Development of a road asset management database for quantitative landslide risk assessment along roads in Colombia

MARCIUS ISIP
MARCH, 2019

SUPERVISORS:
Dr. C.J van Westen
Dr. O.C Mavrouli

Development of a road asset management database for quantitative landslide risk assessment along roads in Colombia

MARCIUS ISIP
Enschede, The Netherlands, March, 2019

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfillment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Applied Earth Sciences, Natural Hazards, Risk and Engineering

SUPERVISORS:
Dr. C.J van Westen
Dr. O.C Mavrouli

THESIS ASSESSMENT BOARD:
Prof. Dr. N. Kerle (Chair)
Dr. A.C Seijmonsbergen (External Examiner, University of Amsterdam)

ABSTRACT

Landslides represent an important hazard that can result in significant damage to properties and may cause substantial economic impacts when they affect essential transportation corridors. Over the past 40 years, landslides in Colombia have resulted in about 400 Million USD in damages. Moreover, 60% of the country's road networks are affected by landslide problems. In response to this, a proactive approach of conducting quantified landslide risk assessments along the roadways is being conceptualized by the Colombian Geological Survey and the road agency INVIAS. This study contributes to the starting point for this proactive and risk-based approach by developing a proposed method for the generation of a road asset management database that allows future quantitative landslide risk assessments (QRA).

Fieldwork was conducted along an initial road section transecting the towns of Copacabana and Girardota of the highway that connects Medellin and Bogota, Colombia to subdivide it into homogenous road segments and characterize each road segment and the immediate slopes while analyzing data sets presently available for integration in the database. The concept of delineating "*areas of influence*" (AOI) was formulated which are part of the standard units for road risk analysis. The AOI was defined as the immediate sloping areas in the vicinity of a road segment, possessing a homogenous set of characteristics related to the terrain, geology, land cover, mitigation measures and type of mass movements that may affect the road segment. The road network was segmented using the criteria mentioned above, and an AOI was delineated per segment.

Different methods of delineating road segment AOI's were evaluated and compared to the field/ground-based AOI's produced. Of these methods, the field-based approach of delineating AOI's works best as a standalone method while the other approaches evaluated were applicable as a supplement. A method for predictive identification of landslide sources using plane fitting and map calculations was created given various release angles and distances from the road. The intersection between the plane and the DEM surface was outlined using raster value thresholding and subsequent classification as the probable landslide initiation areas that would reach the road given a release angle.

For a quantitative analysis of landslide risk, substantial landslide information is required along with a comprehensive maintenance record, data on road network construction and maintenance costs, and data on the state of mitigation measure efficacy. A road asset database structure was formulated to address each of these required types of information and the method was tested for landslide risk analysis utilizing test landslide data over a period of 25 years. The results suggest that the database when accomplished comprehensively, would allow the hazard to be expressed in magnitude-frequency relation through power law model fitting, which is part of an essential procedure for the quantification of the risk. Extrapolation from the power law would yield annual event probabilities and return periods of different landslide volume/magnitude thresholds. The database structure also provides starting information on how to estimate volume and frequency when no historical landslide information is available. Finally, the database testing revealed its applicability for quantification of the direct and indirect risk expressed as the probability of landslide occurrence per year and its respective monetary losses. The results are of importance for road infrastructure managers seeking to apply a risk-based approach to road slope mitigation especially in Colombia. These can also be reproduced in other road networks wherein the prioritization of road segments for long term reduction and management of landslide risk is being considered.

Keywords: database structure, road segmentation, landslides, risk analysis, road management

ACKNOWLEDGEMENTS

I would like to extend my utmost appreciation and recognition to my supervisors: Dr. Cees van Westen and Dr. Olga Mavrouli, for always asking the right and hard questions and being able to give the best suggestions when needed. It was a privilege to be supervised by two of among the best in the field of landslide risk research.

To the people at Facultad de Minas, UNAL-Medellin especially Prof. Edier Aristazabal, along with his staff who made the effort to aid in our research and to make our stay in Medellin worthwhile: Mariana Vasquez Guarin, Maria Isabel Arango, Sandra, Alfredo, Federico, and the rest. Also to Prof. Edwin Aristazabal of the University of Antioquia for valuable insights in road infrastructure management in Colombia. Without the help from these people, this research would not have been possible.

To the ITC Colombia fieldwork team: Felipe Fonseca, Fangyu Liu, and Prof. Dr. Richard Sliuzas. Thank you all for making it an unforgettable and holistic learning experience.

To NUFFIC, thank you for giving students from developing countries the opportunity to experience top-level education in the Netherlands.

To my partner, Yan Cheng, who always provided the needed push and inspiration for me to get going in all aspects and for setting the standards high. Finally, to my family back home in the Philippines for the constant support and understanding.

TABLE OF CONTENTS

1. Introduction ... 1
   - 1.1. Background ... 1
   - 1.2. Research objectives and questions ... 3
   - 1.3. Thesis structure and outline ... 3
2. Study area and data sets ... 5
   - 2.1. Medellin-Bogota road, location, and short description ... 5
   - 2.2. History of significant landslide events in the selected road study area ... 6
   - 2.3. Road management and maintenance practices ... 7
   - 2.4. Existing datasets ... 8
3. Comparison and evaluation of different AOI delineation methods ... 11
   - 3.1. Introduction ... 11
   - 3.2. Method of comparison between each method ... 12
   - 3.3. Method 1: Knowledge-driven/manual approach ... 12
   - 3.4. Method 2: Watershed (sub-basin) approach ... 16
   - 3.5. Method 3: Slope unit approach ... 17
   - 3.6. Method 4: Runout path delineation approach ... 21
   - 3.7. Method 5: Experimental plane fitting method ... 24
   - 3.8. Discussion and conclusions ... 27
4. Development of QRA compatible database ... 30
   - 4.1. Introduction ... 30
   - 4.2. Method of formulating database fields and structure for QRA ... 33
   - 4.3. The current/present database structure of available data at the study area ... 33
   - 4.4. Proposed database structure for QRA integration ... 35
   - 4.5. Maintenance database ... 35
   - 4.6. Landslide inventory database ... 37
   - 4.7. Database of mitigation works ... 38
   - 4.8. Road network database ... 40
   - 4.9. Segment and AOI databases ... 41
   - 4.10. Analysis derived databases ... 41
   - 4.11. Discussion ... 42
5. Application of the database in assessing risk ... 44
   - 5.1. Hazard analysis for segments with previous landslide events ... 44
   - 5.2. Consequence analysis ... 48
   - 5.3. Risk incurred by road infrastructure managers ... 49
   - 5.4. Losses incurred by road users ... 54
   - 5.5. Discussion ... 54
6. Conclusions and Recommendations ... 56
   - 6.1. Conclusions ... 56
   - 6.2. Highlights of the research ... 57
   - 6.3. Recommendations for future study ... 57

Appendices ... 62
   - Appendix 1-Overall description and justification of data fields in proposed databases ... 62
   - Appendix 2-Database structure highlighting most crucial data fields for risk analysis ... 66
   - Appendix 3-Cost tables used ... 67

LIST OF FIGURES

Figure 1.1: *Research framework showing the main responsibilities of road managers in Colombia and the main contribution of this work to road management.* 3
Figure 1.2: *Thesis structure outlining the general method for road landslide risk analysis and flow of this work* 4
Figure 2.1: *Location map of the study area* 5
Figure 2.2: *Representative landslides along the studied road section; A: Copacabana event 2016; B: Progressive downslope mass movement forcing authorities to divert the roadways and to construct of tunnels; C: Large rockslide upslope causing traffic blockage* 6
Figure 2.3: *Combined map of ANI and INVIAS managed highways in Colombia* 7
Figure 2.4: *Maintenance staff working on manually disintegrating a boulder from the upper slope beside the road in Pasto; Photo source: CJ van Westen (2018)* 8
Figure 2.5: *Different maps gathered during fieldwork* **A***: Landslide inventory points from SIMMA-DESINVENTAR;* **B***: DEM of the selected road study area;* **C***: Geological map showing lithologies underlaying the selected road site;* **D***: Landcover map;* **E***: Soil thickness map* 10
Figure 3.1: *Diagram showing how the AOI works for road segments:* 11
Figure 3.2: *Procedures done when applying manual/knowledge driven road segmentation for AOI delineation* 12
Figure 3.3: *Results and findings from the fieldwork in the road study area in Medellin, Colombia;* 14
Figure 3.4: *Resulting AOI map produced from fieldwork and analysis* 15
Figure 3.5: *Overview of the steps done using SWAT tool to create Watershed AOI's* 16
Figure 3.6: *Watershed AOI's produced:* **A***: min. area-100,000m^2,* **B***: min. area-150,000m^2,* **C***: min. area-200,000m^2,* **D***: Field based AOI's* 17
Figure 3.7: *Schematic section/profile showing how SU's are defined with reference to a main drainage line or valley (4); slope units (2) and (3) are defined to its left and right respectively while (1) and (2) shows the ridge lines separating the two topographic highs. Figure modified from Wang et al (2017)* 18
Figure 3.8: *Flowchart showing summary of procedures done in the SU approach for this study* 19
Figure 3.9: *SU alternative maps and comparison to field based AOI's:* 20
Figure 3.10: *Summary of the procedures performed to identify possible source areas of landslides that can be considered as road segment AOI's* 21
Figure 3.11: *Left: The travel angle β when the source is defined at the upslope of the road using the normal configuration of the DEM; Right: The travel angle θ when the source is defined at the road during DEM inversion configuration.* 23
Figure 3.12: *Compiled maps for the runout propagation resulting from variation of the travel angles.* 23
Figure 3.13: *Diagram outlining the principle of plane fitting method: tested:* 24
Figure 3.14: *Detailed procedures conducted to produce the source area raster* 25
Figure 3.15: *Left: Horizontal map produced with the road as reference (0), Right: Height map produced using equation (2) for the 30° plane. Values indicated are in meters.* 25
Figure 3.16: *Projected landslide source maps for release angles 30° (A) and 15° (B). Threshold values set at Z>0* 26
Figure 3.17: *Compiled maps from all methods evaluated for AOI delineation* 29
Figure 4.1: *Summary of procedures undertaken to decide and develop specific database requirements that would allow future QRA* 33
Figure 4.2: *Database structure of all available gathered data sets during fieldwork; blue boxes indicate information directly linked to road segments, the rest of the datasets refer to information linked to the AOI of the road segment.* 34
Figure 4.3: *Map view of the proposed databases that are elaborated in the succeeding sections:* 35
Figure 4.4: *Database form/app created to populate the attributes and avoid errors in the data compilation* 36
Figure 4.5: *Landslide entry form/app for populating attributes of the inventory database* 37
Figure 4.6: *Database entry form and app to fill out attributes for mitigating measures.* 39

Figure 4.7: *Screen capture of the GUI of the basic setup of the road network data set for the study area:* 40

Figure 4.8: *Overall formulated database structure including existing, proposed and foreseen analysis resulting data* 43

Figure 5.1: *Relationship established between the hypothetical volumes of rockslide and rockfall events at segment AOI that were characterized having similar landslide type.* 44

Figure 5.2: *Database structure for hazard assessment for segments with previously recorded landslides, highlighted attributes are used for establishing M-F relation* 46

Figure 5.3: *Database structure showing highlighted attributes that can be used for threshold based hazard analysis* 47

Figure 5.4: *Risk curves showing the total risk in terms of monetary losses per corresponding probability of occurrence per respective volume classes in selected road segments* 50

Figure 5.5: *Database structure highlighting attributes utilized for Consequence/loss analysis*.. 51

LIST OF TABLES

Table 2.1: *Existing data sets compiled.* 9

Table 3.1: *Summary of criteria used to delineate road segment AOI in the knowledge-driven approach* 15

Table 3.2: *Input parameters used for SU-AOI delineation using r.slopeunits tool* 18

Table 3.3: *Summary table of parameters used during the runout simulations in Flow-R.* 22

Table 4.1: *Datasets needed for road network resilience, modified from the World Bank, (2017a)* 32

Table 5.1: *Historical inventory modified from Sola d' Andorra by Corominas et al.,(2018) to demonstrate attributes that are crucial for establishing M-F relations at the study area. The volume attribute can be collected from the proposed multi-temporal landslide inventory or directly from the maintenance records; larger events (>1000m³ volume of material) are expected to be on record in DESINVENTAR databases as well.* 45

Table 5.2: *Volume classes formulated to fit the inventory volume attributes to the power law curve; equation (5.1) was derived from this curve* 45

Table 5.3: *Extrapolated frequencies from the power law equation (1) derived from fitting the hypothetical data in Table 5.1 The frequencies represent the probability of landslide occurrence of a given volume class range. This comprises the hazard component of the QRA procedure.* 46

Table 5.4: *Formulated scenarios by INVIAS envisioning the type of damage to the roads in the event of a landslide; The costs per scenario are different, depending on a number of crucial attributes such as construction costs, the volume of material (Vmat), road toll costs, and length of road damaged.* 49

Table 5.5: *Hypothetical data formulated for demonstration of a risk analysis* 52

Table 5.6: *Loss table calculated per scenario and using Equation 5.2* 53

1. INTRODUCTION

1.1. Background

Landslides represent an important hazard that can result in significant damage to properties (Guzzetti et al., 2012). They may cause substantial impact to the regional economy especially when they affect important transport corridors (Pensomboon, 2007). In addition to this, remediating highway embankments due to slope failures can be expensive especially when numerous landslide events frequently occur, therefore requiring prioritization measures and larger funding (Rose, 2005). Landslides along roads are prevalent in many mountainous regions, including the Andes mountain range of South America, where this research is focused on (Brenning et al., 2015; Hermanns & Valderrama, 2012). In Colombia, 5% of the total 7.1 billion USD the country incurred in losses over the last 40 years is attributed to landslides (Vega, Hidalgo, & Marín, 2017), while GFDRR, (2012) reports that approximately 60% of Colombia's road network is potentially affected by landslides.

Financial institutions such as the World Bank are frequently engaged in risk management projects and stress the importance of developing road asset management databases. These are aimed to account for asset inventories along the road network, road condition surveys, and inventories of protection works with the overall goal of reducing disaster risk along transport corridors. A road asset management database typically contains information on physical infrastructure (pavements, embankments, bridges), equipment and material condition, and other items of value such as vehicular density data (OECD, 2001). However, a good road asset management database must be able to incorporate landslide inventories, geological, mitigation information and most importantly allows the proactive approach of quantitative risk assessment (QRA) in addressing road landslide risk (Fell & Eberhardt, 2005). This is the new approach taken by many road infrastructure managers, in contrast to previous retroactive approaches where the common practice was to remediate slopes only after a failure which has proven to be less cost-effective (Rose, 2005).

Road infrastructure managers around the world have different specific tasks of making sure the roads are of good quality for use by the general public. While maintaining this quality, the advanced and state-of-the-art practice of risk management is being used by several EU member countries (CAREC-ADB, 2009; Rose, 2005). For a risk-based and proactive approach to be incorporated into spatial road planning especially for mitigation works, there must be a definite structure for a database that allows conducting risk analysis along the roadways. The execution of risk analysis, particularly along roadways, entails collection of quantities of datasets which often vary depending on the purpose, data collection method, and frequency. To add to this, some of the datasets that are essential for a successful risk-based approach along roads are not regularly collected especially by road network managers (World Bank, 2017a).

The main objective of road asset management is maximizing economic benefits by reducing maintenance and road user costs for a given road network. The practice also aids in the determination of optimal funding levels and actual funding allocation for specific road segments (CAREC-ADB, 2009). In contrast to passive maintenance implementation, the proactive approach of implementing road asset management aims to achieve a high level of road condition at the lowest cost while having a long-term perspective which considers future impacts such as road damage caused by landslides, blockages and pavement damage (CAREC-ADB, 2009; Rose, 2005). Inventories of road data, condition, unit costs, and deterioration form the basis for road asset management wherein datasets are entered to a road asset management system (CAREC-ADB, 2009). This contains the databases that allow the analysis of data for risk management of certain problematic segments along a road network that may reduce maintenance costs in the future.

QRA is a procedure of analysis and evaluation of risk based on quantified values of hazard probability, vulnerability, and consequences (Fell, Ho, Lacasse, & Leroi, 2005). According to the United States Department of Transportation, (2017), QRA allows a "higher degree of transparency, reproducibility, and comparability in risk assessment" and therefore prefers integration of risk analysis in their asset management systems. On the other hand, some road infrastructure agencies such as the California Department of Transportation use a qualitative risk matrix combining ordinal descriptions of hazard and consequence for their risk analysis of projects (Rose, 2005). This arises from their need of a rapid evaluation system for road maintenance projects and the complexity of data collection required for a quantified assessment of the risk.

Previous work about landslide QRA conducted specifically along transportation corridors consider the population (e.g., fatalities), vehicles and road sections as the main part of the elements at risk component (Ferlisi et al., 2012; Peila & Guardini, 2008). Budetta et al., (2015), adapted the QRA for an important transport corridor in southern Italy while attempting to integrate the efficacy of landslide mitigating measures into the final risk values. Ferlisi et al. (2012), used the QRA to emphasize the difference between estimating the amount of risk to life an individual experiences to that of the overall computed societal risk along an entire road. These studies are successful in determining the level of risk specifically for roads and therefore can be applied to other transport corridors in mountainous regions such as in the Andes mountain range. However, it is optimal that risk outputs from these studies have to be included in road asset management databases that allow risk assessment outputs to be used for effective risk management. QRA approaches such as these works above are still rare; in most cases, the risk is assessed in a semi-quantitative or qualitative approach mainly because of insufficient data.

1.1.1. Problem statement

The proactive approach of conducting risk assessments along roads results in better road infrastructure management practices (CAREC-ADB, 2009; Rose, 2005) including more efficient and objective planning of mitigation measures. However, in most countries, including Colombia, the passive approach of mitigating slopes only after a landslide event is the norm. Moreover, unorganized data collection practices by the road managers do not allow a QRA to be conducted at present. QRA approaches are data demanding and in most cases the limited available data on historical events or maintenance records are not QRA compatible.

Road asset management databases usually do not take into account landslide information for carrying out risk assessments at different road segments or site conditions. This research will contribute solutions to the problems indicated above by developing a road asset database that allows infrastructure managers to quantitatively analyze the risk for road segments. The challenge is to provide the starting point and blueprint for future risk-based approaches to be incorporated by the road managers in Colombia. Currently, Servicio Geológico Colombiano & Instituto Nacional de Vías (2018) are formulating guidelines for QRA along the road networks. However, this activity is hindered by the insufficiency of suitable data. As a possible solution to this, the development of road asset database is a requirement before actual QRA could be conducted in the future.

1.2. Research objectives and questions

Aim/General objective: To develop the structure of a road asset management database that allows semi-quantitative or fully quantitative assessment of landslide risk along roads, based on road segments and their area of influence (AOI).

Specific objectives and related research questions:

1. Examine the current practices of road management and maintenance in Colombia and evaluate the presently available data sets for QRA applicability.
    - What datasets do the road managers collect in their usual routine/practices and at what frequency?
    - How applicable are the current data sets collected by road managers and research institutions with respect to conduct of QRA along roads?
2. Analyze the applicability, advantages, and disadvantages of different segmentation approaches to generate road AOI's and segments which will be considered as the standard unit for risk analysis along roads.
    - How do the different segmentation approaches compare with respect to fieldwork based/manually delineated AOI's?
    - How do the resulting AOI's from different segmentation approaches have an effect on how the risk is estimated for the road segments and what are the ideal conditions for the use of each type of segmentation approach?
    - Can the method for AOI delineation be automated, and which criteria should be considered when delineating an AOI for a given road segment?
3. Design and structure a QRA database which integrates significant information that will allow future conduct of QRA along roads in Colombia.
    - What type of databases and spatial units must be included in the QRA database and how will it be structured?
    - How will the data sets be collected, compiled and with what frequency should they be updated?
    - What are the different data attributes and respective GIS representations of each essential database created for QRA?
4. Apply the risk analysis in test segments using data modified for a highway along Medellin, Colombia.
    - Can the proposed database structure allow quantification of magnitude-frequency of landslides and risk along the test road segments?
    - Does the proposed database structure address the cost and damage scenarios envisioned by the road managers in Colombia?

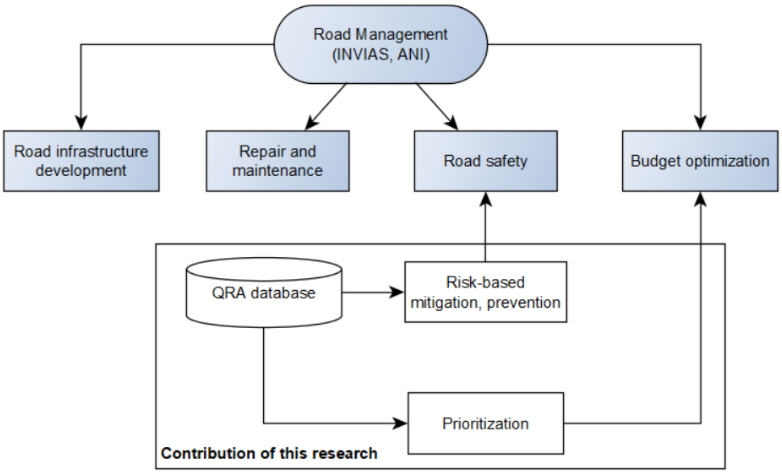


***Figure 1.1**: Research framework showing the main responsibilities of road managers in Colombia and the main contribution of this work to road management.*

1.3. Thesis structure and outline

The thesis is organized according to the two main topics (road segmentation and database structure). The concepts, related problems and literature, methodologies, results, and discussion parts are included in these chapters. The relation of each chapter in the general methodology of landslide risk assessment along roads is summarized in Figure 1.2.

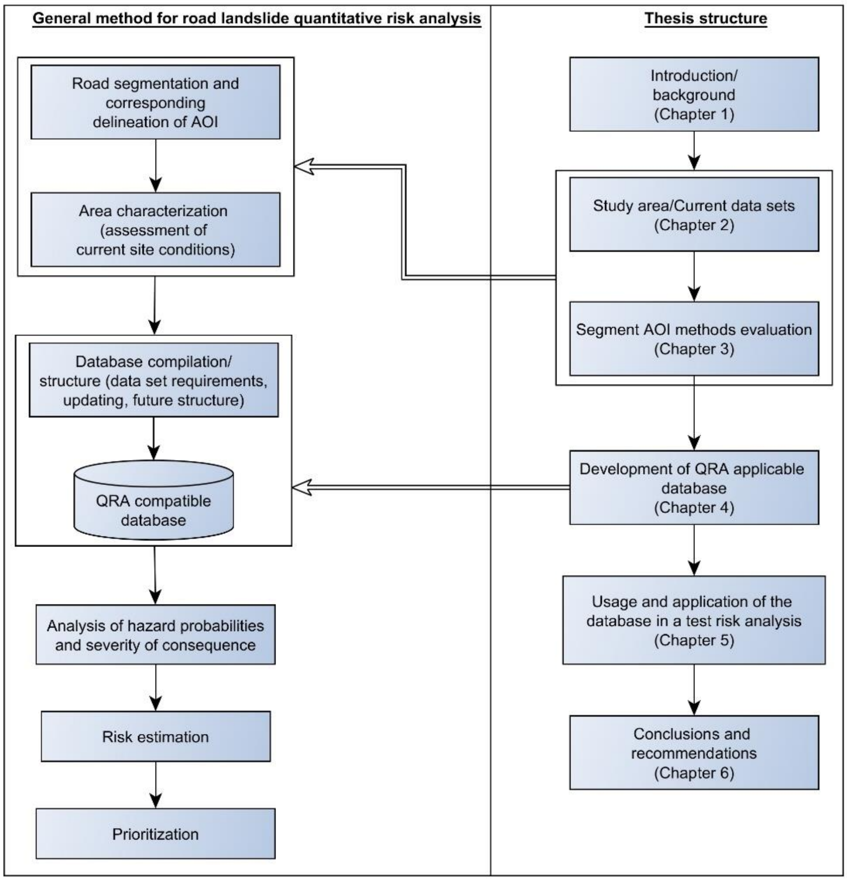


Figure 1.2: *Thesis structure outlining the general method for road landslide risk analysis and flow of this work*

Chapter 1 is the introduction and background chapter and gives an overview of landslide quantitative and semi-quantitative risk assessments and its relation to road asset management, and the challenges for it to be implemented on specific road networks. This chapter also defines the research problem and objectives.

Chapter 2 gives an overview of the study area in Colombia as well as the responsibilities of road management agencies in the area. Also presented in this chapter are the current practices of road management along with the description of available data sets gathered.

Chapter 3 focuses on analyzing and comparing four segmentation approaches to produce road segment AOI's which are vital to a risk analysis along roadways. This chapter presents the possible implications of the different AOI's that result from different segmentation approaches and discusses the advantages and disadvantages of each approach in the context of risk management and prioritization.

Chapter 4 presents the development of the road asset database that is suitable for QRA applications in the future. This includes a justification of the specific fields and formats that were prescribed in each component of the database and its variability depending on a specific end-user along with its purpose within the overall QRA framework.

Chapter 5 demonstrates how to apply the defined database structure and data sets presented in chapter 4 to a risk assessment.

Chapter 6 outlines the conclusions and recommendations of the research. This chapter also contains some topics for future study and improvement.

2. STUDY AREA AND DATA SETS

The selected study area for this research is a road located in Medellin, Colombia. This site was chosen primarily due to a collaboration with the Faculty of Mining of the Nacional University of Colombia in Medellin (UNAL), and due to the history of recent landslide events. The collaboration between ITC and UNAL helped in the initial investigation of available datasets in the region as well as in finding out the current practices of road management in the area. The existing data sets collected during fieldwork will be described in this chapter.

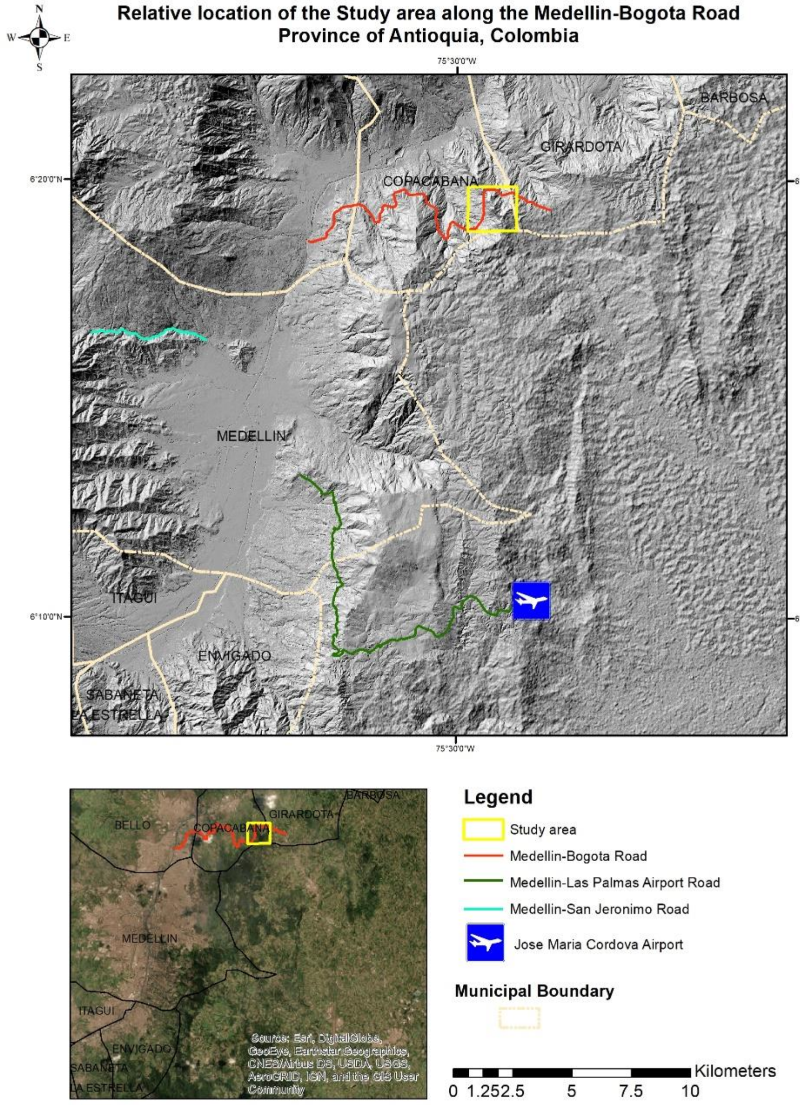


Figure 2.1: *Location map of the study area*

2.1. Medellin-Bogota road, location, and short description

The city of Medellin is located in the Aburra Valley, and although it was confined to the lower and flatter portion, it has expanded in the past decades along the steep slopes surrounding the valley. Generally, the lowest elevation of the valley in Medellin is about 1500m while the surrounding mountainous terrain goes up to 2000m in elevation. The Medellin-Bogota road is located northeast of the city of Medellin. The selected study area traverses the municipality of Copacabana and portions of Girardota (Figure 2.1). The total length of the highway spans about 450km and is an important transportation corridor that connects Medellin which is the second largest city of Colombia, to the capital of Bogota. The selected road section for study measures approximately 5.5km and is representative of the current mass movement problems. Other notable and important highways in the region are the Medellin-San Jeronimo road connecting Medellin to the northern ports of the country, and the Medellin-Las Palmas road which connects Medellin to the Jose Maria Cordova international airport, the main international entry point in the region. The Medellin-Bogota highway also connects to the international airport.

2.2. History of significant landslide events in the selected road study area

The most recent significant landslide event happened on the Copacabana section of the selected road in 2016. This landslide is shown and partly described in Figure 2.2A. This landslide happened on the old section of an active quarry located adjacent the Medellin-Bogota highway. The accumulated rainfall amount for the last 30 days before the event was about 330mm. The event caused 16 casualties, and it took five days to clear the blocking debris from the roadway. Progressive downslope mass movement is also characteristic in the area. As shown in Figure 2.2B, the progressive downslope movement has caused significant damages, and ultimately a tunnel was constructed to address the problem. According to authorities, the movement downslope is still ongoing, and the construction of the tunnel has not solved the problem completely. This example demonstrates the possible structural damage to roads by downslope mass movement. Another representative landslide event in the selected road section is shown in Figure 2.2C. A large rockslide caused blockage of two lanes of the highway for about a month resulting to the construction of the new road lanes away from the upslope. Mitigation measures along the study area are rare with only small portions of the road having them and are also insufficient as evidenced by some debris that go over the structures.

