ADAPTING A PROACTIVE, QUANTITATIVE RISK-BASED APPROACH IN MITIGATING LANDSLIDE RISK ALONG PHILIPPINE ROADWAYS

MARCIUS ISIP

SENIOR GEOLOGIST, MGB-CO

NORTH AVENUE, QUEZON CITY, PHILIPPINES

ISIP.MARCIUSELAEO@GMAIL.COM

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OF TWENTE.

INTRODUCTION

- Landslides = natural hazards which may result to significant damage
- They cause impact to regional economy when they affect important transport corridors
- ~20M Php annual losses, decreased road safety (JICA, 2007)
- Goal: disaster risk reduction along transport corridors → World Bank engages in Road Asset Management projects → Develop Road Asset Management Databases (RAMD)

PROBLEM – PHILIPPINE SETTING AND ASIA

- In the Philippines, JICA (2007) reports a **passive** approach in slope mitigation practices
- Typical RAMD only contains physical infrastructure, equipment, vehicle density data (OECD, 2001; Fell and Edberhardt, 2005).
- Solution: RAMD must incorporate landslide inventories, geological info, mitigation info, allows **proactive approach of quantitative risk assessment (QRA)** in addressing landslide risk (Fell and Edberhardt, 2005).
- Unorganized data collection and insufficiency of suitable data
- Lack of ***standard structure*** for **data collection/storage** and prescribed *road segmentation methods*

CONTEXT - RISK MANAGEMENT FRAMEWORK (FELL, 2012; DAI, 2001; AGS, 2007)

Risk analysis

- Hazard analysis, Consequence scenario building, Risk estimation

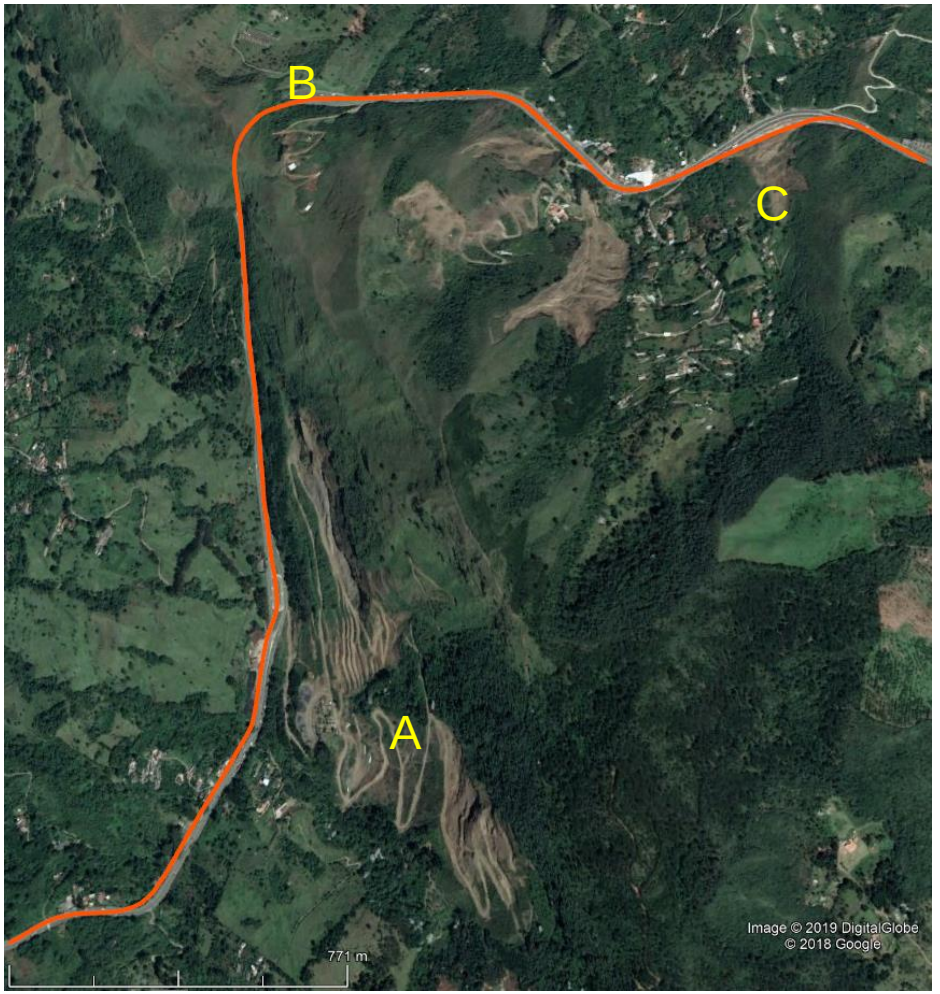
Risk assessment

- Classification of estimated Risk (acceptable, tolerable, unacceptable level)

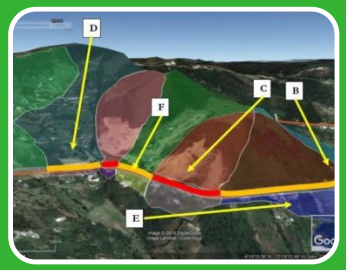
Risk management

- Cost-benefit analysis, Mitigation of risk to achieve desired level (acceptable, tolerable levels)

STUDY AREA CONDITIONS - COLOMBIA



SIGNIFICANCE OF ROAD SEGMENTATION, AOI SELECTION



Spatial aggregation

Standard units for risk analysis

Site-specific action

METHODS-ROAD SEGMENTATION AND AOI DELINEATION

- **Knowledge-driven method**:

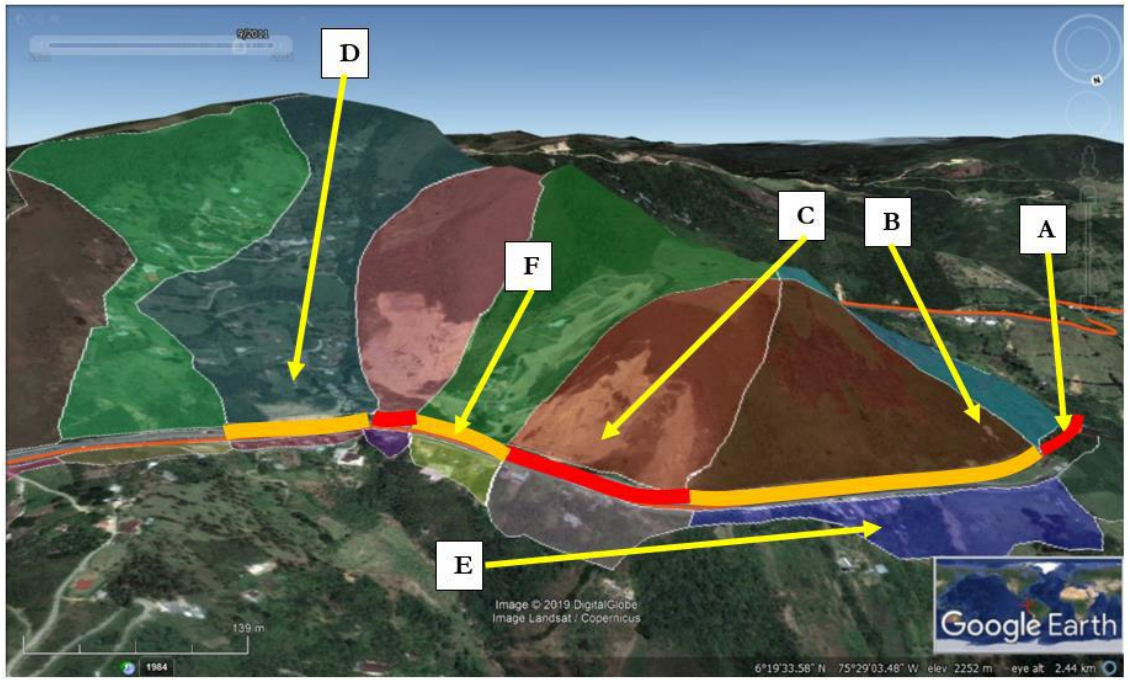
  -Field-based/Manual method

- **Semi-automatic methods**:

  -Watershed delineation

  -Geomorphological Slope Unit (SU)

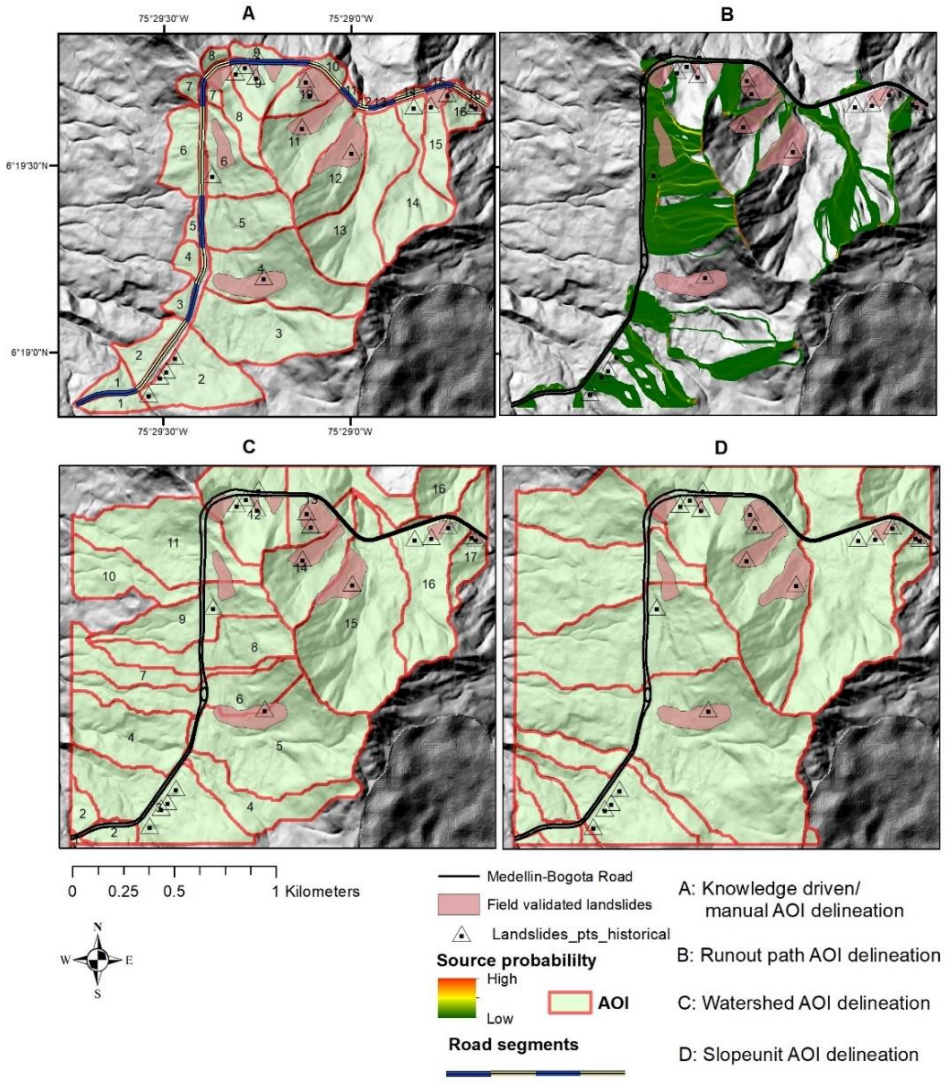
  -Runout modeling



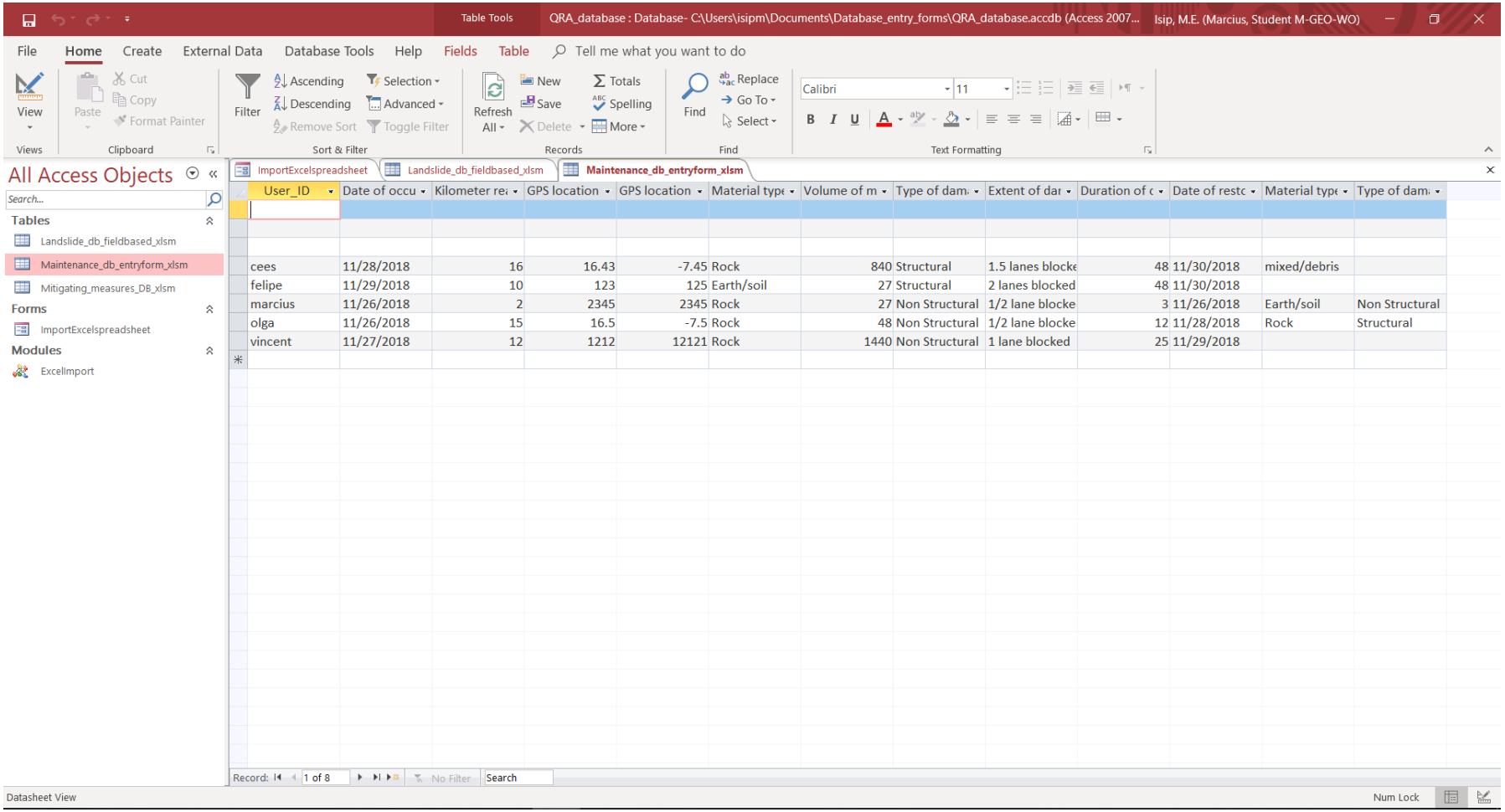
- AOI=immediate sloping areas above or below the road segment that may affect how the risk is analyzed

