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GOVERNMENT OF INDIA
भारतीय भूवैज्ञानिक सर्वेक्षण
GEOLOGICAL SURVEY OF INDIA

विराजपेट ब्लॉक, कोडागु जिला, कर्नाटक के केदामल्लूर (टोरा) में और उसके आसपास मेसो-स्केल
(१: १०,०००) भूस्खलन संवेदनशीलता मानचित्रण

**Meso-scale (1:10,000) Landslide Susceptibility Mapping in and around Kedamallur
(Torah) of Virajpet Block, Kodagu District, Karnataka**

टोपशीट सं ४८पी/१२/Toposheet no.: 48P/12

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Final report for field season 2022-23

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Meso-scale (1:10,000) Landslide Susceptibility Mapping in and around Kedadmallur (Torah) of Virajpet Block, Kodagu District, Karnataka

Item no.: M4LSSM/NC/SR/SU-KG/2022/42402

by

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द्वारा

ऐजाज़ अहमद भट, वरिष्ठ भूवैज्ञानिक; इन्द्राणी कर्मकार, वरिष्ठ भूवैज्ञानिक; जोबिन जे, वरिष्ठ भूवैज्ञानिक

संक्षेप

फील्ड सीज़न 2022-23 के दौरान कर्नाटक के कोडागु जिले के विराजपेट तालुक के कुछ हिस्सों में 10 किमी 2 क्षेत्र में मेसो-स्केल (1:10,000) भूस्खलन संवेदनशीलता मानचित्रण किया गया था। अध्ययन क्षेत्र SOI टोपोशीट संख्या में स्थित है। 48P/12 और अक्षांश 12°8'27" N और 12°11'48" N और देशांतर 75°42'16" E और 75°45'00" E के बीच घिरा है। भू-कारक मानचित्रण में स्केल और भूस्खलन विफलता डोमेन-आधारित दृष्टिकोण को अपनाकर प्रबंधन योजना के साथ-साथ अध्ययन क्षेत्र के मेसो-स्केल (1:10,000) भूस्खलन संवेदनशीलता मानचित्र तैयार करने के उद्देश्य से जांच की गई थी। अध्ययन क्षेत्र में वायनाड समूह (=सरगुर समूह), चार्नोकाइट समूह से संबंधित कूर्ग ब्लॉक और यंगर इंट्रसिव चट्टानों की चट्टानें हैं। हॉर्नब्लेंड डायोपसाइड गनीस इस क्षेत्र में प्रमुख रूप से वितरित है। 1 वर्ग किमी के क्षेत्र में एक गैब्रो पिंड की पहचान की गई है जिसमें सल्फाइड खनिज है। पत्तियों की क्षेत्रीय प्रवृत्ति एनडब्ल्यू-एसई (औसत प्रवृत्ति 338°) दिशा में होती है और औसत कोण 48° एसडब्ल्यू तक गिरती है। क्षेत्र में चट्टानों को पांच संयुक्त सेटों (जे 1, जे 2, जे 3, जे 4 और जे 5) द्वारा पार किया जाता है जो चट्टानों के विघटन, निचले इलाकों में विशाल तलछट प्रवाह के गठन और वर्षा जल की गहरी घुसपैठ में प्रमुख भूमिका निभाते हैं जो अनुमति देता है गहरी अपक्षय प्रक्रिया। ये पांच संयुक्त सेट एक बहुत ही सीमित स्थान में एक दिलचस्प हस्तक्षेप पैटर्न बना रहे हैं जो कई स्थानों पर उपसतह जल को सतह पर भागने की अनुमति देता है। पत्ते और जोड़ सेट J2, J3 और J4 के बीच हस्तक्षेप पैटर्न एक रॉक वेज बनाता है जो ढलान को दिन के उजाले में बदल देता है और यह हस्तक्षेप पैटर्न तोहरा भूस्खलन के लिए एक आनुवंशिक कारण पाया जाता है। कुल 37 नग. क्षेत्र में भूस्खलन की घटनाएं दर्ज की गईं और इनमें से 16 घटनाएं हुईं। मलबे की स्लाइडें हैं, 19 नग। अर्थ स्लाइड और 1 नं. रॉक स्लाइड है। भूस्खलन की लगभग सभी घटनाएं वर्षा के कारण हुईं। अध्ययन क्षेत्र में भूस्खलन की घटनाओं के लिए प्राकृतिक और मानवजनित दोनों ही कारण जिम्मेदार पाए गए। प्राकृतिक कारणों में, उच्च ढलान ढाल, अपवाह जल का उच्च प्रवाह, धारा तट सामग्री का क्षरण या उच्च जल क्रिया द्वारा प्राकृतिक ढलानों का पैर का कटना और चट्टान के टुकड़ों के पृथक्करण के लिए अनुकूल संयुक्त हस्तक्षेप पैटर्न जैसे कारक जिम्मेदार हैं। मानवजनित कारणों में, घरेलू और व्यावसायिक उपयोग के लिए सड़क और बस्ती निर्माण के लिए प्राकृतिक ढलानों को काटना और खेती के उद्देश्यों के लिए प्राकृतिक ढलानों में संशोधन शामिल है। अधिकतर, भूस्खलन मध्यम से निम्न भूस्खलन संवेदनशीलता क्षेत्र में

उच्च जल क्रिया और मानवजनित गतिविधियों के कारण पैर के कटाव के कारण हुआ है और मौजूदा संपत्तियों पर उनके प्रभाव की तीव्रता कम है। जबकि उच्च संवेदनशीलता वाले क्षेत्र में या उसके आसपास मौजूदा संपत्तियों में उच्च जोखिम है और प्रभाव की तीव्रता विनाशकारी होगी। गुणात्मक रूप से, अपनाए गए मॉडल ने उच्च संवेदनशीलता में 20.46 प्रतिशत मानचित्र क्षेत्र और कम संवेदनशीलता में 52.04 प्रतिशत मानचित्र क्षेत्र की कुशलतापूर्वक भविष्यवाणी की है और 27.50 प्रतिशत मानचित्र क्षेत्र में कम से कम अनिश्चितता है, जिसमें मध्यम संवेदनशीलता है। भूस्खलन अनुपात 16 (कम): 9 (मध्यम): 12 (उच्च) बना हुआ है जो क्षेत्र की स्थितियों और श्रमिकों द्वारा किए गए अवलोकन के अनुसार एक संतोषजनक अनुपात है। उच्च संवेदनशीलता वर्ग ने उन ढलानों को बरकरार रखा है जो अंतर्निहित प्रतिकूल सामग्री मापदंडों, चट्टानों के विघटन के लिए अनुकूल संयुक्त हस्तक्षेप पैटर्न, उच्च ढलान ढाल और बढ़ती मानवजनित गतिविधियों के कारण भूस्खलन की अधिक संभावना रखते हैं। कुल 97 ढलान पहलुओं या पहलुओं के हिस्सों को 1.4 वर्ग किमी क्षेत्र को कवर करने वाले अस्थिर ढलानों में वर्गीकृत किया गया था। इन अस्थिर ढलानों ने 52 लोगों के लिए उच्च जोखिम कारक पैदा कर दिया है। उनके प्रभाव क्षेत्र के अंतर्गत बस्ती के घर और 6-लाइन किमी सड़क का विस्तार। भूस्खलन शमन उद्देश्य के लिए आवश्यक सामान्य सिफारिशें सुझाई गईं और किसी भी भूस्खलन आपदा की स्थिति में अध्ययन क्षेत्र के लिए कई भूस्खलन प्रबंधन कदम सुझाए गए।

Meso-scale (1:10,000) Landslide Susceptibility Mapping in and around Kedadmallur (Torah) of Virajpet Block, Kodagu District, Karnataka

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Aijaz Ahmad Bhat, Senior Geologist; Indrani Karmakar, Senior Geologist; Jobin J, Senior Geologist

ABSTRACT

The Meso-scale (1:10,000) Landslide Susceptibility Mapping was carried out in a 10 km² area in parts of Virajpet taluk of Kodagu district, Karnataka during field season 2022-23. The study area lies in SOI toposheet no. 48P/12 and is bound between latitudes 12°8'27" N and 12°11'48" N and longitudes 75°42'16" E and 75°45'00" E. The investigation was carried out with the aim of generating a Meso-scale (1:10,000) landslide susceptibility map of the study area along with a management plan by adopting up scaled and landslide failure domain-based approach in geo-factor mapping. The study area is occupied by rocks of the Waynad Group (=Sargur Group), Charnockite Group relevant Coorg Block and Younger Intrusive rocks. Hornblende Diopside Gneiss is dominantly distributed in the area. A Gabbro body has been identified over an area of 1 sq.km which contains sulphide mineralization. The regional trend of foliation ranges in NW-SE (mean trend 338°) direction and dips an average angle of 48° SW. The rocks in the area are traversed by five joint sets (J1, J2, J3, J4 & J5) which play a dominant role in the disintegration of rocks, formation of huge sediment flow to low-lying areas and deep infiltration of rainwaters that allows deep weathering process. These five joint sets are making an interesting interference pattern in a very confined space which allows subsurface waters to escape to the surface at multiple locations. The interference pattern between foliation and joint sets J2, J3 and J4 makes a rock wedge that makes a slope day-lighted and this interference pattern is found a genetic cause for the Tohra landslide. A total of 37 nos. of landslide incidences were recorded in the study area and among these, 16 nos. are debris slides, 19 nos. are earth slides and 1 no. is rock slide. Almost, all landslide incidences were triggered by rainfall. Both natural as well as anthropogenic-related causes were found responsible for landslide occurrences in the study area. In natural causes, the factors including high slope gradient, the high influx of runoff water, erosion of stream bank material or toe cut of natural slopes by high water action and favorable joint interference pattern for detachment of rock fragments are responsible. In anthropogenic causes, cutting of natural slopes for road & settlement construction for both domestic as well as commercial use and modification of natural slopes for cultivation purposes are included. Mostly, the landslides have occurred due to toe erosion by high water action and anthropogenic activities in moderate to low landslide susceptibility area and their impact intensity to the existing properties is low. Whereas the existing properties in or near the vicinity of high susceptibility area have high risk and the

impact intensity would be disastrous. Qualitatively, the adopted model has efficiently predicted 20.46 percent map area in high susceptibility and 52.04 percent map area in low susceptibility and there is least uncertainty over 27.50 percent map area which has moderate susceptibility. The landslide ratio remains 16 (low): 9 (moderate): 12 (high) which is a satisfactory ratio as per the field conditions and observations made by the workers. The high susceptibility class has retained those slopes which are more prone to landslides due to inherent unfavorable material parameters, joint interference pattern favorable for disintegration of rocks, high slope gradient and rising anthropogenic activities. Total 97 slope facets or parts of facets were categorized into unstable slopes covering 1.4 sq.km area. These unstable slopes have created high risk factor for 52 nos. of settlement houses and 6-line km road stretch under their influenced area. Necessary general recommendations were suggested for the landslide mitigation purpose and several landslide management steps were suggested for the study area in case of any landslide disaster circumstances.



CHAPTER-1

INTRODUCTION

1.1 General

The landslide investigation titled “Meso-scale (1:10,000) Landslide Susceptibility Mapping in and around Kedhamallur (Torah) of Virajpet Block, Kodagu District, Karnataka” has been carried out in a 10 km² area in Virajpet Taluk, Kodagu district Karnataka during field season 2022-23. A mesoscale (1:10,000) landslide susceptibility item is proposed for Kedhamallur (Torah) Kodagu District, Karnataka based on the request received from the office of the Deputy Commissioner, Kodagu District, Karnataka. The area is not part of the 200 vulnerable sites identified/prioritized by NDMA and GSI as per the MoM-approved Landslide Vision and Strategy Document 2020-2030. However, landslide incidences in the area have been reported in the past. The notable landslide is the Torah landslide of August 2019 which cost the lives of 9 local people and damaged the settlements. This investigation was taken up in the landslide-prone area for further detailed investigations to provide long-term solutions will be generated and provided to the stakeholders. This investigation has been done through a domain-specific approach as per the Standard Operating Procedure (SOP) of the Meso-scale (10,000) Landslide Susceptibility Mapping project, in which the following things were brought to achieve quality product; (1) demarcation of landslide failure domains such as rock slide/rock fall domain, debris slide/debris flow domain, earth slide/earth flow domain and cut-slope domain in both rock and overburden covered slopes; (2) the field data density is higher; (3) the validation of geo-factor maps is upscaled with higher accuracy; (4) the landslide susceptibility has modelled as per the types of slope failures; (5) the final landslide susceptibility map is user-friendly and contains additional value-added information for comprehensive landslide risk assessment and management so that the same can be utilized for detailed infrastructure planning and mitigation strategies. Earlier in Macro-scale (1:50,000) landslide susceptibility mapping the landslide failure domain-specific approach has not been adopted. However, in the present investigation, different types of data sets including remote sensing and field data were collected and analyzed separately in each landslide failure domain, and the subsequent landslide susceptibility map for each landslide failure domain has been generated independently. The earlier geological map (1:50,000) of the study area has been updated on a 1:10,000 scale with due care. In rockslide/rockfall domains the kinematic failure analysis has been done for each rock outcrop to find out different rock failure types and to prepare their kinematic failure maps which were later used in modelling for landslide susceptibility in rockslide/rock fall domains. In overburden failure domains the classification of the material (debris or earth) has been done in field mapping and 32 nos. of undisturbed samples in each classified material at different elevations were collected to analyze their geotechnical properties.

1.2 Location, Physiography and Communication

The study area of 10 km² is situated in the Virajpet taluk of Kodagu/Coorg district of Karnataka (see fig. 1.1) and it lies in SOI toposheet no. 48P/12. The study area is bound between latitudes 12°8'27" N and 12°11'48" N and longitudes 75°42'16" E and 75°45'00" E respectively. The localities situated in the study area are Korthikad, Kedhamallur, Thomara, Tharmetta, Palangala villages. The study area lies in the vicinity of the Western Ghats which runs for about 1600 km as an unbroken relief along the western border of Deccan from the river Tapti Valley in Gujarat to Kanyakumari in Tamil Nadu, of the Indian Peninsula. The Western Ghats represent the hilly terrain with steep escarpments parallel to the west coast of India. On the western side, the Western Ghats appear abruptly rising from the Arabian Sea whereas they merge through a series of hills with the Deccan plateau in the east. Due to the unique type of topography and climate in parts of Kodagu district among southern states, it is known to be quite a pleasant and healthy place in south India. The study area has lowly to moderately dissected hill slopes. The study area is a part of the Kallu Hole watershed of the Vallapatanam River basin. The elevation range in the study area varies from 1306m to 800m and the slope angle ranges from 0°-50°. Kodagu is famous for the hilly tourist destinations in India. Some of the most popular tourist destinations in Kodagu are Talakaveri, Bhagamandala, Nisargadhama, Abbey Falls, Dubare, Nagarahole National Park, Iruppu Falls, and the Tibetan Buddhist Golden Temple.

The Kodagu district is bordered by the Dakshin Kannada district of Karnataka in the north, the Mysore district of Karnataka in the east, and the Kasaragod district of Kerala state in the west and south. The study area has a fairly good network of roads that connects the area to the district headquarters stationed at Madikeri. The study area is about 33 km away from Madikeri town, 238 km away from Bangalore (Karnataka State Capital), 105 km from Mysore, and 165 km from Mangalore, respectively. The nearest railway stations to the study area are Hassan (127 km), Mysore (105 km) and Mangalore (165 km). The nearest airport stations to the study area are Mysore (118 km) and Mangalore (171 km).

1.3 Climate and Rainfall

The Kodagu district located in the middle of Western Ghats has a tropical climate characterized by slight to medium-range humidity due to its proximity to the coast (about 32 km away). The weather of Kodagu is pleasant for most of the year and healthy place in South India because of its unique climate, weather conditions and rainfall pattern. The area receives rainfall during the monsoon period starting in June and lasts till the end of September. Even during the post-monsoon months October to November, certain parts of the district receive a significant amount of rainfall.

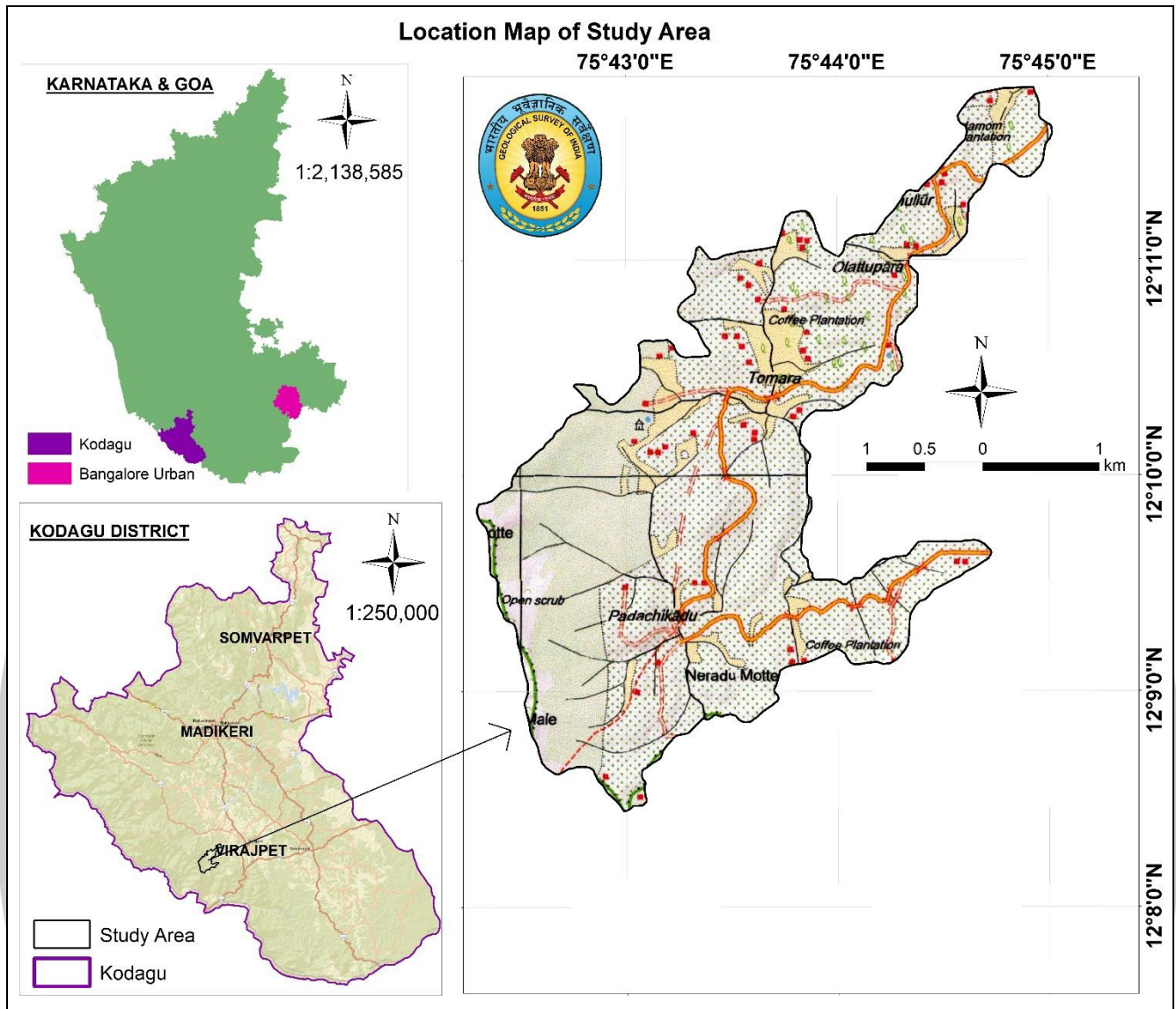


Figure-1.1: Location map of the study area

The climate is dominated by the SW monsoon starting from June end. Because of the cloudy weather, the day would be quite sultry during October, and it is only during the second half of November that the weather becomes very clear. The period from December to February is the cold season marked by bright weather, foggy mornings and cool nights. The day temperature begins to rise sharply during March and marks the commencement of the summer season which lasts till the end of May. The mean average annual normal rainfall of 2874mm and mean average annual actual rainfall of 2664mm for the period 2015-2020 has been recorded in Kodagu district by Karnataka State Natural Disaster Monitoring Centre (KSNDMC) (see figure 1.2). While in the Kedhamallur area of Virajpet taluk (wherein the present study area is situated) of the Kodagu district, the average annual normal rainfall of 2317mm and mean average annual actual rainfall of 2776mm has been recorded for the period 2015-2022 (KSNDMC). The southwest

monsoon reaches usually during early June. Generally, June-September is the period of heavy rainfall (see figure. 1.3).



Figure-1.2: Trend of average annual normal and actual rainfall pattern in Kodagu district from 2015-2020 period. (Source: KSNDMC)

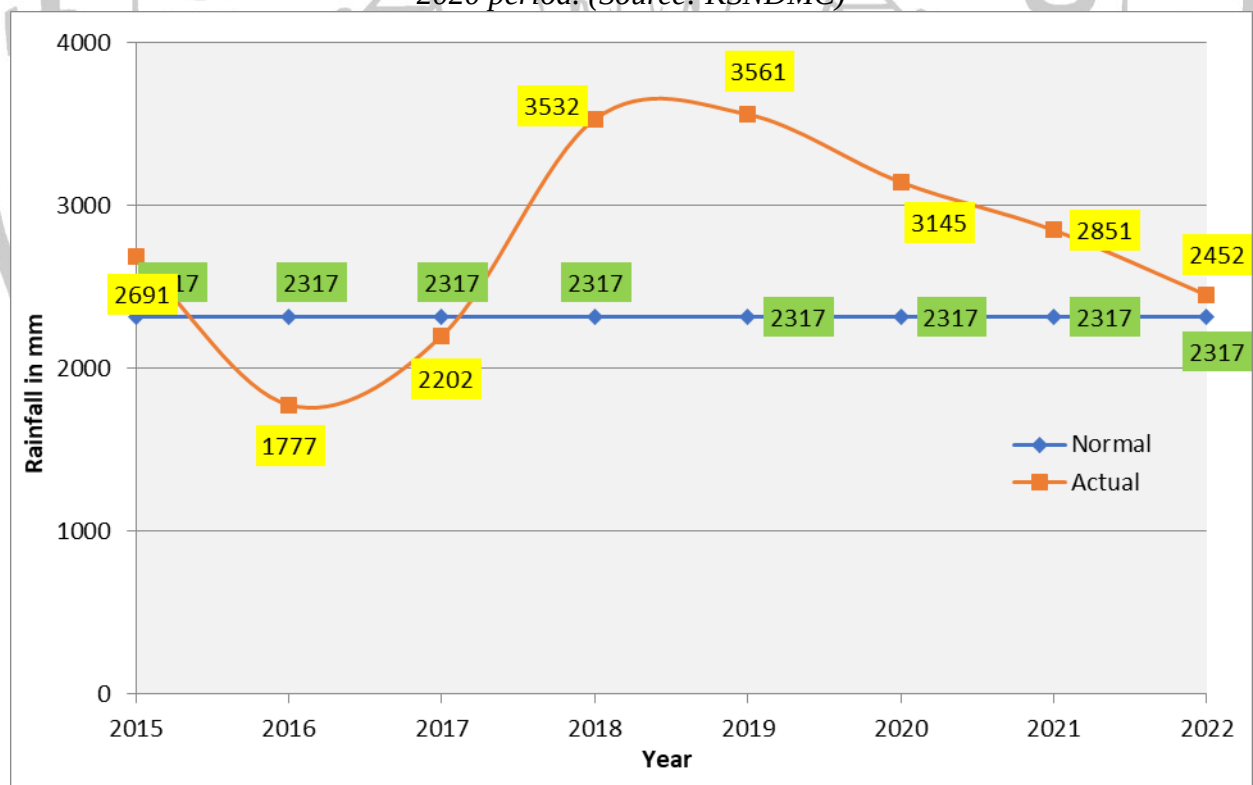


Figure-1.3: Trend of average annual normal and actual rainfall pattern in Kedhamallur GP Virajpet Taluk, Kodagu, Karnataka from 2015-2022 period. (Source: KSNDMC)

Further detailed analysis of rainfall data of June, July and August months of the year 2018 to 2022 has been done for recording rainfall stations at Kedhamallur GP of Virajpet Taluk. As per the information collected in the study area during field mapping, most of the landslide incidences occurred during the August 2018 and 2019 period in which maximum rainfall was recorded in the area. The daily rainfall data recorded during the months of June-August for the period 2018 to 2022 at Kedhamallur rainfall stations show considerable variations. The daily rainfall analysis shows that there were multiple rainfall events above 100mm rainfall recorded (see figure-1.4 a, b & c) between June-August 2018 two longer events (4 days) of rainfall above 100 mm recorded in July and August 2018 would have triggered most of the landslide incidences in the study area. Therefore, indirectly it may be concluded that the slopes having moderate to high slope gradients are vulnerable to failures above 100mm rainfall in the study area and its surroundings.

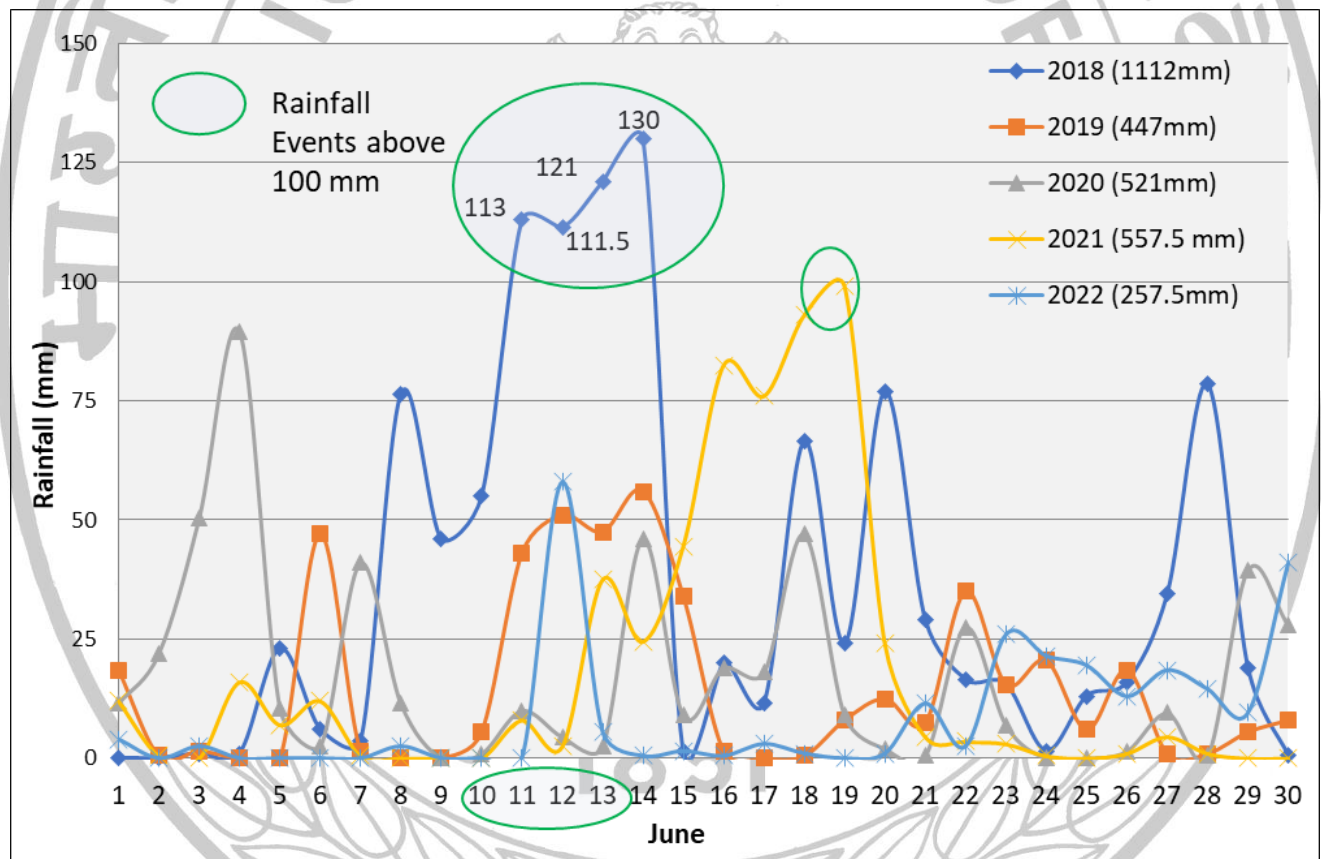


Figure-1.4 (a) Trend of daily rainfall data in the month of June during the period 2018 to 2022 at Kedhamallur rainfall station (Data source: KSNDMC)

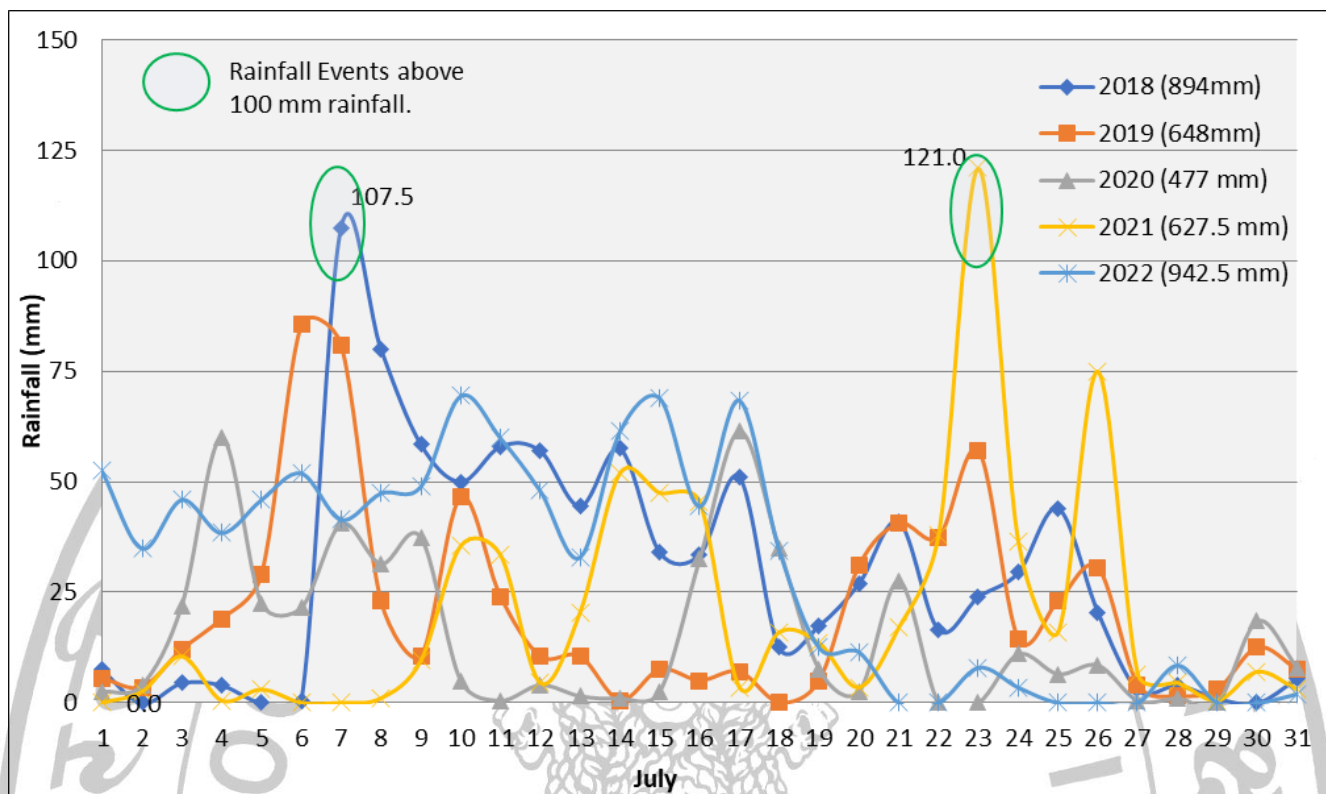


Figure-1.4 (b) Trend of daily rainfall data in the month of July during the period 2018 to 2022 at Kedhamallur rainfall station (Data source: KSNDMC)

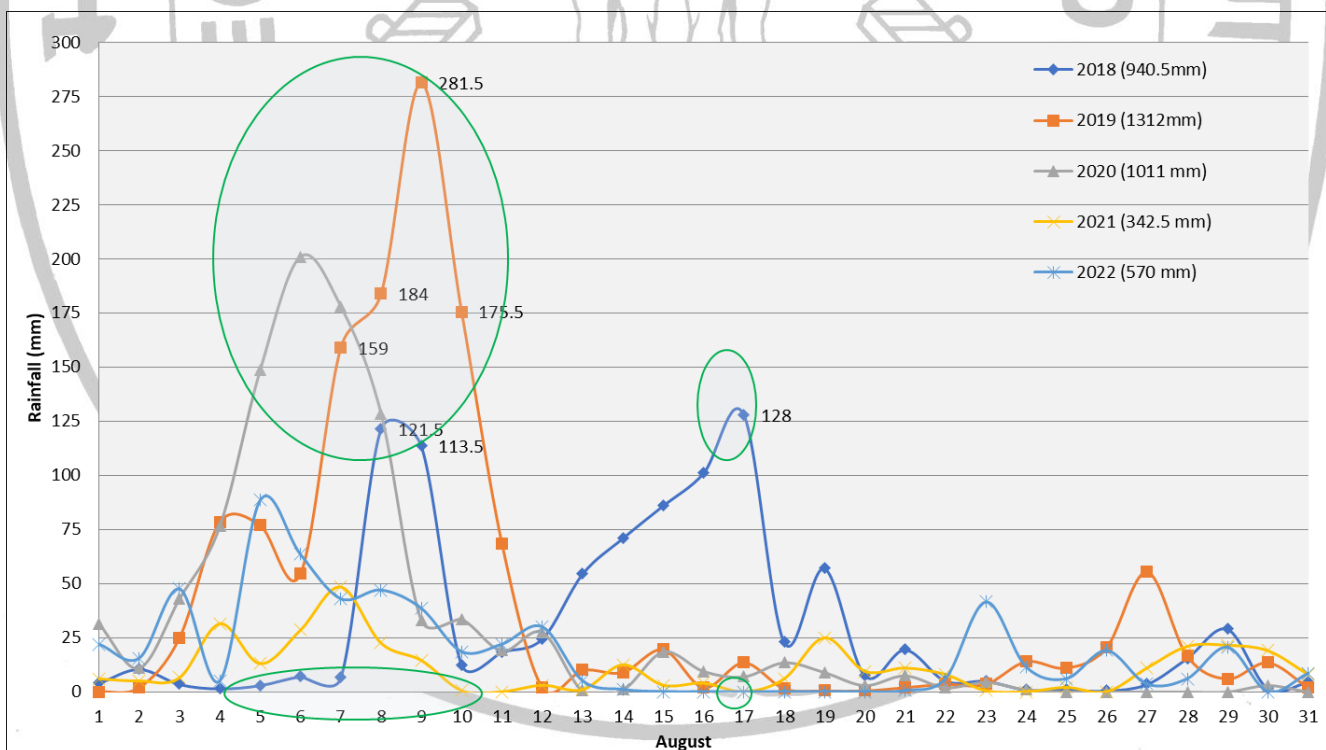


Figure-1.4 (c) Trend of daily rainfall data in the month of August during the period 2018 to 2022 at Kedhamallur rainfall station (Data source: KSNDMC)

1.4 Previous and Present Work

Sir T.H Holland was a pioneer worker who described the Charnockite of Coorg in the Memoir. The Charnockite series of peninsular India'. Later *Mr. B. Jayaram* who made a few traverses in Coorg, recorded his observations and conclusions in the Records of the Mysore Geological Department Vol. XXI – 1922. Later on, systematic geological mapping was carried out in different parts of the study area by the Geological Survey of India during different field seasons. During FS 1949-50, *Dr A.K Dey and Mr C. Gourishankar* carried out a systematic geological survey of the Archaean of Coorg and mapped parts of sheets 48 P/11, 14 and 15. The systematic mapping was continued in North Coorg by *B.R.C Iyengar* in the year 1952-53. *Krishna et al (1972-73)* carried out a preliminary investigation for Talc in parts of Tellicherry taluk, Cannanore district on a 1:63,360 scale in TS 49M/9. Systematic geological mapping of the Wayanad area was carried out by *Nair et al (1974-75)*. *Vidyadharan (1981)* mapped part of the area during mineral investigation. *Warrier et.al., (1982-83)* studied Meta-ultramafic bodies for Nickel near Sreekandapuram in Cannanore District, Kerala.

The earlier workers of GSI have carried out landslide investigations in the area wherein the study area lies, on different mapping scales. In Karnataka, the geotechnical study was initiated during 2002-2003 for unstable slopes of Cabo hills by *R. Panduranga et al.*, and later the feasibility stage investigation was carried out for the construction of the shore-based test facilities for LCA (Navy) at Dabolim Airfield, Goa by *R. Dharuman*. In Kodagu district, the pioneered works of the Geological Survey of India *A. K. Mishra et al., 2008; K.V. Maruthi et al., 2012, 2013, 2010, 2014; and A.K. Srivastava et al., 2016 & 2018* have carried out landslide investigations since 2007. Among these *A. K. Mishra et al., and K.V. Maruthi et al.*, have done landslide inventory, landslide hazard zonation and post-disaster landslide studies while *A.K. Srivastava et al. 2016*, have done Macro-scale (1:50,000) landslide susceptibility mapping (NLSM) which was a national programme launched by GSI in the year 2014 to generate a seamless landslide susceptibility map of landslide vulnerable areas in the country. The areas that have been classified as high and moderate zones of landslide susceptibility by *A.K. Srivastava et al., 2016 & 2018* were severely affected by landslides during the 2018 monsoon period. *K.V. Maruthi and K.V. Chandran* in the year 2013 carried out landslide susceptibility mapping along the Virajpet – Madikeri – Sulya Road corridor, Coorg district, Karnataka. They carried out this work according to the methodology prescribed by Bureau of India Standards IS 14496 (Part 2): 1998, later modified by the Geological Survey of India. They have recommended geometrical modification of the slope by grading and benching, bio-technical measures of slope protection and proper drainage arrangements. However, these works have not recorded any landslide incidence in the present study area. In field season 2013-14, *K. V. Maruthi* carried out landslide inventory along NH & SH of Ghat

roads in Coorg and Uttar Kannada districts, Karnataka and they have investigated the present study area also. However, in this investigation, no landslide incidence has been recorded in the present study area. During F.S. 2016-17, *Thirdeep K. N and Wagh R. L.* carried out macroscale landslide susceptibility mapping in parts of Kozhikode, Wayanad and Kannur Districts on a 1:50,000 scale falling in parts of toposheets Nos. 48P/12, 48P/16, 49M/9 and 49M/13. A total of 115 landslide incidences were compiled and identified during the field study and the landslide inventory map was prepared. The outcome of this study reveals that the majority of the landslide incidences in the study area are debris slides in nature and are within the gneissic terrain. A significant number of debris flows present within the study area are mainly along the hill slopes of the Kudiyanmala-Kappimala area. Considering the frequency of occurrence of debris flows and the number of incidents in this area, the authors suggested taking up mesoscale landslide susceptibility mapping in this area.