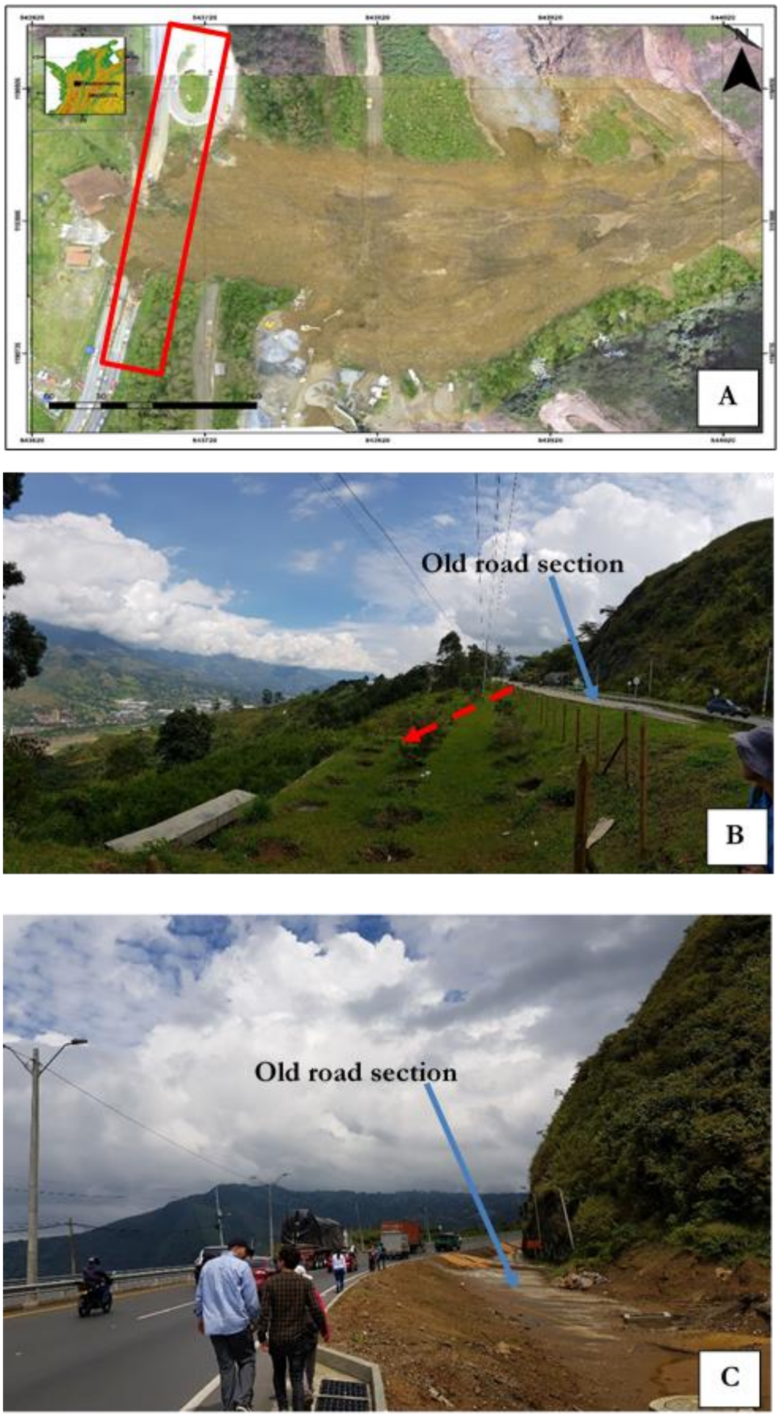


Figure 2.2: *Representative landslides along the studied road section;* ***A****: Copacabana event 2016;* ***B****: Progressive downslope mass movement forcing authorities to divert the roadways and to construct tunnels;* ***C****: Large rockslide upslope causing traffic blockage*

2.3. Road management and maintenance practices

According to interviews conducted with staff of UNAL and the University of Antioquia, road management in Colombia is led by two government agencies namely the Agencia Nacional de Infrastructura (ANI) and Instituto Nacional de Vias (INVIAS). INVIAS is in charge of constructing, maintaining, and regulation of non-concessional highways in Colombia (INVIAS, 2016) while ANI oversees and creates a public-private partnership between the national government and the private road companies to construct new infrastructure (Agencia Nacional de Infrastructura, 2015). Concessional roads in Colombia refer to the road networks managed and maintained by private companies. These companies earn a profit by charging toll fees to road users upon entering the highway. On the other hand, non-concessional roads refer to highway networks that are currently managed and maintained exclusively by the Colombian Government through INVIAS; these roads are those not taken by private companies and are toll-free. The respective road networks handled by INVIAS and ANI all over Colombia are shown in Figure 2.3.

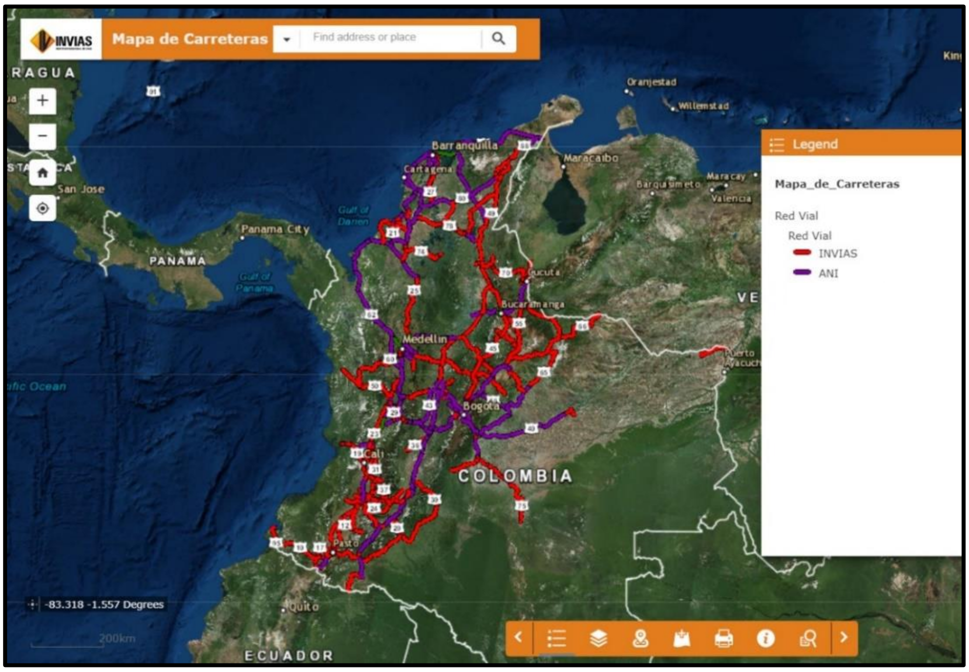


Figure 2.3: *Combined map of ANI and INVIAS managed highways in Colombia*

Roughly 5000km of highways are commissioned and monitored by ANI while the rest are mostly under the maintenance of INVIAS or the respective Departments with jurisdiction. The map is captured from INVIAS carreteras portal at: (https://hermes.invias.gov.co/carreteras/).

The Medellin-Bogota highway is under the concession of a private consortium, DEVIMED. DEVIMED (Desarollo Vial Del Oriente de Medellin) or East road development of Medellin is a consortium consisting of nine contractors (8 Colombian, 1 American) primarily in charge of construction and maintenance of road networks connecting Medellin, with southeast Departments, up to the capital city of Bogota (Agencia Nacional de Infrastructura, 2016). DEVIMED is valued at around 150 million euros in 2014 and is currently under contract with ANI from 1996 until 2021. ANI oversees the periodic performance checks of DEVIMED and all other private concessions in the country. According to reports from Agencia Nacional de Infrastructura (2015), the performance checks mostly comprise of financial auditing and monitoring, and private concessionaires are not required to furnish ANI its daily maintenance, mitigation measure, and traffic data sets. The private concessionaires also have the responsibility to ensure safety along the highways they are maintaining; this includes landslide monitoring and protection from these hazards.

INVIAS mostly operates on its own in maintaining the roads. The main difference between having a concessionaire (ANI) and not having one, e.g., in the case of INVIAS is the easy access to funding maintenance works of the concessional highways. It is expected that highways under the care of ANI and its private concessions are in better condition than highways solely maintained by the government through INVIAS since private companies in charge of concessional roads maximize profit by ensuring maximum number of vehicles that pass through their highways. This is why the Colombian government promotes its public-private partnerships- to have better quality infrastructure, including roads. However, according to Daheshpour & Herbert (2018), the disparity between the quality of the two road types is not large. The primary goal of its road maintenance activities is to achieve an acceptable level of pavement condition which is quantified using the pavement condition index (INVIAS, 2016; Shah, Jain, Tiwari, & Jain, 2013). Its current maintenance practices include a routine check for pavement, drainage, and vegetation clearing check. Periodic preventive treatment of seals, drainage and road pavement is included on top of partial or total reconstruction of damaged roads (INVIAS, 2016).

There is no record of INVIAS or ANI utilizing a road asset management database, and maintenance practices, especially after a landslide or debris clearing, indicate they do not maintain records of the activity as seen below in a photo taken from a road along the municipality of Pasto (Figure 2.4). Currently, INVIAS is developing an application for maintenance recording along the roads which could be useful in the QRA context.

Figure 2.4: *Maintenance staff working on manually disintegrating a boulder from the upper slope beside the road in Pasto; Photo source: CJ van Westen (2018)*

2.4. Existing datasets

Generally, there were three groups of existing data sets, which were obtained primarily by UNAL-Medellin and also from the INVIAS data set portal. These are the DEM derivatives and secondary data such as the geological map, rainfall station data and hazard inventory. Figure 2.5 shows the maps that were compiled from fieldwork.

- Landslide inventory

Sources of the inventories were the SIMMA catalog (SGC-Colombian Geological Survey), and DESINVENTAR historical inventory. SIMMA and DESINVENTAR inventories were taken from the web portal and updated/monitored daily at the National University of Colombia-Medellin (UNAL) using aerial photographs and news reports. The portal can be accessed at https://www.simma.sgc.gov.co and is also the official landslide reporting webpage in Colombia. The uncertainty level for the inventory is indicated for each record with a value ranging from level 1-3. 1 is the highest level of accuracy which means the coordinates indicated is almost exact, 2 is district level accuracy, and 3 is municipality level accuracy. The DISINVENTAR records use the same level of uncertainty levels; however UNAL compensates for this by supplementing spatial location with aerial photograph interpretation.

According to UNAL staff, the inventories are more accurate especially from 1988 onwards. This is due to a change in the method and more attention given to compiling it from after a large event in 1988 in the Aburra Valley region. Previously, the inventories were maintained and updated at the municipality disaster office (AMVA), but the system was transferred to UNAL in 2015 and is presently maintained and updated using a combination of GIS methods, aerial photograph interpretation, and field validation for the most recent landslide events. Temporal range of the landslide inventory dataset gathered spans from 1930-present. Ongoing research by UNAL utilized the landslide inventory for a number of landslide events to correlate with rainfall amount and temporal variability in the Antioquia region. Each event has attributes such as event type, approximate neighborhood location, damage description, source, indicated uncertainty level, and longitude, latitude readings. A plot of the landslide inventory within the selected study area is shown in Figure 2.5A.

Data set	***Source***	***Spatial resolution***	***Last updated/Temporal range***	***GIS representation/data format***
Landslide inventory	UNAL-Medellin, SIMMA-SGC, DESINVENTAR	-	2018/1930-present	Point vector map
DEM and derivative maps (slope, aspect, curvature, TWI)	UNAL-Medellin	2m	2018	Raster map
Geological map	UNAL-Medellin, SGC	-	2017	Polygon vector map
Rainfall station data	Sistema de Alerta Temprana del valle de Aburra (SIATA)	-	2018/daily	Spreadsheet
Landcover	UNAL-Medellin	2m	2017	Raster map
Soil thickness	UNAL-Medellin, AMVA	2m	2017	Raster map
Historical traffic data	INVIAS	-	2016/2003-2016	Spreadsheet
Maintenance and construction costs for roads	INVIAS	-	2016	Table form and reports

Table 2.1: *Existing data sets compiled*

- Digital Elevation Model (DEM)

The DEM provided by UNAL-Medellin spans the entire area of the Aburra Valley; this was clipped to emphasize more on the selected study area (Figure 2.5B). Previously the DEM comprised of 2m resolution for the greater metropolitan area and 5m resolution for the rural areas. This was resampled to an overall resolution of 2m for the whole valley. Resampling of the rural areas having a 5m resolution previously, resulted in the loss of data quality and artifacts. However, since the study area does not encompass the aforementioned rural areas, there was minimal data quality loss and artifacts present. Derivative maps such as the slope gradient map, hillshade, aspect, curvature, and topographic wetness index maps were produced from this DEM. The DEM was also used to delineate sub-basins (watersheds), slope units, and runout paths as possible AOI's in this research.

- Geological map

The geological map provided by UNAL-Medellin contained significant information regarding the types of lithologies underlying the study area. In general, the study area is underlain by the following rock types: Metamorphic rocks (Amphibolites and Gneisses), Surficial mass movement deposits, and few metamorphosed basalts, river deposits and fill materials. The geological map attributes are detailed with important fields such as the age of the rocks. However they were created at a regional scale and is not reliable for site-specific evaluation.

- Rainfall data

The rainfall is monitored closely around the Aburra Valley by SIATA. They have a temporal resolution of about 15 minutes per station, and this data can be easily downloaded from their online portal.

- Landcover map

Land cover data set is represented by raster maps with a 2m cell size that was generated using supervised classification of mosaicked orthophotos from the greater metropolitan area (Figure 2.5D). The reliability of the landcover map is also low given that it was produced on a widely regional scale of the Aburra Valley and most of the units classified within the study area were not correct upon field validation.

- Soil depth/thickness

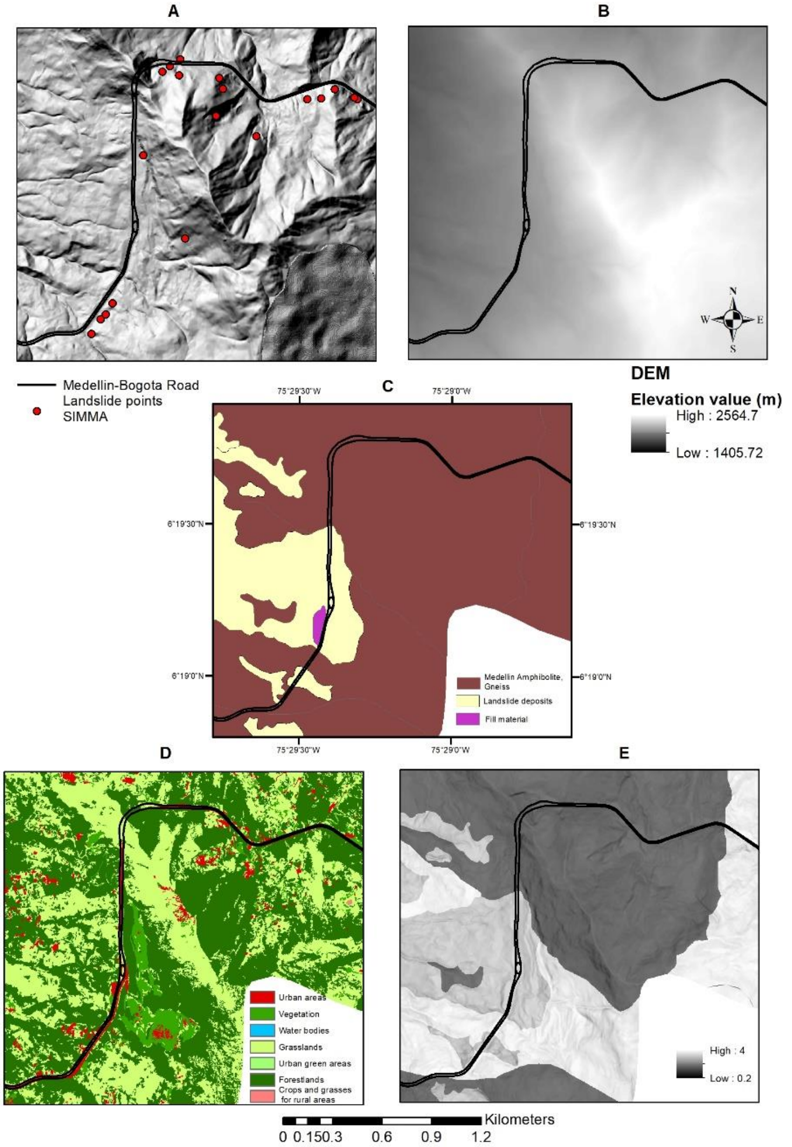


***Figure 2.5**: Different maps gathered during fieldwork **A**: Landslide inventory points from SIMMA-DESINVENTAR; **B**: DEM of the selected road study area; **C**: Geological map showing lithologies underlaying the selected road site; **D**: Landcover map; **E**: Soil thickness map*

The soil thickness map provided by UNAL-Medellin was created using the approach developed by Catani, Segoni, & Falorni, (2010) which defines soil thickness as the depth to bedrock or the depth to a first marked change in hydrological properties. The method is particularly effective for catchment scale estimation of soil depth, and that was utilized by UNAL-Medellin to create the data set as shown in Figure 2.5E. This dataset, however, is not reliable with very generalized thickness values in the study area due to its method of preparation and regional scale.

- Historical traffic data

Historical traffic data or Average daily traffic (ADT) data was obtained from the INVIAS web portal; it contains the ADT per sector and road network for all departments/provinces in Colombia. For the department of Antioquia where the study area is located, the ADT records span from 2003-2016. The percentages of vehicle types traveling along the highways are also indicated in this historical ADT record.

- Maintenance and construction costs for road

The prescribed amount for maintenance and construction costs are published by INVIAS, (2016). The amounts that are charged for maintenance actions such as brushing, and pavement reinforcement, and most importantly the actual road construction costs are outlined by Garzón Iral, Valencia Palacio, & Muñoz Cossio, (2012) & INVIAS, (2016). These values may vary slightly from every department, but it provides good insight on to how much it costs to maintain or construct quality highways. Aside from this, vulnerability values can also be estimated by the road managers using these costs above, utilizing the maintenance/construction costs ratio (Garzón Iral et al., 2012; Jaiswal, 2011).

3. COMPARISON AND EVALUATION OF DIFFERENT AOI DELINEATION METHODS

3.1. Introduction

It is essential for road design and rehabilitation planning projects to subdivide the road into homogenous units before implementation (Misra & Das, 2003). This need arises from avoiding a mixture of pavement condition parameters, slope properties, and other criteria which increases the likelihood of poor uneconomical road design and mitigation, thus the introduction of the concept of road segmentation and delineating their respective "Areas of Influence" or AOI. The procedure of delineating an AOI starts with road segmentation wherein a portion of the road with similar characteristics (e.g., type of slope, mitigated or not) are defined as a segment. After segmentation, each of the segments has an upslope or downslope area wherein mass movement hazard processes may adversely affect the road segment either by runout of materials upslope or progressive erosion downslope. These areas above or below the slope are delineated and defined as the AOI's per road segment. This procedure addresses two key problems: (i.) the type of maintenance or treatment work to be done for roads with similar condition or problem is aggregated and can be addressed efficiently, and (ii.) the basic mapping unit for assessing the risk is established and prioritization can commence systematically for the entire road network.

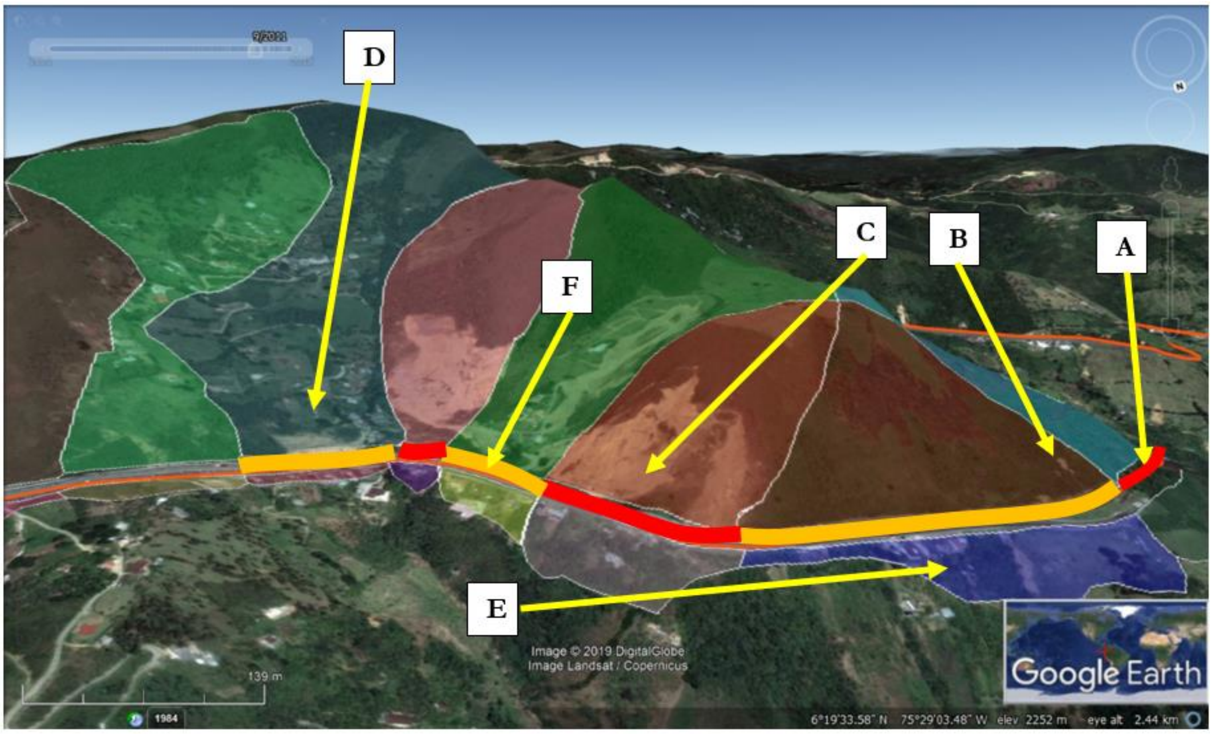


***Figure 3.1**: Diagram showing how the AOI works for road segments:*

***A:** Tunnel installed along the road segment, a mitigated segment is different from a segment without one, **B**: Rockslide scar on a cut slope and corresponding upslope AOI, **C**: Recent landslide on a cut slope. **D**: Natural slope along the highway. **E**: Downslope AOI. **F:** Natural slope road segment*

This concept was developed to bridge the gap between assessing road pavement condition/problems at present and a risk-based proactive approach which provides a long-term perspective for road management and maintenance. The AOI is defined as the immediate sloping areas above or below the road that may affect or influence the road segment condition or treatment in the future (Figure 3.1). In the context of this research, the road segment AOI is the standard unit of assessment and forms the basis for the development of the road asset database for QRA which will be discussed in Chapter 4. Since the road segment AOI's are the most important units for the analysis of risk along roads, examining the various methods that are used to delineate it is of utmost importance. In addition to this, the methods are tested to find an optimal approach that could be automated while providing reliable AOI's for analysis of risk.

3.2. Method of comparison between each method

For this study, four methods of subdividing the road and AOI delineation are evaluated and compared. The four methods are 1-knowledge driven/manual approach (ground truth), 2-sub-basin (watershed) delineation approach, 3-Slope unit delineation approach, and 4- Runout propagation approach. The comparison will be done with respect to the manual method which was delineated after fieldwork in the selected road study area.

3.3. Method 1: Knowledge-driven/manual approach

3.3.1 Concept

The knowledge driven/manual segmentation and delineation of road segments and AOI (Rana, 2017; Sun, 2018) typically involves a combination of terrain unit mapping, identification of topographic factors, and utilizes historical imageries/data, Google Earth, Google Street view, Road videos and fieldwork. The goal of a knowledge-driven manual segmentation is to delineate road segments and respective AOI's with homogenous properties according to specific criteria such as the type of landslide activity, drainage, type of slope, presence or absence of mitigation measures along the road segment, land use, and evidence of past landslide events. This approach allows flexibility in terms of criteria definition and depending on the goal of the study.

3.3.2 Methodology

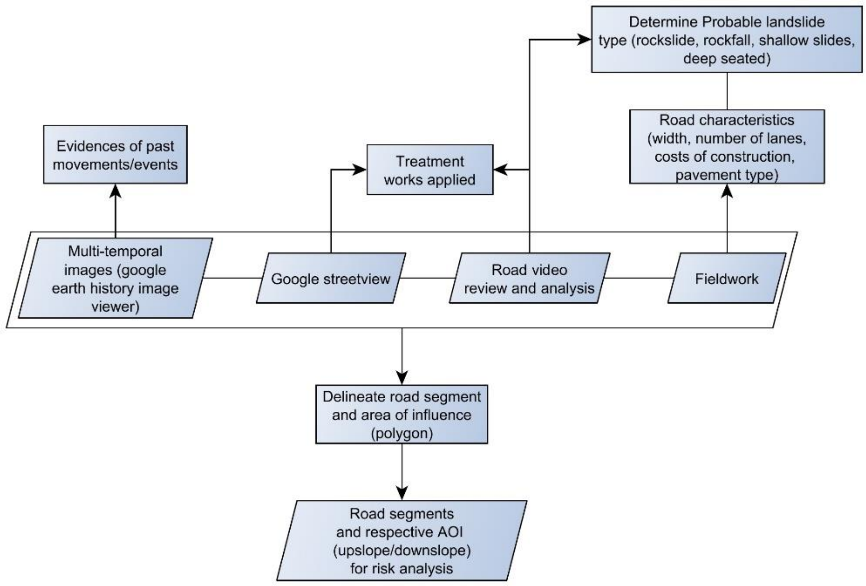


Figure 3.2: *Procedures done when applying manual/knowledge driven road segmentation for AOI delineation*

1. Use of multi-temporal images (Evidences of past movement)

To determine the evidences of previous landslide activity in the road study area, multi-temporal images were used. In addition to this, the available SIMMA historical landslide catalog was also used for verification. Utilizing multi-temporal images and historical landslide data to identify evidences of past events are an important consideration/criteria for delineating AOI's manually especially for hazard analysis, assuming that the occurrence of landslide events in the past is a reliable indication for possible future events (van Westen, van Asch, & Soeters, 2006). The Google Earth historical image viewer allows users to review historical images and also determine evidences that suggest previous landslide activity. In this study, multi-temporal images were inspected before fieldwork and identified evidences indicating past landslides were validated on the ground.

2. **Use of Google Street view and road video analysis (treatment works, landslide type)**
   Assessing landslide along roads in the study area was made convenient with the use of Google Street view, which allows users to review the slope conditions and more importantly, the presence of treatment works along the road without going to the actual field site. The identification of treatment works or mitigation measures along the road was also used as a criteria for delineating the segments and corresponding AOI in this study. The presence of treatment works is vital to the estimation of risk per given road segment (Budetta, 2004; Rose, 2005) and is important to be differentiated from other segments that do not have one. In addition to the use of Google Street view, road video analysis from dashboard camera videos taken during fieldwork allowed the interpretation of the probable landslide types present along the road slopes and also later in the office. This is to account for the different types of slope mitigation/treatment works to be applied (Budetta, 2004; Rose, 2005; Sun, 2018), e.g., rockfall prone slopes are treated differently from shallow landslide-prone slopes, and therefore should be differentiated from one another.

3. **Field inspection and validation (road characteristics, slope type)**
   Field inspection of the road is essential for delineating AOI manually. This allows characterization of the road segments according to their properties such as width, number of lanes, and costs which is important for consequence analysis during the QRA. In addition to determining road properties, the slope types can be identified during field inspection. The type of slope whether they are cut slopes, natural slopes, mixed or embankments is difficult to deduce using Google Earth images and Streetview, and are most of the time difficult to delineate using DEM's. It is also emphasized that the type of slope that is observed influences the type of mitigation measure to be applied. Finally, the geology of the area and landcover are also considered as criteria and were determined using overlay functions in GIS, done post-field after data collection.

4. **Delineation of segments and their AOI**
   The final step of the approach after considering the criteria above is the actual delineation of the road segments and their AOI. This is typically done on a satellite image; in this case, the delineation was done on Google Earth imagery, extracted as a KML file then converted to SHP files using a GIS script. The shp files were overlain on the hillshade map derived from the DEM acquired in the field, and minor corrections such as the initiation boundary were adjusted. Typically, the AOI spans from the roadside to the upper ridge to be able to account for possible mass movement processes, and since the purpose of the AOI is to represent the immediate possible areas along the road upslope or downslope that may affect it in the future.

3.3.3 Results

A segment AOI is homogenous in character and therefore in the delineation procedure, no two adjacent segments possess exactly the same set of criteria/characteristics. This is noticeable in AOI's 6 and 7 wherein although the landslide type for the slopes concerned is the same (rockslide), AOI 6 did not have protection works installed while AOI no. 7 is protected by a gallery and tunnel to prevent damage to the roadway by rockfall and retrogressive erosion of the segment's downslope, which is occurring in AOI no. 9. The results yielded 16 total AOI's, with all of them possessing larger upslope areas than downslope due to significantly less steep slope configuration on downslopes of the roads. The downslope areas even though smaller, are important to consider since it is one of the sources of immediate structural damage to the roadway once they are eroded. AOI no.4 contains the 2016 landslide that caused a week of full road blockage, while AOI 15 contains the rockslide that forced road managers to construct new lanes of the highway after it caused significant damages and delays (Figures 3.3).