ROAD SEGMENTATION AND AOI DELINEATION (RESULTS)

- Manual method works well = field-based approach
- Watershed and SU methods could produce replicable results of the field-based AOI's
- Runout modified = potential landslide sources (ridges, steep cut-slopes)

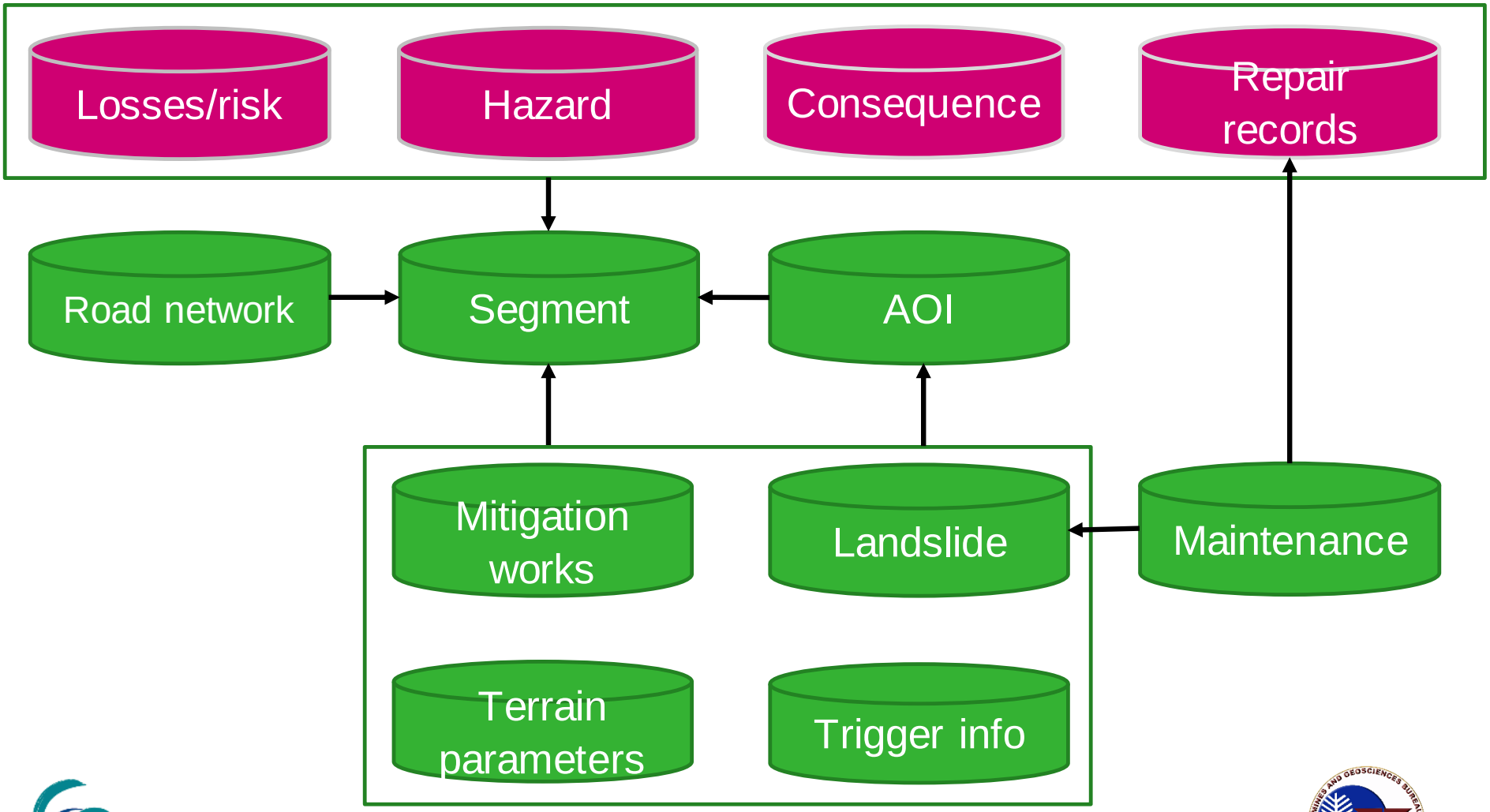


METHODS-DATABASE STRUCTURING

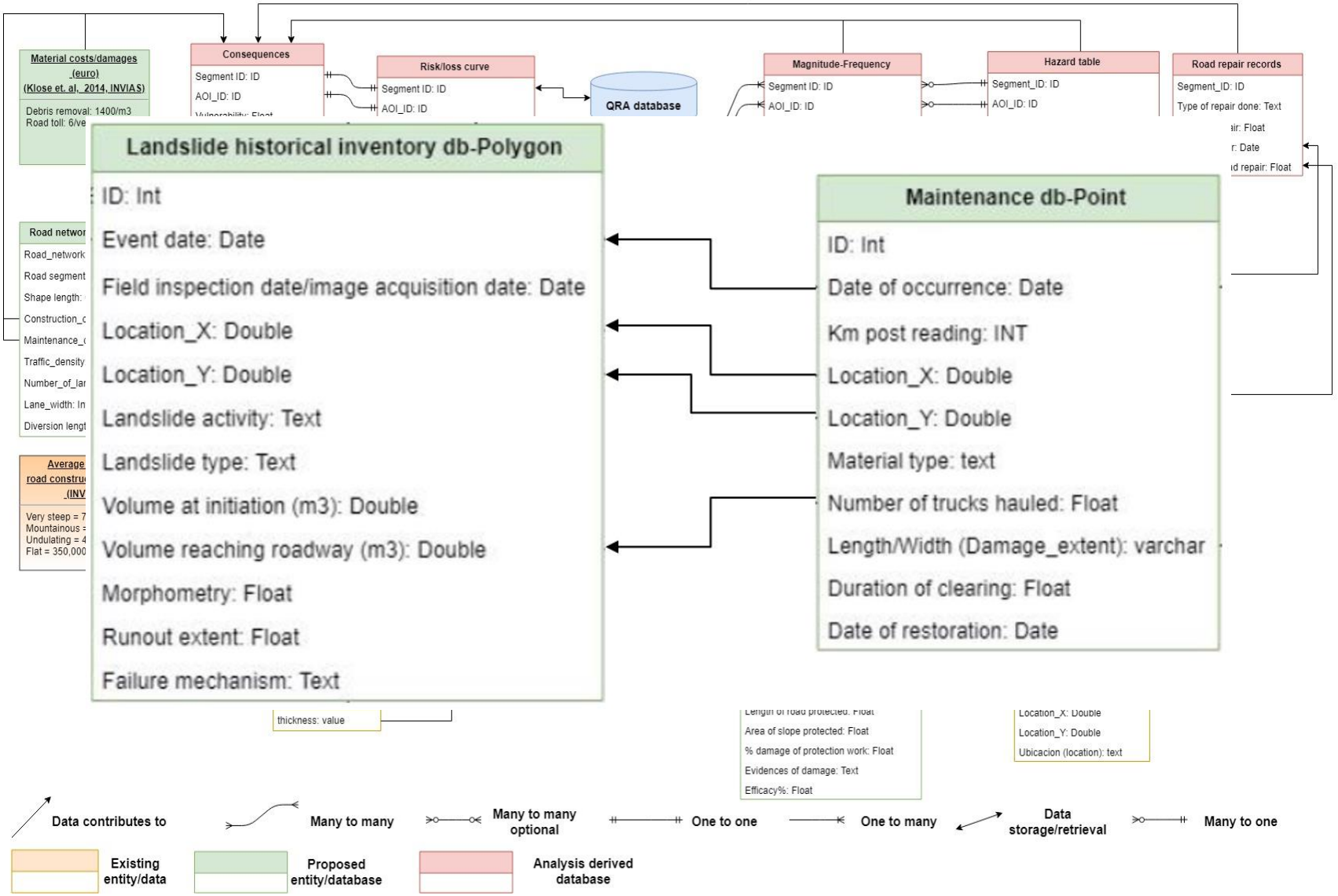


User_ID	Date of occu	Kilometer rea	GPS location	GPS location	Material type	Volume of m	Type of dam	Extent of dar	Duration of c	Date of resto	Material type	Type of dam
cees	11/28/2018	16	16.43	-7.45	Rock	840	Structural	1.5 lanes blocke	48	11/30/2018	mixed/debris	
felipe	11/29/2018	10	123	125	Earth/soil	27	Structural	2 lanes blocked	48	11/30/2018		
marcius	11/26/2018	2	2345	2345	Rock	27	Non Structural	1/2 lane blocke	3	11/26/2018	Earth/soil	Non Structural
olga	11/26/2018	15	16.5	-7.5	Rock	48	Non Structural	1/2 lane blocke	12	11/28/2018	Rock	Structural
vincent	11/27/2018	12	1212	12121	Rock	1440	Non Structural	1 lane blocked	25	11/29/2018		

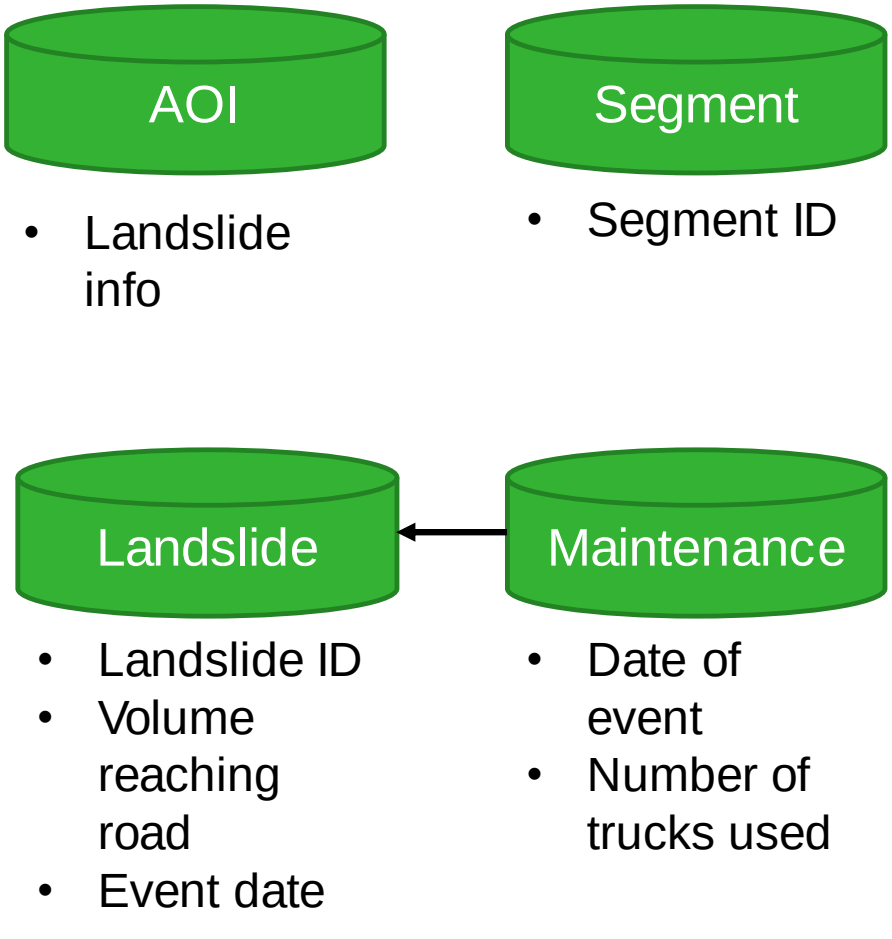
FINAL DATABASE STRUCTURE-OVERALL



FINAL DATABASE STRUCTURE-OVERALL



ATTRIBUTES FOR HAZARD ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)



- Landslide info

- Segment ID

- Landslide ID
- Volume reaching road
- Event date

- Date of event
- Number of trucks used

Segment ID	Event date (year of occurrence)	Volume (m^3)
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
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15	1991	4

