

**INTEGRATION OF RADAR AND OPTICAL REMOTE
SENSING FOR LANDSLIDE INVESTIGATION – CASE
STUDY OF KOSLANDA AREA IN SRI LANKA**

Ahangama Kankanamge Rasika Nishamanie Ranasinghe

(118027 L)

Degree of Doctor of Philosophy

Department of Civil Engineering

University of Moratuwa

Sri Lanka

January 2018

**INTEGRATION OF RADAR AND OPTICAL REMOTE
SENSING FOR LANDSLIDE INVESTIGATION – CASE
STUDY OF KOSLANDA AREA IN SRI LANKA**

Ahangama Kankanamge Rasika Nishamanie Ranasinghe

(118027 L)

Thesis submitted in partial fulfilment of the requirements for the degree
of Doctor of Philosophy

Department of Civil Engineering

University of Moratuwa

Sri Lanka

January 2018

Declaration

I declare that this is my own work and this thesis does not incorporate, without acknowledgement, any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning, and to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also. I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature:

Date:

The above candidate has carried out research for the PhD Thesis under my supervision.

Name of the Supervisor: Prof. U. G. A. Puswewala

Signature of the Supervisor:

Date:

Name of the Supervisor: Dr. T. L. Dammalage

Signature of the Supervisor:

Date:

Abstract

Koslanda, in Sri Lanka is an area that remains in the memories of people due to frequently occurring landslides as the area is made vulnerable by both climatic and geomorphological settings. Additionally, the aftermath of the landslide, i.e. the debris flow, causes more damages when compared to the landslide itself. As such, this study focuses on the integration of radar and optical remote sensing for landslide investigation with inclusion of debris flow. The significance of the data types derived from radar and optical images are examined in terms of sensor characteristics and spectral information.

Radar and optical images before and after the event, geometrically registered and radiometrically normalized, are used to delineate the landslide area by different change detection techniques. Detected landslide areas are compared with the area determined by GPS field surveying. At the comparison stage, landslide detection capacity of the optical images was 76% while it was 86% with the radar images. This is mainly due to inherent nature of radar being able to collect data under any climatic condition.

The Information Value method uses bivariate analysis without radar induced factors (BiNR), and bivariate analysis with radar induced factors (BiWR), while the Multi Criteria Decision Analysis based on AHP uses multivariate analysis without radar induced factors (MNR), and multivariate analysis with radar induced factors (MWR). When utilizing the multivariate method, an increase in the area showing high and moderate susceptibility to landslides was observed as 5% and 3% from the total area, respectively. With the inclusion of radar induced factors (surface roughness, near surface soil moisture from delta index, and forest biomass), high and very low susceptible regions to landslide increased by 7% and 4% when using the bivariate method, while it was 3% for both cases when using the multivariate method. Landslide prediction analysis is enhanced by incorporating debris flow analysis with DEM derived factors, as appropriate for a country like Sri Lanka, where data scarcity of acceptable accuracy is high for smaller scale studies.

Key Words – Radar, Optical, Landslide, Prediction, Debris

ACKNOWLEDGEMENT

First and foremost, I wish to thank my main supervisor, Prof. UGA Puswewala, for accepting me as a PhD candidate, and for his untiring support throughout the work. I am indebted to him for his encouragement and the understanding, but most of all, for the patience extended to me during the most difficult times of my PhD. I am really thankful to you Sir. Secondly, I wish to extend my sincere gratitude to my second supervisor, Dr. TL Dammalage, for providing me wonderful support, especially proper directions at the perfect time, and for 'pumping' me up with enough confidence during my lowest points. Thank you very much for being a mentor in its complete sense, and for showing me the way to learn from mistakes. My sincere gratitude to Dr. Ranmalee Bandara. Though you are not my supervisor in the conventional sense, thank you for sharing all the experiences, providing expert reviews, and encouraging me to “find the light at the end of the tunnel”. Your guidance during the last stage when I needed it most, especially when I was lost and wandering around (and feeling completely lazy to write my thesis), is truly appreciated.