During FS 2016-17, Landslide Susceptibility Mapping in parts of Toposheets no. 48P/07, 48P/11 & 48P/12 were carried out by *A. K. Srivastava and Neha Kumari* to prepare a seamless landslide susceptibility map and spatial (GIS-based) landslide database on a 1:50000 scale using adequate remote sensing and field inputs. During the field studies, 72 slides were observed and recorded, most of the slides were recorded on modified slopes along road sections. The triggering factor for slides in the study area is mainly rainfall which has contributed to an increase in the pore pressure of the weathered rock mass resulting in a reduction of shear strength and subsequent failure. According to the final susceptibility map, about 80.77% map area falls under the low landslide susceptibility zone while 15.70% map area is categorized in the moderate susceptibility zone. About 3.53% map area falls under the high landslide susceptibility zone.

The present study was taken up in pursuance to implement the Ministry of Mines approved Landslide Vision and Strategy Document 2020-2030. The investigation was carried out to generate a Meso-scale (1:10,000) landslide susceptibility map for the study area, to find out the major causative factors of past landslide incidences that occurred in the study area and to suggest generic mitigation/remedial measures so that the risk factor would be minimized. An up-scaled and domain-specific approach was adopted to achieve a quality product. Domain-specific field mapping was carried out to observe and assess the geo-themes of rock-covered and overburden-covered areas separately so that the failure mechanism, landslide material involved, causative factors, and prevailing geological conditions would be understood.

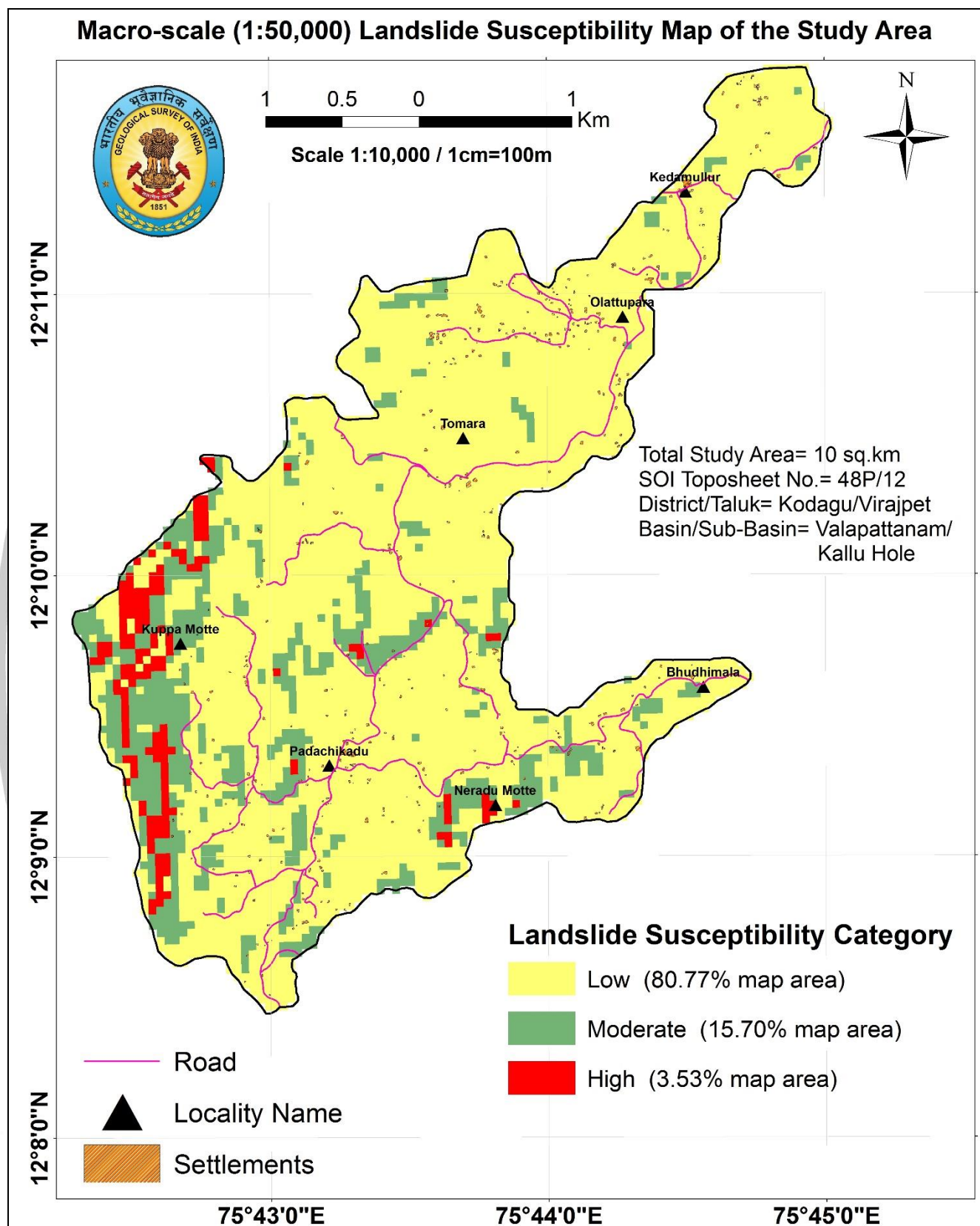


Figure 1.5 Macro-scale (1:50,000) landslide susceptibility map (NLSM) of the study area

Table-1.1: Nature, Quantum and Target of Work Component

Nature of Work		NQT Targets	Achievement during FS 2022-23
1.	Detailed pre-field landslide inventory map including ground deformation, creeps etc. and identification of failure domains	10 sq.km	10 sq.km
2.	Preparation of pre-field thematic geo-factor maps on 10k based on failure domains.		
	a. Land Use/Land Cover Map	10 sq.km	10 sq.km
	b. Drainage Map		10 sq.km
	c. Geomorphology Map / Landform Map		10 sq.km
	d. Slope Morphometry (Slope Angle, Slope Aspect, Slope Curvature, and Relative Relief)		10 sq.km
	e. Slope forming material Map (Geological)		10 sq.km
	f. Stream Power Index Map		10 sq.km
	g. Landslide domain Map		10 sq.km
	h. Overburden thickness Map		10 sq.km
	i. Slope Facet Map		10 sq.km
3.	Field-based studies		
	a. Validation and updation of all thematic maps	10 sq.km	10 sq.km
	b. Data collection for preparation of the Geotechnical map		10 sq.km
	c. Geotechnical field sample collection for determination of geotechnical parameters	30 nos.	32 nos.
4.	Post-field studies and modelling		
	a. Updation and finalization of thematic maps and landslide inventory in the GIS platform.	10 sq.km	10 sq.km
	b. Preparation of Geotechnical map		10 sq.km
5.	Preparation of landslide susceptibility map in GIS platform.	10 sq.km	10 sq.km
6.	Collection of Rainfall data	As per availability	2015-2022 rainfall data collected from Karnataka Natural Disaster Management Centre (KNDMC)

Table-1.2: Total field days spent as per NQT by the officers

Name of the officer	Field days mandatory	Total field days spent
Aijaz Ahmad Bhat, Sr. Geologist	90 days	102 days
Indrani Karmakar, Sr. Geologist (PT)	45 days	41 days
Jobin Jahafar, Sr. Geologist (PT)	45 days	38 days
Dr. R. Sajeev, Director (G)	-	06 days

1.5 Objectives of Work

- To identify slope-failure domains and to prepare domain-specific geo-factor maps in a GIS.
- To rate and weigh relevant geo-factor maps for different failure domains.

- c) To rate and weigh relevant geo-factor maps for different failure domains.
- d) To rate and weigh relevant geo-factor maps for different failure domains.
- e) To integrate the rated and weighted geo-factor maps per identified failure domain in a GIS.
- f) To combine the domain-specific landslide susceptibility models into a combined and classified landslide susceptibility map on a 10k scale.
- g) To qualitatively/quantitatively assess the landslide risk and to frame generic mitigation /management plan on 10k scale for relevant value addition and for direct use by the stakeholders.

1.6 Acknowledgement

The authors wish to thank Additional Director General and HOD, GSI SR, and Dy. Director General, GSI, SU: K&G Bangalore for providing all administrative support. The authors are highly indebted and express their gratitude to Supervisory Officer Dr R. Sajeed Director (G) for providing technical guidance and valuable suggestions during the entire project work. The authors are very grateful to the Director (TC) and the Director & HOO, SU: K&G Bangalore for providing timely technical, logistic, and financial support to execute the project work smoothly. The authors gratefully acknowledge Karnataka State Natural Disaster Monitoring Centre (KSNDMC) for providing available rainfall data. Sincere thanks to the Geotechnical Laboratory, SR for analysis of the samples and provide the data on schedule time without which this report could not completed. Besides, the authors are thankful to the District Administrative Officer of Kodagu district and Virajpet Taluk administration for providing all the support and most importantly the local people/villagers who have rendered immense help and cooperation and providing information during collection of field data.

CHAPTER – 2

GENERAL GEOLOGY AND GEOLOGICAL STRUCTURE

2.1 Regional Geology and Stratigraphic Set-Up

The present study area lies towards the east-southeast of the Coorg Block. Coorg Block is situated in the western Dharwar Craton (WDC). The WDC is mainly comprised of TTG (tonalite–trondhjemite–granodiorite) or Peninsular Gneiss intercalated with highly deformed supracrustal rocks of the Sargur Group having ~3.4–3.0 Ga age (Naqvi and Rogers, 1987; Jayananda et al., 2008). The Coorg Block is a relatively small crustal block located in southern India, sandwiched between the Dharwar Craton in the north and the Neoarchean-Proterozoic crustal blocks to the south. Its western margin is abutting against the ocean along the rifted continental margin of India. It is believed to be an exotic Mesoarchean microcontinent that did not witness any of the subsequent Neoarchean, Paleoproterozoic, and Neoproterozoic tectono-thermal events commonly recorded in the other blocks of southern India. The Coorg Block is bound on the north by the Mercara Shear Zone and to the south by the western extension of the Moyar Shear Zone (Chetty et al., 2012). The Mercara Shear Zone welds the Coorg Block with the Dharwar Craton to the north and is marked by steep gravity gradients (Sunil et al., 2010) suggesting the presence of underplated high-density material in the lower crust. The Mercara Shear Zone is a curvilinear transgressional shear zone that extends for a strike length of more than 100 km and with a width of 20–30 km.

The Coorg Block is dominantly constructed by a suite of arc magmatic rocks including Charnockite, TTG-related granitoids, and felsic volcanic tuffs, together with minor accreted oceanic remnants occurring along the periphery of the block. Coeval mafic and felsic magmatism with magma mixing and mingling in an arc setting characterize the core and the other major domains of the block. The geochronological studies yielded a meso-archean age for the block and the suturing of this block to the Dharwar Craton also happened during the Mesoproterozoic (Santhosh et al 2013, *An exotic Mesoarchean microcontinent: The Coorg Block, southern India, Gondwana Research* 27 (2015) 165–195). Previous studies considered the Coorg Block to be a higher-grade southern extension of the Western Dharwar Craton, with its continuity into the Biligiri Rangan Hills. Earlier the Coorg–Nilgiri–Biligiri Rangan–Salem–Madras Blocks were grouped together and it was considered that the late archean granulite facies metamorphism affected all these blocks (Bhaskar Rao et al., 1992; Peucat et al., 1993; Janardhan et al., 1994; Janardhan and Anto, 1996; Raith et al., 1999; Bhaskar Rao et al., 2003; Devaraju and Janardhan, 2004; Ghosh, 2004; Clark et al., 2009; Sato et al., 2011). Some other studies suggest the Coorg Block is different from other crustal blocks in southern India as the block did not experience the same tectonothermal events that affected the

other blocks. While other blocks have recorded major tectonothermal events at 2.5 Ga, 2.0 Ga, 0.8 Ga, and 0.55 Ga, the Coorg Block has no record of these events. Ishwar-Kumar et al., 2013, opined that the suturing of the Coorg block with the Dharwar craton happened during the Rhodinia assembly and mentioned that the MSZ is connected to the Betsimisaraka suture from Madagascar through Karwar-Kumta region. However, his observations also could not answer the question of how the Coorg block escaped the major tectono-thermal events post-Rhodinia assembly. Abdul Azeez et al., 2015 stated that the Coorg block is sutured to the Dharwar Craton based on the observation of near vertical conductive structures extending from the lower crust to the upper mantle which coincided with the geological transition zone between the two blocks. Some studies suggest that there are minor accreted oceanic remnants present along the periphery of the Coorg Block. The minor amphibolites, BIF and Mg-rich sediments, as well as felsic volcanic layers, might represent remnants of oceanic material accreted onto the arc. Based on all these studies it could be deciphered that the Coorg Block is an exotic block that got sutured with the Indian Subcontinent/Dharwar Craton, however, there are differences in opinion regarding the time of suturing between different workers, which need to be addressed through further research

Table-2.1: Stratigraphic set up of area covered by toposheet 48P/12 after *Geological Survey of India, compiled Geological Map*

Supergroup	Group	Formation	Lithology	Age
		Acid Intrusives	Quartz vein	Neoproterozoic
Southern Granulite Complex	Charnockite		Hornblende Diopside Gneiss	Archean
	Khondalite		Charnockite/Pyroxene Granulite Calc Granulite with Limestone	Archean
Peninsular Gneissic Complex	Peninsular Gneiss-I	Gneisses	Granite Gneiss	Archean
	Wyanad		Amphibolite Garnet-Sillimanite Gneiss + Graphite+Cordierite	Archean

Table-2.2: Lithostratigraphy of the study area deduced from the field observations and established stratigraphy (based on compiled geological map by GSI)

Supergroup	Group	Formation	Lithology	Age
			Laterite	Cenozoic
		Basic Intrusives	Gabbro	Paleoproterozoic
Southern Granulite Complex*	Charnockite		Dolerite	Archean
			High Strained Granite Gneiss	
			Hornblende-Diopside Gneiss	
	Wyanad		Charnockite Amphibolite	Archean

**The area is part of the Coorg block which was earlier considered to be part of the Southern Granulite Terrain, however there are many different scientific opinions regarding the same and it is now widely believed that the blocks are exotic microcontinent which got sutured to the Dharwar Craton in the geological past.*

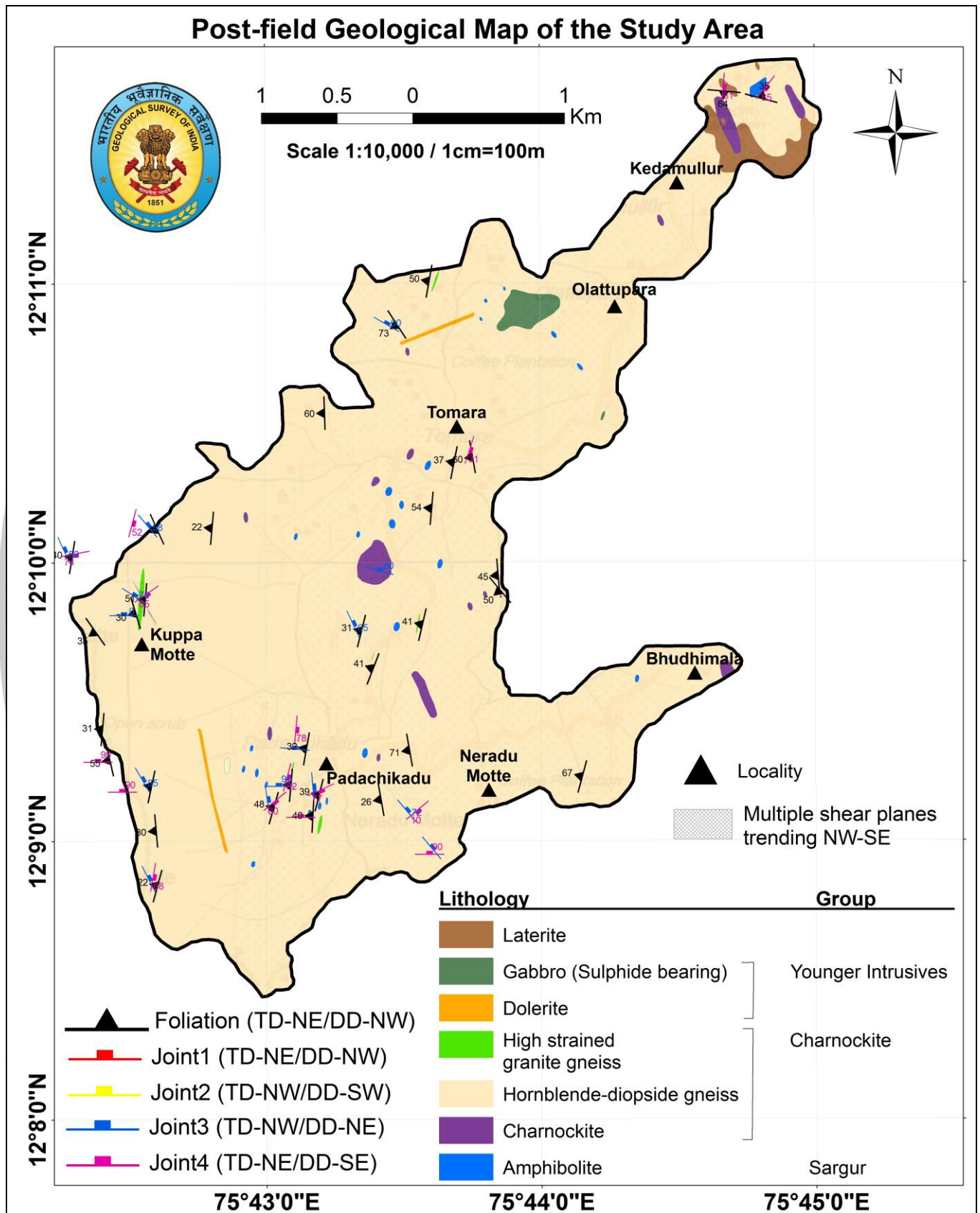


Figure-2.1: Geological Map of the study area on 1:10,000 scale (after Aijaz Ahmad Bhat et al.,)

2.2 Geology of the Study Area

The present study area is occupied by rocks of the Waynad Group which is equivalent to the Sargur Group followed by rocks of the Charnockite clan of rocks of the Coorg Block and Younger Intrusives. In the study area, except the younger intrusive (basic intrusive of Paleoproterozoic age), all the rocks belong to the Archean age. Based on the earlier workers, these rocks are mostly of Meso-Archean age. The earlier compiled geological map (1:50,000 scale) has been modified/updated to the present scale of observation pertaining to the study area (1:10,000) based on the field observations, without any detailed petrography.

2.2.1 Waynad/Sargur Group

Waynad Group of Supracrustal Rocks is equivalent to the Sargur Group of Rocks of the Dharwar Craton. The main rock types seen as part of this group are Garnet-Sillimanite-Biotite Gneiss, Kyanite-Fuchsite-Muscovite-Quartz Schist, Hornblende-Biotite Schist, Amphibolite, Quartz-Sericite Schist/Quartz-Mica Schist, Meta Ultramafites and Garnet-Sillimanite-Biotite Gneiss + Graphite (this is the main member of the Waynad Group and occurs as large bodies)

2.2.2 Charnockite Group

Charnockite constitutes the major rock type in the crustal blocks of Southern Granulite Terrain (SGT) in India. The Charnockite from the Coorg block are metaluminous and represents magnesian, calc-alkaline to calcic series similar to fractionated I-type granites. These Charnockite are dominantly composed of orthopyroxene, clinopyroxene, hornblende, biotite, K-feldspar, plagioclase, ilmenite, and minor garnet. The Charnockites are mostly coarse to medium-grained and mafic to intermediate composition with orthopyroxene, hornblende, and biotite. The intermediate varieties contain clinopyroxene also.

2.2.3 Younger Intrusive Rocks

Younger intrusive suites of the Coorg block in general comprise potassic syenites anorthosites, gabbros and dolerites. These intrusives are of Neoproterozoic age. However, in the study area, only the Dolerite and Gabbro are present.

Amphibolite: This rock type is shiny black to dark green colour, medium to coarse-grained seen as enclaves or narrow bands varying in orientation from NNE-SSW to NW-SE within the country rock, which is hornblende diopside gneiss. It is mostly composed of amphibole and plagioclase in varying proportions with a minor amount of quartz and biotite. Exposures and in general presence of this rock are mostly towards the central and southern part of the study area. In the amphibolite of Coorg, Hornblende is seen extensively replacing the pyroxenes and the volume of Plagioclase present is <15% (Prantick *et al.*,).

Charnockite: The Charnockite suite of rocks of Coorg Block varies from Enderbite to Charnockite which contains K-feldspar, quartz, plagioclase, and orthopyroxene with a minor amount of garnet and hornblende and the proportion of plagioclase, quartz and K-feldspars vary widely (Prantick Santra et al., 2021). The Charnockite Group also comprises Mafic Granulites which are very dark in colour and contain garnet, clinopyroxene, orthopyroxene, plagioclase, and hornblende with minor amounts of magnetite, quartz and pyrite (Prantick Santra et al., 2021). The granoblastic texture is very prominently observed in the hand specimen.

Hornblende Diopside Gneiss: Hornblende Diopside Gneiss is otherwise Charnockite Gneiss in the Coorg area. Megascopically, the rock shows a granoblastic texture with the mineral boundaries fused together. It is leucocratic to mesocratic, medium to coarse-grained consisting of quartz, feldspar, pyroxene, and biotite. This rock type forms the country rock of the study area. The rock exhibits crude foliation and is mostly seen as similar to Charnockite. Even though the rock forms the country rock in the study area, it is almost soil-covered with a few exposures. The foliations in the rock range from NNW-SSE to NNE to SSW with dip of the foliations showing both NW and SW orientations.

Granite Gneiss: Towards the western part of the study area a small band of sheared granite gneiss has been observed. The rock is light pink to whitish pink in colour, composed of K-feldspar, quartz, and biotite. Quartz is seen showing a platy appearance and has formed ribbons and the planar structure formed due to deformation corroborates with the regional foliation. The feldspar crystals are seen altered due to shearing, while elongated ribbons of quartz are still preserved.

Gabbro: Gabbro is seen towards the northern part of the study area as small patches. The rock comprises Plagioclase and pyroxenes with some megascopic sulphide minerals. Plagioclases are present as long disoriented laths and clinopyroxenes are seen as granular. All the interstitial spaces are filled by plagioclase. The sulphides present are disseminated and are not economically significant.

Dolerite: Dolerite dykes are seen towards the northern and southern parts of the study area. There are only two prominent dykes in the study area with the northern dyke showing an orientation of NE-SW and the southern counterpart showing an orientation of NNE-SSW. The rock is dark colored and fine-grained intruding the hornblende diopside gneiss. The rock predominantly consists of Plagioclase, hornblende, and quartz. The outcrops of Dolerite are very limited in the field area due to the thick soil cover.

Laterite: Laterite is a leached residue of lateritization of rocks rich in alumina, iron and silica. Laterite of the study area occurs as thick blankets above the crystalline rocks with brick red colour containing cavities filled with clay. Generally, laterite capping is present over the rocks of all domains in the southern granulite terrain, due to heavy rainfall. In the present study area, which is part of the Coorg Block, laterite

is present towards the northern part of the study area. It is observed that the laterite capping here is associated with the Charnockites and is almost exclusively restricted to this lithology.

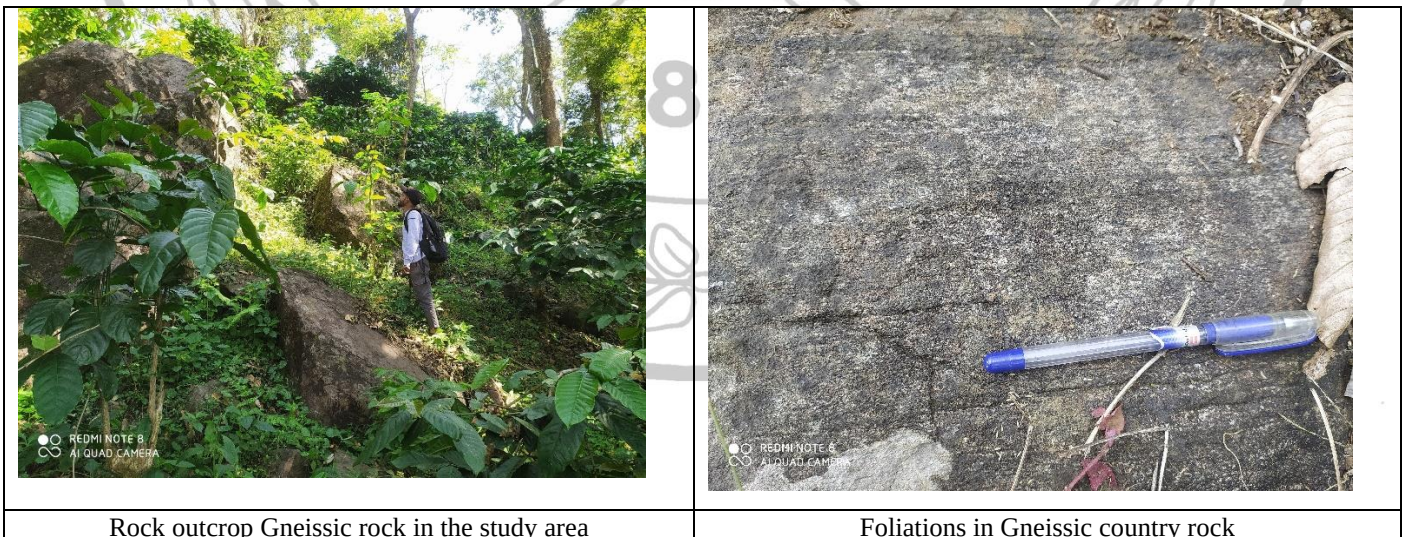
	
Amphibolite of Coorg Block	Weathered Amphibolite
	
Charnockite of Coorg Block	Charnockite of Coorg Block
	
Hornblende Diopside Gneiss in Coorg Block	Hornblende Diopside Gneiss in Coorg Block



Figure-2.2: Field photographs of rocks present in the study area

2.3 Geological Structure in the Study Area

The present study area is primarily an overburden domain with the northern part having several rock outcrops forming a rock domain. The rocks are part of the Coorg Block which was earlier considered as part of the Southern Granulite terrain. The rocks in the study area have foliation trending from NNW-SSE to NNE-SSW with dips ranging from 20° to 70° degrees showing both WNW and WSW dip directions. The average trend of northwesterly dipping foliation is 10° with an average dip of 40° and the average trend of southwesterly dipping foliations is 338° with an average dip of 48° . These foliation data are mostly recorded in the gneisses which form the country rock of the study area. The Charnockites in the area do not show any well-developed foliations and at the same time show very crude foliation. In addition to the foliation, there are 4 prominent joint planes with a fifth less prominent joint plane. The first joint set (J1) is striking along NE-SW with an average strike of 46° . The average dip of this joint set is 52° towards Northwest. J2 has a WNW-ESE strike with an average trend of 297° having a dip varying from sub-vertical to vertical (68° to 90°) with a dip direction varying from South to southwest with an average direction of 185 having an average sub-vertical dip. Joint set J3 has strikes varying from almost E-W to almost N-S having an average strike of 319 with varying dips with an average sub-vertical dip of 67° with NE dip direction. The fourth prominent joint set J4 has an average orientation of NE-SW (43°) with varying dips from shallow to vertical with an average sub-vertical dip of 70° towards the North. Compared to the four prominent joint sets, the fifth joint set is less prominent and is recorded at a few places only. This joint set has a N-S orientation with a sub-vertical to vertical dip. The foliations in the area are also along the same direction and are almost parallel with this joint set. These five joint sets along with foliation are making different interference patterns in the study area by which the rock types are breaking down (physical weathering) even into smaller orthogonal pieces.



	
Outcrop showing foliation plane and joint planes.	Intersection of different joint planes in sheared granite of the field area
	
Jointed Rocks of the Thorah area, where the landslide occurred during 2019	Orthogonal rock fragment generated due to intersection of 2 or more joint planes
	
Fragmentation of rock as a result of joint interference	Wedge formation in rock mass leading to intense fracturing and subsequent movement

Figure-2.3: Field photographs of geological structural elements present in the rocks present in the study area

Table-2.3: Geometrical parameters of foliation and five different joint sets developed in the study area.

Foliation with NW Dip					
Loc. no.	Y	X	Strike	Dip	Azimuth
27	12.16036667	75.72290278	21	41	291
32	12.16296667	75.72588056	13	41	283
46	12.17263889	75.72781944	11	37	281
84	12.15277778	75.71960556	14	39	284
85	12.15148889	75.7192	3	40	273
90	12.15202778	75.71685833	16	48	286
92	12.15553611	75.71885	10	32	280
94	12.15334444	75.71787778	5	38	275
348	12.16989167	75.72645833	5	54	275
510	12.1835	75.72636111	10	50	280
526	12.16446111	75.70908611	5	51	275
554	12.16258889	75.72219444	14	31	284
757	12.15386111	75.73555	15	67	285
808	12.16702222	75.70466389	9	40	279
828	12.15670556	75.70647222	5	31	275
832a	12.1533	75.70943333	12	25	282
841	12.147375	75.70976944	15	22	285
850	12.16874167	75.71313889	5	22	275
Mean			10	40	280
Foliation with SW Dip					
Loc. no.	Y	X	Strike	Dip	Azimuth
5	12.15536944	75.72509444	350	71	260
51	12.17291389	75.72896667	350	60	260
187	12.19453889	75.74451111	275	64	185
347	12.18073056	75.72444444	327	73	237
372	12.175575	75.71999167	358	60	268
444	12.16480556	75.73066667	320	50	230
475	12.16583056	75.73049722	355	45	265

793	12.15243056	75.72336389	350	26	260
804	12.16856389	75.70984167	336	30	246
810	12.16358333	75.70850833	343	30	253
821	12.16238889	75.70611111	325	35	235
826	12.15481111	75.70691389	347	55	257
845	12.15059167	75.70971667	355	30	265
Mean			338	48	248

Joint Set J1					
Loc. no.	Y	X	Strike	Dip	Azimuth
27	12.16036667	75.72290278	57	58	327
90	12.15202778	75.71685833	65	32	335
175	12.1946	75.74683889	5	60	275
187	12.19453889	75.74451111	23	59	293
372	12.175575	75.71999167	75	80	345
791	12.151475	75.72550556	26	41	296
804	12.16856389	75.70984167	50	60	320
850	12.16874167	75.71313889	70	32	340
Mean			46	53	316
Joint Set J2					
Loc. no.	Y	X	Strike	Dip	Azimuth
5	12.15536944	75.72509444	273	68	183
46	12.17263889	75.72781944	290	74	200
90	12.15202778	75.71685833	323	85	233
526	12.16446111	75.70908611	290	84	200
791	12.151475	75.72550556	330	80	240
805	12.16856667	75.70852778	300	38	210
810	12.16358333	75.70850833	295	81	205
828	12.15670556	75.70647222	285	90	0
832a	12.1533	75.70943333	285	66	195
Mean			297	74	185

Joint Set J3					
Loc. no.	Y	X	Strike	Dip	Azimuth
84	12.15277778	75.71960556	355	79	85
90	12.15202778	75.71685833	352	64	82
92	12.15553611	75.71885	275	80	5
94	12.15334444	75.71787778	290	90	0
347	12.18073056	75.72444444	300	60	30
429	12.16611111	75.724	285	80	15
526	12.16446111	75.70908611	304	73	34
554	12.16258889	75.72219444	335	65	65
780	12.14926111	75.72700833	320	64	50
791	12.151475	75.72550556	320	72	50
804	12.16856389	75.70984167	320	58	50
808	12.16702222	75.70466389	336	52	66
810	12.16358333	75.70850833	340	0	0
832a	12.1533	75.70943333	330	85	60
841	12.147375	75.70976944	333	85	63
Mean			320	67	44
Joint Set J4					
Loc. no.	Y	X	Strike	Dip	Azimuth
51	12.17291389	75.72896667	18	31	108
84	12.15277778	75.71960556	65	77	155
85	12.15148889	75.7192	70	90	0
90	12.15202778	75.71685833	50	60	140
94	12.15334444	75.71787778	15	82	105
175	12.1946	75.74683889	38	85	128
187	12.19453889	75.74451111	5	61	95
526	12.16446111	75.70908611	55	85	145
588	12.156175	75.71849722	5	78	95
780	12.14926111	75.72700833	70	90	0
791	12.151475	75.72550556	50	10	140

805	12.16856667	75.70852778	15	52	105
808	12.16702222	75.70466389	79	74	169
825	12.15301111	75.70838889	66	90	0
826	12.15481111	75.70691389	85	90	0
841	12.147375	75.70976944	10	68	100
			43	70	93
Joint Set J5					
Loc. no.	Y	X	Strike	Dip	Azimuth
805	12.16857	75.70853	90	56	0
821	12.16239	75.70611	90	85	0
857	12.16842	75.71309	90	90	0
Mean			90	77	0

CHAPTER – 3

LANDSLIDE INVENTORY

Historic information on landslide occurrences is considered as the fundamental part of landslide susceptibility studies which gives shrewdness into the frequency, volume, damage and types of the landslide phenomena (*Van Westen et al., 2006; Regmi et al., 2014; Youssef et al., 2014*). Therefore, landslide occurrences in the past and present are key to susceptibility modelling, future spatial prediction, hazard and vulnerability analysis. Landslide inventory map provides the basic information for evaluating the landslide hazard or risk and it is a pre-requisite for landslide susceptibility studies (*Guzzetti et al., 1999; Regmi et al., 2014*). In the present study, the landslide inventory was prepared initially from different data sources during pre-field studies and was later validated and updated during field investigation along with different geo-parametric attributes. In pre-field studies, various remote sensing data sources, topographic maps and previously reported landslide inventories by earlier workers have been utilized.

3.1 Remote Sensing Data Inputs

In pre-field studies, freely available satellite images were accessed in Google Earth and were utilized for the demarcation of visible landslide scars and runout boundaries. Landslide locations earlier recorded by previous workers in the present study area were also explored and added to the pre-field landslide inventory. It is worthy to utilize freely available satellite images in Google Earth for landslide boundary demarcation but there are few constraints of having vegetation cover and date of imagery capture. Due to that reason, several landslides were not demarcated during pre-field studies however those landslides were recorded during field study. In the Western Ghats, it is commonly seen that the landslide-affected areas quickly come under vegetation cover after their occurrences. This factor minimizes the level of visibility and demarcation of landslide boundaries on satellite images in Google Earth. Besides the date of imagery capture plays a very important role as the images taken after any landslide event give a clear picture of slope failures. Therefore, there was the least number of landslide incidences demarcated by utilizing satellite images in Google Earth during the pre-field studies. Keeping these constraints in consideration it was necessary to field check, validation and updation of pre-field landslide inventory and other thematic maps during field study even though high-resolution imageries were utilized. These constraints were carefully handled and rectified during field studies in the present investigation.

3.2 Landslide Inventory and Its Correlation with NLSM Study

Preparation of a landslide inventory map is important in landslide susceptibility mapping to document the type, distribution, pattern and period of slope failures and to utilize it in the assessment of

landslide susceptibility and risk of an area. Landslide inventory is a unique and most adopted tool for validation of the landslide susceptibility map of an area and to develop the successive rate of susceptibility prediction. During the investigation in the study area, a total of 37 nos. of landslide incidences have been reported as shown in *Figure 3.4*. All these landslide incidences were approached during field study and were thoroughly investigated on the ground. These landslide incidences were investigated as per the GSI standard format of landslide geo-parametric datasheet. The details of geo-parametric attributes of each landslide incidence are shown in *Annexure II*.