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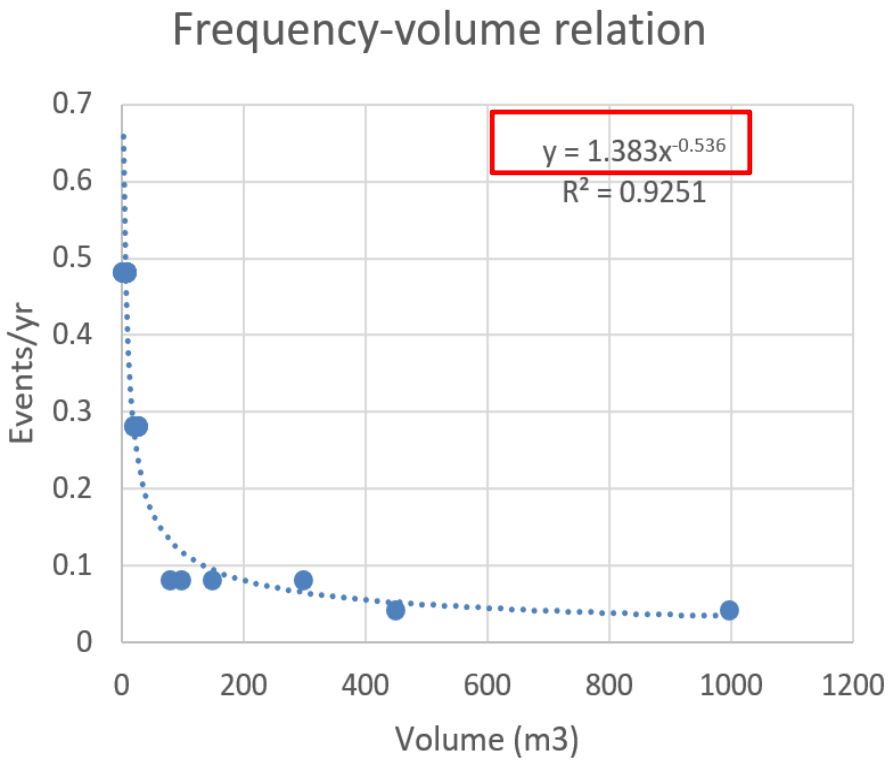
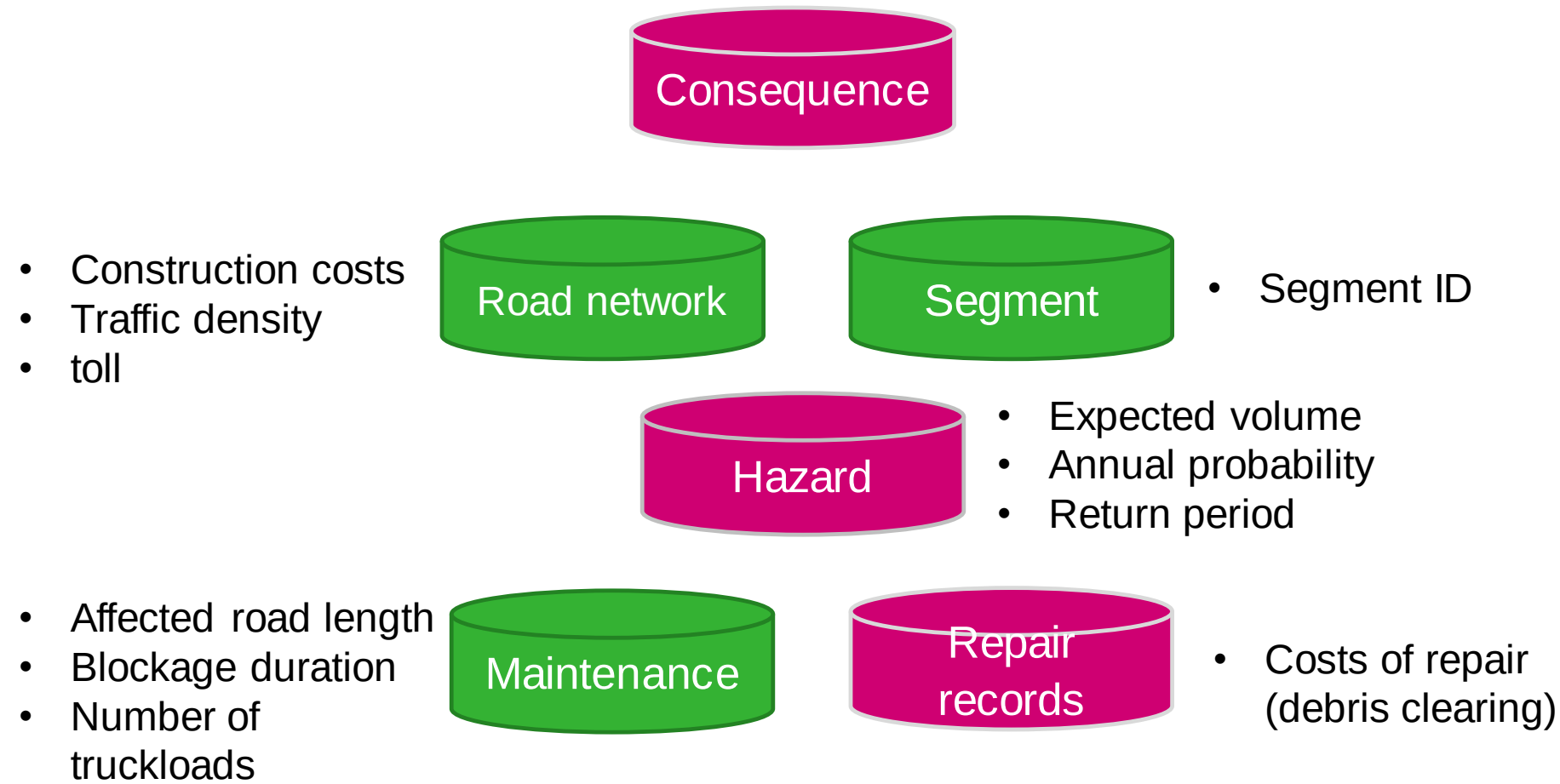


Hazard

- Annual probability of occurrence
- Return period
- Volume class

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

ATTRIBUTES FOR CONSEQUENCE ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)



ATTRIBUTES FOR RISK ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)

Consequence

*Costs = V * Clearing cost*

*Costs = (V * Clearing cost) + (Affected road length * Construction cost)*

*Costs = (V * Clearing cost) + (# of days * Traffic density * Toll per vehicle)*

*Costs = (V * Clearing cost) + (# of days * Traffic density * Toll per vehicle) + (Affected length * Construction cost)*

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ATTRIBUTES FOR RISK ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)

- Step 1: Compile segment attributes, construction costs, traffic density, toll (segment and road network databases)
- Step 2: Compile blockage duration, affected road length, and clearing costs (maintenance/repair records)
- Step 3: Compile annual probability, RP, volume classes (hazard database)

Segment ID	Total Segment length (m)	Constr cost (E	Clearing costs (euro per m^3)	1400	Return Period	Blockage duration (days)[2]
			Toll payment (euro per vehicle)	6		
			Construction (Euro per kilometer)	500,000		
4	320	160000	Historical Average Daily Traffic Medellin-Bogota road, medellin-guarne section (all vehicles)	25000	1	0.1
					2.484150021	0.2
					8.534494835	0.5
					29.32093532	1
					100.7344037	3
					346.0810501	7

ATTRIBUTES FOR RISK ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)

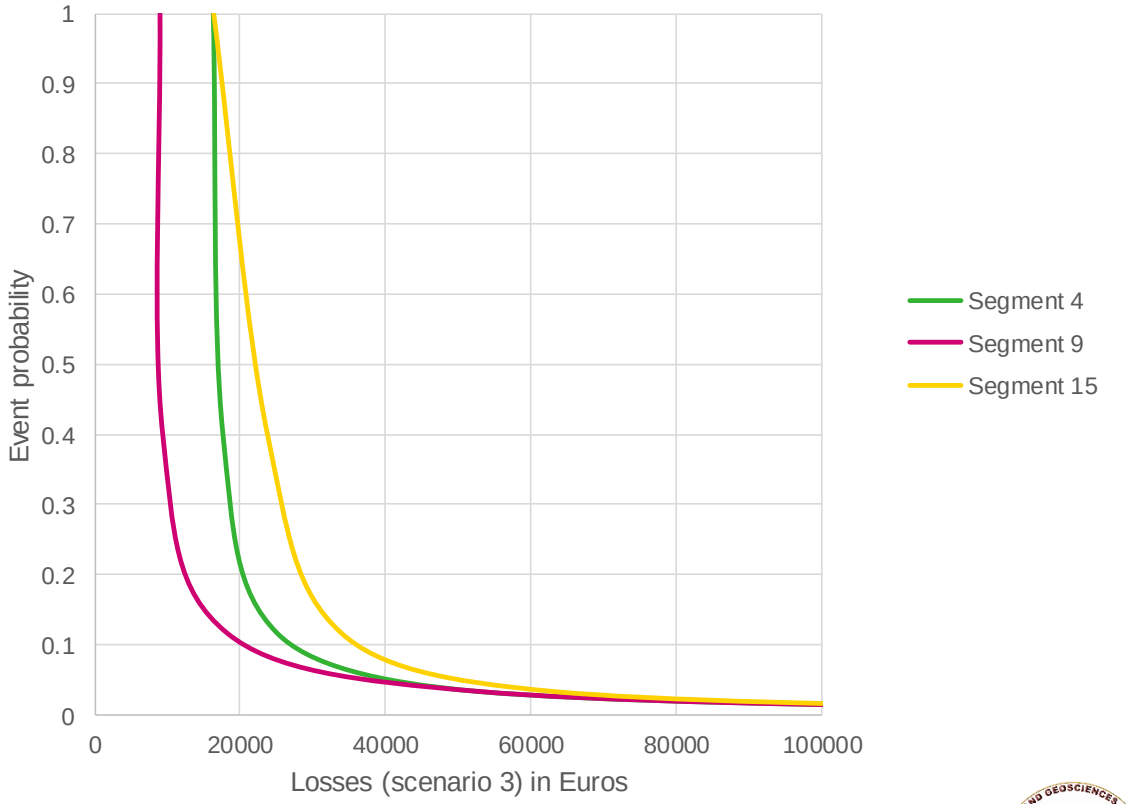
- Step 4: Compute costs per scenario and volume class (Consequence database)
- Step 5: Compute losses per corresponding scenario and annual probability ($R = Hm * Pm * Pt * Costs$)

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

Hm = probability of event occurrence per given magnitude/volume class
Pm = probability that a landslide with magnitude 'm' reaches the road
Pt = Temporal probability of the road to be exposed to landslides
Costs = cost per consequence scenario in Euros

ATTRIBUTES FOR RISK ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)

- Step 6: Repeat process for other segments
- Step 7: Plot risk curves per segment and scenario



CONCLUSIONS

- Database attributes proposed → QRA compatible, reproducible
- Monetary loss outputs → inputs for cost-benefit-analysis and site-specific prioritization

Study contributes to risk assessment through:

- Outlining several methods for homogenous road segmentation (facilitate QRA)
- Providing blueprint for future QRA by road infra managers, reproducible to other roads (Standard structure/guide for data collection and storage)

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RESEARCH OBJECTIVES-SPECIFIC OBJ.

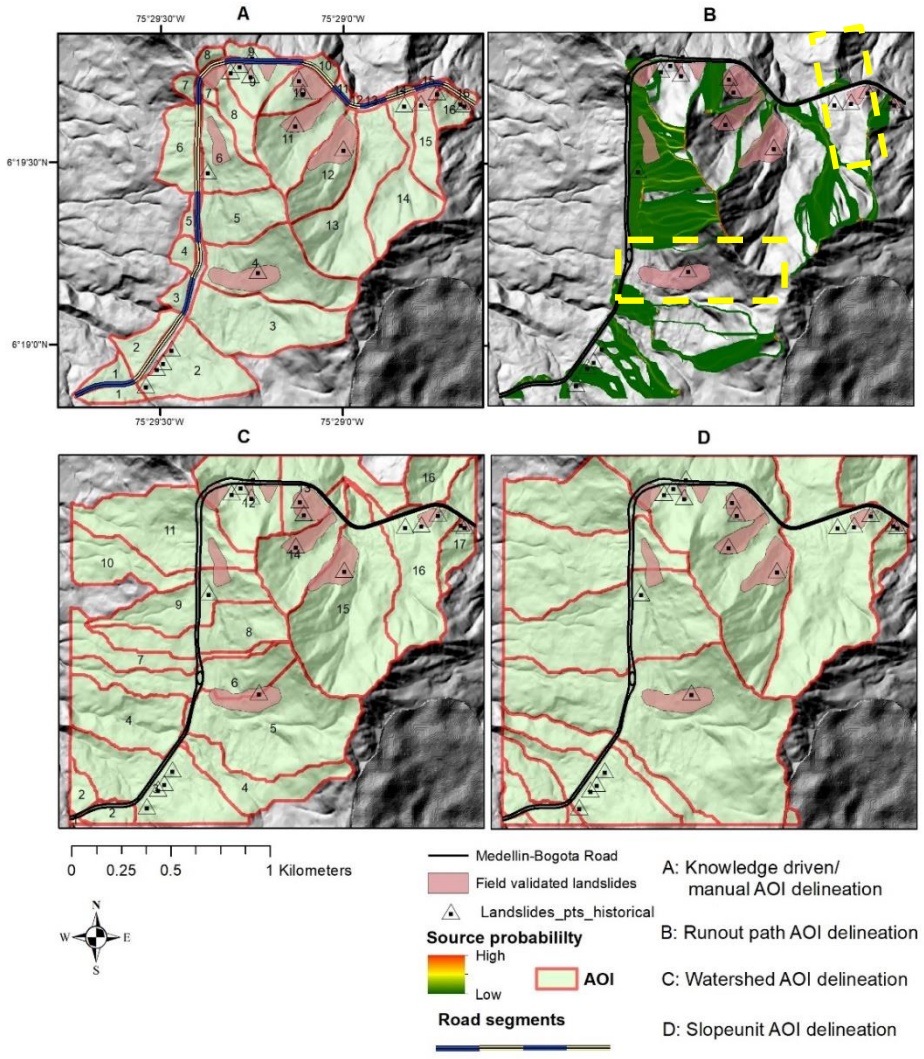
General objective: *Develop structure* of road asset management database allowing landslide QRA based on *road segments* and their *areas of influence (AOI)*.

