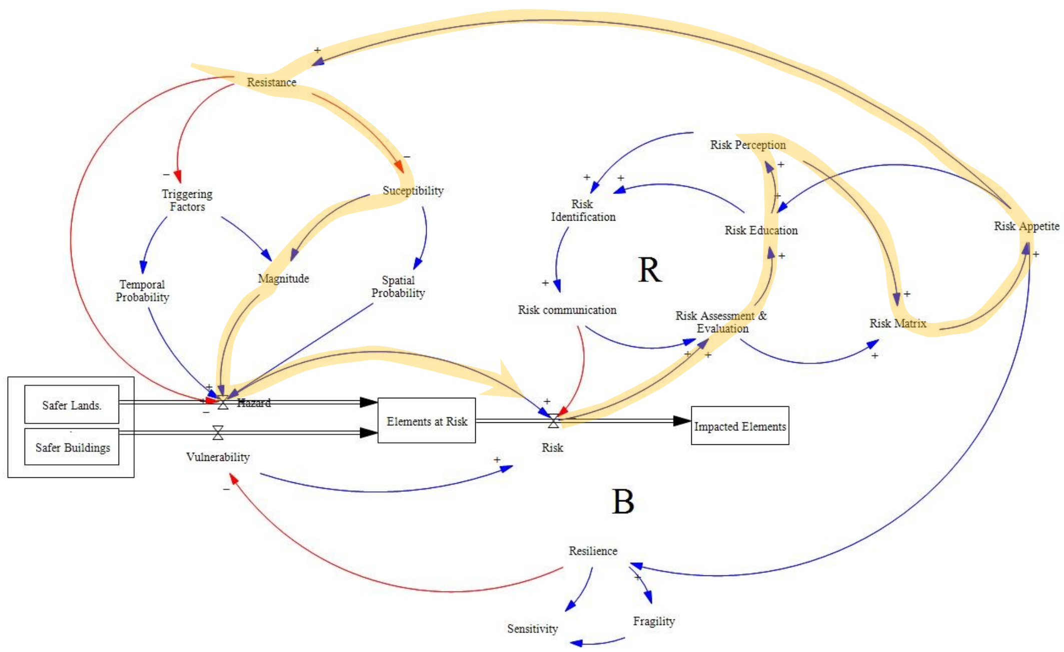

Figure 4-18: Loop 12: Risk- Risk Assessment - Risk Education - Risk Perception - Risk Matrix- Risk Apatite - Resistance - Susceptibility/ Triggering factors- Magnitude - Hazard- Risk

This loop underscores the crucial role of risk education and risk perception in controlling the magnitude of hazards. Through community engagement in educational initiatives, residents can develop a comprehensive understanding of the risks they face, which directly influences their risk perception and informs the risk matrix and risk appetite. For instance, training programs can educate communities about effective non-structural measures, such as implementing tree barriers at downslopes near rockfall-prone areas, which can considerably reduce the magnitude of rockfall events. By transferring this knowledge throughout the community, residents become invested stewards of their natural environment, fostering the maintenance of these barriers and ensuring that forested areas remain intact to prevent rocks from moving.

Beyond non-structural approaches, community engagement also allows for the adoption of vital structural measures such as flood weirs and SABO dams, designed to control flood water and debris flow speeds. These structures play a pivotal role in reducing the magnitude of hazards encountered during flood events. When communities understand the significance of such measures through risk education and recognise them as essential strategies within their risk appetite, they can actively participate in their implementation and upkeep. This collective effort enhances resistance against hazards, decreases susceptibility, and ultimately leads to a reduction in hazard magnitude.

Recommendation: Deploy community-based hazard mitigation applications to effectively reduce hazard magnitudes. Engaging local communities in risk education and perception initiatives will empower them to understand and implement structural and non-structural measures, such as maintaining tree barriers and constructing flood control systems, thereby fostering a proactive approach to managing risks and enhancing resilience.

13. **(Risk -> Risk Assessment -> Risk Matrix -> Risk Apatite -> Resistance -> Triggering Factors -> Temporal Probability -> Hazard ->Risk**)

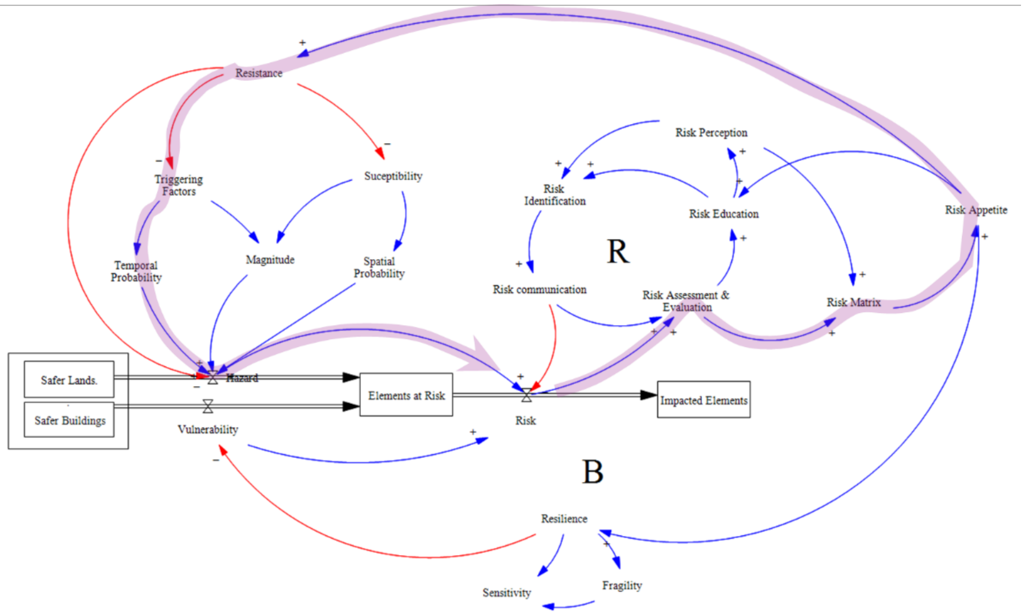

Figure 4-19: Loop 13- Risk - Risk Assessment - Risk Matrix - Risk Apatite - Resistance - Triggering Factor- Temporal Probability- Hazard- Risk

The above loop underscores the crucial role of risk matrix assessment and risk appetite in enhancing resistance to hazards by effectively controlling triggering factors and reducing temporal probabilities. A thorough risk assessment provides insights into the frequencies of triggering factors, enabling communities to develop an accurate risk matrix that categorises these factors based on their likelihood and impact. By aligning the community's risk appetite with the identified temporal probabilities of hazards, residents can implement proactive measures tailored to changing conditions. For instance, understanding that increased rainfall frequency is a significant trigger for landslides allows communities to prepare accordingly by reinforcing drainage systems or initiating early warning systems, thereby enhancing resistance to potential hazards. This strategic focus on managing triggering factors and their temporal dynamics is essential in minimising overall risk.

Recommendation: Communities should prioritise understanding the temporal variations of hazard-triggering factors, such as rainfall patterns, to effectively enhance disaster preparedness.

14. **(Risk -> Risk Assessment -> Risk Education -> Risk Perception -> Risk Matrix -> Risk Apatite -> Resistance -> Triggering Factors -> Temporal Probability -> Hazard ->Risk**)

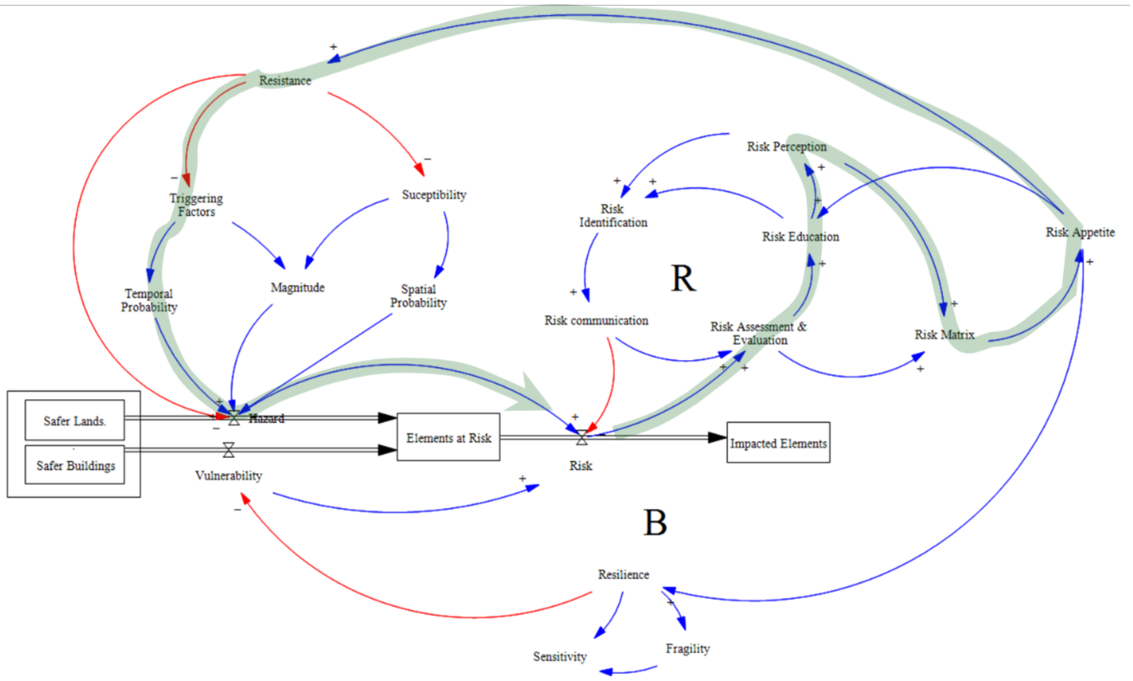

Figure 4-20: Loop 14: Risk - Risk Assessment - Risk Education - Risk Perception - Risk Matrix - Risk Apatite - Resistance - Triggering Factors- Temporal Probability - Hazard- Risk

This loop underscores the critical interplay between risk education and risk perception in informing risk matrix assessment and risk appetite, which in turn enhance resistance and manage hazard-triggering factors to reduce temporal probabilities. Enhancing knowledge within the community about how hazards evolve over time cultivates a deeper understanding of their risks, allowing for informed decisions that shape risk appetite effectively. For instance, recognising that rapid water flow from mountainous regions contributes to soil erosion underscores the importance of protecting forest cover, which acts as a natural buffer and water sponge. Educating communities to maintain upper-slope vegetation not only mitigates soil erosion but also reduces the frequency of hazards in downslope areas by controlling water flow. Consequently, as communities grasp the causal relationships between triggering factors and their temporal dynamics, they become empowered to implement proactive measures that enhance resistance and reduce overall risk.

Recommendation: Implement community-driven hazard mitigation applications that target the reduction of hazard frequencies. By prioritising education and awareness of hazard-triggering factors and their temporal changes, communities can actively participate in preserving natural buffers, such as forests, fostering long-term resilience and minimising the impacts of hazards.

The analysis of the causal loop diagram has allowed us to identify how various risk characteristics propagate through the system, providing a holistic approach to reducing hazards and risks. This comprehensive understanding has also been instrumental in formulating targeted recommendations for various risk reduction strategies. Figure 42 summarises effective strategies, derived from the above risk propagation lops, for mitigating risks and enhancing community resilience.

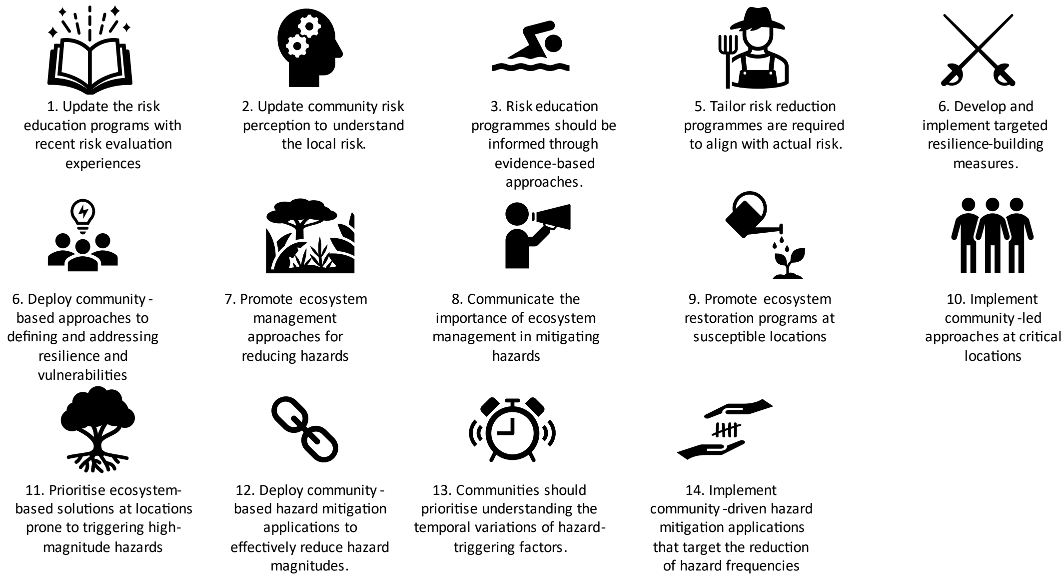

Figure 4-21: List of network-driven risk reduction strategies.

4.4 Summary

This chapter established a detailed risk assessment model that can be used to identify various risk reduction approaches aimed at transforming risk propagation to mitigate future risks. Fourteen risk assessment principles were identified and connected through a causal loop diagram, based on variable relationships. This diagram was then converted into a system dynamics model to estimate the effects of interventions in each loop. The model comprises three stocks (Impacted, Elements at Risk, and a combined unit of Safer Buildings and Lands), three flows (Hazard, Vulnerability, and Risk), and fourteen dynamic variables identified.

Sixteen strategies, focused on risk flow, were identified and validated with stakeholders. During this process, several loops were merged to account for their equal impact on the system. As a result, fourteen loops were selected for final impact evaluation. The subsequent chapter outlines the use of this risk assessment model for creating an urban risk simulator that can be used by decision makers to understand risk behaviour of an environment and explore the impact of various interventions on the overall risk status of an urban environment.

Chapter 5: Risk Propagation Calculation

5.1 Introduction

This research undertakes a comprehensive approach to creating a digital simulation environment based on the risk assessment model developed in the previous chapter. It employs the Design Science methodology, which systematically guides the construction of the artefact through a sequence of five stages. Initially, the problem is explicated, involving the identification and thorough review of the problem statement. Subsequently, requirements are defined, detailing the expected outcomes to address the explicated problem. Then, an artefact is designed and developed, aligning with both the explicated problem and the defined requirements. Following this, the artefact is demonstrated by applying it to a specific scenario, allowing for the exploration of its applicability. Lastly, the artefact is evaluated to assess its effectiveness in addressing the defined problems, measuring its success against the specified requirements, as illustrated in Figure 5-1 (Johannesson & Perjons, 2014).

This chapter mainly focuses on the development of an artefact to assess risk propagation within urban settings while taking human risk characteristics as an important element in the overall risk propagation model. The subsequent chapters will delve into the evaluation of this artefact, using real-world scenarios to illustrate its practical utility and effectiveness.

The following sections present the outcome of the stages of the Design Science methodology in developing the intended artefact.

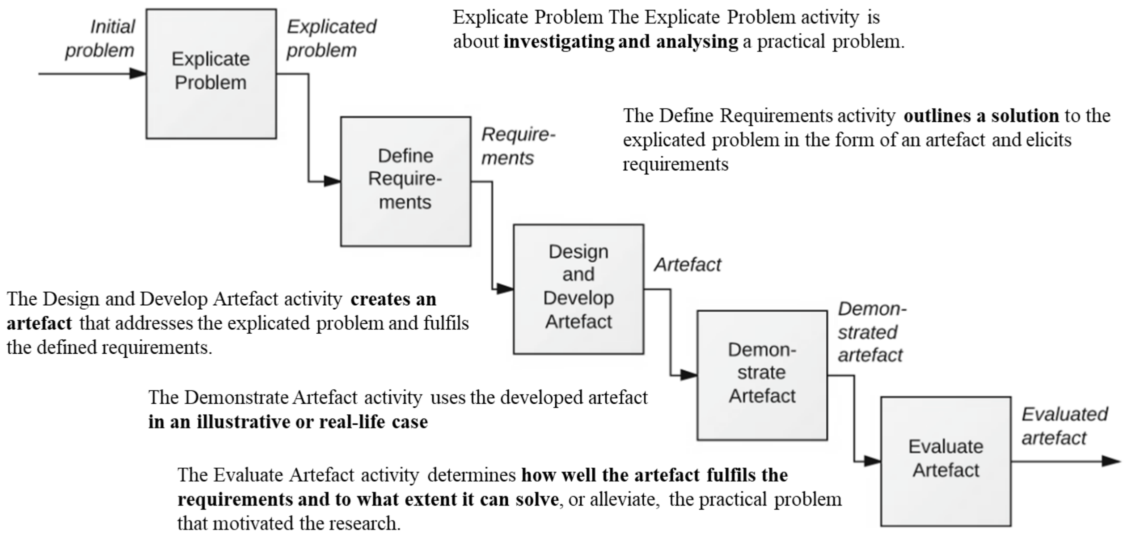

Figure 5-1: Design science methodology

5.2 Explicate the Problem and Define the Parameters.

Urban planners, city governors and disaster managers strive to create resilient urban environments. However, the modelling of urban resilience is inherently complex due to the intricate interactions that exist among various urban systems. These subsystems, ranging from infrastructure to social and environmental networks, interweave in ways that complicate the understanding and prediction of how changes in one aspect can ripple throughout the rest. This complexity is exacerbated further due to the need to consider various human risk characteristics, such as risk perception, risk understanding and risk appetite, which are crucial for building resilience.

Therefore, the main problem is developing a model that can effectively capture the intricate interconnections among urban subsystems, with a particular focus on human risk characteristics such as risk perception, risk understanding, and appetite. Such a model would enable the measurement of an urban environment's degree of resilience and provide insights into how existing vulnerabilities propagate through the urban system to adversely affect resilience over time. By doing so, it would become an invaluable tool for urban planners, city governors, and disaster managers, allowing them to understand the impacts of various interventions on overall urban resilience. This capability would address the current gap in tools available for these stakeholders, enabling them to conduct “What-if” scenarios and identify interventions that offer the most beneficial outcomes in building and sustaining urban resilience.

Numerous researchers have employed system thinking modelling, particularly for dynamic risk analysis in complex settings (N. Bugert & R. Lasch, 2018; Francesca Pianosi et al., 2016). Chapter Two of this thesis provided a comprehensive literature review of various modelling approaches for risk propagation within urban systems, ultimately identifying System Dynamics as the most effective method for addressing this challenge in intricate urban environments. System Dynamics excels in explicating the complex and dynamic relationships among diverse elements through the use of causal loop and stock-flow diagrams (A. Ghadge, Er, Ivanov, & Chaudhuri, 2021). The strength of stock-flow modelling lies in its ability to deconstruct complex problems into manageable components, thus simplifying the representation of intricate interconnections. Consequently, this research leveraged stock-flow diagrams to tackle the risk propagation problem, beginning with the development of an initial model to represent the problem space.

There are numerous climate-induced risks impacting urban environments, including floods, landslides, heatwaves, and coastal erosion. Modelling the risk propagation for all these hazards is indeed a monumental and complex task. Therefore, this research focuses specifically on the risk propagation associated with rain-induced landslides. Despite this specific focus, the approach developed in this study can be adapted and applied to model risk propagation across other climate-induced risks in urban environments. This adaptability makes the methodology valuable for a broader range of applications in understanding and mitigating various urban resilience challenges.

5.3 Defining the Requirements of a Model

In the Requirement Definition stage of the Design Science Methodology, the focus shifts from understanding the problem to specifying the conditions and criteria that the risk propagation simulator must meet to effectively address the complexities identified in the urban context. To accurately model risk propagation within urban systems, particularly incorporating human risk characteristics such as perception, understanding, and appetite, several key requirements must be delineated.

Firstly, the simulator must be capable of capturing the intricate interdependencies among various urban subsystems. This includes not only the physical infrastructure but also social, economic, and environmental networks. The ability to map these interconnections is crucial for understanding how risks propagate through the urban landscape, highlighting potential vulnerabilities that may arise from cascading effects across systems. Secondly, the simulator should integrate human risk characteristics seamlessly into its model. These characteristics include how individuals perceive risks, their level of understanding and education concerning risks, and their risk appetite or tolerance. Incorporating these elements is essential for accurately assessing the resilience of an urban environment, as human behaviour and decision-making significantly influence risk outcomes and resilience strategies. Next, the tool must provide a dynamic analysis capability. Risks are not static; they evolve over time influenced by various factors such as environmental changes, policy interventions, and socio-economic developments. Therefore, the simulator should allow for time-based simulation of risk propagation to reflect how risks and system resilience might change, thereby offering valuable insights into the temporal aspects of risk management.

Moreover, the simulator must offer an intuitive interface that can facilitate scenario analysis and decision-making for urban planners, city governors, and disaster managers. It should enable users to conduct “What-if” analyses, exploring the impact of different interventions or policy decisions on urban resilience. This capability would empower stakeholders to test various strategies and choose those that optimise resilience and minimise risk under different scenarios. Finally, the tool should facilitate comprehensive output visualisations that clearly communicate complex data and outcomes. These visual outputs are vital for stakeholders to understand the implications of risk propagation and resilience measures, enabling informed decision-making that considers both immediate impacts and long-term strategic goals for urban development and risk management.

5.4 Design and Develop Artefact

This section introduces the Design and Develop Artefact stage, where the focus is on transforming theoretical insights and specified requirements into a functional risk propagation simulation tool tailored for urban environments. The development of the artefact involved, developing a stock and flow diagram that capture intricate dependencies among various risk elements and the use of system dynamics tools to develop the simulation tool. The following sections present the overall approach used in designing and developing the artefact.

5.4.1 Design of Underlying Risk Propagation Model

In developing the underlying model for the risk propagation simulation, a comprehensive approach was adopted, as detailed in Chapter Four, which involved an extensive literature survey to identify and establish the interconnections among various risk characteristics. The resulting model was validated with the involvement of 12 experts, ensuring its robustness and relevance to urban contexts.

This model captures the complex inter-relationships among a diverse range of elements critical to understanding risk in urban environments. These elements include exposure, hazards, vulnerability, resilience, risk assessment, and human-related factors such as risk perception, risk understanding, risk education, risk appetite, risk matrix and risk communication. A particular emphasis was placed on the impact of human-related risks such as risk perception, understanding, education, and appetite which play a significant role in shaping the overall resilience of an urban environment. By incorporating these human dimensions, the model provides a holistic view of risk dynamics, recognising the importance of human behaviour and decision-making in resilience-building efforts. Furthermore, a detailed analysis of hazard component was conducted, which includes key influences such as resistance, triggering factors, susceptibility, magnitude, spatial probability, and temporal probability. This comprehensive modelling of hazards is crucial for accurately simulating risk propagation, taking into account how these factors interact to influence urban resilience.

The resulting model, illustrated in Figure 5-2, serves as the foundational model for developing the risk propagation simulator. This model not only reflects the complexity of urban risk environments but also sets the stage for creating a tool capable of providing valuable insights for enhancing urban resilience.

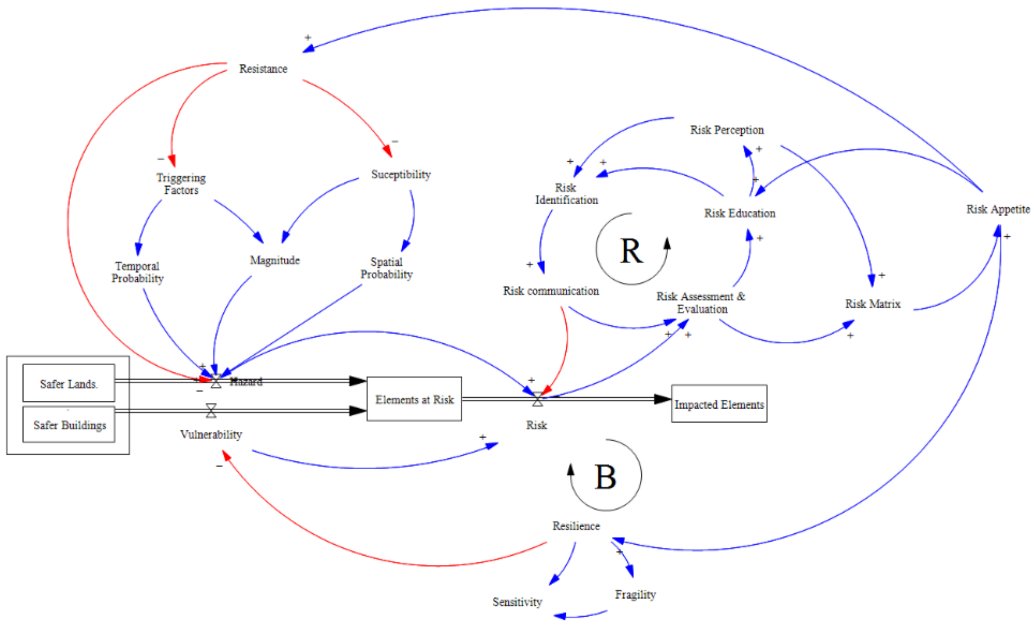

Figure 5-2: Risk assessment base model

5.4.2 Indicators for Evaluating System Performance

The risk propagation model, constructed using stock and flow diagrams, provides a comprehensive methodology for understanding the intricate relationships among various urban risk components. This systems-based approach is instrumental in analysing the performance of urban environments by focusing on four critical aspects: reliability, fragility, sensitivity, and resilience. These aspects are interrelated and essential for evaluating how urban systems respond to risks, adapt to changes, and recover from adverse events.

In this context, reliability refers to the consistency with which urban systems can function under risk conditions and maintain essential services. A reliable urban system is one that not only withstands individual risk events but does so repeatedly across different scenarios, maintaining its performance despite the presence of risks. This includes ensuring that infrastructure and services remain operational during hazard events, supported by robust planning that anticipates both the probability and impact of potential risks. Reliability focuses on sustaining urban functionality through predictable, stable responses to external threats, thereby building trust within the community and ensuring sustained resilience over the long term.

Fragility refers to the inherent weaknesses within an urban system that can lead to increased vulnerability when exposed to hazards. By applying the risk propagation model, stakeholders can identify specific components or subsystems within the urban environment that are particularly fragile. For instance, if a population's risk perception is low due to inadequate risk education, this can be considered a point of fragility. Individuals may not take necessary precautions, increasing vulnerability to hazards like landslides. Hazard characteristics such as low resistance and high susceptibility further contribute to fragility. The model helps identify these fragile points, enabling interventions that enhance risk education and strengthen infrastructure resistance to reduce overall vulnerability.

Sensitivity is another critical aspect, reflecting how susceptible urban systems are to changes in risk factors. The model allows for the simulation of various "What-if" scenarios to observe how different elements react to changes, thereby providing insights into which areas are overly sensitive and may require mitigation measures to prevent destabilisation or degradation. This sensitivity analysis is crucial for adapting urban systems in a way that reduces their susceptibility to external shocks while maintaining essential services and functions. For example, a community with a low-risk appetite might underinvest in protective measures, making it sensitive to triggering factors that could escalate minor hazards into major events. By simulating changes in spatial and temporal probabilities of hazards, the model enables urban planners to identify which components are overly sensitive to fluctuations and require stabilising measures.

Resilience is the ability of an urban system to not only withstand shocks and stresses but also to adapt and recover in a timely and efficient manner. The risk propagation model leverages the concept of resilience by revealing how interconnected components can support or hinder recovery processes. This includes assessing the role of human factors, such as risk perception and community preparedness, in facilitating resilience. By simulating how various resilience strategies could be implemented, urban planners and decision-makers can develop more robust plans that ensure quicker recovery times and stronger adaptive capacities. For instance, by evaluating potential interventions that enhance community awareness and readiness, planners can improve the temporal and spatial response strategies, ensuring a quicker recovery from events triggered by natural hazards. Additionally, strengthening the community's role in risk identification and reduction can enhance resilience by enabling adaptive strategies that align with the population's risk appetite.

Together, these concepts form a comprehensive model for assessing urban performance against risks, empowering stakeholders to develop strategies that address systemic weaknesses, adapt to evolving conditions, and maintain the continuous operation of critical infrastructure under diverse circumstances. This model enables stakeholders to pinpoint areas where targeted interventions can mitigate fragility, regulate sensitivity, and bolster resilience, ultimately contributing to a more robust and adaptive urban system equipped to confront future challenges effectively.

Figure 5-3 shows the role of fragility, sensitivity, and resilience measurements within the context of system performance. Here, the fragility shows the drop in performance when exposed to risks. Sensitivity refers to the rapid changes in system performance in response to risk factors. A highly sensitive system would show sharp inclines or declines in performance when conditions change, reflecting a quick response to external risks. Resilience refers to the loss of performance by calculating the area under the system performance (SP) curve for a given period.

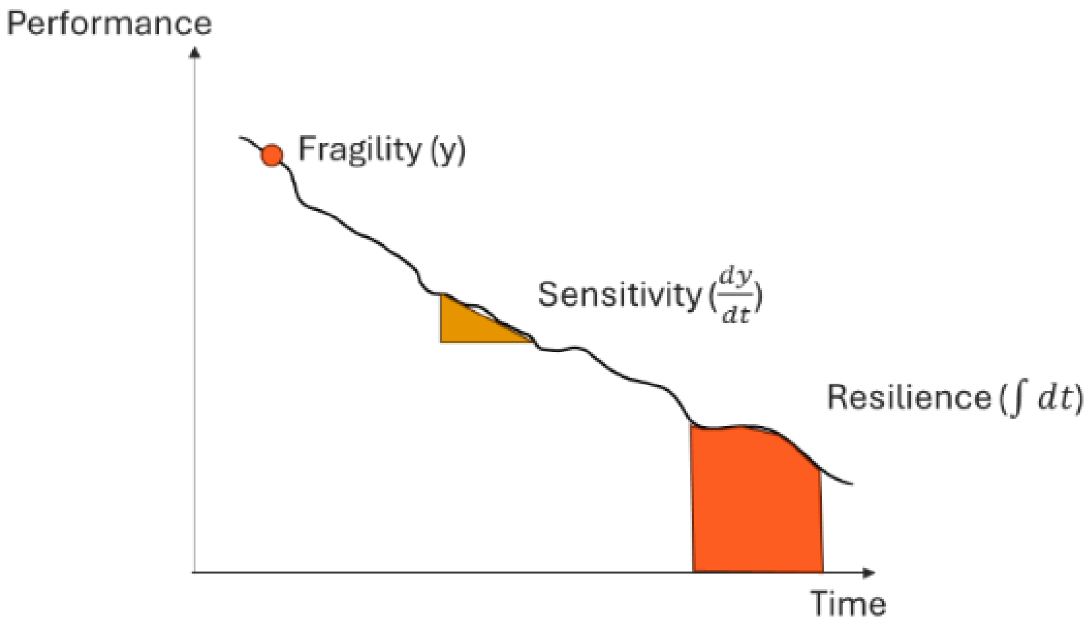

Figure 5-3: Fragility, Sensitivity, and Resilience

5.4.3 Methods for Assessing the System Performance

The system's performance variability must be addressed after the dynamic model is established to ensure the desired outputs are achieved. Various simulation techniques have been used by scholars such as Monte Carlo Simulation, Discrete-Event Simulation, Input-Output modelling, and Interpretive Structure modelling (ISM) to understand the reliability of the overall urban systems against risks (N. Bugert and R. Lasch (2018). However, Monte Carlo simulation stands out as the most effective approach for modelling risk propagation and assessing the reliability and resilience of urban systems due to its capacity to handle uncertainty and variability in input parameters(Y. Liu, Zhou, Su, Xun, & Tang, 2021). Unlike other simulation techniques, Monte Carlo generates a wide range of potential outcomes by repeatedly sampling from probability distributions, providing a robust probabilistic assessment of system performance across various scenarios. This method is particularly valuable in urban contexts, where numerous interconnected factors, such as risk perception and community resilience, significantly influence outcomes (Rao et al., 2021,). Furthermore, Monte Carlo simulation facilitates "What-if" analyses, allowing stakeholders to evaluate the potential impacts of different risk management strategies on system reliability, making it an essential tool for informed decision-making in urban resilience planning (Ben-Akiva et al., 2020). Furthermore, there are several examples where researchers have integrated system dynamics and Monte Carlo simulation successfully for their complex system analyses (Gertsbakh & Shpungin, 2020). Therefore, the Monte Carlo simulation was used to assess the risk propagation simulation in this research study.

Monte Carlo simulation works by generating a large number of random samples of input variables to simulate the behaviour of the risk propagation model under various scenarios (N. Bugert & R. Lasch, 2018). This method incorporates probability distributions for uncertain parameters such as risk perception, hazard intensity, and vulnerability metrics. It helps to Identify and define the critical input variables influencing the urban system's performance. For example, parameters such as the likelihood of hazard occurrence (e.g., landslide triggers), the effectiveness of risk communication strategies, and the community's risk appetite can be modelled with associated probability distributions. By running thousands (or millions) of iterations, each with different random values drawn from the defined distributions, the Monte Carlo simulation generates a distribution of outcomes for the urban system's performance (N. Bugert & R. Lasch, 2018). This simulation effectively captures the range of potential impacts that uncertainties can introduce into the risk propagation model. Consequently, it helps prioritise disaster risk reduction strategies within the system. Therefore, Monte Carlo simulation aids in understanding the most effective measures to implement in the urban context. Specifically, it will be utilised to evaluate the identified risk mitigation strategies proposed in Chapter 4 by calculating the potential impacts of each strategy on system performance, enabling stakeholders to make informed decisions regarding resource allocation and intervention planning.

The Central Limit Theorem (CLT) plays a crucial role in Monte Carlo simulations, particularly in the context of assessing the reliability of complex systems like urban environments. It provides a foundation for understanding the behaviour of the sum (or average) of a large number of random variables, making it essential for interpreting the results obtained from Monte Carlo methods. By applying the CLT, outcomes from the Monte Carlo simulation become normally distributed even if the original input variables are not, as long as the sample size is sufficiently large. This allows for the use of standard statistical tools to analyse the resulting distributions, making it easier to estimate confidence intervals and derive conclusions about system performance based on aggregated data. Therefore, the Central

Limit Theorem was used in modelling the probabilistic nature of the risk elements in the risk propagation model in this research.

5.4.4 Construct the Artefact

This section will describe the implementation of the system dynamics approach in modelling the risk propagation model outlined in Section 5.4.1. It will focus on how this approach captures the complex interdependencies and feedback loops within the urban risk environment, illustrating the interactions among various risk elements. Specifically, the discussion will cover the underlying mathematical principles used to represent risk factors such as risk perception, risk understanding, and risk appetite as nodes within the model, along with their inter-relationships expressed through differential equations and feedback loops. Furthermore, it will discuss the normalisation of stock/flow values and weighting functions to ensure an accurate representation of the contributions of different risk elements. The section will explain how the Central Limit Theorem is applied to define the probability distributions for these risk elements, allowing for a better representation of the inherent variability and uncertainties in the system. Overall, this exploration will highlight how the integration of system dynamics and probabilistic modelling enhances the understanding of risk propagation and its implications for urban resilience.

5.4.5 Method for Calculating Weighting Functions

Establishing a node-adjacent matrix (A_{ij}) is crucial for effectively representing the weighting functions within stock and flow diagrams in a system dynamics model. This matrix provides a systematic means to understand the connections between different stocks and flows, thereby illuminating how various elements influence each other within the model. By delineating these interconnections, the node-adjacent matrix lays the groundwork for further analysis, as it identifies which stocks and flows are directly related and helps in understanding the structural relationships inherent in the risk propagation model.

Once the node-adjacent matrix is completed, the next step involves constructing the weighted-adjacent matrix (W_{ij}) and the time matrix (T_{ij}) associated with each connection. The weighted-adjacent matrix conveys the significance of each connection by assigning weights that reflect the relative importance of the interactions among stocks and flows. This allows for a nuanced understanding of how changes in one element might affect others, facilitating better decision-making regarding system dynamics. To determine these network weights effectively, the Analytical Hierarchical Process (AHP) technique is employed (T. Wang, Yang, Wu, Gao, & Wei, 2020; W. Xu et al., 2020).

In the AHP process, experts and stakeholders evaluate the importance of each stock and flow in relation to others, assigning higher weights to the most critical elements. This hierarchical ranking enables a clear prioritisation of stocks and flows, ensuring that the model appropriately emphasises critical connections. Conversely, less important stocks and flows receive lower weights, which helps simplify the model and focus attention on the key drivers of risk propagation. Overall, this systematic approach to establishing the node-adjacent and weighted-adjacency matrices enhances the robustness of the stock and flow diagrams, providing a comprehensive basis for analysing the dynamics of risk in urban systems.

5.4.6 Method of Calculating Node Values and Normalisation.

Each stock/flow has a different unit of measurement; for example, education attainment is classified according to various levels, while income can be ranked based on income levels.

To facilitate a coherent analysis across these diverse variables, several researchers have used an index-based calculation method for multi-variant analysis (Sauti, Daud, & Kaamin, 2020). Through this approach,, each sector is assigned a generalised index value that is compared against its sector-level information. Consequently, it becomes necessary for this research to adopt a method for synthesising and generalising this information effectively. The following paragraphs present the method adopted to achieve this data generalisation within the model.

To standardise the data, several steps for data generalisation must be followed. Initially, the type of data type in question must be determined. Two main data types can be used for the calculation: scale-type and nominal data. Scale data represent values that change along a continuum, while nominal data categorise information into district groups, such as gender.

However, nominal data must be quantified for analytical purposes, necessitating the use of dummy variables to convert the nominal data sets into scale-based information. For example, risk levels can be categorised as low, medium, and high, and dummy variables can be assigned values of 1, 2, and 3, respectively, with the highest score indicating the highest risk level.