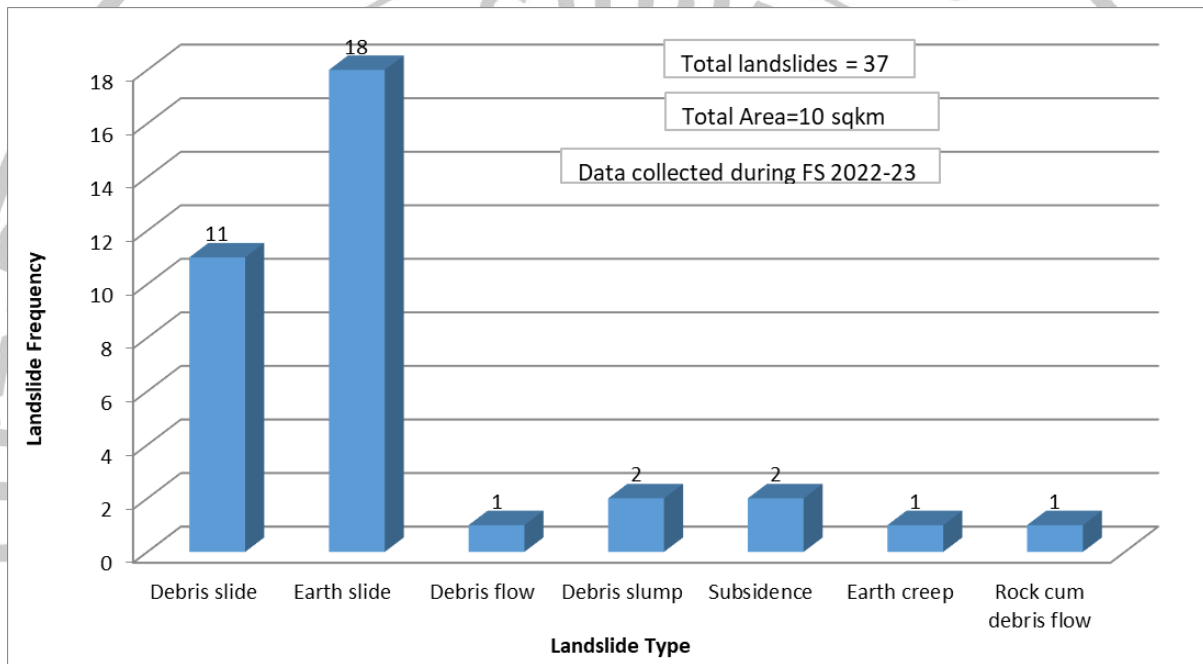


Figure 3.1: Statistics of landslide incidences and their types in the study area

The NLSM susceptibility map of the study area has been correlated with the present landslide inventory in which it has been found that maximum landslide incidences (26 nos.) occurred in low susceptibility areas which should not happen. However, 8 nos. of landslide incidences occurred in the moderate susceptibility area and 3 nos. of landslide incidences occurred in the high susceptibility area (*figure-3.2*). The present up-scaled study has revealed that there was a high influence of natural as well as anthropogenic causative factors in low susceptibility areas (*Figure 3.2*). The toe erosion along stream banks by high water action and frequent cut-slopes given for road and settlement construction in low susceptibility areas were seen as major causative factors. The present study has come up with a worrisome finding that almost 50% of properties in the study area have gone through high-risk factors and this thing can be seen in all susceptibility categories in the NLSM study (*figure-3.3*). That is why the Tohra landslide incidence has affected the properties at a large scale because the Tohra landslide occurred in high susceptibility area where the low and high-risk factor ratio is 2:1. The Present study has concluded

that first if risk factor analysis had been carried out in Tohra village area before the incidence, the disastrous effect would have been minimised. Second, the up-scaled landslide study like Meso-scale (1:10,000) should be carried out in hilly areas of Karnataka & Goa to reveal such aspects that have not been taken into consideration in the NLSM study.

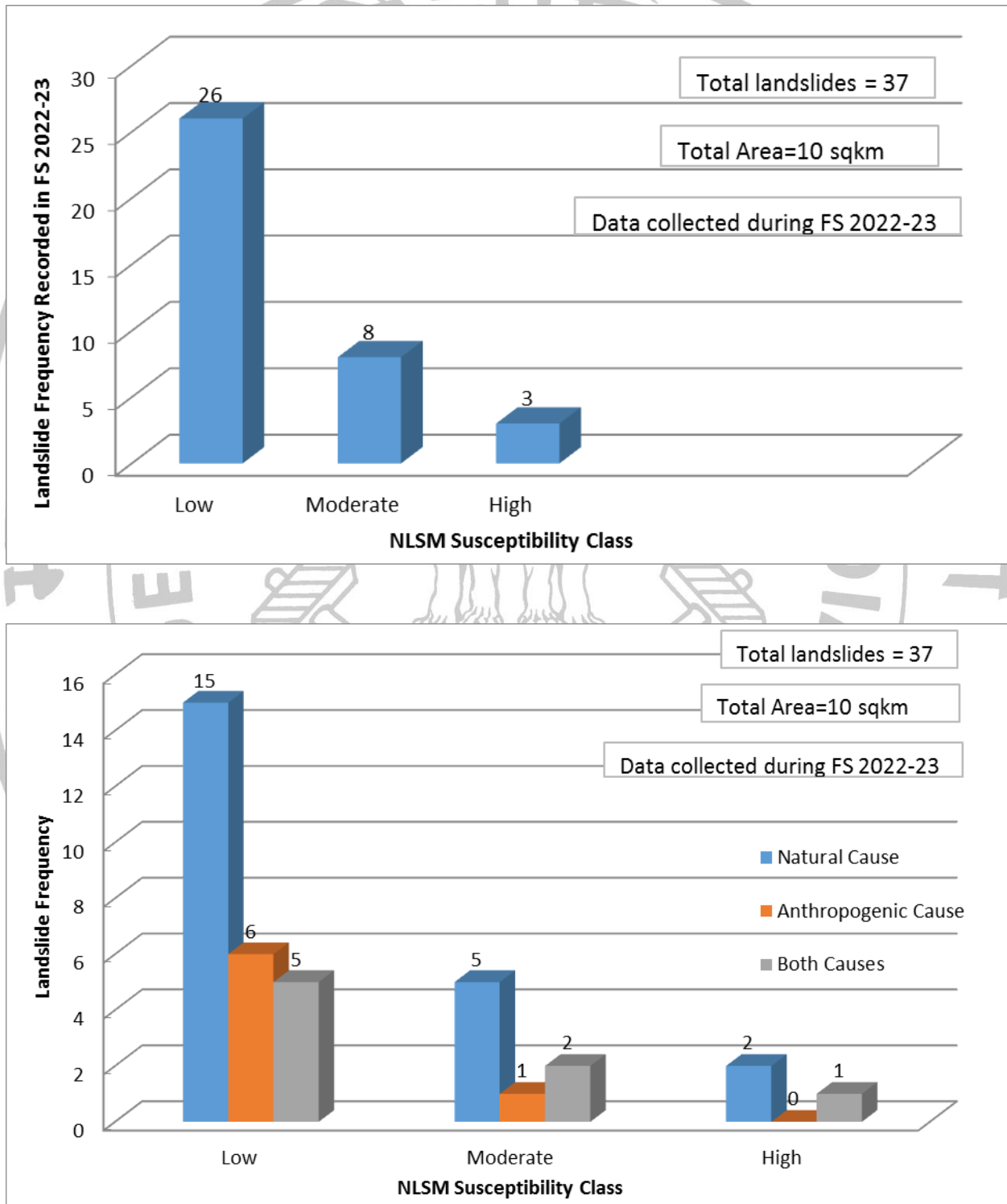


Figure-3.2: Correlation of landslide inventory recorded in present study with NLSM data

Table-3.1: Details of landslide incidences reported in the study area.

Landslide No.	Locality Name	Area (m ³)	Domain Type	Movement Type	Risk Type	NLSM Susc. Type	Latitude	Longitude
1	Korthikad, Thomara village	500	Debris	Slide	I	Moderate	12°9' 15.540" N	75°43' 5.380" E
2	Korthikad, Thomara village	500	Cutslope	Slide	I	Low	12°9' 14.920" N	75°42' 55.170" E
3	Kedhamallur village near Govt. School	1000	Cutslope	Slide	I	Low	12°11' 4.710" N	75°44' 23.660" E
4	Kedhamallur village	3200	Debris	Slide	III	Low	12°11' 17.590" N	75°44' 36.270" E
5	Kedhamallur village	4000	Debris	Slide	III	Low	12°11' 35.530" N	75°44' 43.650" E
6	Kedhamallur village	9000	Debris	Slide	III	Moderate	12°11' 42.840" N	75°44' 54.220" E
7	Kedhamallur village	500	Debris	Slide	I	Low	12°11' 33.740" N	75°44' 49.300" E
8	Kedhamallur village	125	Debris	Slump	I	Low	12°11' 39.880" N	75°44' 41.030" E
9	Thomara village	2000	Debris	Slide	III	Low	12°9' 1.750" N	75°43' 11.530" E
10	Thomara village	4500	Cutslope	Slide	I	Low	12°10' 16.890" N	75°43' 27.960" E
11	Tharmetta Kedhamallur	500	Cutslope	Slide	I	Low	12°10' 58.020" N	75°43' 58.830" E
12	Palangala Kedhamallur	500	Earth	Creep	III	Low	12°10' 46.100" N	75°43' 28.800" E
13	Thomara village	1500	Debris	Slide	I	Low	12°10' 25.640" N	75°43' 25.520" E
14	Thomara village	4000	Earth	Slide	III	Low	12°10' 28.970" N	75°43' 30.130" E
15	Thomara village	9000	Earth	Slide	III	Low	12°10' 15.810" N	75°43' 31.970" E
16	Thomara village	125	Debris	Slump	III	Low	12°10' 13.610" N	75°43' 33.850" E
17	Thomara village	2400	Cutslope	Slide	III	Moderate	12°9' 50.040" N	75°43' 14.060" E
18	Thomara village	1600	Debris	Slide	III	Moderate	12°9' 54.280" N	75°43' 49.350" E

19	Thomara village	1600	Debris	Flow	III	High	12°9' 46.650" N	75°43' 48.920" E
20	Thomara village	5000	Debris	Slide	III	Low	12°9' 40.090" N	75°43' 45.650" E
21	Thomara village	500	Cutslope	Slide	III	Low	12°9' 30.700" N	75°43' 51.000" E
22	Thomara village	500	Earth	Slide	III	Low	12°9' 36.800" N	75°43' 50.400" E
23	Thomara village	500	Debris	Slide	III	Low	12°10' 54.200" N	75°43' 32.300" E
24	Thomara village	12500000	Rock cum debris	Flow	I	High	12°9' 51.029" N	75°42' 32.599" E
25	Thomara village	7500	Cutslope	Slide	I	Low	12°9' 52.560" N	75°43' 37.270" E
26	Thomara village	1600	Debris	Slide	I	Moderate	12°9' 43.000" N	75°43' 25.020" E
27	Thomara village	800	Debris	Slide	I	Low	12°8' 58.500" N	75°42' 43.900" E
28	Thomara village	500	Debris	Slide	III	Low	12°8' 52.360" N	75°42' 50.090" E
29	Thomara village	500	Debris	Subsidence	III	Low	12°9' 29.570" N	75°44' 24.590" E
30	Kottachi Kedhamallur village	1800	Debris	Slide	I	Low	12°9' 28.160" N	75°44' 9.320" E
31	Thomara village	10000	Debris	Slide	III	High	12°9' 11.900" N	75°43' 46.100" E
32	Thomara village	500	Debris	Subsidence	I	Moderate	12°9' 10.490" N	75°43' 36.270" E
33	Thomara village	800	Debris	Slide	II	Low	12°9' 8.370" N	75°43' 18.320" E
34	Thomara village	500	Debris	Slide	III	Moderate	12°9' 11.800" N	75°42' 35.050" E
35	Thomara village	500	Debris	Slide	I	Low	12°9' 25.600" N	75°43' 27.070" E
36	Thomara village	600	Debris	Slide	I	Low	12°9' 33.900" N	75°43' 23.400" E
37	Thomara village	500	Debris	Slide	III	Moderate	12°10' 12.390" N	75°42' 51.580" E

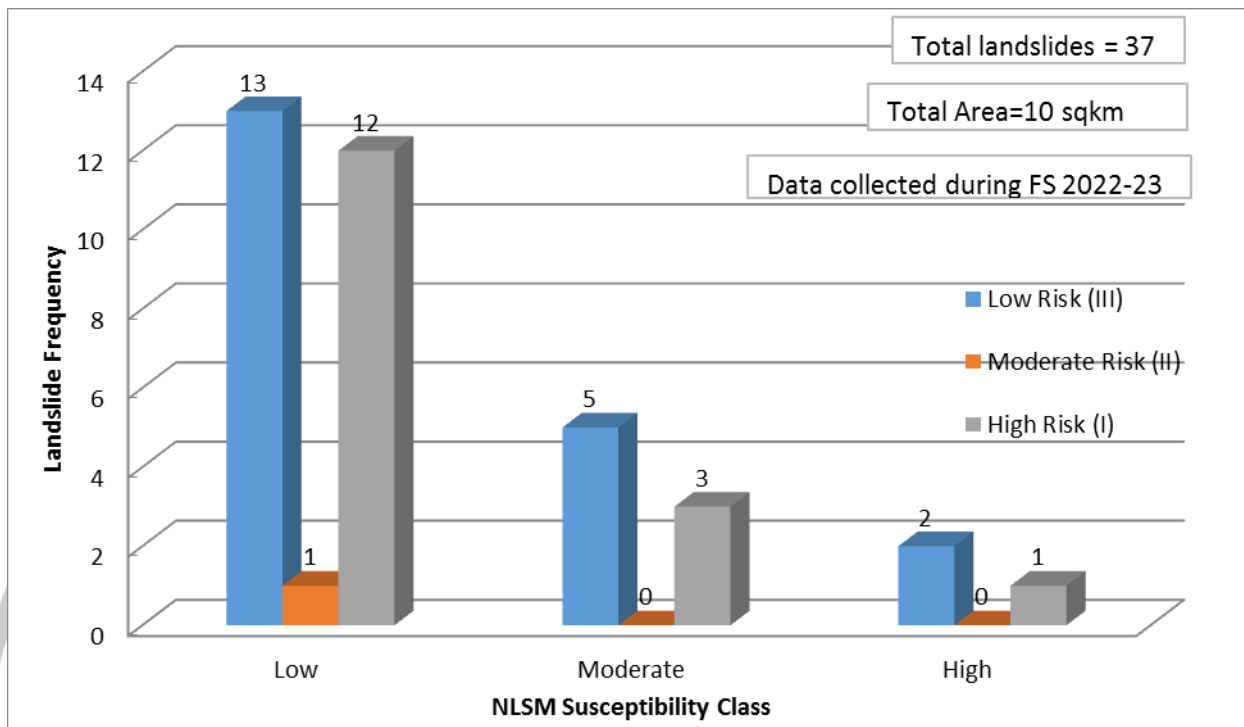


Figure-3.3: Risk factor recorded in present study area in different susceptibility classes of NLSM study

3.3 Landslide Types and Their Causative Factors

Most of the landslide incidences recorded in the study area are distributed in the overburden domain whereas very few rock failures were found at a small scale except Tohra landslide incidence. In the overburden domain the material has moved in a shallow translational path and landslide incidences have smaller dimensions (Approximately, 10m x 10m). Almost all the reported landslide incidences have been triggered by rainfall during the monsoon period of the past several years, particularly in 2018 and 2019 years. Out of 37 nos. landslides incidences reported in the study area, 16 nos. are debris slides; 19 nos. are earth slides and 1 no. rockslide cum debris flow. However, among the debris and earth slides, 4 nos. are debris slumps or subsidence; 1 no. debris flow and 1 no. earth creep (figure 3.1). The rockslide cum debris flow in Tohra village in 2019 has impacted the livelihood at a larger scale as the debris has hit several living settlements in which 9 people and several livestock have died.

The rainfall-induced landslides depend on rainfall intensity, sediment saturation limit, geotechnical parameters, slope morphometry behaviour and performance of drainage morphometric parameters. Both natural as well as anthropogenic-related causes were found responsible for landslide occurrences in the study area. Multiple causative factors both natural as well as anthropogenic have acted. In natural causes, the factors including high slope gradient, the high influx of runoff water, erosion of stream bank material or toe cut of natural slopes by high water action and favourable joint interference pattern for detachment

of rock fragments are responsible. These natural causes came into work by incessant rainfall triggers. Several surface cracks have been developed in the overburden domain material during the rainfall period which is a surface manifestation of overburden material with high tensile strength. The streams with large catchment areas received runoff waters in large quantities that flew with high speed due to which stream bank material eroded. The erosion of stream bank material which always forms the base of the uprising slope, created instability in the uprising slopes that lead to several slope failures in the area. Different joint sets/discontinuity planes interference with each other in the study area due to which several rock-covered slopes were found daylighted. This joint interference factor was found to be a major genetic cause in Tohra landslide incidence.

In anthropogenic causes, cutting of natural slopes for road & settlement construction for both domestic as well as commercial use and modification of natural slopes for cultivation purposes are included. The unplanned/unscientific way of cutting natural slopes can be dominantly seen in the study area. The cut slopes are left without any reinforcement support due to which the uprising slopes seem highly vulnerable to failures during the rainfall period. During the rainfall period, the cut-slopes given on moderate to steep gradient slopes have increased their unit mass slowly and failed under the gravity effect in under-saturated conditions. This process has led to occur small dimensional and shallow surface landslides along roads and in the surroundings of settlements. But the large dimensional and deep surface landslides were also recorded where the overburden material has allowed further saturation deep into the surface on slopes having deep cut-slopes.

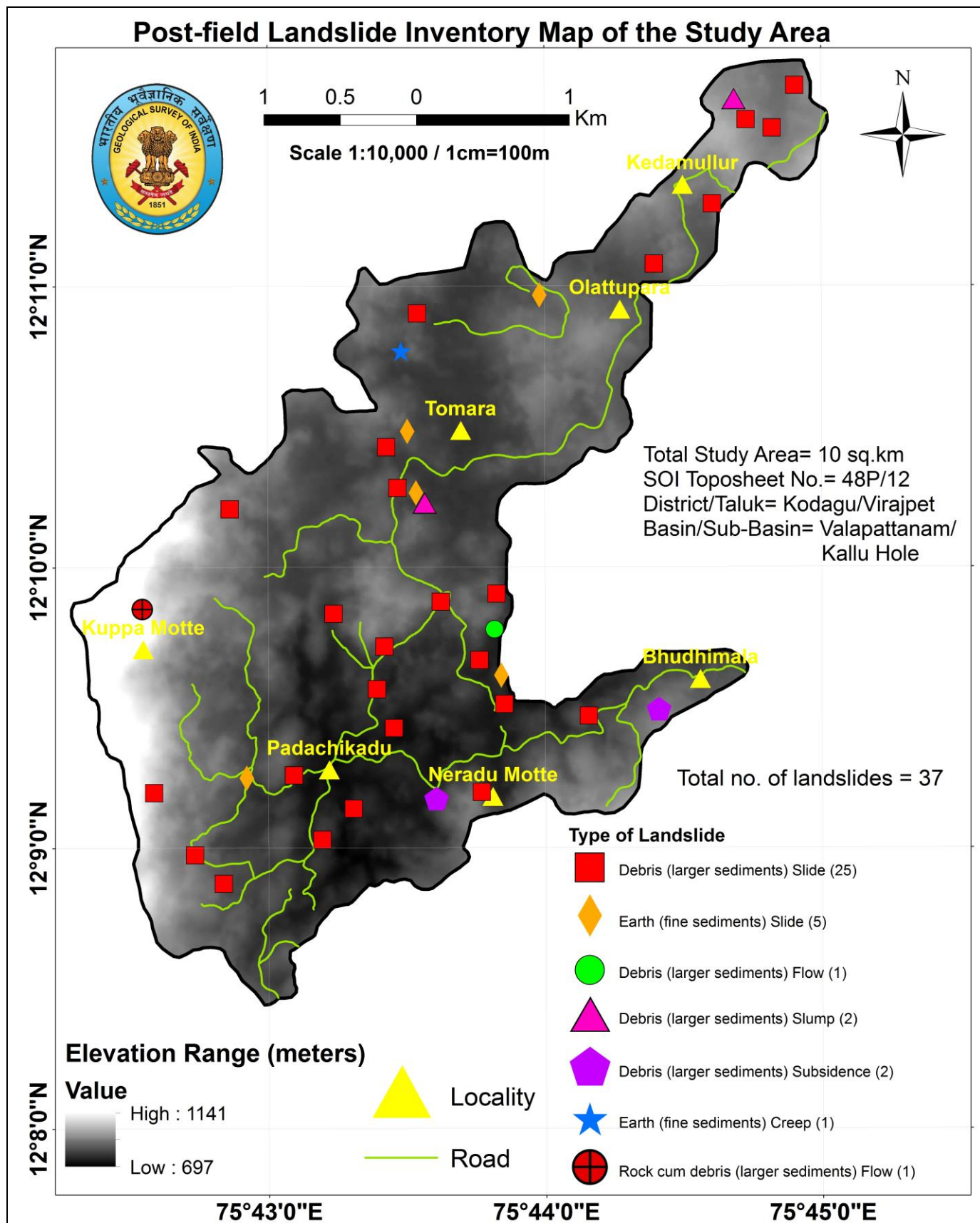


Figure-3.4: Landslide inventory map of the study area



A) Cut-slope failure in Korthikad Thomara village
(12°09'14.92"N/75°42'55.17"E)



B) Cut-slope failure in Thomara village
(12°10'16.89"N/75°43'27.96"E)



C) Rock cum debris flow in Thomara village (Tohra landslide)
(12°09'52.06"N/75°43'32.71" E)



D) View of flow path of Tohra landslide



E) Cut-slope failure in Thomara village
(12°09' 52.56"N/75°43' 37.27" E)



F) Cut-slope failure in Kottachi Kedhamallur village
(12°09'28.16"N/75°44'9.32" E)



G) Debris slide occurred in Thomara village due to toe erosion
(12°09'8.37"N/75°43'18.32"E)



H) Rock wedge came out due to favorable joint interference
(12°10'1.28"N/75°43'16.79"E)



I) View of runout distance of rock cum debris flow in Thomara village (Tohra landslide)
(12°09'49.16"N/75°42'28.94"E)



J) Rock wedge failure due to favorable joint interference
(12°09'14.23"N/75°42'28.95"E)



K) Rock wedge failure due to favorable joint interference
(12°09'11.37"N/75°42'34.31"E)



L) Debris slide occurred in Thomara village due to toe erosion
(12°09'25.6"N/75°43'27.07"E)

Figure-3.5: List of field photographs of different landslide types (A to L) recorded in the study area

CHAPTER – 4

GEO-THEMATIC MAPPING AND LANDSLIDE SUSCEPTIBILITY IN DIFFERENT LANDSLIDE FAILURE DOMAINS

4.1 Concept of Geo-Factor Map and Landslide Failure Domain

A geo-factor map is a spatially prepared geographic theme which shows a particular feature class with a specific geographic area. This map is of any kind of surface, subsurface features, or their parametric theme showing variations at smaller or larger scales which can accelerate any kind of earth's mass movement. Recent studies on landslide/mass movement have gained advanced methods of predicting slope failure susceptibility by analyzing and integrating various feature classes of geo-themes/geo-factors. Integration of various kinds of themes on the desired mapping scale and adopting a precise modelling methodology leads to preparing a categorized landslide susceptibility map. In the present investigation, the upscaled mapping methodology is adopted for the preparation of various geo-factor feature classes which are generic in nature. A landslide failure domain-based approach is adopted in the present investigation for predicting landslide susceptibility in each failure domain with defined responsible causative factors (see Table 4.1). The relevant geo-factor maps in each landslide failure domain were prepared by incorporating both remote sensing as well as field inputs to enhance the qualitative property of each feature class. Although many geo-factors are being acted together in the occurrence of landslides in the study area, the focus was given to the most relevant and responsible geo-factor themes. By definition, a landslide failure domain is characterized by distinct and categorized units on the earth's surface which comprise well-defined earth-forming material of either rock or overburden. Broadly, the landslide failure domain can be the rockslide domain, rockfall domain in rock-covered areas or it can be debris slide/earth slide domain in overburden-covered slopes. There can be cut-slope domains both in rock-covered and overburden-covered domains after getting natural or man-made modifications. Each domain type is characterized by several thematic geo-factor feature classes as well as certain inherent geotechnical properties commonly known as variables that control the slope stability condition (see Table 4.1).

Table 4.1: Landslide Failure domains and their relevant thematic geo-factors

Failure Domain	Field Variables	Thematic maps
Rockslide	1. Daylighted slope 2. Poor rock mass 3. Joint frequency	a. Kinematic failure map (Planar & Wedge) b. Geotechnical map (Rock)
Rockfall	1. Daylighted slope	a. Kinematic failure map (Toppling)

	2. Poor rock mass 3. Joint frequency	b. Geotechnical map (Rock)
Debris slide and Earth slide	1. Rill or gully erosion 2. Micro landform 3. Strength of material (C & ϕ) 4. Vegetation cover and root 5. Slope angle variations 6. Slope covered/forming material 7. Intensity of rock weathering	a. Stream Power Index (SPI) map b. Landform map c. Geotechnical map (Overburden) d. Landuse/landcover map e. High erosive power stream (HEPS) map f. Slope gradient map

4.2 Methodology

Landslide susceptibility mapping is a practical approach for the categorization of hill slopes into zones of varying degrees of susceptibility based on the weightage of prevailing geo-factor themes. There are several methods to carry out landslide susceptibility mapping based on a knowledge-based/data-driven approach on regional scales (1:50000). However, methodologies/guidelines for landslide susceptibility mapping on a larger scale (1:5000/10000) are very few. Among these (Ghoshal T, 2013) proposed a multi-thematic and deterministic cum heuristic approach for the landslide susceptibility mapping on Meso-scale (1:10000) and this model was having high relevance in the present study. The present study is conducted as per the GSI SOP for Meso Scale Landslide Susceptibility Mapping, 2021 in which a terrain-specific rating system has been suggested in separate landslide failure domains.

In the present study, a pixel of 10m resolution has been taken as a mapping unit because it is easy to integrate data in GIS for spatial analysis and mathematical calculations. However, the slope facet map is used for field mapping use only. The geo-factor thematic maps for each landslide failure domain are being prepared by incorporating; pre-field-based inputs from remote sensing sources; field mapping-based inputs and laboratory-based inputs. The relevance of each geo-factor thematic map is being quantified in each landslide failure domain to ensure that the causative factor of one single landslide failure domain would not be extrapolated to other landslide failure domains. CartoDEM 10m derived geo-factor thematic maps (slope angle, stream power index, landform, slope aspect) were prepared in the pre-field study and were validated in field mapping. More than 75% of data from the pre-field study has been found satisfactory during the field validation. The preparation of landslide inventory is important for any model to validate the susceptibility score map at the final. By keeping this thing on priority, the landslide inventory comprising 37 nos. of landslide incidences, has been prepared precisely, initially from multi-temporal satellite images through Google Earth, data from old reports of GSI and other literature. Later it

was validated and updated during field studies. In field mapping, the natural hill slopes were surveyed and categorized into overburden and rock domains. The overburden domain has been further categorized based on slope-forming material type and its shear parameters (Cohesion and angle of internal friction) whereas rocky slopes were categorized based on RMR_{basic} .

In the post-field study, several geo-factor thematic maps were finalized after incorporating the field mapping inputs and the laboratory inputs. The LSER ratings of relevant geo-factor thematic classes in each landslide failure domain were determined heuristically after considering the study area-specific conditions. All rated geo-factor thematic maps were integrated in GIS software by using the Weighted Multi-class Index Overlay method. The categorization of the final landslide susceptibility score map of each landslide failure domain into low, moderate, and high has been performed by considering the satisfactory level of field visualization assessment of hill slope vulnerability to failures and the validation of the susceptibility score map by landslide inventory.

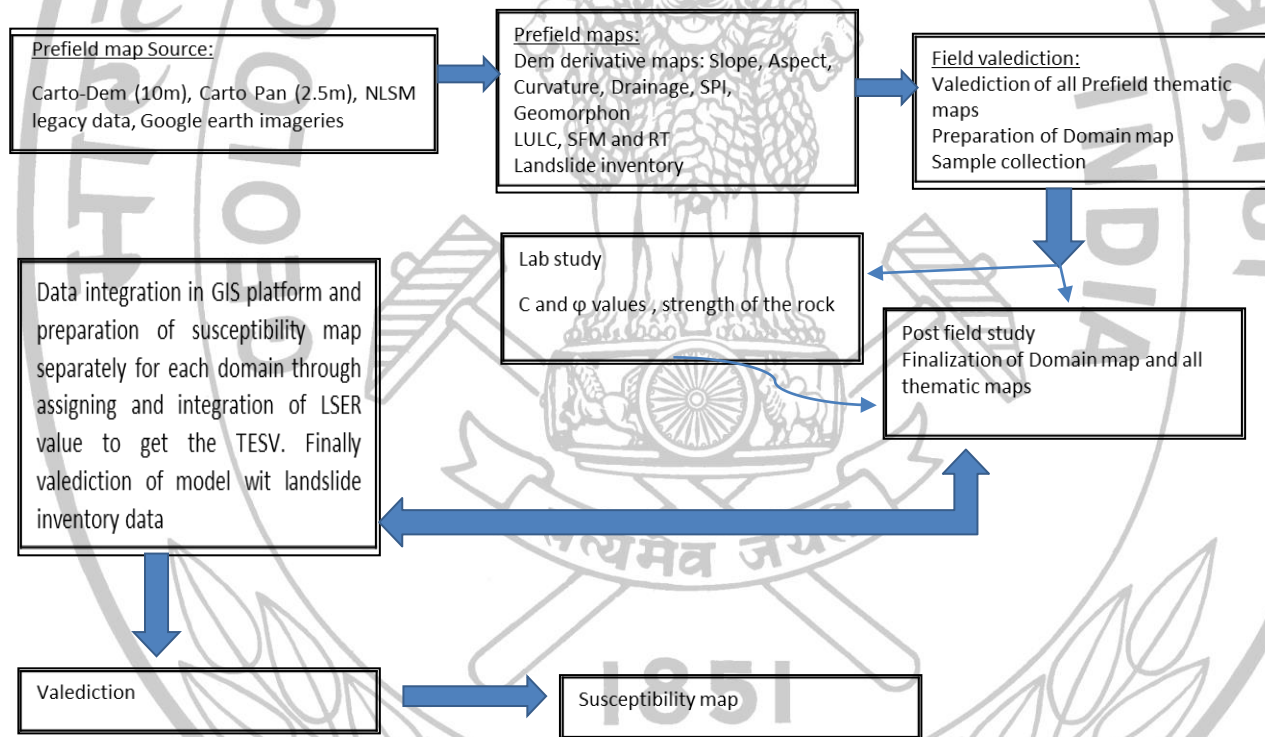


Figure-4.1: Flow chart showing methodology for the preparation of Meso-scale susceptibility map

4.3 Rock Slide and Rock Fall Domains

The rockslide and rock fall domains are failure domains restricted to the rocky slopes on the earth's surface. The stability of rock slopes is significantly influenced by the structural elements of the rock on the slope. Structural elements refer to naturally occurring weak planes in the rock such as bedding planes, joints and faults which are generally termed discontinuities (Aijaz A Bhat et. al., 2021). The

significance of discontinuities is that they are planes of weakness in the intact and much stronger rock which tends to fail preferentially along these surfaces. The rock failure types, rockslide, and rockfall are very often determined by the orientation of discontinuities often dip direction and dip amount with respect to the orientation of the corresponding slope. In the present study, the significance of the orientation of discontinuities in the rock and the orientation of the corresponding slope is taken as an advantage to determine the type of failure that may occur in rock domains shown in Figure 4.2. The very purpose of studying the rockslide and rockfall domains separately is to select the most relevant variables that will determine the strength of the rock mass. Apart from the slope angle map, the kinematic failure analysis and rock mass rating (RMR_{basic}) are the two geo-factors that have been taken into account for landslide susceptibility modelling in both the rockslide and rockfall domain.

4.3.1 Kinematic Failure Analysis

The kinematic failure analysis means identifying possible modes of slope failure by determining the influence of the discontinuities on slope stability, which involves studying the relationship between the orientation of the discontinuity and the slope face. The analysis of this relationship is possible only after the well-planned geological mapping on the desired scale in which different sets of discontinuities in rock would be recorded as much as possible by the field Geologist.

In the present study, the data on the orientation of the discontinuities and the slope faces has been recorded in rock slopes through field-based geological mapping techniques. The recorded data has been geometrically classified into different sets of discontinuities (see Table 4.3) to use in kinematic failure analysis. There is a maximum of 5 sets of discontinuities including the foliation plane which exists in rocks in the study area. The kinematic failure analysis is being done to identify the potential failures of the planar, wedge, and topple by adopting Markland's test for kinematic failures. The data of orientation of different sets of discontinuity planes are being fed in GIS software using a fishnet toolset as a 10m x 10m polygon for identifying planar and topple failures. However, for identifying the wedge failure, the stereo net projections for each single data set of discontinuity planes are prepared. The resulting trend and plunge data of each intersection are also fed in GIS using a 10m x 10m fishnet polygon. For either plane or wedge failure to take place, it is fundamental that the dip of the sliding plane in the case of plane failure or the plunge of the line of intersection in the case of wedge failure, be less than the dip of the slope face. That is, the sliding surface "daylights" in the slope face.

For a toppling failure to occur, the dip direction of the discontinuities dipping into the face must be within about 10° of the dip direction of the face so that a series of slabs are formed parallel to the face. Also, the dip of the planes must be steep enough for the interlayer slip to occur. Moreover, in the case of planar failure, the dip of the sliding plane must be greater than the angle of internal friction (ϕ) and in the

case of wedge failure, the plunge of the line of intersection must be greater than the average friction angle of the two slide planes.

The relationship between the direction in which the block of rock will slide and the orientation of the slope face can be readily identified by plotting the discontinuity data on the stereonet. However, it does not account the external forces such as water pressures or reinforcement procedures. Therefore, the usual practice is to use kinematic analysis to identify potentially unstable rock outcrops followed by a detailed stability analysis of those rock outcrops. In the present study, the slope face direction and slope angle which were used in the kinematic analysis are derived from CartoDEM 10m and the angle of internal friction (ϕ) has been proxy determined from RMR_{basic} of the corresponding rock outcrop (see table-4.2) as suggested by GHRM Division, GSI, CHQ, Kolkata. The critical condition to failure in each pixel was calculated through given formulas as per Markland's test. The critical condition "0" was considered a no-failure condition.

Table 4.2: Relationship between the RMR and angle of internal friction.

Property of Rock	Class				
RMR Value	100-81	80-61	60-41	40-21	<20
Rock Quality	Very Good	Good	Fair	Poor	Very Poor
Angle of internal friction	>45	45-35	34-25	24-15	<15

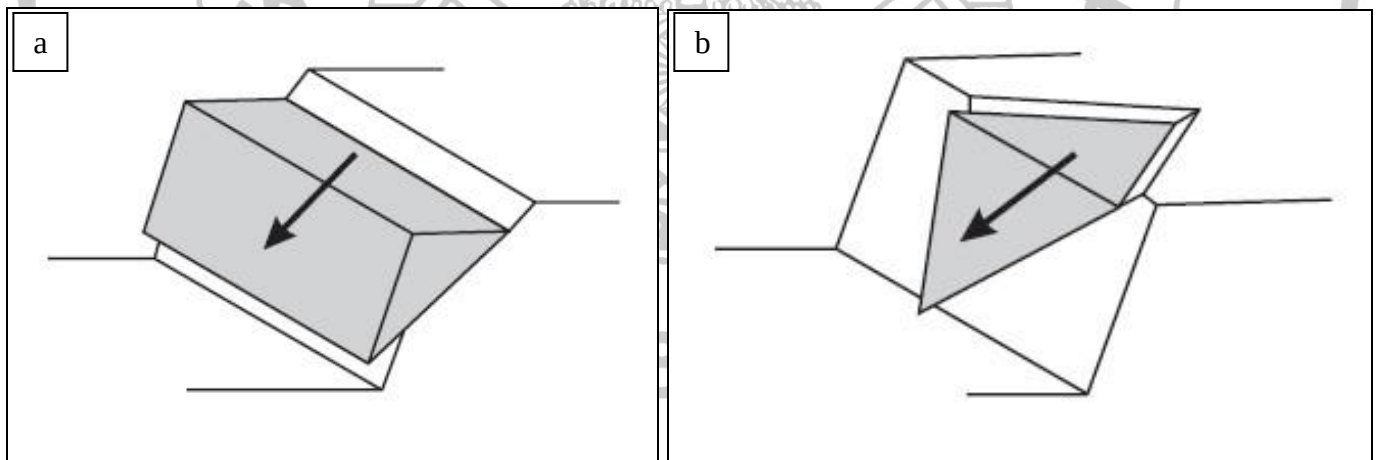


Figure-4.2: Block diagrams for (a) planar failure; (b) wedge failure on a daylighted slope

In case of planar failure, the critical condition to failure in each pixel is calculated by assigning class algorithm condition in ArcGIS platform as “**angle of internal friction of rock mass < dip amount of corresponding discontinuity plane < corresponding slope angle**” (as per the SOP guidelines).

In case of wedge failure, the critical condition to failure in each pixel is calculated by assigning class algorithm condition in ArcGIS platform as “**angle of internal friction of rock mass < plunge amount of intersection of corresponding discontinuity planes < corresponding slope angle**” (as per the SOP guidelines).

In case of toppling failure, the critical condition to failure in each pixel is calculated by assigning class algorithm condition in ArcGIS platform as “**corresponding slope angle $\geq$ angle of internal friction of rock mass + (90°- dip amount of corresponding discontinuity plane)**” (as per the SOP guidelines).