The results show that the manual delineation of AOI's works well in addressing the different site conditions that must be considered by the road managers (Figure 3.4). The manual method allows more flexibility for the road managers to add more criteria, e.g., pavement condition indices or budgetary constraints. These budgetary constraints are common in road asset management practice (CAREC-ADB, 2009; Rose, 2005). Manual /knowledge driven approaches such as this method of delineating road segment AOI's are effective and reliable especially when a technical person who has a solid background in geotechnical, geologic, and geomorphological studies conducts the actual AOI delineation. This is why it is important for road managers to have geotechnical personnel who can facilitate and execute this method when they conduct AOI delineation for the road segments during risk assessments. This method works well for site-specific investigations such as risk analysis of the road segments and can be used alone with minimal data.

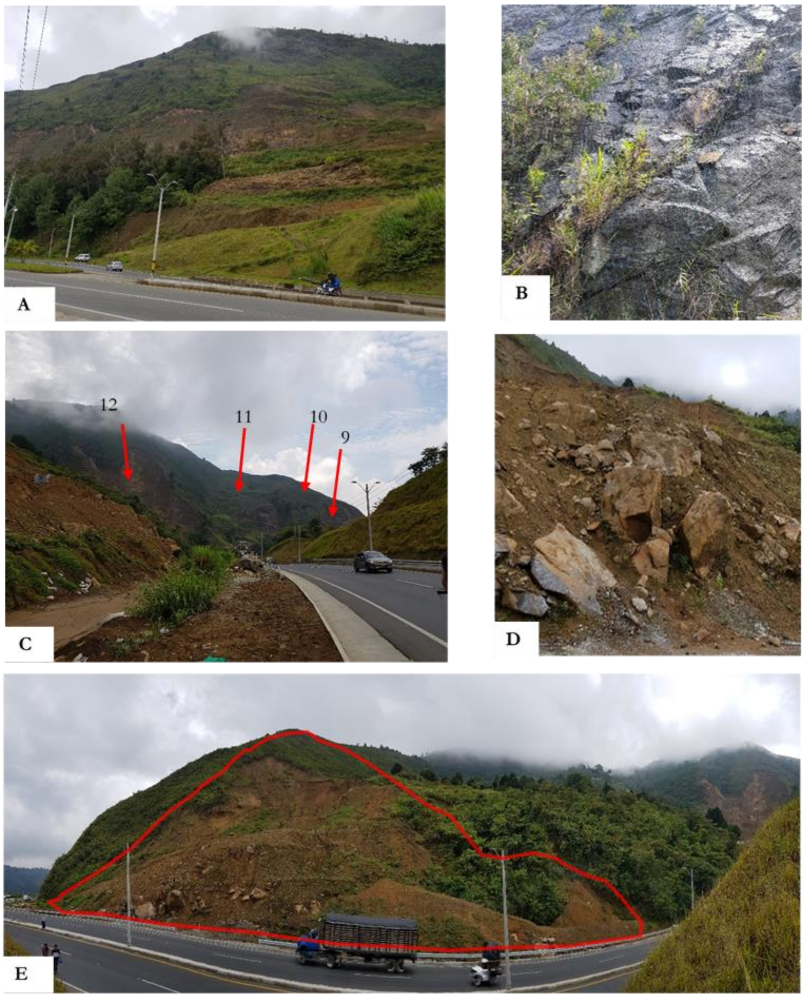


Figure 3.3: *Results and findings from the fieldwork in the road study area in Medellin, Colombia;*
A: Major portion of road segment AOI no.4 encompassing a recent deep-seated landslide event in 2016. B: Rockfall nets/protection works found in the study area. C: Overview of segment AOI nos. 9-12 as seen from road section affected by AOI no. 15. D: material from the recent rockslide event that occurred at AOI no.15. E: Panoramic view of a portion of AOI no.15.

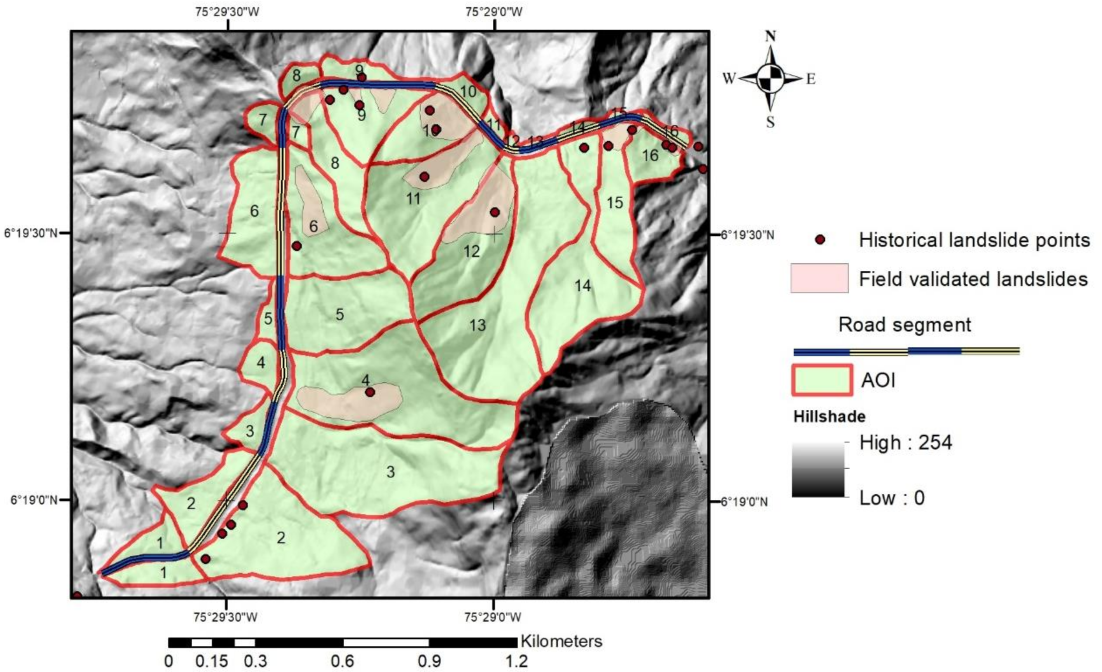


Figure 3.4: *Resulting AOI map produced from fieldwork and analysis*

Table 3.1: *Summary of criteria used to delineate road segment AOI in the knowledge-driven approach*

Criteria AOI	Past events[1]	Protection works[2]	Landcover[3]	Geology[4]	Slope type[5]	Landslide type[6]
1	1	**0**	**R**	**1**	**N**	**RS**
2	1	**1**	**R**	**1**	**C**	**SS**
3	0	**0**	**Q**	**2**	**C**	**0**
4	1	**1**	**Q**	**1**	**M**	**DS**
5	0	**0**	**Q**	**1**	**C**	**0**
6	1	**0**	**B**	**2**	**C**	**RS**
7	1	**1**	**T**	**3**	**N**	**RS**
8	0	**0**	**B**	**3**	**C**	**RF**
9	1	**0**	**B**	**3**	**C**	**SS**
10	1	**0**	**B**	**3**	**N**	**RS**
11	1	**0**	**Q**	**3**	**M**	**DS**
12	1	**0**	**B**	**3**	**N**	**RS**
13	0	**0**	**R**	**3**	**N**	**0**
14	1	**0**	**G**	**3**	**N**	**RS**
15	1	**0**	**G**	**3**	**C**	**RS**
16	1	**0**	**G**	**4**	**C**	**SS**

[1] Historical events (1=present, noted from google earth historical image viewer, 0=absent)

[2] Protection works (1=there are installed protection works observed from fieldwork and Google Streetview, 0=absent)

[3] Landcover (R=Residential, Q=Quarry, B=Bare land, T=tunnel, G=grassland)

[4] Geology (1=predominant landslide deposits with occasional amphibolite and gneiss; 2=predominantly underlain by landslide deposits and amphibolite; 3=gneiss; 4=mixture of gneiss and amphibolite

[5] Slope types (C=cut slope, N=natural slope, M-combined cut slope and natural slope)

[6] Landslide types (RS=rock slide, RF=rockfall, SS=shallow landslide, DS=deep seated landslide, 0=no landslide observed)

3.4. Method 2: Watershed (sub-basin) approach

3.4.1 Concept

The second segmentation approach considered for this study is the semi-automated watershed delineation approach using the SWAT (Soil and Water Assessment Tool) developed by Arnold & Fohrer (2005). The method involves integrated DEM pre-processing to calculate flow accumulation and direction then allows users to set the minimum size of the watersheds to be created, with the tool selecting the optimal flow accumulation and direction for the user determined input size of watersheds. AOI's are strongly influenced by geomorphological processes and drainage delineation and capture may provide a good output for an AOI candidate. The SWAT tool is open source and downloadable at https://swat.tamu.edu/software/arcswat/.

3.4.2 Methodology

1. **DEM preprocessing**

   Pre-processing of the DEM was done automatically within SWAT to remove minor errors in the DEM which could result to the wrong delineation of drainage lines during the procedure (Djokic, 2017; Zhu, 2013). The DEM product of this operation was then processed to calculate flow direction and then the flow accumulation raster.

2. **Setting of the minimum size of watersheds to be created**

   After pre-processing, the minimum area of the watersheds to be created has to be specified in m^2 (Arnold & Fohrer, 2005). This will be important for the tool to delineate the stream networks and the stream junction points (stream order) where it will adjust the size of the watershed candidates. For this research, three minimum watershed sizes were tested ranging from 100000m^2 – 200000m^2.

3. **Delineate watersheds**

   From the minimum area set by the user for the watershed size and the stream network and optimum stream order aggregated within the tool, the watersheds are drawn. The output watersheds are then selected depending on its intersection with the selected road study area and compared to the field based AOI's delineated. Summary of the SWAT process of watershed delineation executed is shown in Figure 3.5.

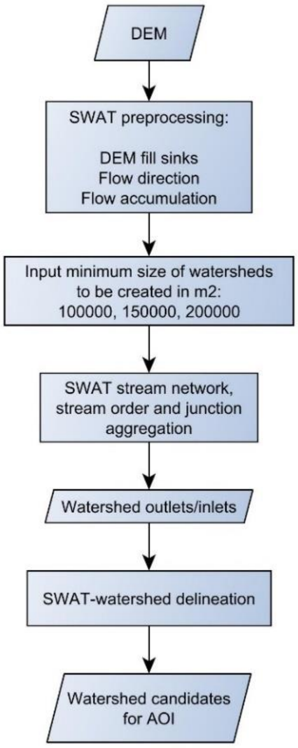


Figure 3.5: *Overview of the steps done using SWAT tool to create Watershed AOI's*

3.4.3 Results and comparison to manual AOI delineation approach

In comparison to the manual/knowledge driven AOI method explained in the previous section, the semi-automated watershed approach using SWAT yielded almost the same number of AOI's with the field based approach. This is evident in the 100,000m^2 minimum area watershed map (Figure 3.6A). The results show that the AOI boundaries generated were close to the field-based AOI's, especially for upslope areas. For downslope areas, it is expected that the Watershed AOI's would be longer and expansive since it captures the entire dimensions of the stream networks it aggregated in accordance with the minimum area size input. Even though watershed delineation is generally a regional scale hydrological procedure, this method can be effective in AOI production when the minimum area of watershed characterized by the SWAT tool is field calibrated. In addition to this, refinement of the method by adding other GIS data such as geomorphological layers, and landslides from historical datasets would further improve its effectivity as a tool for AOI delineation.

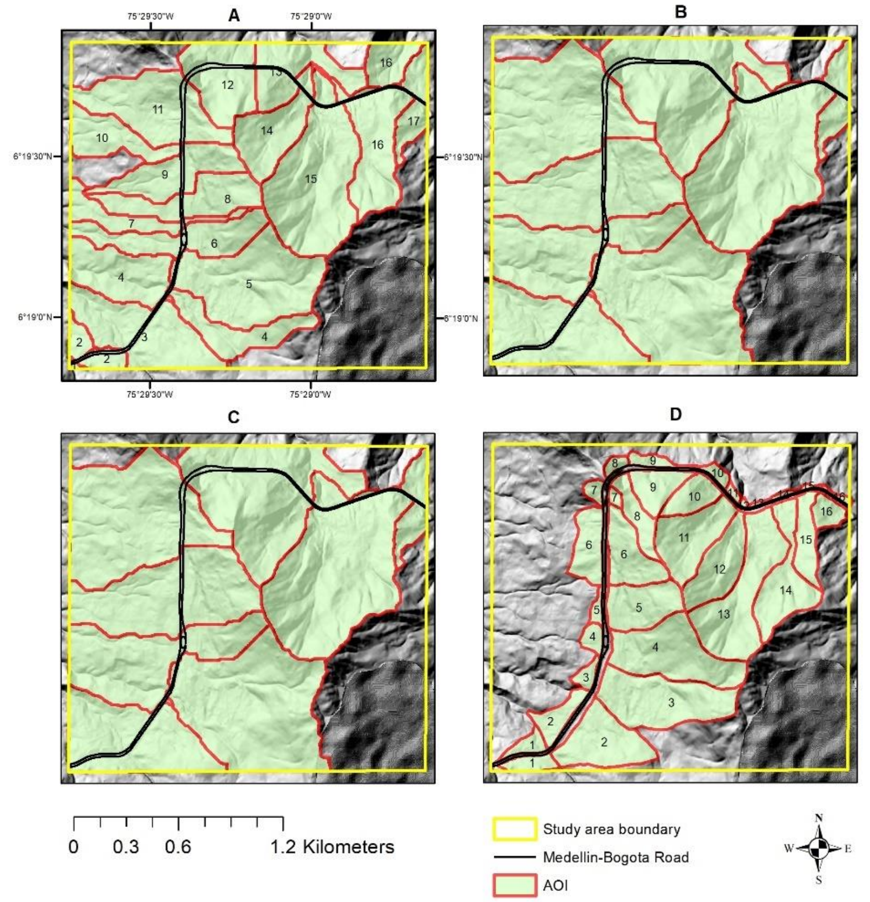


Figure 3.6: *Watershed AOI's produced:* ***A****: min. area-100,000*m^2*,* ***B****: min. area-150,000*m^2*,* ***C****: min. area-200,000*m^2*,* ***D****: Field based AOI's*

Most works involving sub-basin or watershed delineation is only used for hydrological studies, however, with the advancement of GIS tools such as SWAT, this can now be applied in site-specific activities such as delineation of AOI's for road segments in risk analysis. In terms of the SWAT's drawbacks, there could be irregularly shaped watersheds that could be produced as a result of it not taking into account the curvature variances in the DEM; this could cause problems in very small minimum area settings.

3.5. Method 3: Slope unit approach

3.5.1 Concept

The third segmentation approach considered in this study involves automatic delineation of slope units (SU) which is defined as a geomorphological terrain unit that is bound by drainage, and ridgelines or watershed divides (Alvioli et al., 2016; Schlögel et al., 2018). The SU approach is similar to the sub-basin approach however the slope units provide more detailed segmentation since it primarily considers the aspect and curvature in combination with the slope angle of a given slope face (Alvioli et al., 2016). A slope unit according to Guzzetti et al., (2006) is easier to recognize in the field and is also well suited for hydrological and geomorphological studies for landslide zonation. The goal of this approach is to delineate AOI's which possess homogenous terrain parameters (slope and aspect).

According to Alvioli et al. (2016), there are two strategies to delineating slope units. The first strategy involves defining a large number of small areas with homogenous terrain characteristics; this is then enlarged and aggregated to a user-defined maximum area. This strategy results to very small SU size (Espindola, Camara, Reis, Bins, & Monteiro, 2006; Zhao, Li, & Tang, 2012). The second SU delineation strategy described by Alvioli et al. (2016), involves the opposite of the first approach wherein the initially defined homogenous areas are larger. Very similar to sub-basins which are fewer in number and comparable to the previous AOI method evaluated. The second strategy first divides the whole study area into large sub-basins, then is further subdivided into smaller sub-catchments to the left and right side to a drainage line and are then called half-basins (HB). Figure 3.7 shows how Alvioli et al., (2016) and Wang et al., (2017) have employed the second strategy of subdividing large basins into half-basins.

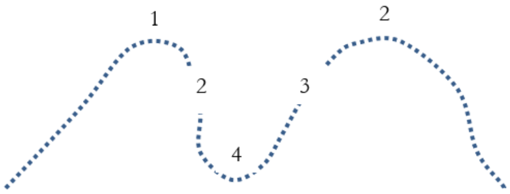


Figure 3.7: *Schematic section/profile showing how SU's are defined with reference to a main drainage line or valley (4); slope units (2) and (3) are defined to its left and right respectively while (1) and (2) shows the ridge lines separating the two topographic highs. Figure modified from Wang et al (2017)*

In the two aforementioned SU delineation strategies, this study applied the second strategy which is also the operating principle of the r.slopeunits tool developed by Alvioli et al. (2016) in Python and Grass GIS.

3.5.2 Methodology

1. **Prepare input DEM and parameters**
   The r.slopeunits tool developed by Alvioli et al. (2016) requires a DEM and the following user provided input parameters (Figure 3.9): 1.) the flow accumulation area threshold, t; 2.) the minimum slope unit planimetric area, a; 3.) circular variance, c; 4.) reduction factor, r; and 5.) Clean size threshold in sq.m.

   The **t** value is used to control partitioning of the watersheds generated from the DEM using the flow accumulation values, flow accumulation value>t is defined as drainage lines which are then used for creating the sub-basins. The **a** parameter is used to define the smallest allowable area for an SU candidate. The **c** value ranges from 0-1 and represents the amount of circular variance that is allowed for an SU candidate; this also represents homogeneity of grid cell direction, e.g., aspect variation. The reduction factor, **r** indicates the subdivision rate of the half-basin process; in this study, the default value of 2 is used. Finally, the **clean size** is an optional filter in the algorithm that makes sure that no final SU's produced have a very small area. Table 3.2 shows the input parameters used for the delineation of SU in the study area. Three alternative SU maps were produced; the best one was selected on the basis of its visual comparison to the manually delineated/field based AOI approach.

DEM: 2 m resolution

Alternative	t (m^2)	a (m^2)	c	r	Clean size (m^2)
1	50000	150000	0.2	2	50000
2	50000	100000	0.1	2	10000
3	50000	10000	0.089	2	1000

Table 3.2*: Input parameters used for SU-AOI delineation using r.slopeunits tool*

2. **Delineation and a, c filtering of half-basins**
   Once the DEM input is processed, the algorithm uses the flow accumulation area threshold **(t)** to first define drainages in the DEM, similarly to the sub-basin approach in the previous section, the drainages serve as the basis for the further delineation of the half-basins (HB) (Alvioli et al., 2016; Wang et al., 2017). After the first delineation of HB's, these resulting HB's are then filtered with respect to parameter **a**, all HB's that are larger than this minimum planimetric area set are considered for the next round of filtering which is according to the set parameter of circular variance, **c**. The preliminary HB's that are smaller than parameter **a**, are then directly considered as SU candidate if they also pass cleansize filtering. In the circular variance filtering, all HB's that have variance values lower than the set parameter **c**, are accepted and will be subjected to the final filtering by cleansize.

The HB's that have a larger value of circular variance than the set parameter **c**, are rejected and excluded from the SU candidates.

3. **Cleansize filtering**

   The final filtering of the SU delineation method used involves the clean size filter; this is also included in the r.slopeunits tool as a separate script. According to Alvioli et al.,(2016) & Schlögel et al. (2018), filtering by using the clean size is an optional procedure. However, this was still performed in this study to make certain the product SU's are not irregularly shaped. This filter is mostly used to remove irregular shaped candidate SU's and also to act as the final filter for rejecting very small SU candidates that may have been accepted from the first filter using parameter **a**. In this study, the clean size parameters used were varied per alternative map (see table 3.2), this is with accordance to the variation in the minimum area threshold, **a** to find the suitable SU AOI products that are comparable to the field based method.

4. **Final SU rendering and AOI selection**

   The final SU's of the input DEM are rendered after the clean size filtering procedure. The SU's produced are then intersected with the road layer to identify which SU's are considered as road AOI for the study area, the rest of the SU's that do not intersect with the road layer are left out. Figure 3.9 shows a summary of the method done in this study involving the delineation of SU to produce road AOI's.

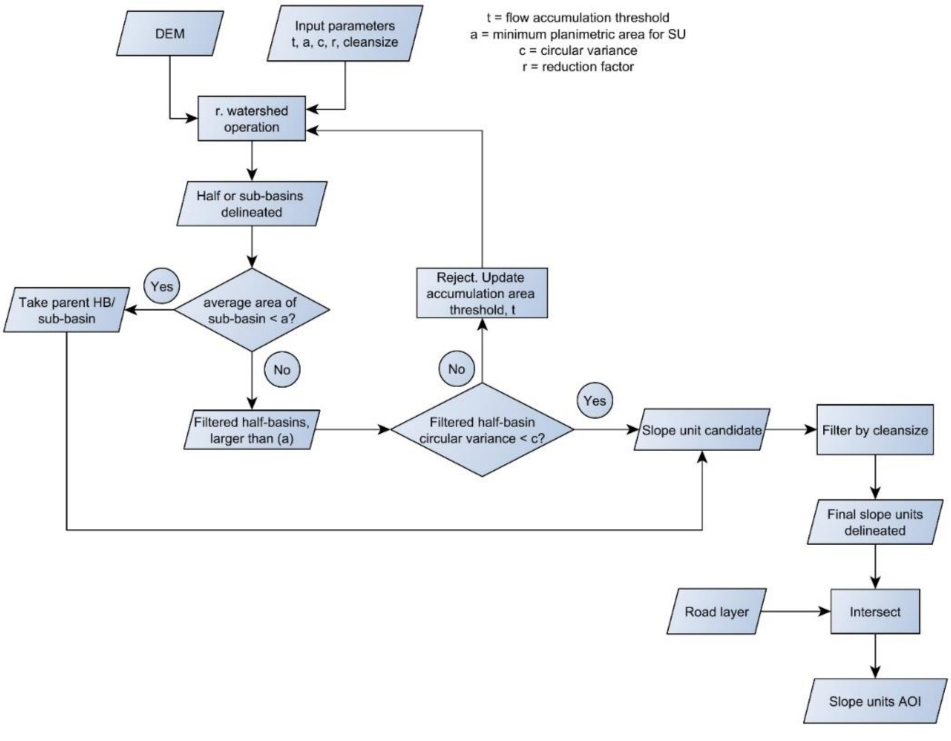


***Figure 3.8**: Flowchart showing summary of procedures done in the SU approach for this study*

3.5.3 Results

The applicability of delineating slope units as an approach to generate road segment AOI's was evaluated. This was done by running the r.slopeunits tool in Grass GIS using the DEM and varying the input parameters t, a, and c to come up with different alternative maps that could represent the AOI's as shown in Figure 3.9. This was compared to the manually delineated/field based AOI's shown in Figure 3.10D. Based on the figures, it was the first alternative map that was selected to be scrutinized in detail with the manually delineated AOI map. It also shows that as the a and c parameters were decreased, the SU's became smaller in area and more homogenous in terms of terrain characteristics. In addition to this, the 50000m^2 difference in the minimum planimetric area parameter set for alternatives 1 and 2 resulted in more SU's that differed substantially from the ground-based road AOI map in Figure 3.9D.

It is important to point out that the operating principle of delineating SU's has a subjective element which is deciding when to stop the partitioning procedure while implementing the whole method. In the context of road segment AOI delineation and future prioritization this could be a disadvantage of the SU approach when applied only on its own, also considering that SU delineation focuses only on terrain characterization which is only part of the criteria for outlining road segment AOI's.

The alternative SU maps showed good results in terms of terrain representation given the low circular variances assigned along with the additional clean size filter that was implemented during the procedure. However, careful comparison with the manually delineated AOI's revealed that delineating SU's alone cannot provide a good representation of all criteria that should be considered when delineating road segment AOI's. In addition to this, manually delineated AOI's were based on road segments characteristics first then drawing their respective AOI's based on combining multiple factors that were not considered using SU alone.

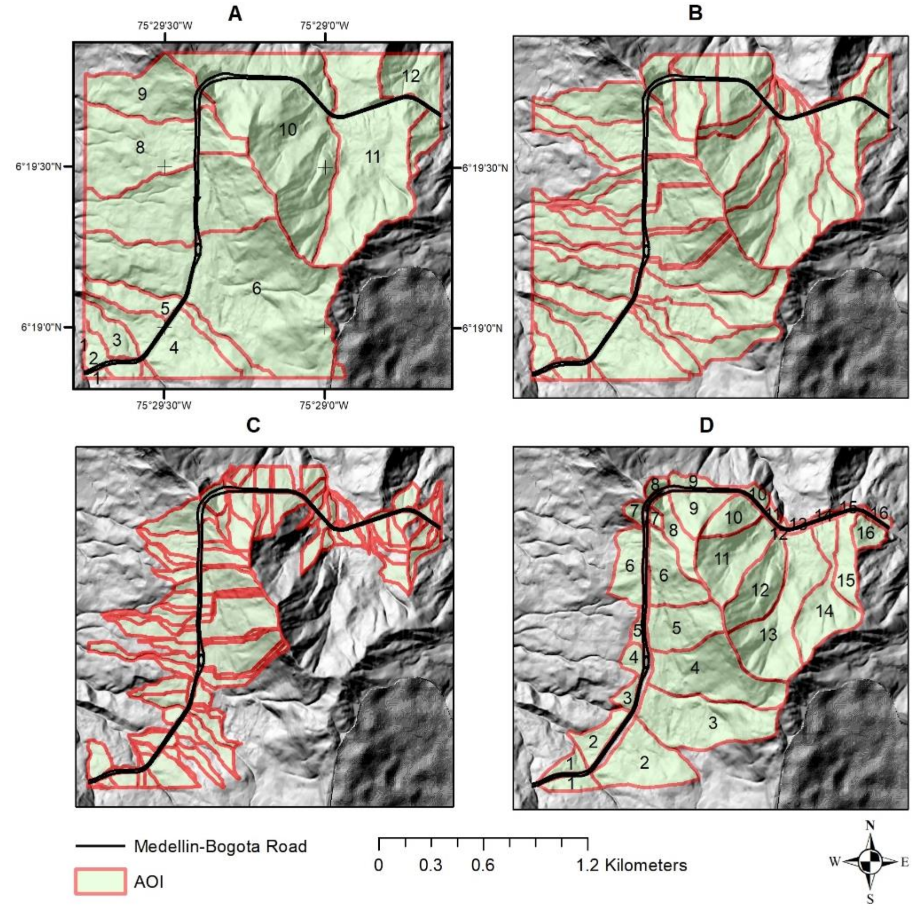


Figure 3.9: *SU alternative maps and comparison to field based AOI's:*

***A**: alternative map 1 showing larger and comparable AOI's, this map is used for the comparison with the manually delineated/field based AOI map in (**D**). **B**: alternative map 2 showing also good results with respect to dividing the sub-basins; however, there were many SU AOI's that were too small or narrow that the clean size filter could not address. **C**: alternative map 3 showing the most number of SU's produced, the very small SU's produced are irregularly shaped mostly representing only small drainage channels.*

The SU AOI's rendered from alternative map 1 showed different SU's associated with the manual AOI 1 and 2. This may imply that the ground-based AOI's may have generalized the terrain characteristics in these sections of the road. In AOI no. 6 of the SU approach (Figure 3.9A), it completely enclosed AOI's 3 and 4 of ground-based AOI's. When this is analyzed with respect to Table 3.1, it reveals that the SU AOI generalized the terrain conditions for both even though there was a reported large deep-seated landslide in manual AOI no. 4 and there was no evidence of past events on AOI no. 3. Overall, the SU AOI's delineated were not generalizing the ground conditions to a great extent, except for AOI nos. 10 and 11 which enclosed most of the important AOI's delineated from fieldwork. It also shows that SU delineation has good potential for AOI production as evidenced by it's complete 1:1 capture of the manual/field AOI's 5, 6, and 7.

From Figures 3.9A and 3.9D, the results show that the boundaries of the AOI's and consequently its discretization on the road are different, mainly due to slope and aspect characterization. As a result of this, there are cases wherein there may be more SU segmentations per AOI unit delineated manually such as manual AOI no.1, or lesser SU segmentations per manual AOI, e.g., manual AOI nos. 3,4, 8-12.

3.6. Method 4: Runout path delineation approach

3.6.1 Concept

The fourth segmentation approach considered for this study is the use of an inverse landslide reach angle approach utilizing the empirical landslide runout model Flow-R developed by Horton et al., (2013). The software simulates the most probable runout paths for landslides from given initiation points using spread algorithms, initiation buffers, travel angle, and landslide velocity parameters. This approach provides areas that are considered to have a higher probability of being on the path of upslope landslide types such as rockfalls, and debris flows. In addition to this, the runout approach can be useful for determining the source areas by varying the travel angles and simulating it in an inverse manner. The runout simulation utilizes the DEM of the study area and a user-defined input source area.

3.6.3 Methodology

The general idea of performing this approach is to be able to determine source areas along the slope that would reach the road study area. To do this, three fundamental steps were performed: (i.) the DEM was flipped/inverted, (ii.) the input parameters such as travel angle, velocity, and flow algorithms were determined, and the road is taken as the source area (iii.) running the Flow-R software, the DEM is inverted again back to its original configuration to identify the location of sources that would reach the road given the travel angle and velocity.