It is essential to acknowledge that this assignment may involve a degree of subjectivity based on the objectives of the study. illustrates the stock/flow value calculation process and highlights the selection methodology based on data types.

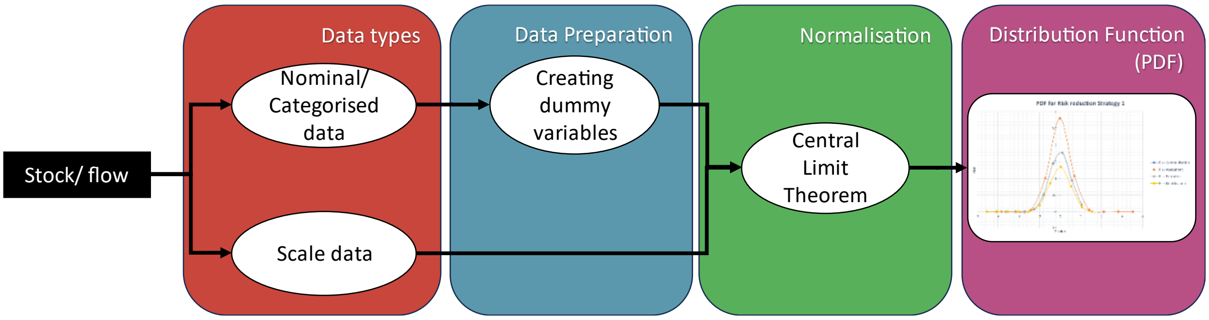

Figure 5-4: Node value calculation process

Once the stock/flow data is collected, it must be converted into a probability distribution curve. However, different data sets exhibit various distribution patterns, which can complicate the specification of algorithms for calculating correlations amid significant variations. As a result, a generalisation method is required to establish these relationships, and the Central Limit Theorem (CLT) serves this purpose effectively. Previous work by Horbacz (2016) has mathematically proved that the Central Limit Theorem (CLT) can be applied within system dynamics approaches to simulate outputs successfully. In this context, the input data represents the z value of its distribution curve.

The CLT is instrumental in generalising the data into the Gaussian distribution, regardless of the original distribution curves. Each parameter requires sufficient input data for accurate calculations, typically needing more than 30 samples to yield a smooth distribution curve. For instance, modelling daily temperature as a flow variable would require data spanning over 30 days to create a reliable distribution. During this process, both the sample mean (μ) and the standard deviation (σ) are computed using the sample datasets, enabling the development of a Gaussian distribution curve that underpins the risk propagation model.

The next step involves understanding the reliable condition of the stock/flow and flow variables within the model. Each flow often has a designated operating range or optimum level recommended at the design stage. For example, some electronic temperature sensors have an optimum temperature range of 25-100 C. Deviating from this range, either below or above this range can lead to deviations in the optimum output. Similarly, each stock/flow in the system has defined optimum values that determine their reliable condition.

When stock or flow values fall outside these optimal ranges, the effects can propagate to other components, potentially compromising overall system performance.

These optimum values can also be represented using a Gaussian distribution curve by calculating the z-value for the relevant data points. The following points show the steps involved in calculating the stock/flow values:

A. Capture the cleaned data set to ensure accuracy in analysis.
B. Identify the required number of samples (N) required for reliable calculation.
C. Calculate the sample mean (μ) and standard deviation (σ) to establish the central tendency and variability of the data. (The following equation shows the sample's standard deviation calculation.)

$$\sigma = \frac{\mu}{\sqrt{N}}$$

D. Generate the Gaussian distribution curve based on the statistical calculations.
E. Identify the optimum range by determining the upper and lower bounds that define acceptable performance levels.
F. Reference the standard normal distribution tables to ascertain the probabilities associated with values falling within this optimal range.

By following these steps, it is possible to quantify how system performance may vary in response to deviations from the established threshold values. This quantification not only aids in monitoring performance but also highlights areas that may require intervention to maintain reliability and resilience in the face of changing conditions.

The use of the above steps can be shown through a hypothetical example to identify the optimum range for a system's overall performance as described below, using temperature as the key variable. This hypothetical case study outlines the calculation procedure for determining the performance of a node within the system. In this example, temperature data has been recorded for 100 days and organised into a tabular format. From this dataset, random samples can be taken to create sample groups. For each sample group, the mean temperature value can be calculated, and distribution graphs can be subsequently developed based on these mean values.

In this example, Let's assume the system to operate at a high performance level when the temperature ranges between 35 to 45 degrees Celsius. To analyse the data further, the z-value for each temperature can be computed, which involve converting the temperature values and referencing the z-table for standardisation. The resulting calculation indicates that the node's current performance value is 48%. This performance value represents the average system efficiency related to temperature within the defined range. Consequently, if the actual temperature falls outside the optimal range of 35 to 45 degrees, the system's performance level is expected to decrease.

5.4.7 Method for Calculating the Risk Propagation

The reliability of a system can be represented as the stock/flow value, where the highest stock flow value indicates the most reliable state and the lowest value represents the less reliable state. The overall network reliability is calculated using the formulas discussed in earlier sections, which can be illustrated through an example.

Consider a stock representing a given sector, with its maximum reliability depicted by the outer boundaries, and its current status represented by the inner circle. (See Figure 5-5). The required threshold limits can be established by referring to the relevant parameters or standards.

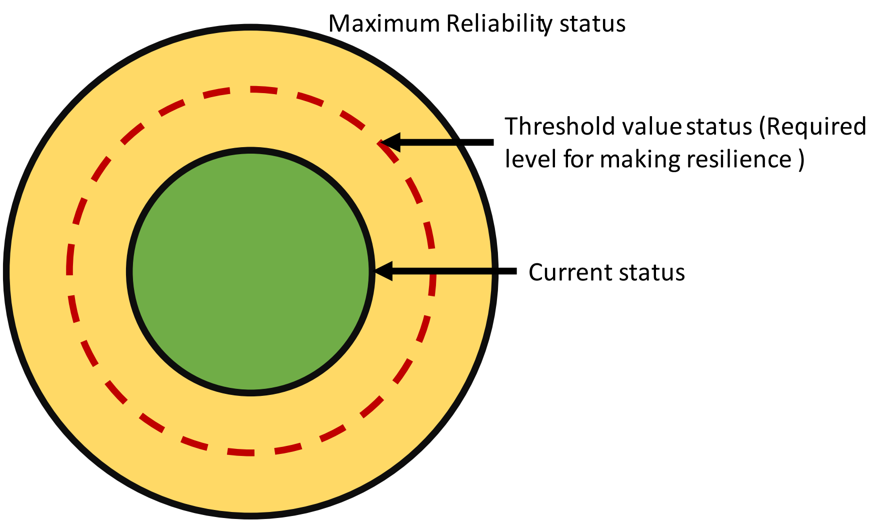

Figure 5-5: Status of the node

In this context, the system can operate under two conditions: one where it lacks sufficient capacity to withstand or engage with impacts, and another where it possesses enough capacity to manage these impacts effectively. The first condition leads to risk propagation while the second condition prevents it. Therefore, understanding the overall probability of the stock requires consideration of both states.

The threshold state of the node is critical in this analysis, and the 'Binomial Probability' can be employed to calculate the node's probability values in a defined set of attempts.

The formula for binomial probability is as follows:

Binomial probability $= \binom{n}{k} x^k a^{n-k}$;

Where,

n is the total number of attempts. It represents the probability of all choices in the settlement or the total population (=100%);

k signifies the chosen quantity of choices or the number of base populations for the assessment.

Using this approach, the system's performance level can be calculated through the reliability formula and plotted on a graph. Figure 5-6 illustrates how the system's performance level changes over time, highlighting the threshold value that signifies the minimum operational level required to deliver services effectively. Thus, if the performance level is above the threshold limit, the system is considered to be operational, while a performance level below the threshold indicates a malfunctioning state.

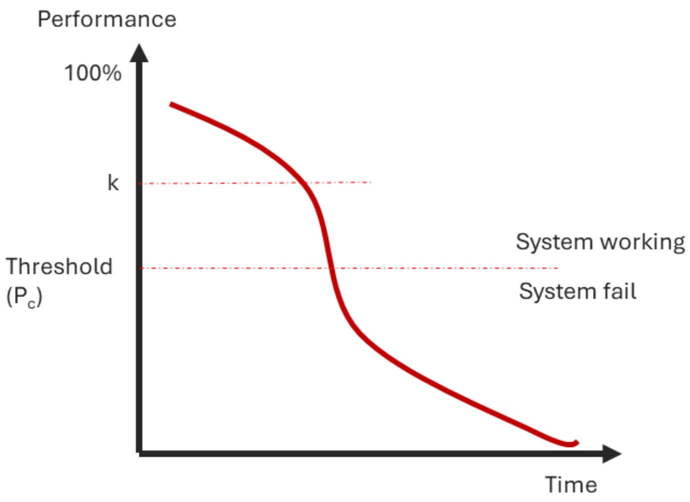

Figure 5-6: Performance value changes over time in a disrupted system

On this graph, the reliability level is plotted on the vertical axis, while the curve represents the reliability state varying over time. Initially, the system operates at full performance, however, following a disruption, the performance level gradually decreases with time. The system functions optimally up to the threshold (Pc); once performance drops below this threshold, the system can no longer provide the necessary services. Therefore, if the performance level is above the threshold limit, the system is considered to be operational, while a performance level below the threshold indicates a malfunctioning state.

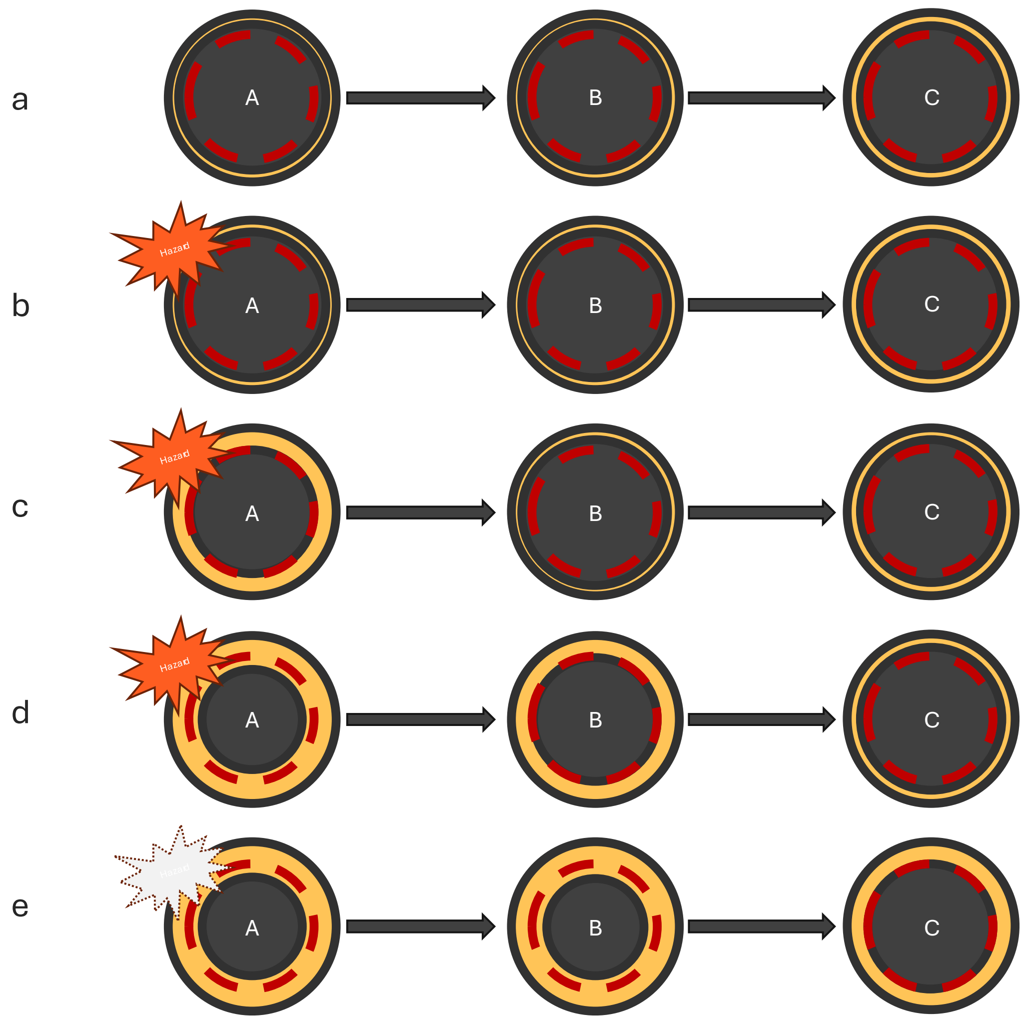

Figure 5-7: Example of risk propagation

However, if one service falls below its threshold level, it can adversely affect connected services, triggering a chain reaction of failures. For example, consider stocks and flows labelled A, B, and C as interconnected. Initially, all three operate normally (Figure 55-a). When a hazardous event impacts stock/flow A, it begins to degrade in performance (Figure 55-b). The risk propagation does not occur until stock/flow A's performance drops below the designated threshold (Figure 55-c). Once this threshold is crossed, stock/flow A's diminished performance subsequently affects stock/flow B (Figure 55-d). The risk propagation will continue as long as any stock or flow remains below the threshold level (Figure 55-e).

To illustrate this risk propagation approach, suppose stocks A, B, and C represent the economic, health, and education sectors, respectively.

Accordingly, the reliability of sector A ($R_{t(A)}$) could be written as (derived from D. Li et al. (2015).);

$$R_{t(A)} = \sum \binom{n}{k} \{ {P_{sector}}^{k} \times (1 - P_{sector})^{(n-k)} \}$$

Here, 'n' represents the maximum performance level, 'k' represents the number of selected items/ individuals for evaluation, and P_{sector} represents the reliability value of the sector. Examples of sectors can be education, economy, health etc. Considering the above example, the sector vice reliabilities could be generated as follows:

$$R_{t(Economy)} = \sum \binom{n}{k1} \{ {P_{Economy}}^{k1} \times (1 - P_{Economy})^{n-(k1)} \}$$

$$R_{t(Health)} = \sum \binom{n}{k2} \{ {P_{Health}}^{k2} \times (1 - P_{Health})^{n-(k2)} \}$$

$$R_{t(Education)} = \sum \binom{n}{k3} \{ {P_{Education}}^{k3} \times (1 - P_{Education})^{n-(k3)} \}$$

In this context, k1, k2, and k3 change according to the damage levels. The propagation can begin if any sector's damage exceeds the threshold limit.

The overall risk propagation arising from failures in sector reliability can be quantified using a universal probability formula:

$$\frac{dx_i}{dt} = W\big(x_i(t)\big) + \sum_{j=1}^{N} [A_{ij}.\, Q\left(x_i(t), x_j(t)\right)]$$

In this equation, $W(x_i)$ accounts for the evolution of x_i in the absence of network interactions, while $Q(x_i, x_j)$ describes the pairwise interactions among connected nodes. A_{ij} matrix illustrates the adjacency of the network.

$$\frac{dx_i}{dt} = [ideal\ state] + \sum_{j=1}^{N} [\{(1 - \mathrm{Rt}(\mathrm{Economic}))\mathrm{x}\,(1 - \mathrm{Rt}(\mathrm{Education}))\} + \{(1 - \mathrm{Rt}(\mathrm{Education}))\mathrm{x}\ (1 - \mathrm{Rt}(\mathrm{Health}))\}]$$

When the system comprises multiple pathways, the risk propagation probabilities across all pathways must be aggregated. These pathways can be identified through a detailed network diagram. Consequently, risk propagation can be evaluated at the stock/flow level, through specific pathways, or across the network as a whole.

5.4.8 Implementation Examples of Modelling Risk Propagation

The risk propagation model developed in Chapter 3 was implemented using the mathematical approach detailed in the previous sections of this chapter. The model proposed in this research consists of 14 risk propagation loops. To illustrate the modelling process of these loops, this section uses the loop - Risk -> Risk Assessment -> Risk Education -> Risk Identification -> Risk Communication -> Risk - as an example. The same methodology was applied to model other risk elements and their respective propagation loops. Figure 5-8 outlines the overall methodology adopted for modelling risks. The risk modelling activities utilised household data collected by the National Building Research Organisation, which is responsible for landslide management. The following paragraph explains the methodology used.

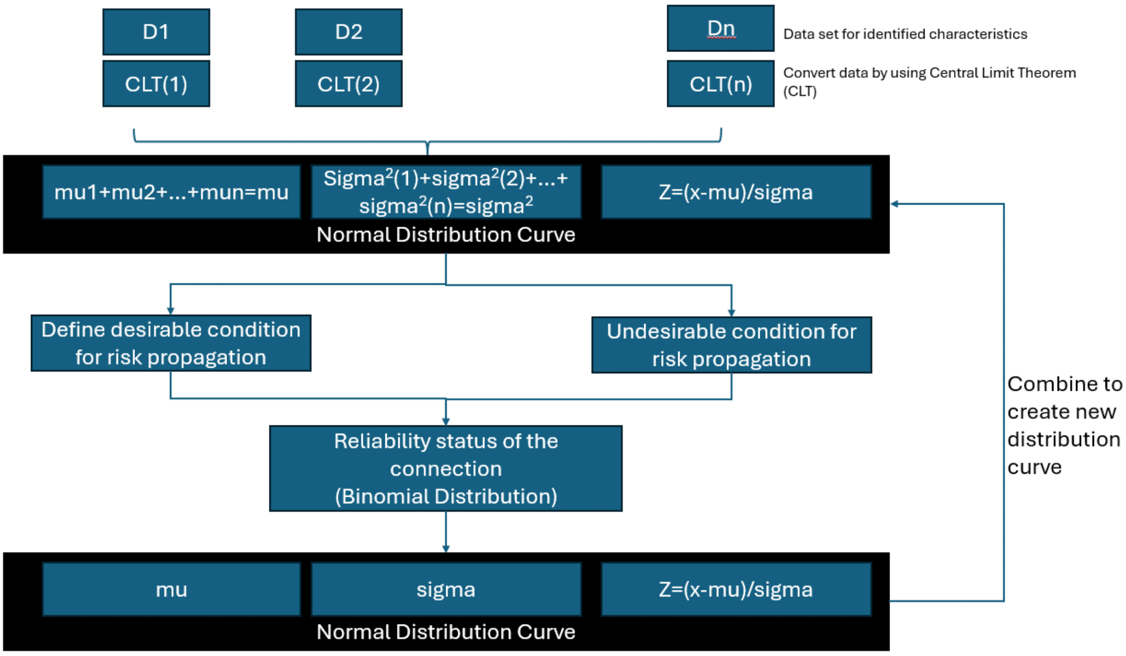

Figure 5-8: Calculation methodology

The modelling begins with utilising data sets collected from high landslide probability zones. Initially, variables relevant to the risk characteristics are selected (D1, D2,..., Dn), and their distribution histograms are identified. Each variable typically exhibits a unique distribution pattern. Therefore, it is essential to transform these distributions into a normal distribution curve to standardise the analysis. The Central Limit Theorem (CLT) is applied for this purpose as explained in previous sections, enabling the conversion of various distributions into a normal distribution (CLT1, CLT2,..., CLTn). Therefore, all normal distribution curves are combined into a normal distribution curve. Accordingly, all the mean values (mu), and sqrt Sigma values are required to calculate ($mu_1+mu_2+...+mu_n=mu$; $Sigma^2 1+ Sigma^2 2+ ...+Sigma^2 n= Sigma^2$). Once standardised, the normal distribution curve can be used to determine the desirable conditions for risk propagation (Figure 5-9). Here, the desirable conditions support the risk propagation, and the undesirable conditions do not initiate propagation. However, this can be a subjective decision connected with risk assessment characteristics. Understanding these conditions is crucial for assessing the reliability of the connections that facilitate risk propagation.

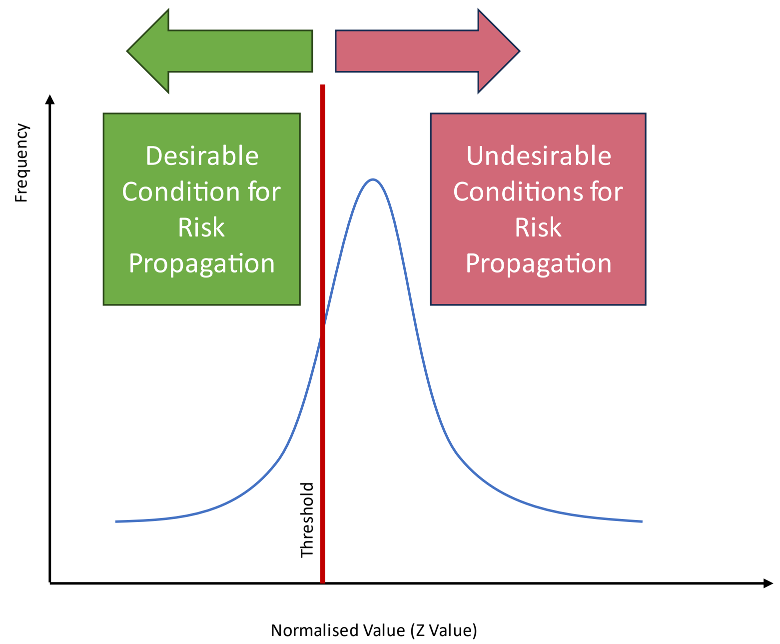

Figure 5-9: Disiarable and not-desirable conditions for the variable

The reliability of these connections is characterised by a binomial distribution, which is also transformed into a normal distribution for uniformity in analysis. From the binomial distribution curve, key statistical measures such as the mean, standard deviation, and z-score values are extracted. These metrics are then used to generate a new normal distribution curve, effectively complementing the original distribution data. By employing these statistical techniques, the model ensures that risk propagation is accurately assessed and represented, allowing for a comprehensive understanding of how risks transition between interconnected elements within the urban landscape.

5.4.9 Application of Monte-Carlo Simulation for selecting of the best strategies

The Monte Carlo Simulation (MCS) is a valuable technique for generating random numbers within a dataset, facilitating the simulation process to determine the most likely state of risk propagation. In a social system, variables interact in complex ways, often involving multiple quantities simultaneously. Consequently, it is challenging to isolate and observe the change in a single variable, making controlled experiments impractical. The MCS method addresses this by generating a wide range of input variations, enabling the measurement of corresponding output fluctuations.

Several steps were taken to implement MCS within the model, such as identifying the changing parameters, probability of change by each, and type of analysis to get results. First, the levels at which parameters would vary were established. In the proposed system dynamics approach, 14 risk assessment characteristics were identified, of which 12 were selected as input parameters. Triggering factors and susceptibility were excluded, as their influencing elements were already accounted for, and changes in these factors reflect alterations in associated attributes. For example, susceptibility mapping typically refers to the identification of the spatial probability and magnitude of hazards.

Two additional input parameters were introduced for simulation purposes: the injection of shocks into the system and the quantification of stakeholder involvement in strategy implementation (represented by the k value in the propagation equation). The shock parameter acts as a pulse, allowing the system's level of resilience to be estimated, and it also enables the generation of various future scenarios. The second parameter focuses on community engagement with the strategies, specifically the degree of participation within the implementing community. As a result, 14 input parameters were incorporated into MCS.

An assumption was made regarding the probability of change for each parameter, with a 5% variation expected at each time interval. However, users can opt for different variation levels. Increasing the variation broadens the range of output from the simulation, leading to more generalised results. In this context, a 5% variation means that the system randomly generates values in the range of ±5%. Increasing this percentage would produce a wider range of randomly generated numbers.

The proposed system automatically records all variations, allowing users to run multiple simulations as part of the MCS process. Appropriate statistical methods can then be applied to analyze the output. In this case, Pearson correlation was used to assess relationships, as all input data had been normalized into distributions. The correlation analysis helps to identify the strength and direction of the interventions. Consequently, users can pinpoint the most influential risk characteristics within the system and determine the highest risk propagation pathway by understanding the combined effects of other factors along the path and system outputs: safer lands, community, exposure, and impacts.

5.5 Risk Propagation Simulator Development

This section discusses the design brief of the application building through a system dynamic software. The previous chapters identified the general algorithms for risk propagation modelling. As a result, general formulas were developed using various algorithms and tested with several system dynamic applications. The 'Any logic' application was selected to create the model for testing purposes. Therefore, the section discusses the codes and related logic in decision-making and the model-building approach through the following subtopics:

1. Anylogic Application and its' capabilities to model the system dynamic concept
2. Model application developments
3. Setting up values, assigning parameters, and interface development

5.5.1 AnyLogic Application and its Capability to System Dynamic Modelling

The Anylogic application was developed by considering three models: System Dynamics, Process-Centric Modelling (Discrete-event modelling), and Agent-Based Modelling (Mahdavi, 2019). Accordingly, the system integrates all these modelling features to develop models on the same platform. Therefore, the Analogic software is considered a "Multi-method or hybrid simulation/modelling", and it is considered the only model that integrates such capacities (Mahdavi, 2019, p. 9).

5.5.2 Model Application Development

Chapter three discussed the risk characteristics, and accordingly, the theoretical stock-flow model was developed. The stock can store the data, and flow can transfer the stored data based on specific conditions. Consequently, the theoretically developed stock-flow model included four stocks (Environment, Exposure, Community, and Risk), and fourteen dynamic variables represent the risk characteristics (Figure 5-10).

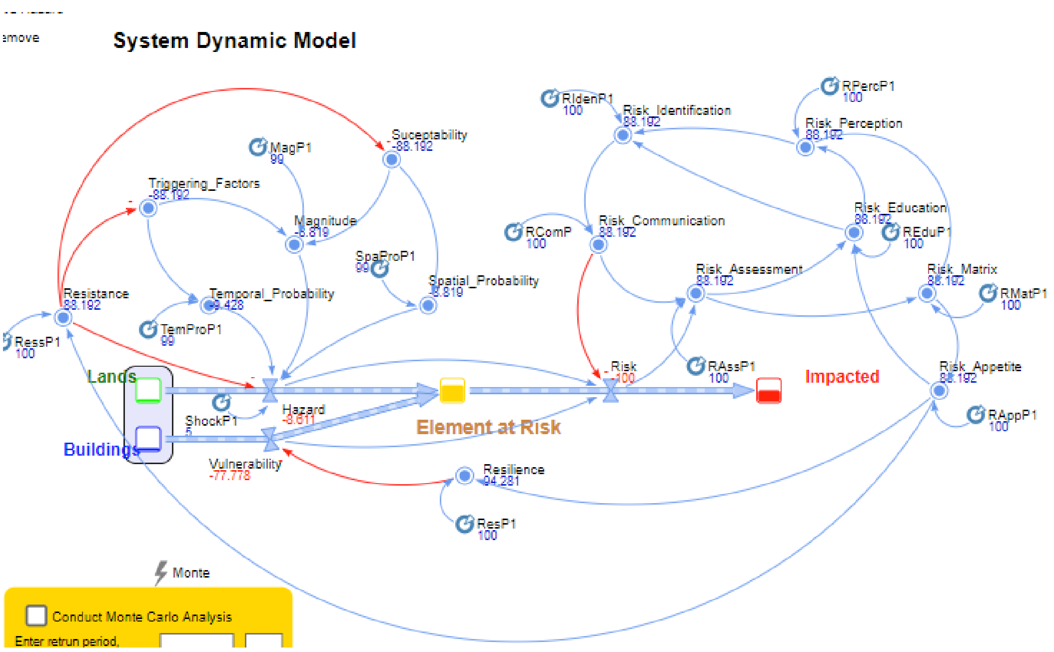

Figure 5-10: Stock-flow model in the Any Logic Software

The table below discusses the meaning of each stock-flow model feature.

Table 8: Definitions of Stocks

Feature	**Description**
Combined Stock - Land (Built-Up)	The 'Combined Stock-Land ' indicates the landscape including agricultural areas and brownfield development. All developable and developed lands are discussed in the stock.
Combined Stock- Building (Built-Up)	The 'Combined Stock- Buildings' indicates the built environment developed or modified through human intervention, such as buildings, infrastructure networks, utilities, and processes, as well as the people living in the chosen built environment.
Hazard Flow	The 'Hazard Flow' indicates the environmental features threatened by the hazardous events. Accordingly, a part of the land is impacted by a hazardous event. The higher flow means a larger area is going to be impacted, and vice versa.

Vulnerability Flow	The ‘Vulnerability Flow’ indicates the poor intrinsic properties in the community stock to cope with identified hazards. Accordingly, the higher flow represents the higher number of poor intrinsic properties associated with the community.
Element at risk Stock	Here the term element at risk refers to the potential for impact on the landscape and the built environment. The ‘Element at risk Stock’ includes the intersected area of both hazard, and vulnerability flows.
Risk Flow	The ‘Risk Flow’ discusses the ability of converting elements at risk to impact. Accordingly, high-risk flow (positive flows) discusses higher impacts and vice versa.
Impact Stock	The ‘Impact Stock’ represents the damaged elements in the system.
Dynamic Variables	The fourteen number of dynamic variables were identified through the literature, and those were connected with each flow. These dynamic variables influence the changing of the flow values in the network.

The research focuses on natural hazards, which originate in the landscape and transfer their impacts to human settlements. The vulnerability of an element, combined with the probability of a hazard occurring, defines the 'elements at risk.' Depending on the effectiveness of risk management, an element affected by a hazard can escalate into a disaster. Consequently, the identified stocks include a combined stock (Land and Buildings), Elements at Risk, and Impacted. Flows represent the rate of change in these stocks and serve as the mechanisms driving changes within the system. For instance, an increase in the hazard rate can transform previously safe areas into hazardous ones, while an increase in the rate of 'Elements at Risk' leads to greater damage.

5.5.3 Setting up Values, Assigning Parameters, and Interface Development.

The research must identify a constant unit that applies across the entire system, referred to as the unit of analysis. In this study, the focus is on human-centred risk and its propagation. Therefore, the building and surrounding space are defined as the unit of analysis in the model as discussed in Chapter four, which can be abstracted as follows:

A unit of Analysis: A tract of land including physical elements like buildings, infrastructure, agricultural lands, and other natural features. E.g., Land parcel.

Figure 5-11: Unit of Analysis

The size of unit space may vary and can be identified as personal space. This personal space can encompass physical elements such as buildings, infrastructure, and agricultural land, as well as social elements like public open spaces, urban parks, and religious sites. Consequently, a hazard event may affect either the elements within this personal space and/or the individual occupying it.

The model was initially developed in a hypothetical environment with default values assigned to each stock. A total of 100,000 units were allocated per stock. During the simulation, these stock values fluctuate based on the flow values determined by the system dynamics model.

5.5.4 Anylogic Application

The Anylogic application integrates multiple methods, bridging macro and micro scale analyses. Specifically, System Dynamics, Agent-Based Modelling, and Discrete-Event Simulation are combined within a single platform, allowing users to select either one modelling method or a combination of several. System Dynamics can be applied to strategic-level modelling, while Discrete-Event Simulation and Agent-Based Modelling are more suitable for technical-level modelling. Additionally, Agent-Based Modelling is ideal for process-level simulations that require detailed interactions and user roles (Grigoryev, 2024).

This research focuses on the System Dynamics modelling approach for assessing urban risk propagation. Accordingly, the literature-based model can be developed using the Anylogic application. The following section discusses the user interface development within the Anylogic application.

5.5.5 User Interface Design

The Anylogic application offers a user-friendly interface for model development and allows for cloud-based publishing, enabling users to access the model via a shared link. Consequently, an Anylogic academic account was created to begin building the application.

Initially, the model's interface elements were determined to represent its input and output parameters. However, the model underwent several iterations to reach its current form. The following elements were considered in developing the interface:

1. Model input parameters
2. Visualisation of the stock-flow model
3. Visualisation of the risk reduction pathways
4. Model outputs

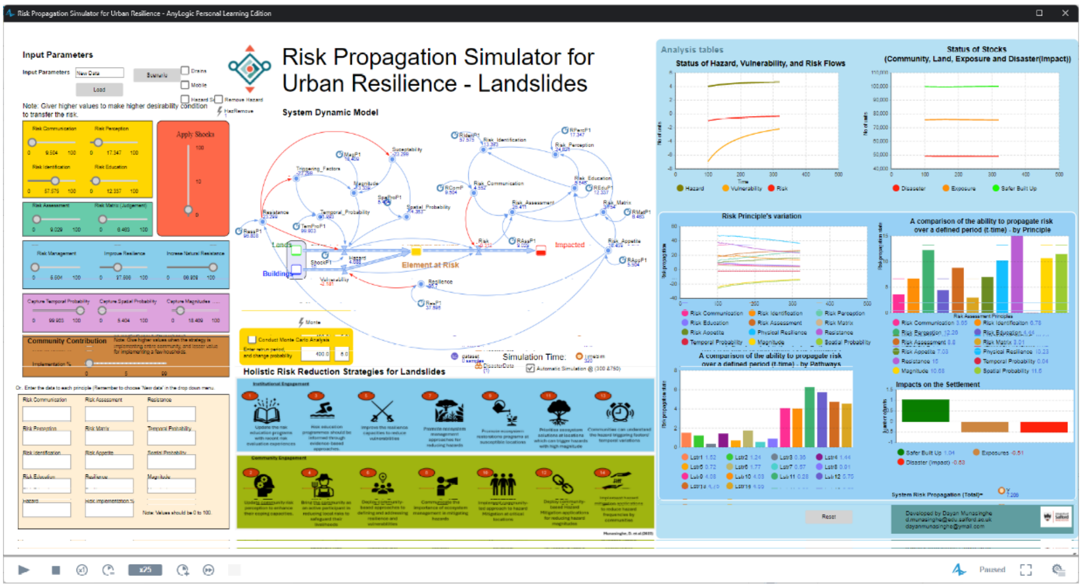

Figure 5-12: Program User Interface

Figure 5-12 shows the system user interface of the designed program. The following section explains various elements in the above interface.

5.5.6 User Interface for the Model Input Parameters

The left-hand corner colour boxes (input parameters) represent the input values of the model. Each parameter has a slider, which can increase or decrease the risk characteristic's value depending on the requirement. The input parameters were classified into seven categories for better understanding.

1. Orange box: Application of shock: This value presents the number of hazard units.
2. Yellow box: social systems' capacity development activities include four parameters: risk communication, education, perception, and identification. Each parameter has a slider bar, and the user can change the values as required.
3. Green Box: measuring the risk levels, which represents two parameters, risk assessment and risk matrix. The risk matrix presents people's ability to recognise risk status and understand risk reduction strategies.
4. Blue Box: Application of risk reduction measures: This includes user engagement in risk reduction activities. These risk reduction measures have three parameters: risk management, resilience and resistance. Here, risk management presents the communities' application of risk management concepts, including risk tolerance, treatment, transfer, and termination. Resilience discusses the settlement's improvement or decrease in intrinsic properties, including physical, social, economic, environmental, and governance aspects. Finally, the resistance includes restoring natural forces to control natural events.
5. Purple Box: Recognising the hazard probabilities: The susceptibility mapping is required to monitor and control the hazard. Accordingly, the ability to recognise trigger factors' probability, events' spatial probabilities, and the event size are presented as variables in here.
6. Brown Box: Level of community engagement: Community engagement is a key factor in implementing the strategies in the area. A higher percentage refers to more people engaged with the process, and vice versa.

7. Gold Box: Monte-Carlo Simulation: Users are allowed to perform the MCS simulation by clicking the check box, and it is required to define the probability of changes, and measuring interval. The probability of change implies, that each variable was changed the given percentage randomly, and provided the output.

A drop-down menu was also created to store known locational data, such as information from the Kalutara district and several divisional secretariats. Furthermore, the drop-down menu includes an option to add 'new data,' allowing users to input numerical values for each parameter in the lower-left box.

5.5.7 User Interface for Visualising Stock-Flow Diagram

The stock-flow diagram shows the connections identified through the literature review, and small text boxes are assigned to each parameter to display the variable value at a given time. Therefore, during the simulation, the user could visualise the value changes on each parameter. Additionally, users can generate individual time-series plots to understand each parameter's behaviour with time.

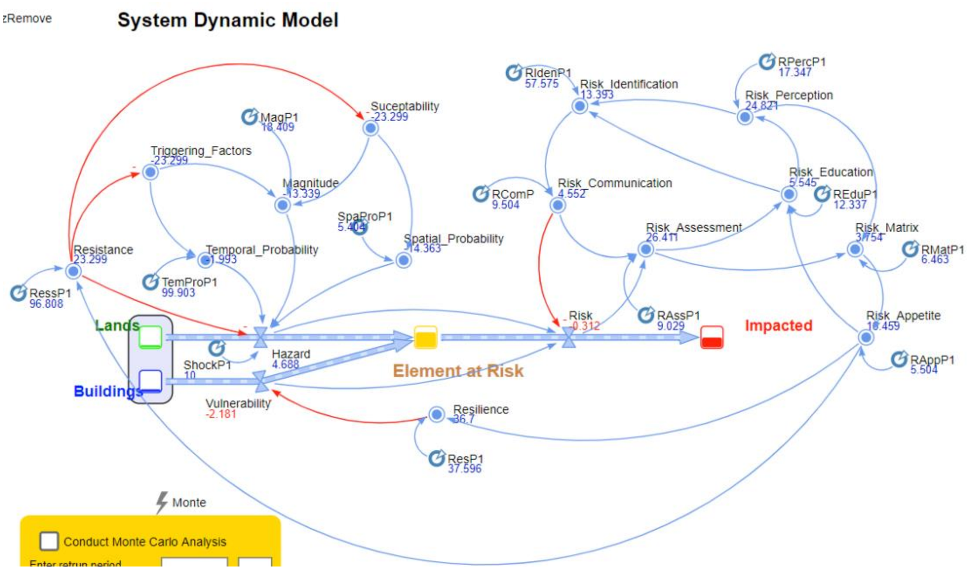

Figure 5-13: System dynamic model with values

5.5.8 User Interface for Visualising the Risk Reduction Pathways

This interface shows risk reduction strategies identified through the literature review. Each strategy is numbered 1 to 14 and connected to output graphs. The strategies are classified into two categories, represented in green and blue. The green square strategies represent the pathways connected with risk perception, with more community engagement in risk reduction activities. Therefore, blue square strategies represent more of other stakeholders' engagement or engineering measurements in risk reduction.