Table 4.3: Geometrically classified data of different sets of discontinuities (J1, J2, J3, J4 and Foliation) recorded in the study area and their interference-based rock wedges

Rock Outcrops Having 2 Joint Sets						
Location no.	Y	X	DA_2set_1	DD_2set_1	DA_2set_2	DD_2set_2
821	12.16238889	75.70611111	35	235	85	0
826	12.15481111	75.70691389	55	257	90	0
828	12.15670556	75.70647222	31	275	90	0
850	12.16874167	75.71313889	22	275	32	340
Rock Wedges Formed on Rock outcrops having 2 Joint Sets						
Location no.	Y	X	W1_Trend	W1_Plunge	Stereo-net No.	
821	12.16238889	75.70611111	273	29	1	
826	12.15481111	75.70691389	265	55	2	
828	12.15670556	75.70647222	285	30	3	
850	12.16874167	75.71313889	289	22	4	

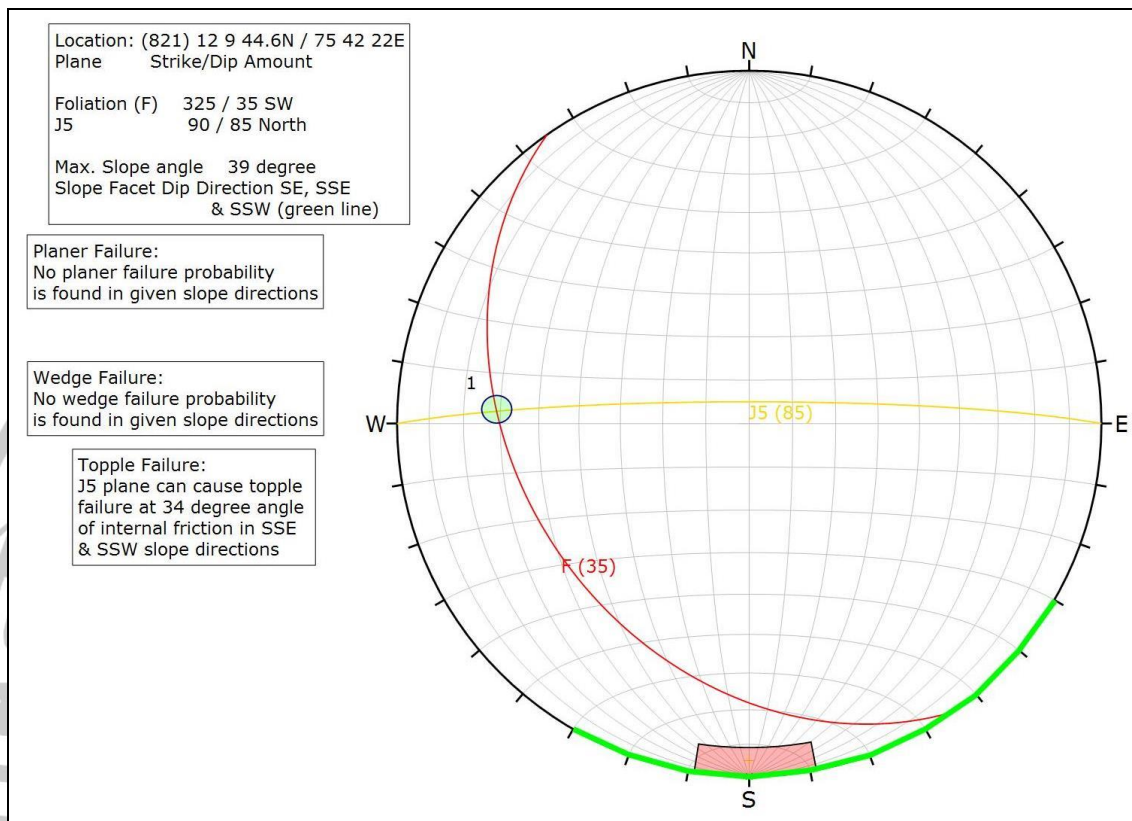
Rock Outcrops Having 3 Joint Sets								
Location no.	Y	X	DA_3set_1	DD_3set_1	DA_3set_2	DD_3set_2	DA_3set_3	DD_3set_3
804	12.16856389	75.70984167	30	246	60	320	58	50
805	12.16856667	75.70852778	38	210	52	105	56	0
832a	12.1533	75.70943333	25	282	66	195	85	60
841	12.147375	75.70976944	22	285	85	63	68	100

Rock Wedges Formed on Rock outcrops having 3 Joint Sets									
Location no.	Y	X	W1_Trend	W1_Plunge	W2_Trend	W2_Plunge	W3_Trend	W3_Plunge	Stereo-net no.
804	12.16856389	75.70984167	250	30	324	7	7	50	5
805	12.16856667	75.70852778	168	30	280	15	56	40	6
832a	12.1533	75.70943333	282	25	331	17	130	76	7
841	12.147375	75.70976944	335	15	11	3	144	61	8

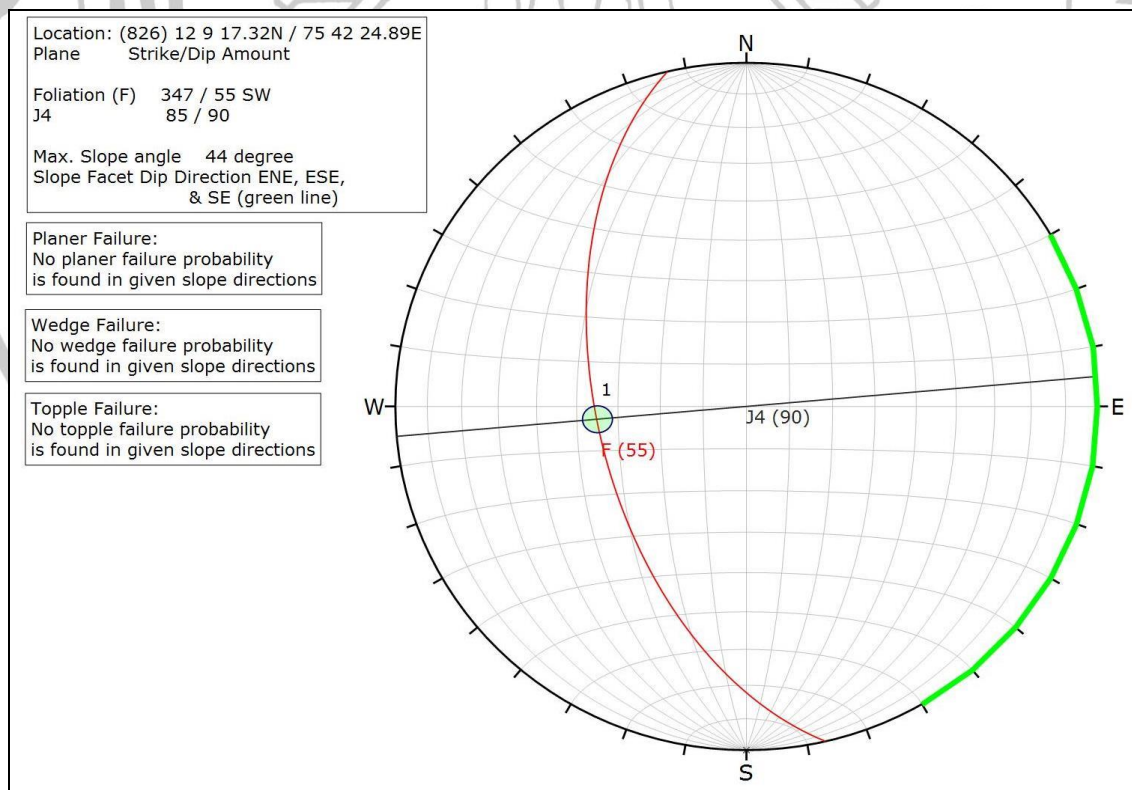
Rock Outcrops Having 4 Joint Sets										
Location no.	Y	X	DA_4set_1	DD_4set_1	DA_4set_2	DD_4set_2	DA_4set_3	DD_4set_3	DA_4set_4	DD_4set_4
526	12.16446111	75.70908611	51	275	84	200	73	34	85	145

Rock Wedges Formed on Rock outcrops having 4 Joint Sets															
Location no.	Y	X	W1_Trend	W1_Plunge	W2_Trend	W2_Plunge	W3_Trend	W3_Plunge	W4_Trend	W4_Plunge	W5_Trend	W5_Plunge	W6_Trend	W6_Plunge	Stereo-net no.
526	12.16446111	75.70908611	283	51	320	41	231	41	114	31	183	84	69	70	9

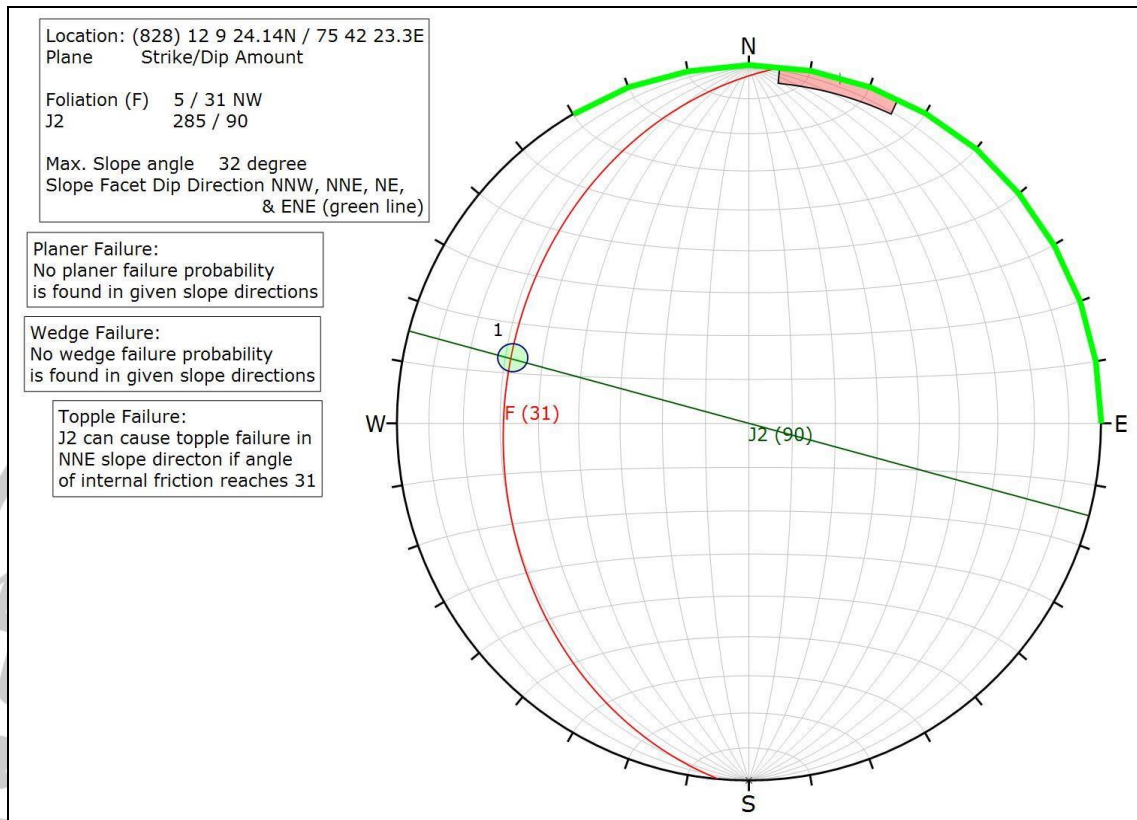
Stereo nets for Rock Outcrops in the study area:



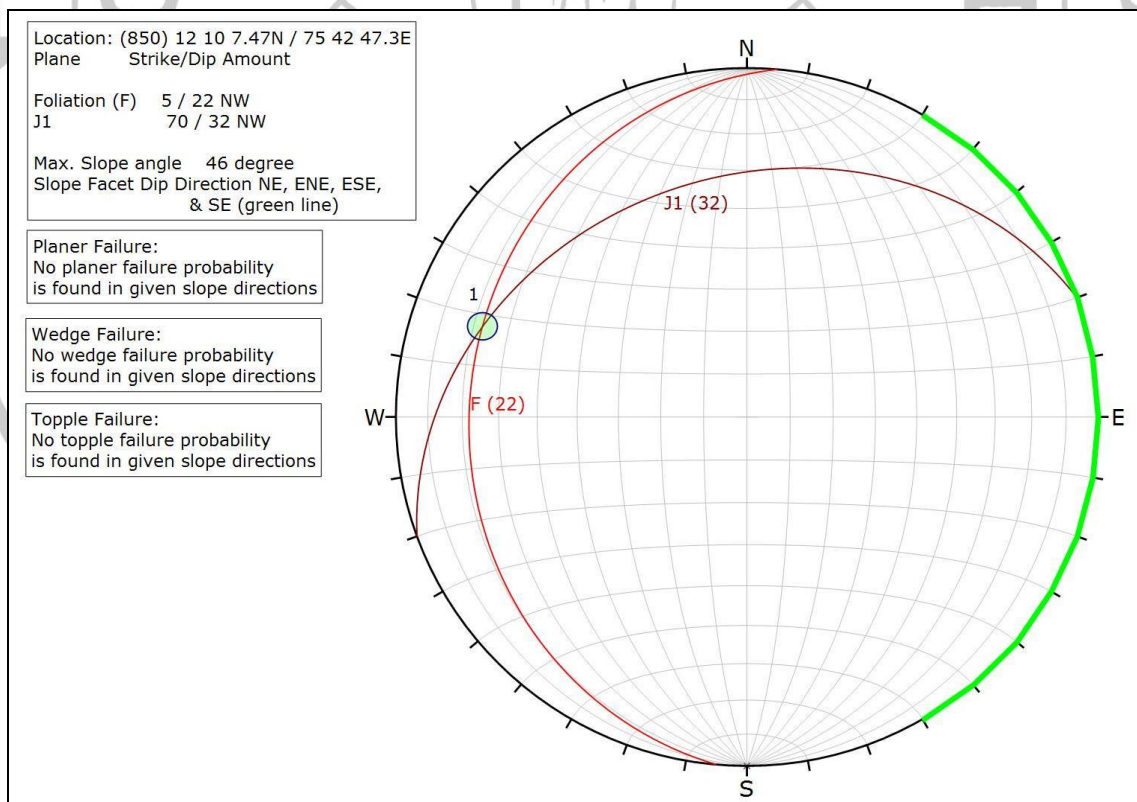
Stereonet No. 1



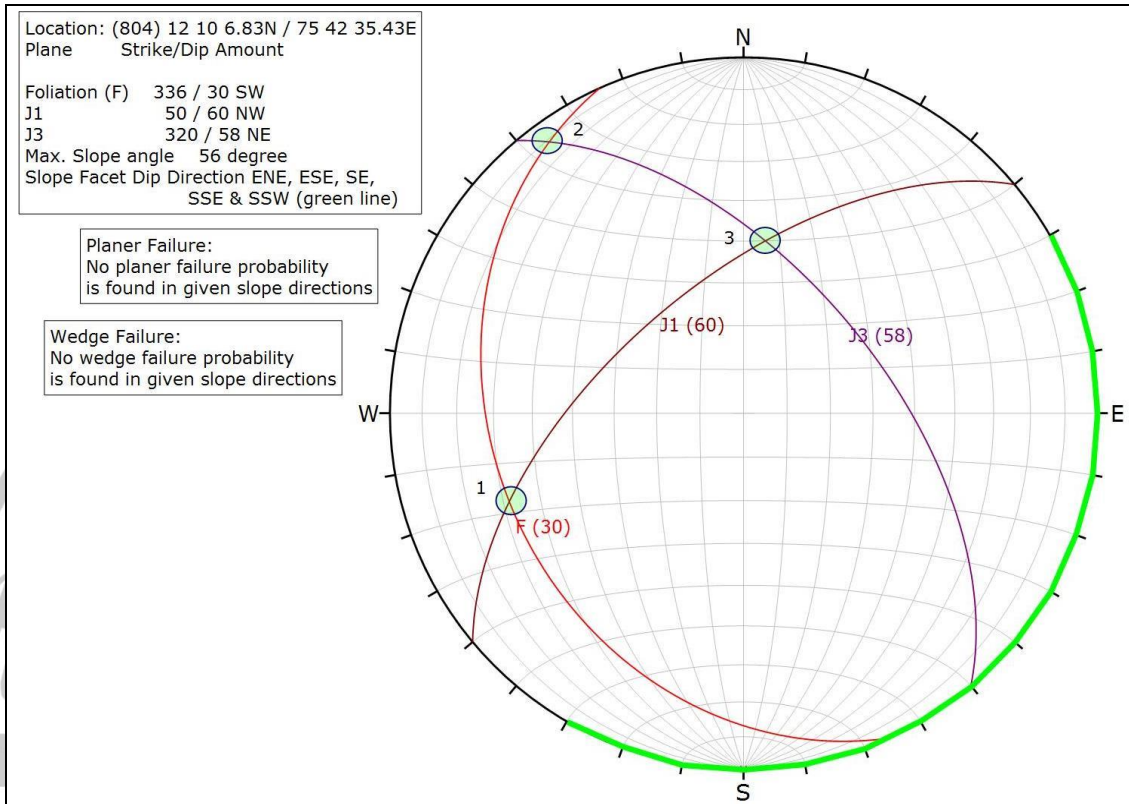
Stereonet No. 2



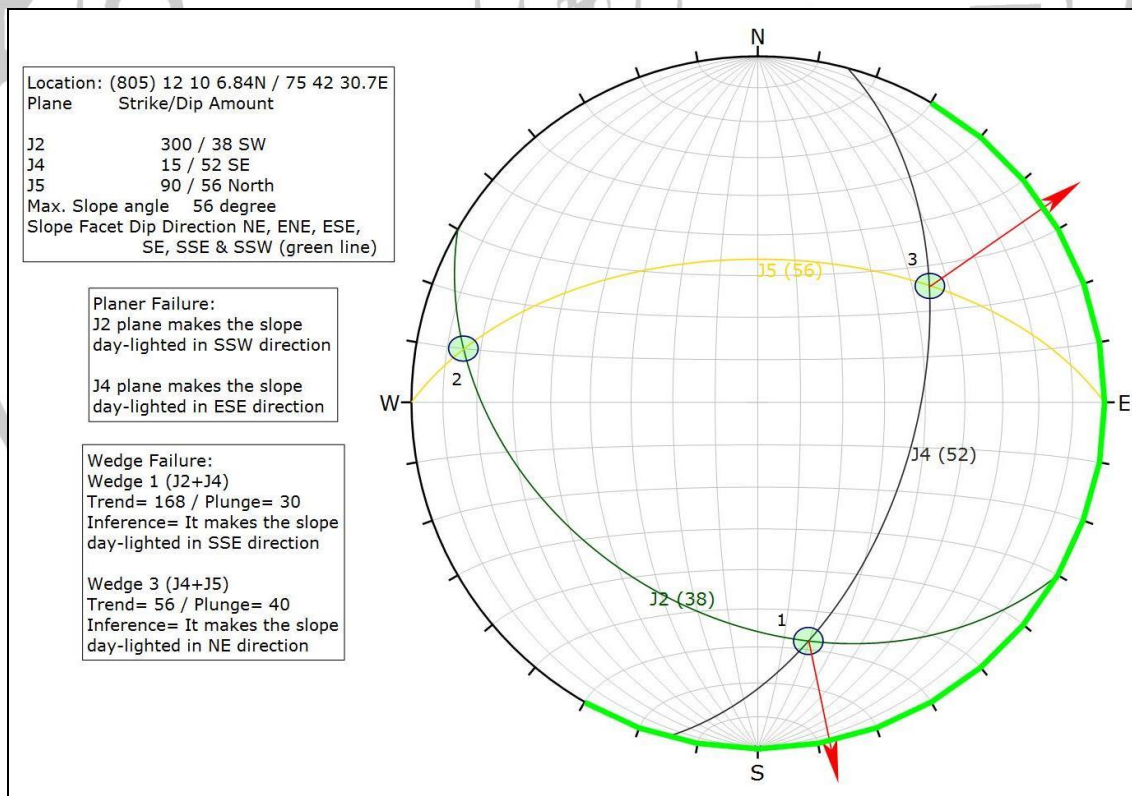
Stereonet No. 3



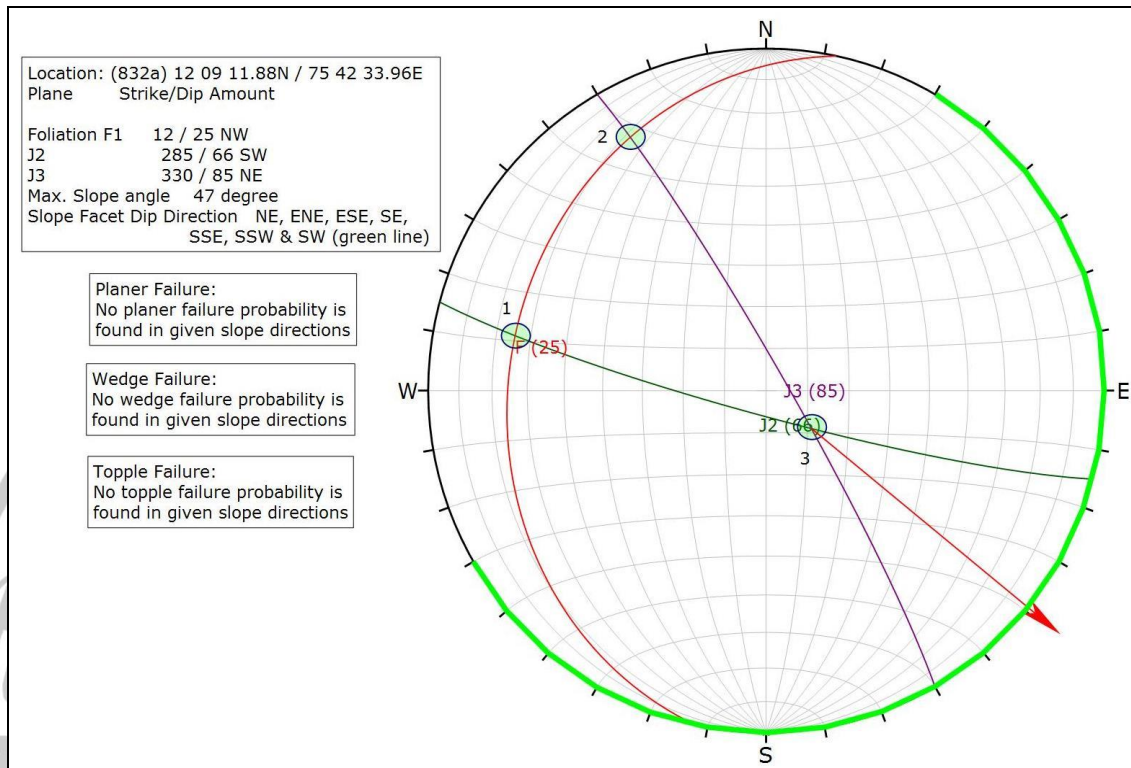
Stereonet No. 4



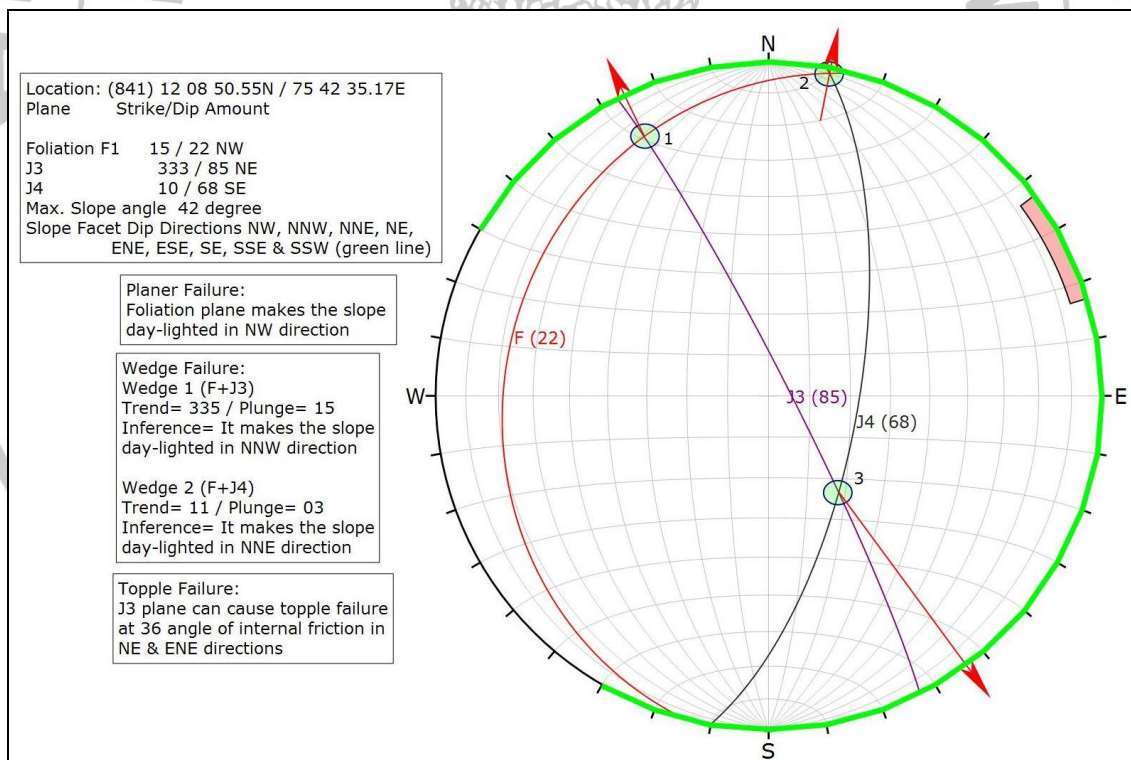
Stereonet No. 5



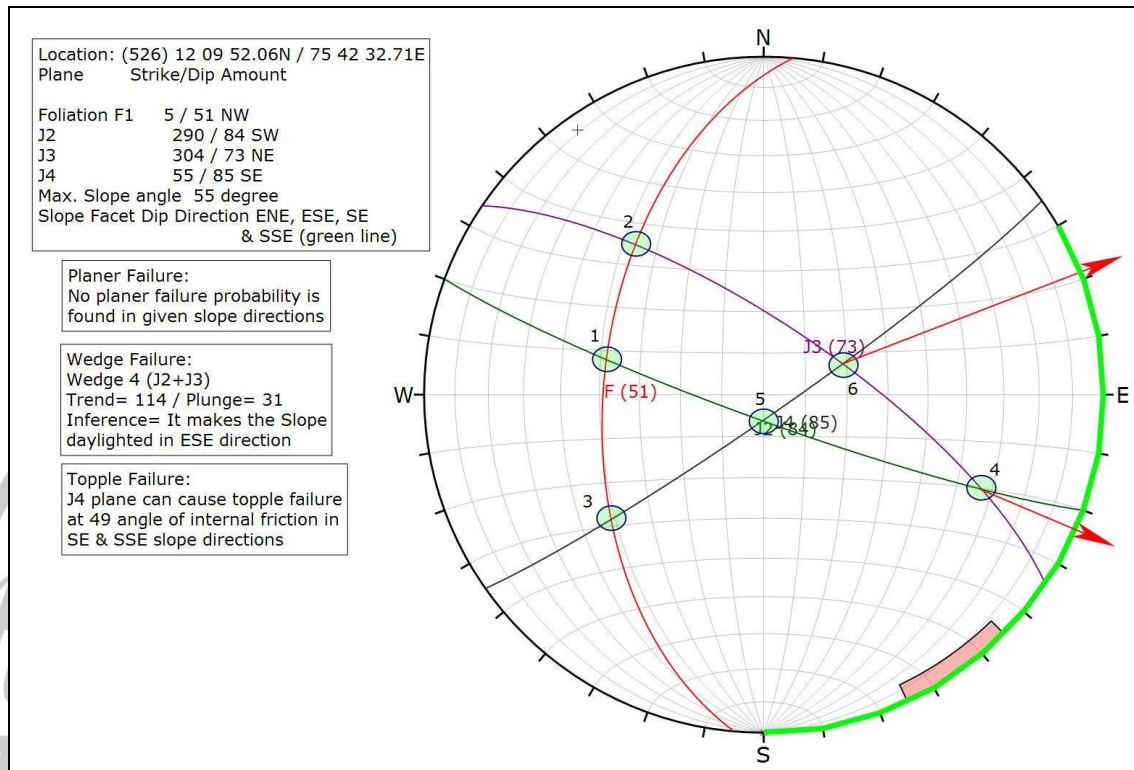
Stereonet No. 6



Stereonet No. 7



Stereonet No. 8



Stereonet No. 9



Figure-4.3: Stereo-net plots of different sets of discontinuities recorded in the study area and field photographs of day-lighted slope facet having stereo-net 9 interference pattern

4.3.2 Geotechnical Geological Mapping of Surface Rock Outcrops and Rock Mass Rating

The surface rock outcrops are variably distributed and can be separated from overburden cover by using basic field geological mapping techniques. The topographical contour map of the desired scale and a calibrated GPS are essential for field geological mapping to draw the contact between rock outcrop and overburden material. This step is initially required for the preparation of a geotechnical map. Once the surface rock outcrops are demarcated, specifically geotechnical investigation is conducted to assess the

rock mass condition. Geotechnical geological mapping aims to investigate the surface rock outcrops to categorize the rock mass with similar geological behaviour. This may include considering the physical characteristics of the intact rock mass and the control of structural geological features thereon. Therefore, one must visualize the rock mass as an assemblage of intact rock blocks separated by different types of geological discontinuities. The importance of the physical properties of intact rock mass must not be overshadowed by the properties of the geological discontinuities in the rock masses. Both things may be given equal attention as if the intact rock is incompetent, deformed, and altered or the geological discontinuities are multiple, widely spaced with wet surfaces, all in a cumulative manner will influence the overall strength of the intact rock mass. It is worth noting that in many instances the RMR_{basic} in a given area does not vary across the RMR scale by Z. T. Bieniawski 1989 and remains in the single value range because of the uniform physical properties of rock outcrop. The reconciliation would be possible to correlate the resulted RMR_{basic} of the given outcrop to its corresponding stability assessment condition (stable, fairly stable, unstable) based on stereo-net analysis (Figure-4.3). Because of this constraint, this type of correlation matrix procedure is being utilized in the present study to improve the RMR_{basic} value and rock quality category.

Finally, the geotechnical mapping of the surface rock outcrops may ensure the investigator to classify the intact rock mass into different categories for stability, commonly known as rock mass classification. The fundamental aim of the rock mass classification is to divide the intact rock mass into a number of structural regions. These regions are geological zones of rock masses in which certain features are more or less uniform. Rock mass classification is a rated base system developed by Z. T. Bieniawski in 1989. This classification is commonly known as the rock mass rating system (RMR). RMR system combines the most significant geological parameters of influence and represents them with one overall comprehensive index of rock mass quality, which is widely used for design and construction purposes in tunnels, mines, foundations and often in rocky slope stability assessment. The following six parameters are used to classify a rock mass using the RMR system.

1. Uniaxial compressive strength of rock material (UCS) or Point load test of rock material
2. Rock quality designation (RQD)
3. Spacing of discontinuities
4. Condition of discontinuities
5. Groundwater conditions
6. Orientation of discontinuities

Each of the above six parameters is assigned a value corresponding to the characteristics of the intact rock mass. The assigned values are derived from geotechnical geological mapping and in-situ rock or laboratory tests. The sum of the six parameters is the "RMR value", which lies between 0 and 100.

Table-4.4: Rock mass classification after Z. T. Bieniawski 1989.

RMR Value	Rock Quality
100-81	Very Good
80-61	Good
60-41	Fair
40-21	Poor
20-0	Very Poor

In the present study, a geotechnical map/engineering geological map has been prepared by incorporating RMR_{basic} values for rocky areas while for overburden-covered slopes the geotechnical map has been prepared by incorporating the C and ϕ values received from the laboratory. As per the availability, CartoDEM 10m derived topographic contour map has been utilized for field mapping purposes. The physical properties and the behaviour of geological discontinuities of intact rock outcrops were investigated in detail during field mapping to ensure the rock mass classification as per the RMR system and to collect the input data for kinematic failure analysis. The compressive strength of rock has been assessed by the use of a Schmidt Hammer. The RQD has been assessed in one cubic meter area of the rock outcrop at multiple locations. These procedures were adopted as an alternative to laboratory-based UCS and drill core-based RQD. Both the parameters could not be performed through real procedures because of the limited resources available at present. However, it is found that the below-shown interference patterns of different joint sets at several parts in the study area are responsible for degrading the rock mass quality.

Post Field Landslide Failure Domain Map of the Study Area

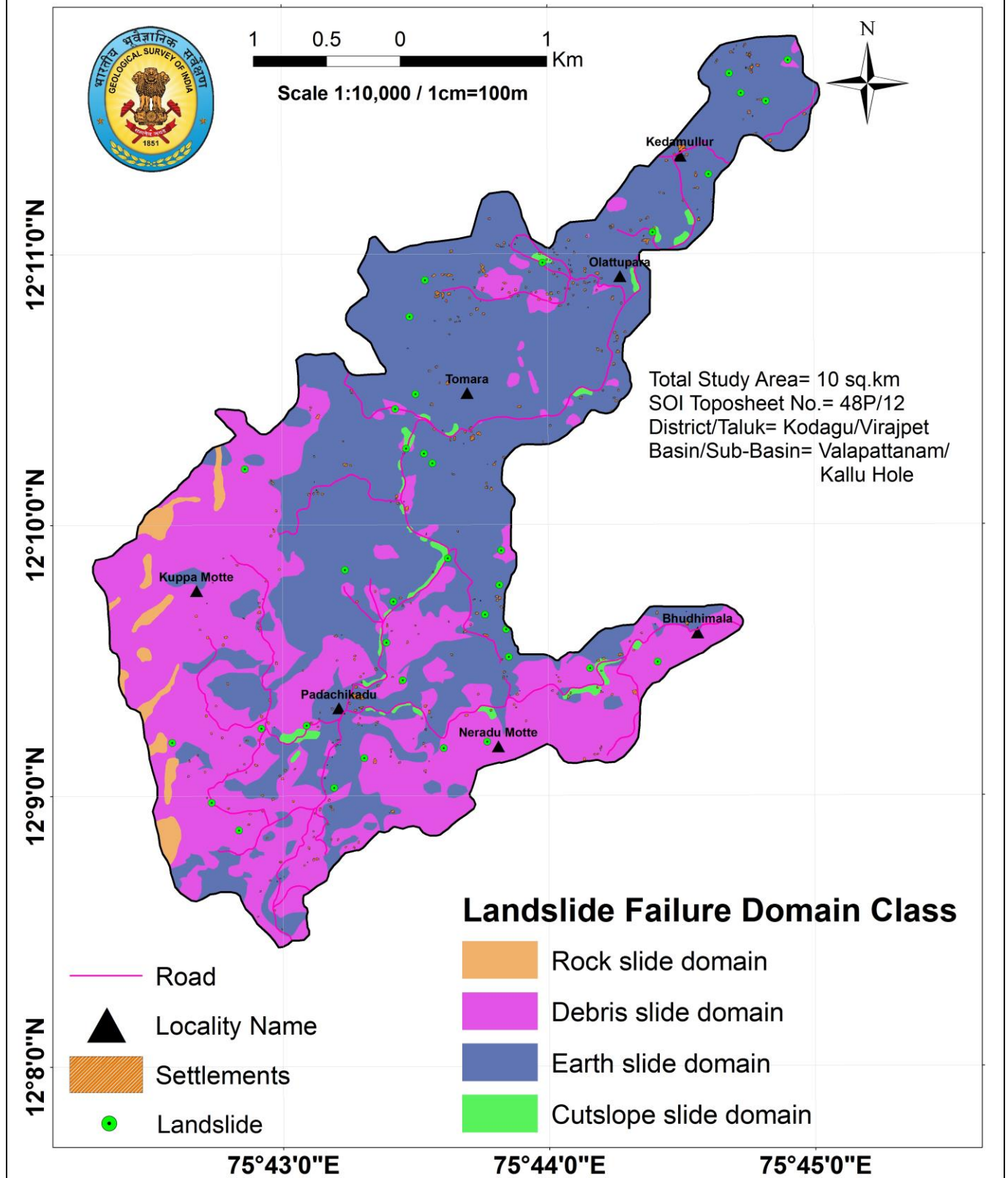


Figure-4.4: Post field-based landslide failure domain map of the study area

Geotechnical (RMR) Map of Rock Domain in the Study Area

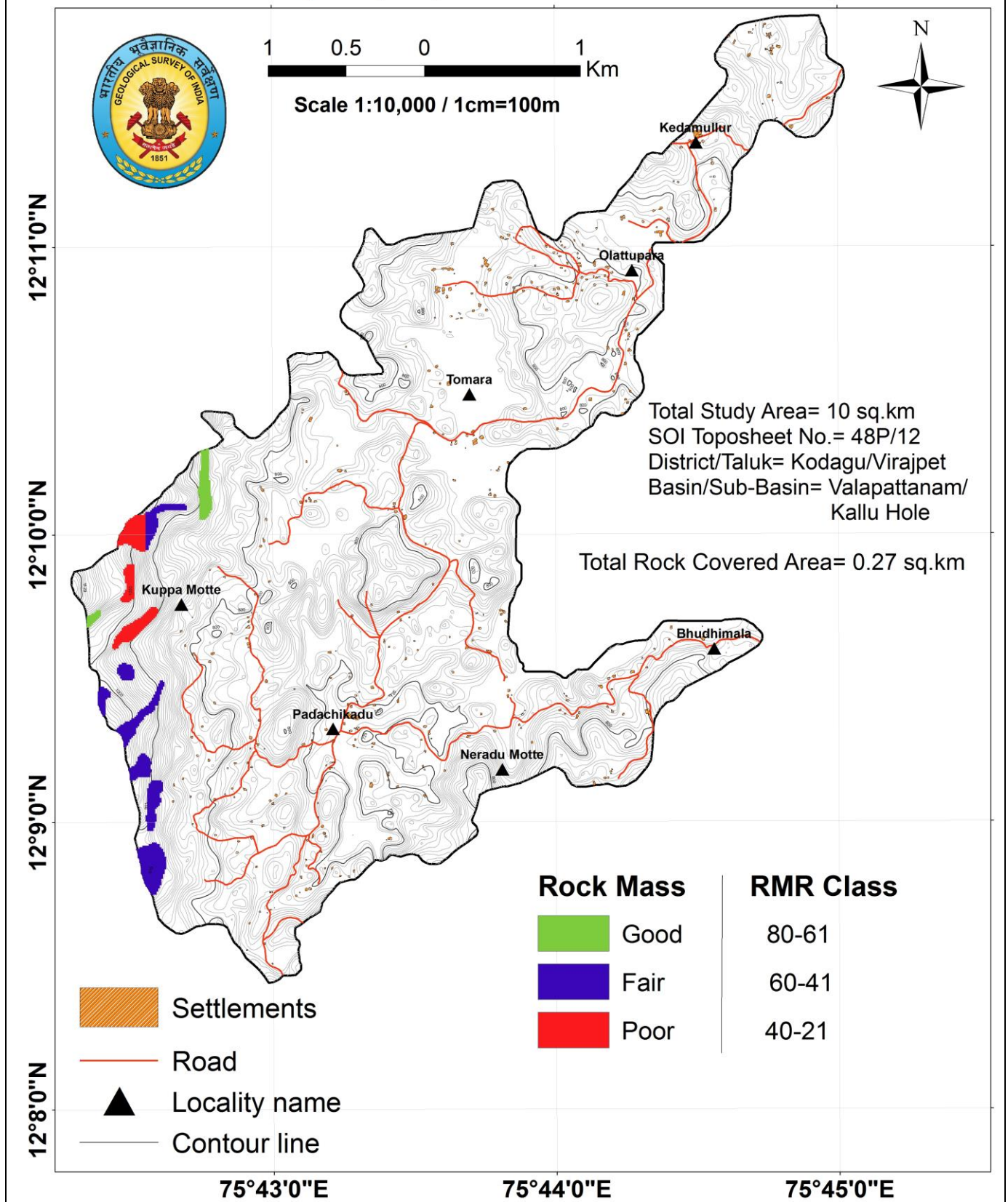


Figure-4.5: Geotechnical map of rock outcrops in the study area based on RMR_{basic}