1. Examine the current practices of road management and maintenance in Colombia and evaluate available datasets for QRA
2. Analyze the advantages and disadvantages of different road segmentation methods to create AOI's and road segments.
3. Design and structure a database integrating information that will allow future QRA
4. Apply risk analysis in selected road segments using test data coming from proposed database structure

ROAD SEGMENTATION AND AOI DELINEATION (RESULTS)

Drawbacks observed:

- Manual method-requires good judgment and geotechnical background in order to reproduce results in other sites
- Runout approach-problems of non-initiation and continuity
- Watershed and SU-requires field calibration to have comparable results



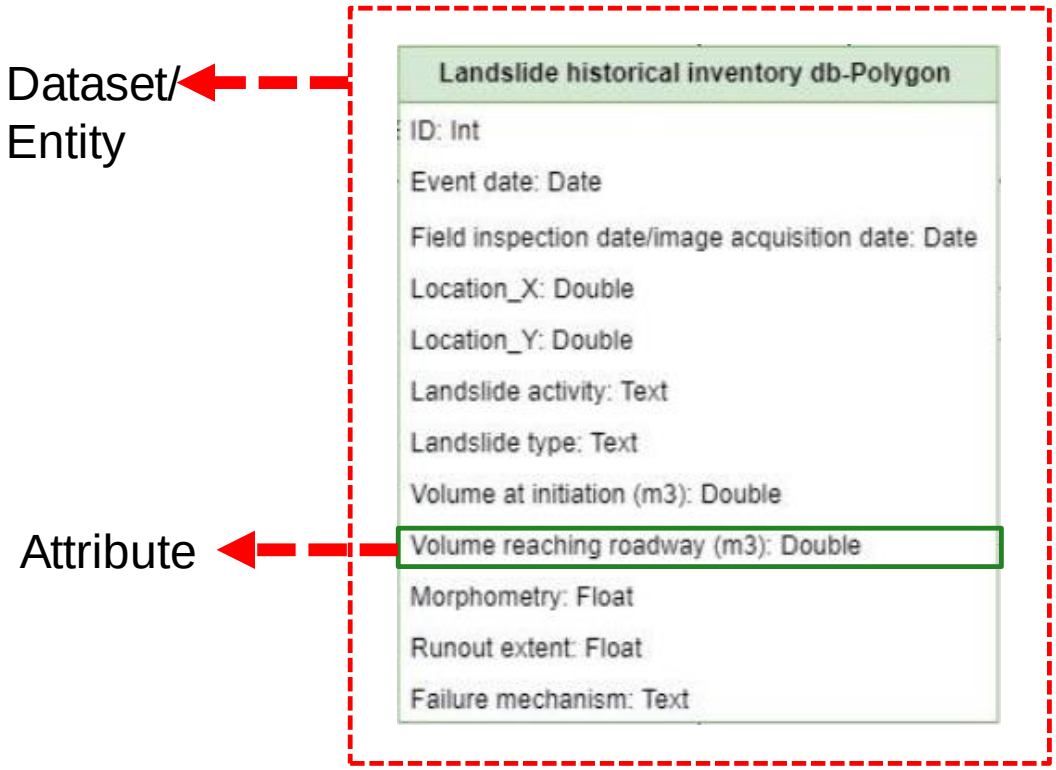
RECOMMENDATIONS FOR IMPLEMENTATION

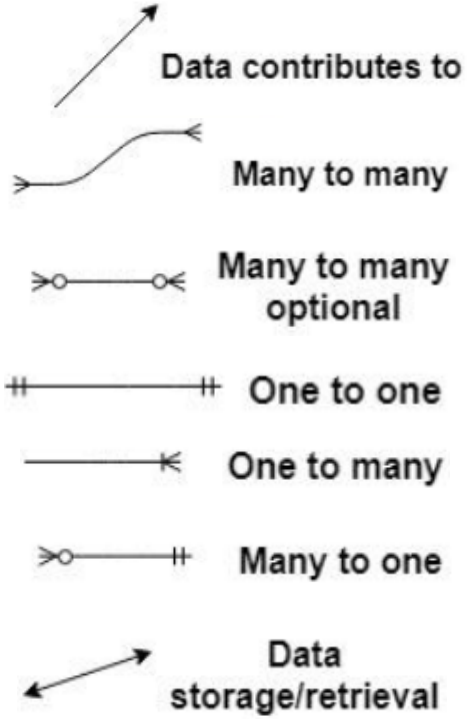
- Systematic production of multi-temporal landslide inventories (OBIA, satellite, manual delineation)
- Improvement of landslide susceptibility maps (inclusion of runout susceptibility, validation, trigger correlation)
- Formulate agreement with DPWH or LGU's for data gathering and storage
- Capacity building for data collectors and analysts
- Designate test road sites for execution of risk analysis, assessment and CBA

ATTRIBUTES FOR RISK ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)

- Step 1: Compile segment attributes, construction costs, traffic density, toll (segment and road network databases)
- Step 2: Compile blockage duration, affected road length, and clearing costs (maintenance/repair records)
- Step 3: Compile annual probability, RP, volume classes (Hazard database)
- Step 4: Compute costs per scenario and volume class (Consequence database)
- Step 5: Compute losses per corresponding scenario and annual probability ($R = Hm * Pm * Pt * Costs$)
  - Hm = probability of event occurrence per given magnitude/volume class
  - Pm = probability that a landslide with magnitude 'm' reaches the road
  - Pt = Temporal probability of the road to be exposed to landslides
  - Costs = cost per consequence scenario in Euros

UNDERSTANDING THE DATABASE STRUCTURE (ENTITY RELATION DIAGRAM)

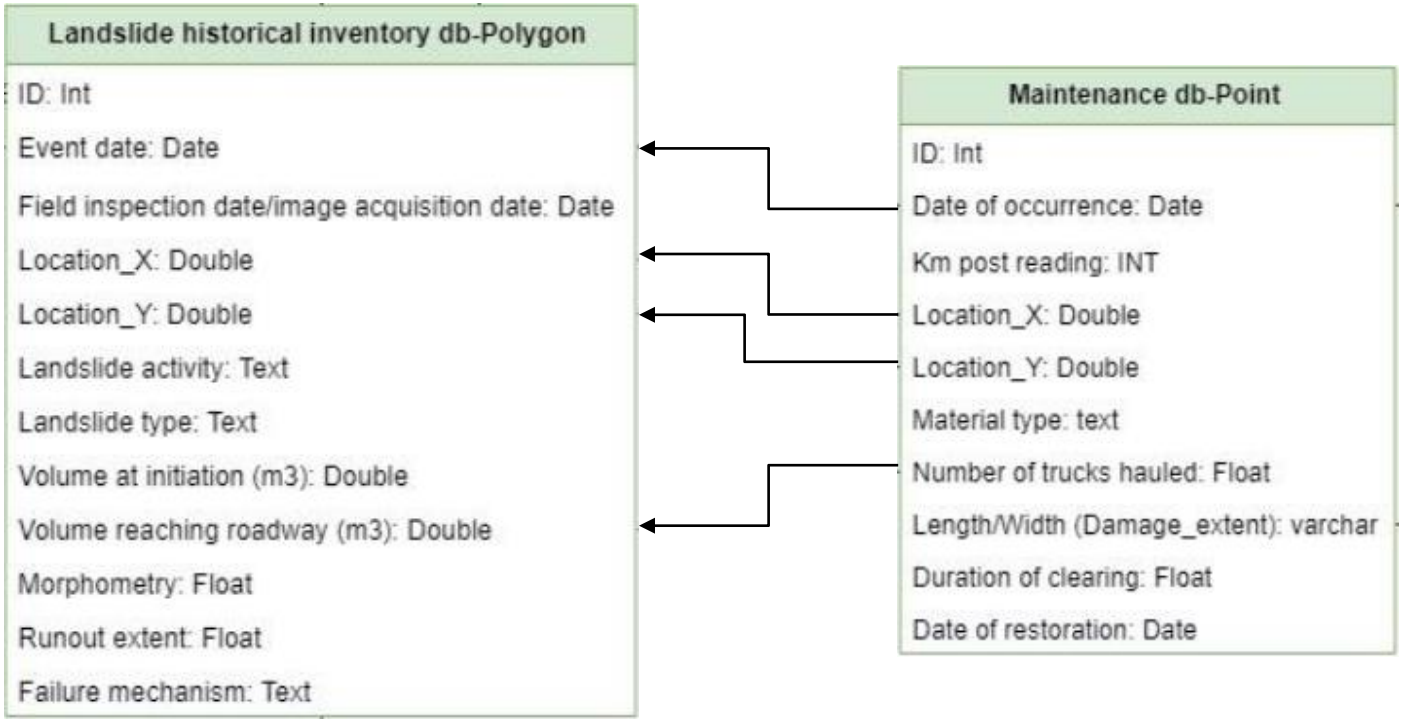




UNDERSTANDING THE DATABASE STRUCTURE (ENTITY RELATION DIAGRAM)

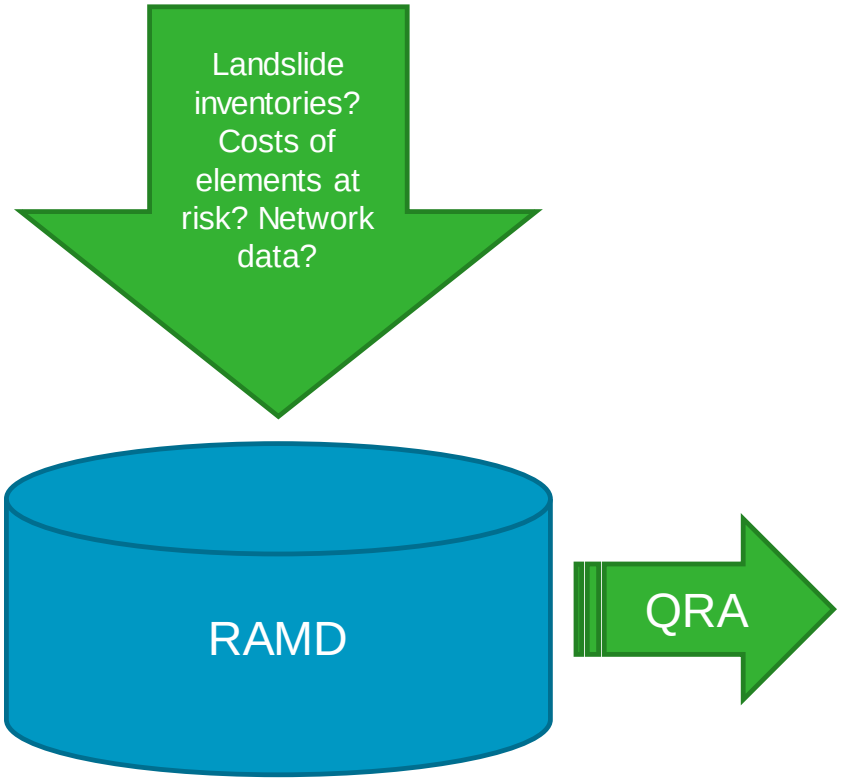
Geologist/Geotechnical engineers

Maintenance personnel



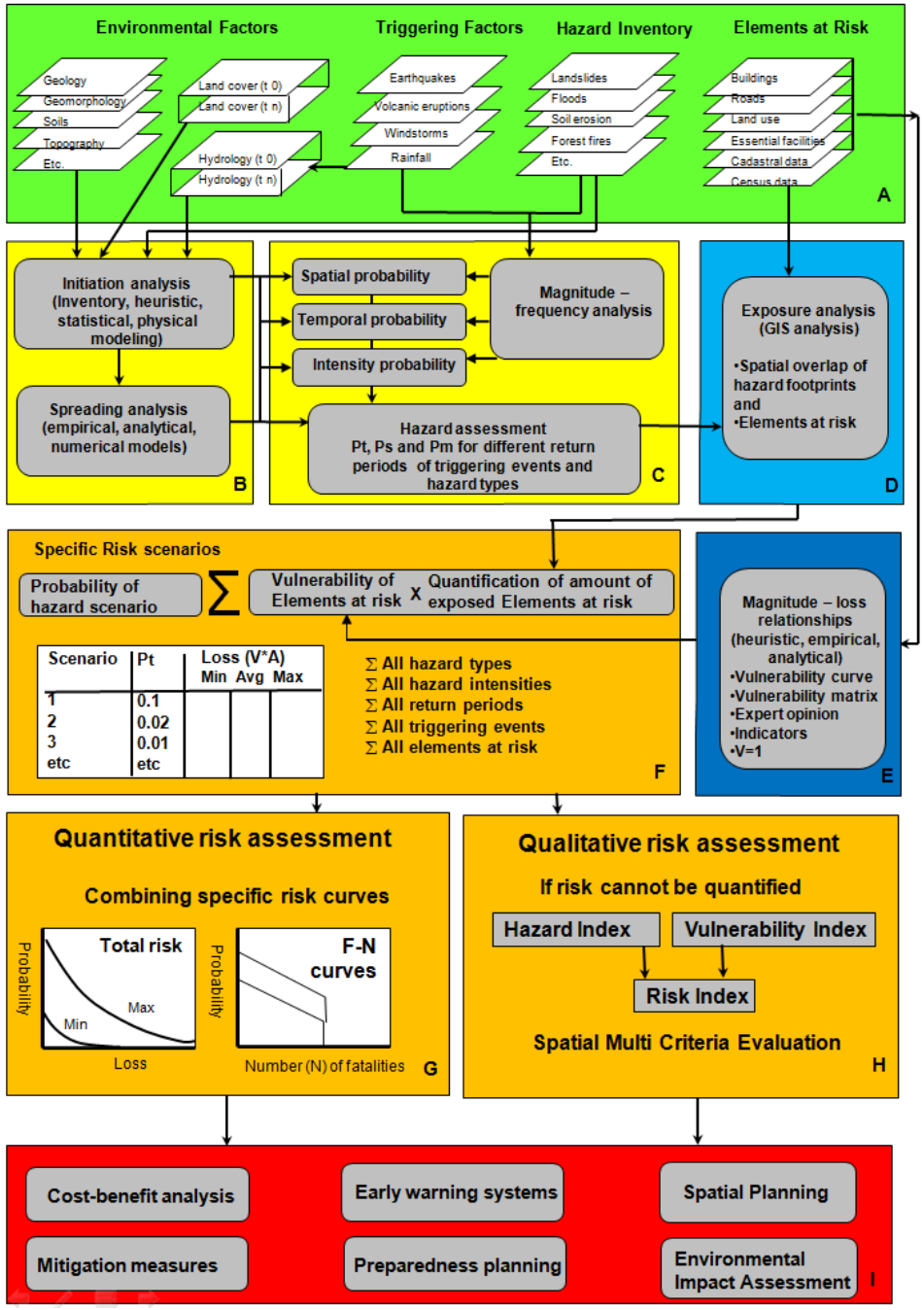
RESEARCH OBJECTIVES AND QUESTIONS

- General objective:



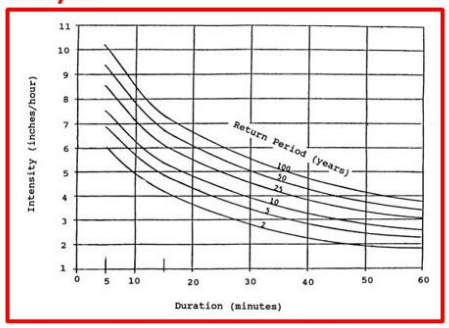
RISK ASSESSMENT

- A: Input data
- B: Susceptibility assessment
- C: Hazard assessment
- D: Exposure analysis
- E: Vulnerability assessment
- F: Risk assessment
- G: Quantitative risk
  - •Economic risk
    - •Direct
    - •Indirect
  - •Population risk
    - •Societal risk
    - •Individual risk
- H: Qualitative risk
- I: Risk reduction measures

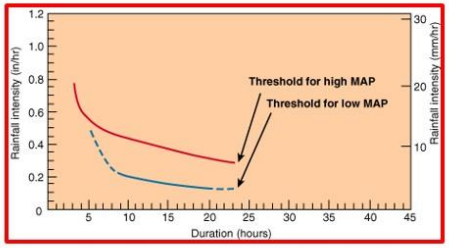


Landslide susceptibility & hazard

Rainfall magnitude/ Frequency analysis

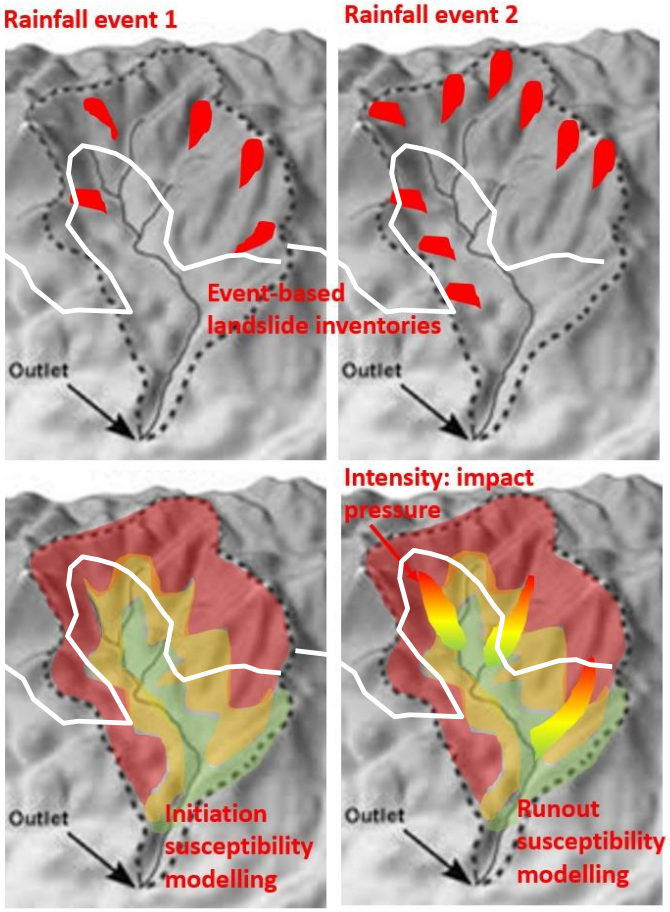


Rainfall thresholds for landslides



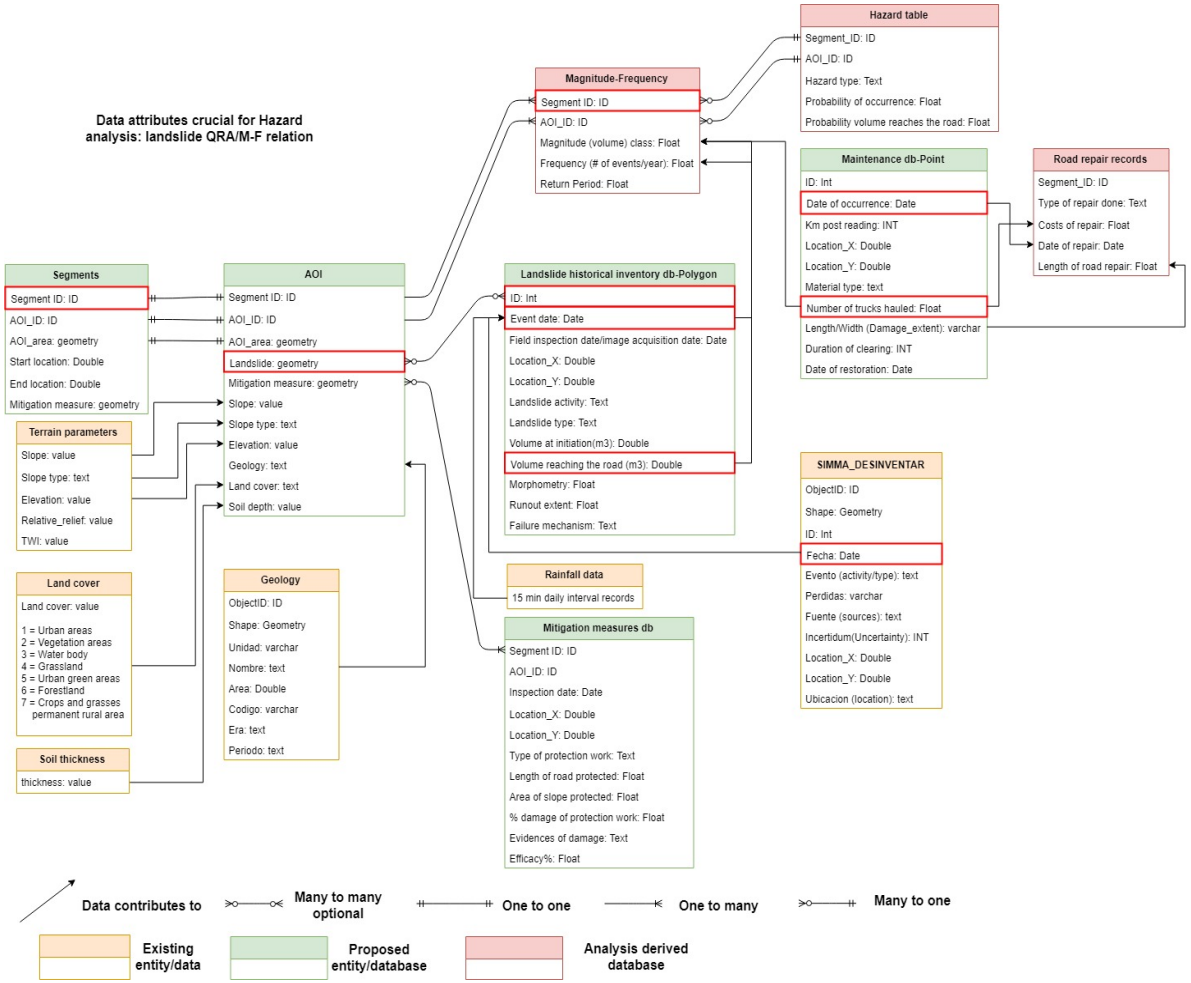
Hazard: spatial probability for different return periods

	Landslide density return period 1	Landslide density return period 2
High hazard		
Moderate hazard		
Low hazard		



- **Landslide susceptibility**: A subdivision in zones that have the same relative likelihood that landslides may occur in future.
  - Where?
  - How much?
- **Landslide hazard**: a subdivision in zones for which it is indicated how often and how much landslides are expected in future.
  - Where?
  - How much? Density or intensity (e.g. debris flow height)
  - How often? Magnitude-frequency
  - How far? Runout.

ATTRIBUTES FOR HAZARD ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)



Segment ID	Event date (year of occurrence)	Volume (m^3)
15	2016	1000
8	1996	450
14	2013	300
6	2001	150
10	2000	100
7	1996	80
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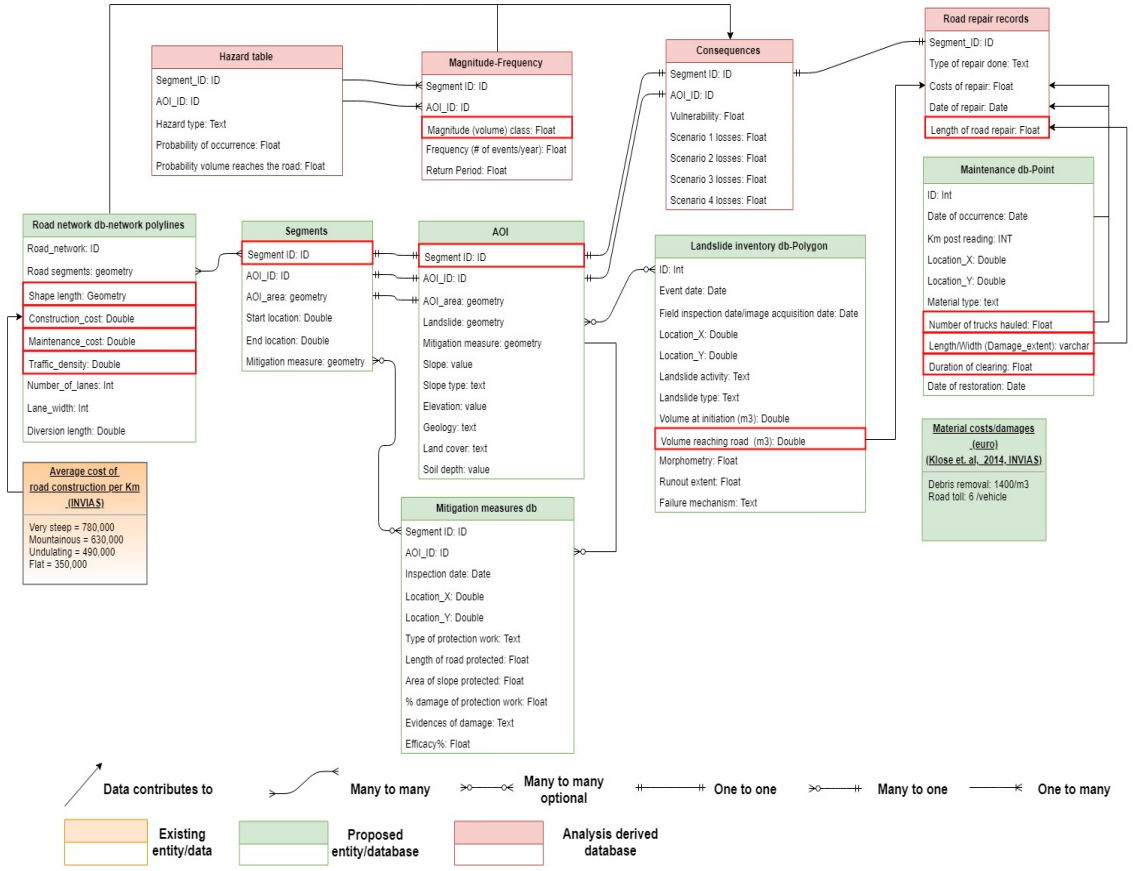
ATTRIBUTES FOR CONSEQUENCE ANALYSIS (WITH PREVIOUS LANDSLIDE ACTIVITY)



Scenario

1-Partial blockage without structural failure

2-Partial blockage with structural failure

3-Complete blockage without structural failure

4-Complete blockage with structural failure

Consequence formula

$Costs = Vmat * Clearing\ cost$

$Costs = (Vmat * Clearing\ cost) + (Damaged\ road\ length * construction\ cost)$

$Costs = (Vmat * Clearing\ cost) + (\#\ of\ days * ADT * Toll\ fee\ per\ vehicle)$