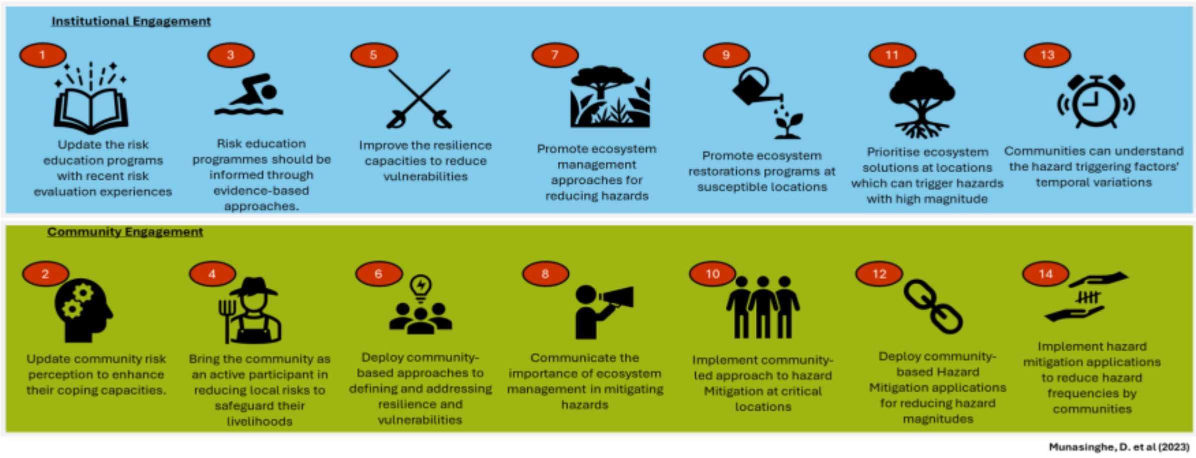

Figure 5-14: List of Strategies shown in the simulation window

5.5.9 Model Outputs

The following sections present several graphs visualising the risk propagation behaviour associated with each strategy. Each strategy reflects the total value of risk propagation through its corresponding loop, with higher strategy values indicating greater risk propagation potential and lower values indicating reduced risk propagation. As the values were generated by normalising each variable, the output values are unitless, illustrating their behaviour over time.

Figure 5-15: Application output graphs

Figure 5-15 presents the output graphs displayed within the application window, which is divided into two sections: Time Series Analysis (in the light blue area) and Total Impact Assessment (in the dark blue area). The Time Series Analysis shows data that evolves over time, while the Total Impact Assessment highlights the start and end points of impact variation. In this application, data is recorded before the selected time frame, and users can adjust parameters to observe changes in impact over time. The system visualises these variations through multiple graphs, offering insights into the effects of specific interventions. The light blue section contains three graphs (Graphs 1, 2, and 3), while the dark blue section includes three more (Graphs 4 to 6). The following sections provide a detailed explanation of each graph.

5.5.9.1 Output Graph 1: Status of Hazard, Vulnerability and Risk

Graph 1 illustrates the status of hazard, vulnerability, and risk over time. These variables represent the flows within the System Dynamics (SD) model, and their fluctuations are captured across the time frame.

In order to demonstrate the functionality of the simulator, case study-specific data is initially input into the simulation. The simulation output subsequently reveals the changes in hazard, vulnerability, and risk values. For demonstration purposes in this chapter, an experimental shock was applied (t=150, equivalent to 35 units of damage), and the shock remained the same for the experimental period. This experiment aimed to demonstrate how hazard, vulnerability, and exposure vary under changing conditions.

The hazard curve initially step up, and increasing gradually. A positive hazard condition indicates a transformation of safer lands into more exposed ones.

The vulnerability curve value is not impacted and it was in the general flow of reducing the negative vulnerability flow. A high negative value of vulnerability indicates a high proportion of safer built environments and communities, while a high positive value of vulnerability suggests a greater level of vulnerable areas and communities. The slight decrease in the vulnerability curve suggests that previously unsafe communities are becoming safer communities.

Finally, the risk curve reflects the variation in risk levels. A positive risk value indicates that more exposed elements are converting into impacted units. The risk communities are increasing and more communities are converting to elements at risk (Figure 5-16).

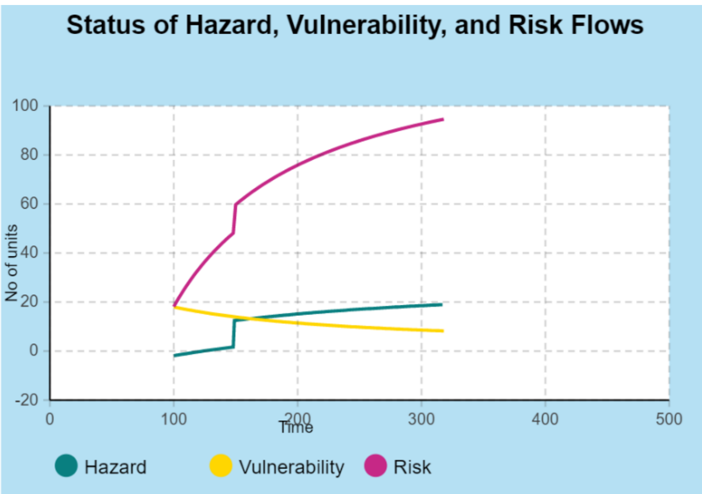

Figure 5-16: Output graph 1- Status of hazard, vulnerability and risk

The result indicates the variation of hazard, vulnerability and exposure values when the strategies are being changed. Accordingly, the user can observe the strategies' influences on the system. For instance, increasing hazard values indicate a tract of land getting influenced, but vulnerability indicates the community becoming more vulnerable, and increasing risk indicates exposed elements impacted. Therefore, decision-makers should focus on achieving negative values.

Although the figure indicates a variation between the variables, it is essential to assess whether the variation has a significant correlation. To achieve this, a detailed study was conducted by gathering simulation data on hazard, vulnerability, and risk variations over time, followed by a regression analysis to determine the presence of significant correlations between the variables. In this model, risk is treated as the dependent variable, while hazard, vulnerability, and communication are considered independent variables. The analysis was supported by SPSS software and Matlab applications.

A coefficients test was conducted to statically justify that the connections' variations are significantly correlated. Accordingly, the MCS was conducted by changing the value ±5% for each variable and measuring the variations every 200 time period. Accordingly, the coefficients test result for Risk, Risk Communication, Vulnerability and Hazard is as shown in Table 9;

Table 9: Coefficients for risk, vulnerability, hazard, and risk communication

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-4.736	.547		-8.659	.000
	Hazard	.479	.030	.728	15.868	.000
	Vulnerability	.394	.018	.766	21.516	.000
	Risk_Communication	-.185	.025	-.369	-7.539	.000

a. Dependent Variable: Risk

The coefficient test results show the effect of the independent variables Hazard, Vulnerability, and Risk Communication on the dependent variable, Risk. These connections are derived from the system dynamics (SD) relationships. The table can be interpreted as follows:

- **Unstandardized Coefficient (B):** The constant factor represents the risk value when the contributions of Hazard, Vulnerability, and Risk Communication are zero, indicating an inherent risk in the settlement. The hazard factor shows that an increase in hazard by one unit increases Risk by 0.479 units, illustrating a positive relationship between Hazard and Risk. Similarly, an increase in Vulnerability by one unit results in an increase of 0.394 units in Risk, also indicating a positive relationship. In contrast, there is a negative relationship between Risk Communication and Risk, as one unit increase in Risk Communication decreases the risk by 0.185 units.
- **Standardized Coefficient (Beta):** This expresses the nature of the relationships between the variables. Hazard and Vulnerability both have a strong positive relationship with Risk, whereas Risk Communication has a negative relationship.
- **t Value:** This indicates the degree of significance of the relationships. Hazard and Vulnerability demonstrate a strong positive relationship with Risk, while Risk Communication shows a strong negative relationship.

All variables have a statistically significant value (Sig < 0.05), indicating the reliability of the results. Thus, it is clear that the relationships within the model are statistically significant.

5.5.9.2 Graph 2: Status of Stocks -Safer Built-up, Elment at Risk and Impacted

Graph 2 illustrates the stock values of the model and their behaviour over time. Initially, the defined stock values were assigned to the model for the simulation requirement. However, the user can add the real values reference to the ground condition. The y-axis shows the land units, and the x-axis shows the time domain.

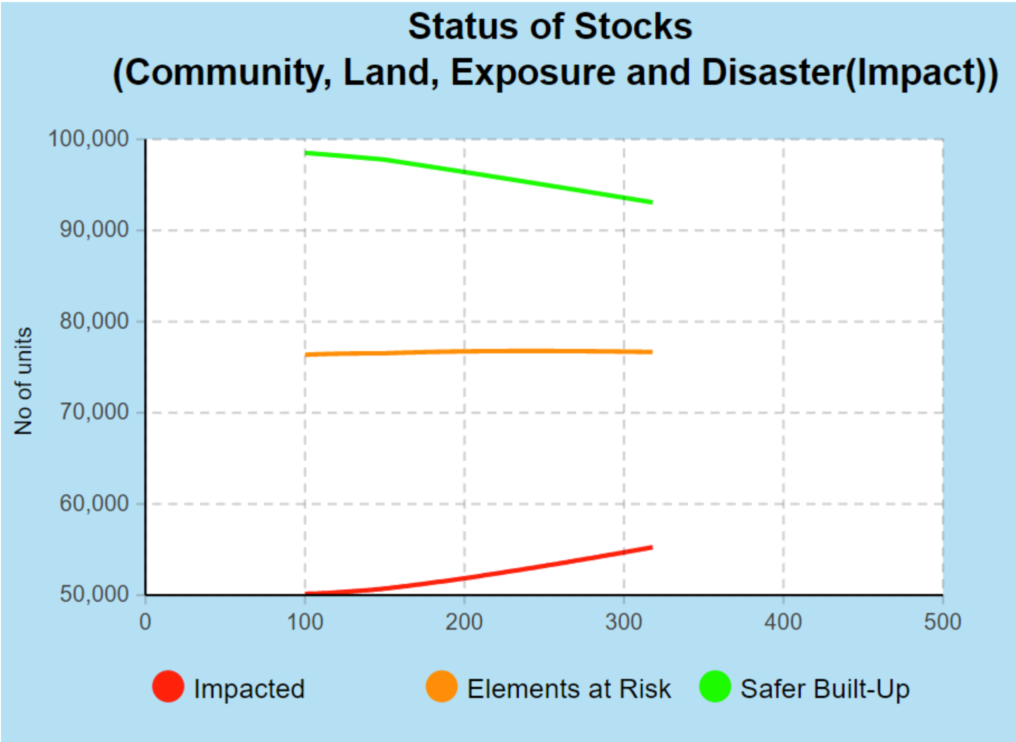

Figure 5-17: Output Graph2- Status of Stocks (Community, Land, Exposure and Disaster(Impact))

The curves illustrate changes in stock values over time, helping users to understand potential variations in impact. Upward curves signify an increase in stock values, while downward curves indicate a decrease. As hazards increase, the curves demonstrate a decrease in safer developed areas, an increase in risks, and consequently, a rise in impacted stock.

5.5.9.3 Graph 3- Intervention by Each Risk Character in a Period.

Graph 3 depicts the intervention of each risk characteristic over a specified period. As with the strategy analysis, each characteristic exerts both positive and negative effects on the model. The magnitude of these interventions is represented by the value on the graph, with higher values indicating greater levels of propagation. Since each strategy encompasses multiple risk assessment characteristics, this chart enables decision-makers to design customised solutions tailored to the specific needs of the settlement to achieve a positive impact in terms of reducing risks and enhancing resilience.

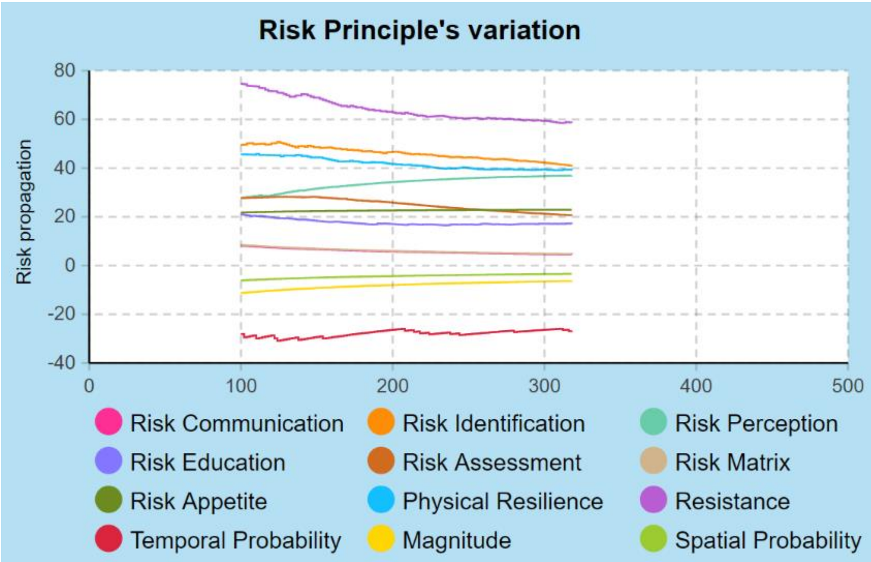

Figure 5-18: Output graph 3- ability to transform risk by each risk character in a period.

For instance, strategy 4, engaging the community as active participants in reducing local risk to safeguard their livelihoods, has a substantial impact on the settlements. This strategy is interconnected with several risk characteristics: Risk Assessment, Risk Matrix, Risk Appetite, Risk Education, Risk Perception, Risk Identification, and Risk Communication. The strategy illustrates that if the communication improves, it connects with risk assessment loop characteristics at various levels. Consequently, decision-makers can craft tailored solutions that emphasise risk communication strategies, thereby enhancing the protection of community livelihoods.

5.5.9.4 Graph 4 - Risk principles Propagation Value Variation Over a Period

While Graph 3 illustrates the variation in risk propagation values for each characteristic throughout a time period, Graph 4 represents the cumulative variation of risk propagation of each risk characteristics over a given period.

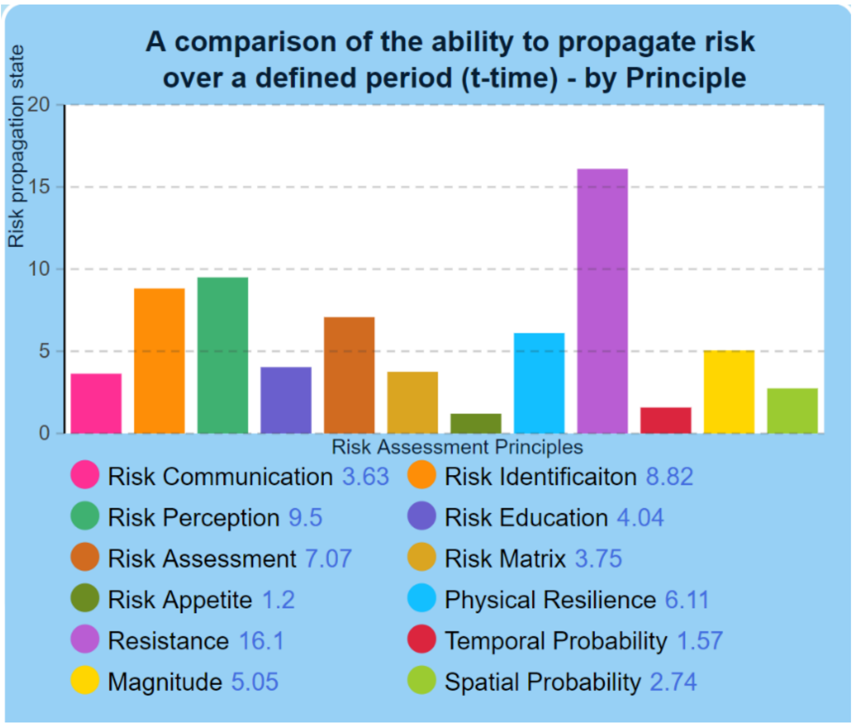

Figure 5-19: Graph 4 - Risk principles risk propagation variation over time

5.5.9.5 Graph 5: Performance of Each Strategy in a Given Period

Graph depicts the changes in strategy values over a specific timeframe. The value for this period is determined by subtracting the initial strategy value from the final value. Positive values signify high-risk propagation along each pathway, whereas low values indicate less risk propagation during the period. Consequently, decision-makers can be guided to prioritize and implement pathways that result in positive outcomes.

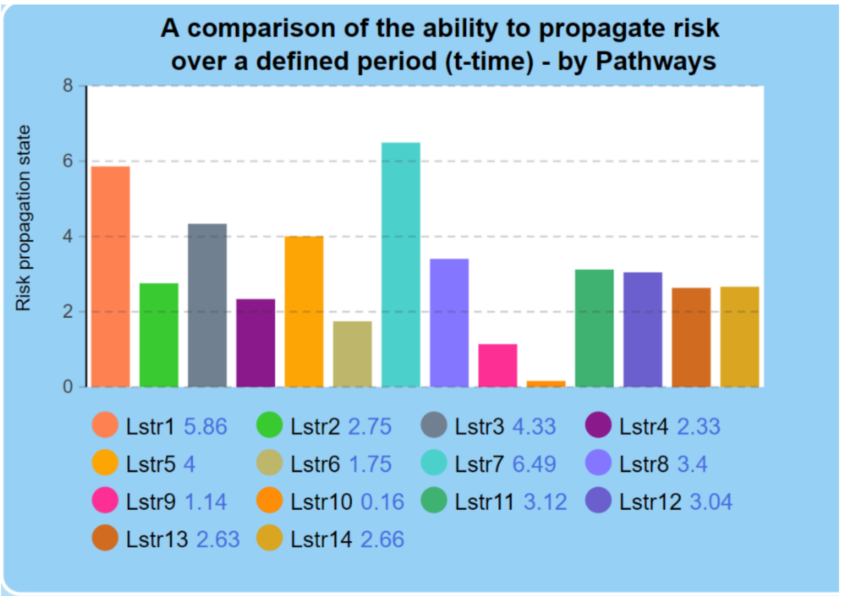

Figure 5-20: Output 5 - Strategy value changes in a given period

5.5.9.6 Graph 6- Expected Outcome

Graph 6 calculates the expected benefits for each period, allowing users to apply various strategies and measure their impacts. The graph displays the variation in three stock values over the given period. "Safer Built Up" represents the amount of land rendered safe and number of buildings that become safer through its application. The "Elements at Risk" illustrates the number of units that transition into an exposed state, and the "Impacted" reflects the number of households adversely impacted.

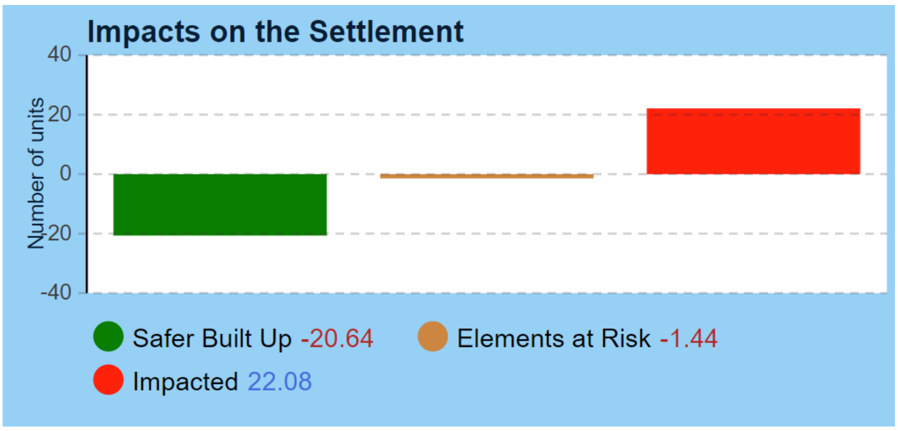

Figure 5-21: Output 6 - Intended impact in a given period

5.5.10 Execution of the Simulation

Figure 5-22 presents the six steps that needs to be followed for running the simulation. First, users must identify the relevant variables associated with risk principles. Next, these variables should be normalized to derive a single representative value for each risk principle. In the third step, threshold values must be established for each principle. The fourth step involves performing a Monte Carlo simulation, defining the time interval and expected variation of the variable. In the fifth stage, multiple iterations are required to achieve stronger correlation and regression values. Finally, the optimal strategy is determined based on the best correlation results.

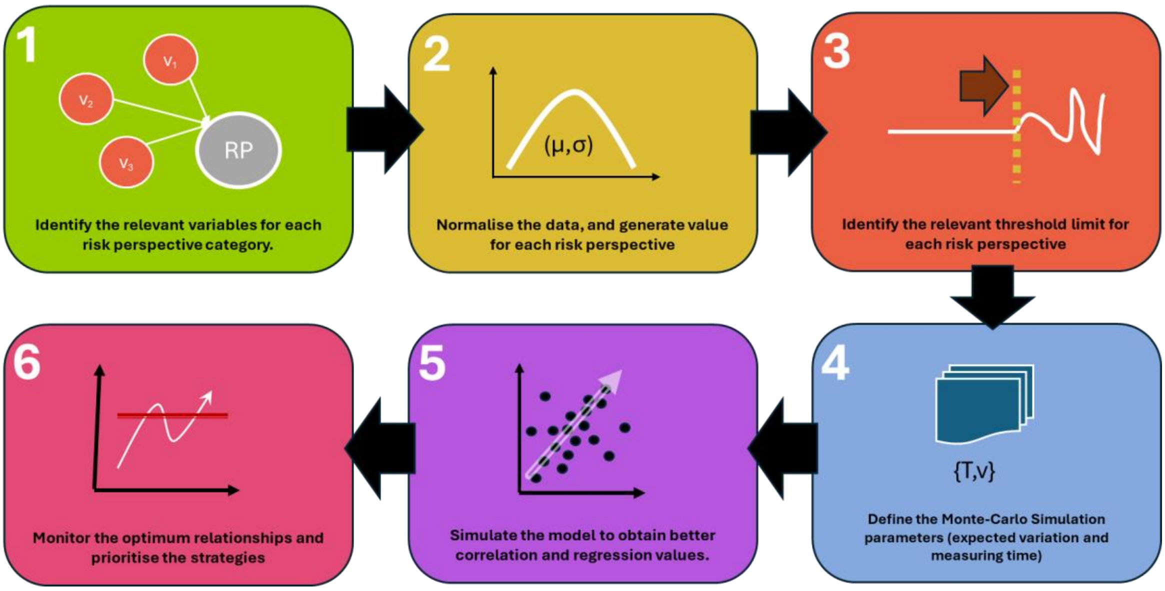

Figure 5-22: Execution step of the simulator

The simulator was developed as an application using Java. This application was successfully uploaded to the Anylogic cloud. Once the application is loaded, users can either select predefined data or input new data, then press the 'Load' button to begin the simulation. The model will run from the start, and relevant graphs will be generated. Based on the input values, the system dynamics model will simulate and display output data. For more detailed analysis, users can click on the "Record Value," "Compare," and "Build Chart" buttons to conduct specific assessments of the selected strategy's impacts.

The following weblink provides online access to the simulator.

Weblink to the programme:

https://cloud.anylogic.com/model/96a1629e-6a7a-4a92-a5ba-d2de1b6d9a28

Figure 5-23: QR code to the application login

5.6 Summary

Chapter five focuses on the development of a risk propagation simulator for assessing risk in urban settings, building upon the risk assessment model developed in Chapter four. It systematically guides the construction of the artefact through the Design Science Methodology: detailing the process of explicating the problem, defining requirements, designing and developing the artefact, demonstrating its applicability, and evaluating its effectiveness. The chapter particularly emphasises the importance of integrating human risk characteristics into the model to accurately assess urban resilience.

Section 5.1 outlines the complex problem of modelling urban resilience, highlighting the need for a comprehensive approach that captures intricate interdependencies and human factors. Section 5.2 then defines the key requirements for the simulator, which include capturing these interdependencies, incorporating human factors, and enabling dynamic analysis.

Section 5.3 delves into the design and development of the artefact, outlining the construction of the underlying risk propagation model, defining indicators for evaluating system performance, and selecting appropriate simulation techniques. Section 5.4 then discusses the implementation of the system dynamics approach using AnyLogic software and the development of the user interface.

Overall, Chapter five presents a detailed explanation of the systematic approach used to develop the risk propagation simulator, emphasising the importance of robust modelling techniques. The next chapter will present the use of the risk simulator within an urban context.

Chapter 6: The Model Applicability for Ground Scenarios

6.1 Introduction

The purpose of this chapter is to detail how the values of each risk variable in the system dynamics model, introduced in Chapters four and five, can be initialised within a specific context and to demonstrate how overall risk can be assessed while taking risk propagation into account. For this analysis, the Palindanuwara Division within the Kalutara District of Sri Lanka is selected due to the availability of high-resolution datasets from the National Building Research Organisation of Sri Lanka.

Having initialised the system dynamics models for the risk propagation simulator, this chapter illustrates how the simulator can be employed to evaluate risk propagation and determine the final risk status of the Palindanuwara Division as a consequence of the following urban development interventions:

- **Drainage Improvement Project**: The simulator is used to assess the effectiveness of drainage improvements in mitigating landslide risks and enhancing community resilience.
- **Communication**: The model examines the impact of improved mobile coverage and risk communication services on community preparedness and communication during disasters.

Finally, the chapter presents the outcomes of the simulator evaluation conducted with twelve experts. A comprehensive set of questions was designed to discuss the empirical structure, empirical performance, and theoretical performance validity of the model. Through this validation process, Chapter six aims to demonstrate the model's utility as a tool for urban planners and decision-makers to assess the potential impacts of development interventions on community resilience. The insights gained contribute to the formulation of more informed and resilient urban planning strategies.

6.2 Pilot Study Area

Kalutara is a district located south of Colombo, the capital of Sri Lanka, covering an area of 1,598 square kilometres, which constitutes 43% of the land in the Western Province. The entire Western Province has been designated as an urban area, with urbanisation expanding under the 'Western Province Megapolis Master Plan.' Consequently, future urban development is expected to occur in the Kalutara district, which serves as a support district to Colombo, the commercial capital of Sri Lanka. The district is administratively divided into fourteen divisional secretariat divisions and 762 Grama Niladari (GN) divisions. The extent of urbanisation within these divisions varies, influenced by factors such as geomorphological conditions, accessibility, and social and physical infrastructure availability.

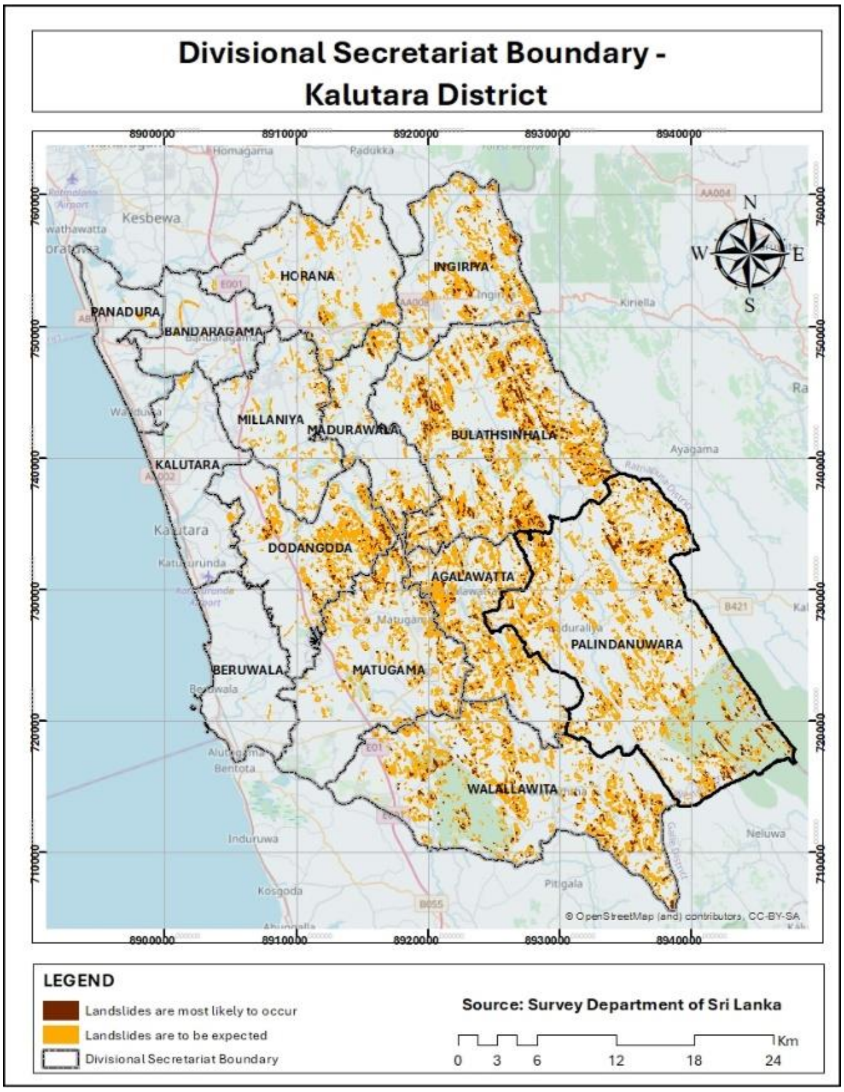

Figure 6-1: Divisional Secretariat areas and landslide high probability zones.

The Kalutara district exhibits diverse geomorphological conditions, with its western boundary bordering the Indian Ocean and its eastern side linked to the mountainous district of Ratnapura. These varied geomorphological features contribute to hazards triggered by both natural and anthropogenic factors. Additionally, these conditions facilitate a range of agricultural practices, which may also play a role in hazard creation.

Previous studies have shown that the economic status of affected communities has been significantly impacted, leading to a notable reduction in their savings capacities (Life After Two Years, 2021). The economic condition of these communities is closely interconnected with other social, physical, governance, and environmental factors, resulting in different impacts from landslide impacts depending on their socio-economic status. Consequently, various risk management approaches have been introduced, tailored to specific landslide conditions. Some residents have been resettled, while others have been advised to implement mitigation measures. These strategies have been developed after assessing the risk levels and socio-economic conditions of the communities, focusing on how these risk mitigation options could improve their overall status.

Several communities in the Kalutara District have been identified as high-risk areas for landslides, prompting the government to implement various risk management interventions. Although several resettlement sites and risk mitigation projects were initiated to address these hazards, many of them faced challenges and were ultimately unsuccessful. One key reason for this failure has been the lack of community engagement in the planning and execution of these initiatives giving consideration to community risk perception and risk knowledge. Consequently, Kalutara district serves as an ideal district to test the proposed community-centric risk propagation model, which aims to incorporate community perspectives into the selection and implementation of effective mitigation strategies.

6.2.1 Access to Risk Information for the Case Study

NBRO is the country's primary authority for landslide risk management. In response to significant landslide events in the central highlands, NBRO initiated the Landslide Hazard Zonation Mapping Programme (LHMP) in 1995, which led to the development of comprehensive landslide risk maps. These maps employ a multi-criteria methodology that encompasses factors such as geology, hydrology, land use management, landform, slope, and landslide overburdens.

In 2015, NBRO initiated the "Risk Profile Development Project" to collect household information in communities at risk of landslides, aiming to better understand these risks and communicate the findings to district secretaries and relevant stakeholders. The project began with a spatial mapping exercise to assess exposure levels across districts and divisions, identifying 100,000 high-risk buildings in ten landslide-prone districts, each assigned an identification number, and generating Grama Niladari (GN) level exposure maps. To ensure data accuracy, NBRO conducted training sessions for GN officers, equipping them with spatial recognition skills necessary for accurately identifying and marking high-risk areas on the maps. Additionally, the exposure maps were provided to these officers for public awareness in their offices and the community.

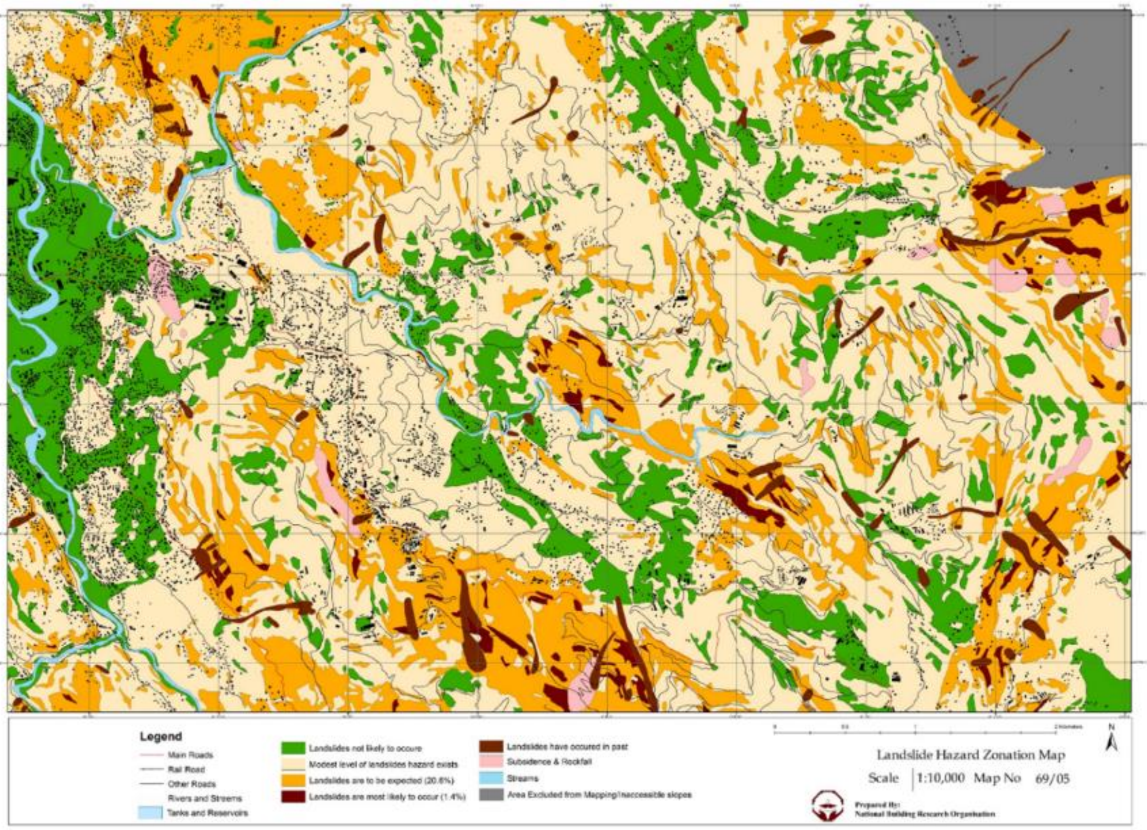

Figure 6-2: Thiniyawala GN division exposure map.

To capture the relevant risk information, a structured questionnaire survey has been used, which included four types of questionnaires based on building use: residential, commercial/industrial, schools, and religious places. At each GN level, 10% of the data was randomly checked, and certification was obtained from the relevant divisional secretariat divisions. All collected household information was recorded in SPSS format. Furthermore, the data was published through an ArcGIS web application, ensuring that the relevant information was accessible to the public.

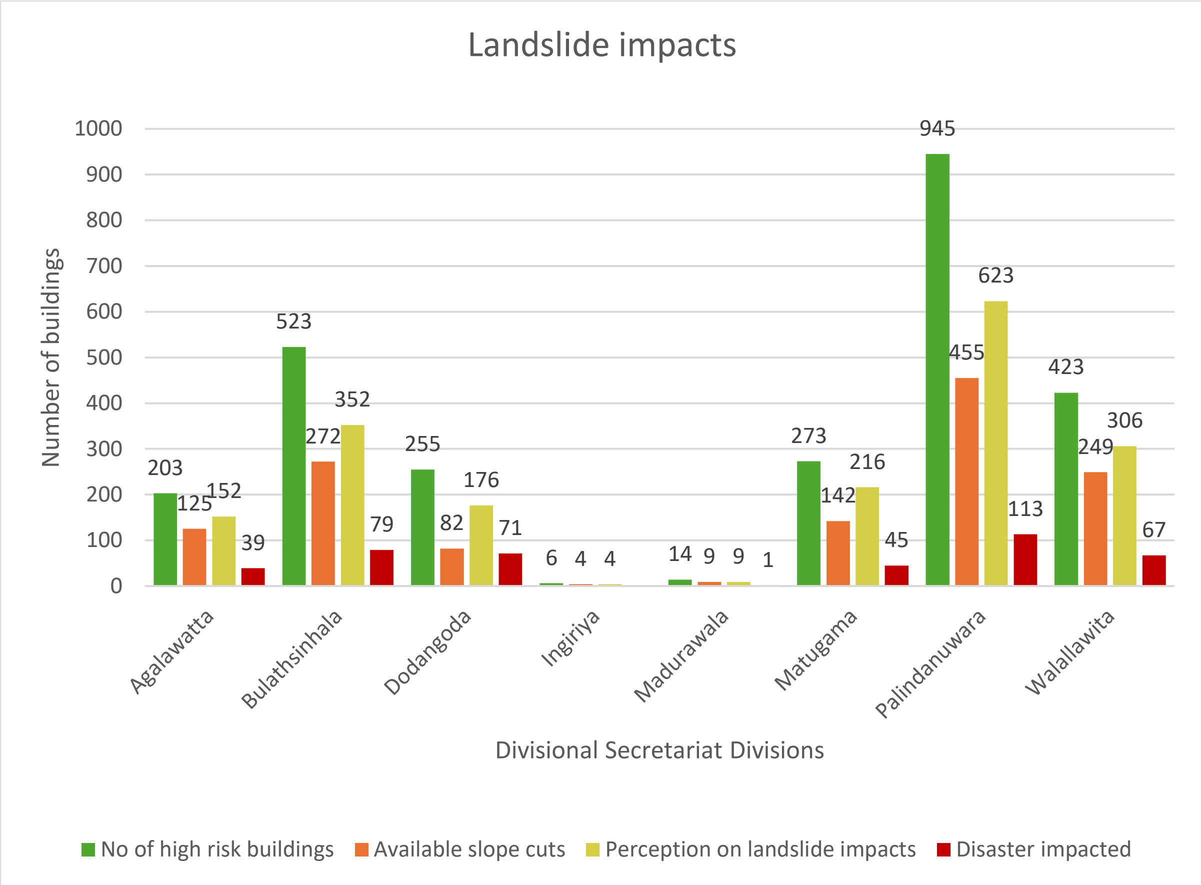

Figure 6-3: Landslide Impacts in Kalutara DSD level

The survey was conducted in eight out of the fourteen Divisional Secretariat Divisions (DSDs) due to the unavailability of landslide hazard susceptibility maps (excluding Ingiriya and Madurawala DSD), encompassing a total of 2,642 building units. In the surveyed DSDs, the following number of landslide-exposed buildings was identified: 945 in Palindanuwara, 523 in Bulathsinhala, 423 in Walallawita, 272 in Matugama, 255 in Dodangoda, and 203 in Agalawatta. Additionally, the survey assessed three critical attributes to evaluate the risk status of each DSD: the presence of cut slopes, residents' perceptions of the impacts of landslides on their homes, and historical landslide incidents affecting their properties.