I also wish to acknowledge the HETC project, Ministry of Higher Education, for providing the financial support for my PhD studies. Special appreciation and gratitude to Prof. Lalith Munasinghe, Project Coordinator, HETC grant, for without his enormous support and understanding in financial matters, I would never have been able to come to this point of completion. Prof. Joachim Ender and Dr. Nies from ZESS, University of Siegen, Germany, are remembered with profound gratitude for giving me the opportunity and space at ZESS for four months, and for providing their fullest support in collecting and initial processing of the TerraSAR-X and TanDEM-X images from DLR, Germany. The DLR, Germany, is remembered with appreciation for providing radar images for free, and the GSMB, Sri Lanka for providing me, freely, the geological data necessary for my PhD research work.

Additionally, I wish to acknowledge the OTS office, and all the academic, academic support, and non-academic staff of Sabaragamuwa University and University of

Moratuwa, for providing me the peaceful environment needed for my research studies. I wish to convey my sincere gratitude to the Dean, all Heads of Departments, and all my colleagues in the academic staff, and all academic support staff of the Faculty of Geomatics, Sabaragamuwa University, for giving me a home away from home, with enough peace and facilities to complete this task successfully.

I also wish to express my deepest appreciation to a number of very special individuals who stood by me during this crucial period of my life. Among them, Darshana, Jayan, Tharaka, Chandima, Pussella, Mahesh, Charith, Amali, Samantha, Dr. DR Welikanna, Prof. PI Yapa, and Dr. Jayathissa (from NBRO) are remembered dearly.

When I sat down to write my acknowledgement, many people and memories swamped my mind. It would not be possible for me mention all of them by name, as the list would be endless. But each of you is dear to me, and I am blessed to have had you all coming into my life at one time or other, helping me overcome troubles, and supporting me through hard and harsh times, and making my life easier and more meaningful. Thank you!

I wish to extend my gratitude and love to my family. My mother Babyhami Ekanayake, and my late father Cyril Ranasinghe, who sacrificed their whole life for the betterment of our future. My father would be the happiest about my achievement if he was with us today. He always believed in me, and had unshakable faith in my capacity. That faith and trust gave me strength to crawl over the worst points and periods in my life. Thank you! You are the best Father a daughter could ever have. My sincere gratitude to my sisters, Niranjala, Thushari, Inoka and Manori, and brothers Nadeera and Pradeep, and their families, for making my life easier during the most difficult time in the past years. I am indebted to my father-in-law Gunapala, mother-in-law Premawathi and sister-in-law Niluka and her family, for their kindness and love towards my family when I was away from home.

My deepest appreciation, gratitude, and love to my loving husband Lakmal, the pillar of strength and backbone of my life, and my lovely kids Geeth, Hasi and Thinu. Thank you for being patient with me when I had to work, for being understanding when I had to miss important activities in your life, and for coping by yourselves when I was away from home. Thank you for all the sacrifices you made to support my studies, especially by accepting my long absence from home graciously.

Ahangama Kankanamge Rasika Nishamanie Ranasinghe

30 January 2018

TABLE OF CONTENTS

Abstract	i
Acknowledgement.....	ii
Table of Contents	v
List of Figures	ix
List of Tables.....	xii
List of Abbreviations.....	xiii
CHAPTER 1 : INTRODUCTION	1
1.1 Problem Statement.....	2
1.2 Koslanda.....	4
1.3 Research Objectives	4
1.4 Outline of Approach.....	5
1.5 Thesis Organisation.....	9
CHAPTER 2 : STUDY AREA AND DATA USED	10
2.1 Introduction	10
2.1.1 Climate of Koslanda.....	11
2.1.2 Geomorphology of Koslanda.....	12
2.1.3 Landslides in Koslanda	13
2.1.4 Meeriyabedda Landslide	15
2.1.5 Debris Flow	17
2.2 Satellite Images and Auxiliary Data.....	18
2.2.1 DEM from Aerial Photogrammetry	18
2.2.2 Radar Images.....	20
2.2.3 Optical Images	22
2.2.4 Auxiliary Data.....	25
2.3 Chapter Summary.....	29
CHAPTER 3 : RELATED WORK - SCIENTIFIC LITERATURE	30
3.1 Landslides.....	31
3.1.1 Landslides in the World	33
3.1.2 Landslides in Sri Lanka.....	36
3.1.3 Present Landslide Studies in Sri Lanka.....	38