$Costs = (Vmat * Clearing\ cost) + (\#of\ days * ADT * Toll\ fee\ per\ vehicle) + (Damaged\ road\ length * construction\ cost)$

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]

LOSSES INCURRED BY ROAD USERS

- $IR = (Dl * ADT * FC * BLT)/Mi$

IR → indirect risk/losses incurred by road users

Dl = *Deviation length* (km), stored in road network database

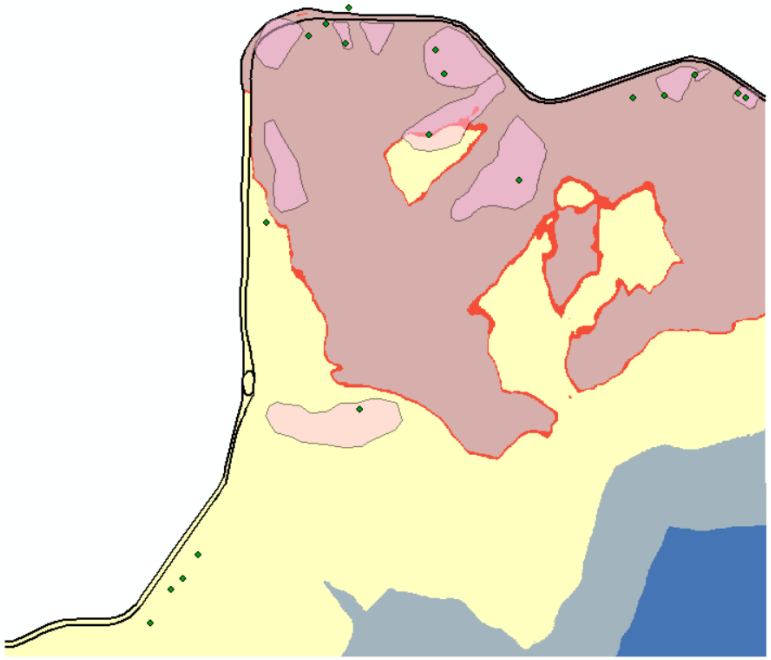
ADT = *Average Daily Traffic*, number of vehicles passing through road per day → **25000** vehicles per 24hrs

FC = cost of fuel (Euros/Liter)

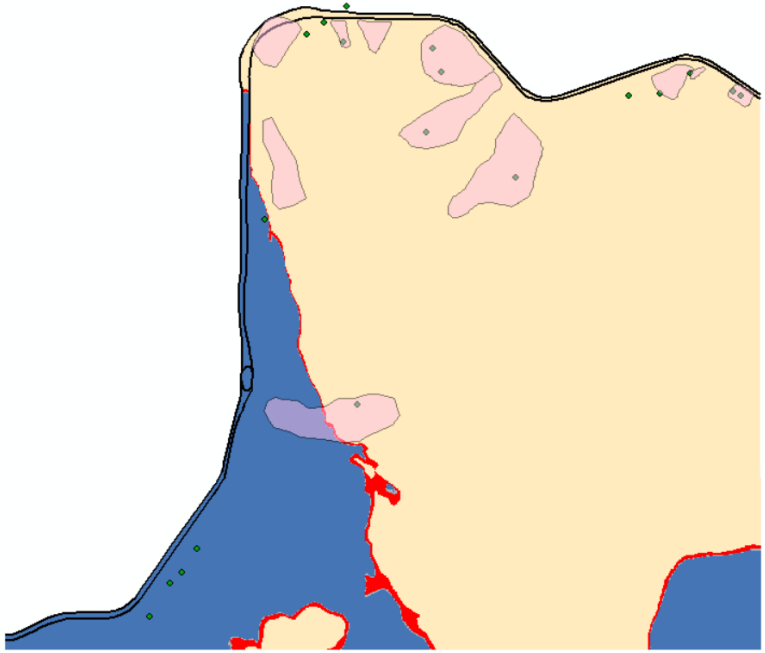
BLT = *total blockage time*

Mi = average vehicle mileage (consumption rate of fuel) in Km/L

EXPERIMENTAL PLANE FITTING METHOD (RESULTS)



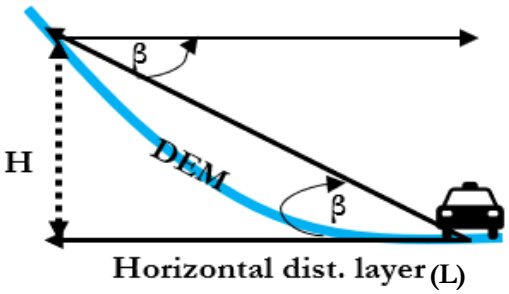
-584.855957 - -314.3639285
-314.3639284 - -159.797055
-159.7970549 - 0
0 - 5
5.000000001 - 173.1162109

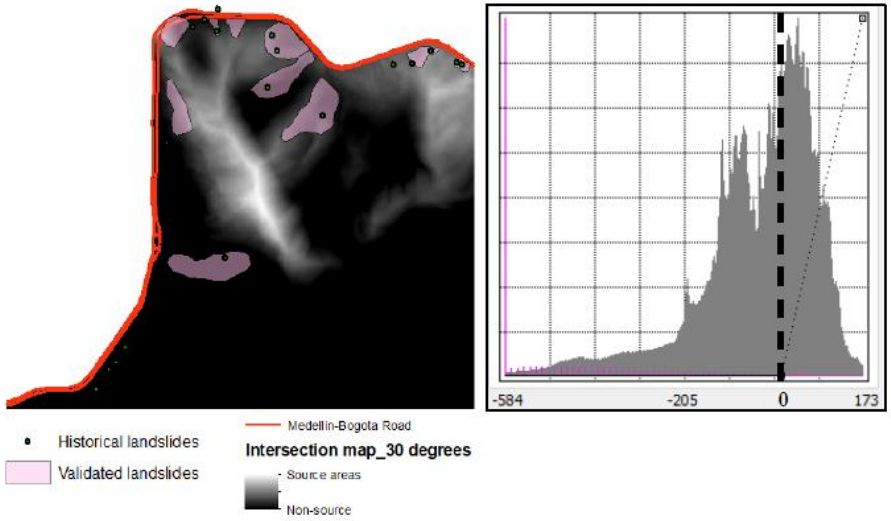


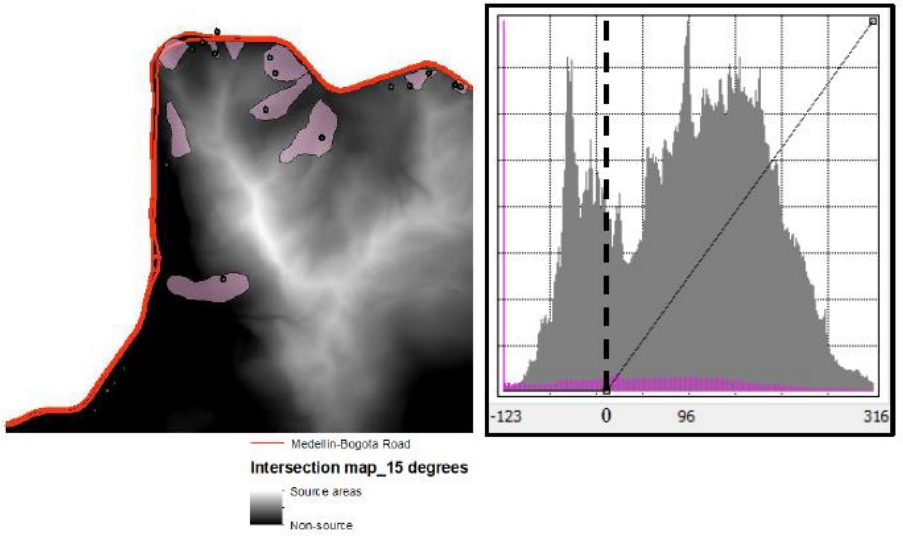
-123.0234375 - -0.67650505
-0.676505055 - 0
0 - 5
5.000000001 - 195.7678653
195.7678654 - 316.3916016

EXPERIMENTAL PLANE FITTING METHOD (RESULTS)

- Cannot represent AOI, fails to differentiate adjacent units
- Good for detecting sources but prone to overestimation
- Overestimation is due to assumption of higher elevation=more potential energy







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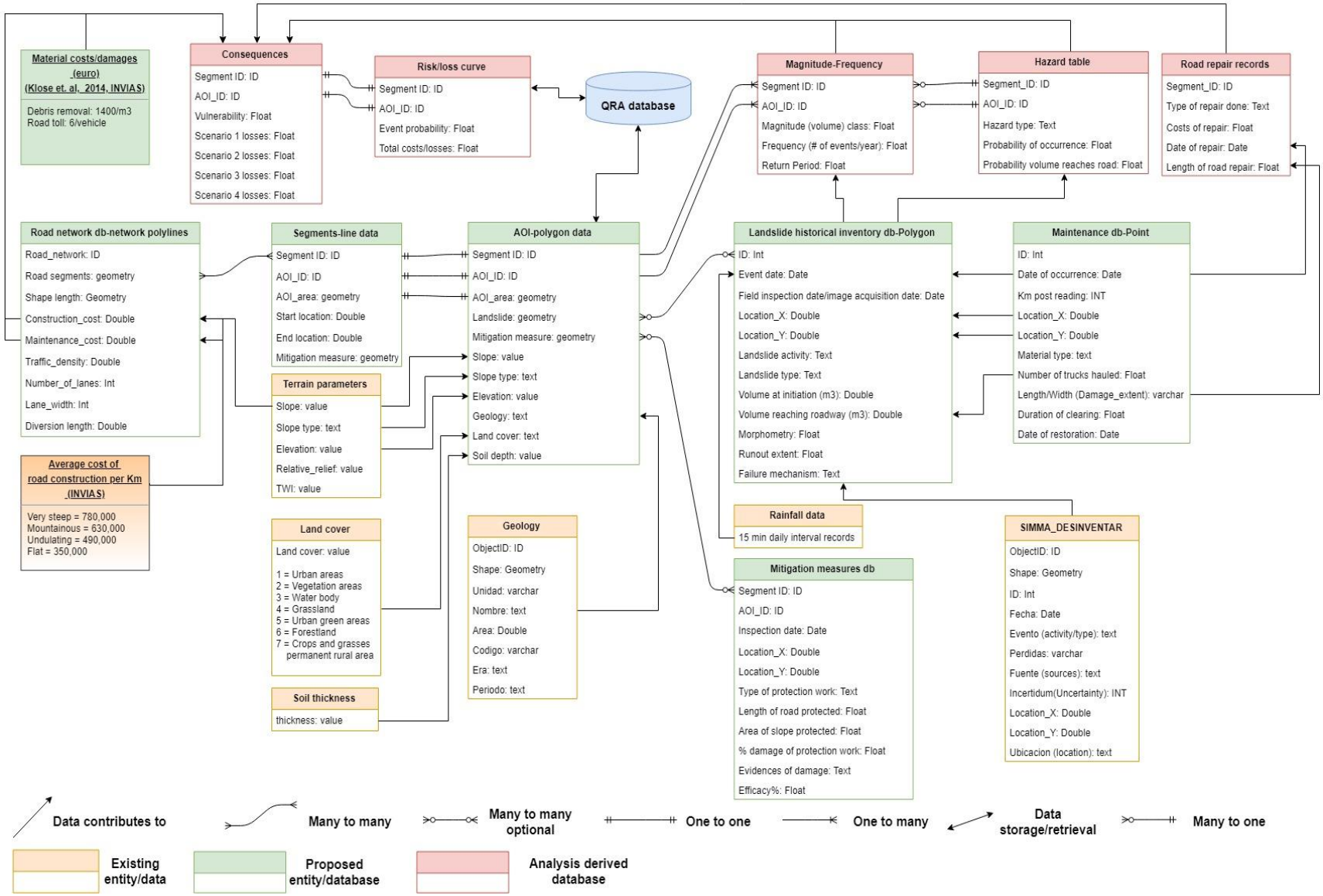
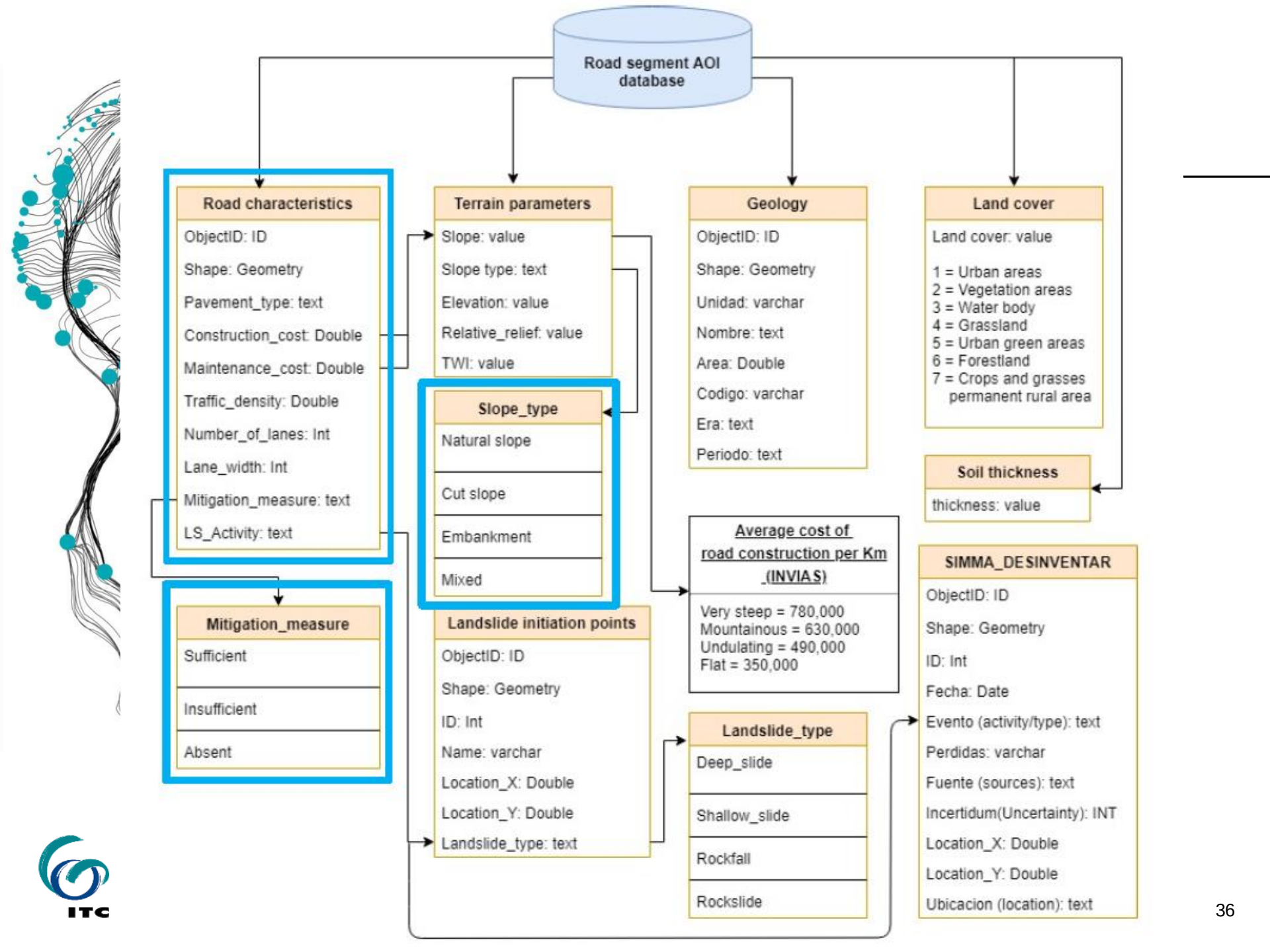