Notably, Palindanuwara DSD exhibited the highest number of landslide-impacted households, with 113 affected units.

The Palindanueward Division was chosen for model validation due to its concentration of high-risk landslide communities and the availability of precise data. The following section discusses the data tabulation and data preparation for model application.

6.2.2 Availability of Development Proposals

Proposed development activities for the Palindanuewara Division were obtained through the Divisional Secretariat Department (DSD), gathering information on transport, healthcare, drainage networks, water supply, communication, and educational development projects. The figure below illustrates the variations in these factors.

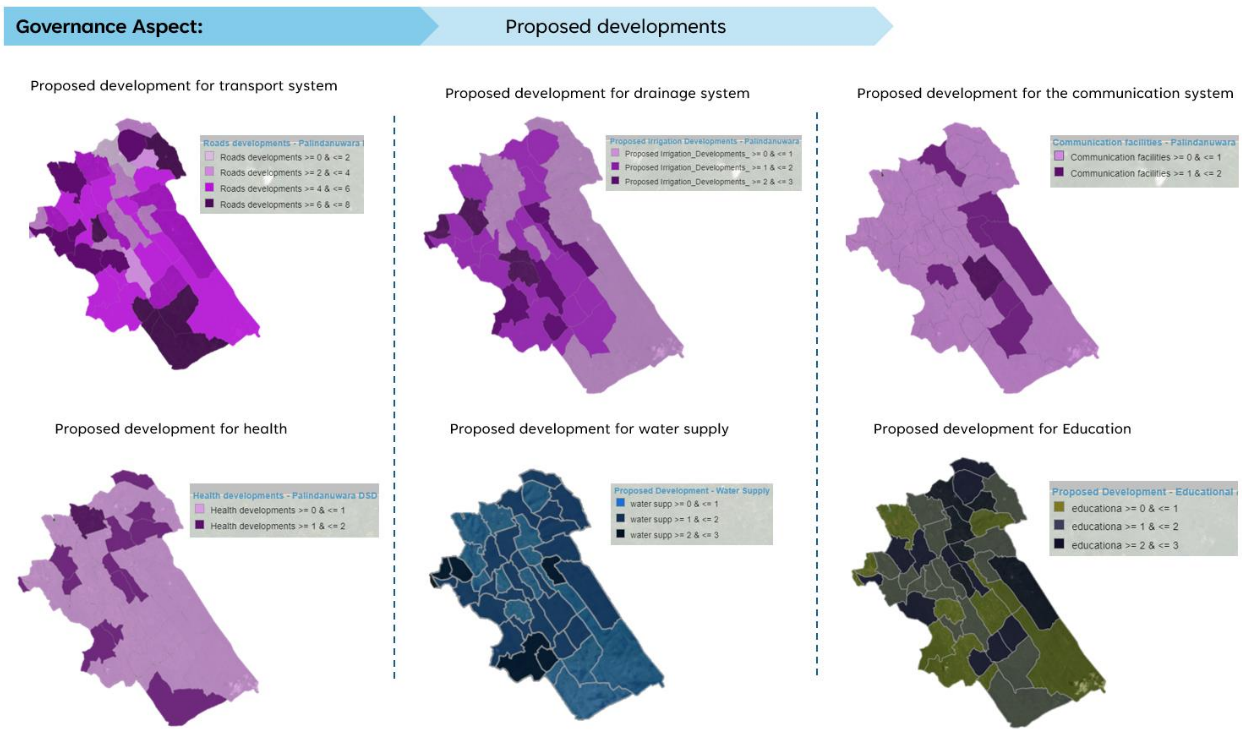

Figure 6-4: Proposed developments in Palindanuwara DSD

These projects are aimed at urban development and reducing the existing disaster conditions. Two projects were selected to demonstrate the risk propagation features in the simulator: one related to institutional engagement through drainage improvements and the other related to community engagement via risk communication.

6.3 Data Collection and Preparation for Analysis

The household data collected from the Risk Profile Development Project of NBRO was used to populate and evaluate the risk assessment model. The data fields were meticulously cross-checked against the risk assessment model to identify relevant fields that represent each perspective of risk.

Applying the concept of system dynamics to disaster risk management is essential for understanding how impacts propagate across various dimensions. This study can thus be utilised to evaluate the impact of proposed development projects on the overall risk level of the communities. The system dynamics model is developed by integrating the theoretical model presented in Chapter 4 with data collected from the Divisional Secretariat Department (DSD) and available institutional databases. Consequently, the integration of relevant connections with this data has resulted in the creation of the following system dynamics model (Figure 6-5).

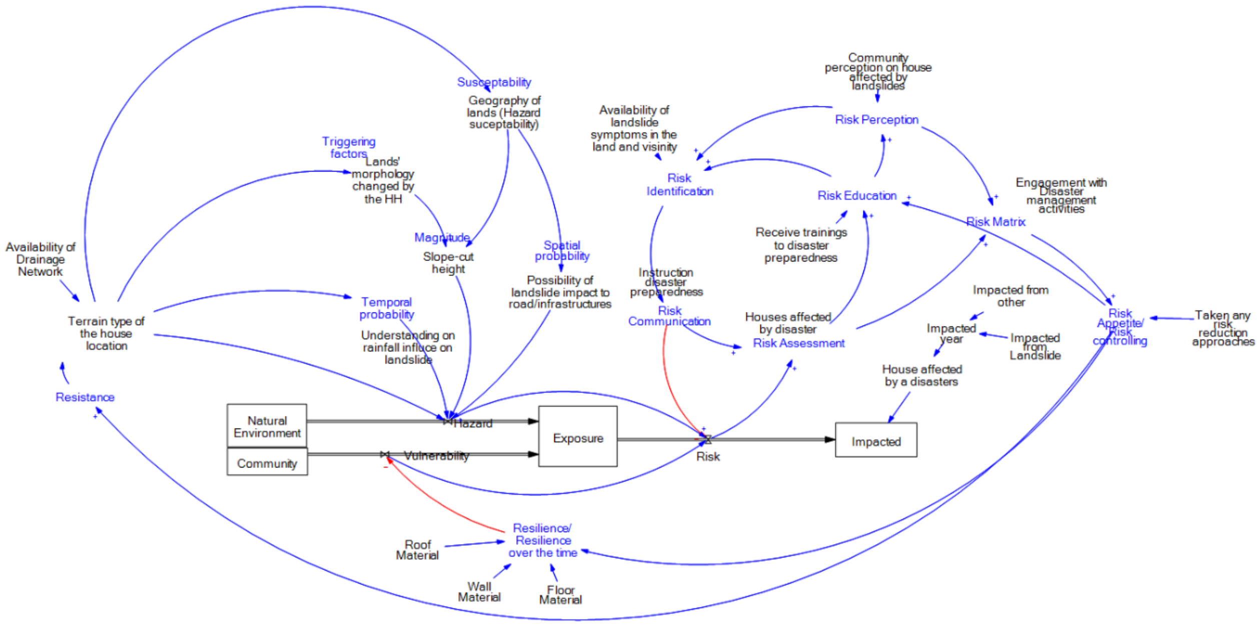

Figure 6-5: Stock-flow model with available datasets

The Stock-Flow diagram incorporates dynamic variables (represented by circles), stocks (depicted as squares), and flows (illustrated as thick arrows with cross triangles). It is essential to identify and assign values to each dynamic variable and stock. Initially, default values must be assigned to the stocks; for example, the "community" stock in the diagram denotes the available households in the area, requiring a numerical value to be established at the start of the simulation. Conversely, the flows derive their values from equations, negating the need for default assignments.

The model was initialised using the available datasets, with the stock-flow model illustrating the identified risk characteristics in blue and the associated datasets in black. All of these datasets were collected from the National Building Research Organisation (NBRO) databases, which were compiled through household surveys conducted in landslide-prone areas.

To clarify the variables used in the model, the data was categorised into a table presented below. This table outlines the dynamic variables incorporated within the system dynamics model, with corresponding data specified in the "selected variable" column. All selected variables contain discrete information that has been clustered based on subjective assessments. For instance, landslide susceptibility was classified according to the likelihood of landslides, as determined by subject matter experts based on scientific analyses.

Table 10 illustrates the dynamic variables and the selected dataset from NBRO. A justification is highlighted for each dynamic variable for the selection of the dataset.

Table 10: Model perspectives and identified variables from the Risk Profile database.

Model perspective	**Explanation of selected data**
Susceptibility	The intrinsic characteristics of a particular land area can create conditions that make it more vulnerable to landslide hazards. Consequently, regions exhibiting higher susceptibility are more prone to developing hazardous environments. The likelihood of a landslide occurring in a given area is based on geological and environmental factors. The information was

	collected through the dataset to understand the community's understanding of landslide susceptible conditions in their vicinity. The landslide susceptibility output data is used to determine the susceptibility level of each spatial unit.
Spatial Probability	The likelihood of property damage was assessed based on the positioning of structures in relation to the landslide's initiation area, flow path, and deposition area. NBRO conducted a detailed survey to evaluate the probability of landslide impacts on infrastructure and homes. The survey results of how many households have the spatial probability of landslide are considered as the input value. Therefore, the data indicates the geographical likelihood that landslides will impact specific locations based on historical data and land characteristics.
Temporal Probability	Rainfall is recognised as a critical temporal factor in triggering landslides, with the likelihood of intense rainfall occurring within a specific timeframe being a key trigger. To assess this risk, several factors can be layered to gather relevant information. For example, satellite data can be utilised to analyse temporal variations in rainfall over time. However, for effective risk management strategies, it is crucial to understand how these temporal probabilities contribute to landslide triggers. In this research, survey results from the National Building Research Organisation (NBRO) are utilised to gather community insights on how rainfall contributes to triggering landslides, which in turn is used to define the temporal probability.
Resistance	Measuring the natural resistance of an area to landslide initiation is essential for effective risk management. Key parameters used in landslide hazard assessments are friction angle and coefficient, which are calculated based on factors such as slope gradient, soil type, and density. Furthermore, managing water flow can

	significantly improve soil resistance capacity. As such, terrain type and the presence of a well-functioning drainage system are critical parameters measured in the study to determine the land's resistance to landslides. Accordingly, the dataset considered the drainage availability and high-slope lands linked to households.
Triggering Factors	Changes in the local landscape or morphology caused by household activities may increase landslide risk (e.g., excavation, vegetation removal). The construction of houses often involves modifications to the natural morphology of the land, disrupting the original slope dynamics and interfering with natural water flow patterns. Consequently, these human-induced alterations to land morphology are recognised as a significant triggering factor for landslides. Accordingly, how many households are significantly threatened by slope modification was considered as input to the SD model.
Magnitude	Due to the geomorphological condition, many houses are situated on or near sloped land. However, a significant number of these houses consist of slope cuts, often without having inadequate slope protections. The characteristics of slope cuts or excavations made near the houses could potentially exacerbate landslides (e.g., depth, angle, and stability of the cut). Consequently, the risk of slope failure or landslide impact is closely correlated to the height of the failing soil mass. According to the NBRO's guidelines, 1.5m height cuts have a high probability of potential failures and vary with the soil type. The households with a significant threat from the cutting failure were considered as input to the model.
Risk Communication	Community preparedness is vital for mitigating the adverse effects of disasters. When communicating with vulnerable communities,

	clear instructions on anticipatory actions are essential. The ability of these communities to understand and effectively implement these instructions should be regarded as a key indicator of successful risk communication. Furthermore, the availability and quality of information provided to residents about disaster preparedness strategies and actions play a significant role in reducing risks.
Risk Assessment	Assessing the consequences associated with risk is of utmost importance. It is essential to recognise the potential for both minor slope failures and warning signs of landslides, as these can often precede a significant event. The capacity to evaluate the implications of such occurrences was a key consideration, and community feedback was collected to inform this assessment.
Risk Education	It is crucial to effectively transfer knowledge from stakeholders to the community to enhance community resilience and improve their capacity to cope with risks. This knowledge transfer can be achieved through various interventions, such as public seminars, workshops, training programmes, and informative posters. The presence of such knowledge-sharing activities was considered a vital component of risk education within the community.
Risk Identification	Landslide symptoms can often be visible in the environment before a landslide trigger occurs. The ability of the community or stakeholders to effectively identify and capture these symptoms is crucial for proactive risk management. Therefore, the ability to recognise and report landslide symptoms in the immediate vicinity was considered an essential aspect of risk identification. The input value was considered as the probability that households can identify the landslide risks.

Risk Perception	Assessing the community's risk perception is crucial. It involves understanding their perception of the probability of a landslide occurring and the likelihood of a landslide mass reaching their homes or infrastructure. This information is critical for determining the need for risk reduction activities, as community perception directly influences their willingness to engage in mitigation efforts. Therefore, the data on how many households believed they are in landslide high-risk areas was considered as the input to this element.
Risk Matrix	The risk matrix offers a systematic framework for evaluating a community's involvement in risk reduction activities. It identifies two crucial curves: the judgment curve and the critical curve. These curves, in conjunction with the community's risk reduction stance, delineate four distinct states of risk management: risk tolerance, treatment, transfer, and termination. Additionally, a community's engagement in disaster risk management significantly influences its position within the risk matrix. Community participation in disaster management initiatives, such as drills and planning sessions, was considered indicative of their engagement. The underlying assumption was that if a community recognises the level of risk, it is more likely to engage positively with these programs and contribute actively to risk management efforts.
Risk Appetite	Communities implement various risk reduction measures to mitigate existing risks. This proactive approach, informed by an understanding of potential consequences, is essential for reducing future impacts. To achieve sustainable risk reduction, the measures must be understood and implemented by the community itself whenever possible. However, certain activities may require implementation by stakeholder agencies, who are

	responsible for providing adequate knowledge and support to ensure the ongoing effectiveness of these actions. The value for risk appetite is considered as the ability to implement risk reduction measures by themselves and have past risk management experiences.
Physical Resilience	Resilience has several dimensions which are discussed in the literature survey. Building resilience is discussed in the model by assessing the building construction material to determine whether it's permanent or temporary structures. Accordingly, the building characteristics were gathered at the household level, and the information was categorised based on the permanent material categorisation of the Census and Statistical Department. The resilience assumes the permanent building has more resilience than the temporary buildings.

6.4 Calculating Dynamic Variable Values

Each dynamic variable requires an assigned value to input into the system dynamics model, and the following section outlines the approach to calculate these values. The calculation process involves the following steps:

1. **Identify Suitable Parameters**: Determine relevant parameters that represent both desirable and undesirable statuses of the dynamic variables. The desirable condition refers to a favourable condition for risk propagation from one node to another.
2. **Generate Normal Distribution Curve**: Create a normal distribution curve based on the gathered data set to better understand the distribution of values within each variable.
3. **Apply Reliability Calculation**: Use the identified parameter values in the reliability calculation formula to derive reliability values for each dynamic variable.

4. **Calculate Cumulative Distribution Function (CDF)**: Compute the Cumulative Distribution Function (CDF) for each dynamic variable to ascertain the required sample size for risk propagation.

The subsequent sections present the identified dynamic variable values relevant to the case study location.

6.4.1.1 Susceptibility:

This research focuses on rain-induced landslide risk in the Palindanuwara DSD area, utilising landslide susceptibility data for analysis. The susceptibility data is sourced from the NBRO's landslide hazard zonation map, as detailed in the previous section. This map categorises landslide susceptibility into four risk levels, ranging from high to low.

To facilitate risk propagation analysis, the landslide susceptibility categories have been classified into desirable and undesirable states. The categories considered as desirable for risk propagation include "Landslides occurred in the past," "Subsidence & rockfalls," "Landslides most likely to occur," and "Landslides are to be expected." Conversely, the categories "Modest level of landslide hazard exists" and "Landslides are not likely to occur" were regarded as undesirable conditions for risk propagation. Accordingly, values of 1 and 2 were assigned to the desirable and undesirable states during the reclassification process (Figure 6-6-Left).

Next, a Central Limit Theorem (CLT) graph was developed (Figure 6-6-Right), including 50 elements per cluster and a total of 5,000 clusters. The "Desirable" option, representing a community facing landslides and a high probability of occurrence, was established as the boundary for the value, which corresponds to a z-value of 0.6641(CLT (μ) = 1.4152; CLTsigma = 0.2001; X = 1.5). Here, the red line indicates the margin between desirable and undesirable states.

As a result, the probability distribution was calculated based on the z-value, yielding a probability of 66.41%. This percentage reflects the likelihood of susceptibility within the dynamic model, effectively summarising the community's vulnerability to landslide risks.

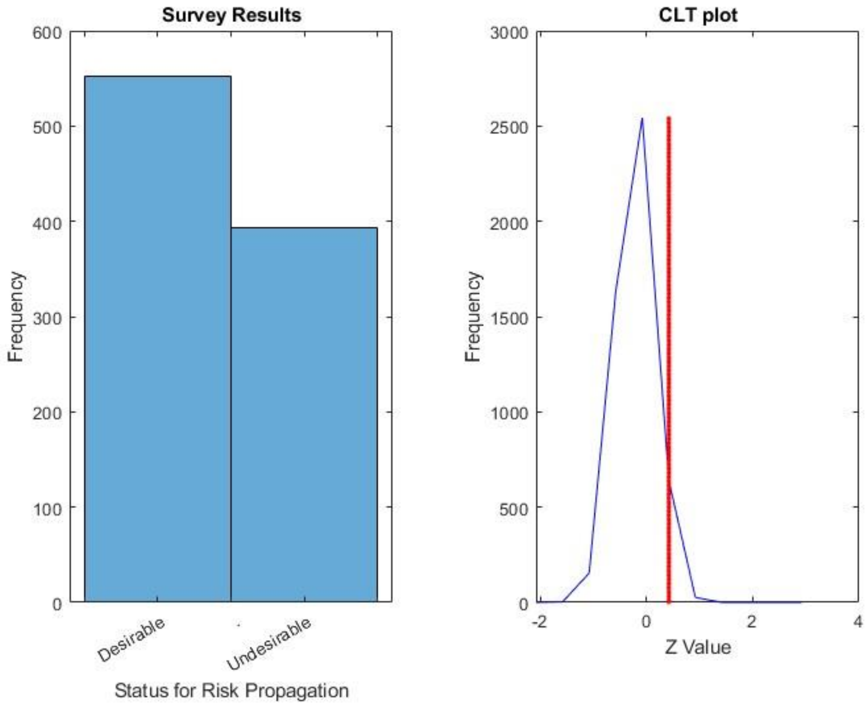

Figure 6-6: Desirability level for Susceptibility and the CLT curve

As discussed in the literature review, the reliability of the connections between elements defines their capacity to propagate risk to neighbouring elements. Consequently, reliability values were calculated. The desirable conditions of a risk element facilitate the transfer of impacts to connected risk elements. For instance, if a community is aware that they reside in a hazardous area, they are more likely to seek precautionary measures. To support this, a reliable connection must exist between the two risk elements, beyond just their threshold values. Therefore, if the connection is deemed reliable, the impact will propagate; conversely, if it is unreliable, the impact will not spread.

The system reliability function was used to calculate the reliabilities of each connection, as represented in the following equation.

System Reliability Function

$$R_s(t) = \sum_{i=1}^{N} \binom{N}{i} R(t)^i \left(1 - R(t)\right)^{N-i}$$

In this equation, (N) represents the total number of communities (100%), while (i) indicates the selected population targeted for the implementation of the proposed strategy. For example, if an activity intends to focus on 10% of the population in the area, then (i = 10%). The (R(t)) value corresponds to the desirable outcome for each parameter. Thus, the reliability values were computed for each parameter, as shown in the figure below, with (i) varying from 0% to 100% based on the number of units engaged in the selected risk.

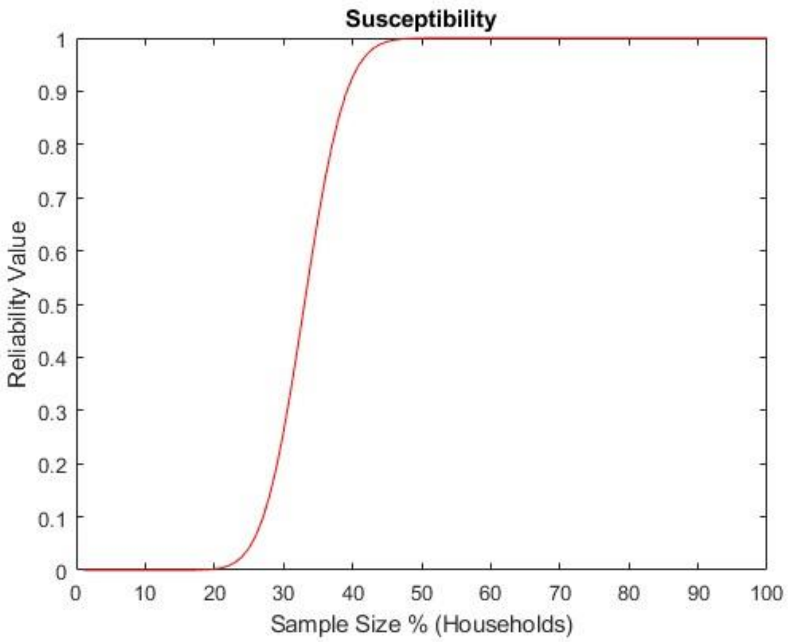

Figure 6-7: Susceptibility CDF

Figure 6-7 illustrates the susceptibility cumulative distribution function (CDF), which was developed by varying the sample size percentage (i-value) from 0% to 100%. It indicates that the risk reduction strategy related to susceptibility propagates within the community and requires engagement from more than 20% of the sample size (tract of land). Notably, if the strategy is implemented for 35% of the sample size, the highest level of propagation is achieved.

6.4.1.2 Spatial Probability:

The spatial probability of landslides was determined using the collected data set, which included questions regarding the community's perception of how the likelihood of landslides affects their living infrastructure facilities. The responses yielded two values: “Yes,” indicating that the community believes landslides will impact their homes, and “No,” indicating that they believe landslides will not affect their homes. This assessment contributes to the understanding of risk propagation, as awareness of potential impacts encourages communication within the community. A distribution plot was generated using the Central Limit Theorem (CLT), as illustrated in Figure 6-8. The results indicate that 5.4037% of the community is in a desirable condition for risk propagation, with a mean (μ) of 1.9411 and a standard deviation (σ) of 0.2745.

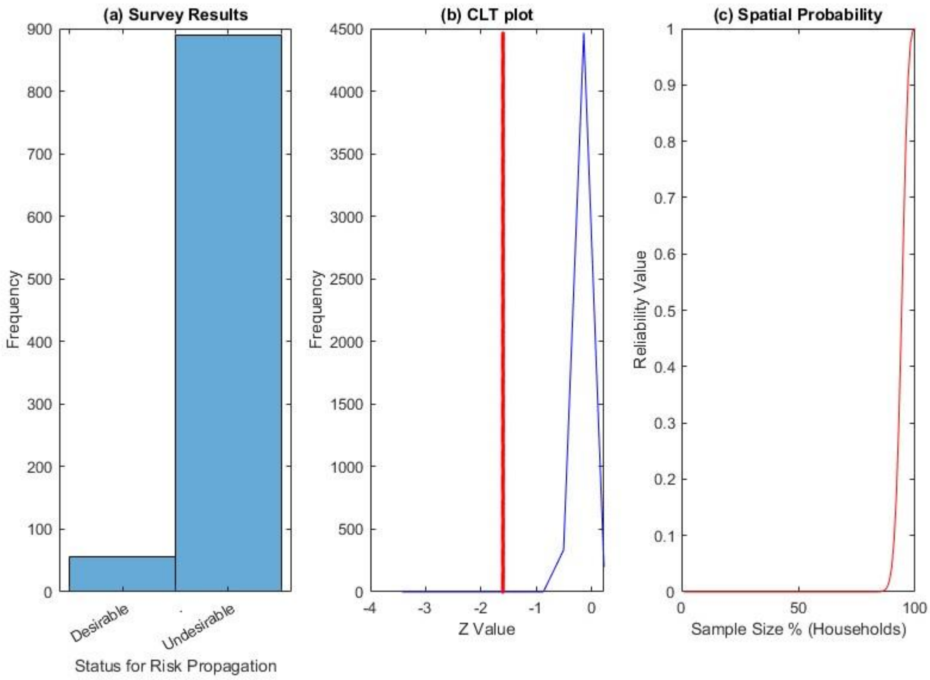

Figure 6-8: Spatial Probability

Following the same approach presented under susceptibility, the reliability values for spatial probability were calculated (Figure 6-8-c). The reliability distribution for spatial probability was developed to determine the effective population required for successful strategy implementation. It was found that at least 85% of households need to be engaged to achieve a significant impact on the community, with the highest reliability reached at approximately 100% of households.

6.4.1.3 Temporal Probability

Here, the focus is on rain-induced landslides in the country; thus, rainfall is a critical temporal factor associated with the occurrence of landslides. Landslide early warnings are issued based on rainfall monitoring, and if the threshold limit is exceeded, these warnings are activated. Currently, the National Building Research Organisation (NBRO) has established threshold limits for landslides in the country. Specifically, a landslide watch level is declared when rainfall exceeds 75 mm within a 24-hour period. Additionally, amber and red warnings are issued if rainfall surpasses 100 mm and 150 mm, respectively, within the same timeframe.

The country experiences two primary rainy monsoons, with peak rainfall typically occurring in May and November, periods during which numerous landslide hazards have been recorded. Monthly rainfall data from 2001 to 2023 was obtained from the CHIRPS satellite dataset for the Kalutara district. Figure 6-9 illustrates the variation in monthly mean rainfall throughout this period, providing essential context for understanding the connection between rainfall patterns and landslide susceptibility.

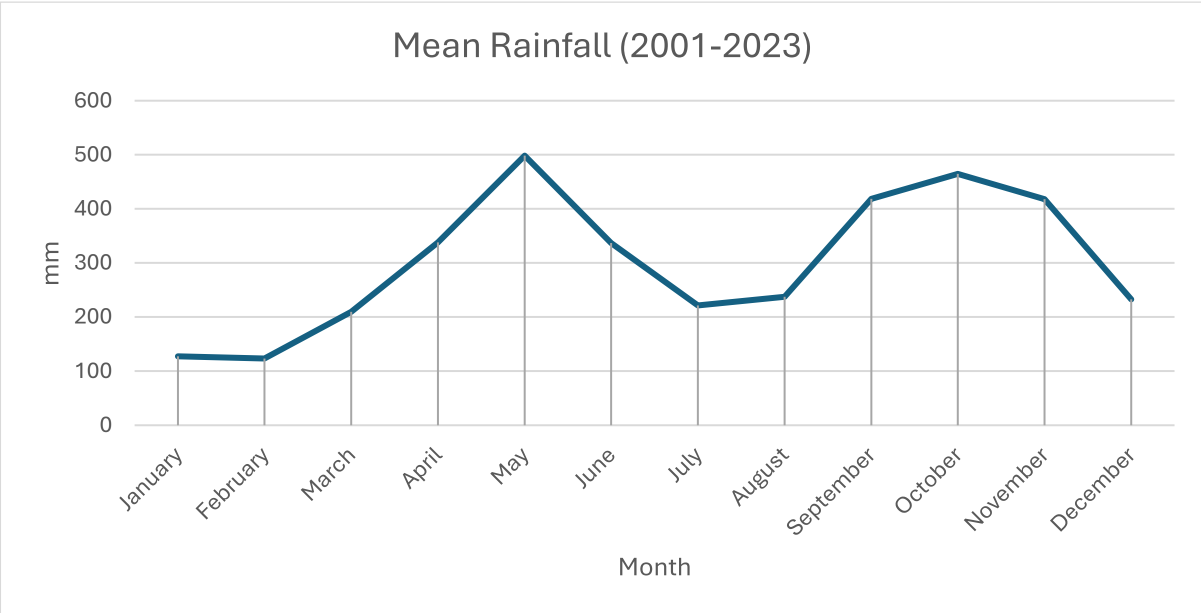

Figure 6-9: Monthly mean rainfall (2001-2023)

However, the majority of landslide events recorded in the country occurred during the months of May, June, October, and November, encompassing both natural slope failures and man-made cutting failures. During this critical period, numerous awareness campaigns and discussions were held within the communities to understand the rainfall conditions and promote disaster preparedness activities.

The survey was conducted to get the community's concern about rainfall as the triggering factor of landslides. Accordingly, the desirability is considered as community believes that the rainfall contributes as a triggering of landslides. Consequently, Central Limit Theorem (CLT) graph was developed to analyse the communities expression on factors contributing to the landslide trigger. The findings reveal that 99.9057% of households believes the rainfall as a triggering factor for initiation of landslides, placing them in desirable conditions for risk propagation, with a mean (μ) of 1.0421and a standard deviation (σ) of 0.1474.

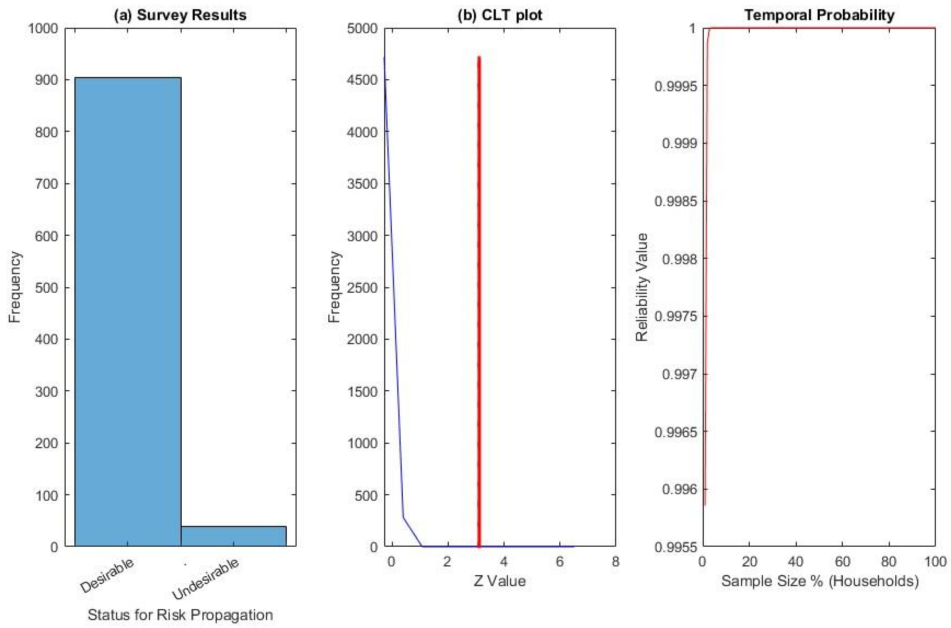

Figure 6-10: Desirable conditions for temporal probability.

The reliability of the strategy is evaluated and presented in Figure 6-10 -c. The results indicate a high-reliability score for the variable, with the highest reliability values achieved by selecting 3% of the households for strategy implementation.

6.4.1.4 Resistance

The parameter of resistance examines the natural forces that mitigate landslide hazards. Among these, slope is a primary factor triggering landslides. Generally, flat land is considered safer than steep slopes when evaluating landslide risk. Therefore, an analysis of house locations was conducted to identify the desirable and undesirable conditions for risk propagation.

For this analysis, slopes were categorised into several segments: flat land (0-11 degrees), gentle slope (11-18 degrees), rolling terrain (18-30 degrees), and steep slope (greater than 30 degrees). Risk propagation is deemed desirable when communities reside in these more hazardous areas; consequently, all houses located outside flat lands were classified as desirable for risk propagation. A Central Limit Theorem (CLT) graph was subsequently developed, revealing that 69.3855% of the variables were classified as desirable for risk propagation, with a mean (μ) of 1.3997 and a standard deviation (σ) of 0.1979.

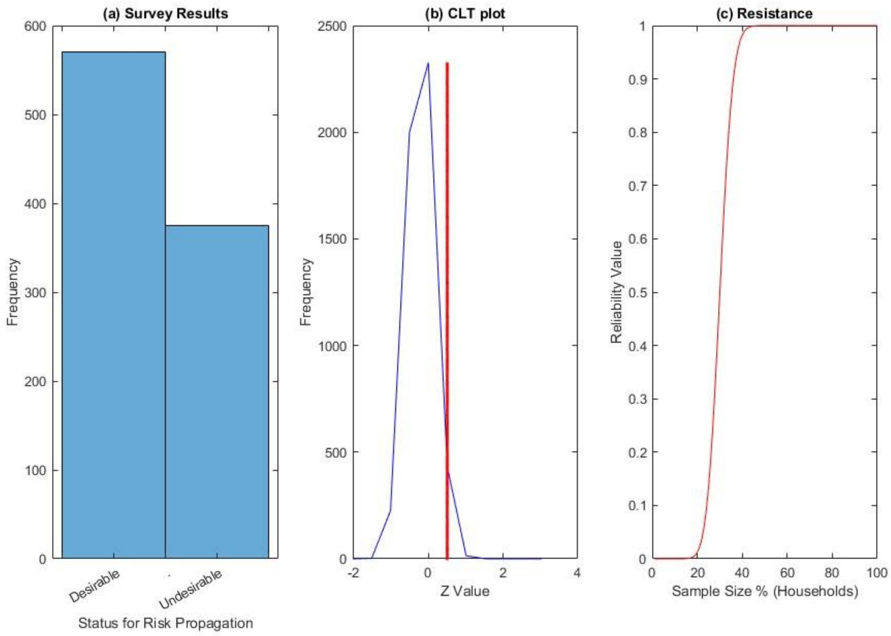

Figure 6-11: Resistance

The reliability of the resistance parameter was calculated, and the distribution curve is presented in Figure 6-11-c. The results indicate that at least 16% of households are required to effectively implement the strategy, while the highest reliability for risk propagation is achieved by selecting 44% of households.

6.4.1.5 Triggering factor

The landslide triggering factor plays a crucial role in initiating landslides. Human intervention, particularly in slope modification during construction, significantly impacts the likelihood of landslide activation. In this context, the number of houses constructed on modified slopes was considered a key triggering factor. The desirable condition refers to the proportion of houses built on these modified slopes. To assess this, a Central Limit Theorem (CLT) analysis was performed, revealing that 38.2740% of the conditions are considered desirable (mean=1.5661; σ=0.2215). Figure 6-12 illustrates both the desirable conditions and the CLT graph for the triggering factor.

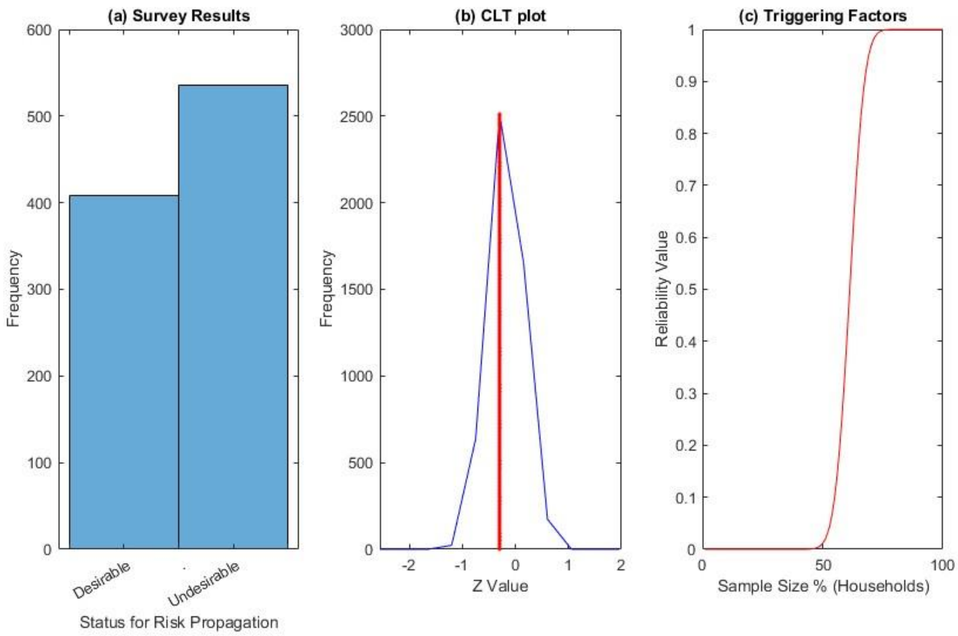

Figure 6-12: Triggering factor: slope modifications

The reliability values associated with the triggering factors were assessed (Figure 6-12-c), indicating that more than 47% of households are required for effective strategy implementation. The highest level of risk propagation is achieved by engaging 76% of households.