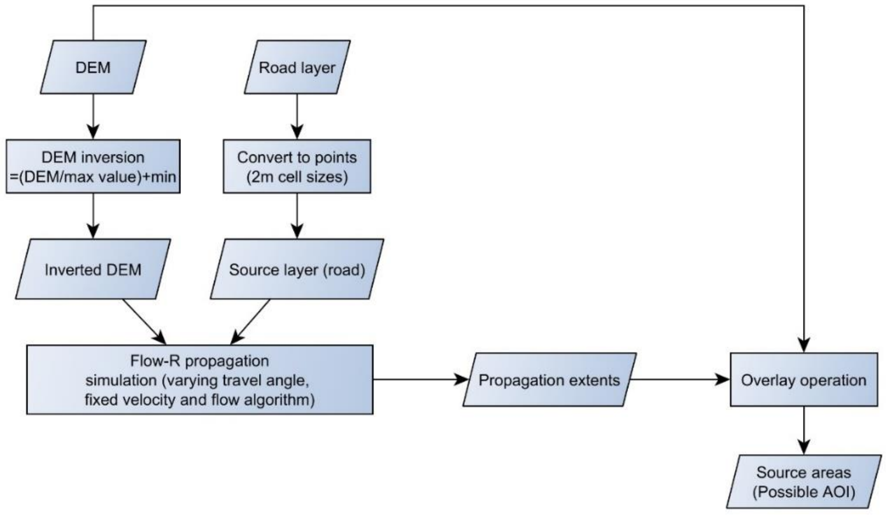


Figure 3.10: *Summary of the procedures performed to identify possible source areas of landslides that can be considered as road segment AOI's*

1. **DEM inversion**

   The first important step performed for the possible source area delineation was inverting the DEM values. By doing so, the surface underlying the road network would be placed at a higher elevation than the slopes and will, therefore, be the initial source areas for the Flow-R simulation. Runout modelling was specialized to project propagation extents of debris flow and other landslides going downslope from a source, and cannot run in the opposite direction. This is why the DEM inversion was necessary as to determine which portions of the upslope areas could reach the road sections while taking the road as the landslide source. This method is similar to what Wang et al. (2017) implemented for delineating slope units and source areas along a river network in Southeast China.
2. **Essential input parameters**

   The travel angle was varied from 5 to 30 degrees to test its effects on the source area projection. The velocity of runout was fixed at 20m/s which is according to the guidebook of landslides published by the USGS and Highland & Bobrowsky (2008). The flow algorithm assigned was D infinity, which gives better spreading than the default D8 algorithm (Horton et al., 2013). The Holmgren coefficient and exponent was fixed at 1 and 5, respectively to ensure maximum propagation and spread to simulate the worst-case scenario. Table 3.3 provides a summary of the input parameters used for the simulation. The road layer was converted to a raster with a cell size of 2m; this was done to link it with the input DEM layer.

DEM: 2m resolution			
Travel angle (°)	**Velocity (m/s)**	**Holmgren coefficient dh**	**Exponent, n**
5	20	1	5
10	20	1	5
20	20	1	5
30	20	1	5

Table 3.3: *Summary table of parameters used during the runout simulations in Flow-*R.

3. **Determine source areas as possible AOI**
   The resulting propagation extents from the simulation is then overlaid in the original configuration DEM to visualize slopes that could be initiated at a given travel angle and velocity and therefore can affect the road network (AOI). The results of the simulations are presented in the next section.

3.6.4 Results and discussion

The applicability of using the runout propagation extents on an inverted DEM as a basis for determining possible road segment AOI's was examined. It is crucial that the sources for run-out simulation is the roadway itself, in order for the analysis to provide all potential landslide paths that may affect the road when the results are visualized on the normal configuration DEM. The results from Figure 3.12 reveal that the lowest travel angle resulted to the most triggered landslide paths that can affect the road. The 30-degree travel angle yielded the least amount of probable source areas given the fixed velocity set at 20 m/s. The results of the simulations indicate that using runout paths as a basis for establishing road AOI's is plausible, as seen from the maps, the uppermost ridgelines and steep cut slopes are well represented and have the highest estimated probability for being sources among the propagation extents.

Although the method is good for identifying possible source areas in the slopes, there are drawbacks in the method. An important drawback for this method is in terms of the runout kinetic energies and its relation to the inversion of the DEM. This is illustrated in Figure 3.11. The figure shows that the travel angle between the two configurations of the DEM are different and therefore the kinetic energy is not the same for both scenarios. When the road is used as the hypothetical source area, the adjacent terrain is usually relatively flatter as a result of the road pavement and its shoulder, therefore the shoulder should not be included as source areas and characterization of the source should begin immediately after the terrain is sloping.

To compensate for this gradual terrain, the travel angle must be decreased to trigger the hypothetical source which is the road. This is why the 30-degree travel angle map did not have numerous runout extents because the majority of the entire road length did not have a 30-degree immediate gradient. The method, however, is still effective in identifying the most plausible source areas such as ridge tops and cut slopes.

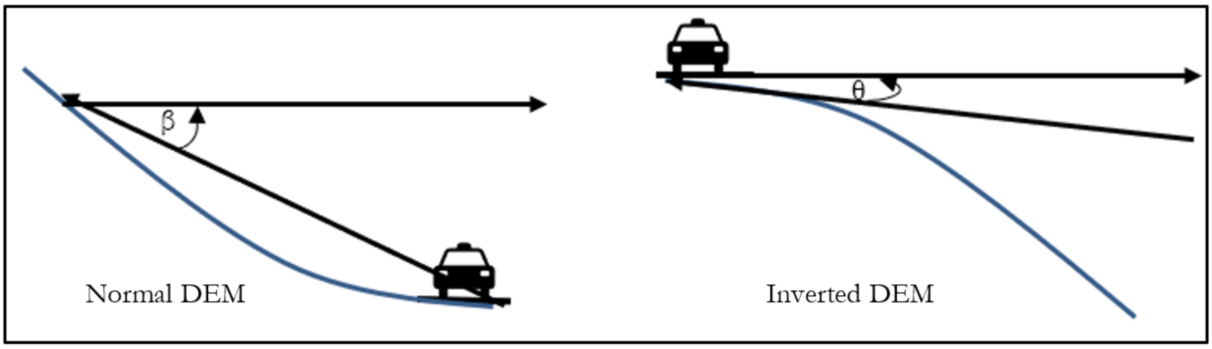


***Figure 3.11**: Left: The travel angle β when the source is defined at the upslope of the road using the normal configuration of the DEM; Right: The travel angle θ when the source is defined at the road during DEM inversion configuration.*

It is also good to emphasize that while the 5-degree travel angle (Figure 3.12A) yields the most amount of projected spreading, it is also considered as the worst case event and would be good to evaluate with the manually delineated AOI map for comparison especially in terms of its ability to represent ground conditions that are important to consider for mitigation prioritization. It is also noticeable that map A does not project the 2016 landslide event, this could be attributed to a possibly lower release angle of the actual landslide, or the DEM was recently updated and does not represent the previous slope configuration that led to the landslide.

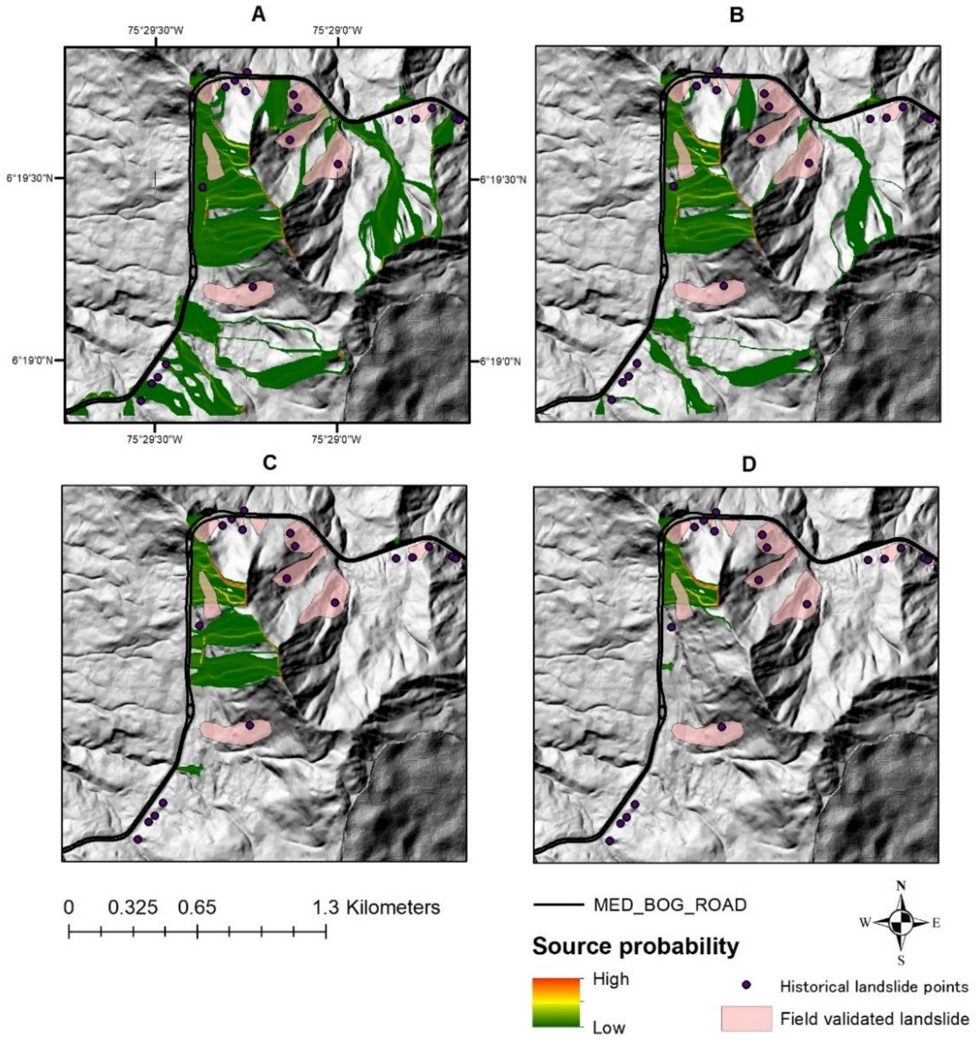


***Figure 3.12:** Compiled maps for the runout propagation resulting from variation of the travel angles.*

3.7. Method 5: Experimental plane fitting method

3.7.1 Concept

Finding the possible landslide sources or initiation points using runout propagation models such as the method used in Section 3.6 has drawbacks with respect to the lesser travel angle assumed to ‘trigger’ the landslide sources. It is also important to emphasize that this task of locating the landslide sources on the DEM surface is based on a principle of plane fitting from the road itself and finding the intersection on the DEM. Since the inversion of the DEM as evidenced in section 3.6 involves significantly lowering the travel angles, another method is presented here that does not involve lowering of the travel angle or specifically the line of sight angle from the road to the slopes. Figure 3.14 illustrates this approach.

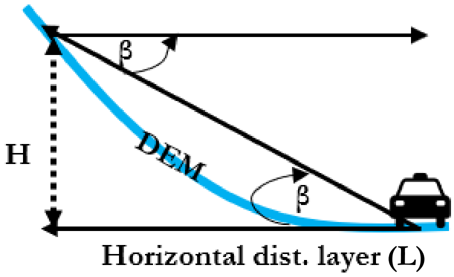


Figure 3.13: *Diagram outlining the principle of plane fitting method:*
Finding the intersection between the plane having a fixed release angle, β and the DEM; the raster values over the intersection is presumed to be the possible landslide source that may affect the road. The height raster, H is calculated from the horizontal distance layer and line of sight angle β which is equal to the release/travel angle.

3.7.2 Method

A summary of the procedures conducted in this experimental method is shown in **Figure 3.14**. The method makes use of the concept of landslide travel/release angle on sloping terrain.

1. **Creating a horizontal distance layer from the road to the upper slopes**
   The first step in the method of plane fitting and intersection is creating the horizontal distance layer, **(L)** from the road. This is done by using the Euclidean distance function and outputs a raster map with distance from the road values per pixel. The assumption in this step would be the horizontal distance is measured as a straight line distance from the road (Figure 3.14). Another consideration would be masking the downslope portions of the road since the method can only consider landslides coming upslope that could reach the road.
2. **Adding the height layer with respect to the horizontal distance and desired angle of release/line of sight**
   Following the creation of the horizontal distance layer, the height raster is produced from multiplying the horizontal raster and the Tan (angle of release, β) and then adding the base level of the road to the result. This is equivalent to raster Equation (3.1). There were two angles of release that were tested, which are 30° and 15°.

$$Hc = L*(\tan(\beta)) + Hr \qquad (3.1)$$

   Wherein, Hc refers to the height of the plane generated from an angle β from the road, L is the horizontal distance layer, and Hr is the average base elevation of the road at 2087m.

3. **Subtracting DEM layer and height layer/raster**
   The altitude/elevation layer (Ac) is subtracted from the height raster produced to yield an intersection/difference map between the two surfaces. This was done using equation (3.2).

$$\mathbf{Z=Ac-Hc} \tag{3.2}$$

Wherein Z is the intersection/difference map produced, Ac is the DEM, and Hc is the height of the plane per cell layer.

4. **Thresholding of raster values to identify possible source areas**

   Thresholding of landslide source raster values is done by manipulating the histogram produced to conditional statements. The threshold can be set by expression (3.3)

$$\textbf{Source: } \mathbf{Z > 0} \tag{3.3}$$

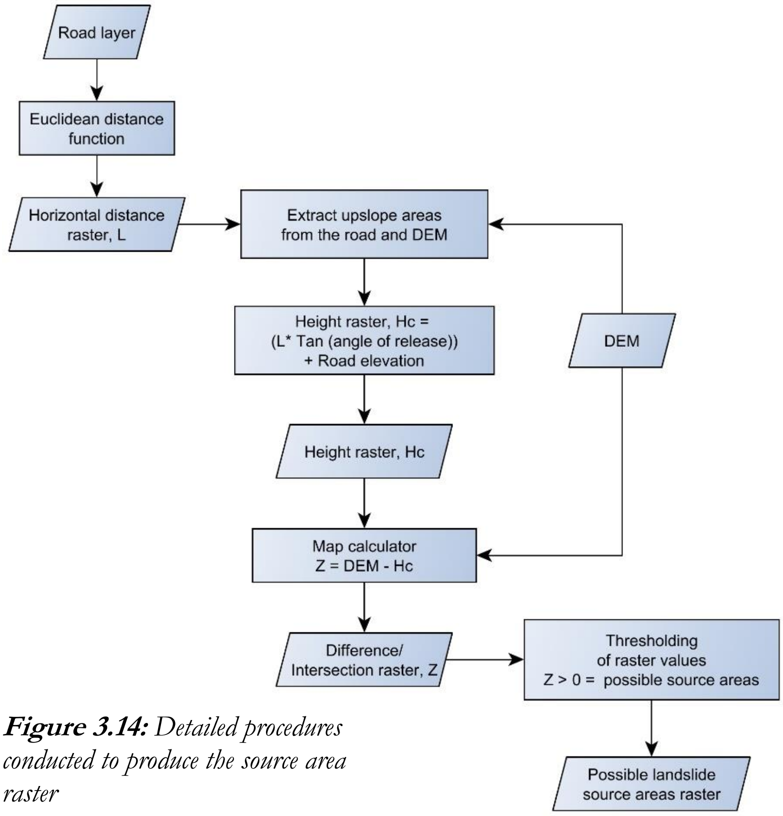


Figure 3.14: *Detailed procedures conducted to produce the source area raster*

3.7.3 Results and discussion

Figure 3.15 shows the results of the initial steps conducted before the source maps were produced.

Since the method was carried out to predict landslide source areas, the landslide points from historical databases and polygons from field observations were plotted to check the resulting map. The landslides are shown together with the predicted source areas for a 30° and 15° release angle is shown in Figure 3.16.

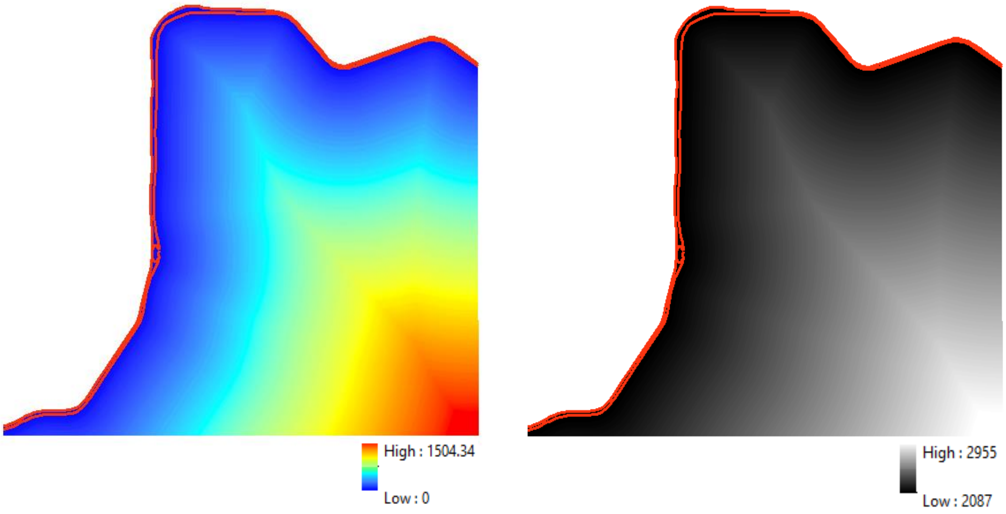


Figure 3.15*: Left: Horizontal map produced with the road as reference (0), Right: Height map produced using equation (2) for the 30° plane. Values indicated are in meters.*

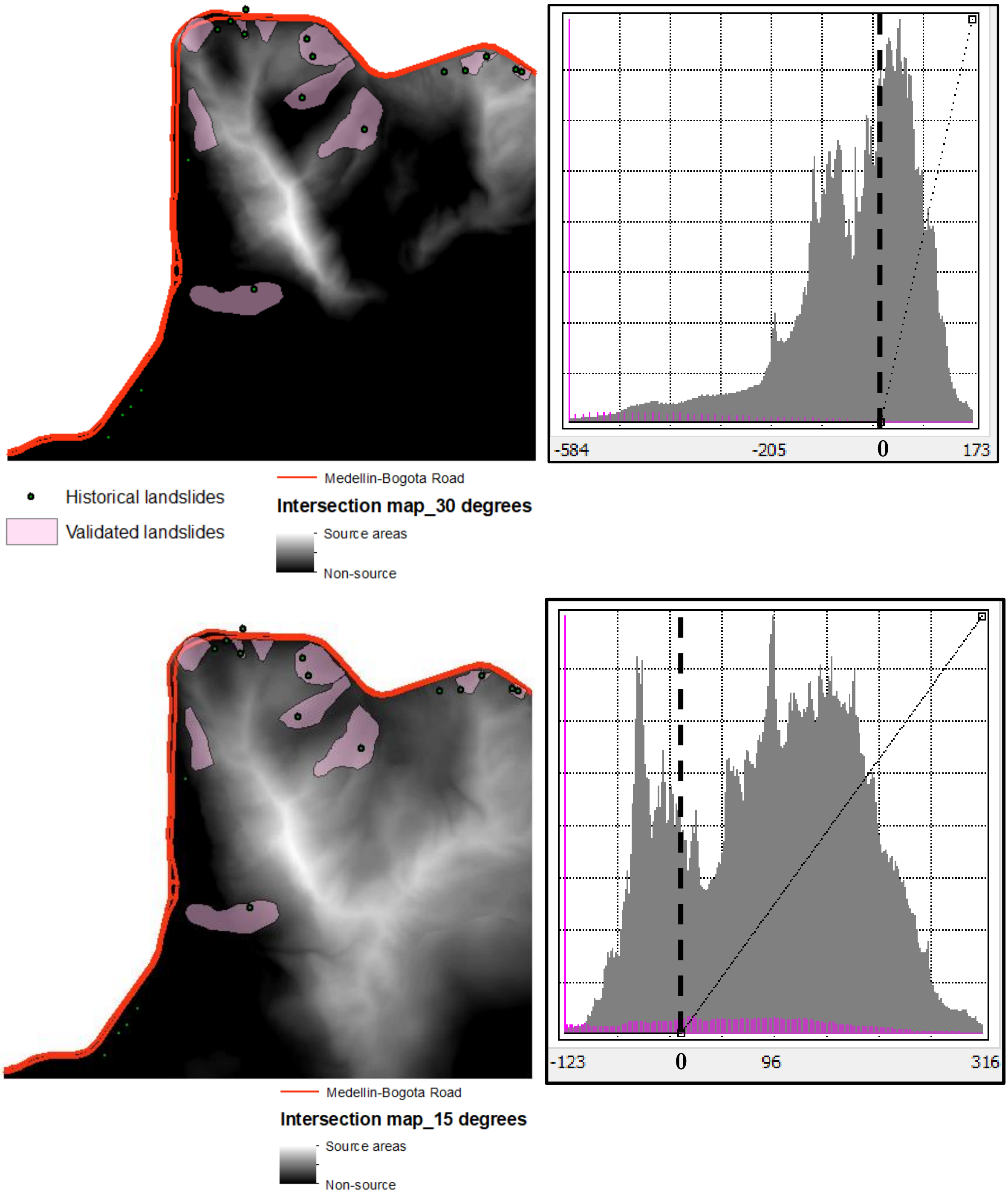


Figure 3.16: *Projected landslide source maps for release angles 30° (A) and 15° (B). Threshold values set at Z>0*

The results show that only 60% of the landslides located within source areas with 30° runout angle, which increased to 80% for the 15° release angle. However, there may be overestimations from this, as this covers nearly all the upslope areas. Lower release angles could be applied for shallow landslides on cut slopes and debris avalanche on the natural slopes such as the 2016 landslide event. Higher release angles are more applicable to rockfalls or rockslides which are fewer in number in the study area. It is interesting to note that the release area of the 2016 event and large rockslide succeeding it were located within the projected source zones, from which landslides could reach the road based on the release/reach angle alone. However, it is not only the type or behavior of the landslide and release angle that should be considered, the volume or amount of material released is also important to take into account when mapping out probable landslide source areas.

Even though the method was able to overlap relatively well for rockfalls and rockslides, there are significant drawbacks to the method. First, the horizontal distance on the ground is not directly flat and the method when the Euclidean distance function was performed assumed that the distance to the slopes is linear therefore terrain inaccuracies may occur from this assumption. Second, the DEM may not be able to accurately represent the small overhanging areas or small cliffs that are present along the slopes. The third drawback foreseen in this method was the use of average road elevation as the base level (**Hr**) in Equation (3.1). This assumes that the road is at a fixed elevation and not sloping which is often not the case especially for mountainous highways. Another major drawback for the method is that it is not capable of analyzing the respective AOI's of road segments since it only determines probable source through a sharp boundary or threshold. Moreover, upon comparison to the runout propagation maps, which follow the actual terrain, the results are very different. Therefore this method may not be applicable for delineating AOI's. Finally, the method proposed operates on the principle of the landslide release angles and transition of the potential energy of sources unto kinetic energy. This may not apply to sub-vertical or vertical slopes since from these slope configurations; the actual landslide path could vary significantly depending on the terrain underneath and are also more complex to predict.

3.8. Discussion and conclusions

3.8.1. Comparing the effectiveness of each method to capture the validated landslides in the area

The main goal of this chapter was to compare different methods that aim to automate the delineation of AOI's of road segments as input in risk assessment. After the analyses, as evidenced in Figure 3.17, we can conclude that the manually delineated/field based method can best capture AOI's. In addition to this, the manually delineated AOI's are based on several criteria that are tailormade for the whole process of risk analysis and can be used alone with minimal data requirements.

The watershed approach and slope units are also able to capture the validated landslides with resulting AOI's that possess comparable boundaries with respect to the field-based AOI's. However, to use them independently for AOI delineation would not be sufficient to incorporate other crucial factors to be considered in risk assessments such as the mitigation measures applied, type of landslide, the material/lithology, and the type of slope. The runout approach, also as observed in Figure 3.17, shows good potential in terms of detecting possible landslide source areas. However, for AOI delineation, it also is not sufficient. For instance, the runout propagation path for the 5° release angle which is already considered as worst-case conditions for shallow landslides, is not able to predict or capture the validated landslides observed in the area or those landslides from historical imagery. Moreover, problems of non-initiation persist as a result of inverting the DEM and compensating for this by assigning lower initiation release angles.

3.8.2. Advantages and disadvantages of employing each method

The manual delineation of AOI has good applicability in terms of its direct approach to risk analysis. It also considers most of the crucial factors involved in risk analysis and is highly flexible in terms of its criteria usage. The approach allows to homogenize important landslide factors such as the type and its extents, and also to allows users to differentiate a segment using the criteria. The drawback of using the manually delineated approach to generate AOI's is its subjectivity which also affects its reproducibility. It is imperative that this activity must be conducted by persons with a geotechnical, geomorphological or geological background, one who is familiar with the processes and also knowledgeable of its implications to the risk analysis. Nevertheless, if the experts sufficiently delineate the AOI's, it is a good approach that can be directly used in risk analysis. Of all the methods evaluated, only the manual method starts by considering the road segment first then delineating the AOI's after. The rest of the methods directly outline the AOI's first then intersect these AOI's with the road to define a segment. Therefore only the manual method is able to incorporate the components needed to define road segments.

The watershed approach using SWAT to delineate road segment AOI's for risk analysis can be used for preliminary definition of AOI's. The main strong points of employing the method are in its ability to delineate watersheds automatically and efficiently. The approach is especially useful as a starting procedure for AOI delineation and can be calibrated with field measurements to further improve its outputs. However, it cannot take into account the landslide types, protection works, and other factors that need to be dealt with separately during road segmentation and risk analysis.

Slope units (SU)delineation has been proven useful in landslide susceptibility studies and can also be used for road segment AOI delineation. Its strong points come in terms of the capability of the approach to homogenize terrain units. The approach may be similar to the sub-basin method in terms of principle, but the procedures used such as setting a minimum threshold value for area and curvature enhances its capability to produce quality AOI's for road segments. Another strength of the method is in its lack of subjectivity during the actual SU delineation in contrast to the manual approach. Reproducibility of the method is good especially with the use of r.slopeunits tool in GIS. However, although the approach accurately represents homogenous terrain characteristics, the output SU's can still become unrealistically small or highly irregular despite the a,c, and clean size filters. It has to be considered that the SU delineation would work best for AOI generation if the minimum planimetric area and circular curvature parameters are field calibrated. This also avoids repetition or trial and error during the parameter setting. Apart from these minor drawbacks of using SU's for AOI's, this approach is still recommended for AOI delineation on the condition that the parameters are field calibrated.

The final method evaluated in this section is the runout approach. The total runout propagation by initiating the road in an inverted DEM setting is advantageous for the identification of possible landslide source areas such as ridges and very steep cut slopes. For AOI production, the runout propagation simulated is not feasible; its representation of known landslides in the study area is also not good. This is because of the lack of continuity in terms of the runout extents. As seen in Figure 3.17, there are areas that do not have a runout propagation extent. This may be reasonable concerning the detection of landslide sources for perceived non-source areas. However, for a road segment AOI, it has to be continuous and not only limited to possible landslide sources but also include areas wherein there was no record of previous events, provided that overestimation of AOI's must also be avoided.

3.8.3. Implications to the risk assessment (how does the approach affect how the risk is estimated)

Currently, INVIAS (2016), keeps a record of maintaining road conditions per kilometer. If the risk assessment is conducted using the current scheme of subdividing the road network, it will result in a repetitive and inefficient analysis of risk. This is because, in a given kilometer, certain characteristics and elements must be treated differently than others, e.g., landslide type, protected slopes and therefore must be aggregated to a different AOI. In terms of risk, the manual approach allows the road managers to treat each segment differently or conduct a risk analysis method differently than others. A rockfall prone segment AOI can be evaluated for risk using the modified rockfall hazard and risk approach by Budetta et al. (2015), while shallow landslide prone segment AOI's can first be correlated with rainfall to come up with a magnitude-frequency relation for the hazard assessment. Since the manual approach can differentiate these landslide types, mitigation works, etc. into separate AOI's, the risk analysis would be reliable and AOI specific. For the SU and watershed approaches, the risk estimation for both is highly variable depending on its calibration to actual field-based parameters. Both methods if not field calibrated can result in AOI's that may generalize landslide types despite a high degree of terrain unit homogeneity and may not represent the presence of protection works along the road segment. Finally, the runout approach would yield risk estimates that are also highly variable, the spatial probability estimation of the method could be a strong point, but it is only limited to that category.

3.8.4. Best method to use for AOI delineation

In conclusion, the manual method is the best/preferred method for delineation of road segments and their AOI. Other methods considered especially the SU and watershed approach can be used as supplementary tools for the procedure but not as standalone tools, for example, the SU's can aid in the refinement of the AOI's delineated manually, which can improve its reproducibility. The combination and application of the manual method with other methods such as the SU and watershed could also be explored.