Kinematic Failure (Plannar) Map of Rock Domain in the Study Area

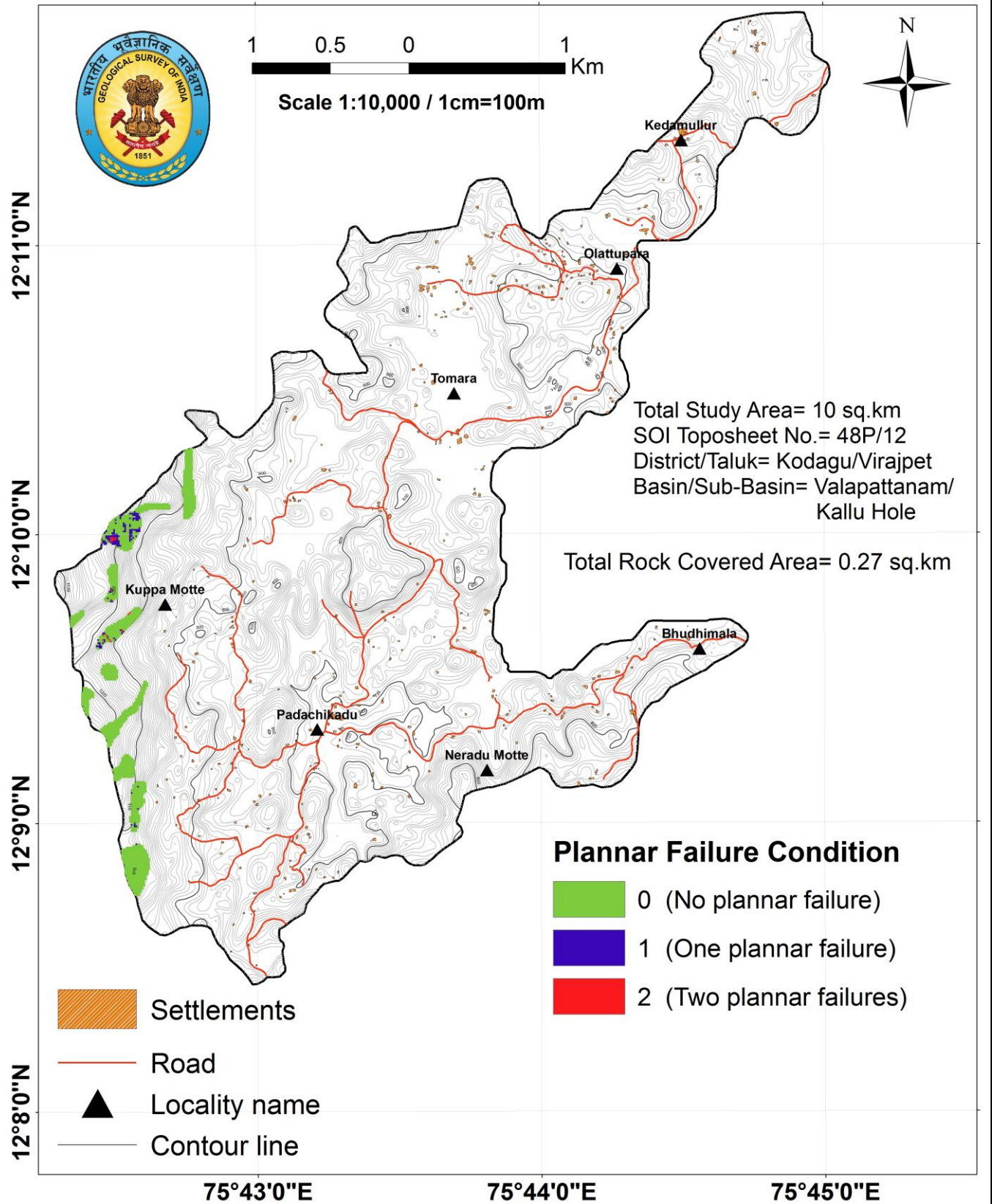


Figure-4.6: Kinematic failure (Planar) map overlapped on CartoDEM 10m derived contour map

Kinematic Failure (Wedge) Map of Rock Domain in the Study Area

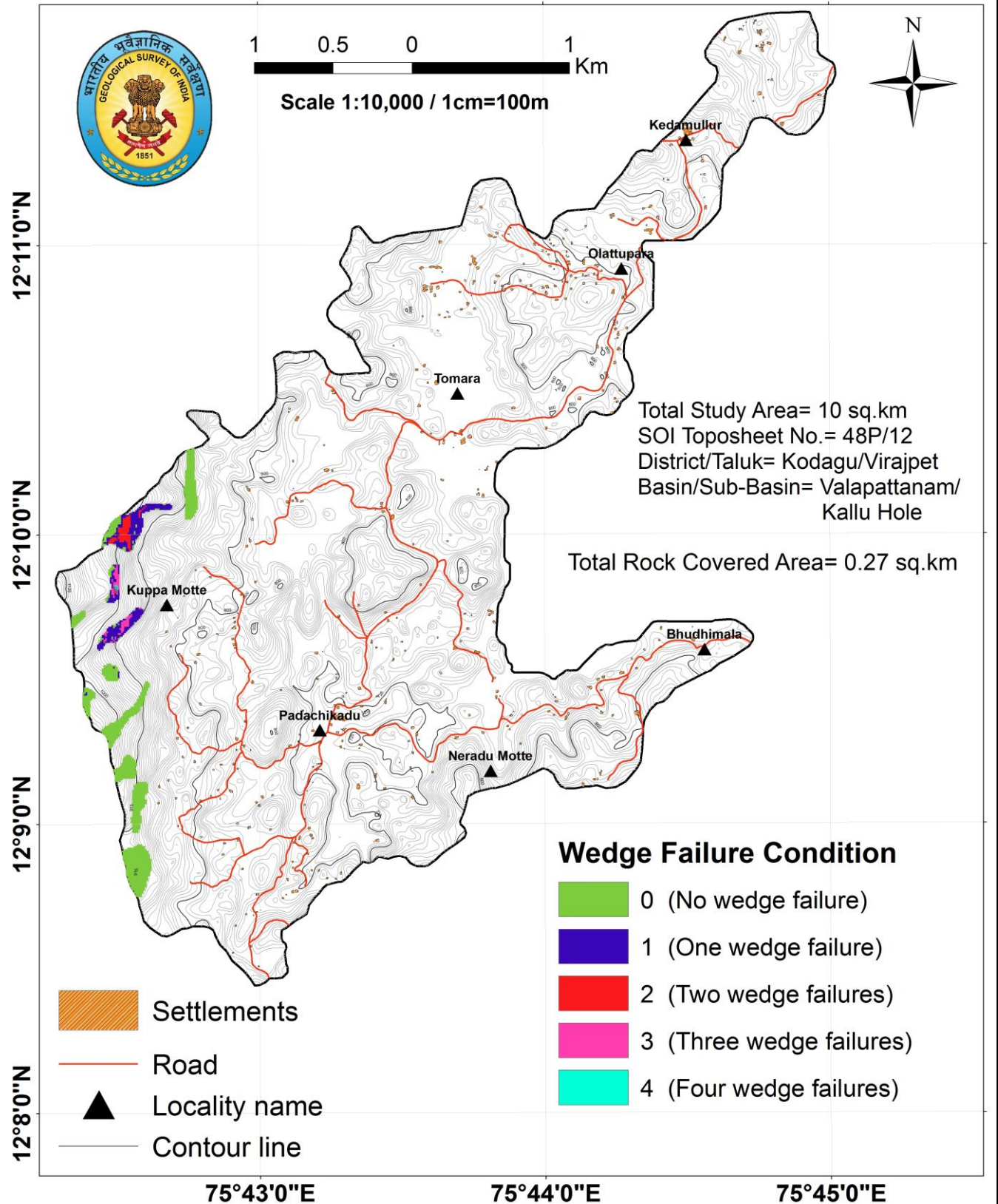


Figure-4.7: Kinematic failure (Wedge) map overlapped on CartoDEM 10m derived contour map

Kinematic Failure (Topple) Map of Rock Domain in the Study Area

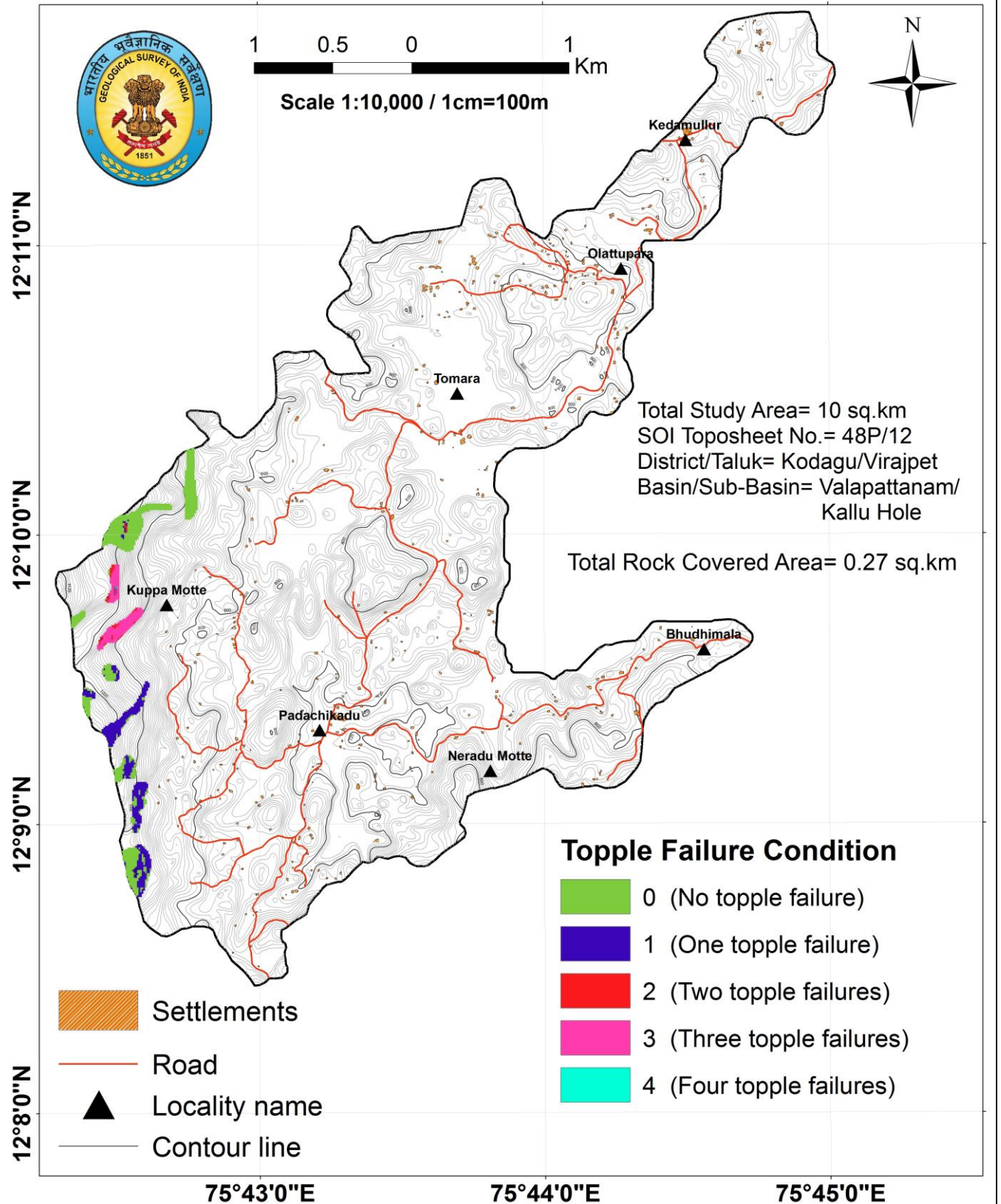


Figure-4.8: Kinematic failure (Topple) map overlapped on CartoDEM 10m derived contour map

4.3.3 Ratings and Integration of Geo-Factor Maps

In rockslide and rockfall domains, the inherent properties of the rocks such as failure condition and rock quality are being assessed based on kinematic analysis and a rock mass rating system. Besides, the slope angle is being incorporated as one of the geo-factor maps in the rock fall domain because of two factors other than the toppling failure condition. These two factors are highly fractured conditions under the highly strained zone and closely spaced cleavage planes, and they play an important role in dislocating rock fragments from intact rock. The dislocated rock fragments have a high tendency to fall under the gravity effect wherever the slope angle gets steep, particularly during rainfall periods. The external forces that are applied to rock outcrops during periods of varying climatic and tectonic conditions were not accounted for in this study. But evidently, the change in the stability condition of any rock outcrop by external forces is a matter of concern. The LSER value has not been kept as 0 (zero) because, under the effect of external forces at any time, the minimum LSER value to any geo-factor class may show a tendency towards increasing vulnerability. The landslide susceptibility evaluation rating (LSER) is being determined heuristically (knowledge-driven approach) as per the current GSI SOP by considering the different failure conditions in kinematic failure analysis and the rock quality based on the RMR system. The landslide susceptibility evaluation ratings were taken for each geo-factor class in the study area from the given rating system as follows;

Table 4.5: Landslide susceptibility evaluation rating (LSER) for planar, wedge and topple failure conditions.

Kinematic Failure Condition	LSER
No critical condition	0.2
1 critical condition	0.4
2 critical condition	0.6
3 critical condition	0.8
4 critical condition	1.0

Table 4.6: Landslide susceptibility evaluation rating (LSER) for RMR_{basic} based geotechnical map

Rock Quality	LSER
Very Good	0.05
Good	0.2
Fair	0.3
Poor	0.5
Very Poor	1.0

The heuristically determined landslide susceptibility evaluation ratings (LSER) mentioned in tables 4.5 & 4.6 have been given to each thematic class of geo-factor maps selected for the generation of landslide susceptibility maps in the rockslide and rockfall domains. The landslide susceptibility evaluation ratings (LSER) for each geo-factor class have been then integrated in the ArcGIS software. The landslide susceptibility evaluation ratings (LSER) for each geo-factor class have been deliberately put below 1 so that the total estimated susceptibility value (TESV) remains below or equal to 10. The calculation of the total estimated susceptibility value (TESV) was performed in the ArcGIS platform by using the below-mentioned formulas for the rockslide and rock fall domains separately (Aijaz Ahmad & Senthilkumar, 2021);

Total estimated susceptibility value (TESV) for rockslide domain = $\sum$ (LSER_Planar failure map + LSER_Wedge failure map + LSER_Geo-technical map)

Total estimated susceptibility value (TESV) for rockfall domain = $\sum$ (LSER_Topple failure map + LSER_Geo-technical map)

Table-4.7: Maximum LSER of geo-factor maps selected for generation of landslide susceptibility map in rockslide domain.

Geo-factor Map	Factor Class	Maximum LSER
Planar failure map	No critical condition	0.2
	1 critical condition	0.4
	2 critical condition	0.6
Wedge failure map	No critical condition	0.2
	1 critical condition	0.4
	2 critical condition	0.6
	3 critical condition	0.8
	4 critical condition	1.0
Geo-technical map	Good	0.2
	Fair	0.3
	Poor	0.5

Table 4.8: Maximum LSER of geo-factor maps selected for generation of landslide susceptibility map in rock fall domain.

Geo-factor Map	Factor Class	Maximum LSER
Topple failure map	No critical condition	0.2
	1 critical condition	0.4
	2 critical condition	0.6
	3 critical condition	0.8
	4 critical condition	1.0
Geo-technical map	Good	0.2
	Fair	0.3
	Poor	0.5

4.3.4 Landslide Susceptibility Map of Rockslide and Rockfall Domain

A landslide susceptibility map is a picture of the total estimated susceptibility value (TESV) calculated for each mapping unit (facet or pixel). The total estimated susceptibility value over an area of investigation would remain below or equal to 10 as per the opinion of the worker. The ratings for each geo-factor class were given as per terrain-specific conditions but at places, the ratings were changed as per the slope stability assessment carried out by the workers on the ground. The landslide susceptibility map has been generated by the overlay method in which the summation of LSER of all geo-factor maps has been done in the GIS platform. The rockslide and rockfall susceptibility have been assessed for a 0.27 sq. km area covered by rock.

Rockslide Domain: In the rockslide domain, the resulting total estimated susceptibility value (TESV) ranges from 0.6 to 1.9 and divided the map area into eight classes as mentioned in table- 4.9. Later these eight classes were reclassified into three categories of landslide susceptibility as mentioned in Table- 4.10.

Table 4.9: Landslide susceptibility map attributes for rockslide domain

Value	Pixel Count	TESV
1	342	0.6
2	1272	0.7
3	282	0.9
4	336	1.1
5	153	1.3
6	125	1.5

7	22	1.7
8	4	1.9
Total	2536	9.7

Table 4.10: Classified landslide susceptibility map attributes for rockslide domain

Value	Pixel Count	TESV	Susceptibility Class	Map Area Percentage	Landslide Ratio
1-2	1614	0.6-0.7	Low	63.64	0
3-4	618	0.9-1.1	Moderate	24.37	0
5-8	304	1.3-1.9	High	11.99	1
Total	2536			100%	01 no.

A total of 1 no. of rockslide was recorded in the study area which has been validated with the susceptibility map area percentage in which the rock slide ratio is 0 (low): 0 (moderate): 1 (high) which is a highly satisfactory ratio. The high susceptibility class has retained those areas which are more prone to rockslides. However, the places showing high susceptibility of rockslides have day-lighted slopes which may fail at low angles of internal friction circumstances. Whereas moderate susceptibility does not exceed more than 30 % of the total map area and remains at 24.37 %. This signifies that qualitatively the adopted model for the rockslide domain has predicted 76 % of the map area with efficacy and there is the least uncertainty in terms of moderate susceptible class over 24 % map area. It would be noted that the impact of external forces, especially rainfall, may change the resulting susceptibility scenario in the study area at any time. The basic parameters like the angle of internal friction, slope angle, and slope window direction may change by either natural agencies or anthropogenic activities that would favour the rockslide failures.

Rock Fall Domain: In the rock fall domain, the resulting total estimated susceptibility value (TESV) ranges from 0.4 to 1.5 and it divides the map area into seven classes as mentioned in Table 4.11. Later these seven classes were reclassified into three categories of landslide susceptibility as mentioned in Table 4.12.

Table 4.11: Landslide susceptibility map attributes for rock fall domain

Value	Pixel Count	TESV
1	342	0.4
2	783	0.5
3	992	0.7
4	16	0.9

5	57	1.1
6	344	1.3
7	2	1.5
Total	2536	6.4

Table 4.12: Classified landslide susceptibility map attributes for rock fall domain

Value	Pixel Count	TESV	Susceptibility Class	Map Area Percentage	Landslide Ratio
1-3	2117	0.4-0.7	Low	83.48	0
4	16	0.9	Moderate	0.63	0
5-7	403	1.1-1.5	High	15.89	1
Total	2536			100%	01 no.

A total of 1 no. of rockslide was recorded in the study area which has been validated with the susceptibility map area percentage in which the rock fall ratio is 0 (low): 0 (moderate): 1 (high) which is a highly satisfactory ratio. The high susceptibility class has retained those areas that are more prone to rockfall due to the topple favourable joint planes and poor strength of rock on the steep slope. This poor strength rock condition is not due to toppling failure condition in the study area, but it is a result of the highly fractured condition under the highly strained zones and closely spaced cleavage planes. These two factors play an important role in dislocating rock fragments from intact rock. The dislocated rock fragments have a high tendency to fall under the gravity effect wherever the slope angle gets steep, particularly during rainfall periods. Whereas moderate susceptibility does not exceed more than 30 % of the total map area and remains at 0.63 %. This signifies that qualitatively the adopted model for the rock fall domain has predicted 99 percent of the map area with efficacy and there is the least uncertainty in terms of moderate susceptible class over 1 percent map area. It is also to be mentioned that the impact of external forces particularly rainfall water action and anthropogenic activities may change the resulting susceptibility scenario in the study area at any time.

Landslide Susceptibility Map of Rock Slide Domain in the Study Area

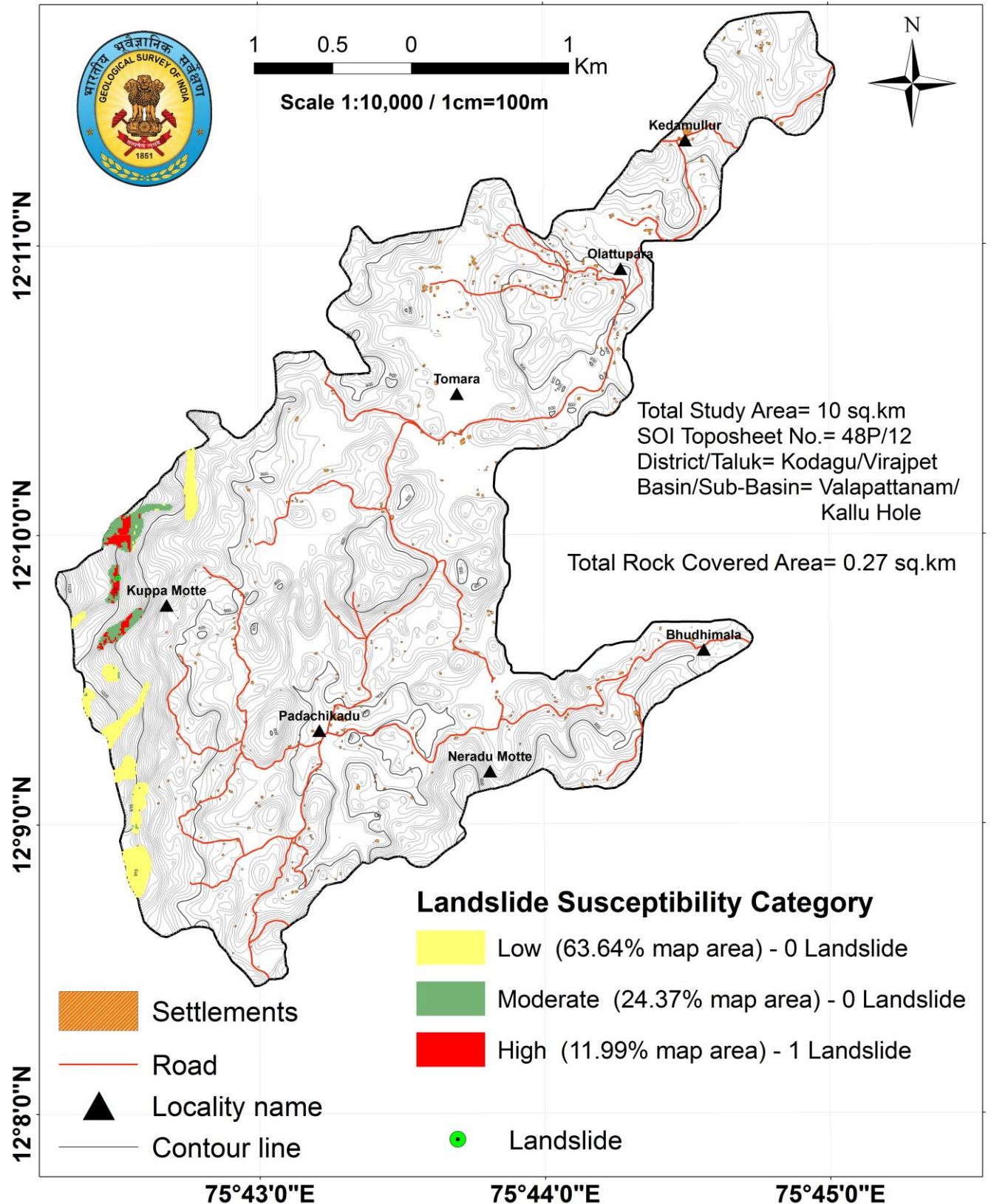


Figure-4.9: Landslide susceptibility map of rock slide domain in the study area

Landslide Susceptibility Map of Rock Fall Domain in the Study Area

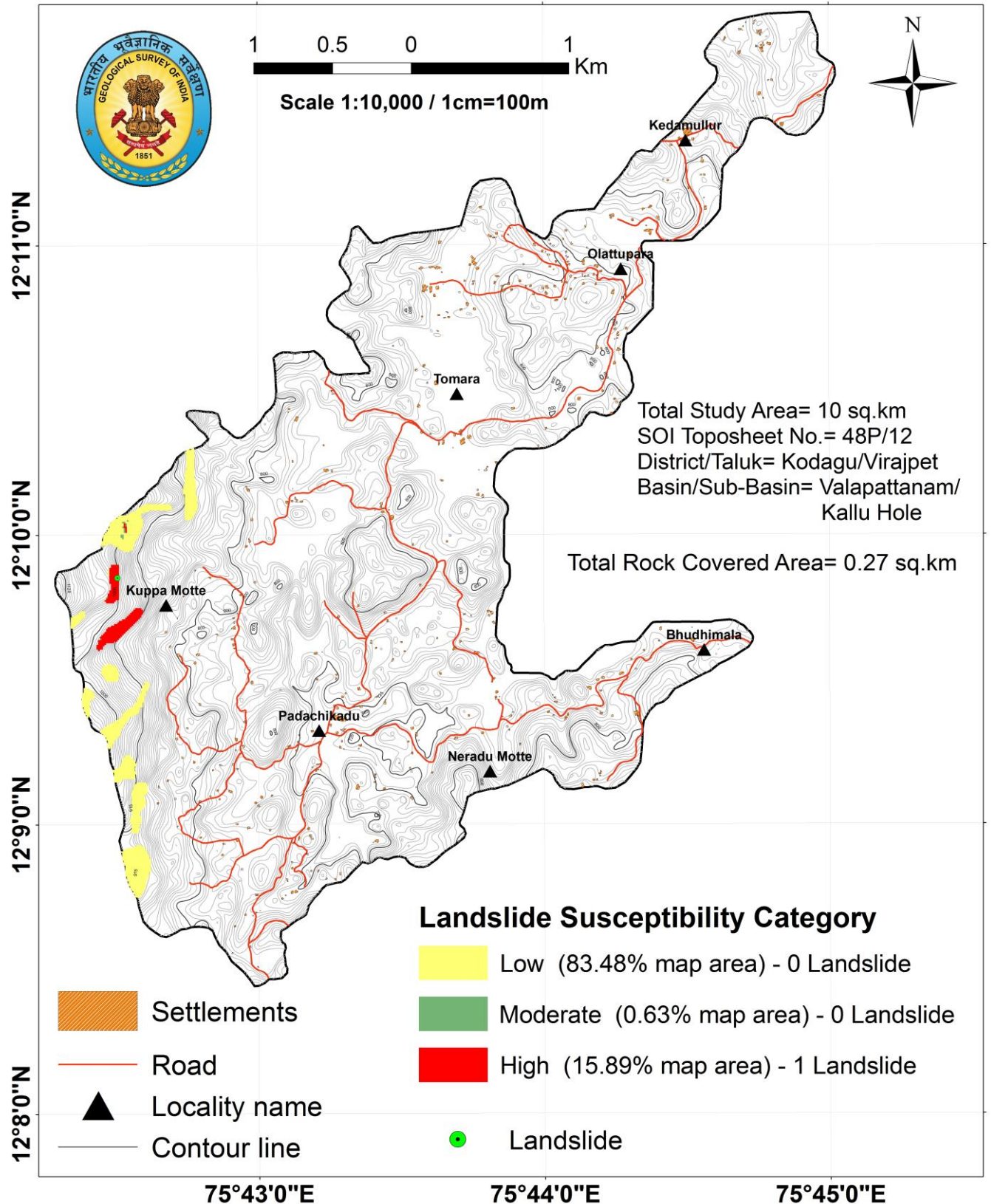


Figure-4.10: Landslide susceptibility map of rock fall domain in the study area

4.4 Debris Slide and Earth Slide Domains

Overburden characters are very important in landslide susceptibility depending on the type of material resting on a particular slope. The landslide domain represents areas having similar physiographic and geological characteristics that control the type of landslide occurring within it. It also helps to understand the dominant landslide processes in the respective domain. The susceptibility for debris slide and earth slide has been assessed for a 9.73 sq km area covered by overburden in the present study area.

The debris slide and earth slide domains were prepared by using the slope-forming material map and landslide inventory which were developed during field mapping. The colluvium, boulder material, in-situ debris material, weathered rock and loose debris material were classified into the debris slide domain and these materials have a high probability of debris slide or flow in the study area. Whereas the in-situ mature and immature soil and transported soil material were classified into the earth slide domain and these materials have also a high probability of slide or flow. A total of 97.3% area is overburden covered in which a total of 36 nos. of landslides were recorded (15 nos. in the debris slide domain and 19 nos. in the earth slide domain). The earth slides were mostly restricted to the vicinity of anthropogenic activity and toe erosion by the streams but mostly the debris slides occurred on the natural slopes. The geo-factor themes that were selected for the landslide susceptibility modelling for debris and earth slide domains have been thoroughly assessed during field mapping so that their role in occurrences of landslides can be understood. These geo-factor themes include land use/land cover, stream power index (SPI), landform, slope angle, slope-forming material, weathering intensity level and strength of slope-forming material.

4.4.1 Land Use and Land Cover Theme

Land use and land cover changes (LULCCs) in mountainous areas may increase the susceptibility to landslides due to modifications of topography, vegetation, and material characteristics. Understanding the relation between LULCCs and landslide occurrences is important for landslide prevention and land resources management. Land cover change denotes a change in certain continuous characteristics of the land such as vegetation type, soil properties, and so on, whereas land-use change consists of an alteration in the way certain area of land is being used or managed by humans. Land cover change denotes a change in certain continuous characteristics of the land such as vegetation type, soil properties, and so on, whereas land-use change consists of an alteration in the way certain area of land is being used or managed by humans. Land use is too often considered a static factor in landslide hazard studies. Changes in land cover and land use resulting from human activities such as deforestation, forest logging, road construction, fire, and cultivation on steep slopes, and urbanization also disturb the natural equilibrium and affect the slope stability. Vegetation effects on slope stability may be broadly classified as either hydrological or mechanical in nature.

The pre-field land use/land cover map of the study area was initially generated by using the high-resolution open-source Google Earth imagery 2022, later the map was checked and validated in the field by accessing possibly each part of the study area. In the pre-field LULC map, the area is broadly classified into thick vegetation and small patches of plantations, settlements, cultivation, etc. A substantial modification has been made by incorporating field inputs. Most of the thick vegetation portion of the pre-field LULC map has been identified as coffee, silver oak and Jungle wood. Likewise, the plantation area changed into coffee, silver oak, banana, areca nut, and coffee with mixed plantations. The mixed plantation includes silver, orange, rosewood, etc. and jungle wood mostly includes athi (*Ficus racemosa* L). Since the maximum area is covered by the coffee and jungle wood class, the maximum landslide incidences were reported from the same LULC class. Most of the low to moderate gradient slopes were modified for this LULC class purpose and that has accelerated the frequency of landslide incidences in the coffee, jungle wood LULC class. The LSER to each LULC geo-factor feature class has been given as per the field observations, however, areca nut plantation and paddy cultivation portions have been assigned 0 LSER because these geo-factors feature classes existing in low-lying areas having $<5^\circ$ slope gradient.

Table-4.13: Landslide susceptibility evaluation rating (LSER) for the Landuse/Landcover map

ID	Class Name	LSER
1	Areca nut plantation	0
2	Bamboo, Jungle wood	0.2
3	Barren land	0.6
4	Coffee, Areca nut	0.4
5	Coffee, Forest vegetation	0.6
6	Coffee, Jungle wood	0.4
7	Coffee, Jungle wood, Silver oak	0.6
8	Coffee, Jungle wood, Areca nut	0.2
9	Coffee, Silver oak	0.6
10	Forest vegetation	0.4
11	Jungle wood, Silver oak	0.6
12	Paddy	0

Post Field Landuse/Landcover Map of Overburden Domain in the Study Area

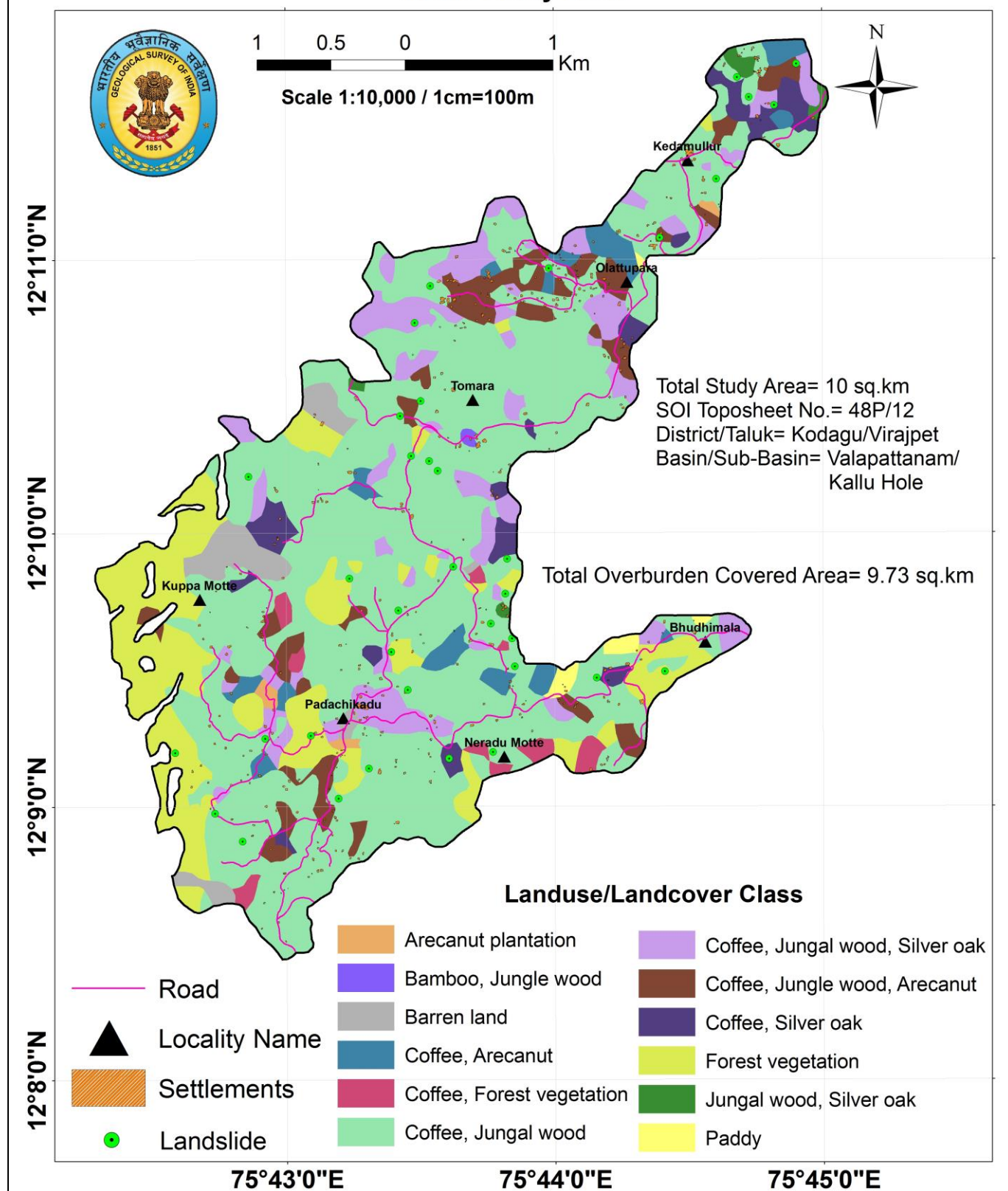


Figure-4.11: Post field land use/land cover map of the study area

4.4.2 Landform Theme

At a larger scale (1:10,000) mapping, the identification of individual geomorphological classes becomes difficult due to the confinement of the observation. At this scale, it is also difficult to match the boundary conditions of different geomorphological processes. To overcome this limitation a new concept of landform mapping by using CartoDEM 10m has been introduced. The landform map is obtained by a manual or automatic process from a DEM. There are many existing methodologies through which landform maps can be prepared automatically by using the geomorphometric variables (Evans, 1972; Pike, 1988; MacMillan et al., 2004; Olaya, 2009) whereas manual classification involves the recognition of whole topographic patterns corresponding to specific landforms. The manual process can bring in errors depending on experience and field knowledge of the terrain. The concept of Geomorphon was introduced which is based on the process of manual classification of landforms using tools in computers to reduce human subjectivity. Geomorphon is a relief-invariant, orientation-invariant and size-flexible abstracted elementary unit of terrain. It uses the 8-tuple pattern (83=6561 possibility) and compares the focus pixel with its eight neighbours starting from the one located to the east (Jasiewicz and Stepinski, 2013). Out of these 8-tuplets, in a typical terrestrial landscape, the most frequent and commonly recognizable geomorphons are flat, peak, ridge, shoulder, spur, slope, hollow, foot-slope, valley and pit (figure-4.12). Different geomorphic classes that were identified in the present study area are shown in Figure 4.13. The above-simplified classification of geomorphons is prepared in GRASS GIS software (Neteler and Mitasova, 2007) by utilizing the script r.geomorphon written in ANSI C (Jasiewicz and Stepinski, 2013). In the present study area, most of the landslides were intact to the slope as it covers the maximum area and all anthropogenic activity is almost confined to it. The landslide susceptibility evaluation ratings (LSER) were assigned to each landform class by keeping their relevance to slope failures in consideration which was assessed during field mapping.