Road segment AOI database
Road characteristics
ObjectID: ID
Shape: Geometry
Pavement_type: text
Construction_cost: Double
Maintenance_cost: Double
Traffic_density: Double
Number_of_lanes: Int
Lane_width: Int
Mitigation_measure: text
LS_Activity: text
Terrain parameters
Slope: value
Slope type: text
Elevation: value
Relative_relief: value
TWI: value
Geology
ObjectID: ID
Shape: Geometry
Unidad: varchar
Nombre: text
Area: Double
Codigo: varchar
Era: text
Periodo: text
Land cover
Land cover: value
1 = Urban areas
2 = Vegetation areas
3 = Water body
4 = Grassland
5 = Urban green areas
6 = Forestland
7 = Crops and grasses permanent rural area
Soil thickness
thickness: value
Slope_type
Natural slope
Cut slope
Embankment
Mixed
Mitigation_measure
Sufficient
Insufficient
Absent
Landslide initiation points
ObjectID: ID
Shape: Geometry
ID: Int
Name: varchar
Location_X: Double
Location_Y: Double
Landslide_type: text
Average cost of road construction per Km (INVIAS)
Very steep = 780,000
Mountainous = 630,000
Undulating = 490,000
Flat = 350,000
Landslide_type
Deep_slide
Shallow_slide
Rockfall
Rockslide
SIMMA_DESINVENTAR
ObjectID: ID
Shape: Geometry
ID: Int
Fecha: Date
Evento (activity/type): text
Perdidas: varchar
Fuente (sources): text
Incertidum(Uncertainty): INT
Location_X: Double
Location_Y: Double
Ubicacion (location): text

OBTAINING PROBABILITY OF CONSEQUENCE SCENARIOS

- For scenario's 1 and 3: Volume probability is used especially for cut-slope segments, the volume of landslide is assumed to reach the road
- For scenario's 2 and 4: Volume probability cannot be used, probability of structural damage is difficult to determine.
- Downslope AOI's can be monitored for movement periodically→ main source of structural damage for roadways

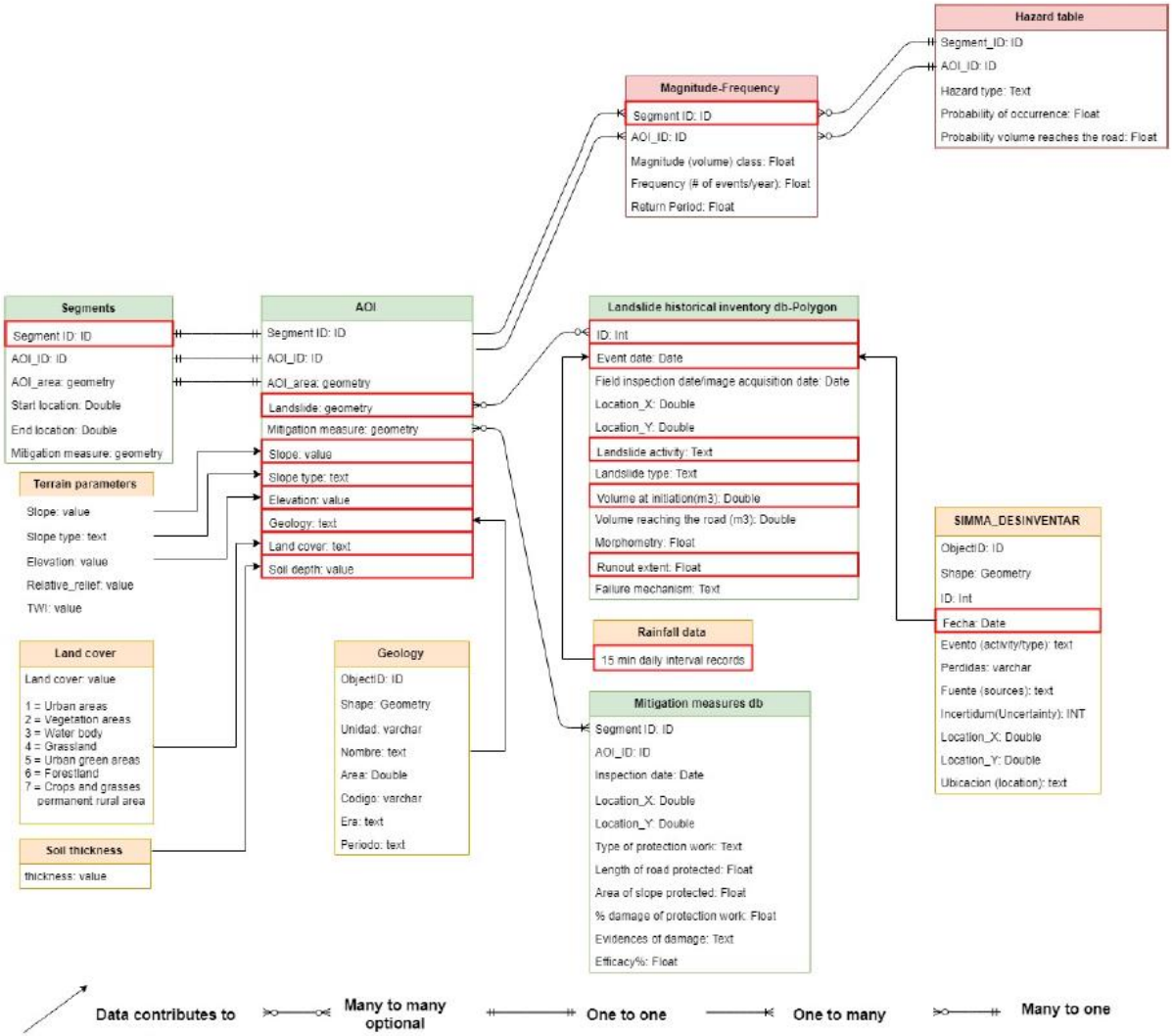
STUDY AREA JUSTIFICATION

- 1. Representative of major problems present in the entire road network: landslide types, downslope erosion, tunnels
- 2. Sufficient amount of data and areal coverage for runout assessment

ATTRIBUTES FOR HAZARD ANALYSIS (WITHOUT PREVIOUS LANDSLIDE ACTIVITY)

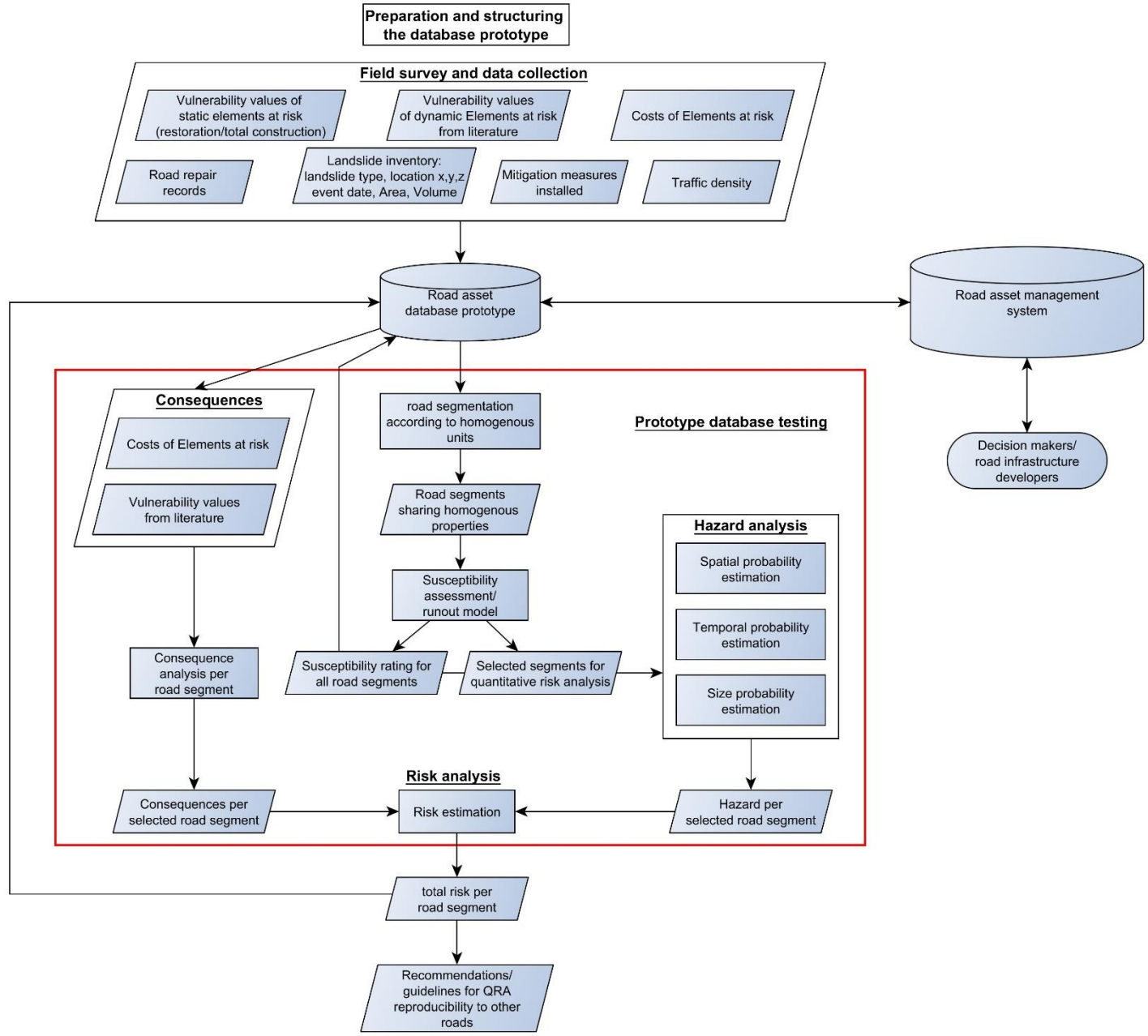
- Spatial datasets for susceptibility analysis
- Runout assessments, physically based models for magnitude probability
- Set thresholds for rainfall-landslide trigger relation → numerical models or empirical models (historical landslide number)

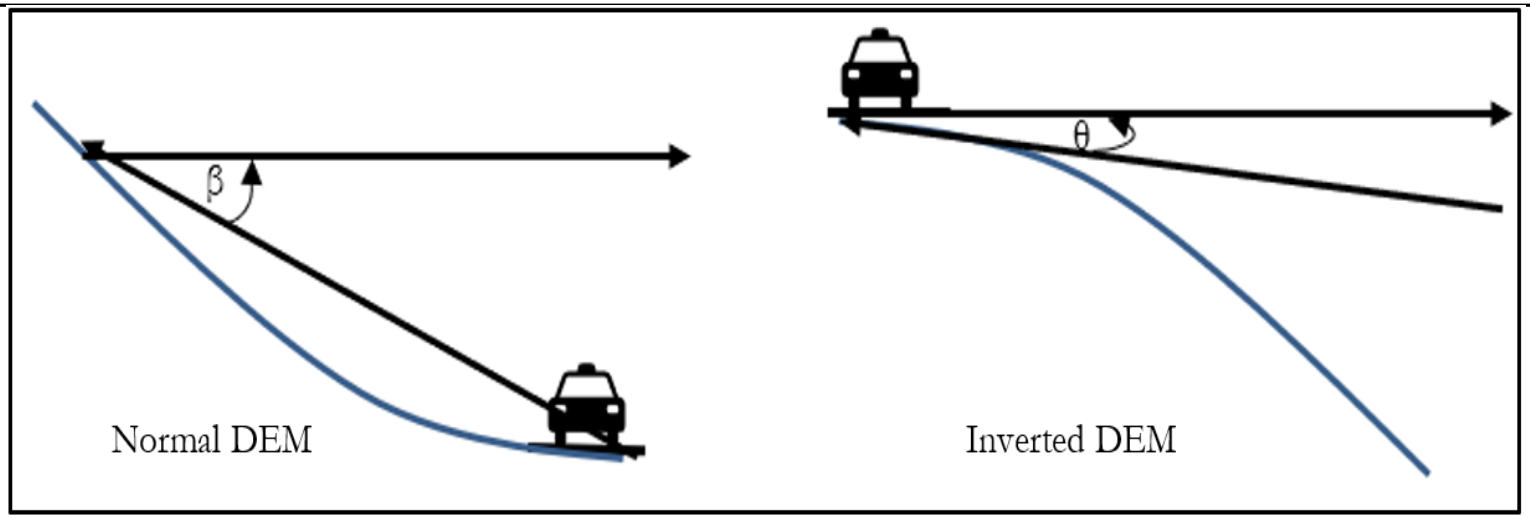
THRESHOLD BASED DB ATTRIBUTES SELECTED



VULNERABILITY

- Vulnerability is usually based on annual repair costs per segment
- It is still included in database structure but was not used in the demonstration
- Was not included because focus was identifying losses incurred and probability of having these losses
- Omitted, *for simplicity purposes,* also
- not relevant for quantifying losses for roadways, it is relevant for population risk or risk to vehicles
- Using repair costs to estimate vulnerability results to overestimation of vulnerability value for small volume landslides