3.2	Integration of Radar and Optical Remote Sensing for Landslide Studies...	39
3.3	Landslide Investigations.....	40
3.4	Remote Sensing for Landslide Investigations.....	41
3.4.1	Remote Sensing for Landslide Detection.....	42
3.4.2	Remote Sensing for Landslide Monitoring.....	43
3.4.3	Remote Sensing for Landslide Susceptibility Analysis.....	44
3.5	Integration of Radar and Optical Remote Sensing for Landslide Investigations.....	45
3.6	Landslide Susceptibility Analysis.....	46
3.7	Landslide Prediction Models.....	47
3.7.1	Qualitative Methods.....	47
3.7.2	Quantitative Methods.....	48
3.8	Predisposal Factors for Landslide Susceptibility Analysis.....	56
3.9	Evaluation of Landslide Prediction Models.....	58
3.10	Landslide Detections.....	60
3.11	Change Detection Techniques for Landslide Detection.....	61
3.12	Post Disaster effect from Debris Flow.....	65
3.13	Chapter Summary.....	66
CHAPTER 4 : PERFORMANCE ASSESSMENT OF RADAR AND OPTICAL REMOTE SENSING FOR LANDSLIDE SUSCEPTIBILITY ANALYSIS.....		68
4.1	Study Area.....	68
4.2	Data and Methodology.....	69
4.2.1	Data.....	70
4.2.2	Methodology.....	70
4.3	Selected Landslide Predisposing Factors.....	72
4.3.1	Topographical Factors.....	73
4.3.2	Hydrological Factors.....	78
4.3.3	Soil Factors.....	81
4.3.4	Land Use.....	84
4.3.5	Geological Factors.....	87
4.4	Landslide Susceptibility Analysis.....	90
4.4.1	Bivariate Statistical Analysis (InfoVal or SI method).....	90

4.4.2	Multivariate Statistical Analysis (MCDA based on AHP)	93
4.5	Results Validation	98
4.5.1	RFD Analysis	99
4.5.2	ROC Curves	101
4.6	Discussions and Conclusions	103
4.7	Chapter Summary	104
CHAPTER 5 : PERFORMANCE ASSESSMENT OF RADAR AND OPTICAL REMOTE SENSING FOR LANDSLIDE DETECTION		106
5.1	Introduction	106
5.2	Study Area	108
5.3	Data and methodology.....	108
5.3.1	Data	109
5.3.2	Methodology	110
5.4	Landslide detection from optical images.....	112
5.4.1	Principle Component Analysis.....	113
5.4.2	NDVI.....	114
5.5	Landslide detection from radar images	115
5.5.1	Correlation and Difference.....	117
5.6	Results Analysis	118
5.7	Discussion.....	119
5.8	Chapter Summary	121
CHAPTER 6 : ENHANCEMENT OF LANDSLIDE SUSCEPTIBILITY ANALYSIS THROUGH THE INTEGRATION OF DEBRIS FLOW		123
6.1	Introduction	123
6.2	Study Area	124
6.3	Data Acquisition.....	125
6.4	Methodology.....	125
6.5	Terrain Failure Susceptibility Analysis	128
6.5.1	Extraction of Terrain Factors from DEM.....	129
6.5.2	Terrain failure susceptibility analysis using Information Value Method	131
6.5.3	Susceptible area discretization	133