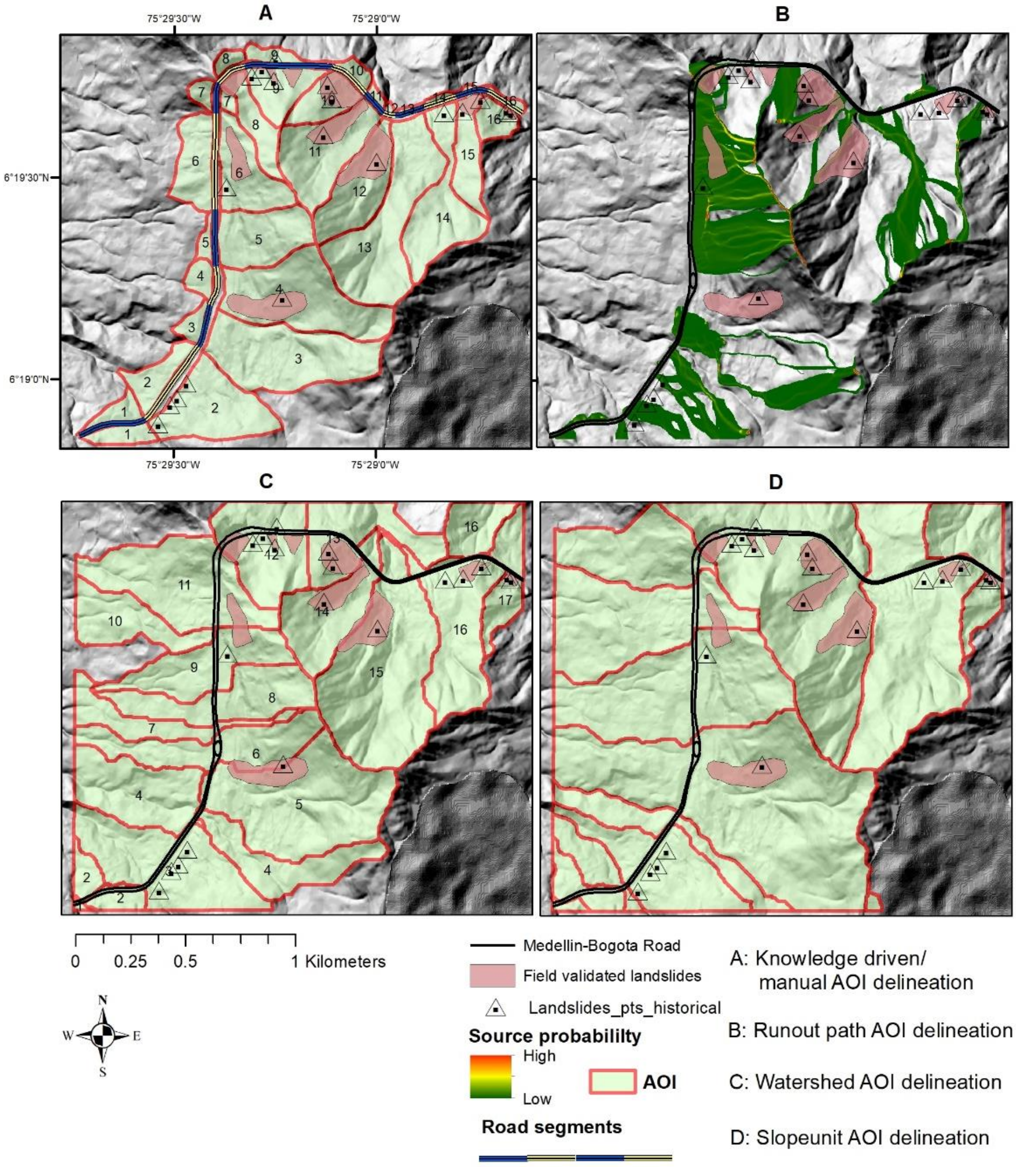


Figure 3.17: *Compiled maps from all methods evaluated for AOI delineation*

4. DEVELOPMENT OF QRA COMPATIBLE DATABASE

4.1. Introduction

The main objective of road asset management is maximizing the safety of road users, and economic benefits by reducing maintenance, road user costs, and road risk for a given road network. The practice also aids in the determination of optimal funding levels and actual funding allocation for specific road segments (CAREC-ADB, 2009). In contrast to passive maintenance implementation, the proactive approach of implementing road asset management aims to achieve a high level of road condition at the lowest cost while having a long-term perspective which considers future impacts such as road damage caused by landslides, blockages and pavement damage (CAREC-ADB, 2009; Rose, 2005). Inventory of road data, pavement conditions, and unit costs form the basis for road asset management which requires a road asset management system. This contains the databases that allow the analysis of data for risk management of certain problematic segments along a road network.

The framework for landslide risk management as published by Fell et al., (2005), involves the Risk analysis, assessment, and management. This chapter presents the development of the database that is QRA applicable in the future. This includes a justification of the specific fields and formats that were prescribed in each component of the database and its variability depending on a specific end user and its purpose within the overall QRA framework.

Risk assessment

Risk assessment according to Fell et al., (2005) pertains to the process of decision making taking into consideration the amount of risk that is tolerable and whether or not risk control measures are needed to decrease the calculated overall risk to acceptable levels. This process typically evaluates the outputs of the risk analysis phase by risk tolerance criteria which are usually set by lawmakers or those accepted by professional organizations, e.g., AGS, (2000) when no tolerance criteria are available.

Risk management

Risk management is the process wherein the resulting risk from the risk assessment is integrated to form strategies within the community affected (Dai, Lee, & Ngai, 2001). Effective risk management, especially for roads, is correlated with effective road asset management (World Bank, 2017b). This relies heavily on consistent monitoring and preventive intervention within roadworks.

4.1.1. Risk analysis

Risk analysis typically involves hazard identification and analysis, consequence analysis and risk estimation. Fell et al., (2005) describe the process of risk analysis as characterizing the danger (hazard), analyzing the hazard frequency, characterization of consequences (elements at risk), analyzing the probability and severity of consequence (vulnerability estimation and costs), and putting it together in the risk estimation process.

For hazard identification along roads, several authors have focused on mapping initiation points with the use of detailed inventories and using runout models to compute spatial and temporal probabilities of rockfalls (Michoud et al., 2012; Guzzetti, Reichenbach, & Ghigi, 2004). The runout paths and respective probabilities of impacts are mostly derived from empirical modeling of the initiation points, e.g., Flow-R (Horton et al., 2013). However, without historical records, landslide initiation points can be delineated from multi-temporal high-resolution satellite images (Martha et al., 2012; Murillo-García et al., 2015), radar interferometry (Colesanti & Wasowski, 2006), and regional aerial image interpretation (Crozier, 2005). Landslide inventories imperatively are important to include in road asset management databases. It comprises the most difficult part of any risk analysis, and a complete landslide inventory would result in better risk assessments including a successful QRA. A substantially complete landslide inventory would allow the hazard to be expressed in terms of frequency-magnitude of landslide events. The magnitude parameter for landslides can be expressed using its area, or volume of material. The areal parameter according to Corominas, Mavrouli, & Ruiz-Carulla (2018) is mostly used as a result of its ease of collection from aerial photographs, maps, or satellite imagery. The magnitude parameter for rockfalls or rockslides is commonly expressed as the volume of the blocks (Corominas et al., 2018; Hungr, Evans, & Hazzard, 1999). The frequency of occurrence is expressed as cumulative/non-cumulative, or as frequency density (Corominas et al., 2018; Guzzetti et al., 2004). QRA requires careful consideration of the different frequencies of varying types of magnitude for landslides and rockfalls.

Analysis of consequence involves the identification of elements at risk, vulnerability, and estimation of their costs and losses (Fell et al., 2005). Direct and indirect losses are common to roads frequently impacted by landslide hazards. The direct losses include road fatalities, roadway damages, and vehicular damages due to landslide or runout contacts. Indirect losses include traffic delays, diversions, and income loss due to road blockage (Ferlisi et al., 2012). Direct and indirect losses expressed in any unit or quantity along with damage data of the roads and element at risk must also be included in road asset management databases, they are also vital for QRA.

Quantitative risk is calculating risk based on numerical values of hazards (probabilities), exposed elements at risk (value), and vulnerability. Quantitative risk can be expressed in different ways: 1.) as number of vehicles damaged per year on a road segment (Guzzetti et al., 2004), 2.) as probability values of fatalities to happen (Ferlisi et al., 2012), 3.) in terms of monetary values lost per year (Martinovic et al., 2017), or 4.) expressed as a combination of the probability values of fatalities and risk zonation (Qi, Li, Guo, Zhan, & Liao, 2015). The ideal road infrastructure risk management systems must have procedures that are compatible with quantitative risk analysis studies (Fell & Eberhardt, 2005)

Qualitative methods for risk estimation typically describe the level of risk or frequency of landslides in a certain area, which is often in terms of risk rating systems or risk scoring schemes (Fell et al., 2005). Qualitative description of the risk is particularly useful for rapid risk assessment of an extensive roadway (Pellicani, Argentiero, & Spilotro, 2017; Pratt & Santi, 2014; Sun,2018; Bles et al., 2016). Qualitative risk assessments are effective for data scarce areas and relative comparison of numerous sites or segments along a road that needs an expert opinion for the assessment. However, it is prone to differing interpretations and lacks transparency and is not easily reproducible in other sites (United States Department of Transportation, 2017).

4.1.2. Datasets to be considered for proactive, risk-based management of infrastructure including roadways

The World Bank (2017a) published a guidebook integrating the effects of climate change onto road asset management systems. Table 4.1 below is a summary of the data requirements for a variety of analyses possible within a road asset management system including risk management.

Dataset	***Applications***	***Is it usually collected?***	***Data domain***	***Data collector and maintenance***
Geospatial analysis data	-Hazard and vulnerability assessment -Infrastructure relationships -Spatial planning of treatment works -Post-disaster event planning	Yes	Infrastructure	Road network concessionaires and managers
Network status data	-identifying critical assets -differential maintenance and prioritization	Yes	Infrastructure	Road network concessionaires and managers
Failure risk and structural health data	-Road segments that could be prone to failure	No	Infrastructure	Road network concessionaires and managers
Landslides, rockfalls and mass movement data	-Landslides and rockfall reporting, monitoring and treatment	No	Infrastructure	Road concessionaires and managers
Rainfall/Storm and weather impact data	-Specific impacts of weather events on asset infrastructure	No	Infrastructure	Road concessionaires and managers
Road function data (community or socio-economic activity data)	-prioritization and optimization of maintenance works -capital investment for pre and post disaster event	No	Socio-economic	Regional and national databases
Physical environment data (soil type, waterways, drainage)	-vulnerability assessments -hazard susceptibility assessments	Yes	Physical data	Regional and national datasets
Historical and current weather patterns	-Useful for hazard assessments -Understanding return periods for design and vulnerability assessments	Yes	Climatic data	Regional and national datasets

Table 4.1: *Datasets needed for road network resilience, modified from the World Bank, (2017a)*

4.2. Method of formulating database fields and structure for QRA

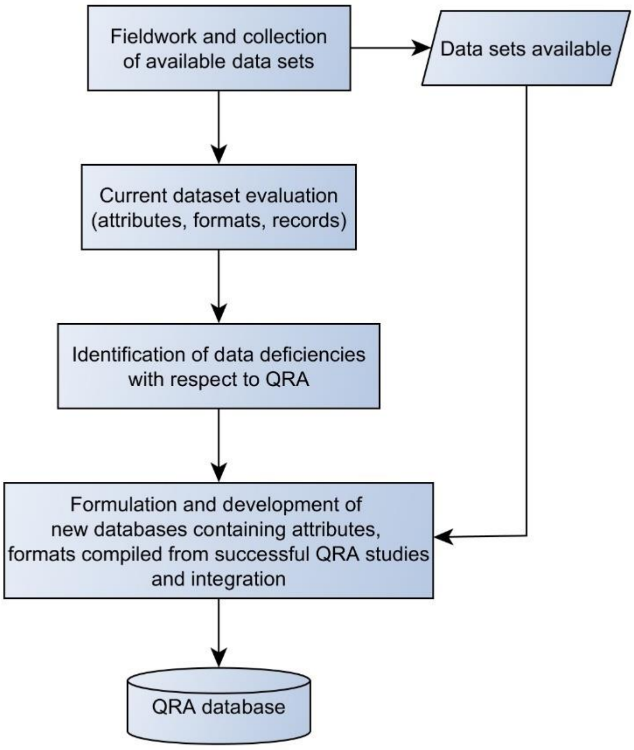


Figure 4.1: *Summary of procedures undertaken to decide and develop specific database requirements that would allow future QRA*

Formulating the required database fields first involved characterizing and collecting all available datasets during fieldwork in Colombia (Figure 4.1). The collected data sets were analyzed per field/attribute and format. The spatial datasets including landslide inventory, DEM derivative maps, landcover, and soil raster maps were also viewed in GIS. Other data sets were on spreadsheets such as maintenance and construction costs were also evaluated.

In addition to the collection of all available data sets, two interviews with professionals in the road management concessionaires were also carried out to further characterize the current practices and structure of road management in Colombia. After characterizing the current condition and availability of data, an initial database structure was formulated to identify the deficiencies with respect to the goal of QRA based management that INVIAS and ANI are aiming to put into practice.

After identifying the deficiencies in the data sets, attributes, and records the database structure and formats that will allow improved future QRA was developed. Other studies that were able to successfully conduct a QRA in many different settings, especially along transportation corridors, were reviewed. In addition, the state-of-the-art in road asset management was also considered especially the best practices and data sets that road infrastructure authorities have successfully integrated into QRA within their road management systems. The data sets and attributes were then compiled and structured for possible QRA integration by Colombian road management authorities. A summary of the databases that were evaluated with a description of its respective attributes, formats, role in QRA is given in Appendix 2.

The database' attributes were first formulated in Excel sheets and coded in apps that would allow a user to populate a specific spreadsheet and perform calculations. After preparation and coding in the Excel VBA app, the databases/tables were imported into MS Access, for storage and retrieval and separate GIS analysis by multiple users. The databases are compiled via Excel sheets first since it is one of the most common software that is also powerful yet simple to operate for end users, QRA integration through databases should start from simple yet substantial record keeping and population first before a full integration to road asset management systems is considered (CAREC-ADB, 2009).

4.3. The current/present database structure of available data at the study area

After fieldwork and data collection, the data sets gathered were compiled and structured to find identify data deficiencies with respect to landslide QRA. Figure 4.2 shows the initial database set-up with the entity

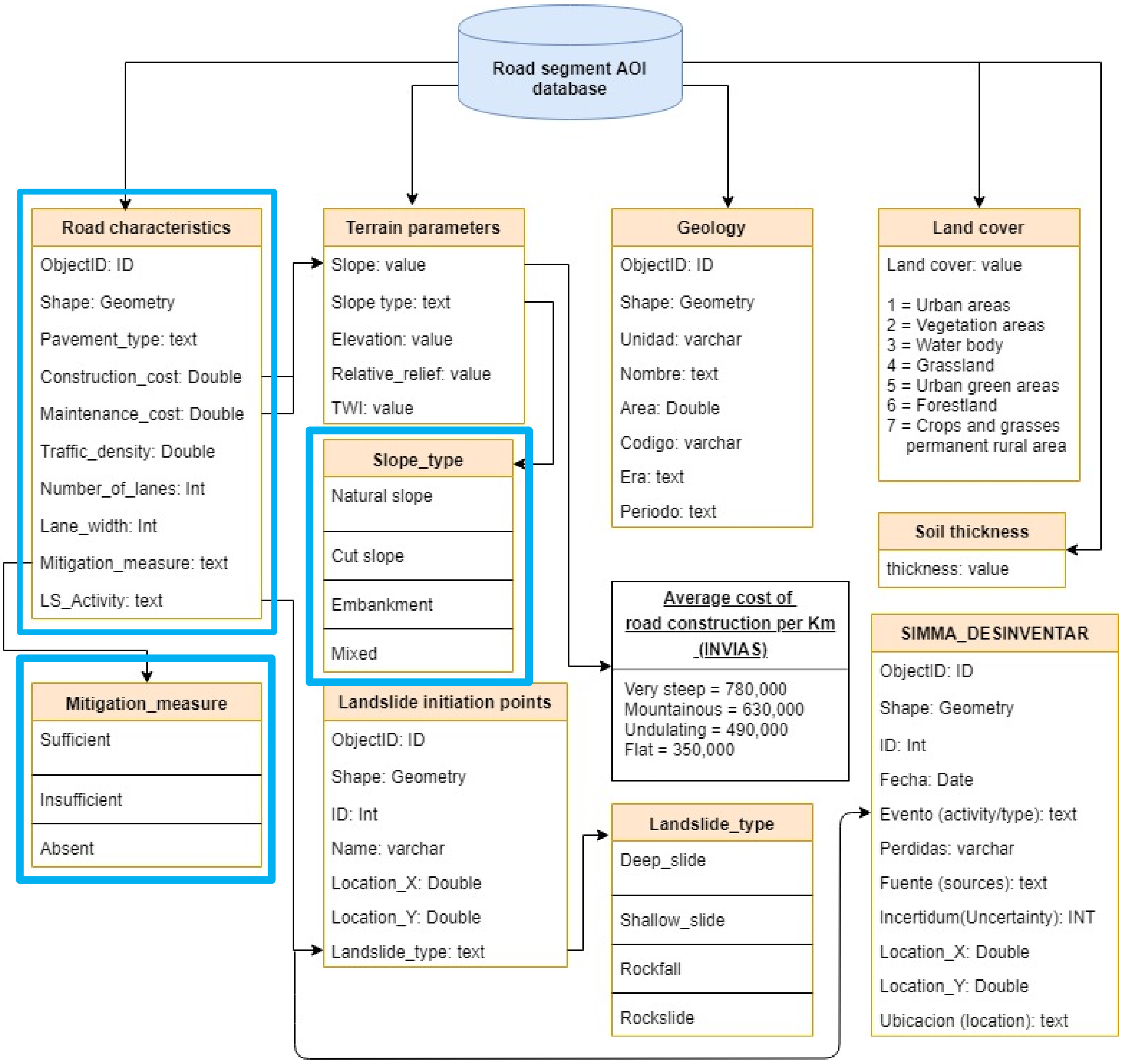


***Figure 4.2**: Database structure of all available gathered data sets during fieldwork; blue boxes indicate information directly linked to road segments, the rest of the datasets refer to information linked to the AOI of the road segment.*

relationship diagram/structure of how the different data sets are connected to one another; the structure reveals that there are sufficient data sets available that allow landslide susceptibility studies in the study area. However, upon evaluating the data sets in GIS, there were important deficiencies that were identified that hamper a QRA:

- The available landslide inventory has less than 15 landslide events spanning the period from 1930 to the present for the entire road section. The spatial location uncertainty of these was only level 3 (least accurate) in the SIMMA-DESINVENTAR event databases.
- The landslides in the inventory do not have a volume attribute. Therefore a frequency-volume analysis which is crucial in hazard assessment in the QRA procedure, cannot be conducted.
- Landslide initiation point data do not have the event date attribute which is also an important component for temporal probability estimation during hazard analysis.
- The dataset indicating the location, condition, and efficacy of mitigating measures along the road was insufficient for a possible risk assessment for rockfall.
- The soil thickness map only contained thickness information that was highly uncertain and generalized with none indication of its type which can be essential during landslide susceptibility assessment.

Of these deficiencies, the most significant factors are those concerning the landslide inventories which is the most important data set for QRA (Corominas et al., 2013). The number of events recorded on the SIMMA-DESINVENTAR landslide database is significantly fewer especially in the study area which is not surprising because the SIMMA-DESINVENTAR database only has records of large landslide events that have caused a large amount of damages and fatalities. The 2016 event and rockslide described earlier in Chapter 2 were recorded in the database. Commonly, for the road study area, the landslides that were noted from historical imagery and visual interpretation are mostly shallow and are not expected to be recorded on databases such as the SIMMA-DESINVENTAR. These deficiencies identified are addressed by developing and proposing new databases with specific attributes and formats that will allow the QRA to be conducted in the future.

4.4. Proposed database structure for QRA integration

To address the deficiencies determined earlier, four new databases were developed. These are the maintenance database, the refined landslide inventory database, mitigation measure database, and road network database (Figure 4.3). All of these databases are linked to the road segment AOI database which serves as the standard unit of analysis for QRA along roads. Each of these databases contains essential/critical attributes that will be explained per section. The rest of the non-critical but still important attributes for consideration during risk assessments are described in Appendix 1.

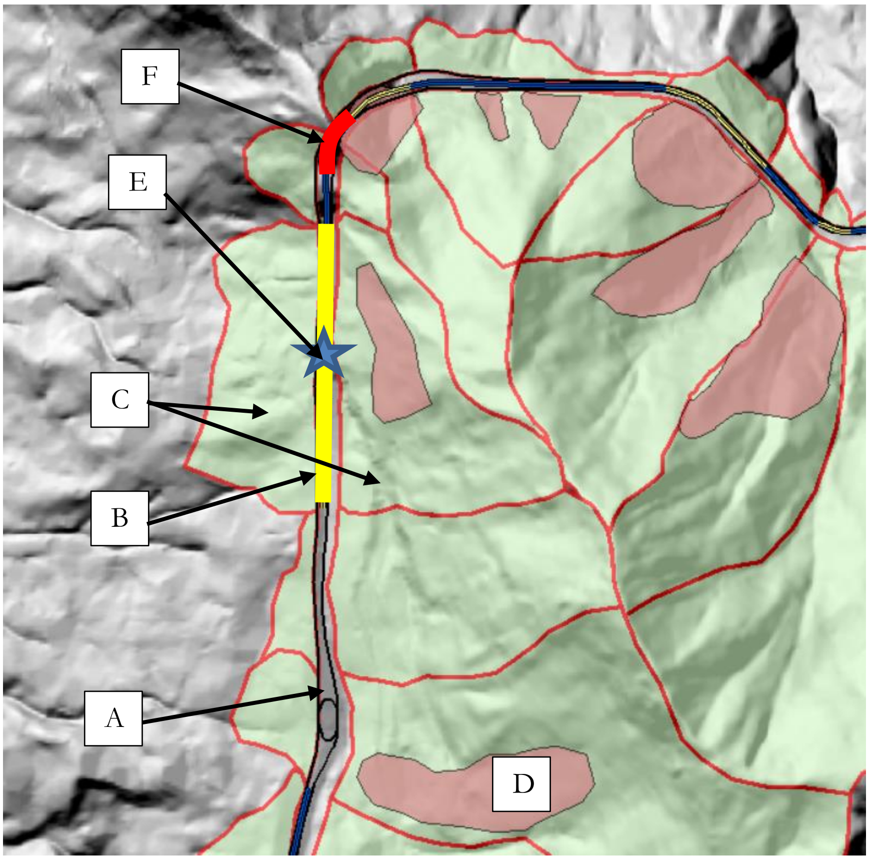


Figure 4.3*: Map view of the proposed databases that are elaborated in the succeeding sections:*
A*: Road network database,* ***B****: Road segment database,* ***C****: AOI DB,* ***D****: Landslide inventory DB,* ***E****: Maintenance DB point,* ***F****: Mitigation measure DB*

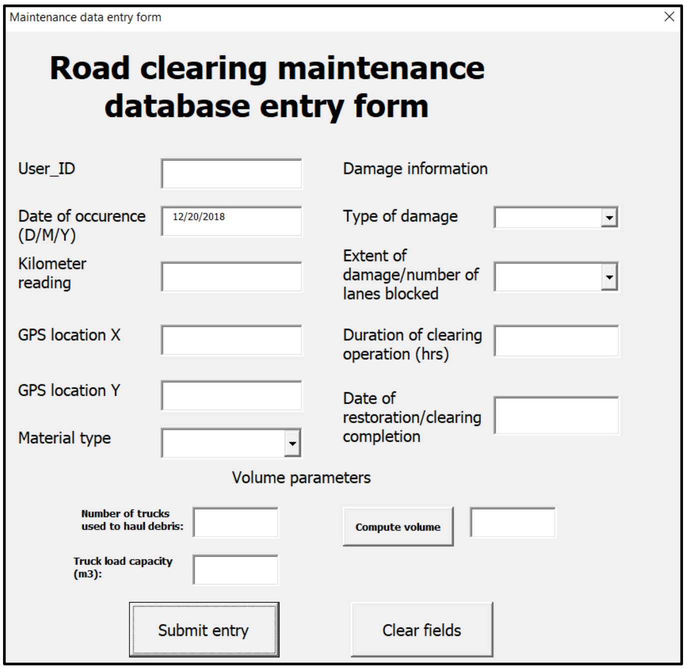
4.5. Maintenance database

4.5.1 Role of the database in QRA

Maintenance records such as road and railway slip registers have proven to be useful for landslide QRA along transportation corridors as these can be used to estimate the hazard component of QRA (Jaiswal, 2011; Martinovic et al., 2017). The maintenance records offer an opportunity to supplement the landslide inventories through a more detailed record of all landslide events and repairs along the road including rockfall/cut slope failures/shallow landslides that are often overlooked. This is in contrast to the existing SIMMA-DESINVENTAR database which only accounts larger reported events, that have actually caused damage or casualties. The practice in Colombia shows that keeping a record of landslide debris clearing is usually not done according to INVIAS (2016) and some interviews with former professionals in the road concessionaires. A detailed and continuous record of slope failures and repairs by road maintenance units would enhance the capability of road managers to integrate landslide QRA in the future. In addition to this, the maintenance databases also support repair records that are crucial for estimating total rehabilitation costs incurred by road managers on specific road sections.

4.5.2 Attributes crucial for landslide QRA

The maintenance database is represented by point data in a GIS. This was proposed for rapid ground application and data collection purposes. Figure 4.4 shows the database form/app created to populate the attributes of the maintenance database and the description and significance of each attribute assigned is detailed further below.



Maintenance data entry form

Road clearing maintenance database entry form

User_ID

Date of occurence (D/M/Y): 12/20/2018

Kilometer reading

GPS location X

GPS location Y

Material type

Damage information

Type of damage

Extent of damage/number of lanes blocked

Duration of clearing operation (hrs)

Date of restoration/clearing completion

Volume parameters

Number of trucks used to haul debris:

Truck load capacity (m3):

Figure 4.4: *Database form/app created to populate the attributes and avoid errors in the data compilation*

The *date of occurrence* attribute is crucial for temporal probability estimation. This attribute is mostly linked with devices that automatically records GPS *location*, which is also an important attribute to record.

The *number of trucks* that were used to haul debris or clear the road is also crucial. This attribute is an important volume indicator of the amount of material that was removed from the road (Jaiswal, 2011). Its Float format allows more precision in terms of defining the number of trucks used, the presumed volume reaching the road can be calculated by multiplying the number of trucks with the truck capacity. In case the material is not hauled by trucks and simply moved to the downslope of the road, it would be difficult to record its actual volume and should be approximated. The number of truck loads is also of importance when compiling landslide historical inventories.

Another crucial attribute is the *extent or length of damage* attribute, formatted by a text and value combination (varchar). This attribute gives information on how much of the roadway is blocked in the event of a landslide; this is also information that is significant when estimating the costs for road repair/rehabilitation. This is an important input to indirect risk and vulnerability value estimation (Jaiswal, van Westen, & Jetten, 2011; Martinovic et al., 2017). Similar to damage extent attributes, the *duration of clearing* is important for indirect risk estimation. The number of hours/duration of clearing activity along the road especially for blocked lanes would lead to significant amount of losses for the road concessionaires and probable increased fuel costs for vehicle users who are non-moving or need to find another route. The maintenance database can also store non-structural types of damage such as hits by rockfall, clearing of drainages, or damage to mitigation measures, and structural damage as well to the road such as eroded embankments. These can be stored by modifying the *type of damage* attribute.

4.5.3 Data Collector and frequency

Most of the datasets will be collected by maintenance personnel who are usually the first to respond to any road related emergencies (INVIAS, 2016). This includes minor debris clearing that could come from shallow landslides that may block some portion of the roadways. The attributes defined constitute the most significant fields for maintenance records that will contribute to full QRA integration. For a QRA campaign to be successful, it is important that data collection schemes, requirements, and specific formats are identified and defined to maintenance personnel. Moreover, since the maintenance staff is deployed daily to the roads to perform other types of inspection and activities such as vegetation clearing, they can also be the first to report signs of slope instability.

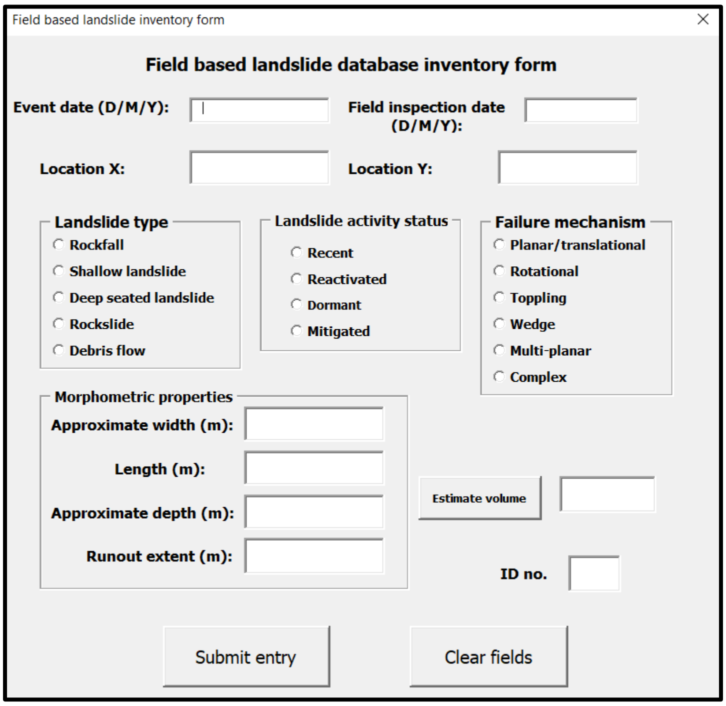
INVIAS is currently developing a mobile app that lets road users report problems on the roadway while also informing other users of the problem. The app could be useful for maintenance teams of road concessionaires since the reports by the general public can also contribute to actual maintenance records especially for partial road blockages or minor road damages such as rockfall impacts on the roadway.

The period of collection of these data attributes defined depends on whether there are reported debris or damage along the road that needs to be cleared. This is also done by maintenance teams that patrol the highway every day for routine pavement and slope checks (INVIAS, 2016; Universidad Nacional de Colombia & Instituto Nacional de Vías INVIAS, 2006). On such occasions, the maintenance teams who will undertake clearing activities and collect the data attributes for records, are immediately deployed, this task has to be considered as an emergency task (INVIAS, 2016; Turner & Waibl Consulting, 2016).

4.6. Landslide inventory database

4.6.1 Role of the database in whole QRA

The landslide inventory is the most important dataset for quantifying landslide hazards and risk (van Westen, Castellanos, & Kuriakose, 2008). A substantial and comprehensive record of landslides through multiple years and multiple events will allow accurate susceptibility assessment, and spatial, size, and temporal probability estimation for the hazard assessment component of the QRA.


Field based landslide inventory form

Field based landslide database inventory form

Event date (D/M/Y):
Field inspection date (D/M/Y):
Location X:
Location Y:

Landslide type
○ Rockfall
○ Shallow landslide
○ Deep seated landslide
○ Rockslide
○ Debris flow

Landslide activity status
○ Recent
○ Reactivated
○ Dormant
○ Mitigated

Failure mechanism
○ Planar/translational
○ Rotational
○ Toppling
○ Wedge
○ Multi-planar
○ Complex

Morphometric properties
Approximate width (m):
Length (m):
Approximate depth (m):
Runout extent (m):

ID no.

Figure 4.5: Landslide entry form/app for populating attributes of the inventory database

4.6.2 Attributes crucial for landslide QRA

The landslide inventory database is represented by polygons in GIS. This was chosen over point data format to avoid uncertainties such as lack of areal representation of point data which can still be useful for identifying landslide initiation points (Simon, De Roiste, Crozier, & Rafek, 2017). The database app created to fill out the attributes is shown in Figure 4.5.