6.4.1.6 Magnitude

The magnitude of a hazard significantly impacts the environment. Low-magnitude events result in minimal impacts, while high-magnitude events cause substantial impacts. To assess the magnitude of initiation, this research considered human interventions in slope modification measures. Specifically, this research evaluated the height of man-made cut slopes and their level of protection. The evaluation consists of different scenarios: slopes with complete protection measures, slopes with partial protection measures, slopes without protection measures. Unprotected slopes are considered the most desirable condition for risk propagation, while the other scenarios are viewed as undesirable states. The analysis identified that 18.5547% of the surveyed conditions are desirable (mean = 1.7172; sigma = 0.2429). Figure 6-13 illustrates the survey results along with the Central Limit Theorem (CLT) curve.

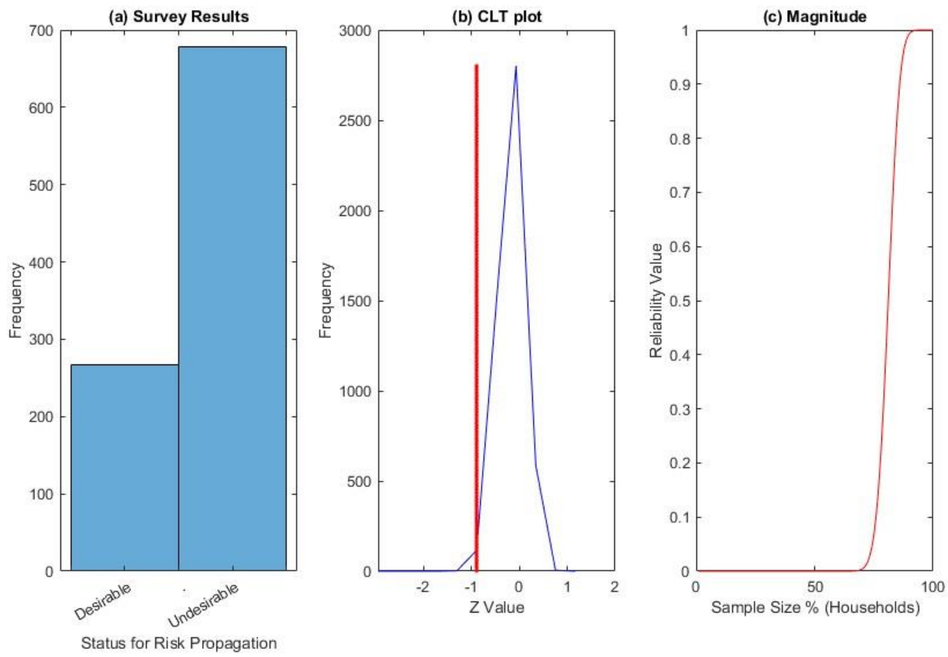

Figure 6-13: Nature of slope cut- Magnitude

The reliability value for risk magnitude was calculated, as illustrated in Figure 6-13-c, which shows the reliability distribution. Risk propagation occurs when the strategy is implemented in more than 70% of households, reaching its peak propagation value at 90% of household implementation.

6.4.1.7 Risk Communication:

This variable examines the presence of disaster management committees and their communication efforts in reducing risk. Village-level disaster management committees facilitate ongoing discussions and monitoring of weather-related or other hazards at the local level. However, survey results revealed that a majority of households (90.5%) were unaware of active disaster management committees in their village. Consequently, only a few households communicated their risks with these committees.

The survey included "Yes," "No," and "Don't Know" responses. The "Yes" response was considered desirable, while "No" and "Don't Know" were deemed undesirable. Values of 1, 2, and 2 were assigned to these responses, respectively, based on their desirability in terms of risk propagation. A CLT graph was developed using 50 elements per cluster across 5,000 clusters. The "Desirable" scenario, defined as a community actively engaged with the disaster management committee, was used as the threshold, with a z-value boundary of -1.3106 (CLTmu = 1.8413; CLTsigma = 0.2604; X = 1.5). This resulted in a calculated probability distribution of 9.4991%.

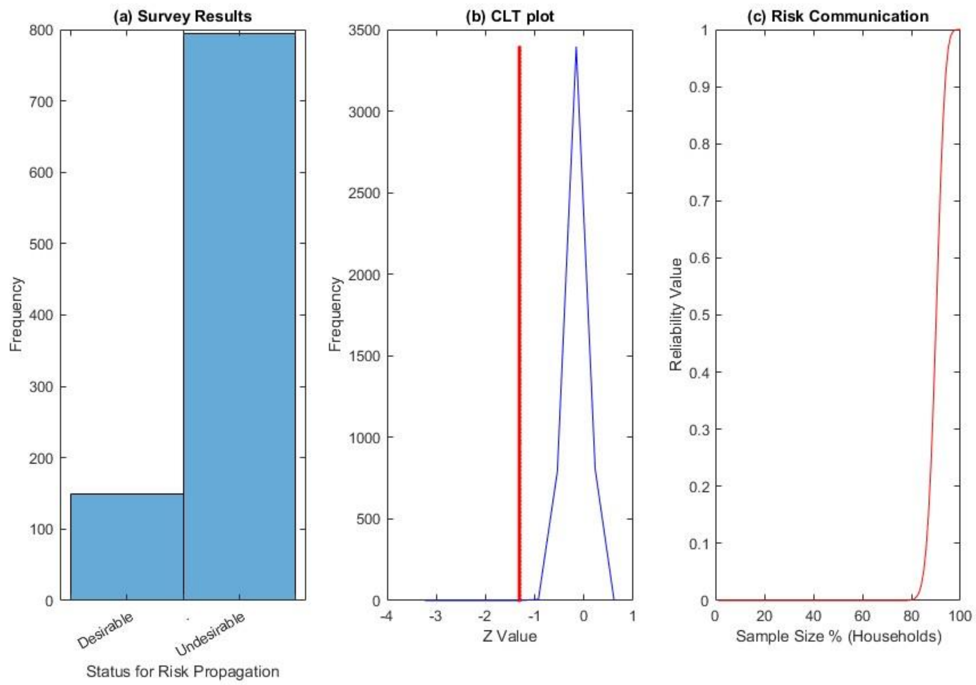

Figure 6-14: Risk Communication

The reliability of the propagation output was calculated, as illustrated in Figure 6-14-c, which displays the risk communication reliability distribution curve. The results indicate that the strategy needs to be implemented in more than 81% of households to be effective, with the highest reliability achieved when over 96% of households participate.

6.4.1.8 Risk Assessment/Evaluation:

This parameter was evaluated to determine the impact of landslide disasters on the community. The outcomes are categorized into three values: "Yes," indicating the community was impacted by a landslide; "No," indicating the community was not affected; and "Don't Know," indicating unawareness about risk assessment or a lack of consideration for risk monitoring. Given the focus on disaster impact experience, the "Yes" response was considered desirable, while "No" and "Don't Know" were considered undesirable.

The graph shows survey results and the application of Central Limit Theorem (CLT) to normalize these values. Responses were reclassified, assigning 1 to "desirable" and 2 to "undesirable." The CLT graph, based on 50 elements per cluster and 5,000 clusters, transforms the data into a Gaussian distribution. The threshold for the "desirable" category was set at 1.5, translating to a z-value of -1.3369. The range, from minus infinity to -1.3369, defines the positive status for risk propagation, with the remaining area as negative (CLT_mu = 1.8497; CLT_sigma = 0.2616; X = 1.5). According to the Z-table, this accounts for 9.0633%.

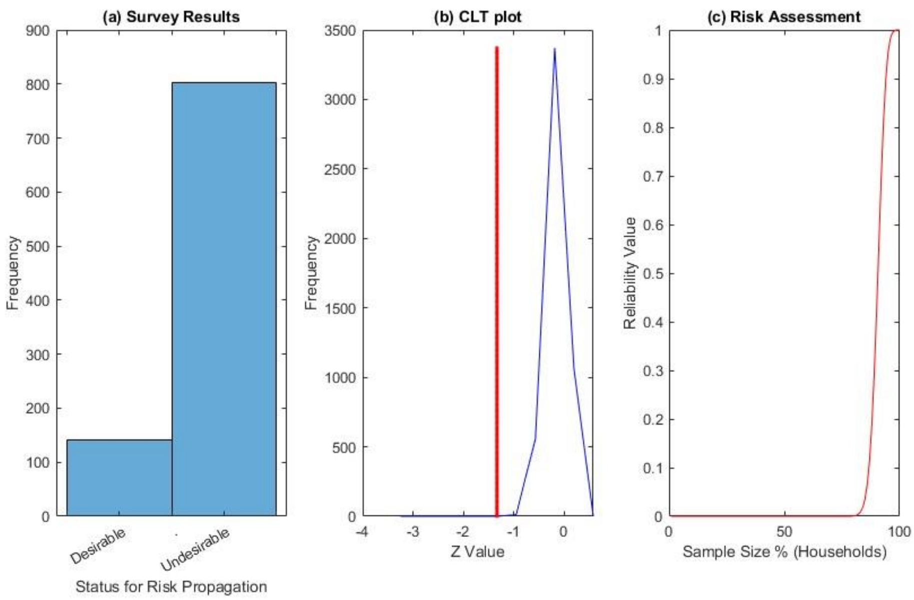

Figure 6-15: Risk Assessment/Evaluation

The risk assessment/evaluation reliability curve was created by aligning the strategy with the targeted population size under existing desirable conditions. Figure 6-15 displays the distribution of reliability values, indicating that the strategy must be implemented in over

80% of households for effectiveness, with peak propagation achieved at 95% implementation.

6.4.1.9 Risk Education:

This parameter evaluates the adequacy of training and education for disaster preparedness activities. Various organizations have conducted programs on preparing emergency kits, relocating to safer areas, constructing drainage systems, and cleaning. Households that received any training were marked as "Yes," while those that did not were marked as "No." The "Don't Know" category indicates a lack of familiarity with disaster awareness programs**.**

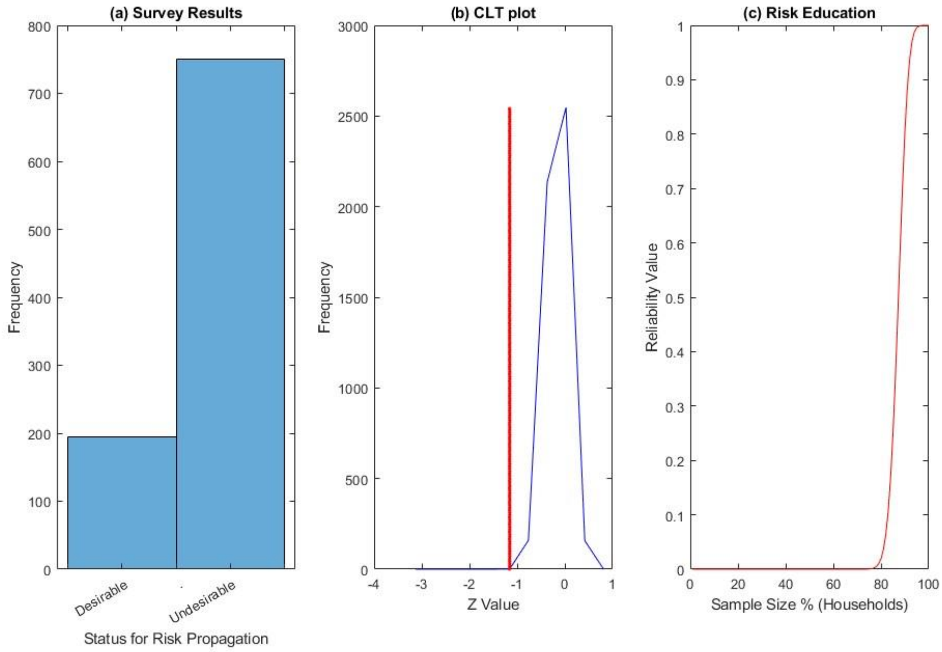

Figure 6-16: Risk Education

The parameter values were reclassified from nominal to scale categories based on their relevance to risk propagation. "Yes," "No," and "Don't Know" responses were converted to 1, 2, and 2, respectively, with 1 labelled as "desirable" and 2 as "undesirable." A CLT graph was created using 50 elements per cluster and 5,000 clusters from the survey data (Figure 6-16). A threshold value of 1.5 was set for the "desirable" category, corresponding to a z-value of -1.1584, indicated by a red line on the graph (CLTmu = 1.7939; CLTsigma = 0.2537; X = 1.5). Thus, the percentage contributing to risk propagation, ranging from minus infinity to -1.1584, is 12.3357%.

The reliability curve for risk education was developed to evaluate the strategy's effectiveness in the community. Risk propagation begins when more than 75% of households are engaged, reaching its peak at 95% implementation.

6.4.1.10 Risk Identification:

This parameter examines the ability to recognize landslide symptoms in one's vicinity. The survey focused on areas with a high probability of landslides, as determined by the country's technical agency for landslide risk monitoring through susceptibility mapping. These areas may exhibit landslide symptoms noticeable by experienced community members or individuals. Hence, the users' capability to identify such symptoms was assessed through targeted questioning.

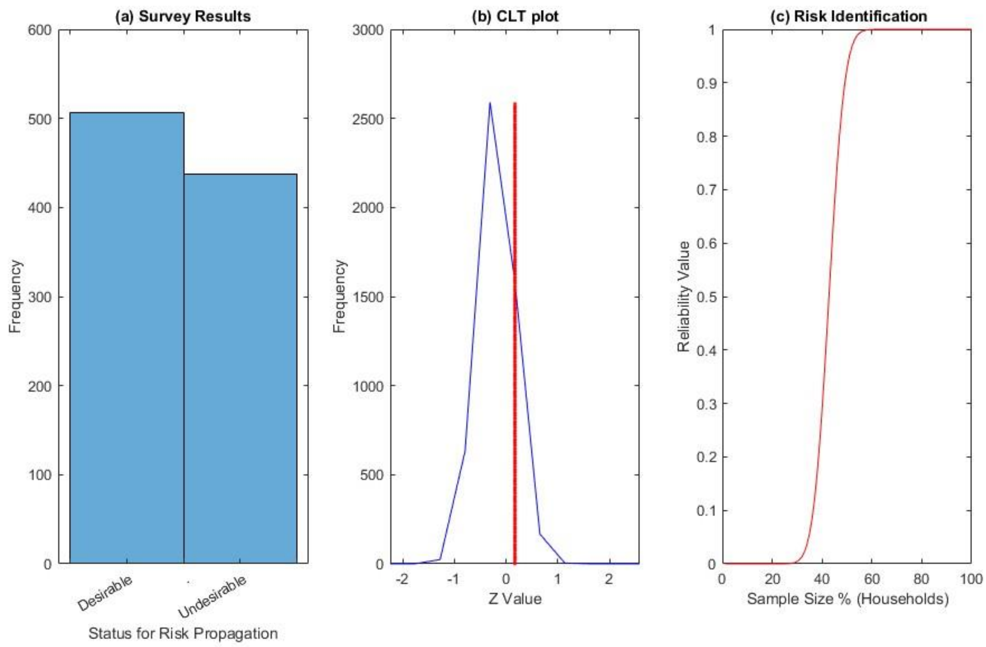

Figure 6-17: Risk Identification

According to the survey, 7.06% of households reported having more than one landslide sign, and 46.67% had one sign in their vicinity. The categories were reclassified to reflect their capacity to transfer risk to other sectors, with the lowest value assigned to the category with the highest transferability potential, and the highest value assigned to the lowest transferability potential. Consequently, the reclassified values are as follows: more than one sign (1), one sign (1), no sign (2), and don't know (2).

A CLT graph was developed using this reclassified dataset, with 50 elements per cluster across 5,000 clusters (Figure 6-17). The boundary was set at the one-sign margin. On the category axis, a value of 1.5 corresponds to a z-value of 0.1692 (CLTmu = 1.4649; CLTsigma = 0.2072; X = 1.5). Therefore, the area from minus infinity to 0.1692 is considered to contribute to risk propagation, accounting for 56.7177%.

Figure 6-17-c illustrates the reliability curve for risk identification. Impact propagation occurs with the involvement of over 30% of households, peaking at more than 55% participation.

6.4.1.11 Risk Perception:

This parameter examines the impact of landslides on houses and the linked infrastructure network. Specifically, it focuses on how landslides affect their buildings and access roads where essential services like water and electricity are located. Responses were categorised into two options: "Yes," indicating that landslides would impact their buildings and their infrastructure access, and "No," indicating that the building and access would not be affected. The "Yes" option was deemed desirable, with a calculated prevalence of 17.4659% (mean = 1.7288; sigma = 0.2445).

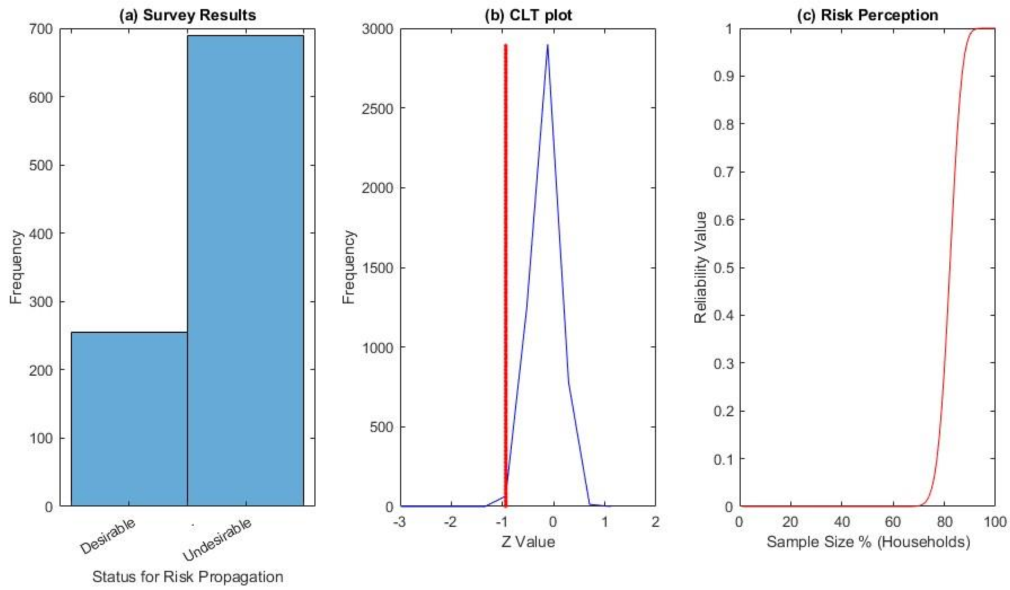

Figure 6-18: Risk Perception on landslide impacts on infrastructure facilities

The reliability level for risk perception was calculated as described beforehand. The resulting distribution curve is presented in Figure 6-18-c. For any strategy related to risk perception to effectively propagate its impact to adjacent nodes, it must be implemented in over 75% of households. Maximum propagation is achieved when more than 95% of households are engaged.

6.4.1.12 Risk Matrix

The risk matrix evaluates the level of threat faced by the community and emphasises the importance of assessing risk levels to define community engagement. The village Disaster Management Committee facilitates discussions and conducts awareness programmes, mock drills, and participatory activities. In most cases, the community have a discussion between themselves before acting on specific uncontrollable activities. For instance, the community act together to make their resettlement decisions. Accordingly, the survey asked whether the community is involved in disaster management activities. Responses were categorized as "Yes" or "No," with the "Yes" option deemed desirable for risk propagation. The results indicate that this desirable condition for risk propagation was found in 6.4266% of responses (mean = 1.9107; sigma = 0.2702). Figure 6-19 displays the survey results alongside the CLT graph for the risk matrix.

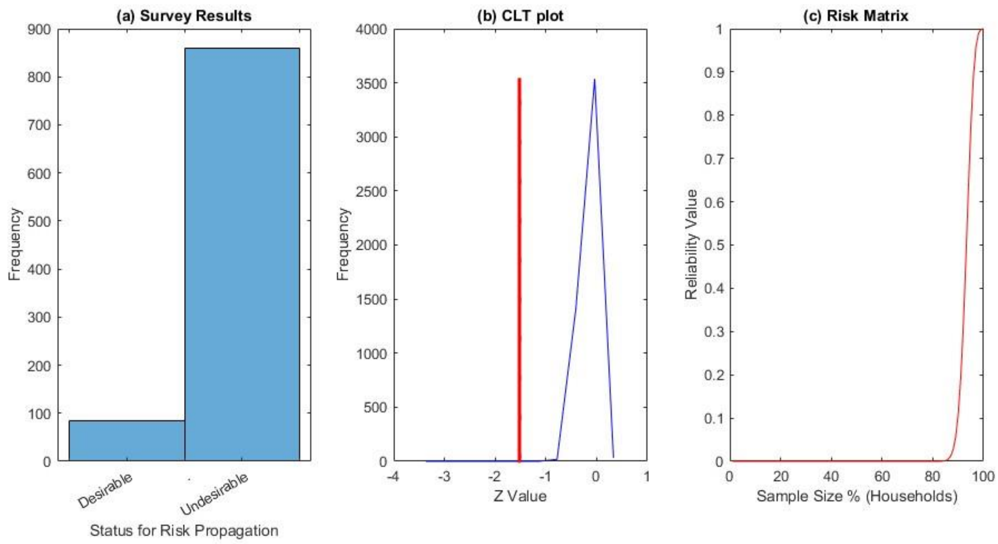

Figure 6-19: Risk Matrix-engage with DM activities

The reliability curve for the risk matrix is shown in Figure 6-19. The graph indicates that impact propagation occurs when at least 85% of households are engaged, reaching its maximum level when 100% of households are included.

6.4.1.13 Risk Appetite

This variable examines whether the community has taken precautions against prevailing hazards over the past three years, based on their risk status. The survey responses were limited to two options: "Yes," indicating that the community has engaged in disaster risk reduction efforts, and "No." The "Yes" response is considered the desirable condition for risk propagation. The collected data were then converted into a normal distribution using the Central Limit Theorem (CLT), revealing desirability for risk propagation of 5.5351% (mean = 1.9369; sigma = 0.2739).

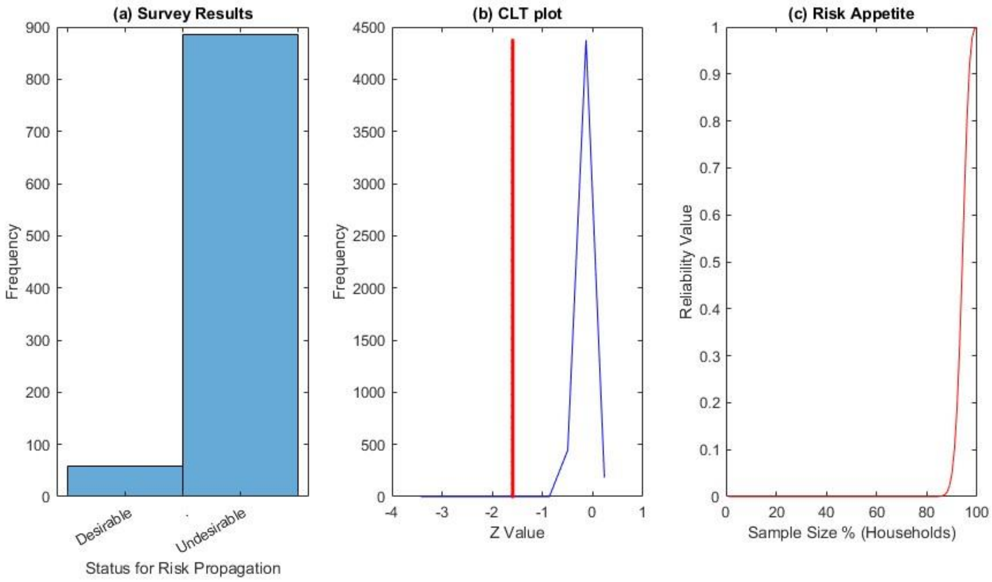

Figure 6-20: Risk Appetite (Taken DM action within last 3 years)

The reliability curve for assessing risk appetite is presented in Figure 6-20-c.The results indicate that more than 85% of households must be engaged for effective implementation, with maximum reliability achieved when the strategy encompasses all households.

6.4.1.14 Resilience

Resilience can be examined across multiple dimensions, including social, economic, environmental, physical, and governance. In this research, only the physical environment was considered, with the physical condition of buildings serving as the measure of resilience. This evaluation includes the materials used in construction, categorising buildings as permanent or temporary (Census and Statistics Department, 2001). Accordingly, floor, wall and roof materials were considered and categorised based on their permanent condition.

The analysis focused on the floor construction materials, identifying "Cement" and "Concrete" as permanent materials, while "Mud" and "Other" materials were classified as temporary. Thus, temporary materials were considered associated with desirable conditions for risk propagation, whereas permanent materials were considered to introduce undesirable conditions. The resulting CLT graph (Figure 6-21), derived from the dataset, indicates a 37.5403% prevalence of desirable conditions (mean = 1.5705; sigma = 0.2221; z = -0.3176).

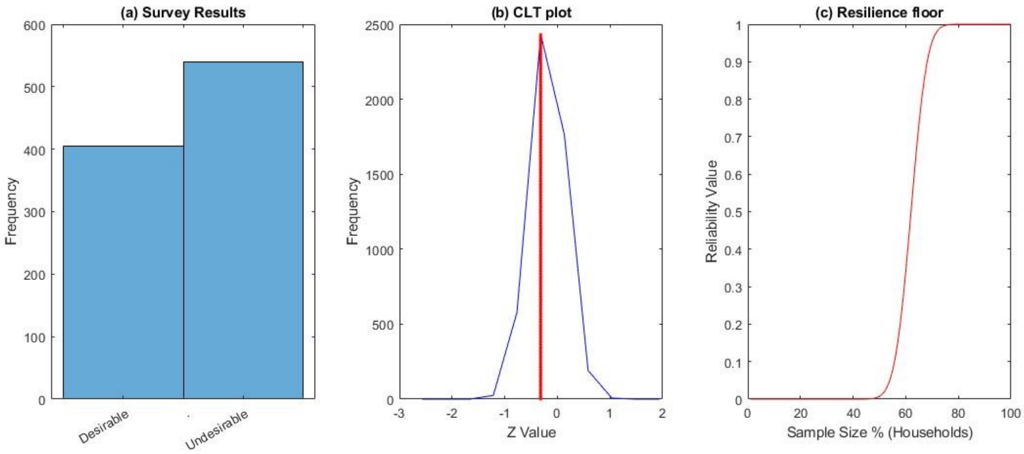

Figure 6-21: Floor materials

The materials used for wall construction were analyzed. "Small bricks," "large bricks," and "blocks" were classified as permanent materials, while "clay" and "other materials" were categorized as temporary materials. Temporary materials are associated with desirable conditions for risk propagation, whereas permanent materials are considered undesirable. A CLT graph was created by considering the wall materials. According to the graphs, 48.9419% is identified as desirable for risk propagation (mean = 1.5056; sigma = 0.2129; z = -0.0265).

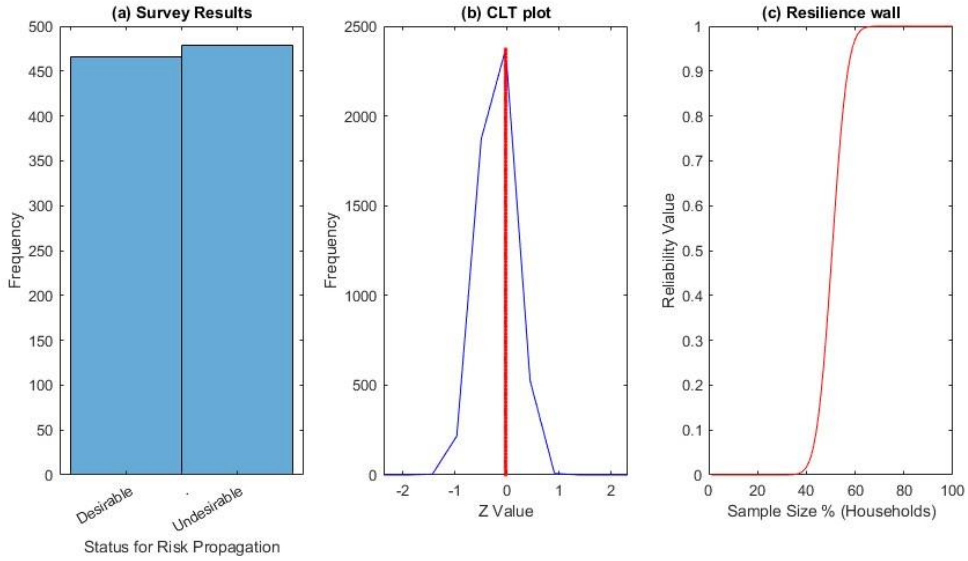

Figure 6-22: Wall Materials

The roof materials were also analysed to identify permanent houses. "Tile" and "Asbestos" were classified as permanent materials, while "Iron sheets" and "Other" categories were considered temporary materials. A CLT graph was developed to reflect the desirable status, with temporary materials representing a desirable condition for risk propagation and permanent materials indicating an undesirable condition. The results show that 26.1578% of the cases fall into the desirable state (mean = 1.6489; sigma = 0.2332; z = -0.6385).

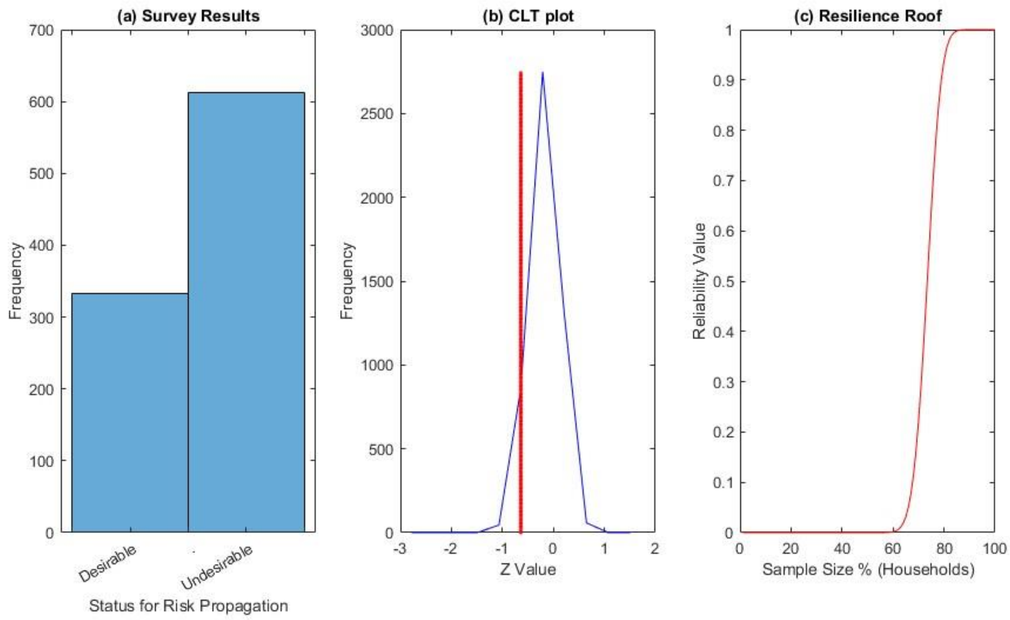

Figure 6-23: Roof Materials

Resilience is represented by the permanent houses constructed within the community, necessitating that the roof, wall, and floor materials be permanent. A composite curve was developed by aggregating the mean and standard deviation values. The following table illustrates the distribution of permanent and temporary housing materials.

Table 11: Resilience: Desirable condition for risk propagation

	Floor	**Wall**	**Roof**	**Composite**
Mean	1.5705,	1.5056,	1.6489;	4.725
Std. deviation	0.2221	0.2129	0.2332	0.3860
Margin z-score	-0.3176	-0.0265	-0.6385	-0.3238
Desirable condition	37.5403%	48.9419%	26.1578%	37.45%

The composite value could be calculated by considering the following steps.

1. Composite mean: adding all mean values together.
2. Composite standard deviation: adding the square value of each standard deviation, and taking the square root. E.g., $[(\text{std. floor})^2 + (\text{std. wall})^2 + (\text{std. roof})^2]^{1/2}$
3. Composite z-value: Initially, the desirability marginal values of each variable need to be added together (X), and use the standard z-value calculation equation. Accordingly, composite Z value = [(X- Composite mean)/(Composite Std.)]
4. Calculate the desirable percentage: Refer to the z tables to get the percentage value.

The results indicate that only 37.45% of the community is classified under desirable conditions for risk propagation.

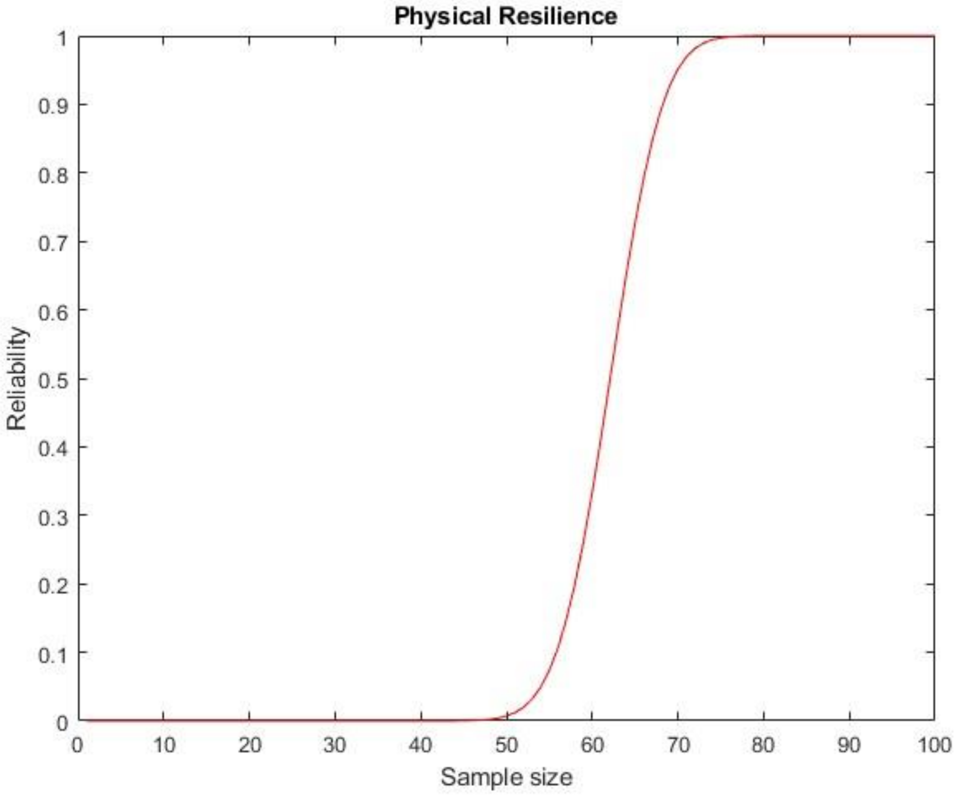

Figure 6-24: Reliability curve for physical resilience.

The reliability curve for physical resilience is illustrated in Figure 6-24. The results indicate that over 50% of the population must be engaged for effective risk propagation, with maximum propagation achieved when activities involve 75% of the population.

6.5 Dataset Application to the System Dynamic Model

Table 12 presents the distribution values for each dynamic variable applied to the system dynamics model. Additionally, it describes specific data, captured from the NBRO's dataset.

Table 12: Description of dataset considered to the simulation

Dynamic variable	**Description of the information**	**Normal distribution curve values**
Temporal distribution	NBRO's household survey results were used to understand community	99.9027% (mu=1.0430, sigma=0.1475)

	perceptions about the temporal distribution. The findings revealed that 99.9% of the surveyed communities believed that rainfall significantly triggers landslides.	
Magnitude	The households with a significant threat from the cutting failure were considered as input to the model. Accordingly, 18.4% of communities are living closer to hazardous slope cuts.	18.4090% (mu=1.7187, sigma=0.2431)
Triggering factors	The land morphological changes due to construction or other agricultural activities were considered. Accordingly, 38% of communities have already modified the ground for development.	38.0106% (mu=1.5677, sigma=0.2217)
Susceptibility	The information was collected through the dataset to understand the community's understanding of landslide susceptible conditions in their vicinity. Accordingly, more than 66% of communities believe that they are living in a landslide susceptibility zone.	66.2749% (mu=1.4159, sigma=0.2002)
Spatial probability	The landslide impact-reaching probability was considered. Accordingly, 5.4% of the community believes their houses are in a landslide-reaching probability zone.	5.4038% (mu=1.9411, sigma=0.2745)

Resistance	Taking the level of granularity, the slope and drainage datasets for the study area were utilised to calculate the resistance parameter. Normal distribution curves were developed for each variable to obtain a composite value. It was found that 69.9% of the community resides in steep slope areas, while 98.9% faces issues with the drainage network, including the absence of drains or poorly functioning drains. The composite value indicates that 96.8% of the community experiences landslide resistance issues.	Steep slope: 69.9686% (mu=1.3966, sigma=0.1975) Drainage: 98.9165% (mu=1.1323, sigma=0.1601) Composite: mu=2.5289, sigma=0.2542, X=96.808%
Risk communication	The existing level of communication for preparedness at the household level was taken as an input value for the system dynamics model. Accordingly, only 9.5% of the community reported having received information regarding preparedness actions.	9.5038%, (mu=1.8412, sigma=0.2604)
Risk identification	The presence of observable indicators of landslide risk in the local environment, such as cracks in the ground or changes in vegetation, was noted. Observations collected through the survey indicated that 57.57% of the community were able to recognise the symptoms of landslides in sloped areas.	57.5746% (mu=1.4605; sigma=0.2066

Risk Education	The level of awareness and training received by community members regarding how to prepare for and respond to landslides was evaluated through the survey. Accordingly, 12.34% of the community reported having knowledge of landslides and their potential consequences.	12.3368% (mu=1.7939, sigma=0.2537)
Risk Assessment	The community's engagement in risk assessment and evaluation activities was included as an input to the model. Accordingly, only 9.02% of the community reported being familiar with assessing and evaluating the risks in their living environment.	9.0286% (mu=1.8504, sigma=0.2617)
Risk Perception	The survey assessed how communities perceive and understand the effects of landslides on local infrastructure and their livelihoods, as these perceptions can influence response actions and preparedness. Accordingly, 17.35% of the community demonstrated a comparative understanding that positively impacts risk propagation.	17.3471% (mu=1.7301, sigma=0.2447)
Risk matrix	The survey examined the community's past actions regarding disaster risk reduction, including participation in awareness programmes, training sessions, and community-based risk reduction activities. Accordingly, only	6.4627% (mu=1.9097, sigma=0.2701)

	6.46% of the community reported having engaged in risk quantification activities.	
Risk appetite	The survey results were captured to understand the experience of conducting risk reduction activities to mitigate prevailing landslide risk by communities. Accordingly, 5.5% of the community reported having experienced the implementation of landslide risk management activities.	5.5037% (mu=1.9379, sigma=0.2744)
Resilience	Building materials were assessed in three categories: roof, wall, and floor. Accordingly, 26.3% of households showed resilience in their roofing materials, 48.74% in their wall materials, and 37% in their flooring materials. Overall, 28% of the community is considered to have resilience.	Roof: 26.3084% (mu=1.6477, sigma=0.2330) Wall: 48.7361% (mu=1.5068, sigma=0.2131) Floor: 37.5965% (mu=1.5702, sigma=0.2221) Composite: mu=4.7247, sigma=0.3860 X=28.024%

6.6 Desirable State for Risk Propagation by Characteristics

The desirable statuses for all parameters were calculated, and the following table summarises the conditions for risk propagation. Notably, temporal distribution exhibits the highest desirable state at 99.9057%, while spatial probability shows the lowest desirable condition at 5.403%. In addition, the table shows the minimum and maximum performance sample sizes, showing the required sample for the implementation of each risk characteristic.