Table 4.14: Landslide susceptibility evaluation rating (LSER) for landform theme

ID	Class Name	LSER
1	Flat	0
2	Summit	0.2
3	Ridge	0.2
4	Shoulder	1
5	Spur	0.4
6	Slope	0.6
7	Hollow	1

8	Foot-slope	0.4
9	Valley	0
10	Depression	0.2

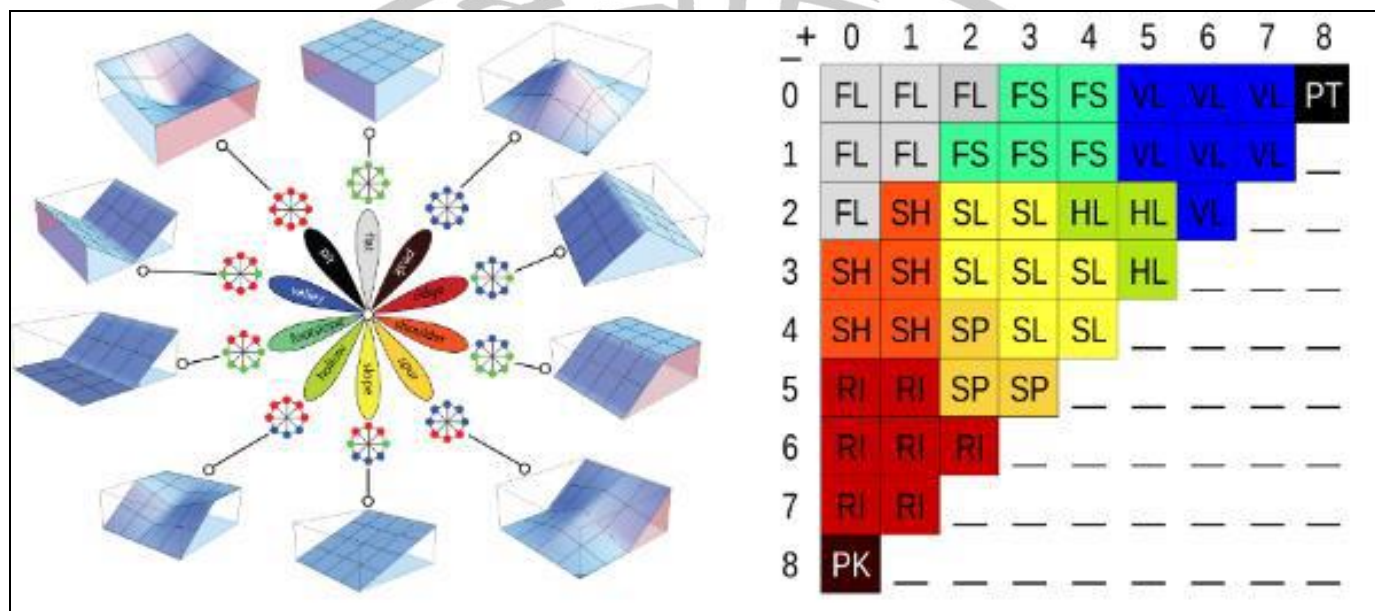


Figure-4.12: Representative 3-D pattern of 10 most common landforms and lookup table for reclassification of landforms into the 10 common landform types. Rows/columns in a table indicate the number of $(-1)/(1)$ ternary elements in the landform pattern. Abbreviations for common landform elements are: FL — flat; PK — peak; RI — ridge; SH — shoulder; HL — hollow; SL — slope; SP — spur; FS — footslope; VL — valley; PT — pit

Landform Map of Overburden Domain in the Study Area Derived From CartoDEM 10m

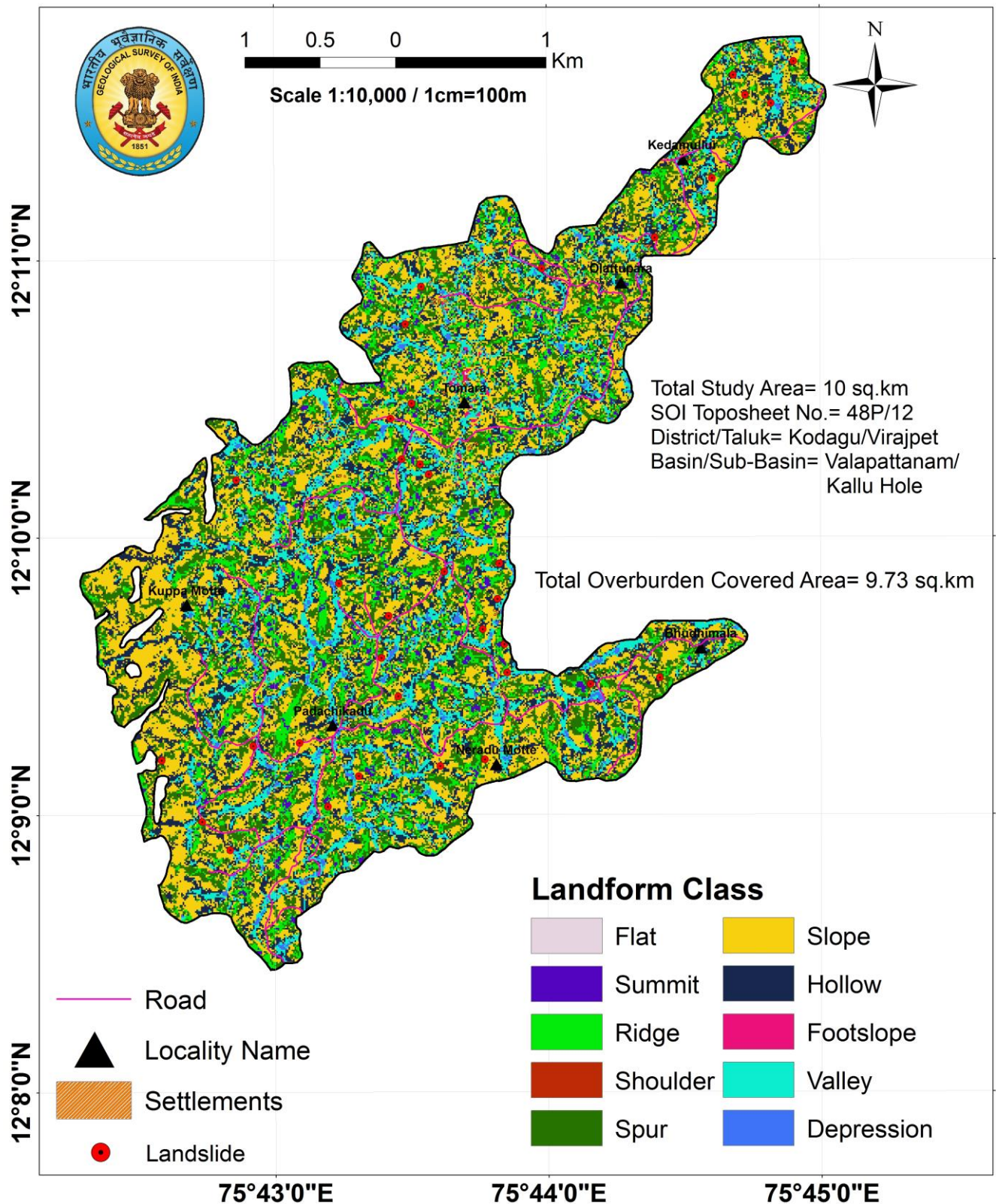


Figure-4.13: Landform map of the study area

4.4.3 Stream Power Index (SPI) Theme

The landslide occurrence near the stream is due to natural toe erosion by stream water action and is a common phenomenon in the hilly topographic region of Western Ghat. Erosion triggered by rainfall disturbs the slope equilibrium and causes landslides (Levy *et al.*, 2012). It was observed by Wistuba *et al.* (2015) that slope failures and erosion, once triggered by precipitation, can occur alternately in years with average precipitation and reinforce one another. This impact can be understood by the stream power index (SPI) concept which is a tool to define the potential flow erosion at a given point of the topographic surface (Moore *et al.*, 1991) and it has been widely used in landslide susceptibility mapping (Pourghasemi *et al.*, 2012a, b; Devkota *et al.*, 2013; Park *et al.*, 2013; Pradhan and Kim, 2014; Saadatkhah *et al.*, 2014). It is a way of measuring the erosive power of water flow based on the assumption that discharge is proportional to a specific catchment area (Conforti *et al.*, 2011). As catchment area and slope gradient increase, the amount of water contributed by upslope areas and the velocity of water flow increases, hence stream power index and erosion risk increases (Florinsky, 2016). In the present study, the SPI of the study area was calculated for every pixel which was later classified into five classes from very low erosion to very high erosion.

SPI is expressed as $SPI = \alpha \times \tan(\beta)$, where α is the specific catchment area and β is the local slope gradient measured in degrees (Moore *et al.*, 1988; Park *et al.*, 2013). The higher SPI value represents higher erosion rates in the catchment area.

The SPI theme has been prepared from CartoDEM 10m for the debris slide and earth slide domain. The pre-processed DEM fill was used to develop several intermediate raster datasets like slope, flow direction and flow accumulation. Percent slope also referred to as 'percent rise' was calculated by the rise divided by run multiplied by 100. With the use of the raster calculator in the Map algebra tool of ArcGIS software, SPI was calculated for each pixel using the following equation;

$$SPI = \ln([FlowAccum_Raster] + 0.001) * ((Slope_Raster]/100) + 0.001))$$

The erosion condition along the slopes is a function of the linear distance of drainage. However, the study area represents slopes of varying gradients which would variably affect the erosive power of the streams depending on both the gradient and catchment area. The landslide susceptibility evaluation ratings (LSER) were assigned to each SPI class depending on the power of erosion and order of stream. It was observed during the field mapping that mostly slope failures occurred in the vicinity of low erosive power streams. This is because of other geo-factors like lithology incompetency, relative relief and competition of lower order streams for base erosion. To overcome this limitation, the high erosive power stream map was prepared during field mapping in which those low erosive streams have been assigned high LSER which has a defined role in the occurrence of slope failures.

Stream Power Index Map of Overburden Domain in the Study Area Derived From CartoDEM 10m

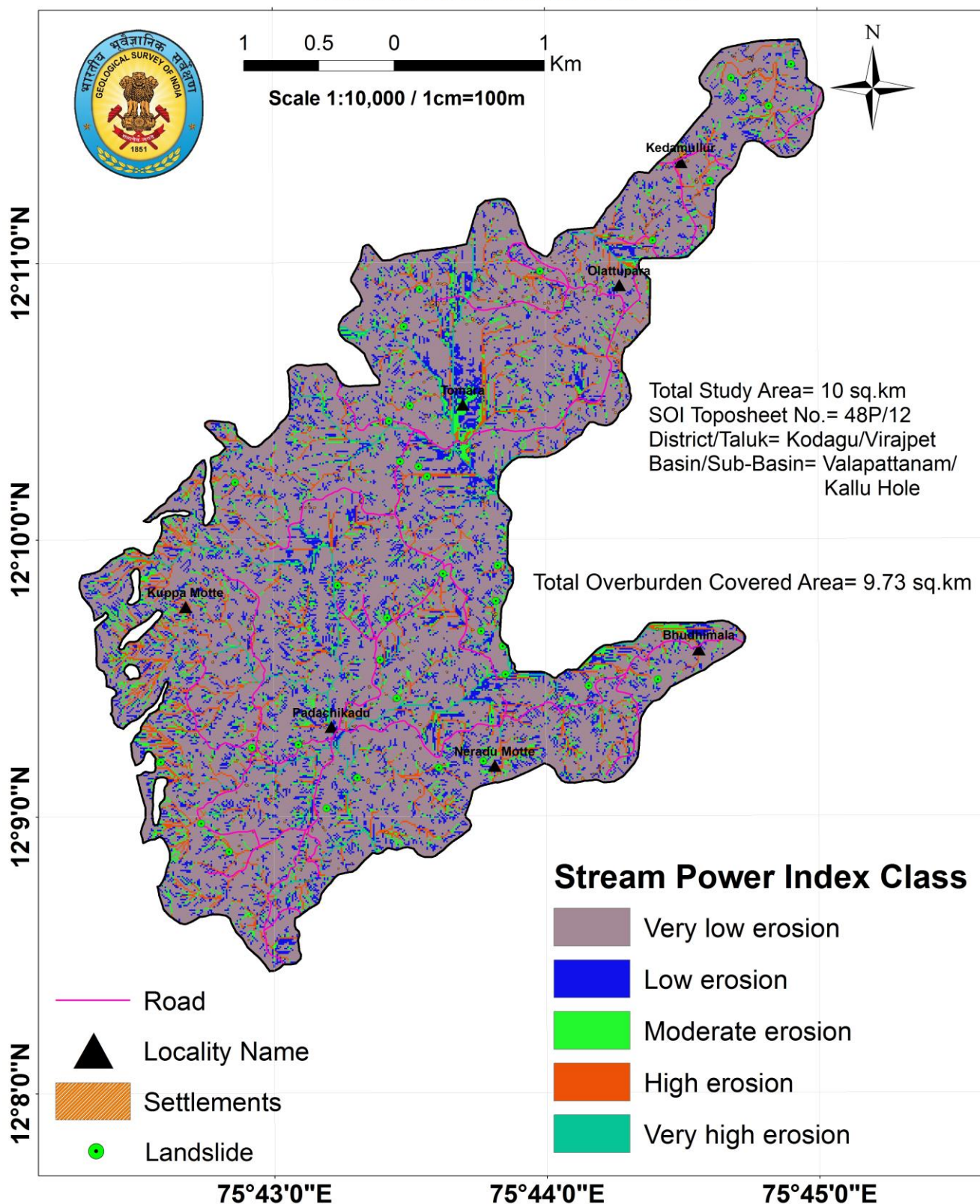


Figure-4.14: Stream power index (SPI) map of the study area

Table-4.15: Landslide susceptibility evaluation rating (LSER) for Stream power index (SPI) map

Sl. No.	Class	LSER
1	-13 to -5 (Very low erosion)	0.2
2	-5 to 0 (Low erosion)	0.3
3	0 to 4 (Moderate erosion)	0.4
4	4-8 (High erosion)	0.6
5	8-11(Very high erosion)	1

4.4.4 Slope Forming Material (SFM) Theme

SFM is one of the important static factors for causing landslides that controls the spatial distribution of landslides. The distribution of SFM units largely depends on underlying lithology, their degree of weathering and structural disposition, mass wasting history, and sometimes anthropogenic intervention.

SFM map has been prepared by using the 1:50000 scale geological maps as the base map, by downscaling the map from the NLSM project (*Ankur Kumar Srivastava et al., 2017*) and using Google Earth image, Cartosat-1 panchromatic image with 2.5 m spatial resolution and several proxies viz. geomorphology, geology, slope, LULC, landslide incidence. The entire study area has been classified into two basic SFM units i.e., overburden cover and rock cover. The slope having less than 1 m thick overburden cover has been considered a rocky slope. Overburden cover slopes are identified using geomorphology, geology, slope, LULC, and landslide incidence maps. From the LULC map, all the cultivated areas of the plantation have been extracted assuming the probable locale of a superficial deposit, likewise from the geomorphology map, alluvial plains, valley fill, and palaeo-landslides polygons have been imported as a superficial deposit. From the slope map all the gently sloping areas viz. ridge tops, on either side of rivers are mapped as superficial deposit polygons. During the extensive field study, the slope-forming map was validated and modified as per the ground conditions.

A total of 8 different types of slope-forming materials have been identified in the field. At a larger scale of the map, more detailed information on SFM classes was captured of which few are significant to slope stability. In the SFM classes, in situ immature soil has the maximum spatial distribution, followed by in situ mature soil, in situ debris material, boulder material, loose debris material, and weathered rock material and the rest area is covered by other SFM classes. Figure- 4.16 shows the different slope-forming material classes observed in the study area. The association of the boulder material and colluvium are mostly adjacent to each other. The distribution of the immature and mature soil was noted all around the

study area and transported materials occupying the low-lying area. The south-central part of the study area is occupied by in situ debris material whereas the southwestern part having a highly elevated area is covered by rocky slope material. The LSER of the geotechnical map of the debris slide and earth slide domain was corrected by using the correction values of SFM classes which were generated based on the physical strength of slope-forming materials classes.

Table 4.16: Slope forming material classes identified during field mapping

ID	Class Name	LSER Correction Values
1	Boulder material	(+) 0.1
2	Colluvium	(+) 0.2
3	Insitu debris material	(+) 0.1
4	Loose debris material	(+) 0.2
5	Insitu immature material	(-) 0.1
6	Insitu mature material	(-) 0.2
7	Transported soil	0
8	Weathered rock	(+) 0.2

4.4.5 Slope Gradient Theme

The slope gradient theme has been derived from CartoDEM 10m in the ArcGIS platform. For integration and modelling purposes the derived slope gradient is reclassified into 5 classes (Table 4.). The slope gradient varies up to 50° over the area of investigation. The slope gradient ranging between 10°- 30° has been observed as a positively responded range to occur landslides in the study area because all the anthropogenic activities and toe erosion by streams have been observed confined to this slope gradient range. Hence this observation rules out that landslide vulnerability increases with increasing the slope gradient and focuses on the fact that slope response is dependent on other variable geo-factors also.

Table 4.17: Slope forming material classes identified during field mapping.

ID	Slope Class	LSER
1	0°-10°	0.2
2	11°-20°	0.4
3	21°-30°	0.6
4	31°-40°	0.8
5	41°-50°	1.0

Slope Angle Map of Overburden Domain in the Study Area Derived From CartoDEM 10m

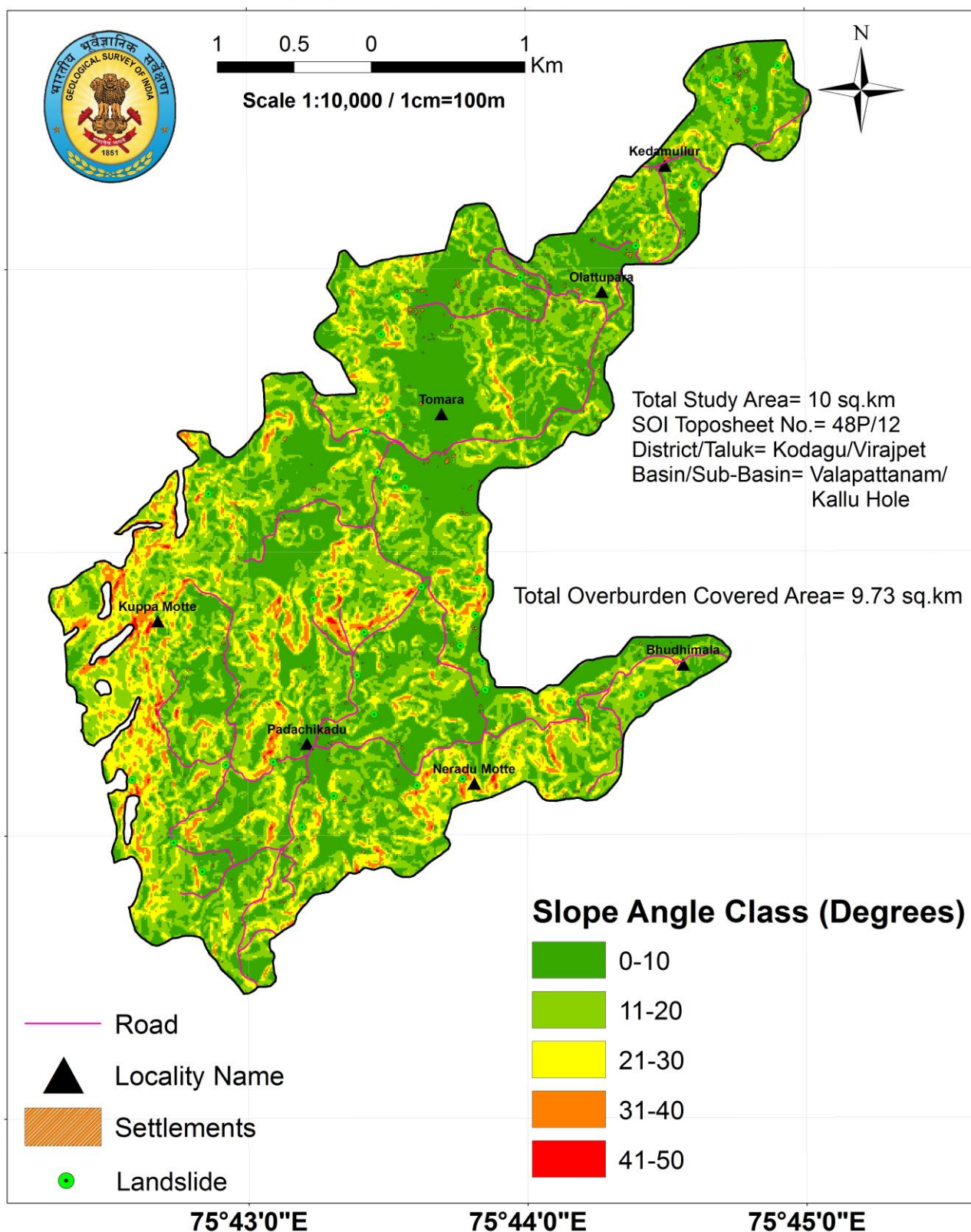


Figure-4.15: Slope gradient map of the study area

Post Field Slope Forming Material Map of Overburden Domain in the Study Area

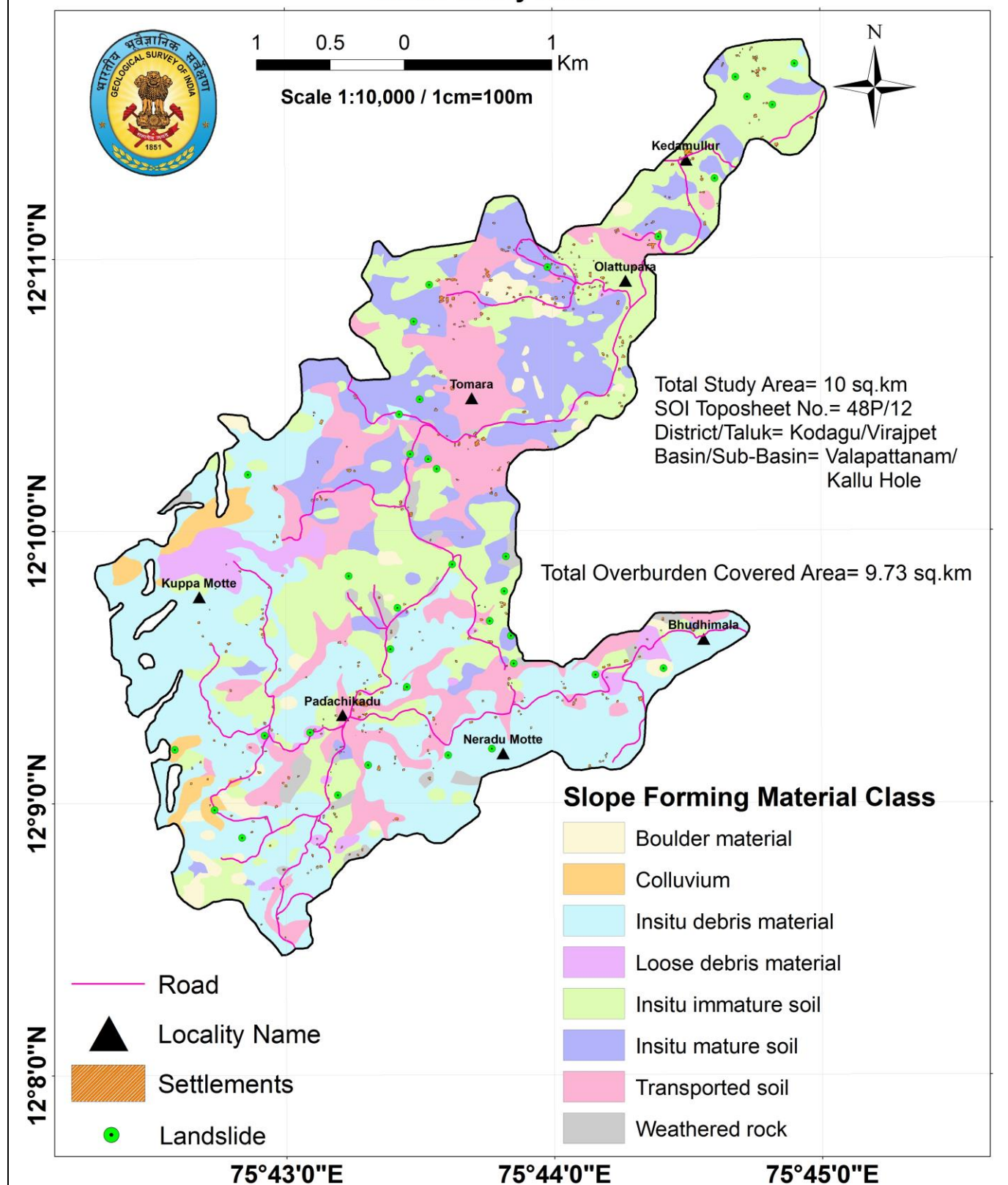


Figure-4.16: Slope forming material (SFM) map of the study area

4.4.6 High Erosive Power Stream (HEPS) Buffer Theme

During the field investigation, it was observed that several lower-order streams, which were classified as very low to moderate erosion streams, are cutting the slopes very deep and leaving the slopes unstable. This kind of erosion and formation of such unstable slopes seems very vulnerable to slope failures in the study area. Therefore, the workers identified these streams during field mapping and made a stream buffer theme to introduce in landslide susceptibility modelling for debris slide and earth slide domain. By using this theme those areas taken a satisfactory landslide susceptibility class.

Table 4.18: Landslide susceptibility evaluation rating (LSER) for high erosive power stream (HEPS) buffer map

ID	Buffer Class	LSER
1	25m	0.8
2	50m	0.6
3	75m	0.4
4	100m	0.2
5	>100m	0

4.4.7 Geotechnical Theme

The stability of a slope depends on the nature of the material, its inherent disposition, shear strength, pore water pressure, groundwater regimes, etc. The geotechnical properties of the slope-forming material provide the basis for stability analysis of any overburden material. This requires a detailed mapping of the area to map and categorize different slope-forming materials based on their field character. A geotechnical map would give a detailed assessment of the strength of the slope-forming material which directly or indirectly depends on the type of lithology, weathering level, weather conditions and pressure-temperature. The strength parameters (C & ϕ) of the slope-forming material are always determined by laboratory analysis. These strength parameters hence later converted to the geotechnical theme by matrix correlation procedure, which represents the overall characteristics of the material.

The cohesion (C) and internal angle friction (ϕ) are the important strength parameters of the slope-forming material that determine the shear strength of the material and its ability to resist failure. In the present study, the samples from different slope-forming material classes were collected in a 1km x 1km grid at different elevation contours. A total of 32 nos. of samples were collected from undisturbed slope-forming material in 4-inch diameter x 16-inch length iron tubes. Laboratory tests for the determination of the geotechnical parameters of these samples were conducted by the GSI Geotechnical Laboratory SR Hyderabad. Laboratory results show that cohesion ranges from 19.6133 to 36.28461 kN/m² while the angle of internal friction ranges from 23.6 to 34. To prepare the geotechnical theme of slope-forming materials, the matrix correlation between c & ϕ is an important step. In the present study, the procedure

outlined by Ghoshal *et al.*, 2013 for matrix classification is adopted. Since the values of cohesion fall in the same category given by Ghoshal *et al.*, 2013, the matrix classification is readjusted as per the present study area terrain-specific conditions. The matrix classification was done by keeping the unstable slopes in consideration.

Table- 4.19: Matrix table of cohesion and angle of internal friction for classification of slope-forming material with LSER ratings

Cohesion (c) as per Ghoshal <i>et al.</i> , 2013	Cohesion (c) Re-adjusted	Angle of Internal Friction (ϕ) as per Ghoshal <i>et al.</i> , 2013	>30	21-30	11-20	<=10
		Angle of Internal Friction (ϕ) Re-adjusted	<20	20-25	26-31	>31
<5 kN/m ²	<24 kN/m ²		-	-	Fair (0.6)	Fair (0.6)
5-15 kN/m ²	24-29 kN/m ²		-	-	Fair (0.6)	Fair (0.6)
16 to 30 kN/m ²	30-34 kN/m ²		-	Bad (0.8)	Bad (0.8)	Fair (0.6)
>30 kN/m ²	>34 kN/m ²		-	-	Good (0.4)	Very Good (0.2)

Further, the corrections have been done in the above matrix classification LSER by considering the field observation, grain size, physical nature and plasticity index. Hence the matrix classification LSER is later modified by adding and subtracting the corrected LSER as shown in the slope forming material theme section (table 4.16). The set of procedures has been followed to prepare the geotechnical theme of the study area as mentioned below.

1. Initially the low-lying areas covered with transported material were demarcated, then a raster theme was created based on cohesion and angle of internal friction matrix values.
2. The raster theme has been classified from bad to very good categories, then each category has been further divided based on field observation, grain size and physical nature and plasticity index of slope forming material and adjusted as per corrected LSER of slope forming material classes (table 4.16).
3. The final geotechnical theme has been prepared by dissolving all similar LSER classes (Figure 4.19).

Field Based High Erosive Power Stream Buffer Map of the Study Area

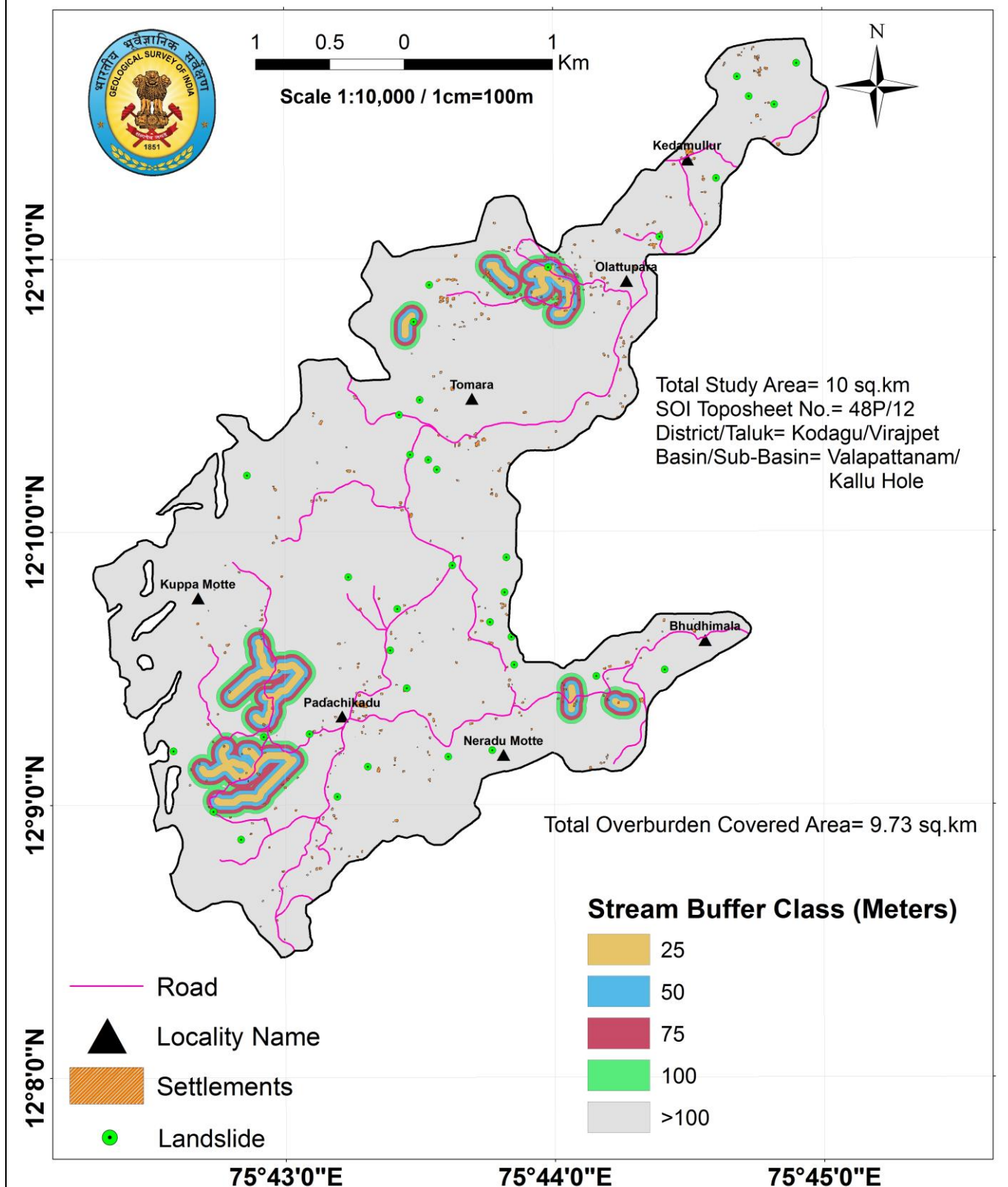
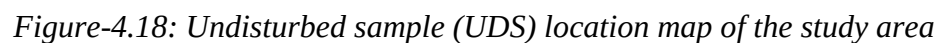


Figure-4.17: High erosive power stream (HEPS) buffer map of the study area



Geotechnical Map of Overburden Domain in the Study Area

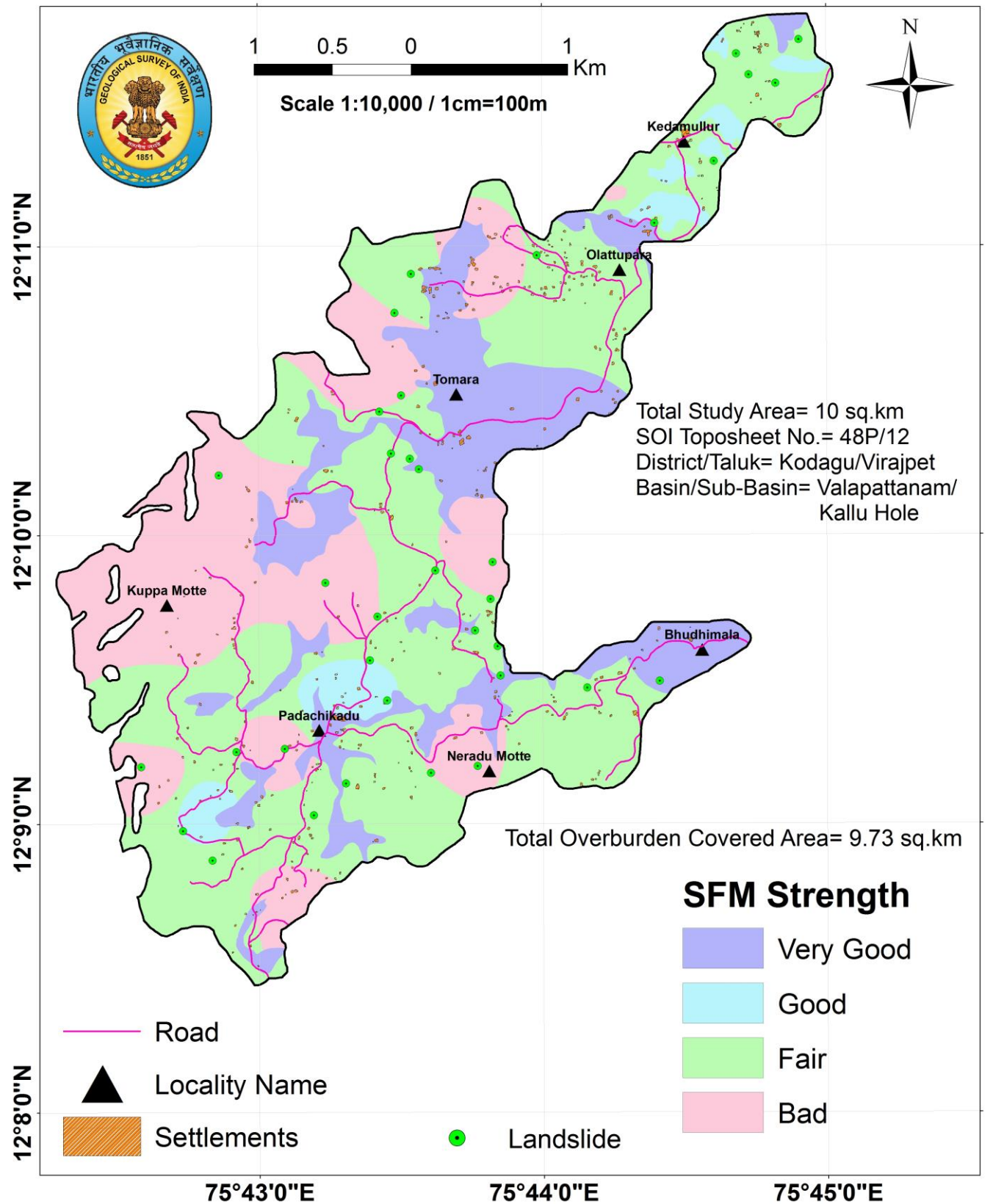


Figure-4.19: Geotechnical map of debris slide and earth slide domains of overburden in the study area

4.5 Landslide Susceptibility Map of Debris Slide and Earth Slide Domains

A landslide susceptibility map is a representation of the Total Estimated Susceptibility Values (TESV) of each mapping unit in an area in terms of different susceptibility classes (Ghoshal *et al.*, 2013). By keeping the LSER in consideration the total estimated susceptibility value over an area of investigation should remain below or equal to 10 as per the opinion of the workers. The ratings for each geo-factor class were given as per their role in changing the slope stability as assessed during field mapping. The debris slide and earth slide susceptibility have been assessed for a 9.73 sq km area covered with an overburden material. The total estimated susceptibility value (TESV) for debris slides and earth slide domain has been calculated by using the map algebra tool of ArcGIS by the addition of all relevant geo-factor themes as mentioned below.