Landslides recorded in the field are almost impossible to delineate using polygons, in these cases, the landslides can be stored as points first then the final landslide polygons and records are usually outlined in the office after fieldwork using satellite imagery or aerial photographs. It is also important to differentiate between landslide source areas and runouts. Landslide initiation points/sources can be stored initially using points or polylines, but upon recognition of the runout extents, they must be outlined with a polygon for final storage in the landslide database.

In addition to the *location of landslide*, the *landslide event date* can be taken from the maintenance records and validated by geotechnical personnel. This is a crucial attribute for frequency-volume analysis of landslides (Corominas et al., 2013; van Westen et al., 2006). The event date has to be specified in the landslide inventory. If the landslide inventory is acquired using satellite imagery, the event dates may not correspond to the date of acquisition of the image, therefore prior to preparing a landslide inventory, the event date must be known locally and must be immediately put on record. This attribute is also useful for estimation of temporal probability or return periods using extreme value analysis, e.g., Gumbel plots for relating number of landslides to amount of rainfall as a triggering factor.

The *landslide type* is an important attribute in landslide inventories. This attribute is frequently used for susceptibility assessments and hazard analysis (Sterlacchini, Frigerio, Giacomelli, & Brambilla, 2007; van Westen et al., 2006). The landslide type affects how the susceptibility analysis is carried out, e.g., assessment for rockfalls and shallow landslides using a statistical approach are different. Further, the landslide type is one of the most important criteria used for road segmentation and AOI delineation.

The *volume* attribute, is also crucial, which serves as a magnitude proxy during the establishment of magnitude-frequency relation in the study area (Budetta, 2004; Corominas et al., 2013; Guzzetti et al., 2012). The volume considered in this database can be either the *volume of landslide at the initiation points* or *volume of a landslide that reaches the roadway*. The latter is more important. This attribute can be supplemented by maintenance records, pending validation and analysis of the maintenance records by geotechnical personnel. This attribute addresses the deficiency present in the available landslide inventory (SIMMA-DESINVENTAR) in the study area.

4.6.3 Data Collector and frequency

The landslide inventory databases have to be filled out and compiled by a geologist or a geotechnical professional within the road management agency. Although some of the records from the maintenance database are linked to the landslide inventory such as location and volume of material along with damage extents, these attributes should be validated by technical personnel with geotechnical knowledge. This also suggests that the landslide database should be carefully maintained, stored by technical persons within the road management authority.

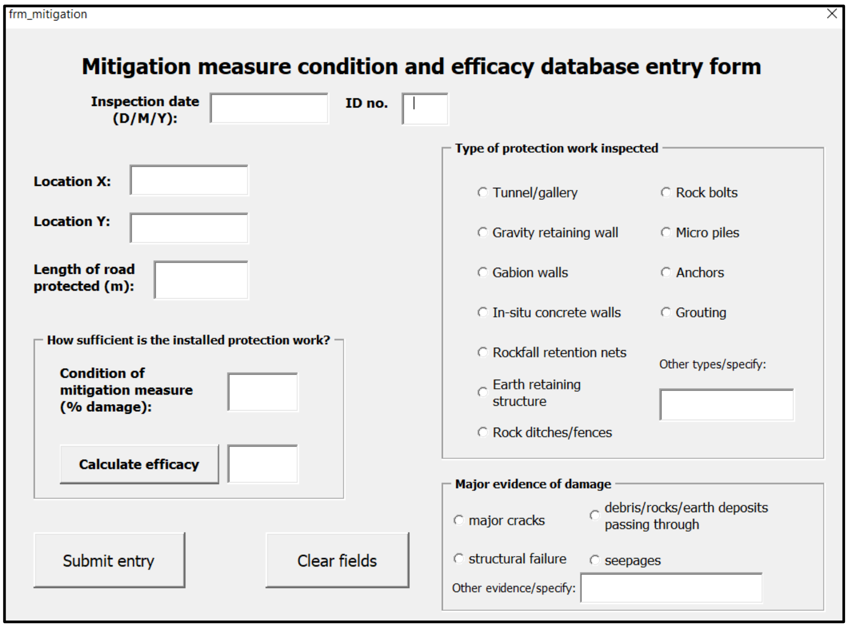
The landslide inventory should be collected and updated regularly especially after significant landslide events. Landslide activity attributes can be updated annually depending on the observations of maintenance teams (e.g., reactivated or mitigated slides), however monitoring for new landslide movement along the roads has to be done on a daily basis (van Westen et al., 2008). In cases wherein there are landslide reactivations, the landslides can have multiple records of information but under the same landslide ID, with the landslide type clearly defined as reactivated. The location of the reactivations can also be cross-checked with previously recorded landslides for confirmation of the activity and location buffers can also be used to confirm the reactivations. Finally, in cases where the road can be affected by multiple landslide sources and runouts, it is very important for geotechnical teams to trace back the landslide extents/runout back to the sources using runout models or satellite images before storing the landslides in the database. An ID can be assigned once the source area is identified and the volume of material reaching the road attribute can also be estimated after analysis.

4.7. Database of mitigation works

4.7.1 Role of the database in whole QRA

A database containing information on protection/mitigation works along the roads is an important component for landslide QRA. The data attributes compiled are important for rockfall hazard and risk assessments (Budetta, 2004). Apart from rockfall risk, hazard frequency can be inferred from damages incurred by protection works (Sun, 2018). Information on protection works such as its current state and condition is significant for road asset planning and management. In addition to this, the presence of protection works are used as criteria for segmentation of the road and delineation of its AOI.

The mitigation measure database representation in a GIS may vary depending on the type of mitigation works either as those that protect the slopes from landslide initiation e.g. rock bolts, terracing (represented by polygons) or those that are located on the road segment itself to protect the pavement from damage e.g., retaining walls (represented by polylines). The mitigation works database has to be directly linked to the road segment database and AOI database depending on the type of mitigation work that is recorded. The database app created to fill out the attributes during or after inspections is shown in Figure 4.6.


frm_mitigation

Mitigation measure condition and efficacy database entry form

Inspection date (D/M/Y):
ID no.

Location X:
Location Y:
Length of road protected (m):

How sufficient is the installed protection work?
Condition of mitigation measure (% damage):

Type of protection work inspected
○ Tunnel/gallery
○ Gravity retaining wall
○ Gabion walls
○ In-situ concrete walls
○ Rockfall retention nets
○ Earth retaining structure
○ Rock ditches/fences
○ Rock bolts
○ Micro piles
○ Anchors
○ Grouting
Other types/specify:

Major evidence of damage
○ major cracks
○ structural failure
○ debris/rocks/earth deposits passing through
○ seepages
Other evidence/specify:

Figure 4.6: *Database entry form and app to fill out attributes for mitigating measures.*

The **location** of the mitigation measures including the *length of the road being protected* by mitigation works is an important consideration for QRA since it indicates where the risk is expected to significantly reduce as a result of decreasing the hazard probability and exposure to landslide (Budetta, 2004; Jaiswal, 2011). The most important attribute in the database for mitigation measures is the *%efficacy* of the mitigation measure installed. This is a significant addition and consideration for QRA along roads especially for rockfall hazards (Budetta, 2004; Budetta et al., 2015). The efficacy % indicates the overall level of effectiveness of the mitigation work, and it affects how the risk is calculated by increasing it when the % efficacy of the mitigation measure is significantly decreased. The % Efficacy can be estimated by the *amount of damage* a mitigation work has incurred overtime. The efficacy could be assessed by conducting stability tests annually, having multiple sensors that detect ground movements such as GPS, inclinometers, or tilting meters (Popescu & Sasahara, 2008). % Efficacy is an attribute that is difficult to measure and most of the time assumed as 100% in most assessments, future works could focus on how to translate % efficacy into landslide frequency (Budetta et al., 2015).

4.7.3 Data collector and frequency

The datasets/attributes prescribed above must be collected by technical staff familiar with how mitigation measures are constructed and damaged. The location of the mitigation works must first be recorded, then an annual inspection and inventory of their effectiveness or damage have to be conducted. Damage can accumulate overtime for mitigation works, therefore, it is crucial to identify the amount of damage incurred, its evidences, repair needs, and most importantly the level of efficacy of a specific protection work in question.

According to (INVIAS, 2016; Universidad Nacional de Colombia & Instituto Nacional de Vías INVIAS, 2006), the inspection of mitigation works along the roads is done periodically, mostly quarterly. The exception to this data update frequency is for mitigation works that need immediate repairs, mostly those that have incurred structural damages that need to be addressed quickly to prevent aggravation. The maintenance or inspection aspects of the mitigation works can be stored in the proposed database since the most important attributes to record are their amount of damage/condition. If the mitigation work is newly installed, its location can be recorded immediately, and its condition can be described as no damage or 100% efficacy.

4.8. Road network database

4.8.1 Role of the database in QRA

The main role of the road network database in QRA is to have a detailed data set that will allow analysis of consequence along the roadways in conjunction with repair records acquired by maintenance personnel. QRA along roads is a more specific undertaking wherein the elements at risk are restricted to the roadway pavements or vehicles that pass by the highway. Substantial and continuous data population of the road network database ensures reliable vulnerability value estimates through cost ratios and accurate analysis of consequences as part of the QRA.

4.8.2 Attributes crucial for landslide QRA

The road network database is created in the GIS platform (ArcGIS) via the network analysis module. This database is represented by network polyline data, the majority of the fields included in the database are available in the road study area, this database compiles them in a more orderly manner for convenient future analysis. There is no app developed for filling out information on the road network database. However, the GUI of the basic setup of the road network data set for the study area is shown in Figure 4.7.

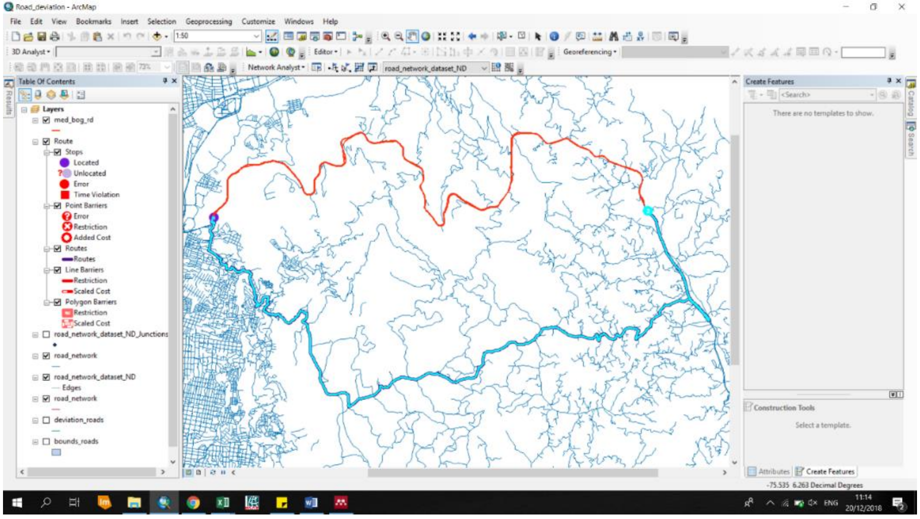


Figure 4.7*: Screen capture of the GUI of the basic setup of the road network data set for the study area:*

this shows the network dataset computing for the shortest route in the event of total road blockage in the study area.

The *length of the road* segment polyline is a crucial attribute in vulnerability estimation and consequence analysis component of the QRA (Jaiswal, 2011; Martinovic et al., 2017). The attribute is used to estimate construction costs that are vital in maintenance/construction ratios representing the vulnerability. Apart from the length, the road network database must have the corresponding amount of *maintenance costs*. This refers to the costs the road maintenance organizations spend on repairing the road segment in the event of landslides, this may include clearing operation costs spent on specific segments, or costs spent to rehabilitate the road pavement from landslide damage, e.g., ditch repairs. All of these repair types are also supplements to repair records compiled by maintenance personnel. Similar to maintenance costs, the road segment total *construction costs* are crucial to the consequence and vulnerability analysis component of the landslide QRA (Garzón Iral et al., 2012; Jaiswal, 2011; Martinovic et al., 2017).

Apart from the maintenance, construction costs and total length, the *average daily traffic* (ADT) is also considered as a crucial component for estimating the losses incurred by road managers along specific road segments (Budetta, 2004; Rose, 2005; Turner et al., 2016). The ADT consists of the number of vehicles passing through the toll gates in 24 hrs. Finally, the *road deviation length* attribute is essential in the road network database. This field refers to the additional length that is covered by vehicles/road users in the event a blockage occurs within the network. This attribute allows a more accurate estimation of risk or losses to road users when full blockage of the road occurs (Jaiswal et al., 2011).

4.8.3 Data collector and frequency

Majority of the data attributes has to be collected and maintained by technical staff with GIS background. The attributes are mostly derived from GIS operations of the road network including cost assignments, calculation of deviation length, traffic changes, etc. The average daily traffic attribute is collected at tollways and must be transferred to the road network data set being maintained and operated by technical staff at the office. The length, width, number of lanes, cost attributes, and average daily traffic are monitored continuously by toll stations, but its most useful form is when it is compiled annually for analysis. The diversion/deviation length is monitored annually, but its update frequency depends on the construction of new secondary roads that connect to the primary or main highway.

4.9. Segment and AOI databases

The road segment and AOI databases are closely linked to one another. The road segment database is derived from the road network and contains the sets of information that made it a homogenous road segment. It contains its Segment ID, an AOI ID, and geometry linking the segment to the area on its upslope or downslope that may influence the risk, start/end coordinate locations, and mitigation measure ID as optional data attribute if present for the segment. The segment ID is the only attribute in the database structure (Figure 4.8) that is central to all analysis derived databases; this is because the analysis of the hazard, consequences, and risk are based per road segment and are automatically translated to the road segment database as the final repository. In addition, the construction and maintenance costs from the road network database is also linked to the segments.

The AOI database is an important component of the QRA database given that they influence how the risk is calculated in the road segment. The AOI database contains all the attributes that are contained within the upslope or downslope polygons delineated immediately beside the road segment. The types of data sets that contribute to the AOI database are mostly spatial data in the form of geological data, DEM derivatives, landslide inventories, and regionally available data such as rainfall (Figure 4.8).

4.10. Analysis derived databases

After populating all the above-mentioned databases and crucial attributes, and aggregating information per respective segment and corresponding AOI, databases with data derived from analysis can then be produced. Starting from the maintenance database, the *repair records*, containing aggregated records of repair per segment that entailed maintenance costs to the road managers are compiled. These records emphasize the costs per type of repair done per road segment. The road repair records are contributors to the estimation of the total consequences/costs which are compiled separately into a *consequence table*/dataset wherein costs per road damage scenario are computed. The detailed information regarding the road damage scenarios is presented in Chapter 5. Perhaps the most important analysis derived database are the *hazard table*/dataset and *magnitude-frequency* database. These two datasets are linked and derived from analyzing the event date, and volume attributes stored in the landslide historical inventory. The most difficult part of a landslide QRA is establishing the M-F relation and having a good estimate of the annual probability of event occurrence per volume and the probability that a landslide volume reaches the road segment.

4.11. Discussion

In this chapter, the databases and most crucial data attributes that are essential for a landslide QRA were defined and elaborated. The proposed entities/databases were formulated taking into consideration the existing datasets in the study area. The relationship between each database and all the attributes proposed are illustrated in the overall database structure in Figure 4.8. The fields are further described in Appendix 1. Interpreting the structure, the road network database is directly linked (can access all attributes) to the road segment database, and the risk analysis is performed per defined homogenous segment. From the figure, the road segment database collates the segment information linked to the road network database (construction costs, maintenance, traffic density, etc.), its corresponding AOI's (AOI ID) and AOI geometric properties, and mitigation measure information if available.

Closely linked to the road segment database is the AOI database, containing mostly spatial information that affect how the risk is calculated per segment. Spatial datasets particularly contributing to the AOI database are mostly produced by research institutes or in this case by UNAL. These datasets were used by UNAL to come up with regional-scale susceptibility maps generated using statistical methods; the data sets could complement the AOI's delineated, however, the scale of the data sets, e.g., geological map, landcover must be reconsidered since the risk assessment is segment specific. Therefore a site-specific scale is required. This is also true for assessments on other roads, the scale of the spatial datasets must be compatible with the scale of the segments, and corresponding AOI's that would be produced. Other data sets such as the tabular construction costs are contributors to the road network database and finally the rainfall data (continuous) can be used for landslide trigger correlation in the landslide inventory for frequency-magnitude analysis.

Maintenance database attributes rely heavily on the data collection of maintenance teams who in real situations preferably want the job done as soon as possible. Although the app form and database sheet developed for maintenance teams will contain valuable information for the QRA, it takes considerable time to accomplish which could present some problems in the data collection and recording. Some assistance to the maintenance teams can be provided by the road users/general public in the simple form of reporting incidents through apps which already store the location automatically on the road, with some descriptions of an incident. This activity could reduce the workload and probability of data collection errors for the maintenance teams. A good collection scheme by the maintenance teams would lead to better road repair records, and more records for the geotechnical teams to scrutinize for the landslide inventory and other analyses.

Finally, the analysis derived databases have to be prepared from the crucial database attributes outlined. All of the analysis derived databases are essential for the landslide QRA procedure translated per segment; their preparation along with all the databases that were defined, heavily relies on the quality of data collection and organization of all data attributes and users involved in road management.

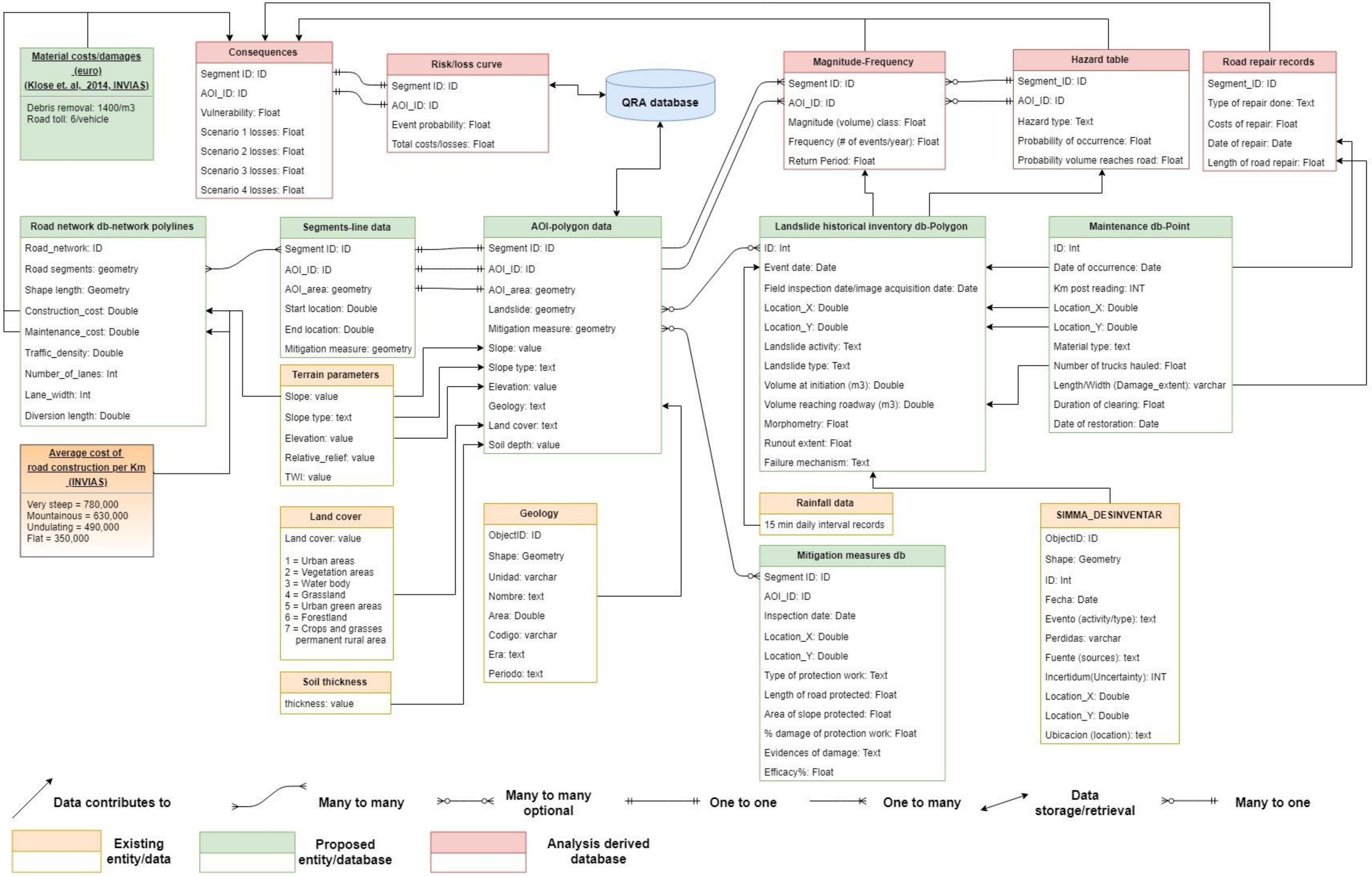


Figure 4.8: *Overall formulated database structure including existing, proposed and foreseen analysis resulting data*

5. APPLICATION OF THE DATABASE IN ASSESSING RISK

In this chapter, the use of the data attributes defined in Chapter 4 will be demonstrated utilizing hypothetical datasets, and with an assumption that all databases defined are complete for risk analysis. Artificial data was used due to the lack of actual datasets from the study area, that allow to carry out QRA. A sample demonstration of the defined databases for each component of the risk will give more insight with respect to conducting the actual risk analysis in the future. The chapter is broken down into the hazard analysis section, consequence analysis, and finally the risk estimation. Each section will show which specific attributes are required for a specific analysis and the usage in the procedure is discussed.

5.1. Hazard analysis for segments with previous landslide events

Hazard in the QRA context is usually defined using a magnitude-frequency relation. These relations according to Corominas et al. (2018), often follow a power law with minor deviations at high and low magnitude values. To demonstrate the application of the proposed databases, hypothetical data regarding the volumes of rockfalls/rockslides along the field based AOI's will be used. Table 5.1 shows a hypothetical landslide inventory dataset in Sola d' Andorra modified from Corominas et al. (2018). It contains the historical volumes of rockfalls and rockslides modified in this example over a 25-year span. The inventory is considered substantial and complete for segments that have volume records reaching the road and can be analyzed for M-F curve fitting for the power law that will allow extrapolation of frequencies or return periods per given expected volume classes. The volume classes formulated to derive equation (5.1) is outlined in Table 5.2.

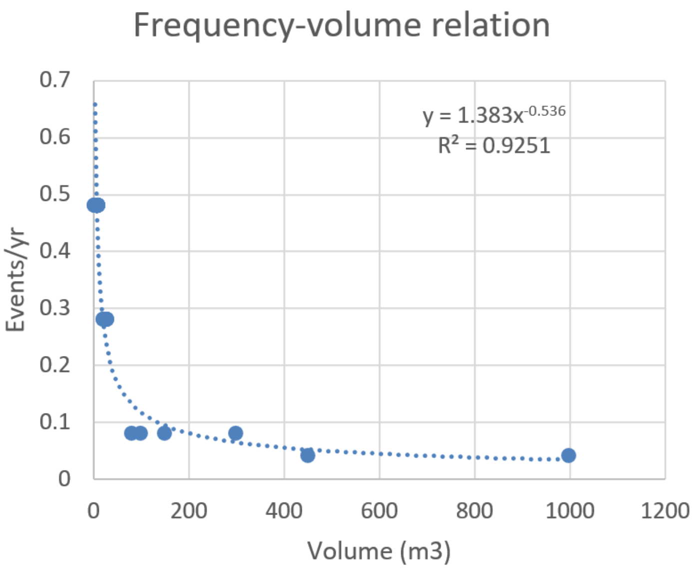


***Figure 5.1**: Relationship established between the hypothetical volumes of rockslide and rockfall events at segment AOI that were characterized having similar landslide type.*

The relationship established in Figure 5.1 fits sufficiently to the power law given equation (5.1):

$$N = 1.383V^{-0.536} \tag{5.1}$$

Wherein N refers to the number of rockfalls/rockslides expected per year exceeding a given volume (V). Extrapolating from equation (5.1), rockfall/rockslide volumes that could be larger than the 25 inventoried events results to annual frequencies and their respective return periods for specific ranges of volume classes indicated. These results are outlined in Table 5.3. Equation (5.1) was established by creating representative volume classes of the sample inventory, counting the number of events of each volume class, and dividing this by the total number of years of the sample interval (25), similar to the approach implemented by Hungr et al. (1999).

Segment ID	Event date (year of occurrence)	Volume (m3)
15	2016	1000
8	1996	450
14	2013	300
6	2001	150
10	2000	100
7	1996	80
1	2011	30
6	2010	30
7	1997	30
12	2004	25
1	2009	25
10	2016	20
14	2004	20
7	2011	10
1	1993	10
6	2011	10
12	1999	10
8	2010	10
1	2003	10
1	1994	10
1	2016	5
1	1995	5
6	1992	5
1	2001	4
15	1991	4

Table 5.1: *Historical inventory modified from Sola d' Andorra by Corominas et al.,(2018) to demonstrate attributes that are crucial for establishing M-F relations in the study area. The volume attribute can be collected from the proposed multi-temporal landslide inventory or directly from the maintenance records; larger events (>1000m^3 volume of material) are expected to be on record in DESINVENTAR databases as well.*

Volume class	Count	Frequency (events/year)
>1	12	0.48
>10	7	0.28
>30	2	0.08
>100	2	0.08
>300	1	0.04
>500	1	0.04

Table 5.2: *Volume classes formulated to fit the inventory volume attributes to the power law curve; equation (5.1) was derived from this curve*

Volume class range (m^3)	Frequency (events/year)	Return Period (years)
>1	1.383	0.72
>10	0.402	2.5
>100	0.117	8.5
>1000	0.034	29
>10,000	0.010	100
>100,000	0.003	346

Table 5.3: *Extrapolated frequencies from the power law equation (1) derived from fitting the hypothetical data in Table 5.1 The frequencies represent the probability of landslide occurrence of a given volume class range. This comprises the hazard component of the QRA procedure.*

Ideally, the M-F relation should be established per road segment since the final risk values would also be expressed per segment. However, it could be difficult to obtain a substantial amount of records within a single road segment and corresponding AOI. In addition to this, for segments that do not have recorded previous activities, they will be presumed as having no probability of having a landslide event in the future, which is incorrect in principle. Moreover, since the M-F relation represents the hazard, it is possible that some AOI's could exhibit similar landslide characteristics/types. Therefore, it is sufficient to combine their landslide event attributes particularly their volumes and event dates to come up with an M-F relation that characterizes that hazard for a given area. The database structure for doing the hazard analysis for segments with previously recorded landslides with volumes is shown in Figure 5.2 below. A proposed method of assessing the hazard using some attributes also included in the database structure introduced in Chapter 4 is presented next.

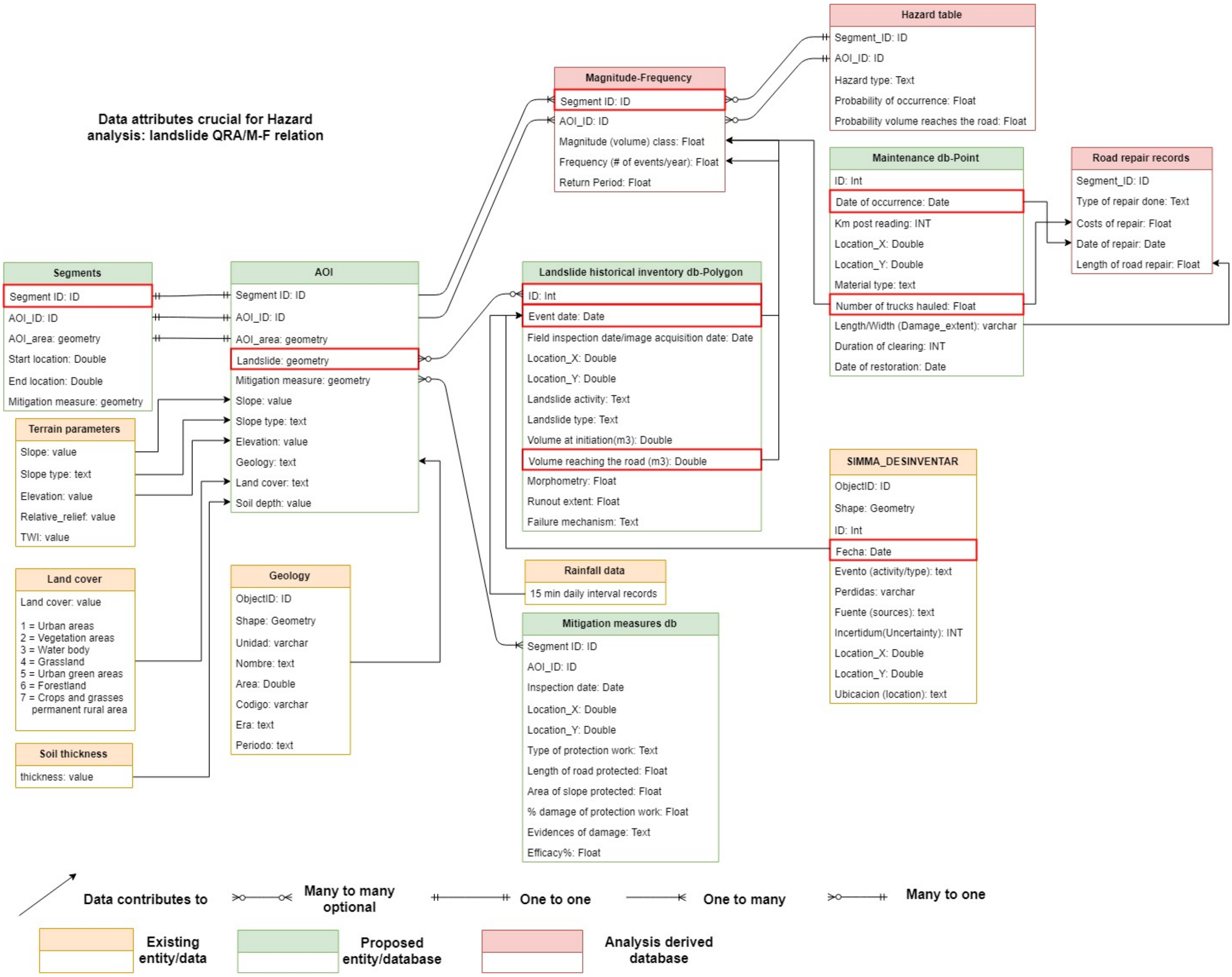


Figure 5.2*: Database structure for hazard assessment for segments with previously recorded landslides, highlighted attributes are used for establishing M-F relation*

Figure 5.2 shows the database structure and attributes utilized to come up with the results in Table 5.3. It all begins with the definition of the segments followed by accessing landslide information on volume reaching the road and event dates within the respective AOI's per road segment. Historical databases such as the SIMMA-DESINVENTAR catalog can also be referenced for large event dates while the number of truck loads and reported occurrence dates from the maintenance database could also be used to supplement landslide information. Once the datasets are organized (Table 5.1), the establishment of the M-F relation can proceed, and in the demonstration above, this is through fitting the landslide events in a power law model shown in Figure 5.1.