6.5.4	Results Validation	133
6.6	Debris Flow Susceptibility Analysis	135
6.6.1	Debris Flow Susceptibility Assessment	135
6.6.2	Results Validation	135
6.7	Integration of Terrain Failures and Debris Flow Susceptibility Regions..	137
6.8	Discussions and Conclusions	139
6.9	Chapter Summary	141
CHAPTER 7 : CONCLUSIONS AND RECOMMENDATIONS		143
7.1	Fundamental Contribution of this Research to the Field of Landslide Studies	143
7.2	Conclusions of the Research	145
7.3	Discussions on Conclusions	146
7.3.1	Main Objective – Investigate the integration of radar and optical remote sensing for landslide prediction through a detailed study of landslides	146
7.3.2	Detection of Meeriyabedda landslide using different change detection techniques inherent to radar and optical	147
7.3.3	Identification of the most prominent landslide pre-disposing factors from remotely sensed sources, i.e. DEM, Optical and Radar	148
7.3.4	Building landslide prediction models from bivariate and multivariate statistical methods	149
7.3.5	Investigation of the performance of landslide prediction model, with the inclusion of landslide causal factors derived from radar images.....	150
7.3.6	Comparing the performance of differently built landslide prediction models	151
7.3.7	Investigation the post disaster effects from debris flow due to landslide failures	152
7.4	Future Works	153
REFERENCES.....		155
APPENDIX A – Weight of Influence for Landslide predisposing factors		170
APPENDIX B – Questionnaire Survey for MCDA based on AHP technique		181
APPENDIX C – AHP Calculation Procedure.....		187

LIST OF FIGURES

Figure 1-1 : Conceptual methodology for radar and optical remote sensing for landslide investigations	8
Figure 2-1 : Average minimum and maximum monthly temperature from year 2000 to 2012 in Koslanda	12
Figure 2-2 : Precipitation and average monthly rain fall from year 2000-2012 in Koslanda.....	13
Figure 2-3 : Locational map for Koslanda, Sri Lanka with historical landslide experiences from Google earth.	14
Figure 2-4 : Nature of Meeriyabedda Landslide in 29 th October, 2014.....	15
Figure 2-5 : Meeriyabedda landslide disaster and its damages.....	16
Figure 2-6 : DEM Generation from Imagine photogrammetry tool from ERDAS Imagine 2014.....	19
Figure 2-7 : Landslide failure map of the Koslanda area with two different training and validating samples with Google image as background.....	26
Figure 3-1 :Block Diagram of a Landslide showing commonly used nomenclature, Source : (USGS, 2004).....	32
Figure 3-2: Chain of natural events causing Landslides and their reporting Source: (Abella <i>et al.</i> , 2008)	35
Figure 3-3 : Annual distribution of Landslides in Sri Lanka from year 2000 to 2015. (Source: www.desinventar.lk, accessed on 10 th January 2016)	37
Figure 3-4 : Monthly distribution of Landslides (Source :www.desinventar.lk, accessed on 10 th January 2016).....	38
Figure 3-5 : Hyper-planes for (a) linearly separable data and (b) non-linear separable data (Kavzoglu <i>et al.</i> , 2014).....	54
Figure 3-6 : Distributed decision tree learning for mining big data streams, (Murdopo, 2013)	55
Figure 3-7: Prediction performance of multiple factor combinations. (a). success rate curve from the training data set; (b). prediction rate curve from the validation data set (Che <i>et al.</i> , 2012).....	59
Figure 3-8 : Success rate and prediction rate curves for the landslide susceptibility map (Jaafari <i>et al.</i> , 2015).....	59
Figure 4-1 : Topographical formation of the selected Koslanda area for Landslide susceptibility analysis.....	69
Figure 4-2 : Methodological flow of the Landslide susceptibility analysis using Bivariate and Multivariate approaches.....	71
Figure 4-3 : Topographical factors, from top to bottom as Elevation and Slope used in Landslide Susceptibility Analysis.....	74