Preparation and structuring the database prototype
Field survey and data collection
Vulnerability values of static elements at risk (restoration/total construction)
Vulnerability values of dynamic Elements at risk from literature
Costs of Elements at risk
Road repair records
Landslide inventory: landslide type, location x,y,z event date, Area, Volume
Mitigation measures installed
Traffic density
Road asset database prototype
Road asset management system
Decision makers/ road infrastructure developers
Prototype database testing
Consequences
Costs of Elements at risk
Vulnerability values from literature
road segmentation according to homogenous units
Road segments sharing homogenous properties
Susceptibility assessment/ runout model
Hazard analysis
Spatial probability estimation
Temporal probability estimation
Size probability estimation
Consequence analysis per road segment
Susceptibility rating for all road segments
Selected segments for quantitative risk analysis
Risk analysis
Consequences per selected road segment
Risk estimation
Hazard per selected road segment
total risk per road segment
Recommendations/ guidelines for QRA reproducibility to other roads


β
θ
Normal DEM
Inverted DEM

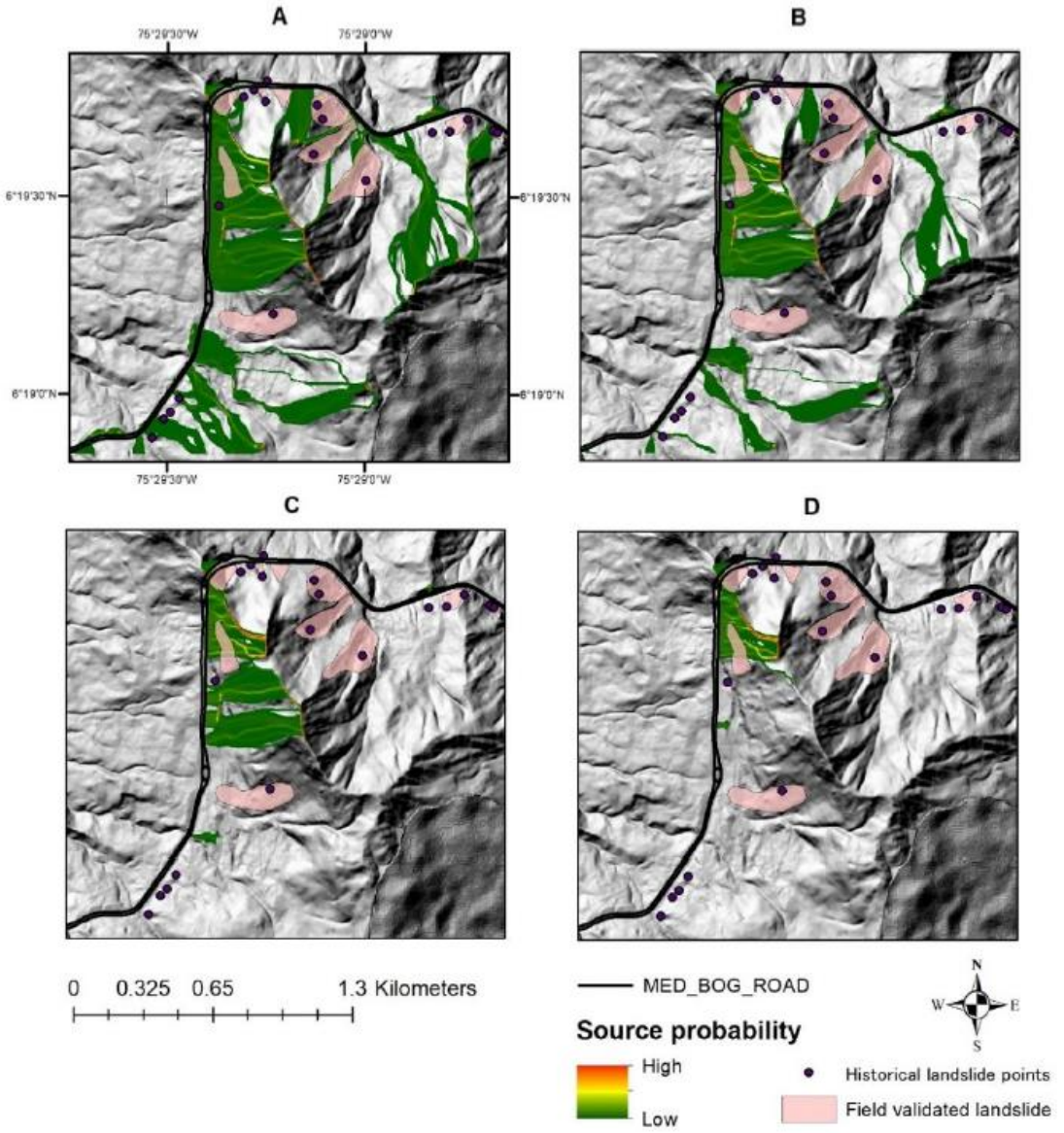
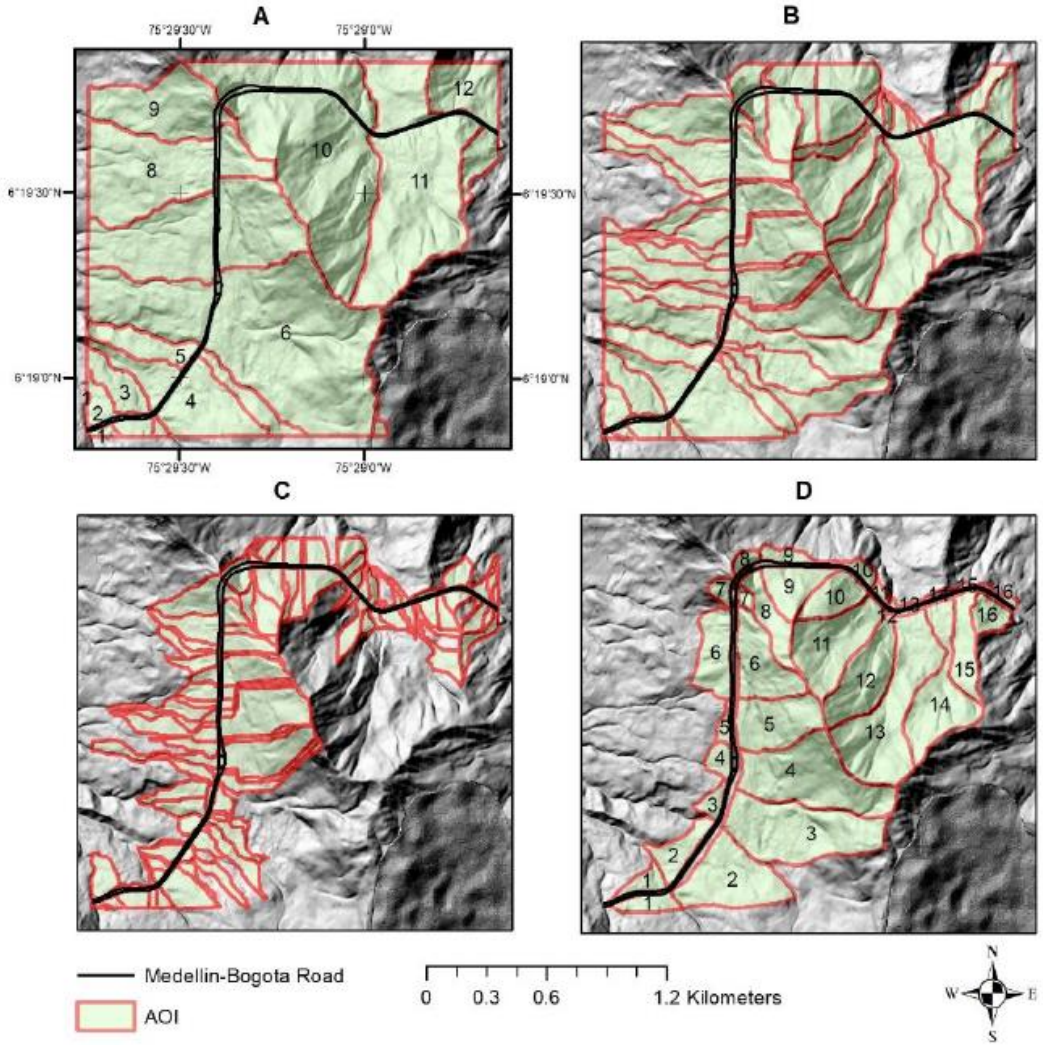
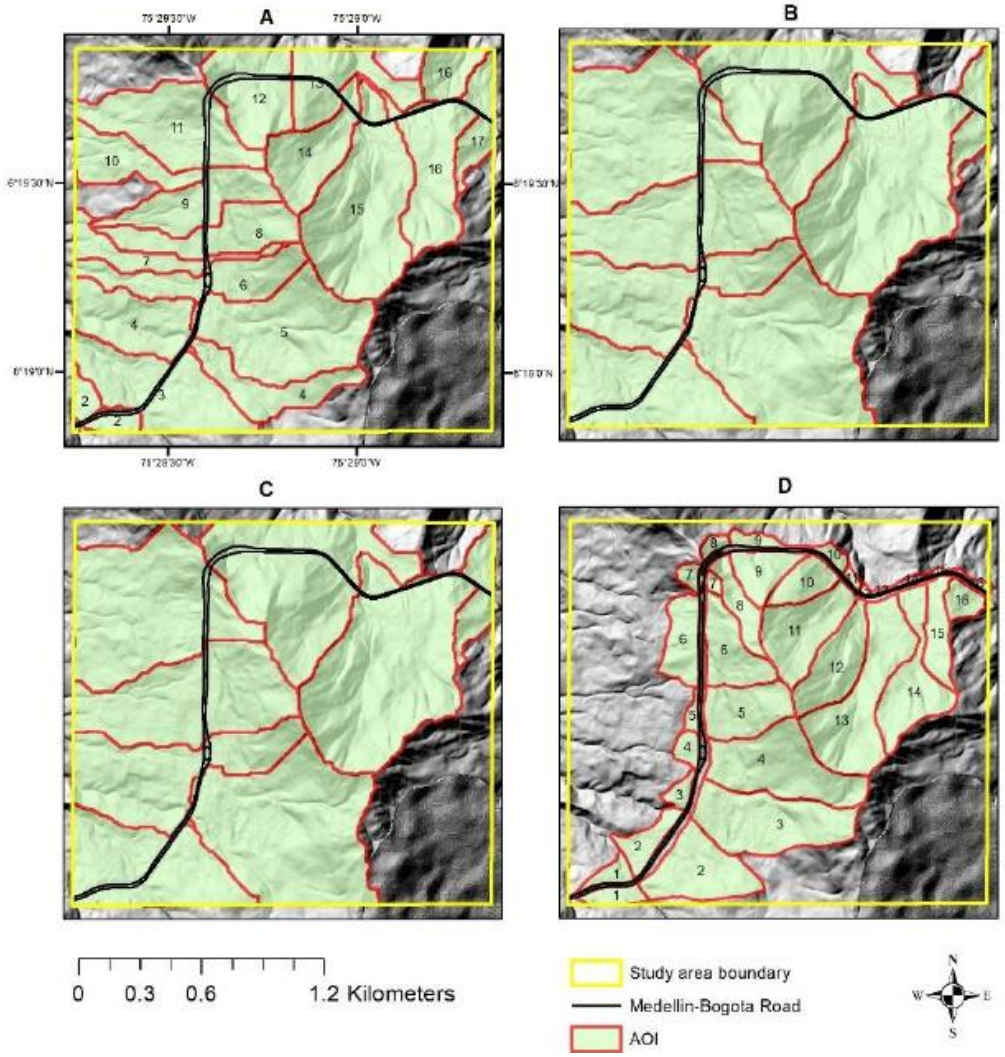


Figure 3.12: Compiled maps for the runout propagation resulting from variation of the travel angles.

SU MAPS


A
B
C
D
75°29'30"W
75°29'0"W
6°19'30"N
6°19'0"N
Medellin-Bogota Road
AOI
0 0.3 0.6 1.2 Kilometers
N
W
E
S

WATERSHED MAPS



FIELD PHOTOS


A


B

C


D


E

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CALCULATION TABLE

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

CALCULATION TABLE

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