Total estimated susceptibility value (TESV) for overburden domain = $\sum$ (LSER_land use and land cover map + LSER_landform map + LSER_geotechnical map + LSER_stream power index map + LSER_slope gradient map + LSER_high erosive power stream map)

The map area has been segmented into twenty-one distinct classes, each represented by a total estimated susceptibility value (TESV) ranging from 0.4 to 4.7, as indicated in Table 4.20. Later these twenty-one classes were reclassified into three categories of landslide susceptibility by keeping the field experience of landslide vulnerability on slopes in consideration (Table 4.21)

Table 4.20: Landslide susceptibility map attributes for debris slide and earth slide domains

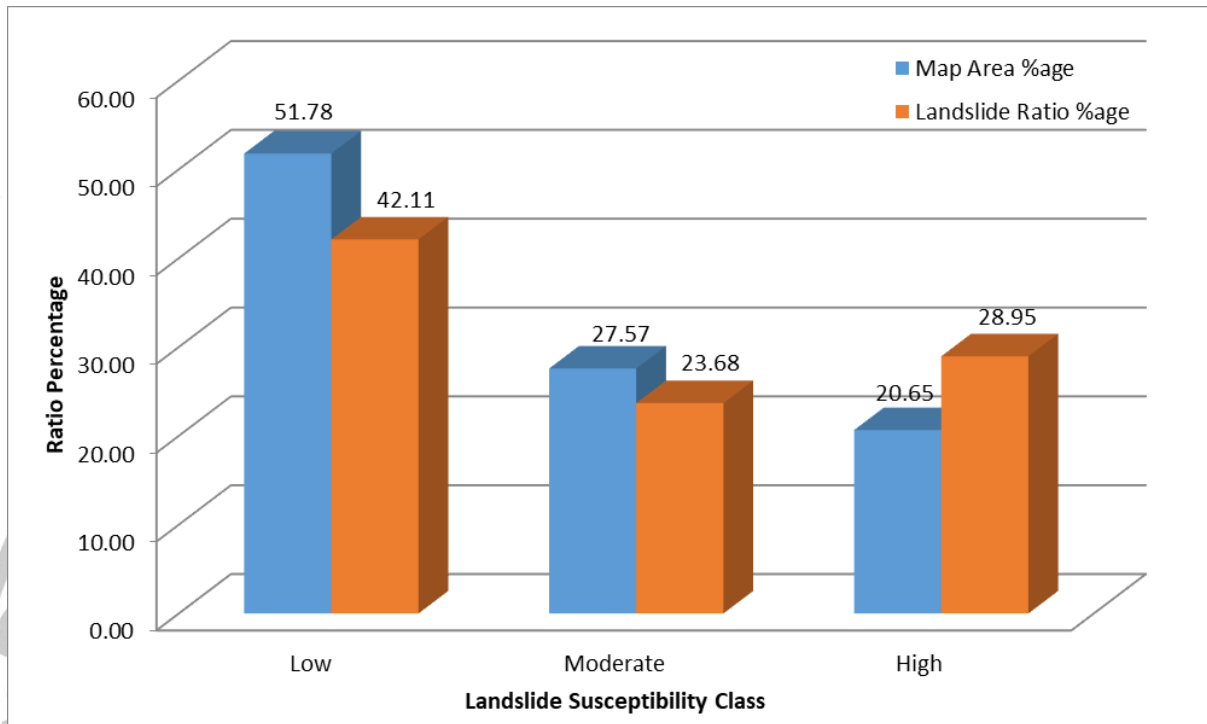
Value	Pixel Count	TESV
1	82	0.4
2	216	0.6
3	2222	0.8
4	2703	1.0
5	2493	1.2
6	9158	1.6
7	11353	2.0
8	11762	2.1
9	7662	2.2
10	11106	2.3
11	10221	2.4

12	9528	2.5
13	11542	2.8
14	14059	2.9
15	4216	3.3
16	2575	3.5
17	1437	3.7
18	756	3.9
19	377	4.1
20	8	4.2
21	2	4.7

Table 4.21: Classified landslide susceptibility map for debris slide and earth slide domains

Value	Pixel Count	TESV	Susceptibility Class	Map Area Percentage	Landslide Ratio
1-10	58757	0.4-2.3	Low	51.78	16
11-13	31291	2.4-2.8	Moderate	27.57	9
14-21	23430	2.9-4.7	High	20.65	11
Total	113478			100%	36 nos.

A total of 36 nos. of landslides were recorded in the debris slide and earth slide domain and have been validated with the susceptibility map area percentage. The landslide ratio is 16 (low): 9 (moderate): 11 (high) which is a satisfactory ratio as per the field conditions and observations made by the workers. The high susceptibility class has retained those slopes that are more prone to landslides. However, the places showing high susceptibility to landslides have unstable slopes that may fail at low angles of internal friction and low cohesion circumstances. Whereas moderate susceptibility does not exceed more than 30 % of the total map area and remains at 27.57 %. This signifies that qualitatively the adopted model for debris slide and earth slide domains has predicted 72 percent of the map area with efficacy and there is the least uncertainty in terms of moderate susceptible class over 28 percent map area. It would be noted that the impact of external forces, especially heavy rainfall, may change the resulting susceptibility scenario in the study area at any time. The basic parameters like the angle of internal friction, cohesion and slope gradient may change by either natural agencies or anthropogenic activities that would favour the slope failures. The graph given below depicts the landslide ratio versus susceptibility map area percentage in the overburden domain.



Geographically the western and southwestern parts of the study area have high landslide susceptibility to debris slide and earth slide failures. Besides the far southern parts of Thakeri and Biligeri villages also show high susceptibility to debris and/or earth slide failures. Moderate susceptible slope facets are widespread in the area and represent areas that are relatively stable but can initiate landslides under the interactions of dynamic geo-environmental factors, particularly during intensive rainfall. Presently the low susceptible slope facets are considered stable under the given set of geo-environmental conditions in the study area. However, the adverse anthropogenic interference and intensive incessant rainfall have accelerated landslides from the low susceptible area.

Landslide Susceptibility Map of Debris/Earth Slide Domain in the Study Area

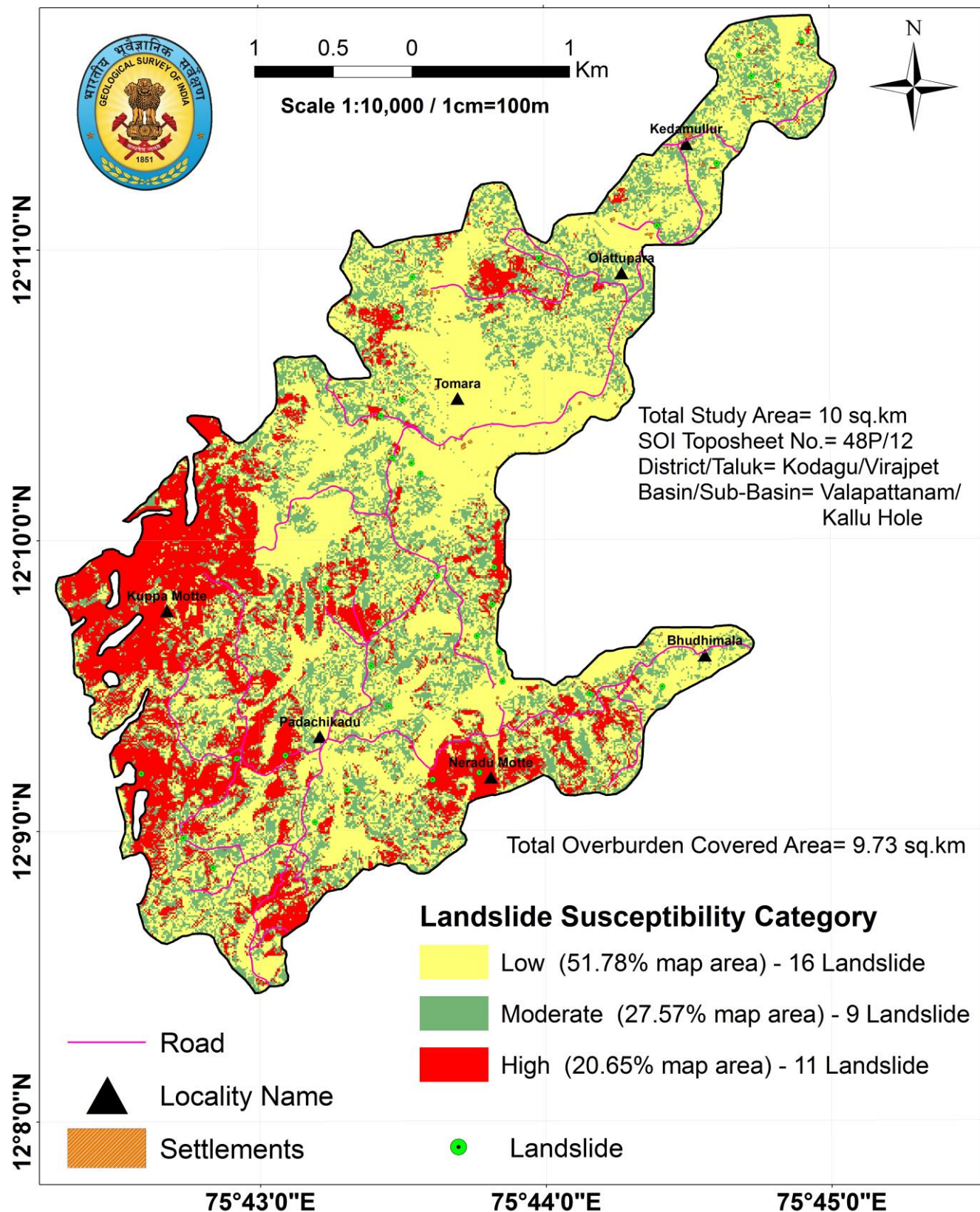


Figure-4.20: Landslide susceptibility map of debris slide and earth slide domains of the study area

CHAPTER – 5

CONCLUSIONS AND RECOMMENDATIONS

In this chapter, we present the conclusions drawn from a comprehensive analysis of the study area, encompassing field observations, geotechnical assessments of slope materials, rock kinematic failure analyses, rainfall patterns, and the resulting landslide susceptibility maps across various domains.

5.1 Conclusions

The study area, spanning 10 square kilometers, is situated within the Western Ghats, a hilly topographic region. It primarily comprises overburden materials, covering approximately 9.73 square kilometers, while the rock-covered area is limited to 0.27 square kilometers. Hornblende Diopside Gneiss is the predominant rock type, characterized by well-developed foliations oriented at an average trend of 338 degree and dipping southwestward at an average angle of 48 degree. Additionally, another foliation trend averaging at 10 degree with a northwestward dip of approximately 40 degrees has been observed. The study identified five joint sets (J1, J2, J3, J4, J5) with a significant impact on rock disintegration, sediment flow formation, and rainwater infiltration, fostering deep weathering processes. A stereo-net analysis revealed that these joint sets created an intricate interference pattern, facilitating subsurface water emergence at multiple locations, contributing to the presence of 37 springs in the area. The interference pattern formed by foliation and joint sets, particularly J2, J3, J4, was identified as a key factor in the formation of rock wedges, leading to slope daylighting and potential failures under low-angle internal friction conditions. The study recorded a total of 37 landslide incidents, comprising 16 debris slides, 19 earth slides, and 1 rockslide. These incidents were primarily triggered by rainfall during the monsoon seasons, with both natural and anthropogenic factors contributing to landslide occurrences.

The study emphasized the high susceptibility of the area, with nearly 50% of properties falling into high-risk categories, affecting various susceptibility levels in the landslide susceptibility model (NLSM). This underscores the importance of conducting risk factor analysis and upscaling landslide studies to minimize potential disasters. The study also highlighted the influence of heavy rainfall events, particularly in 2018, 2019, and 2021, with rainfall exceeding 100mm, posing a constant threat in the hilly topographic region. The Tohra landslide incident, occurring during a rainfall event from 7th to 10th August 2019, serves as a stark reminder of the potential for disastrous situations during such events. In different domains (rockslide, rockfall, and overburden), the landslide susceptibility model demonstrated varying levels of efficacy, providing valuable insights into susceptibility patterns and areas prone to landslides.

The high susceptibility class in each domain retained areas more prone to specific landslide types, primarily driven by unfavorable material parameters, toe erosion by streams and anthropogenic activities.

5.2 General Recommendations

- ✓ The study's general recommendations serve as guidelines for the entire study area, laying out precautionary measures and strategies to mitigate landslide risks. While specific recommendations for critical areas are provided in the landslide management map, the general recommendations are as follows:
- ✓ **Preservation of Natural Streams:** Given the evolving nature of watersheds, it is essential to avoid blocking natural streams and ensure that human development activities, particularly settlements, are located away from these vital watercourses.
- ✓ **Avoidance of Settlements in Flooding Areas:** Settlements should be steered clear of flooding areas associated with higher-order streams, especially during heavy rainfall periods when lower hierarchy streams contribute to water flow.
- ✓ **Drainage Network Construction:** Construct properly lined drainage networks on natural slopes of societal significance and along roads to facilitate the efficient drainage of rainfall runoff.
- ✓ **Maintenance of Concrete Culverts:** Implement arc-type concrete culverts at designated locations to allow the free flow of rainfall waters and conduct regular maintenance of existing culverts.
- ✓ **Priority Reinforcement in High Susceptibility Zones:** Prioritize reinforcement measures in areas falling within high susceptibility zones and their downstream influence areas.
- ✓ **Management of Cut-slopes:** Anthropogenic modifications and cutting of natural slopes should be avoided, but if necessary, untreated cut-slopes with high susceptibility should be immediately stabilized.
- ✓ **Utilization of Susceptibility Map:** The provided landslide susceptibility map may be utilized by the Kodagu district administration for necessary arrangements under the district's disaster management plan.

- ✓ **High Rainfall Alert:** Whenever rainfall exceeds 150mm in the study area, district authorities should be on high alert to evacuate residents from high to moderately landslide susceptible hill slopes.
- ✓ **Critical Rainfall Event:** Rainfall between 150mm to 300mm over 3 to 4 days should be considered critical, as slopes with inherent weaknesses may fail at low values of cohesion and internal angle of friction.
- ✓ **Consultation for Development:** These recommendations are general and should guide regional development planning rather than site-specific developmental planning. Stakeholders are advised to consult the given landslide susceptibility map during preliminary stages of developmental activities in the study area.

These general recommendations aim to enhance the resilience of the study area's communities and infrastructure against landslide hazards, providing a framework for proactive risk management and disaster preparedness.

5.3 Landslide Management Map

It was imperative to gain a comprehensive understanding of the study area, encompassing factors such as the causes of slope failures, variations in topography, agricultural and horticultural practices, the response of slope-forming materials to continuous rainfall, human-induced modifications of slopes for road and settlement infrastructure, and the level of community awareness regarding slope failures and their detrimental effects on the local economy. This comprehensive understanding has provided valuable insights for the present study, enabling the formulation of a landslide management plan that can serve as a foundation for the disaster management plan in the study area. The landslide management plan, within the context of a meso-scale landslide study, comprises three key components. Firstly, it involves conducting on-site assessments to evaluate the stability of slope facets, identifying properties at high risk, and designating safe shelters. Secondly, it entails the development of a visual evacuation plan to be implemented in the event of a landslide disaster. Lastly, it focuses on prioritizing specific areas, including road segments, settlements, and developmental infrastructure, where a range of stabilization measures can be recommended for mitigation purposes.

5.3.1 Slope Stability Assessment and Potentially High-Risk Properties

The evaluation of the stability of natural slope facets was carried out using a field mapping-based approach to identify areas prone to instability. This assessment involved a detailed field examination to identify inherent weaknesses in the natural slope, including the likelihood of planar, wedge, and topple failures, as well as the presence of loose overburden material, the development of surface cracks, and the impact of human activities. Subsequently, the identification of properties at potentially high risk situated on these unstable slopes was conducted on a facet-by-facet basis. In total, 97 slope facets or sections of facets were classified as unstable slopes, covering an area of 1.4 square kilometres. These unstable slopes pose a high risk to 52 settlement houses and a 6-kilometer stretch of road within their influence zone. Figure-5.1 and table-5.1 visually represent the spatial distribution of these unstable slopes, high-risk settlement houses, and road segments in the event of a disaster.

Table-5.1: Spatial location of settlements at high risk in the study area

Sl. No.	X	Y
1	75° 43' 56.064" E	12° 10' 56.097" N
2	75° 43' 55.669" E	12° 10' 52.496" N
3	75° 43' 34.659" E	12° 10' 51.428" N
4	75° 43' 15.719" E	12° 10' 28.713" N
5	75° 43' 37.343" E	12° 10' 41.844" N
6	75° 43' 16.775" E	12° 9' 42.954" N
7	75° 43' 20.876" E	12° 9' 45.427" N
8	75° 43' 27.109" E	12° 9' 43.783" N
9	75° 43' 33.973" E	12° 9' 49.494" N
10	75° 43' 48.574" E	12° 9' 44.863" N
11	75° 43' 42.897" E	12° 9' 37.399" N
12	75° 43' 40.513" E	12° 9' 36.409" N
13	75° 43' 46.293" E	12° 9' 35.302" N
14	75° 43' 46.597" E	12° 9' 18.876" N
15	75° 43' 38.244" E	12° 11' 0.610" N
16	75° 43' 28.492" E	12° 9' 42.795" N
17	75° 43' 26.625" E	12° 9' 42.283" N
18	75° 43' 22.751" E	12° 9' 39.477" N
19	75° 43' 39.462" E	12° 9' 58.608" N
20	75° 43' 51.588" E	12° 10' 50.596" N

21	75° 43' 53.230" E	12° 10' 50.889" N
22	75° 44' 50.146" E	12° 11' 24.967" N
23	75° 44' 33.501" E	12° 11' 17.506" N
24	75° 44' 23.884" E	12° 11' 5.683" N
25	75° 42' 46.419" E	12° 9' 52.915" N
26	75° 42' 54.981" E	12° 9' 15.386" N
27	75° 43' 5.595" E	12° 9' 16.614" N
28	75° 43' 6.445" E	12° 9' 16.287" N
29	75° 43' 9.490" E	12° 9' 1.110" N
30	75° 43' 9.414" E	12° 9' 3.995" N
31	75° 42' 57.251" E	12° 10' 9.949" N
32	75° 42' 40.374" E	12° 9' 9.548" N
33	75° 43' 6.824" E	12° 8' 50.802" N
34	75° 42' 56.914" E	12° 8' 41.148" N
35	75° 42' 39.028" E	12° 9' 4.745" N
36	75° 42' 42.796" E	12° 8' 59.600" N
37	75° 42' 59.655" E	12° 9' 3.990" N
38	75° 42' 59.083" E	12° 9' 4.513" N
39	75° 42' 51.690" E	12° 9' 12.401" N
40	75° 42' 56.767" E	12° 9' 10.594" N
41	75° 43' 0.065" E	12° 9' 21.412" N
42	75° 43' 4.424" E	12° 9' 27.852" N
43	75° 44' 19.123" E	12° 9' 32.235" N
44	75° 44' 9.419" E	12° 9' 28.190" N
45	75° 44' 13.907" E	12° 9' 22.618" N
46	75° 44' 10.921" E	12° 9' 23.970" N
47	75° 44' 4.779" E	12° 9' 22.687" N
48	75° 44' 4.333" E	12° 9' 22.049" N
49	75° 44' 4.174" E	12° 9' 21.542" N
50	75° 44' 1.040" E	12° 9' 23.255" N
51	75° 44' 2.343" E	12° 9' 25.474" N
52	75° 43' 55.672" E	12° 9' 14.633" N

Slope Stability Assessment and Potentially High Risk Property Map of the Study Area

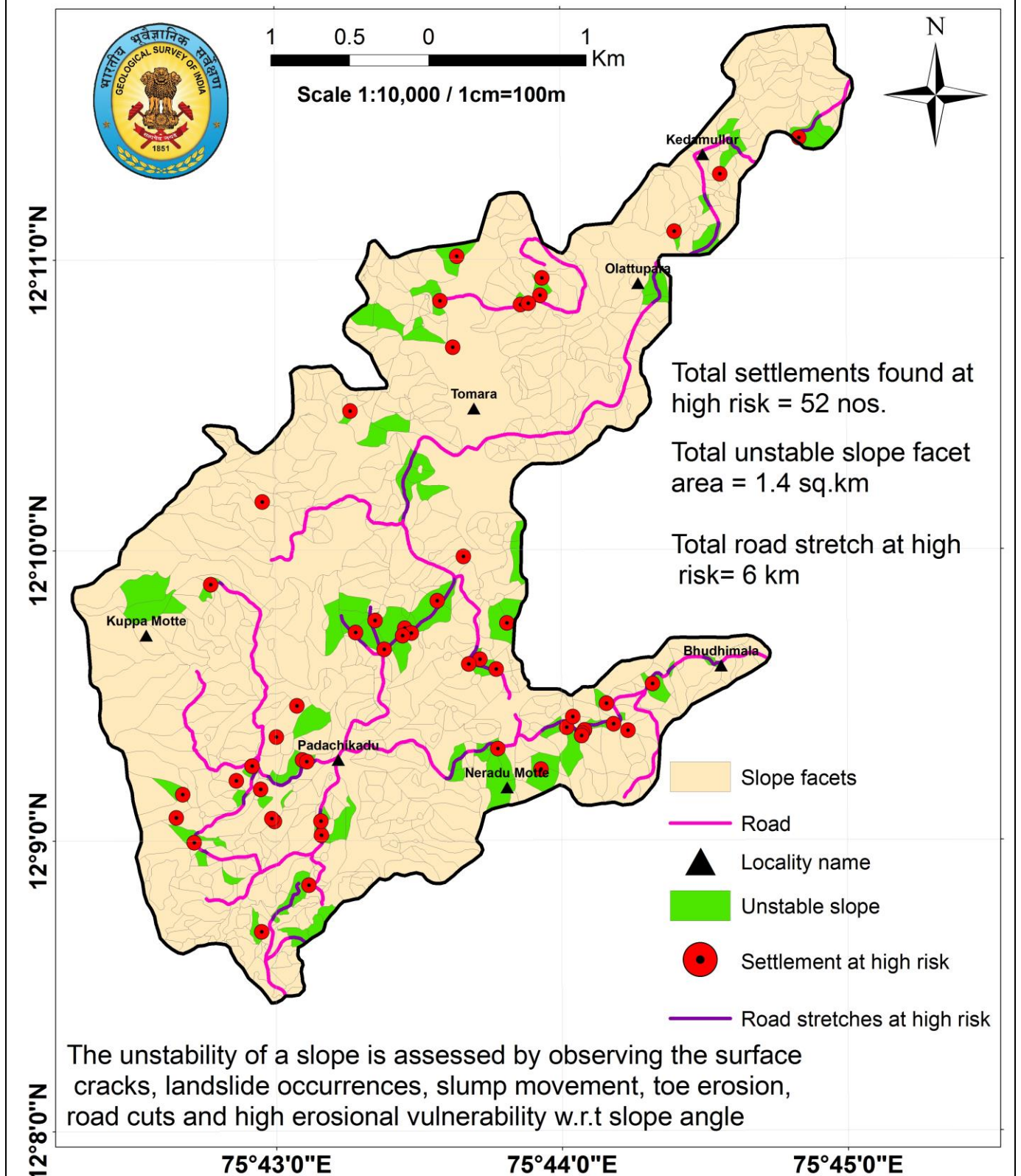


Figure 5.1: Slope stability assessment and potentially high-risk property map of study area

5.3.2 Evacuation Plan for the Study Area

The proposed evacuation plan for the study area, in the event of a landslide disaster, has been meticulously designed with considerations for the rugged topographic terrain, the high percentage of landslide susceptibility, unstable slope facets, and properties at potentially high risk. This evacuation plan specifically targets areas that could face acute challenges during a landslide disaster. One such critical area is depicted in Figure 5.2. To ensure the effectiveness of this plan, safe shelters have been strategically designated in nearby areas. Moreover, potential accessibility challenges for reaching these safe shelters have been identified to minimize the suffering of people and streamline the efforts of disaster management planners. The plan also includes the identification of suitable locations for culverts along roads to prevent rainwater blockage.

In the initial stages of disaster response, rainfall gauge stations are poised to provide crucial real-time information to reporting authorities, particularly when rainfall exceeds 150mm in the study area. Disaster management planners are advised to prioritize the evacuation of settlement houses listed in table-5.1. Ensuring safe access along road stretches that fall within the high-risk zone influenced by unstable slopes is of utmost importance during the evacuation plan. The plan acknowledges the presence of several high-energy drainage outlets and erosion-prone stream paths intersecting roads at multiple points, potentially acting as barriers during heavy rainfall. To address this concern, it is recommended that concrete culverts be constructed in an arc-type model. This design facilitates the efficient passage of high-energy water flows and substantial sediment loads without causing damage to the roads. All such measures were listed out for stabilization of unstable slopes and safe evacuation plan and are shown in given landslide management map in figure 5.3. For convenience, the spatial location of each listed out measure has been given in table 5.2.

Additionally, particular attention is drawn to a bridge constructed over a higher-order stream in Tohra village. The current draining capacity of this bridge is inadequate to handle the accumulated rainfall waters during heavy downpours, which could lead to overflow (figure-5.2). Measures should be taken to address this potential issue to ensure the safety and success of the evacuation plan.

Table-5.2: Various measures necessary for stabilization and safe evacuation plans and their spatial location.

Sl. No.	Type of Measure	X	Y
1	Retaining wall required	75° 44' 38.690" E	12° 11' 21.130" N
2	Retaining wall required	75° 43' 45.597" E	12° 9' 35.289" N
3	Retaining wall required	75° 43' 23.551" E	12° 9' 34.082" N
1	Breast wall required	75° 43' 21.572" E	12° 10' 25.410" N

2	Breast wall required	75° 43' 40.192" E	12° 9' 50.104" N
3	Breast wall required	75° 43' 43.530" E	12° 9' 35.878" N
4	Breast wall required	75° 43' 37.363" E	12° 9' 53.309" N
5	Breast wall required	75° 43' 33.887" E	12° 9' 48.043" N
6	Breast wall required	75° 43' 29.842" E	12° 9' 44.589" N
7	Breast wall required	75° 43' 24.620" E	12° 9' 41.254" N
8	Breast wall required	75° 43' 46.925" E	12° 9' 19.384" N
1	Bridge constructed	75° 43' 14.952" E	12° 9' 18.796" N
2	Bridge constructed	75° 43' 13.874" E	12° 9' 18.599" N
3	Bridge constructed	75° 44' 12.300" E	12° 9' 25.213" N
1	Reinforcement required	75° 44' 30.819" E	12° 9' 37.387" N
2	Reinforcement required	75° 43' 18.370" E	12° 9' 19.260" N
3	Reinforcement required	75° 43' 21.480" E	12° 9' 18.880" N
4	Reinforcement required	75° 43' 24.400" E	12° 9' 18.920" N
5	Reinforcement required	75° 43' 17.970" E	12° 9' 24.360" N
6	Reinforcement required	75° 43' 32.688" E	12° 9' 46.676" N
7	Reinforcement required	75° 43' 37.133" E	12° 9' 54.962" N
8	Reinforcement required	75° 43' 31.920" E	12° 9' 57.430" N
9	Reinforcement required	75° 43' 27.450" E	12° 10' 3.960" N
10	Reinforcement required	75° 43' 29.016" E	12° 10' 19.585" N
11	Reinforcement required	75° 43' 31.580" E	12° 10' 23.220" N
12	Reinforcement required	75° 43' 47.870" E	12° 10' 23.840" N
13	Reinforcement required	75° 44' 18.230" E	12° 10' 57.260" N
14	Reinforcement required	75° 43' 11.530" E	12° 9' 6.370" N
15	Reinforcement required	75° 44' 4.839" E	12° 11' 3.483" N
16	Reinforcement required	75° 44' 10.799" E	12° 10' 51.616" N
17	Reinforcement required	75° 44' 5.812" E	12° 10' 53.266" N
18	Reinforcement required	75° 43' 32.622" E	12° 10' 34.395" N
19	Reinforcement required	75° 43' 15.342" E	12° 10' 12.811" N
20	Reinforcement required	75° 43' 8.063" E	12° 10' 6.434" N
21	Reinforcement required	75° 43' 27.500" E	12° 10' 20.400" N

22	Reinforcement required	75° 43' 41.704" E	12° 9' 37.976" N
23	Reinforcement required	75° 43' 28.152" E	12° 10' 38.909" N
24	Reinforcement required	75° 42' 42.651" E	12° 9' 34.822" N
25	Reinforcement required	75° 42' 42.332" E	12° 9' 17.662" N
26	Reinforcement required	75° 43' 27.070" E	12° 9' 25.600" N
1	Culvert required	75° 44' 48.410" E	12° 11' 34.628" N
2	Culvert required	75° 44' 40.109" E	12° 11' 20.246" N
3	Culvert required	75° 44' 30.342" E	12° 11' 13.345" N
4	Culvert required	75° 44' 14.795" E	12° 10' 44.002" N
5	Culvert required	75° 44' 13.433" E	12° 10' 39.796" N
6	Culvert required	75° 43' 55.250" E	12° 10' 23.494" N
7	Culvert required	75° 43' 35.899" E	12° 10' 20.359" N
8	Culvert required	75° 43' 27.162" E	12° 10' 11.480" N
9	Culvert required	75° 43' 28.104" E	12° 10' 1.394" N
10	Culvert required	75° 43' 21.725" E	12° 9' 29.040" N
11	Culvert required	75° 43' 19.814" E	12° 10' 9.269" N
12	Culvert required	75° 43' 32.748" E	12° 9' 57.129" N
13	Culvert required	75° 43' 42.758" E	12° 9' 47.282" N
14	Culvert required	75° 43' 26.946" E	12° 9' 42.916" N
15	Culvert required	75° 43' 22.273" E	12° 9' 31.597" N
16	Culvert required	75° 43' 16.546" E	12° 9' 24.761" N
17	Culvert required	75° 43' 2.638" E	12° 9' 12.290" N
18	Culvert required	75° 42' 57.126" E	12° 9' 13.699" N
19	Culvert required	75° 43' 21.969" E	12° 9' 28.395" N
20	Culvert required	75° 43' 27.890" E	12° 10' 1.350" N
21	Culvert required	75° 43' 27.370" E	12° 10' 11.140" N
22	Culvert required	75° 44' 12.850" E	12° 10' 40.220" N
23	Culvert required	75° 44' 15.043" E	12° 10' 44.711" N
24	Culvert required	75° 44' 40.430" E	12° 11' 20.130" N
25	Culvert required	75° 44' 11.031" E	12° 10' 54.773" N
26	Culvert passage not sufficient	75° 44' 46.245" E	12° 11' 30.214" N

27	Culvert passage not sufficient	75° 43' 1.692" E	12° 9' 10.394" N
28	Culvert passage not sufficient	75° 43' 5.500" E	12° 9' 15.376" N
29	Culvert passage not sufficient	75° 42' 57.928" E	12° 9' 30.186" N
30	Culvert constructed but not functional	75° 43' 27.187" E	12° 10' 15.168" N
31	Culvert constructed but not functional	75° 43' 22.761" E	12° 9' 38.227" N
32	Culvert constructed but not functional	75° 42' 56.694" E	12° 9' 23.488" N

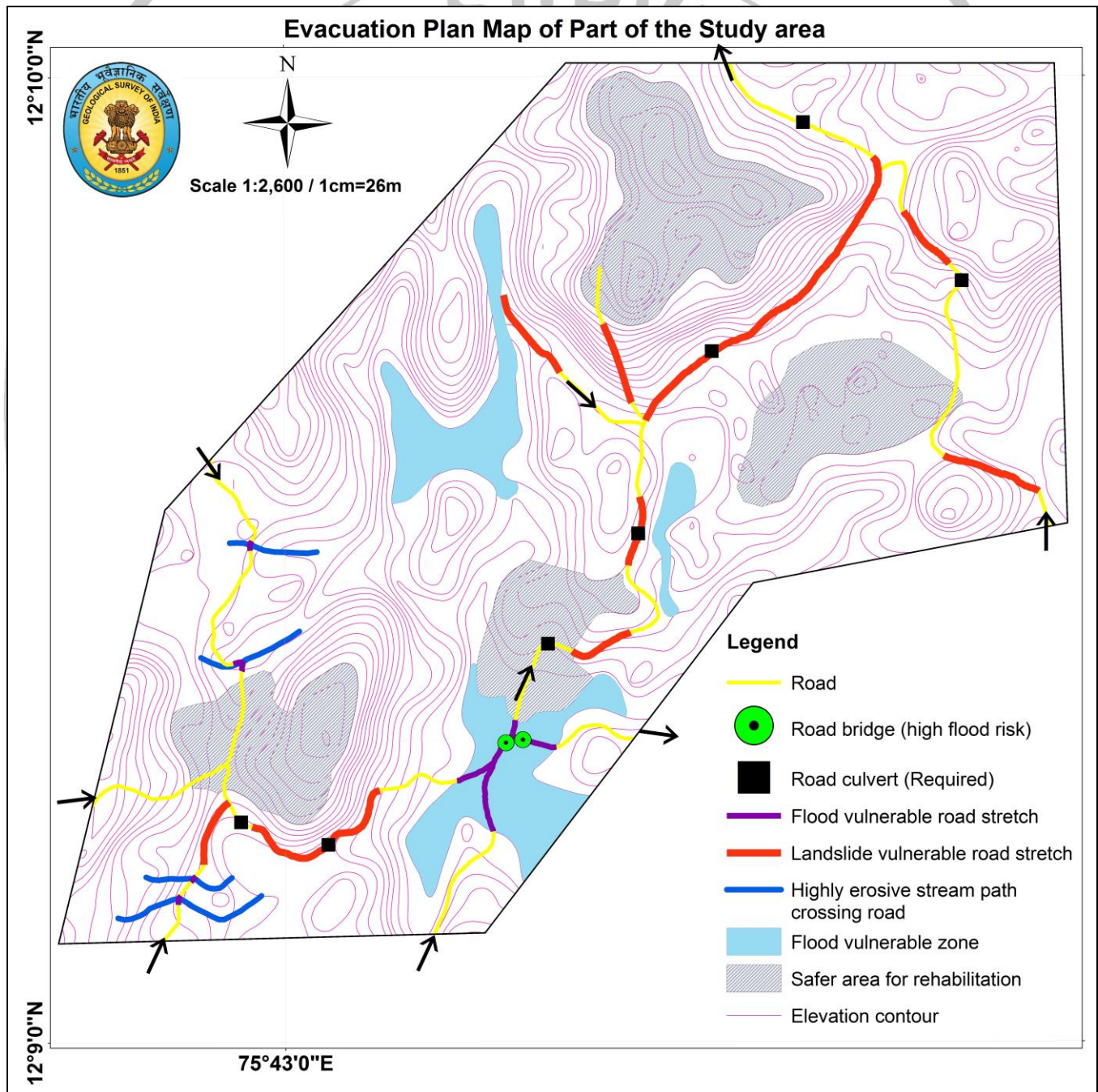


Figure 5.2: Evacuation plan map for a critical area in study area

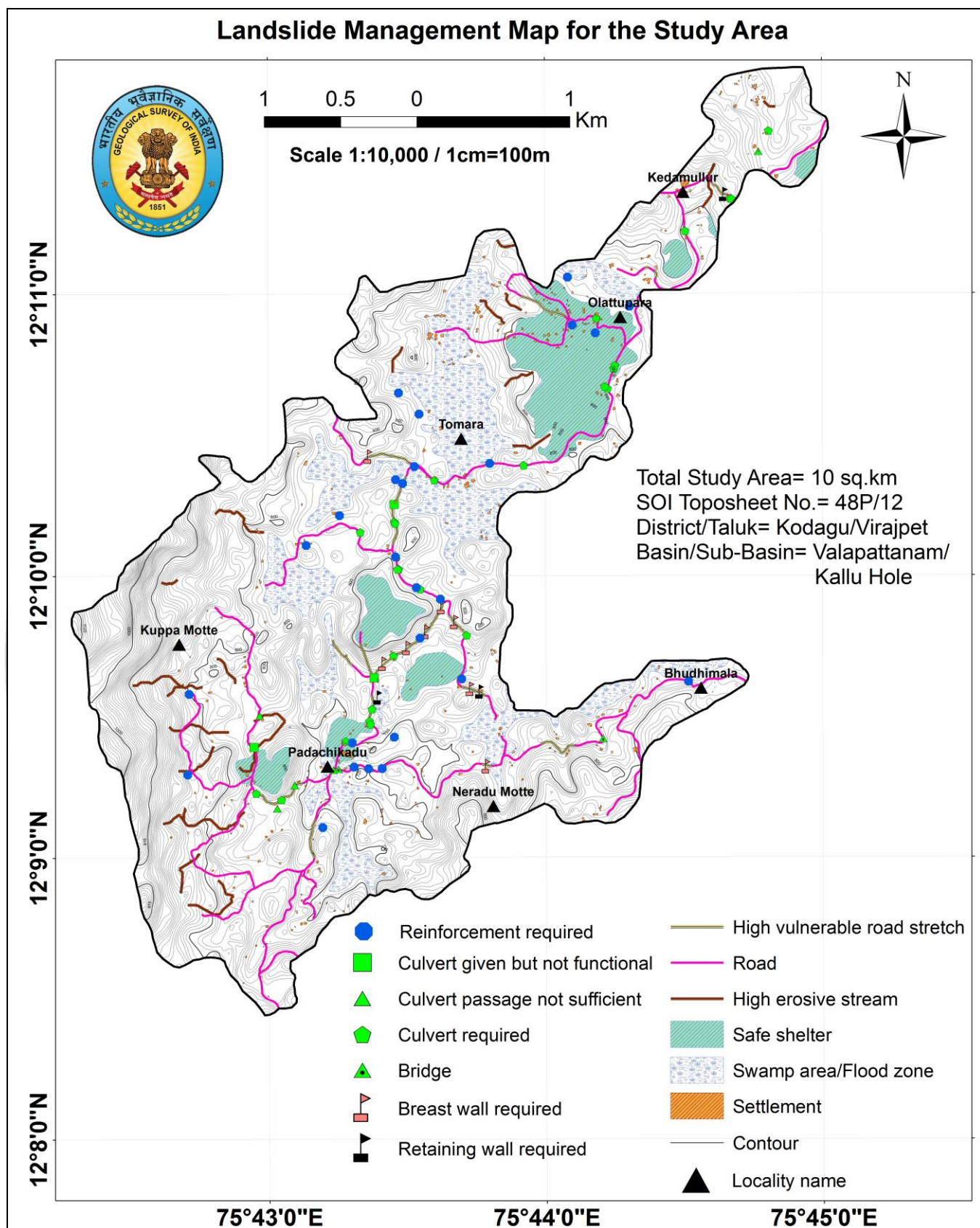
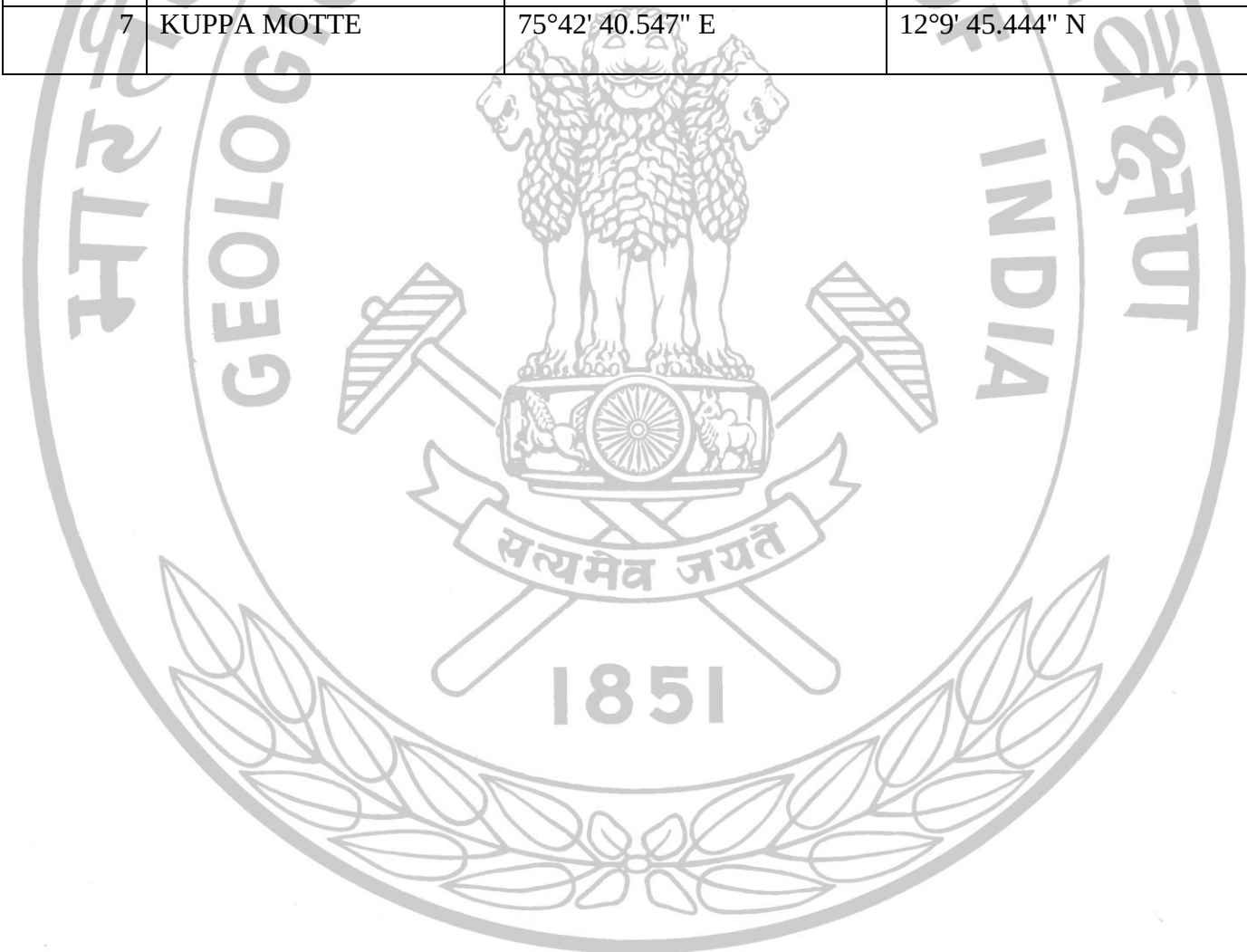