Figure 4-4 : Topographical factors, from top to bottom as Aspect and Planar Curvature used in Landslide Susceptibility Analysis.....	76
Figure 4-5 : Topographical factors, from top to bottom as Profile Curvature and Surface Roughness used in Landslide Susceptibility Analysis.....	77
Figure 4-6 : Hydrological factors from top to bottom as Distance to hydrology and Topographical Wetness Index (TWI) used for Landslide Susceptibility Analysis.....	79
Figure 4-7 : Hydrological factor, Average Rainfall for 2014 used for Landslide Susceptibility Analysis.....	80
Figure 4-8 : Soil factors top to bottom as Soil Moisture Index (SMI) from optical approach and Delta Index from radar approach used for Landslide Susceptibility Analysis.....	82
Figure 4-9 : Land use factors top to bottom as Land use from Sentinel – 2A (10 m resolution), and estimated Forest Biomass from TerraSAR-X (3 m resolution) Radar image, which are used in Landslide susceptibility analysis	85
Figure 4-10 : Geological factors top to bottom as 1:100,000 scale Geological map from GSMB, Sri Lanka and Lineament density with the lineaments derived from 10 m resolution Sentinel -2 image used for landslide susceptibility analysis.....	89
Figure 4-11: Landslide Susceptibility Map from Bivariate, Information Value Method (without Radar Induced Factors)	92
Figure 4-12 : Landslide Susceptibility Map from Bivariate, Information Value Method (with Radar Induced Factors)	93
Figure 4-13 : Landslide susceptibility map from Multivariate, AHP based on MCDA (without Radar Induced Factors).....	96
Figure 4-14 : Landslide susceptibility map from Multivariate, AHP based on MCDA (with Radar Induced Factors).....	97
Figure 4-15 : Graphic display of validation results for each landslide susceptibility class from bivariate and multivariate techniques with and without radar induced factors.....	100
Figure 4-16 : Success rate and Prediction rate curves with AUC for the bivariate analysis without radar induced factors.....	101
Figure 4-17 : Success rate and Prediction rate curves with AUC for the bivariate analysis with radar induced factors	101
Figure 4-18 : Success rate and Prediction rate curves with AUC for the multivariate analysis without radar induced factors.....	102
Figure 4-19 : Success rate and Prediction rate curves with AUC for the multivariate analysis with radar induced factors.....	102
Figure 5-1 : Meeriyabedda Landslide in Koslanda, Sri Lanka and its pre and post high resolution satellite views	109
Figure 5-2 : Conceptual methodology for detecting Meeriyabedda Landslide from radar and optical satellite images	111

Figure 5-3 : Worldview II satellite image (before) with damaged properties and Geoeye image (after) with Meeriyabedda Landslide	112
Figure 5-4 : Landslide detection from PCA applied for high resolution optical images. (a) – red colour, (b) – white represent detected change from the pre and post images.....	113
Figure 5-5 : Landslide detection from NDVI analysis for high resolution optical images. Red colour features are detected change from pre and post images	115
Figure 5-6 : Radar images before and after the Meeriyabedda Landslide in Koslanda area	116
Figure 5-7 : Areas detected as change from 19 th - 31 st October 2014 from image correlation and difference domain	117
Figure 6-1 : Methodological flow to analyse the terrain failure susceptibility regions	126
Figure 6-2 : Methodological flow to analyse the debris flow susceptibility regions	127
Figure 6-3 : Interpretation of geographical formation through planar and profile curvature. Planar curvature: A – surface is laterally convex and divergence flow across a surface, B – surface is laterally concave and convergence flow across a surface, C – surface is linear	129
Figure 6-4 : Thematic maps obtained from the DEM. Each thematic map illustrates the generated terrain factors with discretized number of classes. Left to right and top to bottom, aspect, profile curvature, planar curvature and slope.	130
Figure 6-5 : Terrain failure susceptibility map with four landslide susceptibility classes.....	134
Figure 6-6 : Graphic showing of RFD for each terrain failure susceptibility class .	134
Figure 6-7 : Graphic showing of RDFD for each Debris Flow susceptibility class	136
Figure 6-8 : Debris flow susceptibility map with four susceptibility classes	137
Figure 6-9 : Matrix with terrain susceptibility classes in the columns and debris flow susceptibility classes on the rows	138
Figure 6-10 : Landslide susceptibility map with integration of terrain failure and debris flow susceptibility analysis	138
Figure 6-11: Susceptibility maps from terrain failure (a) debris flow analysis (b) and their integration (c) overlaid with the prominent landslides occurred in the study area and (d) number of landslide failure pixels in the terrain failure, debris flow, and integrated map.....	139