Table 13: Desirable condition for risk propagation by each variable

Risk characteristics	**Desirable conditions for the risk propagation (%)**	**Population sample size**	
		Minimum performance sample size %	Maximum performance Sample size %
Risk assessment/evaluation	9.0633	80	95
Risk education	12.336	75	95
Risk identification	56.717	30	55
Risk communication	9.4991	81	96
Risk perception	17.467	75	95
Risk matrix	6.4266	85	100
Risk appetite	5.5351	85	100
Resilience	37.45	50	75
Resistance	69.3855	16	44
Susceptibility	66.41	20	35
Triggering factors	38.274	47	76
Spatial distribution	5.403	85	100
Temporal distribution	99.9057	0	3
Magnitude	18.5547	70	90

6.7 Calculation of Reliability of Loops

The system dynamics model identified fourteen loops corresponding to fourteen distinct strategies, with a focus on the most applicable strategies across various scales. For instance, some strategies may target specific households, while others can be implemented as large-scale initiatives, such as awareness programmes for the entire community within a village.

Figure 3 illustrates these identified strategies, which have been classified into two levels: institutional and community engagement. Strategies that are linked to risk perception are particularly noteworthy, as they emphasise active community participation in disaster risk management.

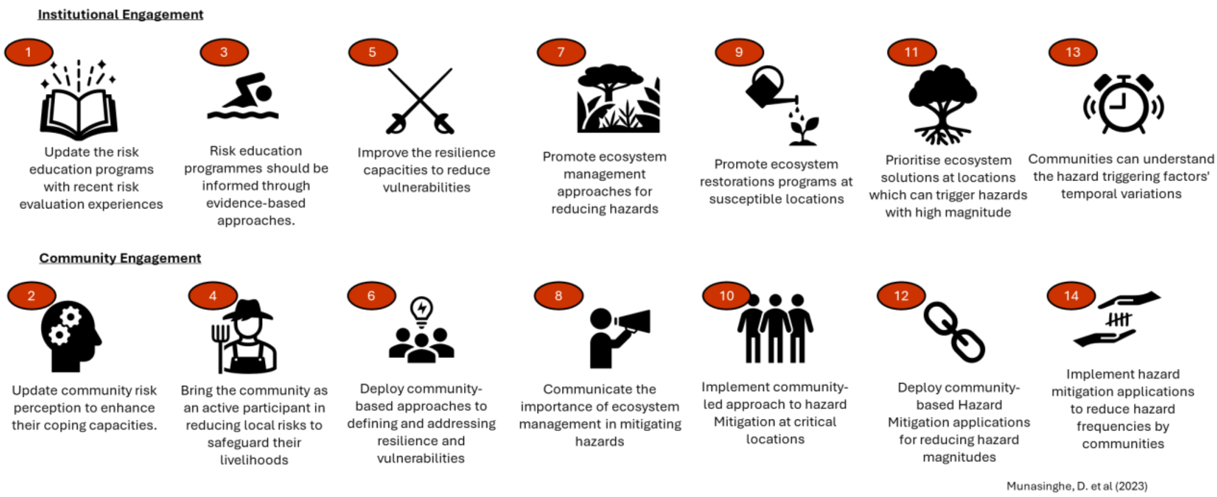

Figure 6-25: Identified strategies

To accurately simulate the behaviour of each causal loop associated with the corresponding strategies for risk management, it is essential to determine an appropriate sample size to ensure reliable output. In this context, the targeted population size (or focused population) was adjusted to evaluate the reliability of each causal loop effectively.

To calculation process of reliability, consider Loop 1, which focuses on updating risk education programmes based on recent risk evaluation experiences. This loop consists of four key characteristics: Risk Assessment/Evaluation, Risk Education, Risk Identification, and Risk Communication. Reliability curves for each of these characteristics were generated (Figure 6-26), and the average values were combined to create a composite reliability graph. This approach allows for a clear understanding of the overall reliability of the loop based on its individual components.

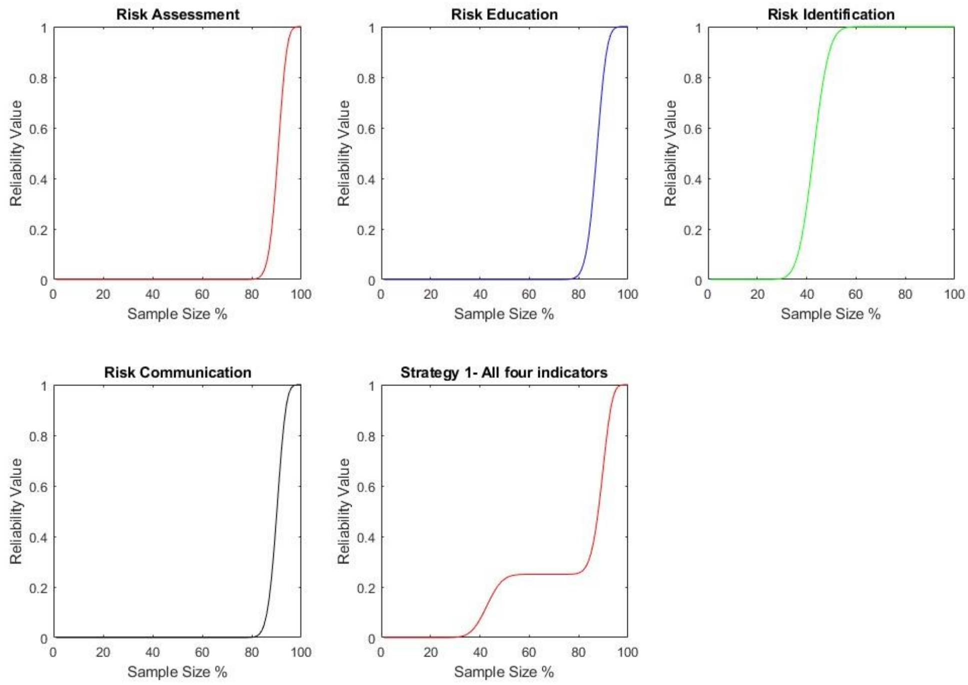

Figure 6-26: Reliability curves of each loop 1 variables

Accordingly, the composite reliability value was calculated by taking the mean of reliability curves. Similarly, the overall reliability of each of these loops was computed by aggregating the reliability values of the individual nodes within that loop.

Figure 6-27 shows the reliabilities of each strategy with the targeted population. The x-axis represents the population sample size, and the y-axis represents the reliability value of each pathway.

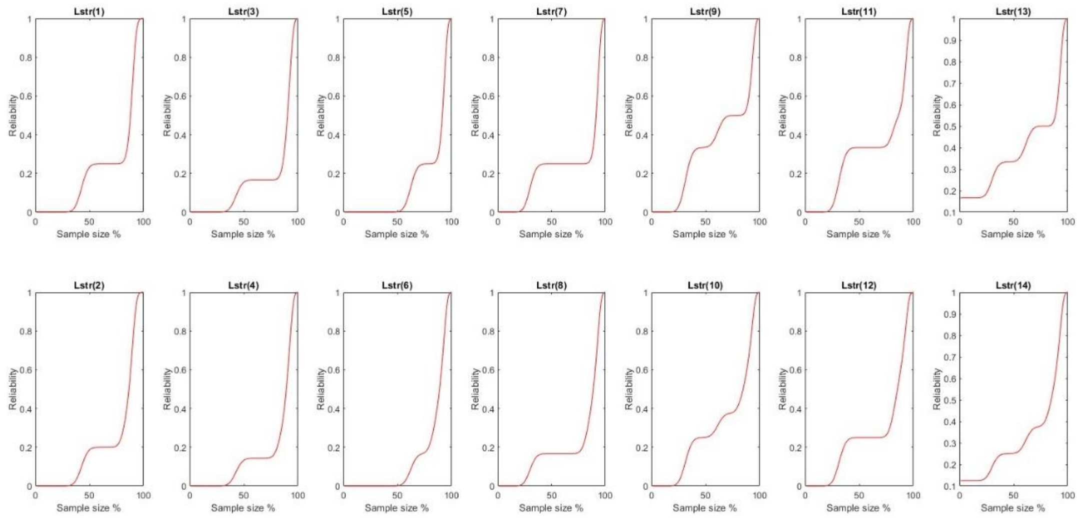

Figure 6-27: Composite Risk Propagation for all strategies.

Table 14 below shows the identified generic patterns in these graphs. Several observations on the graphs were identified, and their interpretation is discussed in the table.

Table 14: Observations on the strategy's reliability curves

Observation of the graph	**Interpretation**
Zero reliability value was observed for a certain level of the sample population. (strategies 1-12)	This includes a strategy that needs a considerable sample size to initiate the work. These activities cannot be conducted with a small sample population.
Some activities have initial reliabilities at the zero-sample size. (Strategies 13-14)	This implies that the community has some knowledge of some aspects of the strategy. These activities can be started with a small sample population.
Several steps on the curve (Strategies 5-14)	Some graphs illustrate several steps, representing several size of samples are required to enhance their reliabilities.

Reliability reaches Max when working with the entire population (all strategies)	The strategies are effective when the entire population is concerned about DRR activities.

According to the output graphs, the first six strategies cannot commence with a small sample size, requiring more than 40% of the population to reach a more reliable state. The first four strategies are associated with vulnerability reduction and long-term risk mitigation. In contrast, the last eight strategies (7-14) can be initiated with a smaller population size, as these are linked to hazard mitigation. Generally, hazard mitigation activities can be carried out with small community groups, focusing on local levels of risk reduction.

6.8 Investigating Best Strategies for Palindanuwara

Designing the best strategies for risk reduction is a crucial task that assists decision-makers in achieving resilience within a specified timeframe. The model simulates the most effective approaches to mitigate the consequences of hazards faced by the community. Here, the consequences are monitored through outputs, and the most appropriate strategies are selected based on the following assumptions:

- The strategy should aim to reduce the impact on and exposure of communities. (Values for Disaster Impact Stock and Exposure Stock should be negative.)
- The strategy should aim to improve the safety of communities and the environment. (Values for Built-up Stock should be positive.)

Accordingly, a Monte Carlo simulation was employed to select the best strategies by randomly varying parameter values and measuring the resulting outputs.

The Palindanuwara dataset was utilised, with input risk characteristic parameters being randomly altered at specific intervals to measure their impact over time. All data were recorded using the AnyLogic application and subsequently transferred to the SPSS application for in-depth analysis.

The correlation between the *loops corresponding to the* strategies and output values *(stocks)* provides crucial insights for selecting the most suitable strategy for *reducing the risk in an area*. The data were collected by randomly distributing input values and capturing the corresponding outputs. A total of 800 simulations were conducted, each recording the specific characteristics, strategies, and output values. The Pearson Correlation, a statistical measure ranging from -1 to 1, quantifies the strength and direction of the linear relationship between two variables. A coefficient close to 1 indicates a strong positive correlation, while a coefficient close to -1 indicates a strong negative correlation. In this context, the Pearson Correlation coefficients help identify how closely related the selected strategies are to the observed output values, thus aiding in selecting the most effective strategies for risk reduction. The table below displays the Pearson Correlation coefficients between the output *stocks* and the strategies.

Table 15: Pearson Correlation between strategies and outputs

Correlations

		St1	St2	St3	St4	St5	St6	St7	St8	St9	St10	St11	St12	St13	St14
Disaster	Pearson Correlation	-.081*	-.088*	-.177**	-.173**	-.248**	-.225**	-.260**	-.232**	-.259**	-.230**	-0.009	-.074*	0.035	-0.040
	Sig. (2-tailed)	0.021	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.808	0.035	0.330	0.253
Exposure	Pearson Correlation	-.081*	-.088*	-.177**	-.173**	-.248**	-.225**	-.260**	-.232**	-.259**	-.230**	-0.009	-.074*	0.035	-0.040
	Sig. (2-tailed)	0.021	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.808	0.035	0.330	0.253
Built-up	Pearson Correlation	0.059	0.068	.143**	.142**	.231**	.176**	.211**	.160**	.258**	.178**	.099**	.083*	0.052	0.051
	Sig. (2-tailed)	0.094	0.055	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.020	0.143	0.154

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The table presents the Pearson correlation coefficients alongside their significance levels. The relationship is strong when the coefficient value is greater than 0.7, moderate from 0.5 to 0.7, and low from below 0.5. A relationship is considered statistically significant if the p-value (Sig. 2-tailed) is less than 0.001. Additionally, negative coefficients denote an inverse relationship between the variables.

In line with the assumptions, St3 to St10 loops show a low-level negative correlation with disaster and exposure, while exhibiting low-level positive correlations with 'Built-up'. The strongest negative correlation is observed with Strategy 7, which focuses on promoting ecosystem management approaches for reducing hazard, while the positive correlation is linked to Strategy 9, which promote ecosystem restoration programmes at susceptible locations.

Figure 6-28 shows the variance of correlation values. Here, the positive correlation refers to the assumption that the strategy should aim to improve the safety of built-up, and the negative correlation refers to the assumption that the strategy should aim to reduce the impact and exposure of communities. Accordingly, Lstr9 has the highest impact on risk reduction, while Lsrt13 and Lsrt14 have the lowest.

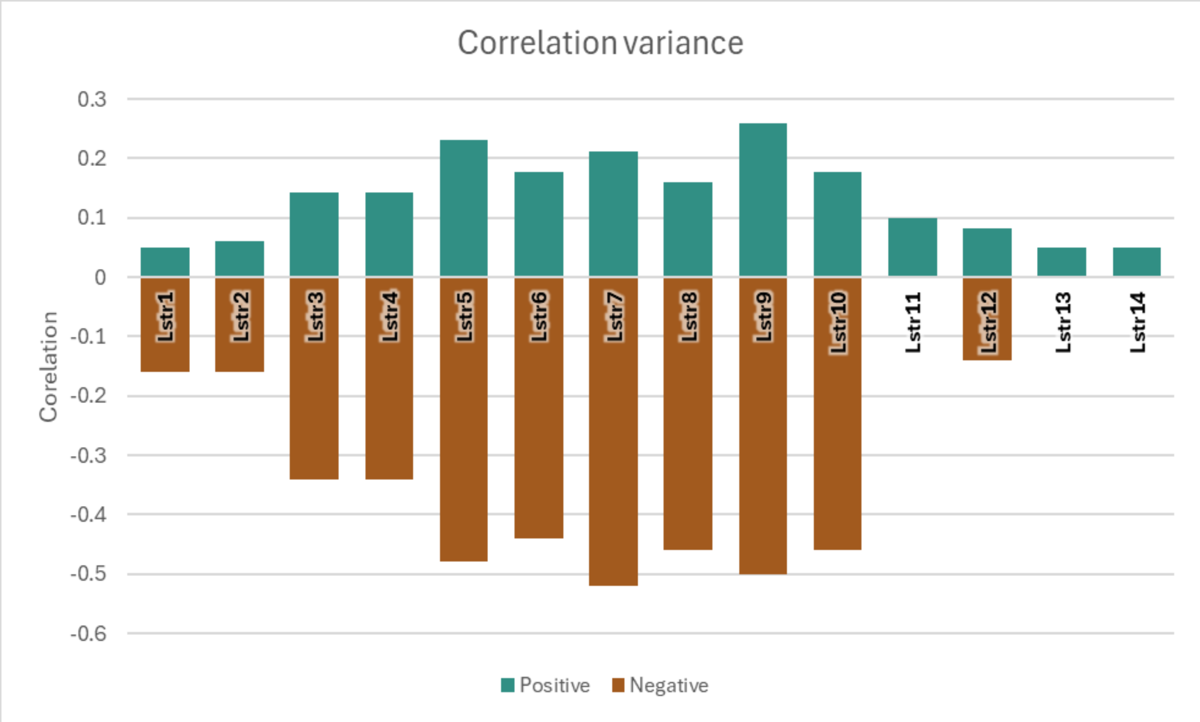

Figure 6-28: Correlation variations (positive and negative)

The system characteristics described above were further evaluated in detail through two intervention projects: one focused on drainage improvements and the other on digital communication. The results of this evaluation are presented in the following section.

6.8.1 Risk Propagation due to Drainage Improvements

Drainage improvement projects are currently being implemented in the Magura East, Diggoda, Addaragoda, Lathpadur East, and Viharagama Grama Niladhari Divisions (GNDs) in the Palindanuwara Division. The urgency for enhanced drainage systems is particularly pronounced in these areas due to their location on geomorphologically sloped terrain. Effective drainage systems can manage water flow to downstream locations, thereby alleviating excess moisture on the slopes. Additionally, horizontal drains play a crucial role by directing water away from failure zones and removing moisture from unstable masses, which reduces the friction coefficient in these areas. By decreasing water flow, these management practices can significantly enhance resistance to hazards.

As a result, these drainage improvement interventions are expected to increase the resistance node value in the system dynamics model within the simulator, subsequently impacting the overall flows, namely, community risk, vulnerability, and hazards, as well as the related stocks (Built-up, Impact, and exposure). Furthermore, this increase in resistance could directly influence the loops associated with strategies 7 to 14, demonstrating the interconnectedness of these factors.

To assess the impact of the increased resistance, the risk propagation simulation was employed. The reliability, sensitivity, and resilience values derived from enhancements to the drainage system were considered key resistance factors in this model. Two primary resistance parameters were incorporated: the presence of drainage networks and the existence of constructions on steep slopes. Currently, the desirability index for the drainage network is an impressive 98.92%, underscoring its vital role in enhancing slope stability and mitigating risk.

The proposed drainage improvement programme is anticipated to directly benefit landslide hazard-prone communities, with a total of 240 households affected (Magura East - 10, Diggoda - 70, Addaragoda - 140, Lathpadura East - 10, and Viharagama - 10). This figure represents the direct benefits to households through the diversion of water into the drainage system; however, the cumulative impact is likely to be more significant, as it also encompasses the broader commuter population.

These drainage improvements are expected to lower the desirability level of risk propagation, illustrating an inverse relationship between resistance and hazard. Consequently, the overall resistance value is adjusted to 96.023%, representing a slight decrease from the previous desirable value of 96.808%, with a reduction of only 0.785%. The simulation was conducted using the developed model, which computed the new status of risk propagation throughout the system.

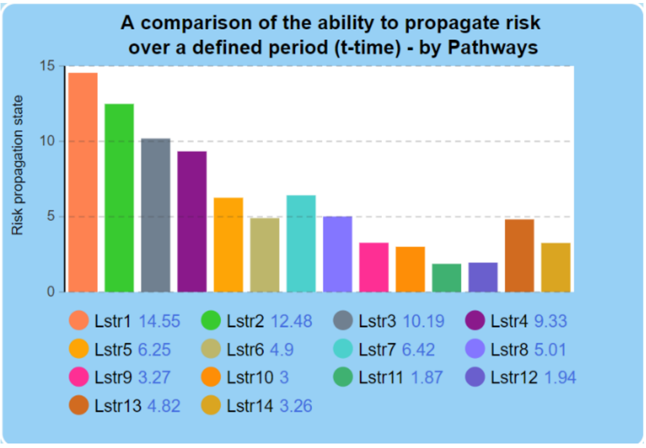

Figure 6-29: Ability to risk propagation (Strategy level)

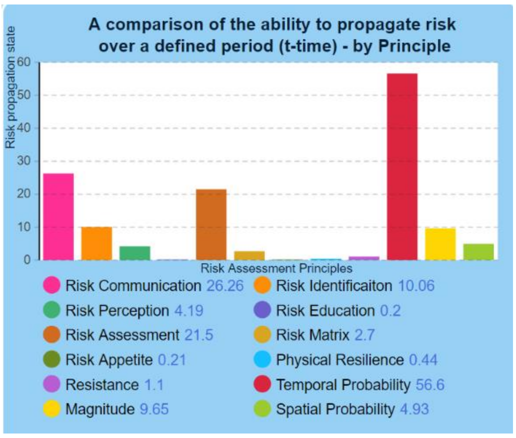

Figure 6-30: Ability to risk propagation (Characteristic level)

In this simulation, an increase in resistance resulting from the drainage intervention was implemented at time = 150 and the impact was measured at time = 320.

Figure 6-29 illustrates the degree of risk propagation across all loops associated with the fourteen strategies. As shown, the loops corresponding to Strategies 1 through 4 exhibit a higher level of risk propagation. In contrast, Figure 6-30 shows the behaviour of individual risk characteristic levels. As shown in Figure 6-30, the introduction of the drainage system significantly influences to risk communication, risk identification, risk assessment, and temporal probability.

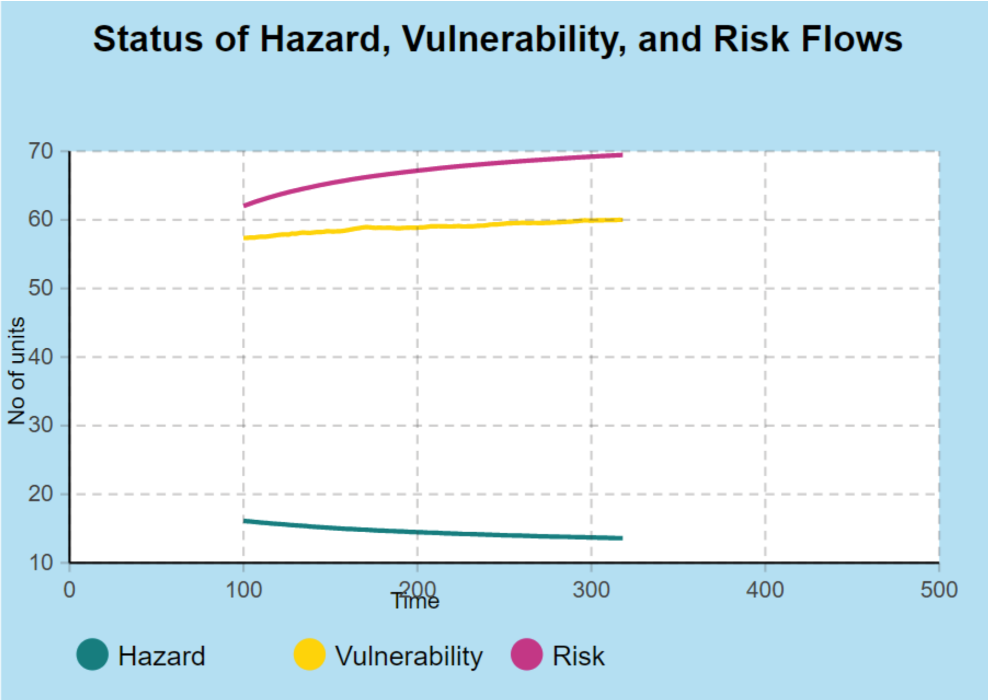

Figure 6-31: Status of hazard, vulnerability, and risk flows without applying any strategies

Figure 6-31, Figure 6-32 and Figure 6-33 below illustrate how the risk propagation depicted in Figure 6-29 and Figure 6-30 affects the flows of hazard, vulnerability, and overall risk. The graph illustrates a decrease in hazards as a result of this intervention, leading to a significant reduction in overall risk levels. An increase in resistance has resulted in a decrease in both the magnitude and spatial probability of hazards, ultimately leading to a reduction in hazards, as illustrated in Figure 6-32 and Figure 6-33.

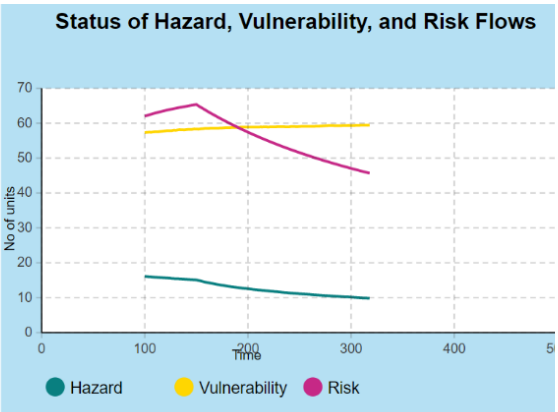

Figure 6-32: Risk input value changes over time

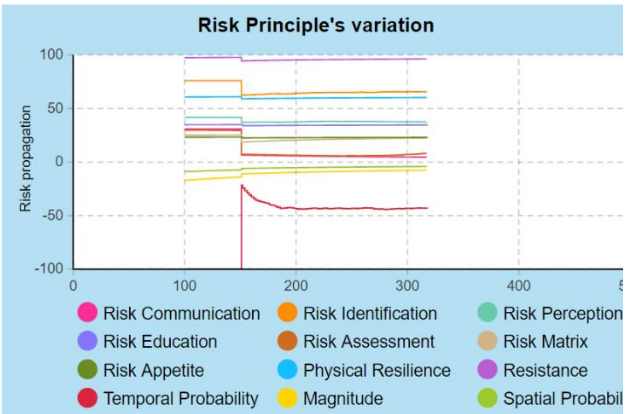

Figure 6-33: Risk characteristic value changes over time

Figure 6-34 and Figure 6-35 below illustrate the behaviour of the stocks: Built up, Exposure, and Disaster Impact in response to the increase in resistance risk characteristics resulting from the drainage improvements. The simulated output demonstrates that the implementation of drainage improvements leads to an increase in safer land by 27.73 units, a increases in exposure by 18.48 units, and increases in disaster impact by 9.25 units, due to existing hazard flow. Thus, it is evident that enhancing the drainage system in the landslide-prone area of Palindanuwara has a substantial impact on improving overall community resilience.

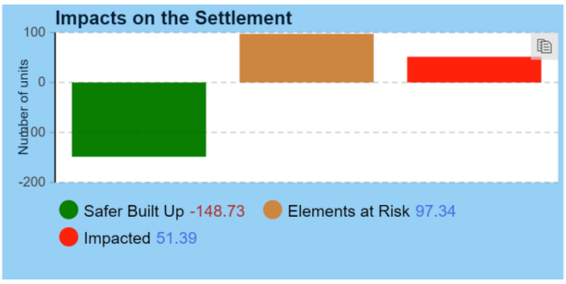

Figure 6-34: Damage statistic at the without any DRR application

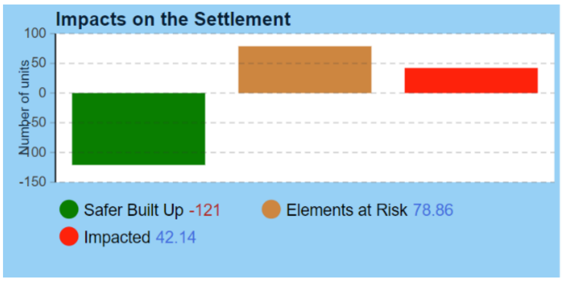

Figure 6-35: Output after the implementing drainage improvement

6.8.2 Risk Propagation Due to Improved Mobile Communication

The Palindanuwara Divisional Secretariat District (DSD) has limited coverage for 2G signals, with only a few areas benefiting from 3G or higher technology. To address this issue, communication infrastructure has been enhanced across several Grama Niladhari Divisions (GNDs), specifically Diganna, Athwelthota, Belahena, Hadigalla, and Ingurudalluwa. This improved infrastructure allows the National Building Research Organisation (NBRO) to maintain regular risk communication with the community, particularly in disseminating early warnings and sharing information about landslide preparedness with residents in these GNDs.

Improvements to the communication infrastructure and associated risk communication activities are anticipated to enhance the risk communication node value within the system dynamics model operating in the simulator. This, in turn, is expected to impact overall flows, including community risk, vulnerability, and the related stocks (community and disasters). Moreover, this increase in risk communication could directly influence the loops linked to Strategies 1 to 4, highlighting the interconnectedness of these factors. The desired transformation rate for risk communication currently stands at 9.5038%, which is relatively low. Nonetheless, with this development, the selected GNDs will be able to communicate risk information effectively, benefiting 172 households. Consequently, the desirability level for risk communication is expected to increase by 17.541%, raising the new value for risk communication to 27.0448%.

The simulation was conducted using the developed model to compute the updated status of risk propagation throughout the system. The risk propagation simulator was first allowed to run for an extended period (t = 150) to achieve stability. Following this, a scenario was implemented in which risk communication was enhanced by 17.541% for 172 households, increasing overall risk communication from 20% to 60%. These input parameters were then entered into the simulator, and the results were generated accordingly.

In this simulation, an increase in risk communication was implemented at time = 150 and the impact was monitored at time = 320.

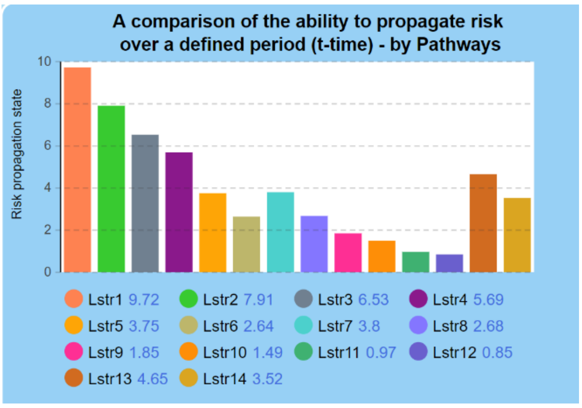

Figure 6-36: Risk Propagation (Strategy level)- after enhancing mobile coverage

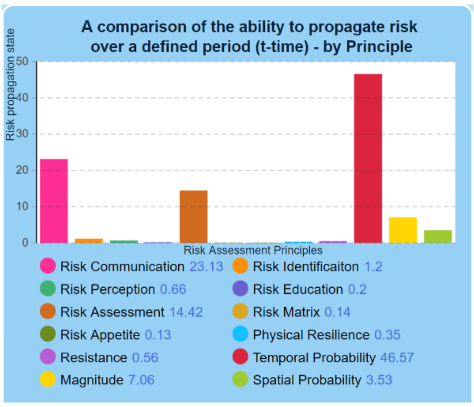

Figure 6-37: Risk Propagation (characteristics level)- after enhancing mobile coverage

Figure 6-36 illustrates the degree of risk propagation across all loops associated with the fourteen strategies. As depicted, the loops corresponding to Strategies 1 through 10 exhibit a gradually decrease of risk propagation, but Strategy 7, 11 and 12 has a little increase. This indicates that the influence of risk communication extends beyond the loops directly associated with the risk communication node, affecting other loops.

Figure 6-37 illustrates the behaviour of individual risk characteristic levels. As indicated in Figure 6-36, the introduction of risk communication significantly influences on risk communication, risk assessment and temporal probability.

Figure 6-38 and Figure 6-39 below illustrates how the risk propagation depicted in Figure 6-36 and Figure 6-37 affects the flows of vulnerability and overall risk. The graph shows a significant reduction in vulnerability and overall risk levels at first, but settling back to a high level, but a lower level than before.

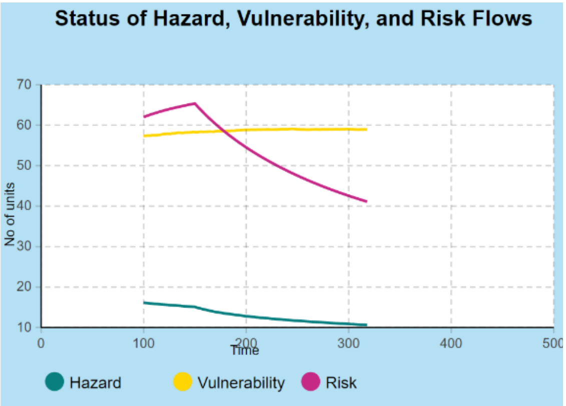

Figure 6-38: Hazard, vulnerability and risk flow status on case study 2

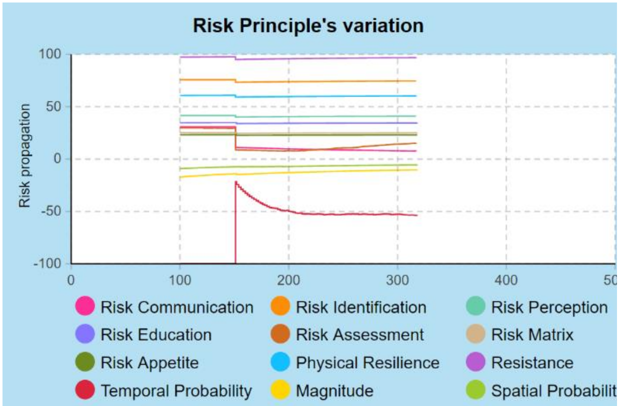

Figure 6-39:Risk characteristic value changes over time (Case S.2)

Figure 6-40 and Figure 6-34 illustrate the behaviour of the stocks: Environment, Community, Exposure, and Disaster Impact in response to the increase in resistance risk characteristics resulting from the improvements to the risk communication. The simulated output demonstrates that the implementation of risk communication improvements leads to an increase in safer built up lands by 35.05 units, while exposures increases by 23.78 units and disasters by 11.27 units, due to existing hazard flow. Thus, it is evident that enhancing risk communication in the landslide-prone area of Palindanuwara has a substantial impact on improving overall community resilience.

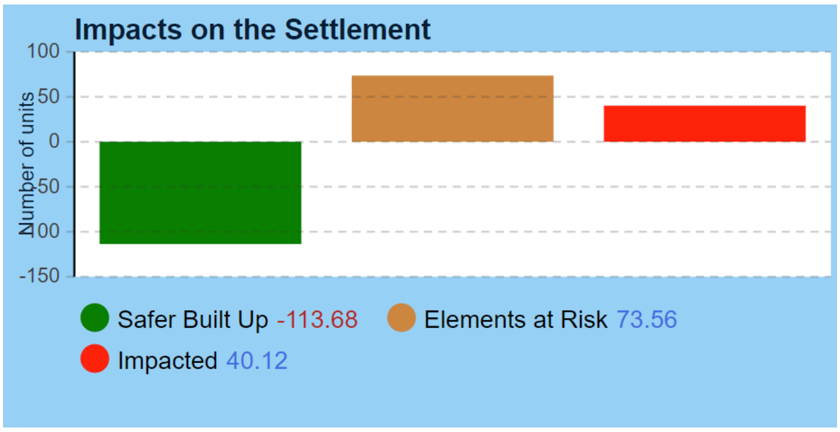

Figure 6-40: Output graph of improving the mobile coverage

6.9 Validation Methodology

This section presents the outcomes of the expert interviews conducted to evaluate the benefits of the simulator for decision-makers. Insights from stakeholders at various levels were collected to assess the advantages of the model outputs. To facilitate this feedback, the following questions were posed after presenting the model's characteristics and its capacity to evaluate the impacts of the two interventions discussed earlier:

- Do you agree that the defined strategies can be effectively applied to enhance landslide resilience?
- In what ways can the proposed system serve as a decision-making tool for building resilience, and how does it influence decision-making ?
- How do you perceive the potential application of the model in other fields?

Interviews were conducted with the twelve practitioners who possess extensive knowledge and experience in relevant fields. These stakeholders were carefully selected based on their close ties to the community and government, ensuring informed and relevant feedback.

Figure 6-41: Stakeholder discussion (Palindanuwara Divisional Secretary)

The table below presents the positions of each stakeholder within their respective fields.

Table 16: List of Stakeholders

Stakeholder Identification	Designation	Experience
SID1	Former director of the National Building Research Organisation, Sri Lanka,	More than 30 years of experience in landslide risk management in Sri Lanka.
SID2	Former Director of Asian Disaster Preparedness Center, Thailand.	Over 30 years of experience in landslide risk management in Asian countries.
SID3	Disaster Risk Management Expert, World Vision.	Over 15 years of disaster risk management experience and community-based disaster risk management activities.
SID4	Disaster Management Expert, working on UN agencies as a DRR consultant/ expert.	Over 25 years of experience in landslide risk management, urban resilient planning, and international coordination

		between the country's risk management institutes.
SID5	District Officer, National Building Research Organisation.	More than 15 years of experience in landslide risk investigation, coordination, and management at the district level (regional level).
SID6	Disaster Risk Management in NGO, OPEN.	Over 15 years of experience in community-based disaster risk management activities and empowering communities to be resilient.
SID7	Community development expert in an NGO, Sevanatha.	Over 30 years of experience in community-based disaster risk management, planning, and community capacity development.
SID8	Divisional Secretary, Palindanuwara.	Over 20 years of experience in administrative setup at the district, divisional and institutional levels. Coordinating the divisional disaster management committee and governing the divisional secretariat area.
SID9	Urban planning consultant, a former Institute of Town Planners Sri Lanka president.	Over 35 years of experience in urban planning, creating resilient environments, urban regeneration, and waste management.
SID10	A former lecturer at the University of Moratuwa.	Over 15 years of experience in economic resilience, urban planning, and community engagement.