For analysis of hazard when there is not enough historical data per road segment, the hazard assessment could be threshold based. This may be applicable to segment no. 4 wherein the large landslide of 2016 occurred, prior to the event, there were no reported landslides within the AOI. The database structure showing the selected attributes for conducting such hazard assessment methodology is shown in Figure 5.3.

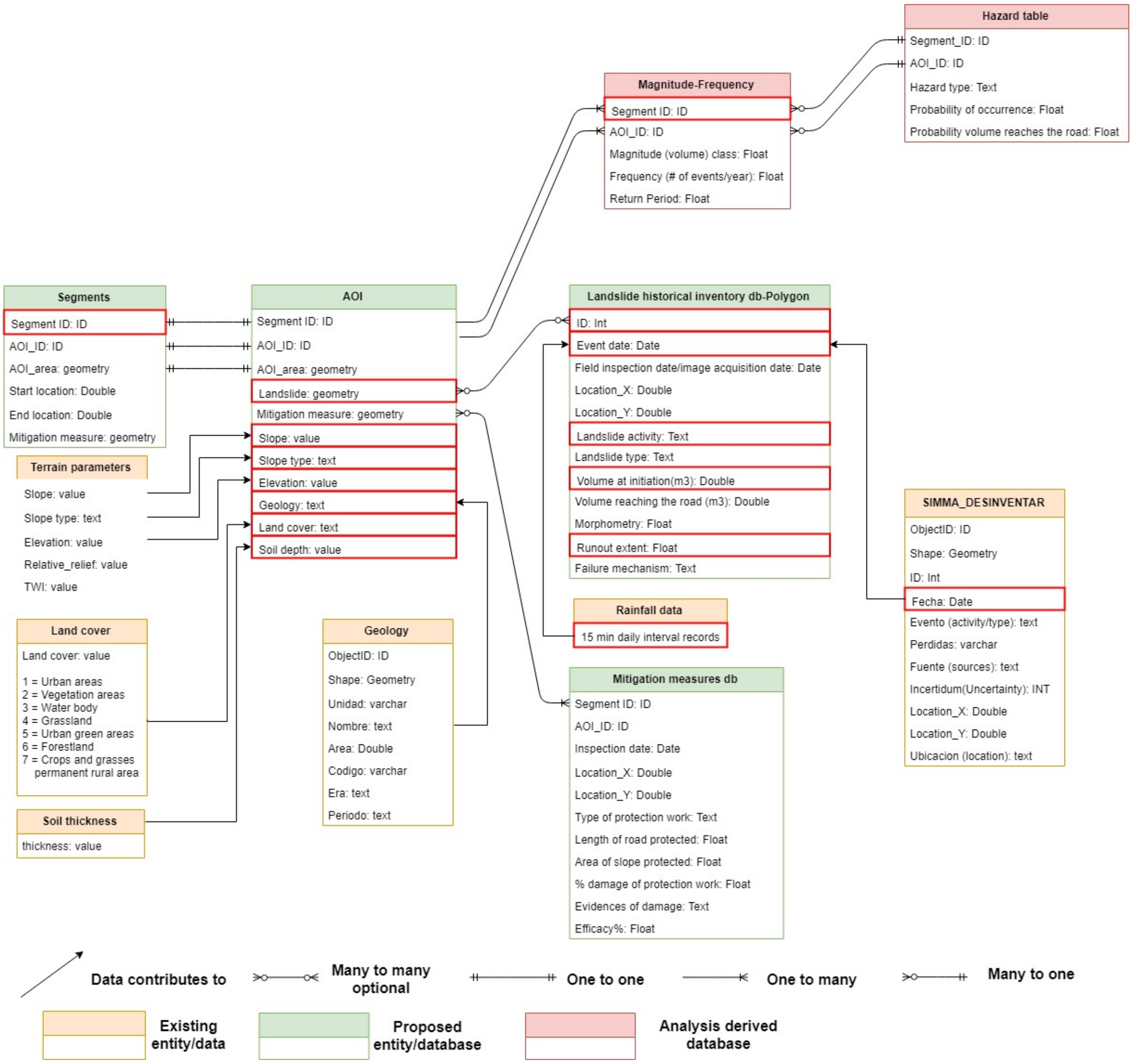


***Figure 5.3**: Database structure showing highlighted attributes that can be used for threshold based hazard analysis*

The method begins with first assessing the landslide susceptibility of the AOI. This can be done by using the spatial datasets connected to the AOI database such as the DEM derivative maps, geological data, and landcover, etc. using statistical analysis or physical models. After which the spatial probability could be estimated after finding the susceptibility. The runout probability would also have to assessed using empirical models and the initiation probability along with magnitude probability could be estimated by physically based models, utilizing limited attributes from the landslide inventory database. Finally, the annual probability of occurrence of triggering events could be estimated by setting rainfall thresholds and extreme value analysis such as the Gumbel distribution function (Jaiswal et al., 2011; Martha et al., 2012). The hazard could then be calculated by multiplying the spatial, temporal and magnitude probabilities of a landslide in a study area.

5.2. Consequence analysis

In the context of this research, estimating the costs for landslide occurrence along the segments primarily involves considering how much the road is obstructed by the landslide, and the level of structural failure the road has incurred. This is expressed in four scenarios formulated by INVIAS. To estimate the costs, the hypothetical volume classes in Table 5.3 were used, as well as the costs for road construction, average daily traffic (ADT) and debris clearing which were obtained from Klose (2014), and INVIAS. Table 5.4 outlines how the costs could be estimated per landslide scenario using the data attributes defined earlier in Chapter 4. In this example, an assumption was made that irrespective the volume of the landslide, it would reach the road, thereby also affecting the estimation of the consequences. However, in reality, careful considerations must be made concerning the volume of landslides and how it correlates to the calculation of the consequences and the probability that certain landslide volume classes would cause roadway damage. These considerations are explained and demonstrated further by Mavrouli & Corominas, (2018).

Scenario		**Consequence formula**
1-Partial blockage without structural failure		$Costs = Vmat * Clearing\ cost$
2-Partial blockage with structural failure		$Costs = (Vmat * Clearing\ cost) + (Damaged\ road\ length * construction\ cost)$

3-Complete blockage without structural failure		$Costs = (Vmat * Clearing\ cost) + (\#\ of\ days * ADT * Toll\ fee\ per\ vehicle)$
4-Complete blockage with structural failure		$Costs = (Vmat * Clearing\ cost) + (\#of\ days * ADT * Toll\ fee\ per\ vehicle) + (Damaged\ road\ length * construction\ cost)$

Table 5.4: *Formulated scenarios by INVIAS envisioning the type of damage to the roads in the event of a landslide; The costs per scenario are different, depending on a number of crucial attributes such as construction costs, the volume of material (Vmat), road toll costs, and length of road damaged.*

In addition to the amount of structural damage and duration of road blockage, the vulnerability of the road segment can be estimated using its rehabilitation cost divided by the total construction cost of the segment (Garzón Iral et al., 2012; Jaiswal, 2011). The volume of material reaching the road also affects the vulnerability estimation through the costs incurred by having to conduct debris clearing activities, since the vulnerability is based on cost ratios, the volume would be a factor during estimation. The data attributes required for estimating costs per respective scenario presented in Table 5.4 are also defined in the proposed database. The entity relationship diagram for consequence analysis highlighting the crucial data fields in the database structure is presented in Figure 5.5. Of all these crucial datasets presented, the amount of road length damaged is the most important since it affects many attributes including duration of road blockage, rehabilitation costs, clearing costs and ultimately the risk.

The probability of structural damage is difficult to estimate given that it is not dependent on the volume of material that reaches the road from upslope landslides. Moreover, structural damage to the road is mostly attributed to downslope failures which also presents an additional challenge for risk analysis. In the consequence scenarios presented in Table 5.4, it is not possible to estimate the probability of structural damage.

5.3. Risk incurred by road infrastructure managers

The risk to the roadway for landslides occurring per respective road segment was estimated making use of the hypothetical volume classes and respective return periods outlined in Table 5.3. Using the equation adapted from AGS (2000), Fell et al. (2005) and Jaiswal (2011), the risk was calculated per consequence scenario as:

$$R = Hm * Pm * Pt * Costs \tag{5.2}$$

R is the risk in terms of monetary losses per consequence scenario and segment. H_m, is the hazard due to magnitude class 'm' (volume in m^3) expressed as the probability of event occurrence per given volume class. P_m, is the probability that the landslide of magnitude/volume 'm' reaches the road, assumed as 1 in this demonstration. P_t, is the temporal probability of the road to be exposed to the landslide, also assumed as 1 since the roadway is stationary. Finally, Costs is the amount in monetary terms per consequence scenario computed using formulas outlined in Table 5.4. The losses for this demonstration was calculated per road segment and for the consequence scenarios 1-4. The results of the risk estimation for segments 4, 9, and 15 for demonstration of the compatibility and completeness of the proposed landslide QRA database is shown in Figure 5.4 as risk curves for scenario 3. The critical attributes in the database structure used to come up with the risk estimation below are outlined in Figure 5.5.

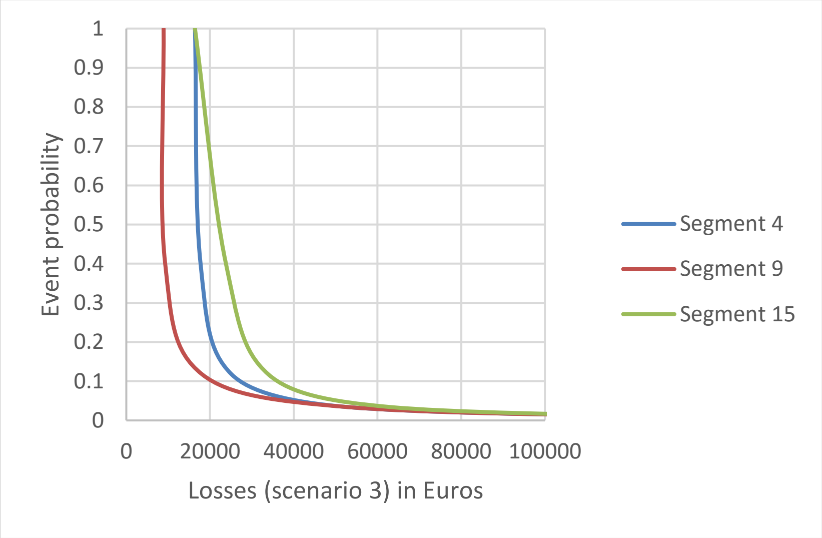


Figure 5.4: *Risk curves showing the monetary losses per corresponding probability of occurrence per respective volume classes in selected road segments*

To come up with the risk curves in Figure 5.4, segments were first chosen based on their previous record of having landslides in the study area, and their respective segment lengths were taken from the segment database. The construction costs for the segment were calculated by multiplying its length by the cost of construction per meter attribute that is taken from the road network database. Hypothetical test data for the volumes were then formulated as shown in Table 5.5 and were first populated using volume attributes from Table 5.3 in Section 5.1 to determine the effects of having increasing landslide volume to the consequences and the risk. The volume information per segment would come from landslide inventory databases. The annual/event probability of having a landslide per given expected volume was then calculated using Equation 5.1. Blockage duration and length of road affected attributes were then populated, these attributes come from the maintenance database and repair records (Figure 5.5). The blockage duration was estimated based on the 2016 landslide event wherein 25000m^3 of material took approximately 7 days before the road was passable. The 2016 event happened on segment 4 of the study area. In segment 15, there was also a large rockslide event that reportedly took more than a week before vehicles could pass through the highway. The rehabilitation costs refer to losses incurred due to road clearing expenses, and construction/maintenance costs for affected length of the road. The consequences/costs were computed per scenario equation outlined in Table 5.4, and finally the losses per scenario per segment were calculated by using Equation 5.2.

The probability of having consequence scenarios 1 and 3 (with non-structural damage) can be estimated with the probability of occurrence since they are related to volume of materials that may come into contact with the road from the upslope. However for scenarios 2 and 4 (with structural damage), the probability of these types of damages occurring are difficult to assess and cannot be determined by the volume probability, therefore the calculations for scenarios 2 and 4 have to be reconsidered.

The hypothetical risk curves shown in Figure 5.4 reveal the total risk for selected segments 4, 9, and 15. To calculate the specific risk, the area under the risk curves must be estimated. In this example, foreseeing damage scenario 3 (full road blockage), road segment 9 has a relatively lesser risk in comparison to segments 4 and 15. Although the resulting risk curves are relatively close to one another visually, the minute differences in the area under the curve could prove vital for prioritization procedures. For this demo analysis, it shows that the proposed database structure along with its compiled attributes when it is substantially accomplished allows the quantitative estimation of the hazard, vulnerability, costs, and direct risk. The complete dataset and table of operations conducted for this example are shown in Tables 5.5 and 5.6.

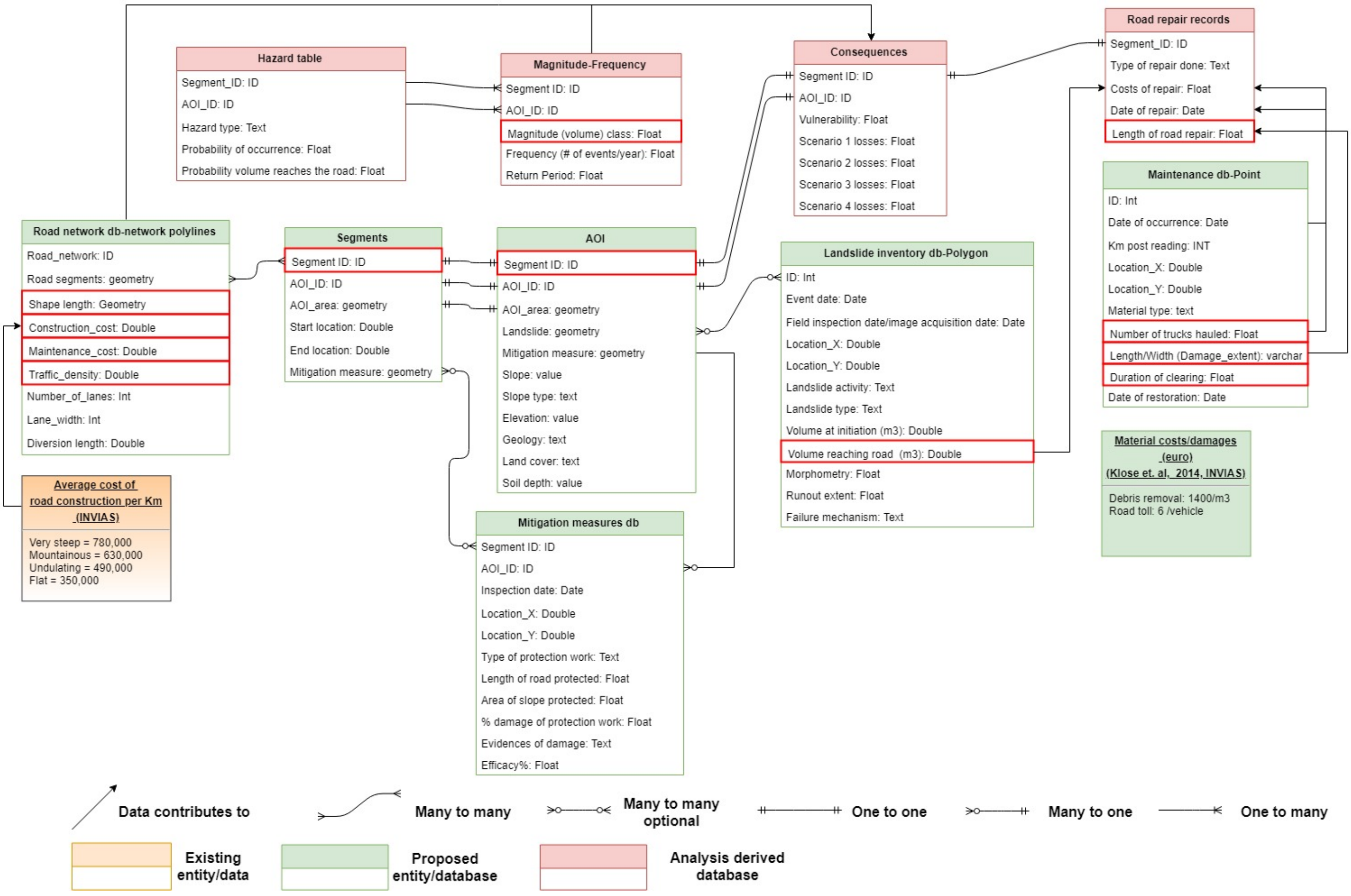


Figure 5.5: *Database structure highlighting attributes utilized for Consequence/ loss analysis*

Segment ID	Total Segment length (m)	Construction cost (Euro)	Rehabilitation cost (affected length*construction cost per meter)+(clearing costs)	Affected length (m)[1]	Expected Volume (m3)	Hazard: Probability of occurrence (events/yr)	Return Period	Blockage duration (days)[2]
4	320	160000	1900	1	1	1	1	0.1
			16500	5	10	0.402552177	2.484150021	0.2
			145000	10	100	0.117171551	8.534494835	0.5
			1410000	20	1000	0.034105324	29.32093532	1
			14015000	30	10000	0.009927095	100.7344037	3
			140075000	150	100000	0.002889497	346.0810501	7
9	400	200000	1900	1	1	1	1	0.05
			15000	2	10	0.402552177	2.484150021	0.06
			142500	5	100	0.117171551	8.534494835	0.1
			1405000	10	1000	0.034105324	29.32093532	1
			14012500	25	10000	0.009927095	100.7344037	2
			140015000	30	100000	0.002889497	346.0810501	3
15	200	100000	3900	5	1	1	1	0.1
			19000	10	10	0.402552177	2.484150021	0.3
			147500	15	100	0.117171551	8.534494835	1
			1415000	30	1000	0.034105324	29.32093532	3
			14025000	50	10000	0.009927095	100.7344037	5
			140050000	100	100000	0.002889497	346.0810501	10

Table 5.5: *Hypothetical data formulated for demonstration of a risk analysis*

[1] **estimated from the segment length and expected volume**

[2] **estimated from worst-case event and volume of Copacabana event in 2016**

Segment ID	Scenario 1 (costs in Euro)	Scenario 2 (costs in Euro)	Scenario 3(costs in Euro)	Scenario 4(costs in Euro)	Risk (scenario 1)	Risk (scenario 2)	Risk (scenario 3)	Risk (scenario 4)
4	1400	1900	16400	16900	1400	1900	16400	16900
	14000	16500	44000	46500	5635	6642	17712	18718
	140000	145000	215000	220000	16404	16989	25191	25777
	1400000	1410000	1550000	1560000	47747	48088	52863	53204
	14000000	14015000	14450000	14465000	138979	139128	143446	143595
	140000000	140075000	141050000	141125000	404529	404746	407563	407780
9	1400	1900	8900	9400	1400	1900	8900	9400
	14000	15000	23000	24000	5635	6038	9258	9661
	140000	142500	155000	157500	16404	16696	18161	18454
	1400000	1405000	1550000	1555000	47747	47917	52863	53033
	14000000	14012500	14300000	14312500	138979	139103	141957	142081
	140000000	140015000	140450000	140465000	404529	404572	405829	405873
15	1400	3900	16400	18900	1400	3900	16400	18900
	14000	19000	59000	64000	5635	7648	23750	25763
	140000	147500	290000	297500	16404	17282	33979	34858
	1400000	1415000	1850000	1865000	47747	48259	63094	63606
	14000000	14025000	14750000	14775000	138979	139227	146424	146672
	140000000	140050000	141500000	141550000	404529	404673	408863	409008

Table 5.6: *Loss table calculated per scenario and using Equation 5.2*

5.4. Losses incurred by road users

The proposed database is also applicable for estimation of losses that road users experience in the event of a landslide causing full blockage of the roadway. This can be estimated using the deviation length and average daily traffic attributes from the road network database. The duration of clearing/road blockage can be extracted from the maintenance database, while information regarding the approximate fuel costs and mileage per vehicle are readily published by daily local news outlets and automobile companies, respectively. Equation (5.3) below shows the indirect risk formula due to additional fuel consumption for road users adapted from Jaiswal (2011) to estimate indirect risk for a single vehicle type.

$$\mathrm{I}R = (Dl * ADT * FC * BLT)/Mi \tag{5.3}$$

Wherein IR, refers to the indirect risk/losses incurred by road users. Dl, refers to the total deviation/detour length (Km), ADT (number of vehicles passing through the road per 24 hours) is the average daily traffic, FC (Euro/L) is the published cost of fuel, BLT (days) is the total blockage time (hours) estimated depending on how large the landslide is, and Mi is the published average mileage (Km/L) of the vehicle type considered. In order to estimate indirect risk, a simulated landslide blockage must be placed in one of the road segments, the road network dataset allows calculation of an alternative route and its distance given a specific blockage on the road network. This will serve as the starting point (deviation length) for indirect risk estimation. The total blockage time is a major source of uncertainty for estimating the indirect risk due to road blockage, it is important to have this parameter validated and checked from the maintenance database records.

5.5. Discussion

The proposed database structure supports the collection of relevant data for the estimation of landslide risk quantitatively. The hazard expressed as the annual probability of event per segment for a given magnitude (volume) class was appropriate in determining the risk. This was derived from fitting a power law model in the hypothetical landslide dataset. However for segments with no previous landslides in their respective AOI's, the quantification of the hazard and eventually the risk is more complicated and would have to start from susceptibility analysis. Aside from the volume, the number of landslides per segment could also be used to represent landslide magnitude given a landslide database that has more extensive temporal range.

For estimating the consequences, the proposed database structure allows calculation of the costs for the road manager's (INVIAS) envisioned four (4) damage scenarios in the event of a landslide along the road. Of these scenarios, those involving structural damage to the road (scenarios 2 and 4) are the most difficult to quantify mainly due to varying amounts of construction costs needed for the road and difficulty in estimating the probability of occurrence, since it is not based on past landslide events. The probability of occurrence for each scenario varies depending on the presence of structural damage or non-structural damage. For scenarios 1 and 3, the probability of occurrence can be estimated using the volume of landslide material reaching the road since road blockage (non-structural damage) is directly related it. However, for scenarios 2 and 4, the probability of structural damage cannot be determined by the volume of materials that reach the road; but rather through determining the probability that a landslide with a given magnitude occurring on the downslope AOI of a road segment would cause structural failure (e.g., resulting from significant erosion of the embankment).

The risk is most sensitive to the blockage duration and the affected length of the road. This is because the losses in the event of total road blockage are higher than clearing high volume landslides that do not cause full blockage of the roadways. In addition to this, rehabilitation costs increase significantly with an increase in affected road length. Moreover, an increase in the affected length of the road would lead to longer blockage duration.

In terms of indirect risk, the scope of the database does not include quantification of losses due to delays of transportation delivery, loss of working hours/salary, or social risks. The database structure was designed to express direct risk in monetary terms. The risk in terms of monetary loss was selected since the main objective of the risk assessment for roads is the prioritization of road segments due for mitigation. Moreover, the losses calculated serve as an input for future cost-benefit analysis studies to be done by infrastructure managers. Although the risk to life is also important to be considered, it could be included in future studies aimed to establish tolerable, acceptable or unacceptable risk limits along the highways.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

This research aimed to provide a detailed database structure for a road asset management system that would allow integrating landslide QRA, in order to change from reactive road risk management in Colombia to a proposed risk-based and proactive approach. The present datasets collected by road managers in the area were only sufficient for addressing current road pavement conditions on a daily basis, while research institutes such as UNAL only have adequate datasets to conduct landslide susceptibility analysis on a regional scale. During fieldwork, it was identified that the road managers do not have a road asset management database and they also do not have detailed records of landslide events along the road network. Under these conditions, it is not possible to conduct risk assessments in a quantitative approach at present. With this background, the proposed database structure would be of significant value as a blueprint for the QRA consideration of road managers in the study area.

In order to make the transition to a risk-based approach, the concept of delineating homogenous road segments with their areas of influence (AOI) was formulated. Different segmentation approaches and their resulting AOI's were compared to the field-based AOI's. In conclusion, the field-based method of delineating AOI's works best as a standalone method while the other approaches evaluated were applicable as a supplement. The use of watershed delineation and slope units are ideal for an initial screening of problematic areas or may yield AOI boundaries that are comparable to the ground truth. However, the methods cannot be used as a standalone approach for delineating AOI's because the methods may overgeneralize the landslide type and important road segment characteristics. The application of runout simulation is suitable for delineating possible landslide sources. However, its lack of continuity with respect to delineating AOI's on the road is a significant drawback. A method was developed to reveal possible landslide source areas that may affect the road. The threshold raster values between source and non-source areas were identified when the plane intersection raster value, Z goes above zero ($Z > 0$). This would be applicable in identifying probable landslide sources along shorter road segments wherein the gradient does not vary greatly.

The database structure developed combines several components related to maintenance, landslides, mitigation measures, and road network. The database when sufficiently completed can be stored in a Database Management System (DBMS) such as MS Access, Oracle, or PostgreSQL. This allows flexibility of data attribute use in GIS analysis and ease of sharing between multiple users within the road management. The data attributes stored within these databases allow the hazard to be expressed in a power law M-F relation using volume as a magnitude proxy and frequency represented as annual probability while also providing starting information on how to estimate volume and frequency when no historical landslide information is available. It also accommodates cost estimates for different landslide event damage scenarios along the road. The data attributes in these databases as demonstrated in Chapter 5 are applicable for quantification of direct and indirect landslide risk in monetary terms per road segment. This can serve as a significant input for future cost-benefit analysis and subsequent mitigation prioritization of road segments.

The methods presented for road segmentation and AOI delineation along with the database structure defined contributes to the guidelines formulated by INVIAS and the Colombian Geological Survey by providing a standard structure for data collection and storage, as well as methods for segmenting the road network to begin quantitative analysis of the risk.

6.2. Highlights of the research

1. The research defined the databases required as the initial blueprint for conducting landslide QRA along roadways. It also highlighted the crucial attributes that have to be collected and stored to enable the QRA procedure, including specific recommendations on who collects the data, for whom it is for, and how often should it be collected or updated.
2. The research presented and demonstrated a database structure/entity relation system that is applicable for establishing the M-F relation of landslides in a catchment scale, provided the database is sufficiently completed.
3. The research presented and demonstrated that the proposed database along with its respective attributes could accommodate cost calculations for consequences and risk.
4. The research demonstrated that the proposed database structure was applicable for expressing the risk in monetary terms per segment that is incurred by road managers and also indirect risk to road users in the event of a landslide along the roadway.

6.3. Recommendations for future study

1. The concept of fully automated road segment AOI delineation can be further explored. Starting from road segmentation and identifying problematic upslope and downslope areas.
2. Further refinement of the method developed for delineating landslide sources is recommended. Better thresholding metrics done per pixel value instead of elevation average of the road should be developed to make the method applicable to longer road networks with varying gradients.
3. It is recommended that the database structure be improved also to accommodate assessing the population risk along the roadways. This direction will allow the development of risk tolerance criteria along the roads.
4. A web-application is recommended to integrate the proposed database structure and allow centralized data management and validation while providing multiple users access to encode in the proposed databases.
5. Exploring the options for integrating the structure into a DBMS is recommended. DBMS platforms will make the editing, maintenance, and analysis involving the different proposed databases, more efficient, especially for GIS processing.