LIST OF TABLES

Table 2-1 : Sensor characteristics and spectral information for WorldView -2, GeoEye-1 and Landsat -8 Satellite images	24
Table 3-1: World Statistics for Landslides. Source: EM-DAT Database for the period 2000-2016 (OFDA/CRED, 2016).....	34
Table 3-2 : Fundamental scale of absolute number between two parameters in AHP (Saaty, 2000)	52
Table 3-3 : Number of causative factors used for Landslide susceptibility analysis in recent literature.....	57
Table 4-1: Selected Predisposing Factors for Landslide susceptibility analysis.....	73
Table 4-2 : Geological Structures of the Koslanda area obtained from the 1:100,000 Geological Map of GSMB, Sri Lanka	88
Table 4-3 : Landslide susceptible area comparison from bivariate and multivariate analysis with and without radar induced factors.....	98
Table 4-4 : Comparison of area under Success rate and Prediction rate curves for bivariate and multivariate analysis with and without radar induced factors.....	103
Table 5-1: Comparison of the detected landslide area from optical and remote sensing techniques with the area from GPS survey	119
Table 6-1 : Computed Information Value weights for each factor class in the four thematic maps.....	132
Table 6-2 : Landslide susceptibility classes in the Terrain Failure, Debris Flow and the Integrated analysis	141

LIST OF ABBREVIATIONS

AHP – Analytic Hierarchy Process

ALOS - Advanced Land Observation Satellite

ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer

AUC - Area Under Curve

AVNIR-2 - Advanced Visible and Near Infrared Radiometer type 2

CI – Consistency Index

CR - Consistency Ratio

CVA - Change Vector Analysis

DEM - Digital Elevation Model

DFR - Debris Flow Regions

DGPS - Differential Global Positioning System

DI – Delta Index

DInSAR – Differential Interferometric SAR

DLR - German Aerospace Center

DMC – Disaster Management Center

DN - Digital Numbers

DT - Decision Tree

EEC - Enhanced Ellipsoid Corrected

EM-DAT - Emergency events data base

ENVISAT – Environmental Satellite

EO - Earth Observation

ERDAS - Earth Resource Data Analysis System

ERTS - Earth Resources Technology Satellite

ERS - European Remote Sensing

ESA - European Space Agency

EW - Extra Wide swath
FR - Frequency Ratio
GCP - Ground Control Points
GEC - Geocoded Ellipsoid Corrected
GIS – Geographical Information System
GPS – Global Positioning Systems
GRD - Ground Range Detected
GSMB - Geological Survey Mines Bureau
IDW - Inverse Distance Weighting
InfoVal - Information value
InSAR - Interferometric SAR
IRS – Indian Remote Sensing
IW - Interferometric Wide swath
JICA - Japan International Co-operation Agency
LST – Land Surface Temperature
MCDA – Multi Criteria Decision Analysis
MGD - Multi look Ground range Detected
MSL – Mean Sea Level
NBRO - National Building Research Organization
NDVI - Normalized Difference Vegetation Index
NIR - Near Infrared
OCN – Ocean
OLI - Operational Land Imager
PALSAR - Phased Array type L-band Synthetic Aperture Radar
PCA – Principle Component Analysis
PRISM - Panchromatic Remote-sensing Instrument for Stereo Mapping
RDFD - Relative Debris Flow Density
RFD - Relative Failure Density

ROC - Receiver Operating Characteristics
SAFE - Standard Archive Format for Europe
SAR - Synthetic Aperture Radar
SI - Statistical Index
SM - Strip Map
SMI – Soil Moisture Index
SPI - Stream Power Index
SRTM - Shuttle Radar Topographic Mission
SSC - Single look Slant range Complex
SVM - Support Vector Machine
T - Temperature
TauDEM - Terrain analysis using DEM
TFSI - Terrain Failure Susceptibility Index
TIRS - Thermal Infrared Sensor
TM - Thematic Mapper
TOA - Top-Of-Atmosphere
TWI - Topographical Wetness Index
UDA – Urban Development Authority
WOE - Weight of Evidence