SID11	A director of Urban Development Authority.	20 years of experience in urban development, participatory planning, and governance planning.
SID12	A former director of the Land Use Policy Planning Department.	Over 30 years of experience in land use planning, geography, and management.

6.10 Qualitative Data Analysis with Stakeholders

The discussion was mainly conducted with selected officers using different channels, both online and face-to-face. The discussions were prepared for analysis after translating and transcribing. The NVIVO software was used to record the important statement categories of each discussion. The outcome of their feedback is presented in the following subsections.

6.10.1 Do you concur that defined strategies can be applied to enhance landslide resilience?

Figure 6-42 presents a conceptual map developed through in-depth discussions with stakeholders. The following paragraphs provide a detailed explanation of this map, highlighting risk reduction strategies essential for building a resilient environment.

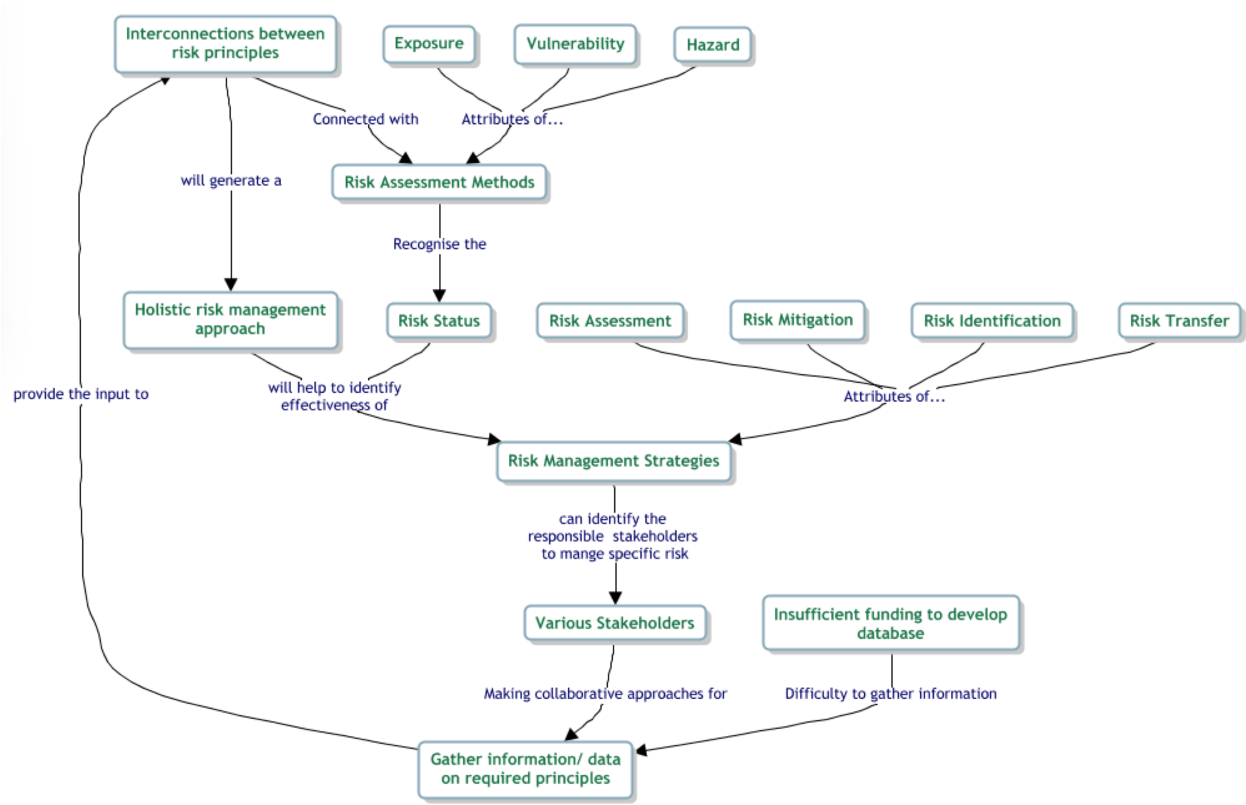

Figure 6-42: Research Validation Discussion- Question one

All the interviewees highlighted the necessity of common risk principles, such as those proposed in the simulator, for implementing effective risk management activities. They unanimously agreed on the importance of educating stakeholders about the interconnections between these various risk principles to foster a holistic approach to risk management. As SID10 pointed out, comprehending these links is vital for enhancing the effectiveness of risk management strategies.

In addition, SID4 noted that the initial stage involves understanding the risk levels, which can be achieved by applying several risk assessment methods supported by the simulator. The outputs generated from these assessments not only provide valuable insights into risk status but also help identify the parties responsible for managing those risks and suggest appropriate actions for risk reduction. Moreover, the collaborative nature of the simulator promotes active participation from both communities and stakeholders in the data collection process, bridging community-based information gathering with the technical investigations carried out by stakeholder agencies. This holistic approach to risk modelling enhances the overall understanding of risk dynamics, ultimately leading to more informed decision-making and improved risk management outcomes.

SID4 emphasised the importance of integrating four main principles, namely risk identification, risk assessment, risk mitigation, and risk transfer into discussions across all sectors. This emphasis reflects the foundational elements of the simulator, reinforcing the necessity of understanding these principles for effective risk management. SID1 acknowledged that these risk principles are widely practised within the risk management domain, highlighting their relevance and applicability. Furthermore, SID4 stressed the need to identify the vulnerability, exposure, hazard, and risk associated with specific scenarios, which is essential for a comprehensive risk assessment.

However, several interviewees pointed out significant challenges in gathering the detailed datasets required for comprehensive model generation. SID3 explained that obtaining high-quality data presents a major challenge in disaster risk assessment, as the general public often has limited access to necessary information. This issue is compounded by insufficient funding to develop comprehensive databases for effective risk assessment (as noted by SID3 and SID10). Additionally, SID10 mentioned that sometimes the available information is collected without considering its intended use, creating a challenging environment for economists trying to make informed decisions.

Several factors were also identified that can distort the understanding of risk phenomena. For example, SID4 noted the political influence on risk understanding, highlighting that solutions for the human-elephant conflict were heavily swayed by political interests. Moreover, SID8 emphasised that political influences often dictate that disaster risk reduction (DRR) should be solely the responsibility of government entities, resulting in reduced community intervention. SID9 reiterated the concern that government officers frequently fail to adhere to proper frameworks or methodologies when investigating risks and identifying necessary mitigation measures.

6.10.2 How can the suggested system serve as a decision-making tool (Building Resilience)? How does it impact decision-making?

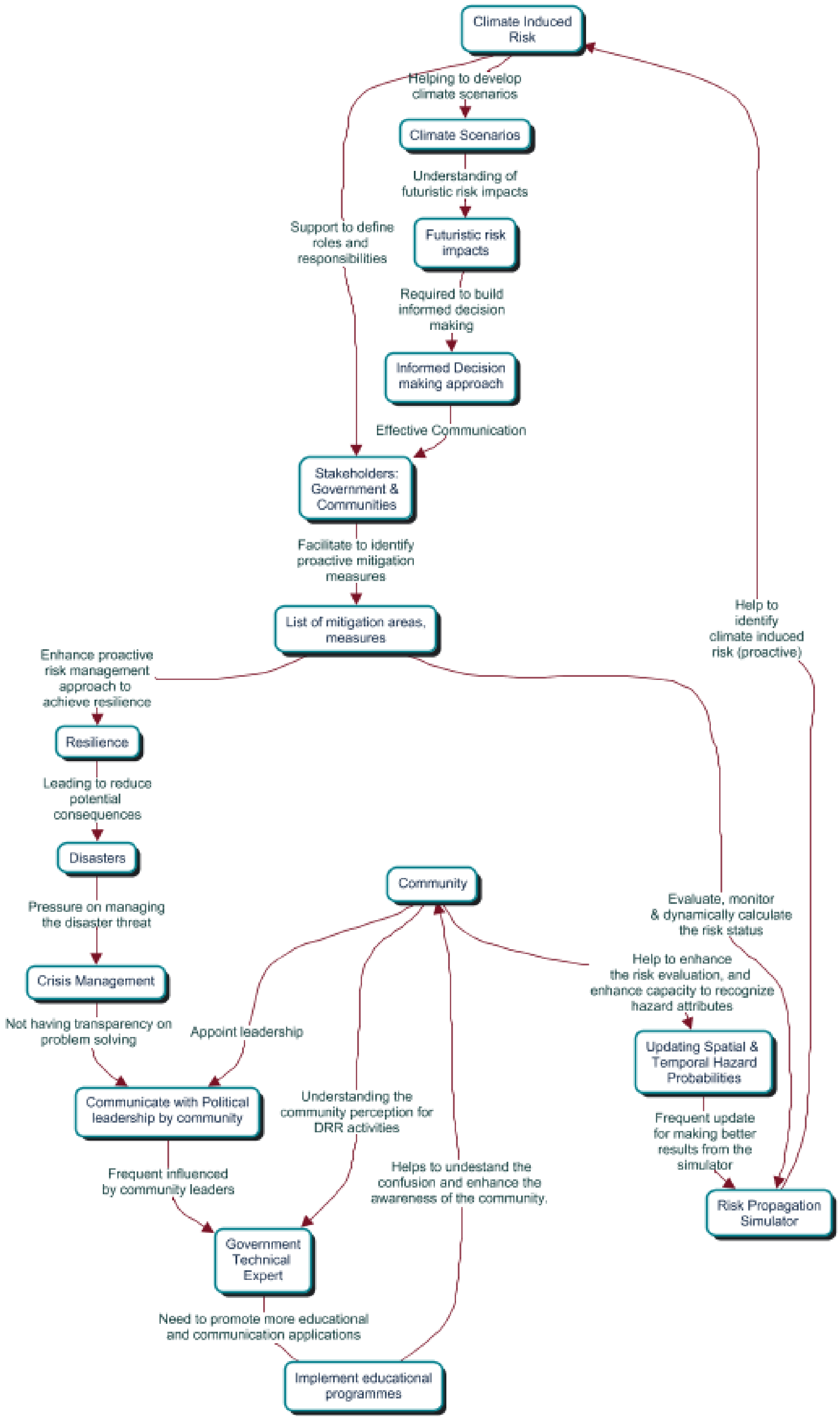

Figure 6-43: Validation discussion on the second question

Figure 6-43 presents a conceptual map of the research validation discussion, illustrating how the risk propagation simulator aligns with the informed decision-making approach. The following section provides a step-by-step explanation, with reference to the SIDs.
The proposed simulator emerges as a valuable tool for assessing climate-induced risks, particularly by bridging the gap between government agencies and local communities. Interviewees unanimously acknowledged the necessity for proactive risk mitigation measures and the importance of integrating potential climate scenarios into the development of risk assessments. Currently, decision-makers struggle to conduct comprehensive futuristic assessments that truly capture long-term risks, which are crucial for informed decision-making (SID1). With the simulator, however, stakeholders can dynamically calculate, record, and monitor risk levels over time, allowing for timely updates to spatial and temporal probabilities that are essential for effective preparedness planning (SID1).

The interviewees collectively recognised the importance of both proactive and reactive risk mitigation measures, with a consensus that proactive strategies are essential for achieving resilience (SID2). They emphasised that risk scenarios should be developed in conjunction with potential climate scenarios, resulting in what they termed climate-inclusive risk assessments (SID2). SID1 noted that there is often a lack of comprehensive futuristic assessments to understand long-term risks, which are crucial for informed decision-making. Therefore, updating spatial and temporal probabilities to conduct time-series analyses is necessary (SID1). Interviewees stressed that dynamic risk levels must be calculated, recorded, and monitored using effective risk mitigation approaches, advocating for the establishment of a dynamic risk monitoring system that aligns with preparedness planning activities (SID1). By incorporating all these crucial characteristics, the proposed simulator was seen as a robust model for conducting dynamic risk assessments that enhance resilience and improve decision-making in the face of climate-induced risks, by the interviewees.

Despite recommendations, SID3 pointed out that the prevalent practice in Sri Lanka tends to focus more on crisis management rather than adopting a proactive stance on risk management or risk preparedness. Interviewees also discussed the two governing systems in Sri Lanka, the political system and the district secretariat system, and highlighted the lack of understanding regarding their interconnection with disaster risk management. Political representatives, elected by the community, attempt to serve as advocates but often lack a solid technical understanding of the issues at hand. Conversely, government officers, who are technical experts adept at handling complex data and making informed decisions, are frequently influenced by political agendas (SID1). The proposed simulator was seen as a tool by the interviewees that can help bridge this gap by providing a platform that facilitates communication and collaboration between technical and political personnel, thereby enabling informed decision-making that aligns with both community needs and expert insights.

Proper integration of community perceptions with technical expertise is seen as vital for creating sustainable disaster risk reduction (DRR) solutions. Furthermore, interviewees underscored the need for future risks to be investigated beyond the current perceptions, advocating for theoretical interventions to predict potential impacts. SID4 anticipated that climate risk management would soon overshadow disaster risk management as a significant area of concern. To facilitate this transition, effective communication of emerging hazards is essential, alongside increased training and awareness for both officials and the general public to reduce confusion regarding new risk management initiatives (SID6).

SID9 specifically identified several climate impact scenarios facing Sri Lanka, including the inundation of low-lying coastal areas and shifting weather patterns where wet regions become wetter and dry regions drier. They suggested that managing natural ecosystems, such as maintaining mountainous forests to capture and regulate rainfall, could serve as a key long-term solution to mitigate erosion and flash flooding in downstream areas. These natural strategies can enhance water retention and transfer to dry zones through irrigation or canal networks (SID9). In addition, SID9 asserted that while technical solutions are important, non-structural measures like reforestation and ecological restoration could be effective strategies for addressing slow-onset hazards, such as those posed by climate change.

The proposed simulator was seen as a more effective tool in comparison with tradtional approach in risk assessment. Unlike traditional methods that often rely on reactive crisis management (SID3), the simulator empowers decision-makers to engage in proactive risk management by facilitating climate-inclusive assessments and incorporating community perceptions alongside technical expertise (SID1). This integrated approach enables more strategic planning and enhances the understanding of complex climate risks, driving more informed and sustainable disaster risk reduction (DRR) solutions. Furthermore, the simulator supports the exploration of future risks and climate impact scenarios, enabling officials and communities to anticipate and prepare for challenges that lie ahead (SID4). By fostering collaboration and improving the flow of information between government bodies and local communities, the simulator not only enhances risk management strategies but also helps build resilience against the growing threats posed by climate change (SID9).

6.10.3 How do you perceive the potential application of the model in other fields?

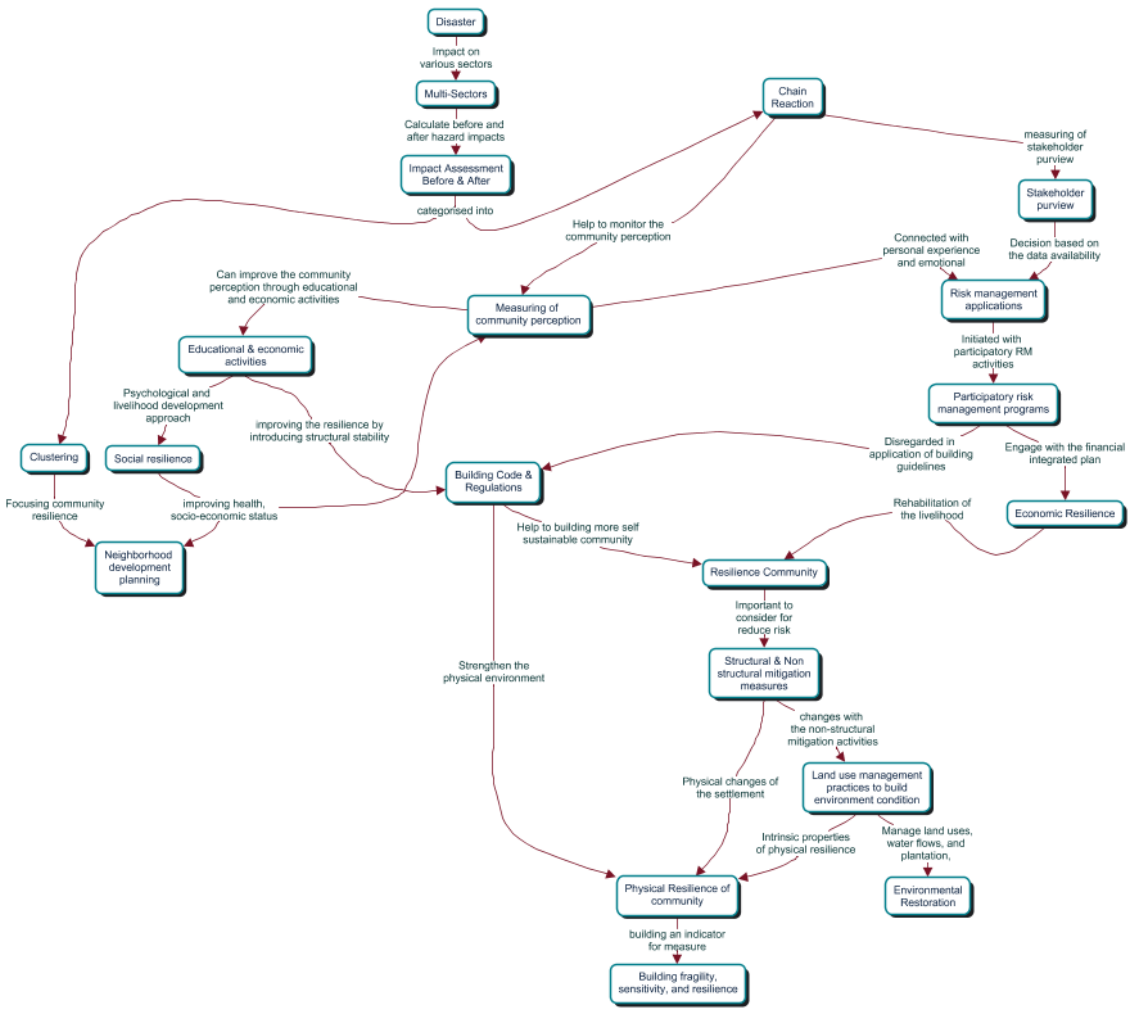

Figure 6-44: Validation discussion on the third question

The conceptual map was developed based on in-depth discussions with stakeholders. Figure 6-44 illustrates this map, capturing the key aspects of the discussion. The following section provides a detailed analysis of its connections.
The interviewees expressed the view that disasters can occur across various sectors and can significantly impact others, including the economic sector. They emphasised that risk cannot be examined in isolation; instead, cross-cutting themes must be explored. As SID4 stated, the principles of risk assessment guide the creation of a generic model. SID4 highlighted that different analytical patterns can be employed to understand the flow of impacts in urban economics. For instance, changes in economic patterns can be tracked before and after a disaster, with clustering and chain analyses shedding light on disruptions like those seen during COVID-19, which affected numerous food supply chains (SID10). This comprehensive analysis fosters a rational decision-making approach to resilience (SID9). Thus, interviewees agreed that chain risk levels must be included in risk mitigation strategies, which are currently lacking (SID1).

The importance of risk perception levels was frequently mentioned as essential for understanding chain reactions, encompassing the views of both communities and stakeholders (SID1). Both perspectives are critical for the successful implementation of risk management projects, with stakeholders often viewing risks through a lens of data and facts, while communities perceive risks based on personal experiences and emotions. Consequently, SID7 stressed the necessity for stakeholders to listen to the narratives and voices of the communities before drawing conclusions. Therefore, participatory disaster risk management programmes should be initiated during the early stages of risk assessment (SID11), as matching both perspectives can lead to more sustainable solutions (SID1).

Interviewees noted that some individuals possess strong emotional attachments to their locations, leading some to disregard building regulations (SID5, SID8). However, these attitudes can often be positively influenced through education and economic improvement (SID8). For example, masonry training could be provided to communities lacking knowledge of proper construction practices (SID12). The perceptions of communities are also influenced by intrinsic factors such as health, knowledge, beliefs, and socioeconomic status (SID2). As a result, psychological approaches may sometimes be required when engaging with the community (SID2). Ultimately, fostering strong community perceptions contributes to the development of a self-sustaining environment (SID2).

The interviewees outlined the necessity of both structural and non-structural mitigation measures for reducing landslide risks. Structural mitigation focuses on physical changes in the urban landscape, while non-structural approaches encompass various strategies such as early warning systems, land use planning, and community empowerment (SID4). Both types of mitigation contribute to enhancing community resilience.

Physical resilience pertains to the structural development of the urban environment (SID3), yet climate change and various geographical factors pose challenges, as existing structures may not possess adequate capacity to cope with new hazards (SID3). Therefore, it is essential to monitor the disaster sensitivity of buildings. Additionally, the effectiveness of retaining walls and other mitigation measures must be evaluated to ensure they perform within their designed capacities.

Land use practices are intrinsically linked to physical resilience. For example, the 'Kandiyan garden concept', which advocates for adaptive crop changes based on slope conditions in home gardens, enhances settlement resilience. Such beneficial practices can lead to worthwhile investments for households while simultaneously improving community perceptions (SID2). Proper management of water flows through plantations and effective drainage systems is also critical, as highlighted by experiences in landslide-prone areas like Meeriyabedda (2014) and Aranayake (2016).

The interviewees underscored the need for environmental restoration programmes in landslide-prone regions. Historically, people used to convert landslide flow areas into paddy fields while managing slopes effectively, which significantly reduced the incidence of landslides (SID2). However, such practices have diminished in modern times, underscoring the need for appropriate land development initiatives by environmental agencies (SID2).

Social resilience can be bolstered through educational initiatives, religious involvement, recreational activities, and diverse livelihoods (SID7). The most effective solutions emerge from dialogue and discussions with the community (SID7). Neighbourhood-level planning serves as an excellent tool for fostering community resilience at the village or small group level, enabling collaborative action during disaster events (SID7).

Interviewees identified economic resilience and risk financing as critical components of all activities. Most development and risk management initiatives are not realised without sound financial planning. Hence, every risk management project must develop a comprehensive financial plan for implementation, including a cost-benefit analysis to evaluate project effectiveness (SID1). Many projects fail to clearly articulate their outcomes and long-term implications, impacting necessary government allocations (SID5). Additionally, communities often exhibit reluctance to leave their original locations, necessitating comprehensive solutions that focus on improving their income and livelihoods for a sustainable future (SID6).

Technology plays an integral role in all aspects of disaster risk reduction (DRR). Technological innovations are directly linked to DRR practices and methods (SID5). As such, DRR managers should prioritise research and development in conjunction with necessary technologies to expedite both risk assessment and management processes (SID5). Significant effort must be invested in leveraging existing technologies to define appropriate

6.11 Summary

Chapter 6 focuses on demonstrating the applicability of a developed system dynamics model for assessing risk propagation in a real-world context. The chapter illustrates how the model can be initialised and used to evaluate the potential impacts of development interventions on community resilience, specifically focusing on two example projects: drainage improvements and enhanced communication infrastructure.

To illustrate its capabilities, the research uses the Palindanuwara Division within the Kalutara District of Sri Lanka as a case study. This location was chosen due to the availability of detailed and high-resolution datasets from the National Building Research Organisation (NBRO) and the presence of high-risk landslide-prone communities. To ensure the accuracy of the data used, the NBRO datasets were meticulously reviewed and validated. The Central Limit Theorem (CLT) was then employed to generate distribution curves for each of the risk characteristics in the model. This data was incorporated into the model to simulate the risk propagation behaviour within the context of the Palindanuwara Division.

A Monte Carlo Simulation was conducted to identify the most effective strategies for mitigating landslide risk in the Palindanuwara Division. This involved randomly varying key parameters within the model and analysing the resulting outputs. Furthermore, the study examined the correlation between the loops corresponding to the strategies and output values (stocks), using the Pearson Correlation coefficient. This analysis provided crucial insights for selecting the most suitable strategy for reducing risk in the area.

The analysis revealed that all fourteen identified strategy loops exhibit a low-level negative correlation with disaster and exposure stocks, while displaying medium to strong positive correlations with land and community stocks. The strongest negative correlation was observed in the loop associated with Strategy 5 (Lstr5), which focuses on enhancing resilience capacities to reduce vulnerabilities. Conversely, the strongest positive correlation was seen in the loop linked to Strategy 3 (Lstr3), which advocates for evidence-based risk education programmes. Further analysis of the correlation variance revealed that Strategy 5 (Lstr5) had the highest impact on overall risk reduction, while Strategy 11 (Lstr11) had the lowest impact. Strategies 1 to 8 demonstrated a significant impact on risk reduction, while strategies 9 to 14 showed less of an impact on risk reduction.

The model simulated the effects of two interventions: drainage improvement and enhanced communication, focusing on their impact on overall risk, vulnerability, and hazard, as well as the stocks representing community, environment, exposure, and disaster impact.

An increase in resistance due to drainage improvements resulted in a decrease in both the magnitude and spatial probability of hazards, ultimately leading to a reduction in hazards. This subsequently reduced vulnerability and overall risk. The simulated output showed that the implementation of drainage improvements resulted in an increase in safer land by 27.73 units, a reduction in exposure by 18.48 units, and a decrease in disaster impact by 9.25

units. These results demonstrate that enhancing the drainage system in the landslide-prone area of Palindanuwara has a substantial impact on improving overall community resilience.

Similarly, the simulation results show that improvements to mobile communication infrastructure and associated risk communication activities contribute to a reduction in vulnerability and overall risk in Palindanuwara. The simulated output demonstrates that the implementation of risk communication improvements leads to an increase in safer lands by 35.05 units, while exposures decreased by 23.78 units and disasters by 11.27 units. Thus, enhancing risk communication in the landslide-prone area of Palindanuwara has a substantial impact on improving overall community resilience.

In this Chapter, the user validation process involved a set of interviews with twelve experts from various fields, including disaster risk management, community development, and urban planning. They were asked to assess the benefit of the simulator for decision-making in creating resilient environments and communities. The experts generally agreed that the model is a useful tool for urban planners and decision-makers, as it offers a practical approach to understanding the impact of development interventions on community resilience. The model was commended for its ability to integrate various risk factors, incorporate community perspectives, and simulate the propagation of risks in a dynamic way. Additionally, the experts highlighted the model's potential for broader applications in assessing climate change risks and for promoting more effective disaster risk management practices.

Overall, Chapter six demonstrates the applicability of the developed system dynamics model in evaluating the impact of development interventions on community resilience, highlighting its potential to inform more informed and resilient urban planning strategies.

Chapter 7: Conclusion and Recommendation

7.1 Introduction

This research recognises that the growing threat of climate-induced disasters, such as floods, landslides, and heatwaves, significantly impacts urban environments, highlighting the urgent need for effective risk assessment models. The research found that current established risk assessment models fall short in capturing the complexity of climate risks, as they typically focus on isolated risk factors and struggle to integrate the dynamic interplay of risks exacerbated by climatic changes, often overlooking critical socio-technical and environmental interdependencies. Therefore this research placed greater emphasis on understanding these complex interdependencies and modeling cascading risks to devise comprehensive risk management strategies that promote urban resilience.

Furthermore, the research found that, in addition to structural interconnections, human behaviour plays a crucial role in risk dynamics. People's perceptions, knowledge, and risk communication can significantly influence a community's overall resilience against disasters. Therefore, incorporating these human behavioural factors into risk assessments was considered vital for establishing a more holistic understanding of community vulnerabilities and capacities, which are often underrepresented in existing models.

Due to the static nature of the existing risk assessment model, it was apparent from the research that there is a lack of tools for decision-makers to model the dependencies of risk elements and simulate "what-if" scenarios to predict the impact of their interventions on reducing overall community risks and enhancing community resilience. One of the assumptions made in this research was that such tools would enhance the ability of decision-makers to strategise and implement measures that can effectively reduce overall risk and improve community resilience in the face of climate challenges.

Therefore this research took the challenge of developing an interactive urban risk simulator for decision-makers that can model risk propagation through interdependent risk elements, with a particular emphasis on incorporating community risk characteristics as a critical component. The following objective was set to achieve this aim :

1. Develop a conceptual risk assessment model that encompasses a range of risk elements, including human risk characteristics and their interconnections.

2. Develop a detailed risk assessment model capable of simulating risk propagation across interconnected urban and human risk elements, and exploring the impact of interventions on the urban environment

3. Implement an interactive simulator for decision-makers to assess urban risks using an appropriate state-of-the-art risk propagation modelling technique, informed by the risk assessment model developed in Objective 2.

4. Demonstrate the application of the risk propagation model for evaluating the impact of various interventions on overall urban risks.

5. Validate the risk propagation simulator involving decision-makers to assess its usefulness for evaluating the impacts of various interventions on overall urban resilience.

This chapter presents the outcomes of each objective and the contributions to scientific knowledge. It also outlines the limitations of this research and proposes future research to address these limitations and build on the current findings.

7.2 Outcome of the Research Objectives

The following section summarises the achievement of each research objective from this research.

7.2.1 The Outcome of the Research Objective 1:

Develop a conceptual risk assessment model that encompasses a range of risk elements, including human risk characteristics and their interconnections.

This objective is closely connected to the research question RQ1: "What risk elements must be considered when defining landslide disaster risks in an urban environment?" The research commenced with a comprehensive literature review in Chapter Two, aimed at gathering relevant published literature from databases such as Web of Science and Scopus. Several filters were applied to conduct a targeted literature search. The review process was facilitated by NVIVO, which helped categorise risk characteristics as nodes associated with each paper. Although typically used for qualitative assessments, NVIVO was effectively employed to organise the findings from the literature survey.

This approach identified risk-defining characteristics (hazard, vulnerability, and exposure), risk assessment process characteristics (analysis, evaluation, perception, predictive behaviour, appetite, and propagation), and propagation-defining characteristics (system connectivity, system complexity, state, system reliability, failures, and threshold). The analysis emphasised the importance of understanding risk through a systemic lens, acknowledging the interconnectedness of different elements within urban environments. It also highlighted the crucial role of human perception in shaping risk reduction strategies and underscored the importance of community engagement in effectively managing risks.

The identified risk characteristics were discussed in detail in Chapter two, providing their definitions, units, and methods of calculation. Moreover, the connections between these characteristics were mapped to develop a conceptual diagram that integrates all the identified risk elements, as shown in Figure 7-1 below.

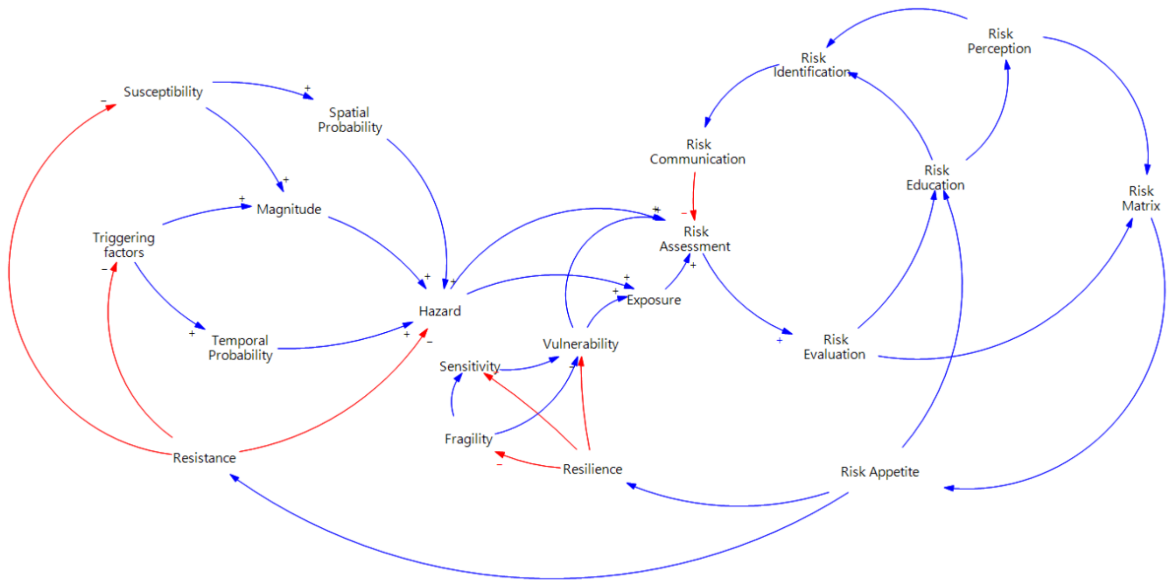

Figure 7-1: Risk Assessment Characteristics

Detailed focus group discussions were conducted with twelve disaster management professionals to assess the reliability of these connections and to explore further improvements to the model. As a result, several risk characteristics were merged and simplified in the model to better represent the interconnections among the risk elements.

This work resulted in fulfilling Objective 1 to establish a conceptual risk assessment model that encompasses a variety of risk elements, including human risk characteristics and their interconnections, thereby answering the research question RQ1.

7.2.2 The Outcome of the Research Objective 2:

Develop a detailed risk assessment model capable of simulating risk propagation across interconnected urban and human risk elements, and exploring the impact of interventions on the urban environment.

This objective is linked to answering the research question RQ2: *How can we model the interdependencies among risk elements to develop a model-based risk assessment framework, using appropriate modelling techniques, to assess the risks of a local urban environment?*

To objective, a literature survey was conducted to identify the available approaches for modelling risk propagation and their respective advantages and disadvantages, leading to the identification of methods such as Bayesian Networks (BN), Network Analysis (NA), Agent-Based Models (ABM), and System Dynamics (SD). The research revealed that, although Bayesian Networks (BN) offer flexibility and the ability to incorporate prior knowledge for quantifying uncertainty through probabilistic reasoning, they are hindered by high computational demands and assumptions about prior distributions that limit their applicability (Lasch, 2018; Liu et al., 2021). Likewise, while Network Analysis (NA) effectively identifies nodes and linkages within a system and quantifies network properties, its complexity and significant data requirements obstruct practical use (Arosio et al., 2020; Lasch, 2018). Agent-based Models (ABM) offer advantages for micro-level modelling and capturing complex interactions; however, they also face considerable challenges, including substantial data demands and assumptions about agent behaviour that restrict both their granularity and overall applicability (Kanj et al., 2022; Lasch, 2018; Vitali et al., 2016).

In contrast, System Dynamics (SD) was identified as the most suitable technique for modelling risk propagation. One of its primary advantages is its holistic perspective, which enables examining the entire system rather than concentrating solely on individual components. This holistic view is critical when assessing complex scenarios involving interrelated risk elements, such as those encountered in the context of urban landslides. The dynamic modelling capabilities of system dynamics allow for the representation of feedback loops and interactions over time, providing insights into how risks propagate through the system and evolve under different scenarios. Although system dynamics does have some limitations, such as complexity in development, data requirements, and sensitivity to initial conditions, the benefits it offers in integrating both quantitative and qualitative data, along with its capacity for long-term scenario analysis, make it a superior choice. Therefore, System dynamics stood out as the appropriate solution for modelling risk propagation in this domain, since it effectively captures the dynamic nature of risk interactions and fosters a deeper understanding of the systemic relationships involved. Therefore, System Dynamics was chosen to implement the risk propagation features of the risk assessment model in this research.

The stock and flow concept was employed to transform the conceptual risk assessment model established under Objective 1 into a System Dynamics model. In this model, four stocks were introduced: Safer Buildings Stock, Safer Lands Stock, Elements at Risk (which combines hazardous lands and vulnerable buildings), and Impacted Stock (representing both lands and buildings). Additionally, three flows were incorporated into the model: Hazard, Vulnerability, and Risk. The fourteen risk elements identified in Objective 1 were linked to the model as dynamic variables within these flows, as illustrated in Figure 7-2.

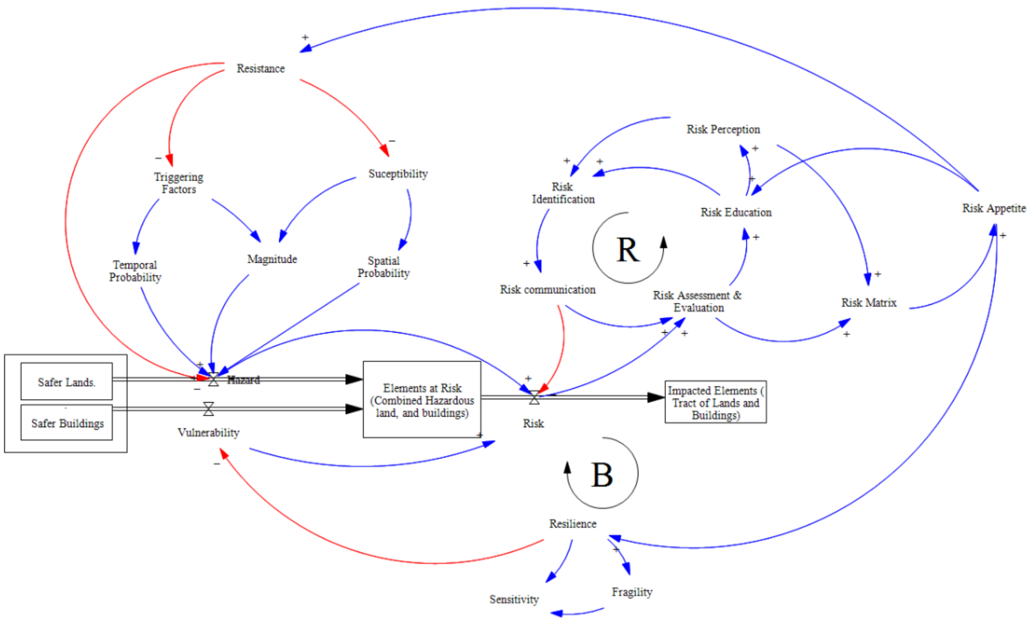

Figure 7-2: SD model for Assessing Risk

The application of the System Dynamics approach resulted in a graph featuring reinforcing loops (represented as “R”) and balancing loops (represented as “B”). The reinforcing loops amplify changes in a variable, leading to growth or decline as the system progressively reinforces the direction of change. In contrast, the balancing loops, also known as negative feedback loops, counteract changes and promote stability by restoring the system to a desired equilibrium state when variables deviate from their intended levels. In the graph, blue arrows indicate positive connections, while red arrows represent negative connections.