LIST OF REFERENCES

Agencia Nacional de Infraestructura. (2015). *GESTIÓN CONTRACTUAL Y SEGUIMIENTO DE PROYECTOS DE INFRAESTRUCTURA DE TRANSPORTE.*

Agencia Nacional de Infraestructura. (2016). Desarrollo Vial del Oriente de Medellín (DEVIMED) | Portal ANI. Retrieved January 10, 2019, from https://www.ani.gov.co/proyecto/carretero/desarrollo-vial-del-oriente-de-medellin-devimed-21663

AGS. (2000). Landslide Risk Management Concepts and Guidelines. *Australian Geomechanics*, (March), 49–92. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:LANDSLIDE+RISK+MANAGEMENT+CONCEPTS+AND+GUIDELINES+AUSTRALIAN+GEOMECHANICS+SOCIETY+SUB-COMMITTEE+ON+LANDSLIDE+RISK+MANAGEMENT#2

Alvioli, M., Marchesini, I., Reichenbach, P., Rossi, M., Ardizzone, F., Fiorucci, F., & Guzzetti, F. (2016). Automatic delineation of geomorphological slope units with r.slopeunits v1.0 and their optimization for landslide susceptibility modeling. *Geoscientific Model Development*, *9*(11), 3975–3991. https://doi.org/10.5194/gmd-9-3975-2016

Arnold, J. G., & Fohrer, N. (2005). SWAT2000: Current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes*, *19*(3), 563–572. https://doi.org/10.1002/hyp.5611

Bles, T., Bessembinder, J., Chevreuil, M., Danielsson, P., Falemo, S., Venmans, A., … Löfroth, H. (2016). Climate Change Risk Assessments and Adaptation for Roads - Results of the ROADAPT Project. *Transportation Research Procedia*, *14*(0), 58–67. https://doi.org/10.1016/j.trpro.2016.05.041

Brenning, A., Schwinn, M., Ruiz-Páez, A. P., & Muenchow, J. (2015). Landslide susceptibility near highways is increased by 1 order of magnitude in the Andes of southern Ecuador, Loja province. *Natural Hazards and Earth System Sciences*, *15*(1), 45–57. https://doi.org/10.5194/nhess-15-45-2015

Budetta, P. (2004). Assessment of rockfall risk along roads. *Natural Hazards and Earth System Sciences*, *4*(1), 71–81. https://doi.org/10.5194/nhess-4-71-2004

Budetta, P., De Luca, C., & Nappi, M. (2015). Quantitative rockfall risk assessment for an important road by means of the rockfall risk management (RO.MA.) method. *Bulletin of Engineering Geology and the Environment*, *75*(4), 1377–1397. https://doi.org/10.1007/s10064-015-0798-6

CAREC-ADB. (2009). *Compendium of best practices in road infrastructure asset management*. https://doi.org/10.1017/CBO9781107415324.004

Catani, F., Segoni, S., & Falorni, G. (2010). An empirical geomorphology-based approach to the spatial prediction of soil thickness at catchment scale. *Water Resources Research*, *46*(5). https://doi.org/10.1029/2008WR007450

Colesanti, C., & Wasowski, J. (2006). Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry. *Engineering Geology*, *88*(3–4), 173–199. https://doi.org/10.1016/j.enggeo.2006.09.013

Corominas, J., Mavrouli, O., & Ruiz-Carulla, R. (2018). Magnitude and frequency relations: are there geological constraints to the rockfall size? *Landslides*, *15*(5), 829–845. https://doi.org/10.1007/s10346-017-0910-z

Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., … Smith, J. T. (2013). Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment*, *73*(2), 209–263. https://doi.org/10.1007/s10064-013-0538-8

Crozier, M. J. (2005). Multiple-occurrence regional landslide events in New Zealand: Hazard management issues. *Landslides*, *2*(4), 247–256. https://doi.org/10.1007/s10346-005-0019-7

Daheshpour, K., & Herbert, S. (2018). *Infrastructure project failures in Colombia.*

Dai, F. ., Lee, C. ., & Ngai, Y. . (2001). Landslide risk assessment and management: an overview. *Engineering Geology*, *64*(1), 65–87. https://doi.org/10.1016/S0013-7952(01)00093-X

Djokic, D. (2017). Creating a Hydrologically Conditioned DEM. In *ESRI business Conference.*

Espindola, G. M., Camara, G., Reis, I. A., Bins, L. S., & Monteiro, A. M. (2006). Parameter selection for region-growing image segmentation algorithms using spatial autocorrelation. *International Journal of Remote Sensing*, *27*(14), 3035–3040. https://doi.org/10.1080/01431160600617194

Fell, R., & Eberhardt, E. (2005). Landslide Risk Management. In E. Hungr, O; Fell, R.; Couture, R.; Ederhardt (Ed.), *International Conference on Landslide risk management.* Vancouver, Canada: A.A Balkema, Taylor and Francis Group.

Fell, R., Ho, K. K. S., Lacasse, S., & Leroi, E. (2005). State of the art paper: a framework for landslide risk assessment and management. In *International Conference on Landslide Risk Management* (p. 23).

Ferlisi, S., Cascini, L., Corominas, J., & Matano, F. (2012). Rockfall risk assessment to persons travelling in vehicles along a road: The case study of the Amalfi coastal road (southern Italy). *Natural Hazards*, *62*(2), 691–721. https://doi.org/10.1007/s11069-012-0102-z

Garzón Iral, J. M., Valencia Palacio, E., & Muñoz Cossio, J. A. (2012). *Evaluación de la vulnerabilidad y consecuencias por deslizamiento en la conexión vial Aburrá- Río Cauca entre las abscisas Km 04+000 y Km 39+000*. Retrieved from http://repository.udem.edu.co/bitstream/handle/11407/254/Evaluación de la vulnerabilidad y consecuencias por deslizamiento en la Conexión Vial Aburrá - Río Cauca entre las abscisas km 04%2B000 y km 39%2B000.pdf?sequence=1&isAllowed=y

GFDRR. (2012). *Analysis of Disaster Risk Management in Colombia: A Contribution to the Creation of Public Policies*. Bogota.

Guzzetti, F., Galli, M., Reichenbach, P., Ardizzone, F., & Cardinali, M. (2006). Landslide hazard assessment in the Collazzone area, Umbria, central Italy. *Natural Hazards and Earth System Science*, *6*(1), 115–131. https://doi.org/10.5194/nhess-6-115-2006

Guzzetti, F., Mondini, A. C., Cardinali, M., Fiorucci, F., Santangelo, M., & Chang, K. T. (2012). Landslide inventory maps: new tools for an old problem. *Earth-Science Reviews*, *112*(1–2), 42–66. https://doi.org/10.1016/j.earscirev.2012.02.001

Guzzetti, F., Reichenbach, P., & Ghigi, S. (2004). Rockfall hazard and risk assessment along a transportation corridor in the Nera valley, central Italy. *Environmental Management*, *34*(2), 191–208. https://doi.org/10.1007/s00267-003-0021-6

Hermanns, R., & Valderrama, P. (2012). Landslides in the Andes and the need to communicate on an interandean level on Landslide Mapping and Research. *Revista de La …*, *69*(3), 321–327. Retrieved from http://ppct.caicyt.gov.ar/index.php/raga/article/view/1824

Highland, L. M., & Bobrowsky, P. (2008). *Basic Information About Landslides*.

Horton, P., Jaboyedoff, M., Rudaz, B., & Zimmermann, M. (2013). Flow-R, a model for susceptibility mapping of debris flows and other gravitational hazards at a regional scale. *Natural Hazards and Earth System Sciences*, *13*(4), 869–885. https://doi.org/10.5194/nhess-13-869-2013

Hungr, O., Evans, S. G., & Hazzard, J. (1999). Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. *Canadian Geotechnical Journal*, *36*(2), 224–238. https://doi.org/10.1139/t98-106

INVIAS. (2016). *Manual de Carreteras*.

Jaiswal. (2011). *Landslide risk quantification along transportation corridors based on historical information* (PhD Thesis). University of Twente Faculty of Geo-Information and Earth Observation (ITC).

Jaiswal, P., van Westen, C. J., & Jetten, V. (2011). Quantitative assessment of landslide hazard along transportation lines using historical records. *Landslides*, *8*(3), 279–291. https://doi.org/10.1007/s10346-011-0252-1

Klose, M. (2014). Landslide cost modeling for transportation infrastructures: a methodological approach. *Landslides*, (March), 1–27. https://doi.org/10.1007/s10346

Martha, T. R., van Westen, C. J., Kerle, N., Jetten, V., & Vinod Kumar, K. (2012). Landslide hazard and risk assessment using semi-automatically created landslide inventories. *Geomorphology*, *184*, 139–150. https://doi.org/10.1016/j.geomorph.2012.12.001

Martinovic, K., Doherty, P., Reale, C., Gavin, K., Zhang, L., Joyce, C., … Callanan, S. (2017). Chapter 6 : Landslide risk assessment for engineered slopes on transport networks : case study of Irish rail network, 91–113.

Mavrouli, O., & Corominas, J. (2018). TXT-tool 4.034-1.1: Quantitative Rockfall Risk Assessment for Roadways and Railways. In *Landslide Dynamics: ISDR-ICL Landslide Interactive Teaching Tools* (pp. 509–519). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-57777-7_30

Michoud, C., Derron, M. H., Horton, P., Jaboyedoff, M., Baillifard, F. J., Loye, A., … Queyrel, A. (2012). Rockfall hazard and risk assessments along roads at a regional scale: Example in Swiss Alps. *Natural Hazards and Earth System Sciences*, *12*(3), 615–629. https://doi.org/10.5194/nhess-12-615-2012

Misra, R., & Das, A. (2003). Identification of homogeneous sections from road data. *International Journal of Pavement Engineering*, *4*(4), 229–233. https://doi.org/10.1080/10298430410001672237

Murillo-García, F. G., Alcántara-Ayala, I., Ardizzone, F., Cardinali, M., Fiourucci, F., & Guzzetti, F. (2015). Satellite stereoscopic pair images of very high resolution: a step forward for the development of landslide inventories. *Landslides*, *12*(2), 277–291. https://doi.org/10.1007/s10346-014-0473-1

OECD. (2001). *Asset Management for the Roads Sector. GESTION DU PATRIMOINE D'INFRASTRUCTURE DANS LE SECTEUR ROUTIER* (Vol. 1).

https://doi.org/10.1787/9789264193208-en

Peila, D., & Guardini, C. (2008). Use of the event tree to assess the risk reduction obtained from rockfall protection devices. *Nat. Hazards Earth Syst. Sci*, *8*, 1441–1450. Retrieved from www.nat-hazards-earth-syst-sci.net/8/1441/2008/

Pellicani, R., Argentiero, I., & Spilotro, G. (2017). GIS-based predictive models for regional-scale landslide susceptibility assessment and risk mapping along road corridors. *Geomatics, Natural Hazards and Risk*, *8*(2), 1012–1033. https://doi.org/10.1080/19475705.2017.1292411

Pensomboon, G. (2007). Landslide risk management and Ohio database. *Australian Geomechanics*, *42*(1), 1–227.

Popescu, M. E., & Sasahara, K. (2008). Engineering Measures for Landslide Disaster Mitigation. *Landslides – Disaster Risk Reduction*, 609–631. https://doi.org/10.1007/978-3-540-69970-5_32

Pratt, D., & Santi, P. (2014). A Landslide Hazard Rating System for Colorado Highways. *Rocky Mountain Geo-Conference*, 120–138.

Qi, S., Li, X., Guo, S., Zhan, Z., & Liao, H. (2015). Landslide-risk zonation along mountainous highway considering rock mass classification. *Environmental Earth Sciences*, *74*(5), 4493–4505. https://doi.org/10.1007/s12665-015-4453-0

Rana, S. (2017). Development of a direct method for local scale post-earthquake multi- hazards susceptibility assessment (MSc Thesis). University of Twente Faculty of Geo-Information and Earth Observation (ITC), 71.

Rose, B. (2005). *Tennessee Rockfall Management System* (PhD Disser).

Schlögel, R., Marchesini, I., Alvioli, M., Reichenbach, P., Rossi, M., & Malet, J. P. (2018). Optimizing landslide susceptibility zonation: Effects of DEM spatial resolution and slope unit delineation on logistic regression models. *Geomorphology*, *301*, 10–20. https://doi.org/10.1016/j.geomorph.2017.10.018

Servicio Geológico Colombiano – Instituto Nacional de Vías. (2018). *Guía metodológica para la evaluación del riesgo físico por movimientos en masa en la infraestructura vial*. Bogota.

Shah, Y. U., Jain, S. S., Tiwari, D., & Jain, M. K. (2013). Development of Overall Pavement Condition Index for Urban Road Network. *Procedia - Social and Behavioral Sciences*, *104*, 332–341. https://doi.org/10.1016/j.sbspro.2013.11.126

Simon, N., De Roiste, M., Crozier, M., & Rafek, A. G. (2017). Representing landslides as polygon (areal) or points? How different data types influence the accuracy of landslide susceptibility maps. *Sains Malaysiana*, *46*(1), 27–34. https://doi.org/10.17576/jsm-2017-4601-04

Sterlacchini, S., Frigerio, S., Giacomelli, P., & Brambilla, M. (2007). Landslide risk analysis: A multi-disciplinary methodological approach. *Natural Hazards and Earth System Science*, *7*(6), 657–675. https://doi.org/10.5194/nhess-7-657-2007

Sun, A. O. (2018). *DEVELOPMENT OF A RAPID MULTI-HAZARD ASSESSMENT ALONG ROADS : A CASE STUDY FROM CHINA* (MSc Thesis). University of Twente Faculty of Geo-Information and Earth Observation (ITC).

Tegtmeier, W., van Oosterom, P., Zlatanova, S., & Hack, R. (2009). Information management in civil engineering infrastructural development: with focus on geological and geotechnical information. *Proceedings of the ISPRS Workshop GeoWeb 2009 Academic Track Cityscapes*, *XXXVIII-3-*(May 2014), 68–73.

Turner, S., Waibl, C., & Waibl Consulting (2016). Infrastructure Risk Rating Manual, (July). Retrieved from https://www.pikb.co.nz/assets/Uploads/Documents/IRR-Manual-FINAL-Issued-13-07-2016.pdf

United States department of transportation. (2017). *Unstable slope management program for federal land management agencies*.

Universidad Nacional de Colombia, & Instituto Nacional de Vías INVIAS. (2006). Manual para la Inspección visual de Obras de estabilización, 43.

van Westen, C. J., Castellanos, E., & Kuriakose, S. L. (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. *Engineering Geology*, *102*, 112–131. https://doi.org/10.1016/j.enggeo.2008.03.010

van Westen, van Asch, T. W. J., & Soeters, R. (2006). Landslide hazard and risk zonation - Why is it still so difficult? *Bulletin of Engineering Geology and the Environment*, *65*(2), 167–184. https://doi.org/10.1007/s10064-005-0023-0

Vega, J. A., Hidalgo, C. A., & Marín, N. J. (2017). Landslide Risk: Economic Valuation in the North-Eastern Zone of Medellin City. *IOP Conference Series: Materials Science and Engineering*, *245*(6), 0–11.

https://doi.org/10.1088/1757-899X/245/6/062010

Wang, F., Xu, P., Wang, C., Wang, N., & Jiang, N. (2017). Application of a GIS-Based Slope Unit Method for Landslide Susceptibility Mapping along the Longzi River, Southeastern Tibetan Plateau, China. *ISPRS International Journal of Geo-Information*, *6*(6), 172. https://doi.org/10.3390/ijgi6060172

World Bank. (2017a). Integrating Climate Change into Road Asset Management, (April).

World Bank. (2017b). Strengthening Resilience to Geohazards in Transport. In *Annual South to South Learning Workshop on Strengthening resilience to geohazards in transport*. Kathmandu, Nepal.

Zhao, M., Li, F., & Tang, G. (2012). Optimal Scale Selection for DEM Based Slope Segmentation in the Loess Plateau. *International Journal of Geosciences*, *03*(01), 37–43. https://doi.org/10.4236/ijg.2012.31005

Zhu, D. (2013). An effective depression filling algorithm for DEM-based 2-D surface flow modelling. *Hydrology and Earth System Sciences*, *17*, 495–505. https://doi.org/10.5194/hess-17-495-2013

7. APPENDICES

7.1. Appendix 1-Overall description and justification of data fields in proposed databases

Maintenance database attributes:

- *Attribute or field:* ***User_ID/Code,*** *Data domain/format:* ***Integer***

The userID or code is essential for all database types since it serves as a key identifier of a specific record in the database (Tegtmeier, van Oosterom, Zlatanova, & Hack, 2009). In the case of this maintenance database, the userID or code is used to track records of a presumed road clearing activity and is essential for data retrieval, manipulation, and storage purposes as part of the analysis that could be undertaken using it, including QRA (Guzzetti et al., 2004; Turner & Waibl Consulting, 2016).

- *Attribute:* ***Kilometer reading,*** *Data domain/format:* ***Integer***

The kilometre reading or kilometre post reading attribute does not have a significant role in the context of QRA. However for purposes of convenient identification of relative location along the road, it is still useful to include in the database (Martinovic et al., 2017; Turner et al., 2016).

- *Attribute:* ***GPS location,*** *Data domain/format:* ***Double***

The location of road clearing is often times a good indicator that a minor landslide event has occurred (Jaiswal, 2011). This also aids in the population of the landslide inventory by technical personnel. The coordinates of such activity should be on record since spatial location of presumed events or landslides can be used for susceptibility assessment and subsequent spatial probability estimation (Corominas et al., 2013; van Westen et al., 2006).

- *Attribute:* ***Material type,*** *Data domain/format:* ***Text***

The material type attribute is not directly involved in the QRA process. However, this field is useful for identification of the landslide type e.g. rockfall, shallow landslide by geotechnical staff (Jaiswal, 2011) and landslide characterization e.g. solid rock or soil material.

- *Attribute:* ***Duration of clearing,*** *Data domain/format:* ***Float***

Similar to damage extent attributes, the duration of clearing is important for indirect risk estimation (Jaiswal et al., 2011). The number of hours/duration of clearing activity along the road especially for blocked lanes, would lead to significant amount of losses for the road concessionaires and probable increased fuel costs for vehicle users who are non-moving or need to find another route (Jaiswal, 2011).

- *Attribute:* ***Date of restoration,*** *Data domain/format:* ***Date***

The date of restoration attribute is also included for the database since it is also an important component for indirect risk estimation (Jaiswal, 2011). The date of restoration indicates when the roadway returns to 100% operational capacity. The duration of clearing, damage extents and date of restoration form the most significant attributes with regards to estimation of indirect risk along the road ways.

- *Attribute:* ***Number of trucks used to haul debris,*** *Data domain/format:* ***Float***

The number of trucks that were used to haul debris or clear the road is a crucial attribute to be included. This field is an important volume indicator of the amount of material that was moved or volume of the shallow landslide or rockfall boulders that were cleared (Jaiswal, 2011). The Float format of this attribute gives it more precision in terms of defining the number of trucks used, the presumed volume would be calculated by multiplying the number of trucks with the truck capacity.

- *Attribute:* ***Damage extent,*** *Data domain/format:* ***Text***

The extent of damage attribute is formatted by text and gives a description of how much of the roadway is blocked. This is according to amount of structural damage the road pavement incurs and the estimates of the number of lanes in the highway was blocked as a result of the event and clearing activity. This is an important input to indirect risk assessment and also for vulnerability estimation (Jaiswal et al., 2011; Martinovic et al., 2017).

Landslide historical inventory database attributes:

- *Attribute:* **Landslide ID,** *Data domain/format:* **Integer**

The landslide ID serves as the primary key of the landslide inventory, one unique integer value is assigned per landslide. The ID is used primarily for data storage, retrieval for analysis, and for monitoring its activity e.g. reactivation, mitigated.

- *Attribute:* **Inspection date,** *Data domain/format:* **Date**

The inspection date is not essential for QRA conduct, however it is still important to record when the inventory or mapping activity was conducted with respect to the actual landslide event date. Generally, the less time difference between the event and the inspection date, the more reliable the inventory is, given that material movement and amount of interference is less.

- *Attribute:* **Centroid GPS location,** *Data domain/format:* **Double**

For landslide inventories, the GPS location can be in the centroid of the polygon covering the landslide area. The location of the landslide is essential for susceptibility studies and spatial probability estimation as part of the hazard component of QRA (Corominas et al., 2013; van Westen et al., 2006). The location of landslide initiation is also crucial to estimate runout propagation for shallow, deep-seated landslides, debris flows, rockfall simulations, and prediction of other source areas.

- *Attribute:* **Landslide Activity,** *Data domain/format:* **Text**

The identification of landslide activity plays an important role in susceptibility studies and hazard assessment (Corominas et al., 2013). Landslide activity affects hazard assessment in QRA because the approach to quantify the hazard for areas that have not undergone failures is different to areas that have previously recorded landslide activity such as reactivated cut slopes along the road (Jaiswal, 2011). With this, it is necessary to include the type of landslide activity in the landslide inventory database.

- *Attribute:* **Landslide Type,** *Data domain/format:* **Text**

Similar to landslide activity, the landslide type is an important attribute in landslide inventories that will be used for susceptibility assessments and hazards (Sterlacchini et al., 2007; van Westen et al., 2006). The landslide type also affects how the susceptibility analysis is carried out, e.g. assessment for rockfalls and shallow landslides using a statistical approach are different. Therefore, the landslide type is an important attribute to be included in the landslide inventory.

- *Attribute:* **Volume (m^3),** *Data domain/format:* **Double**

The volume attribute in the landslide inventory database is important as a proxy for magnitude in frequency-magnitude analysis (Budetta, 2004; Corominas et al., 2013; Guzzetti et al., 2012).This is especially true for cut slope shallow landslides which are prevalent along roads. This attribute is connected to maintenance records of slide records, the volume data inferred from maintenance records can be used to supplement this attribute in the landslide inventory database. This attribute addresses the deficiency present in the available landslide inventory (SIMMA-DESINVENTAR) in the study area.

- *Attribute:* **Landslide morphometry,** *Data domain/format:* **Float**

Landslide morphometry especially length provides a good insight with regards to how much of the roadway is affected. Morphometric measurements of the landslides especially larger ones can be useful for detailed scale geotechnical assessments which involve more accurate and precise area and volume measurements.

- *Attribute:* **Runout extent,** *Data domain/format:* **Float**

The runout extent attribute is important to be included in susceptibility assessments and hazard analysis (Horton et al., 2013; Jaiswal, 2011). The runout outlines how far landslides reach after initiation, and in the context of road QRA, landslides reaching the road would constitute blockage for a certain duration. This is also an important parameter for indirect risk estimation involving road blockage of landslides along roads especially some empirical models such as Flow-R by Horton et al., (2013). This can define runout extents accurately given a high-resolution DEM and initiation points.

- *Attribute:* ***Failure mechanism,*** *Data domain/format:* ***Text***

Apart from location, types, activity, the frequency of occurrence, and volumes, landslide inventories should also contain information regarding its failure mechanism (van Westen et al., 2008). The type of failure mechanism is also included for susceptibility mapping (Jaiswal, 2011).

Mitigation measure database attributes:

- *Attribute:* ***Protection work ID,*** *Data domain/format:* ***Integer***

The mitigation measure ID serves as its primary key for data storage and retrieval purposes.

- *Attribute:* ***Inspection date,*** *Data domain/format:* ***Date***

The inspection date is related to the monitoring done by maintenance teams along the entire road network. Although this is not essential for QRA, it is important to keep on record the latest date the mitigation measure was inspected for its condition.

- *Attribute:* ***Location,*** *Data domain/format:* ***Double***

Same with the previously defined databases, the location of the protection works is essential for QRA. This is especially valid for rockfall susceptibility analysis and risk assessments (Budetta et al., 2015). The location of the protection work will typically have significantly reduced hazard and risk.

- *Attribute:* ***Type of protection work,*** *Data domain/format:* ***Text***

The type of protection work present (e.g., gabions, retaining structures) are not significant for QRA conduct. However records of these must be kept for asset database management.

- *Attribute:* ***% damage,*** *Data domain/format:* ***Float***

The condition or % damage to the protection work is not used in QRA. However, it is an important parameter which may indicate hazard frequency. Also it is important for estimating the efficacy of the mitigating measure.

- *Attribute:* ***Evidence of damage,*** *Data domain/format:* ***Text***

Evidence of damage for the protection works are also not used QRA, but since it is important to be monitored periodically for asset management purposes, it is still included in this proposed mitigation measure database.

- *Attribute:* ***Efficacy,*** *Data domain/format:* ***Float***

The most important attribute in the database for mitigation measures is the efficacy %. This is a significant addition and consideration for QRA along roads especially for rockfall hazards (Budetta, 2004; Budetta et al., 2015). In addition to this, efficacy % indicates the overall level of effectiveness and it affects how the risk is calculated by increasing it when the % efficacy of the mitigation measure is significantly decreased. A constant monitoring and checking of mitigation measure efficacy can also aid in crude hazard frequency estimation.

Road network database attributes:

- *Attribute:* ***road ID,*** *Data domain/format:* ***ID/varchar***

The road ID for this database represents segments, and this field serves as the key identifier of the database. It is important for road segments to have sufficient codes or ID for easier recognition and faster data retrieval (Rose, 2005; Turner et al., 2016). The format for this attribute is the variable character ID which differs from the integer formats set for the other primary keys. This is because most road segment keys are made with consideration to the locality where the segment of the road belongs and its relative location along the network, e.g. kilometer reading. This is also for easier modification by the road managers and faster identification of maintenance teams.

- *Attribute:* ***Segment_ID,*** *Data domain/format:* ***ID/varchar***

The segment ID is an attribute that is created after an AOI delineation procedure (Chapter 3). The segment ID identifies the immediate road way that is directly affected by the AOI defined. This attribute is assigned here since it refers mostly to road way properties equivalent to the road network but on a more specific aspect of a given road segment that may possess different properties such as pavement type, number of lanes, width, and maintenance/construction costs.

- *Attribute:* ***Lane width,*** *Data domain/format:* ***Text***

The lane width of the road is an important attribute for estimating cost ratios, vulnerability values, and also for indirect risk estimation (Martinovic et al., 2017; Rose, 2005). In the context of indirect risk estimation, the width or amount of road way that is blocked, whether partial blockage or full blockage, will affect the overall indirect risk estimates.

- *Attribute:* ***Number of lanes,*** *Data domain/format:* ***Integer***

The number of lanes the road network has also plays a crucial role in determining vulnerability values and also for indirect risk estimation (Martinovic et al., 2017; Rose, 2005). The number of lanes multiplied by the lane width attribute would constitute to total width of the road way, the assessment with regards to how much a road way is blocked is partly based on this total width parameter. This also affects how the runout from landslides is interpreted.

- *Attribute:* ***total construction costs,*** *Data domain/format:* ***Double***

Similar to maintenance costs, the road total construction costs are vital to the consequence and vulnerability analysis component of the QRA (Garzón Iral et al., 2012; Jaiswal, 2011; Martinovic et al., 2017). It is imperative that this attribute is also included in the road network database.

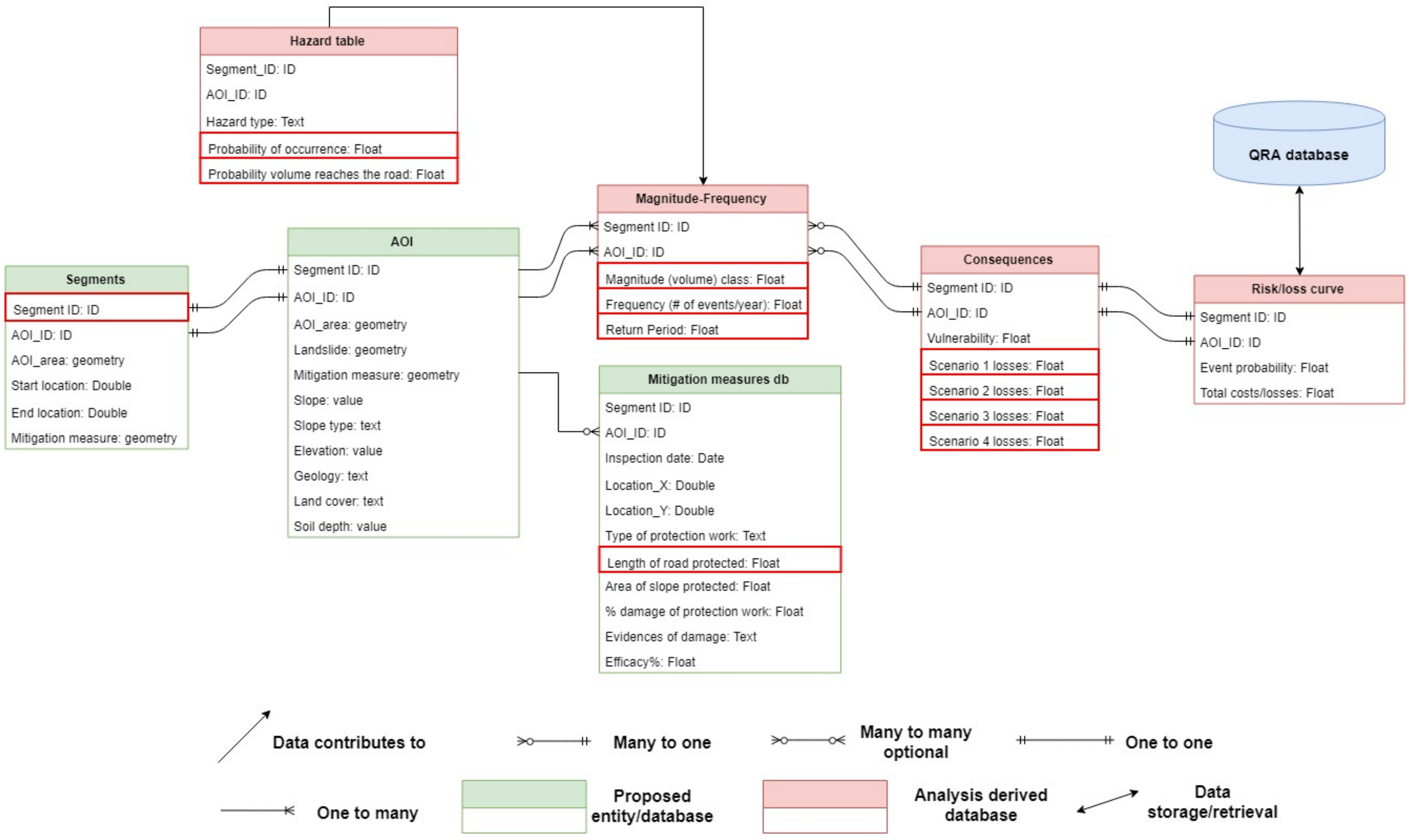
- *Attribute:* ***Average daily traffic,*** *Data domain/format:* ***Float***

The average daily traffic is a crucial component for estimating population risk and vehicular risk along specific road segments (Budetta, 2004; Rose, 2005; Turner et al., 2016). The average daily traffic attribute in the case of the available data at the study area, consists of number of vehicles passing through the toll gates in 24 hrs. The average daily traffic can also be used as a parameter for estimating the amount of losses the road concession may incur in the event of a full road way blockage due to a landslide.

- *Attribute:* ***Deviation/diversion length,*** *Data domain/format:* ***Double***

The road deviation length refers to the additional length that is covered by vehicles in the event a blockage occurs within the network. This is an important addition to the database currently maintained in the road study area. This attribute allows a more accurate estimation of indirect risk when full blockage of road lanes occurs (Jaiswal et al., 2011)

7.2. Appendix 2-Database structure highlighting most crucial data fields for risk analysis



7.3. Appendix 3-Cost tables used

Cost tables used, Adapted from INVIAS and Klose (2014)

Clearing costs (euro per m3)	1400
Toll payment (euro per vehicle)	6
Construction (Euro per kilometer)	500,000
Historical Average Daily Traffic Medellin-Bogota road, medellin-guarne section (all vehicles)	25000