The System Dynamics Model, shown in Figure 7-2, was developed as a detailed interactive risk assessment model capable of simulating risk propagation across interconnected urban and human risk elements to fulfill Objective 2. This model allows for the exploration of various interventions aimed at different risk elements, enabling an assessment of their impact on overall urban risk. It assists decision-makers in evaluating how specific interventions may influence the total urban risk through the propagation of risks arising from the interconnectedness of these elements. This capability empowers decision-makers to identify effective strategies for mitigating risks, ultimately informing policies and fostering more resilient urban environments.

Further research was conducted to analyse the loops within the System Dynamics model described above, leading to the identification of 14 primary loops. The analysis of the risk propagation behaviour of these fourteen primary loops helped to extract 14 risk reduction strategies for decision-makers. These strategies were categorised into institutional-level strategies and community engagement strategies, as illustrated in Figure 7-3. Depending on the priorities of the decision-makers, these strategies enable them to explore various interventions and assess their impact on overall urban risk using the proposed risk assessment model.

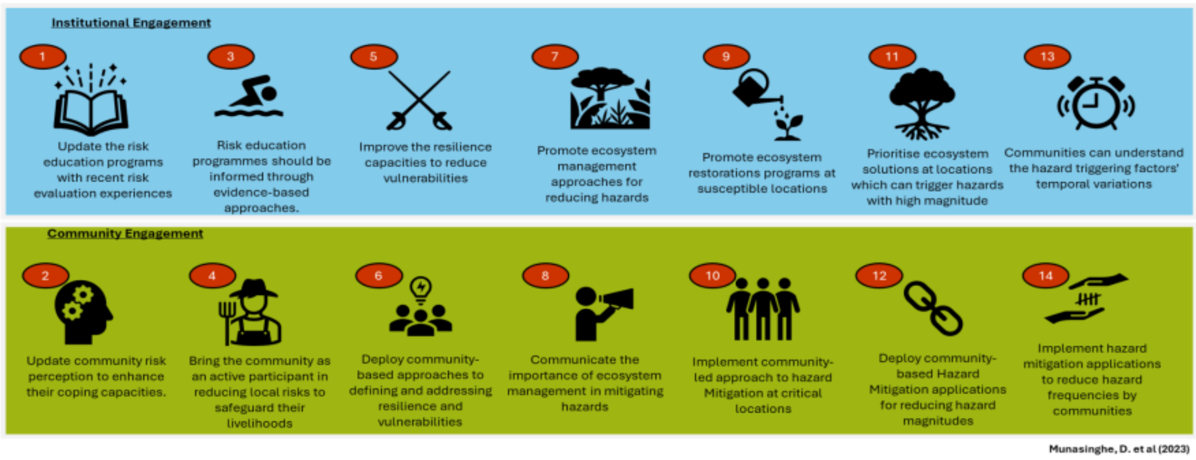

Figure 7-3: Risk Reduction Strategies

A detailed discussion of the approach used for fulfilling Objective 2 was presented in Chapter Four.

7.2.3 The Outcome of the Research Objective 3:

Implement an interactive simulator for decision-makers to assess urban risks using an appropriate state-of-the-art risk propagation modelling technique, informed by the risk assessment model developed in Objective 2

This objective is linked to the research question RQ3: *How can we establish an interactive risk simulator that can allow decision-makers to assess the impact of cascading risks on the overall urban risks?*

In order to implement a risk simulator for calculating risk propagation, research was conducted to define the mathematical constructions required for calculating node values for each risk element and risk propagation. Each risk variable typically exhibits a unique distribution pattern and therefore it was necessary to transform their distribution functions into a normal distribution curve using the Central Limit Theorem (CLT). Each risk variable has a “desirability” condition which initiates risk propagation to the connected risk elements. These desirability conditions were therefore defined for each of the risk elements. However, the threshold for the desirability conditions was derived using the reliability of the connections to facilitate risk propagation.

The reliability of these connections was assessed by first characterising them with a binomial distribution, which was subsequently transformed into a normal distribution to maintain uniformity in analysis. Key statistical measures, the mean, standard deviation, and z-score values, were extracted from the binomial distribution curve. These metrics were then used to construct a new normal distribution curve, complementing the original distribution data. By applying these statistical techniques, the model ensures that risk propagation is accurately assessed and depicted, leading to a comprehensive understanding of how risks transition between interconnected elements within the urban landscape.

The Monte Carlo Simulation (MCS) was used to identify the most influential risk characteristics in the system by generating a range of input variations and measuring corresponding output fluctuations. The simulation assumes a 5% variation for each parameter, providing flexibility for users to adjust this level and broaden output ranges. The Pearson correlation was proposed as the statistical method to analyse relationships between input variations and outputs. This approach helps users identify the most impactful risk characteristics and determine the highest risk propagation pathways within the system.

By employing the above mathematical constructs, the risk assessment model outlined in Objective 2 was transformed into a stock-flow model Figure 7-4,enabling the creation of an interactive urban risk simulator using AnyLogic software.

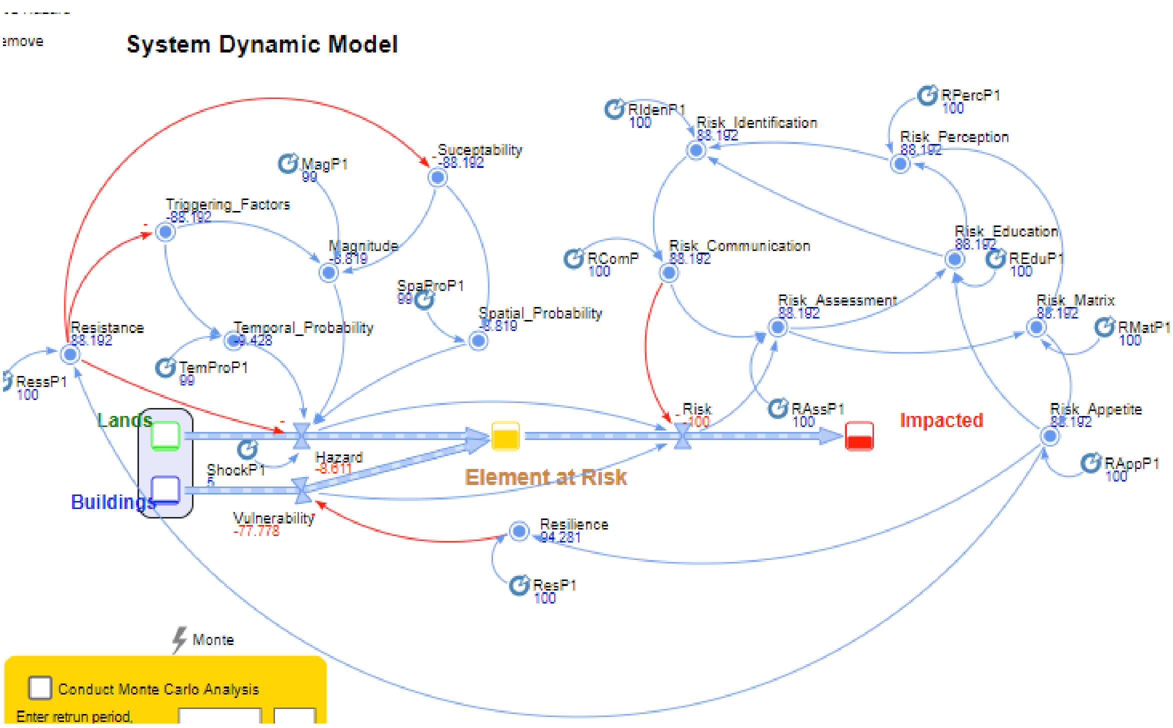

Figure 7-4: SD model in the Anylogic Application

Since the simulator was targeted at non-technical decision-makers, an intuitive user interface (UI) was designed. This UI comprises several subcomponents, allowing users to apply shocks, explore interventions for enhancing community risk characteristics, adjust risk assessments and matrices, introduce risk reduction activities, set hazard probabilities, determine levels of community engagement, and run simulations using Monte Carlo techniques. The initial design was created and refined through discussions with stakeholders to assess usability. Based on the feedback received, multiple iterations of the UI were developed and published to the cloud for further review and collaboration. Figure 7-5 illustrates the look and feel of the final simulator interface.

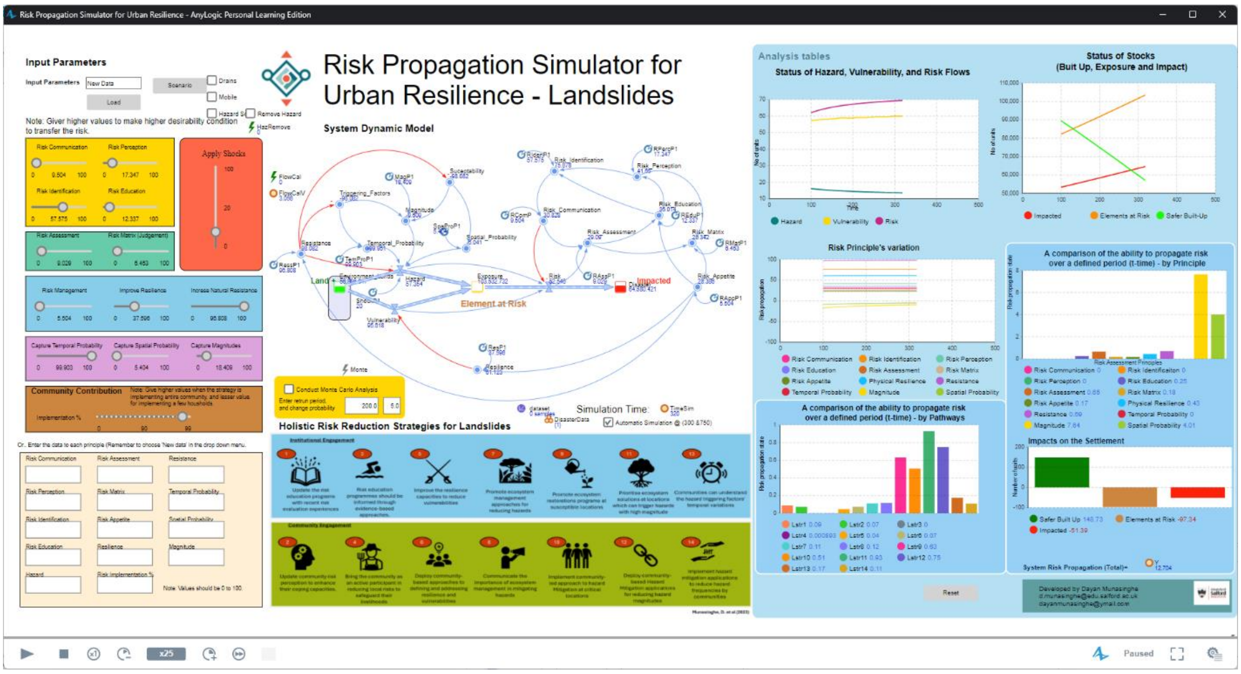

Figure 7-5: Existing UI design of the simulator

7.2.4 The Outcome of the Research Objective 4:

Demonstrate the application of the risk propagation model for evaluating the impact of various interventions on overall urban risks

The capabilities of the urban risk simulation were demonstrated using the Palindanuwara Division in Sri Lanka since this area is considered as landslide-prone area by NBRO. The data of 2,642 households, collected by the National Building Research Organisation was used to configure the urban risk simulator.

Using the mathematical constructs outlined in Chapter 5, the values for each risk element were calculated through the following steps: 1) identify parameters to represent desirable and undesirable conditions, 2) generate a normal distribution curve for each risk element using the Central Limit Theorem, 3) calculate the reliability value for each risk element, and 4) compute Cumulative Distribution Function (CDF) for each dynamic variable representing the risk propagation value. These derived values were used to configure the urban risk simulator, specific for the Palindanuwara Division.

The simulator was used to analyse the risk propagation characteristics and the overall risk reduction behaviour of two interventions: 1) a drainage improvement project, and 2) a risk communication project. Figure 6-29, Figure 6-30, Figure 6-36, and Figure 6-37 illustrate how the impacts of these interventions propagate through the interconnected risk elements. Furthermore, Figure 6-34, Figure 6-35, and Figure 6-40 demonstrate how the risk values and the overall risk in Palindanuwara change over time to establish more resilient environments.

The simulator indicated that implementing drainage improvements results in an increase of 43.41 units in safer land, an increase of 61.28 units in safer communities, a reduction in exposure of 30.51 units, and a decrease in disaster impact of 30.51 units. Similarly, the implementation of risk communication improvements leads to an increase in safer lands by 43.73 units, safer communities by 61.28 units, while exposure and disaster impact both decrease by 20.18 units.

This analysis successfully fulfilled Objective 4, demonstrating the application of the risk propagation model for evaluating the impact of various interventions on overall urban risks.

7.2.5 The Outcome of the Research Objective 5:

Validate the risk propagation simulator involving decision-makers to assess its usefulness for evaluating the impacts of various interventions on overall urban resilience.

This objective is linked to the research question RQ4: *How useful is an interactive risk simulator for decision-makers in making informed decisions for building resilient urban environments?*

Twelve experts were used to assess the usefulness of the simulator for decision-makers to assess the impact of their interventions for building urban resilience. This assessment was conducted to identify the following aspects: 1) identified strategies for building urban resilience 2) support for decision makers, 3) the potential of the simulator for other fields.

All the interviewees agreed that the urban risk simulator serves as a critical decision-making tool for building resilience by providing common risk principles essential for effective risk management. Interviewees unanimously agreed that educating stakeholders about the interconnections between these risk principles fosters a holistic approach, crucial for informed decision-making. They appreciated the ability of the simulator to utilise multiple risk assessment methods, offering valuable insights into risk levels, and risk reduction strategies, and recommending appropriate actions for risk reduction. By emphasising key principles, risk identification, assessment, mitigation, and transfer, the simulator was considered as a useful tool for reinforcing its foundational role in comprehensive risk management discussions in an inclusive manner. Despite challenges in data gathering due to limited access and funding, interviewees found that the simulator assists decision-makers in overcoming obstacles to make informed choices. While concerns were raised about political influences, interviewees appreciated the role of the simulator in providing a proper approach, ultimately improving risk decision-making processes and enhancing urban resilience.

The proposed simulator was recognised as a valuable tool for assessing climate-induced risks, effectively bridging the gap between government agencies and local communities. Interviewees unanimously acknowledged the necessity for proactive risk mitigation measures and highlighted the importance of integrating potential climate scenarios into risk assessments. By enabling stakeholders to dynamically calculate, record, and monitor risk levels over time, the simulator was seen as a valuable tool that offers timely updates that are essential for effective preparedness planning. Interviewees emphasised the need for climate-inclusive risk assessments and the importance of establishing a dynamic risk monitoring system that aligns with preparedness activities. The simulator was viewed as a robust model that enhances resilience and improves decision-making in response to climate-induced risks, facilitating communication and collaboration between technical and political personnel. This integration of community perceptions with technical expertise was considered deemed vital for sustainable disaster risk reduction, and the simulator supports this process by driving proactive risk management, contrasting with traditional methods that often rely on reactive crisis management. The simulator's ability to foster collaboration and enhance the flow of information between government bodies and local communities was viewed as a significant contribution to strengthening resilience against the challenges posed by climate change.

The interviewees highlighted the simulator's significant usefulness across various fields beyond landslides, underscoring that disasters could impact multiple sectors, including the economy, and that risk should be examined comprehensively rather than in isolation. The simulator effectively employed principles of risk assessment to create a model, utilising diverse analytical patterns to understand the flow of impacts, particularly in urban economics. Interviewees emphasised the importance of incorporating chain risk levels into mitigation strategies, as well as the need to balance stakeholder and community perspectives for effective risk management. They noted that participatory disaster risk management programmes facilitated by the simulator could integrate community narratives, thereby encouraging compliance with building regulations through enhanced education and economic improvement. Furthermore, feedback indicated that the simulator supported both structural and non-structural mitigation measures essential for building resilience, as well as effective land use practices and economic resilience considerations. By prioritising technology and research within disaster risk reduction, the simulator aided in improving risk assessment and management processes across multiple sectors, as recognised by the interviewees.

7.3 Research Contribution to Knowledge

This research advances the current state of the art through two primary contributions: the development of a holistic risk assessment model and an urban risk simulator.

Holistic Risk Assessment Model: This research proposes a comprehensive novel risk assessment model that integrates both conventional and human-centric elements, representing a significant advancement in urban risk management. By combining traditional risk components, such as risk identification, assessment, and matrices, with factors accounting for human dimensions like risk perception, understanding, and communication, the model advances existing methodologies. It introduces the inclusion of vulnerability, resilience, resistance, susceptibility, and triggering factors, offering a holistic approach that provides a multidimensional view of urban risk. This innovation enables a systemic evaluation that considers both physical and behavioural aspects, addressing gaps in prior models that often treated these components in isolation. By bridging these elements, the research not only enriches the understanding of risk interdependencies but also aligns with emerging trends in risk management that emphasise comprehensive, integrative strategies. This model contributes to knowledge by offering novel insights into the complexity of urban environments and the dynamic interactions within, facilitating more effective risk assessment and strategic planning.

Urban Risk Simulator: Building upon this robust model, the research develops an advanced urban risk simulator tailored for decision-makers managing urban risks associated with landslide hazards. Utilising the comprehensive model, the simulator employs system dynamic modelling to illustrate how various urban risk elements are interconnected and how these relationships affect risk propagation. This approach marks a significant advancement in the state of the art of risk simulation, as it moves beyond traditional models that often focus on isolated risk factors without considering the complex interactions within urban systems.

By allowing users to explore the impacts of different urban development interventions on the overall risk profile, the simulator provides a sophisticated platform for predictive analysis and scenario testing. It enhances decision-making by enabling users to visualise potential outcomes based on varying inputs and interventions, thereby fostering a deeper understanding of the cascading effects of their actions. This capability is particularly relevant in the context of creating resilient environments, as it encourages proactive planning and informed risk management strategies.

Moreover, by incorporating elements of human risk behaviour outlined in the model, the simulator offers a refined understanding of risk dynamics that aligns with contemporary approaches emphasising the role of human factors in urban resilience. The integration of human behaviour into simulation not only enriches the model but also aligns it with recent research advocating for participatory and adaptive risk governance. This contribution fundamentally enhances the way decision-makers engage with risk assessment and intervention planning, paving the way for more resilient urban environments through informed and strategic decision-making.

These contributions collectively provide an innovative approach to urban risk management, enhancing the ability to anticipate and mitigate environmental hazards through a detailed and interactive assessment process.

7.4 Research Limitations.

The research has several limitations as discussed below.

1. This research focused exclusively on rain-induced landslides in the country. While this specific focus allowed for an in-depth analysis of the unique characteristics and dynamics associated with landslide risks, it also underscores a limitation of the study. Many regions are susceptible to multiple hazards, including floods, droughts, and earthquakes, often occurring simultaneously or in succession. By concentrating solely on landslides, the research may not adequately address the complexities of risk interactions that arise in these multi-hazard contexts. Consequently, developing solutions specifically for one hazard may limit their applicability and effectiveness for decision-makers who must consider the broader spectrum of risks affecting their communities. This singular focus could lead to a narrow understanding of how different hazards coalesce and influence each other, potentially undermining comprehensive disaster risk management strategies.

   Despite these limitations, the findings nevertheless provide valuable insights for stakeholders aiming to create a landslide-resilient environment. They highlight the importance of targeted approaches in addressing the specific dynamics of landslides while also suggesting avenues for further research that could integrate multi-hazard perspectives. Future studies should consider the interconnectedness of various hazards and explore solutions that account for the complex realities faced by communities at risk from multiple threats. This broader approach would ultimately enhance the utility of risk management strategies for decision-makers operating in diverse hazard environments.

2. The relationships between the risk assessment characteristics were identified through a literature review and were subsequently verified with tweleve stakeholders. However, this research may have limitations due to the scope of the literature survey and the number of interviewees involved. The literature review may have resulted in the omission of some key relationships that are discussed in other relevant studies or recognised by practitioners in the field. Moreover, the limited number of interviewees may not fully represent the diverse perspectives and experiences of all stakeholders involved in risk assessment and management. As a result, important insights and relationships that could enhance the understanding of risk dynamics might have been overlooked. Future research would benefit from a more extensive literature review and a larger participant pool to capture a broader range of perspectives and to ensure a more comprehensive analysis of the relationships among risk assessment characteristics.
3. In the system dynamics model proposed, the research primarily focused on one aspect of risk propagation, which may limit the comprehensiveness of the analysis. While the propagation equation incorporates a weighting function to adjust the output from each node, this function is inherently influenced by a range of factors, including financial, social, environmental, political, technological, and legal attributes. However, this study did not address these critical components in detail, potentially resulting in an incomplete understanding of how these multifaceted influences interact and affect risk propagation. By not incorporating these diverse aspects, the model may overlook essential dynamics that could significantly impact the effectiveness of proposed strategies for risk management. Consequently, the findings may be less applicable in real-world scenarios where decision-makers must consider the broader context in which risk factors operate. This limitation indicates that future research should strive to adopt a more holistic approach by investigating how various external factors influence the weighting function and overall risk propagation. Doing so could develop a more robust and nuanced understanding of risk dynamics, ultimately enhancing the model's applicability and providing decision-makers with more actionable insights for managing risks effectively in complex environments.

4. The system dynamics model used in this study effectively models the relationships between various risk elements, providing valuable insights into their interactions. However, it is important to note that this model is primarily statistical and has not been connected to a spatial dimension. This inherent limitation is significant, as disaster risk management relies heavily on understanding spatial relationships. The locations of hazards, populations, infrastructures, and vulnerabilities are all crucial factors influencing the impacts of disasters.

   Without integrating spatial dimensions, the model fails to account for important contextual elements such as geographical features, land use patterns, and the distribution of resources. For instance, certain areas may be more susceptible to specific hazards due to their topography or proximity to risk sources, such as rivers prone to flooding. By excluding these spatial aspects, the model risks oversimplifying the complexities of risk dynamics and may provide recommendations that lack applicability in real-world scenarios.

   To overcome this limitation, adopting a spatial system dynamics model could be a beneficial approach. Such a model would incorporate geographical information systems (GIS) and spatial analysis techniques, enabling a more comprehensive understanding of how risk elements interact within specific spatial contexts. By integrating spatial dimensions, decision-makers can better assess how risk propagation varies across different geographic areas and identify targeted interventions that address localized vulnerabilities. This enhancement would not only improve the relevance and applicability of the model's findings but also enable more effective disaster risk management strategies tailored to the unique characteristics of various regions, ultimately fostering greater resilience in the face of diverse hazards.

5. Another significant limitation of the current system dynamics model is the lack of time series data that accurately captures the realistic delays in risk propagation and

flows. The research underscored the importance of having a comprehensive time series dataset for more effective application; however, the simulation time could not be precisely defined in terms of days, months, or years. This lack of temporal granularity prevents the model from effectively illustrating how risks evolve over specific timeframes and how the effects of interventions may not be immediate.

In the context of disaster risk management, time is a critical factor influencing the behavior of risk dynamics. Delays in risk propagation can stem from a variety of sources, such as the time taken for responses to be implemented, the duration it takes for impacts to manifest after a hazard occurs, and the lag in community readiness or recovery efforts. Without incorporating these delays, the model may inaccurately represent the temporal relationships between risk factors, leading to misleading conclusions about the efficacy of proposed strategies. Moreover, the absence of time series data limits the model’s ability to conduct historical analyses that could provide insights into long-term trends and patterns in risk propagation. Incorporating time series data would allow for the integration of observed historical data on risk events, enabling the model to better simulate and understand the impact of time-related variables on risk dynamics.

To address this limitation, future research could focus on gathering and integrating relevant time series datasets that reflect delays in risk propagation. This could involve collaborating with government agencies, NGOs, and other stakeholders to access historical data on disaster events, response times, and recovery processes. By incorporating such data into the system dynamics model, researchers could create a more robust and realistic simulation that accurately reflects the complexities of temporal dynamics in disaster risk management. This enhancement would not only improve the model's applicability but also provide decision-makers with more reliable insights for planning and implementing effective risk mitigation strategies.

7.5 Future Research Proposals

The following research can be conducted to overcome the limitations addressed in the previous section and advance the current knowledge in the area of urban risk simulation :

1. **Multi-Hazard Focus**: The urban risk simulator, developed using a system dynamics modelling approach, can be expanded to incorporate a multi-hazard focus by integrating the dynamics of various hazards such as floods, droughts, earthquakes, and other relevant risks. To achieve this, the model can be enhanced to simulate the interactions between different hazards and their cumulative impacts on urban areas.

   To implement this, the simulator must first identify the specific characteristics and dynamics of each hazard to be included. By analysing historical data and risk assessments for each hazard, researchers can develop a comprehensive understanding of how these risks combine and interact within the urban landscape. This involves not only quantifying individual risks but also recognising and mapping their interdependencies. For example, an earthquake may lead to structural failures that increase flooding risk if drainage systems are compromised or disrupted.

   Next, the model should incorporate feedback loops that represent the interconnectedness of these risks. For instance, the effects of flooding on community resilience could be analysed not only concerning flood risk but also in relation to concurrent risks such as public health crises stemming from contaminated water sources. By representing these interlinked dynamics, the simulator can provide a more realistic depiction of risk propagation across multiple hazards. Additionally, the model could include the socio-economic impacts of these hazards, considering how different communities in an urban setting might respond to, recover from, or adapt to various disaster scenarios. This could involve simulating community engagement in risk management practices, as well as assessing the effectiveness of mitigation strategies in reducing vulnerability across multiple hazards.

   By adopting this multi-hazard approach, the urban risk simulator will not only enhance decision-making capabilities for urban planners and policymakers but also improve the resilience of communities facing diverse and concurrent threats. This expansion will ensure a more holistic understanding of the complexities of urban risk management, ultimately leading to the development of more comprehensive and inclusive disaster risk reduction strategies.

2. **Holistic Risk Propagation Model:** Future research should adopt a holistic approach that incorporates various dimensions of resilience into the risk simulator. By examining how diverse external factors, including financial, social, environmental, political, technological, and legal attributes, impact the weighting function and overall risk propagation, the simulator can provide a more nuanced understanding of risk dynamics. In this context, financial resilience can be evaluated by assessing the economic capacity of communities to absorb and recover from disasters. This includes examining budgets for disaster preparedness, funding for infrastructure improvements, and the availability of insurance options that mitigate financial losses during catastrophic events. Integrating financial data into the simulator would allow users to model different fiscal scenarios and their impacts on risk management strategies, enabling decision-makers to identify the most cost-effective interventions. Social resilience is another crucial dimension to consider. Future studies should explore how community cohesion, social networks, and public awareness influence risk factors and recovery efforts. By incorporating social vulnerability indicators and community engagement metrics, the simulator can assess how social dynamics affect the implementation and success of disaster risk reduction measures. This could involve simulating community responses and adaptation strategies in the face of multiple hazards, gaining insights into how social capital can bolster resilience.

   Additionally, the model should address environmental resilience by integrating ecological data that reflects the health and sustainability of natural systems. For instance, assessing how ecosystem services like wetlands and forests mitigate hazards such as flooding or landslides can provide valuable insights into the role of natural resources in enhancing urban resilience. By simulating scenarios where environmental stewardship is prioritised, researchers can identify methods to leverage ecosystems as buffers against disasters.

Political factors must also be integrated into the simulator to evaluate how governance, policy frameworks, and institutional capacities affect risk management outcomes. This includes assessing the efficacy of policies, emergency response strategies, and the roles of different government entities in managing disaster risks. Future research can explore how political considerations, such as funding allocations and political will, influence the effectiveness of resilience-building initiatives.

Technological resilience is another significant dimension, involving the exploration of how technological innovations and infrastructures are employed in disaster risk management. The simulator could model the impact of various technologies, such as early warning systems and data analytics, on enhancing preparedness and response capacities. Additionally, the impact of technology on community empowerment and participation in risk management should be evaluated, as access to technology can shape how communities prepare for and respond to hazards.

Finally, legal frameworks play a pivotal role in shaping disaster risk management practices. Future research should examine how existing laws, regulations, and governance structures influence the implementation of risk reduction strategies. By incorporating legal dimensions into the model, researchers can evaluate the effectiveness of current policies and propose legal reforms that strengthen resilience-building efforts.

By integrating these various dimensions of resilience into the risk simulator, future research can develop a more comprehensive and holistic understanding of risk dynamics. This enhanced model will not only facilitate better decision-making for urban planners and policymakers but also promote adaptive strategies that consider the complex interplay of factors contributing to community resilience in the face of diverse and evolving hazards.

3. **Integration of Spatial System Dynamics:** Future research could enhance the urban risk simulator by incorporating a spatial system dynamics model that integrates geographical information systems (GIS) and spatial analysis techniques. This

integration would provide a comprehensive understanding of how risk elements interact within specific spatial contexts, enabling decision-makers to visualise and analyse the complexities of hazard impacts, vulnerabilities, and resource distributions across different geographic areas.

By implementing GIS tools, researchers could map critical spatial data, such as population densities, infrastructure locations, environmental features, and historical hazard occurrences. This spatial foundation would allow the model to simulate how risks propagate and interact differently based on geographic factors, such as topography, land use, and proximity to hazard sources. For example, the model could illustrate how areas with a high concentration of vulnerable populations near flood-prone zones are more susceptible to adverse effects during heavy rainfall events. Incorporating spatial analysis techniques into the simulator would also facilitate the assessment of localised vulnerabilities and the effectiveness of targeted interventions. By analysing spatial patterns, researchers could identify risk hotspots, allowing for tailored disaster risk reduction strategies that address specific community needs. For instance, the model could simulate the implementation of flood mitigation measures in identified high-risk areas and assess their impact on surrounding regions, thereby evaluating the broader implications of such interventions on urban resilience.

Furthermore, the integration of spatial dimensions would enable scenario planning that considers various land-use changes, urban development plans, and environmental restoration efforts. Researchers could examine the potential effects of these changes on risk dynamics and explore how modifications in land use might influence the likelihood and severity of disasters. By modelling multiple scenarios, the simulator could provide stakeholders with valuable insights into the long-term implications of spatial decisions made today.

Additionally, incorporating spatial components would allow for enhanced stakeholder engagement by creating visual representations of risks and solutions. Interactive maps and visual tools developed through GIS integration could facilitate discussions with community members, local governments, and other stakeholders, allowing them to better understand the spatial nature of risks and actively participate in identifying and implementing risk reduction measures.

Overall, integrating spatial system dynamics into the urban risk simulator represents a significant advancement that would provide a powerful tool for analysing and addressing the complex interactions of risk elements across different geographic contexts. This enhanced model would empower decision-makers with the knowledge needed to implement effective interventions that promote resilience and safeguard communities against a multitude of hazards.

4. **Incorporation of Temporal Dynamics**: Future research should prioritise the incorporation of time series data to enhance the urban risk simulator, focusing on gathering and integrating datasets that accurately reflect the delays in risk propagation and flows associated with various disaster scenarios. To facilitate this, researchers should collaborate with government agencies, non-governmental organisations (NGOs), and other stakeholders to access historical data on disaster events, response times, and recovery processes. By integrating this comprehensive time series data, the model will be better equipped to represent the temporal aspects of risk dynamics, resulting in a more realistic simulation of how risks evolve over time.

   Additionally, studies must enhance the model's capacity to conduct historical analyses by integrating observed data on risk events that accurately portray the impacts of specific time-related variables on risk propagation. By incorporating time series data, the simulator can effectively model delays between hazard occurrences, community responses, and subsequent impacts, thereby improving understanding of how various factors influence the timing and intensity of risk propagation.

   In practical terms, researchers can implement time series analysis techniques within the simulator to examine patterns and trends over extended periods. By assessing past disaster events and their temporal characteristics, the model can identify critical delays in response and recovery phases, enabling stakeholders to recognise periods of heightened vulnerability.

Furthermore, integrating time series data will facilitate scenario planning that accounts for historical trends in risk events, allowing decision-makers to simulate various future scenarios based on past experiences. This approach will enhance the simulator's predictive capabilities, offering insights into the potential effectiveness of different interventions over time.

Ultimately, incorporating time series data into the urban risk simulator will enrich the model's realism and applicability, leading to a more comprehensive understanding of the dynamics of risk propagation. Such enhancements will enable decision-makers to develop informed and effective strategies for disaster risk management, improving community resilience in the face of evolving hazards.

By addressing these areas in future research, the model can be strengthened, contributing to more effective risk management strategies that are better aligned with the multifaceted realities of disaster risk dynamics.

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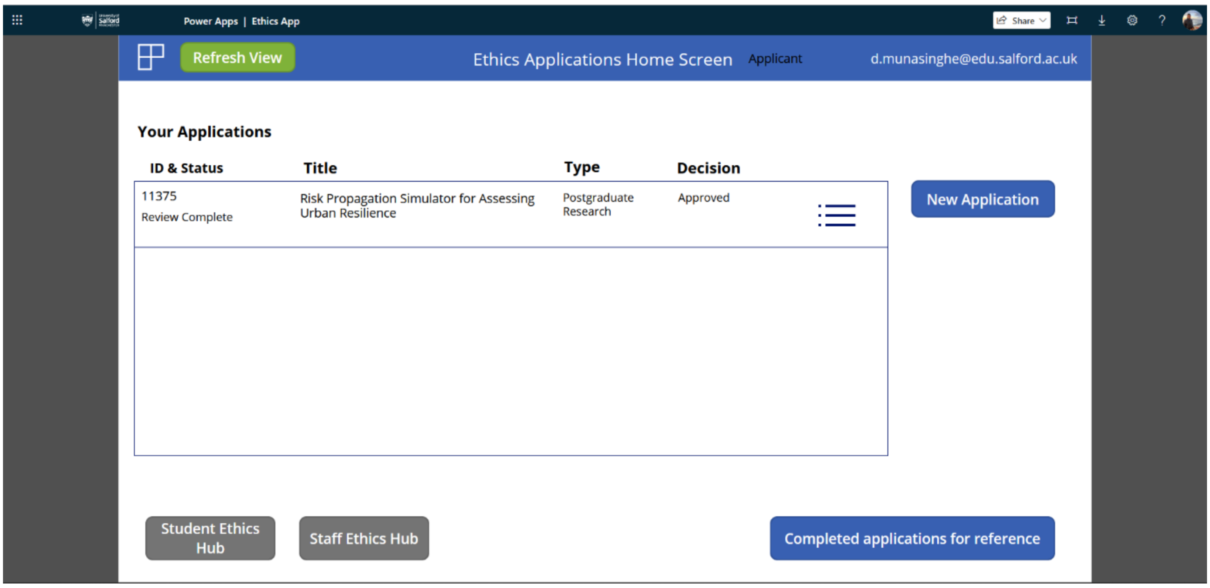
Annexure 1: Ethical Approval



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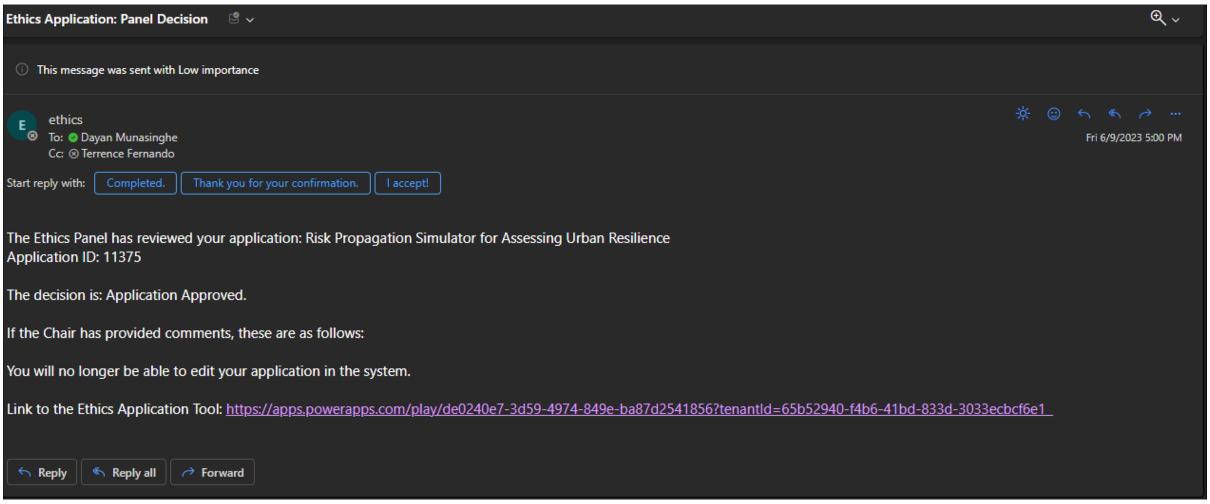

Annexure 2: Research Publication

Munasinghe, D., Fernando, T., Keraminiyage, K., Karunawardena, A. (2023). A Review of the Disaster Risk Assessment Perspectives. In: Alcántara-Ayala, I., *et al.* Progress in Landslide Research and Technology, Volume 2 Issue 2, 2023. Progress in Landslide Research and Technology. Springer, Cham. https://doi.org/10.1007/978-3-031-44296-4_18