Figure 5.3: A comprehensive landslide management map for the study area

LOCALITY INDEX

Sl. no.	Locality Name	Longitude (DMS)	Latitude (DMS)
1	PADACHIKADU	75°43' 12.612" E	12°9' 19.377" N
2	NERADU MOTTE	75°43' 48.525" E	12°9' 10.889" N
3	TOHRAH	75°43' 41.729" E	12°10' 29.160" N
4	KEDHAMULLUR	75°44' 29.882" E	12°11' 21.610" N
5	OLATTUPARA	75°44' 16.257" E	12°10' 54.983" N
6	BHUDHIMALA	75°44' 33.531" E	12°9' 35.999" N
7	KUPPA MOTTE	75°42' 40.547" E	12°9' 45.444" N



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Annexure-I: Geotechnical results of undisturbed samples (UDS) of slope forming material samples

Sample No.	Y	X	Specific gravity	Moisture content (%)	Bulk density gm/cm ³	Dry density gm/cm ³	Void ratio (e)	Porosity (n)
G1A/SUKG/42402	12.14661	75.71202	2.69	24.56	1.89	1.52	0.77	0.44
G2A/SUKG/42402	12.15058	75.71954	2.47	4.81	1.58	1.51	0.64	0.39
G3A/SUKG/42402	12.1505	75.72574	2.56	27.58	1.63	1.28	1	0.5
G4A/SUKG/42402	12.15614	75.71086	2.59	18.39	1.63	1.38	0.88	0.47
G5A/SUKG/42402	12.15686	75.72183	2.56	20.46	1.85	1.54	0.66	0.4
G6A/SUKG/42402	12.15975	75.72846	2.44	24.15	1.67	1.35	0.81	0.45
G7A/SUKG/42402	12.15461	75.73369	2.5	17.07	1.34	1.14	1.19	0.54
G9A/SUKG/42402	12.16353	75.71207	2.57	26.42	1.5	1.19	1.16	0.54
G10A/SUKG/42402	12.16285	75.72108	2.5	14.99	1.69	1.47	0.7	0.41
G11A/SUKG/42402	12.16341	75.72569	2.56	21.81	1.47	1.21	1.12	0.53
G12A/SUKG/42402	12.17088	75.71207	2.49	16.3	1.5	1.29	0.93	0.48
G13A/SUKG/42402	12.17316	75.71744	2.49	22.15	1.45	1.19	1.09	0.52
G14A/SUKG/42402	12.17359	75.73213	2.75	16.88	1.55	1.33	1.07	0.52
G15A/SUKG/42402	12.17813	75.73304	2.19	22.62	1.9	1.55	0.41	0.29
G17A/SUKG/42402	12.18101	75.72581	2.02	18.55	1.74	1.47	0.37	0.27
G18A/SUKG/42402	12.18123	75.73512	2.96	15.58	1.77	1.53	0.93	0.48
G19A/SUKG/42402	12.18462	75.74202	2.62	19.24	2.07	1.74	0.51	0.34
G21A/SUKG/42402	12.1906	75.74828	2.53	22.77	1.73	1.41	0.79	0.44
G1B/SUKG/42402	12.1506	75.71334	2.49	27.21	1.55	1.22	1.04	0.51
G2B/SUKG/42402	12.14488	75.71809	2.55	22.01	1.56	1.28	0.99	0.5
G4B/SUKG/42402	12.15258	75.71056	2.03	21.21	1.43	1.18	0.72	0.42
G5B/SUKG/42402	12.15394	75.71789	2.03	24.67	1.56	1.25	0.62	0.38
G6B/SUKG/42402	12.15489	75.7285	1.98	27.94	1.36	1.06	0.87	0.47

G7B/SUKG/42402	12.16033	75.74053	1.97	17.71	1.51	1.28	0.54	0.35
G10B/SUKG/42402	12.1672	75.71549	2.05	19.7	1.55	1.29	0.59	0.37
G11B/SUKG/42402	12.16587	75.73034	2.13	26.37	1.67	1.32	0.61	0.38
G14B/SUKG/42402	12.17721	75.72386	2.04	22.79	1.58	1.29	0.58	0.37
G17B/SUKG/42402	12.1816	75.72978	2.13	19.96	1.77	1.48	0.44	0.31
G21B/SUKG/42402	12.19074	75.74283	2.57	8.57	1.95	1.8	0.43	0.3
G2C/SUKG/42402	12.14389	75.71513	1.97	21.97	1.51	1.24	0.59	0.37
G5C/SUKG/42402	12.15918	75.71743	2.2	22.61	1.74	1.42	0.55	0.35
G14C/SUKG/42402	12.17114	75.72421	1.93	18.83	1.53	1.29	0.5	0.33

Sample No.	Gravel %	Sand %	Silt %	Clay %	Cohesion (c)	Angle of internal friction (ϕ)	Liquid limit %	Plastic limit %	Plasticity index	Shrinkage limit %
G1A/SUKG/42402	4	21	70.83	4.17	0.23	34	47	37	10	29
G2A/SUKG/42402	8	31	43.83	17.17	0.25	32	46	39	7	30
G3A/SUKG/42402	12	42	33.31	12.69	0.28	32.1	46	37	9	30
G4A/SUKG/42402	5	37	47.64	10.36	0.3	29.8	45	40	5	29
G5A/SUKG/42402	42	23	19.08	15.92	0.36	30.9	46	37	9	30
G6A/SUKG/42402	12	30	54.06	3.94	0.32	30.8	52	44	8	34
G7A/SUKG/42402	31	37	21.6	10.4	0.29	28.6	45	40	5	29
G9A/SUKG/42402	9	36	47.04	7.96	0.34	23.6	45	40	5	29
G10A/SUKG/42402	2	49	42.02	6.98	0.33	24.6	45	40	5	29
G11A/SUKG/42402	32	30	28.63	9.37	0.2	32.2	46	39	7	30
G12A/SUKG/42402	34	22	27.49	16.51	0.34	23.6	45	40	5	29
G13A/SUKG/42402	23	25	44.72	7.28	0.2	32.2	46	39	7	30
G14A/SUKG/42402	23	34	34.54	8.46	0.37	32.2	46	37	9	30

G15A/SUKG/42402	19	49	4.77	27.23	0.22	29.8	46	39	7	30
G17A/SUKG/42402	26	37	28.28	8.72	0.23	29.7	46	39	7	30
G18A/SUKG/42402	55	27	11.92	6.08	0.26	30.2	46	39	7	30
G19A/SUKG/42402	48	24	18.25	9.75	0.27	31.2	46	39	7	30
G21A/SUKG/42402	37	45	11.14	6.86	0.29	32	47	37	10	29
G1B/SUKG/42402	54	23	17.18	5.82	0.37	31.5	46	37	9	30
G2B/SUKG/42402	3	27	67.15	2.85	0.32	29.8	52	44	8	34
G4B/SUKG/42402	5	23	61.36	10.64	0.32	29.8	52	44	8	34
G5B/SUKG/42402	30	30.96	13.52	25.52	0.35	31	46	37	9	30
G6B/SUKG/42402	1	41	44.05	13.95	0.34	30	46	37	9	30
G7B/SUKG/42402	7	30	30.89	32.11	0.37	32.1	46	37	9	30
G10B/SUKG/42402	29	31	29.42	10.58	0.32	29.8	52	44	8	34
G11B/SUKG/42402	21	51	23.25	4.75	0.32	29.8	52	44	8	34
G14B/SUKG/42402	8	29	60.2	2.8	0.34	23.6	45	40	5	29
G17B/SUKG/42402	8	25	57.55	9.45	0.34	23.6	45	40	5	29
G21B/SUKG/42402	19	34	43.1	3.9	0.26	30.2	47	37	10	29
G2C/SUKG/42402	13	22	61.35	3.65	0.28	30.8	47	37	10	29
G5C/SUKG/42402	9	44	43.68	3.32	0.24	31.5	47	37	10	29
G14C/SUKG/42402	32	26	37.3	4.7	0.22	29.6	47	37	10	29

Annexure-II: Geo-parametric attributes of 37 nos. of landslides recorded in the study area

Sl. No.	1
Landslide No.	LS1
Deg.	12°
Min.	9'
Sec.	15.54"
Y	12.15431667
Deg.	75°
Min.	43'
Sec.	5.38"
X	75.71816111
Locality Name	Korthikad, Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Old Slide but reactivated on 9th Aug 2019 night
Lithology	Granite gneiss contains deformed and stretched quartz and feldspar mineral grains
Landuse/Landcover	Coffee with mostly jungal wood
Hydrological Condition	Wet, groundwater comes on surface from July to September
Element at Risk	Settlement, road and cultivation
Geo-scientific Cause	Excess rainfall; incompetent debris material; drain blockage due to lack of proper lined drainage and culvert maintenance
Remedial Measures	Do not remove the slided material; there is need to construct a proper lined drain on upslope side and modify the culvert to arch type so that runoff water along with eroded material would escape easily
Alert	I
Remarks	There is an old landslide scar observed on upslope side which is having steep

	slope angle. On the foot slope there are two settlement houses which have high risk if any land movement happen on upslope side. Therefore, the place is not safe for shelter.
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Sl. No.	2
Landslide No.	LS2
Deg.	12°
Min.	9'
Sec.	14.92"
Y	12.15414444
Deg.	75°
Min.	42'
Sec.	55.17"
X	75.715325
Locality Name	Korthikad, Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m

Height	5m
Area	500m ³
Type of Material	Earth
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	9th Aug 2019 around 06:00 am
Lithology	Amphibolite
Landuse/Landcover	Settlement having coffee with mostly jungal wood in surroundings
Hydrological Condition	Dry
Element at Risk	Settlement and cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls
Remedial Measures	There is need to reinforce the cut-slope by stone masonry wall and/or by wooden logs; give proper drains in the surrounding of settlement house to drain the runoff water smoothly
Alert	I
Remarks	Avoid to give vertical cut slopes and if given, do not left the cut slopes untreated.



Sl. No.	3
Landslide No.	LS3
Deg.	12°
Min.	11'
Sec.	4.71"
Y	12.18464167
Deg.	75°
Min.	44'
Sec.	23.66"
X	75.73990556
Locality Name	Kedhamallur village near govt. school, Kodagu district, Karnataka
Length	10m
Width	20m
Height	5m
Area	1000m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	9th Aug 2019 initiated and movement occurs every year during rainfall
Lithology	Not visible
Landuse/Landcover	Settlement having coffee with mostly jungal wood in surroundings
Hydrological Condition	Wet
Element at Risk	Settlement, road and cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls
Remedial Measures	Do not remove slided material which may form base as a toe support; however, there is need to reinforce the cut-slope by stone masonry wall and/or by wooden logs; give proper drains in the surrounding of settlement house to drain the runoff water smoothly
Alert	I
Remarks	Avoid to give vertical cut slopes and if given, do not left the cut slopes

untreated.



Sl. No.	4
Landslide No.	LS4
Deg.	12°
Min.	11'
Sec.	17.59"
Y	12.18821944
Deg.	75°
Min.	44'
Sec.	36.27"
X	75.74340833
Locality Name	Kedhamallur village, Kodagu district, Karnataka
Length	20m
Width	20m
Height	8m
Area	3200m ³

Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational deep
History	2019
Lithology	Coarse grained limonitised rock
Landuse/Landcover	Coffee with mostly jungal wood
Hydrological Condition	Dry
Element at Risk	cultivation
Geo-scientific Cause	Incompetent insitu immature material; high influx of runoff waters from upslope side
Remedial Measures	Do not remove the slided material; however, there is need to reinforce the toe of the slide by wooden logs so that advance in movement do not occur; there is also need to divert the upslope runoff waters through proper channels
Alert	III
Remarks	-



Sl. No.	5
Landslide No.	LS5
Deg.	12°
Min.	11'
Sec.	35.53"
Y	12.19320278
Deg.	75°
Min.	44'
Sec.	43.65"
X	75.74545833
Locality Name	Kedhamallur village, Kodagu district, Karnataka
Length	20m
Width	20m
Height	10m
Area	4000m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational deep
History	Very old scar
Lithology	Laterite
Landuse/Landcover	Coffee with mostly jungal wood
Hydrological Condition	Dry
Element at Risk	cultivation
Geo-scientific Cause	Since it is a very old slide therefore it is difficult to observe the causative factors but it seems the slide occurred due to incompetent insitu overburden material; high influx of runoff waters from upslope side and steep slope angle >35°
Remedial Measures	Slope now stabilized
Alert	III
Remarks	-



Sl. No.	6
Landslide No.	LS6
Deg.	12°
Min.	11'
Sec.	42.84"
Y	12.19523333
Deg.	75°
Min.	44'
Sec.	54.22"
X	75.74839444
Locality Name	Kedhamallur village, Kodagu district, Karnataka
Length	10m
Width	150m
Height	6m
Area	9000m ³

Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Old Slide but the reactivation has been occurred recently
Lithology	Granite gneiss with bands of charnockite
Landuse /Landcover	Coffee with mostly arcanut
Hydrological Condition	Flowing
Element at Risk	cultivation
Geo-scientific Cause	Toe erosion by stream water action
Remedial Measures	There is need to shift the stream course to the centre part; give toe support to the slope by available means like stone walls or wooden logs
Alert	III
Remarks	The flowing stream has been continuously shifted towards the foot slope by cultivation activity and the stream water action erodes the toe of slope during rainfall periods which results slope failures on stream banks

Sl. No.	7
Landslide No.	LS7
Deg.	12°
Min.	11'
Sec.	33.74"
Y	12.19270556
Deg.	75°
Min.	44'
Sec.	49.3"
X	75.74702778
Locality Name	Kedhamallur village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2022 August
Lithology	Granite gneiss
Landuse/Landcover	Coffee with mostly arcanut and settlement
Hydrological Condition	Flowing
Element at Risk	Settlement and cultivation

Geo-scientific Cause	Toe erosion by stream water action
Remedial Measures	There is need to shift the stream course to the centre part; give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall
Alert	I
Remarks	Several surface cracks have been developed in settlement house premises on the crown of the slide which has increased the risk to properties at places



Sl. No.	8
Landslide No.	LS8
Deg.	12°
Min.	11'
Sec.	39.88"
Y	12.19441111
Deg.	75°
Min.	44'
Sec.	41.03"
X	75.74473056
Locality Name	Kedhamallur village, Kodagu district, Karnataka
Length	5m
Width	5m
Height	5m
Area	125m ³
Type of Material	Debris
Type of Movement	Slump
Failure Mechanism	Translational shallow
History	2019 August
Lithology	Granite gneiss with quartz veins
Landuse/Landcover	Settlement with mostly coffee & jungal wood in surroundings
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Initially cut-slope given by anthropogenic activity and later toe erosion by a seasonal stream water flow; natural course of stream has been modified and blocked
Remedial	There is need to remove the blockage of stream and give a proper lined drain across

Measures	the settlement premises to drain the upslope stream water smoothly
Alert	I
Remarks	The seasonal stream which plays a role in eroding the toe of slope has high erosive power
	

Sl. No.	9
Landslide No.	LS9
Deg.	12°
Min.	9'
Sec.	1.75"
Y	12.15048611
Deg.	75°
Min.	43'
Sec.	11.53"
X	75.71986944
Locality Name	Thomara village, Kodagu district, Karnataka

Length	20m
Width	10m
Height	10m
Area	125m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational deep
History	2019, 9 th August
Lithology	Deformed and highly stretched granite gneiss
Landuse/Landcover	Barren land
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Lack of vegetation support; incompetent insitu immature material; steep slope angle; high gravity pulls
Remedial Measures	There is need to give multiple check walls at different contour levels from toe of the slide to upslope by using wooden logs or deep-rooted trees
Alert	III
Remarks	Only natural causative factors involved



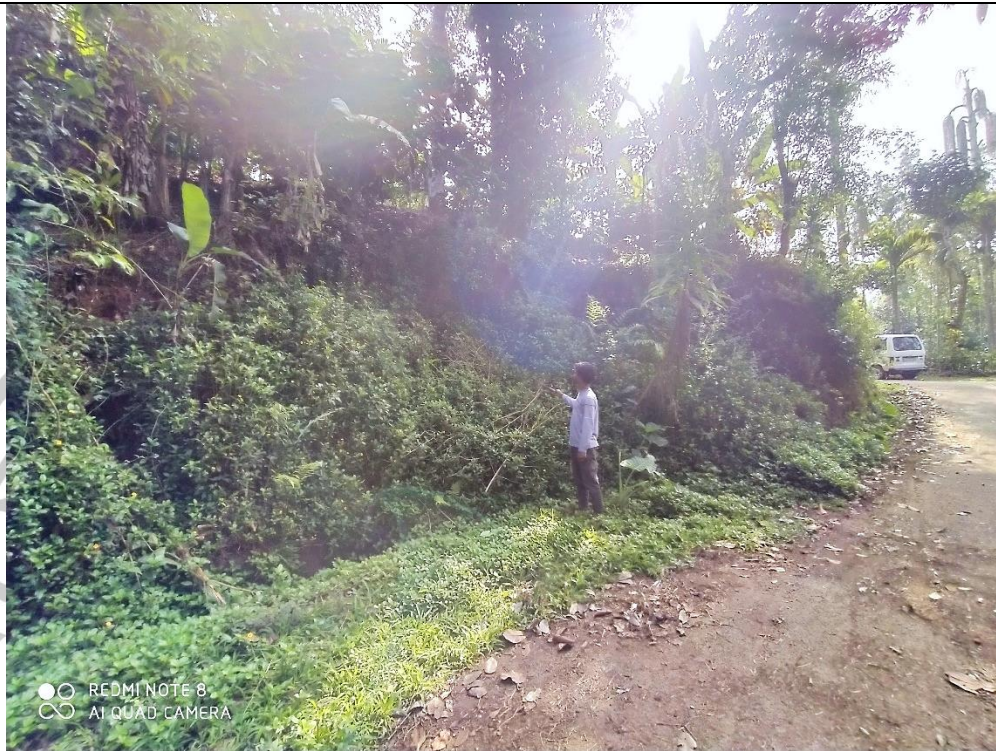
Sl. No.	10
Landslide No.	LS10
Deg.	12°
Min.	10'
Sec.	16.89"
Y	12.17135833
Deg.	75°
Min.	43'
Sec.	27.96"
X	75.72443333
Locality Name	Thomara village, Kodagu district, Karnataka
Length	15m
Width	30m
Height	10m
Area	4500m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2019, August
Lithology	Not visible
Landuse/Landcover	Road having coffee with mostly jungal wood in both sides
Hydrological Condition	Wet
Element at Risk	Road and Cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls; incompetent insitu overburden material
Remedial	Do not remove the slided material; however, there is need to reinforce the toe of the

Measures	slide by appropriate concrete structure so that advance in movement would stop; there is also need to divert the upslope runoff waters through proper channels and construct a lined drain in upslope side of road
Alert	I
Remarks	Anthropogenic causative factors involved



Sl. No.	11
Landslide No.	LS11
Deg.	12°
Min.	10'
Sec.	58.02"
Y	12.18278333
Deg.	75°
Min.	43'
Sec.	58.83"
X	75.73300833

Locality Name	Tharmetta Kedhamallur village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³
Type of Material	Earth
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2019, August
Lithology	Not visible
Landuse/Landcover	Road having coffee with mostly arcanut in both sides
Hydrological Condition	Wet
Element at Risk	Road and Cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls
Remedial Measures	Although a lined drain has been constructed towards upslope side of road but there is need to reinforce the cut-slope by appropriate concrete structure so that further movement would stop
Alert	I
Remarks	Anthropogenic causative factors involved; if the cut-slope would not be reinforced the chances of upslope failure may remain high as the upslope is steep



Sl. No.	12
Landslide No.	LS12
Deg.	12°
Min.	10'
Sec.	46.1"
Y	12.17947222
Deg.	75°
Min.	43'
Sec.	28.8"
X	75.72466667
Locality Name	Palangala Kedhamallur village, Kodagu district, Karnataka
Length	5m
Width	5m
Height	5m
Area	125m ³
Type of Material	Earth

Type of Movement	Creep
Failure Mechanism	Translational shallow
History	Not known
Lithology	Granite gneiss & dolerite
Landuse/Landcover	Road having coffee with mostly aracanut in both sides
Hydrological Condition	Wet
Element at Risk	Road and Cultivation
Geo-scientific Cause	Steep slope angle; toe erosion by stream water
Remedial Measures	Avoid the slope facet for any settlement purpose or road
Alert	III
Remarks	Only natural causative factors involved

Sl. No.	13
Landslide No.	LS13
Deg.	12°
Min.	10'
Sec.	25.64"
Y	12.17378889
Deg.	75°
Min.	43'
Sec.	25.52"
X	75.72375556
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	15m
Area	1500m ³
Type of Material	Debris
Type of Movement	Slide

Failure Mechanism	Translational shallow
History	Not known
Lithology	Granite gneiss
Landuse/Landcover	Road having coffee with mostly jungal wood in both sides
Hydrological Condition	Flowing
Element at Risk	Road and Cultivation
Geo-scientific Cause	Toe erosion by stream water action
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall
Alert	I
Remarks	Only natural causative factors involved



Sl. No.	14
Landslide No.	LS14
Deg.	12°
Min.	10'
Sec.	28.97"

Y	12.17471389
Deg.	75°
Min.	43'
Sec.	30.13"
X	75.72503611
Locality Name	Thomara village, Kodagu district, Karnataka
Length	20m
Width	20m
Height	10m
Area	4000m ³
Type of Material	Earth
Type of Movement	Slide
Failure Mechanism	Translational deep
History	Not known
Lithology	Granite gneiss
Landuse/Landcover	Coffee with mostly jungal wood
Hydrological Condition	Wet
Element at Risk	Settlement, road and cultivation
Geo-scientific Cause	Toe erosion by stream water action
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall
Alert	III
Remarks	Only natural causative factors involved. The settlement house has been already shifted to safer place.



Sl. No.	15
Landslide No.	LS15
Deg.	12°
Min.	10'
Sec.	15.81"
Y	12.17105833
Deg.	75°
Min.	43'
Sec.	31.97"
X	75.72554722
Locality Name	Thomara village, Kodagu district, Karnataka
Length	30m
Width	20m
Height	15m
Area	9000m ³
Type of Material	Earth

Type of Movement	Slide
Failure Mechanism	Translational deep
History	Not known
Lithology	Granite gneiss
Landuse/Landcover	Forest
Hydrological Condition	Wet
Element at Risk	Forest vegetation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle
Remedial Measures	The area should be avoided for any type of settlement which would increase the risk factor
Alert	III
Remarks	Only natural causative factors involved



Sl. No.	16
Landslide No.	LS16
Deg.	12°
Min.	10'
Sec.	13.61"
Y	12.17044722
Deg.	75°
Min.	43'
Sec.	33.85"
X	75.72606944
Locality Name	Thomara village, Kodagu district, Karnataka
Length	5m
Width	5m
Height	5m
Area	125m ³
Type of Material	Debris
Type of Movement	Slump
Failure Mechanism	Translational shallow
History	2019, August
Lithology	Granite gneiss
Landuse/Landcover	Coffee with mostly silver oak
Hydrological Condition	Wet
Element at Risk	Cultivation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall or deep root plantation
Alert	III
Remarks	Only natural causative factors involved



Sl. No.	17
Landslide No.	LS17
Deg.	12°
Min.	9'
Sec.	50.04"
Y	12.1639
Deg.	75°
Min.	43'
Sec.	14.06"
X	75.72057222
Locality Name	Thomara village, Kodagu district, Karnataka
Length	20m
Width	20m
Height	6m
Area	2400m ³

Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Granite gneiss
Landuse/Landcover	Coffee with mostly jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls; incompetent insitu overburden material
Remedial Measures	Do not remove the slided material; although the slide has been stabilized naturally but there is need to reinforce the toe of the slide by wooden logs or by planting deep rooted plantation
Alert	III
Remarks	Anthropogenic cause



Sl. No.	18
Landslide No.	LS18
Deg.	12°
Min.	9'
Sec.	54.28"
Y	12.16507778
Deg.	75°
Min.	43'
Sec.	49.35
X	75.730375
Locality Name	Thomara village, Kodagu district, Karnataka
Length	20m
Width	10m
Height	8m
Area	1600m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2019 Aug 9th
Lithology	Granite gneiss
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Steep slope angle; toe erosion by stream water; incompetent weathered rock material
Remedial Measures	Avoid the slope facet for any settlement purpose or road; need to give toe support by wooden logs, soil bags; need to give deep root plantation at the toe of the slope
Alert	III
Remarks	Only natural causative factors involved



Sl. No.	19
Landslide No.	LS19
Deg.	12°
Min.	9'
Sec.	46.65"
Y	12.16295833
Deg.	75°
Min.	43'
Sec.	48.92"
X	75.73025556
Locality Name	Thomara village, Kodagu district, Karnataka
Length	20m
Width	10m
Height	8m
Area	1600m ³

Type of Material	Debris
Type of Movement	Flow
Failure Mechanism	Translational shallow
History	2020 Aug 9th
Lithology	Granite gneiss
Landuse/Landcover	Coffee, jungal wood having contact with forest
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Steep slope angle; incompetent debris material; high influx of water
Remedial Measures	Do not remove the slided material; although the slide has been stabilized naturally but there is need to reinforce the toe of the slide by wooden logs or by planting deep rooted plantation
Alert	III
Remarks	Only natural causative factors involved



Sl. No.	20
Landslide No.	LS20
Deg.	12°
Min.	9'
Sec.	40.09"
Y	12.16113611
Deg.	75°
Min.	43'
Sec.	45.65"
X	75.72934722
Locality Name	Thomara village, Kodagu district, Karnataka
Length	25m
Width	20m
Height	10m
Area	5000m ³
Type of Material	Debris
Type of Movement	slide
Failure Mechanism	Translational deep
History	2021 Aug 9th
Lithology	Not visible
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle; incompetent debris material
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall or deep root plantation
Alert	III
Remarks	Only natural causative factors involved



Sl. No.	21
Landslide No.	LS21
Deg.	12°
Min.	9'
Sec.	30.7"
Y	12.15852778
Deg.	75°
Min.	43'
Sec.	51.00"
X	75.73083333
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³

Type of Material	Debris
Type of Movement	slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Not visible
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls; incompetent insitu overburden material
Remedial Measures	Do not remove the slided material; although the slide has been stabilized naturally but there is need to reinforce the toe of the slide by wooden logs or by planting deep rooted plantation
Alert	III
Remarks	Anthropogenic cause



Sl. No.	22
Landslide No.	LS22
Deg.	12°
Min.	9'
Sec.	36.8"
Y	12.16022222
Deg.	75°
Min.	43'
Sec.	50.4"
X	75.73066667
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³
Type of Material	Earth
Type of Movement	slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Not visible
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall or deep root plantation
Alert	III
Remarks	Only natural causative factors involved



Sl. No.	23
Landslide No.	LS23
Deg.	12°
Min.	10'
Sec.	54.2"
Y	12.18172222
Deg.	75°
Min.	43'
Sec.	32.3"
X	75.72563889
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³

Type of Material	Debris
Type of Movement	slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Not visible
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall or deep root plantation
Alert	III
Remarks	Only natural causative factors involved



Sl. No.	24
Landslide No.	LS24
Deg.	12°
Min.	9'
Sec.	52.06"
Y	12.16446111
Deg.	75°
Min.	43'
Sec.	32.71"
X	75.72575278
Locality Name	Thomara village, Kodagu district, Karnataka
Length	500m
Width	500m
Height	50m
Area	12500000m ³
Type of Material	Rock cum debris
Type of Movement	Flow
Failure Mechanism	Translational (Deep); Planar & Wedge failure
History	2021 Aug 9th
Lithology	Deformed and sheared granite gneiss
Landuse/Landcover	Forest vegetation, coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Settlement, road and cultivation
Geo-scientific Cause	Incompetent rock having multiple shear planes and several joint sets; favorable joint interference pattern; steep slope angle; high influx of water during rainfall probably by drainage blockage
Remedial Measures	There is need to give multiple check walls at different contour levels from toe of the slide to upslope by using wooden logs or deep-rooted trees so that slid material would stabilize
Alert	I

Remarks	Only natural causative factors involved
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Sl. No.	25
Landslide No.	LS25
Deg.	12°
Min.	9'
Sec.	52.56"
Y	12.1646
Deg.	75°
Min.	43'
Sec.	37.27"
X	75.72701944
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	150m
Height	5m

Area	7500m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2019 August
Lithology	Not visible
Landuse/Landcover	Forest vegetation, coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls; incompetent insitu overburden material
Remedial Measures	Do not remove the slided material; although the slide has been stabilized naturally but there is need to reinforce the toe of the slide by wooden logs or by planting deep rooted plantation or by appropriate concrete measures
Alert	I
Remarks	Anthropogenic cause



Sl. No.	26
Landslide No.	LS26
Deg.	12°
Min.	9'
Sec.	43.00"
Y	12.16194444
Deg.	75°
Min.	43'
Sec.	25.02"
X	75.72361667
Locality Name	Thomara village, Kodagu district, Karnataka
Length	20m
Width	10m
Height	8m
Area	1600m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2019 August
Lithology	Granite gneiss
Landuse/Landcover	Road, coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Steep slope angle; incompetent debris material; high influx of water
Remedial Measures	Do not remove the slided material; although the slide has been stabilized naturally but there is need to reinforce the toe of the slide by wooden logs or by planting deep rooted plantation
Alert	I
Remarks	Only natural causative factors involved



Sl. No.	27
Landslide No.	LS27
Deg.	12°
Min.	8'
Sec.	58.5"
Y	12.14958333
Deg.	75°
Min.	42'
Sec.	43.9"
X	75.71219444
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	8m
Area	800m ³

Type of Material	Debris
Type of Movement	Slump
Failure Mechanism	Translational shallow
History	Not known
Lithology	Granite gneiss
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle; incompetent debris material
Remedial Measures	There is need to give toe support to the slope immediately by appropriate concrete measures like erosion resistant retaining wall
Alert	I
Remarks	Only natural causative factors involved



Sl. No.	28
Landslide No.	LS28
Deg.	12°
Min.	8'
Sec.	52.36"
Y	12.14787778
Deg.	75°
Min.	42'
Sec.	50.09"
X	75.71391389
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Not visible
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Flowing
Element at Risk	Cultivation
Geo-scientific Cause	Toe erosion by stream water action
Remedial Measures	There is need to give toe support to the slope by strong wooden logs
Alert	III
Remarks	Only natural causative factors involved

Sl. No.	29
Landslide No.	LS29
Deg.	12°
Min.	9'
Sec.	29.57"
Y	12.15821389
Deg.	75°
Min.	44'
Sec.	24.59"
X	75.74016389
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	10m
Area	1000m ³
Type of Material	Debris
Type of Movement	Subsidence
Failure Mechanism	Translational shallow
History	Not known
Lithology	Not visible
Landuse/Landcover	Forest vegetation
Hydrological Condition	Dry
Element at Risk	Forest vegetation
Geo-scientific Cause	High rainfall water influx; seems to be an unground water flow path
Remedial Measures	There is need to divert the surrounding rainfall water influx and drain it through proper drainage channels; seal the open pit formed by subsidence with a water-resistant material
Alert	III
Remarks	Only natural cause



Sl. No.	30
Landslide No.	LS30
Deg.	12°
Min.	9'
Sec.	29.57"
Y	12.15821389
Deg.	75°
Min.	44'
Sec.	24.59"
X	75.74016389
Locality Name	Kottachi Kedhamallur village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	10m
Area	1000m ³
Type of Material	Debris
Type of Movement	Slide

Failure Mechanism	Translational (Deep)
History	2019 Aug 9th
Lithology	Not visible
Landuse/Landcover	Settlement, coffee, jungal wood in surroundings
Hydrological Condition	Dry
Element at Risk	Settlement and Cultivation
Geo-scientific Cause	Untreated vertical cut slope; increase in unit mass during rainfall; high gravity pulls; steep slope angle; incompetent insitu overburden material
Remedial Measures	Do not remove the slided material; there is need to give toe support to the slope immediately by appropriate concrete measures; put deep root plantation on slope
Alert	I
Remarks	Both anthropogenic and natural cause
	

Sl. No.	31
Landslide No.	LS31
Deg.	12°
Min.	9'
Sec.	11.9"
Y	12.15330556
Deg.	75°
Min.	43'
Sec.	46.1"
X	75.72947222
Locality Name	Thomara village, Kodagu district, Karnataka
Length	40m
Width	10m
Height	25m
Area	10000m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Old
Lithology	Not visible
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle; incompetent debris material
Remedial Measures	Although the slide seems to be stabilized by naturally but there is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall of wooden logs; there is need to divert the stream course to the center zone and do not block the stream course
Alert	III
Remarks	Both anthropogenic and natural cause



Sl. No.	32
Landslide No.	LS32
Deg.	12°
Min.	9'
Sec.	10.49"
Y	12.15291389
Deg.	75°
Min.	43'
Sec.	36.27"
X	75.72674167
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³

Type of Material	Debris
Type of Movement	Subsidence
Failure Mechanism	Translational shallow
History	2019 Aug 9th
Lithology	Not visible
Landuse/Landcover	Settlement, coffee, jungal wood in surroundings
Hydrological Condition	Dry
Element at Risk	Settlement road and cultivation
Geo-scientific Cause	Poor drainage arrangements; blockage of natural drainage; excess rainwater influx
Remedial Measures	There is need to seal the open pit formed by subsidence with a water-resistant material and construct proper lined drainage network to drain the runoff waters quickly; do not block the nature stream course
Alert	I
Remarks	Both anthropogenic and natural cause



Sl. No.	33
Landslide No.	LS33
Deg.	12°
Min.	9'
Sec.	8.37"
Y	12.152325
Deg.	75°
Min.	43'
Sec.	18.32"
X	75.72175556
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	8m
Area	800m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2019 Aug
Lithology	Dolerite
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Flowing
Element at Risk	Access road and cultivation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle; incompetent debris material; upslope modified for road purpose
Remedial Measures	There is need to give toe support to the slope immediately by appropriate concrete measures like erosion resistant retaining wall; there is need to construct proper channel network drainage towards upslope side
Alert	II
Remarks	Both anthropogenic and natural cause



Sl. No.	34
Landslide No.	LS34
Deg.	12°
Min.	9'
Sec.	11.8"
Y	12.15327778
Deg.	75°
Min.	42'
Sec.	35.05"
X	75.70973611
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³

Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Not visible
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Forest vegetation
Geo-scientific Cause	Toe erosion by stream water action; steep slope angle; incompetent debris material
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall of wooden logs
Alert	III
Remarks	Only natural cause



Sl. No.	35
Landslide No.	LS35
Deg.	12°
Min.	9'
Sec.	25.6"
Y	12.15711111
Deg.	75°
Min.	43'
Sec.	27.07"
X	75.72418611
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	2019 Aug 9th
Lithology	Not visible
Landuse/Landcover	Settlement, coffee, jungal wood in surroundings
Hydrological Condition	Flowing
Element at Risk	Settlement and cultivation
Geo-scientific Cause	Toe erosion by stream water action; modification and shifting of stream course
Remedial Measures	There is need to give toe support to the slope immediately by appropriate measures like erosion resistant retaining wall of wooden logs
Alert	I
Remarks	Both anthropogenic and natural cause



Sl. No.	36
Landslide No.	LS36
Deg.	12°
Min.	9'
Sec.	33.9"
Y	12.15941667
Deg.	75°
Min.	43'
Sec.	23.4"
X	75.72316667
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	6m
Area	600m ³

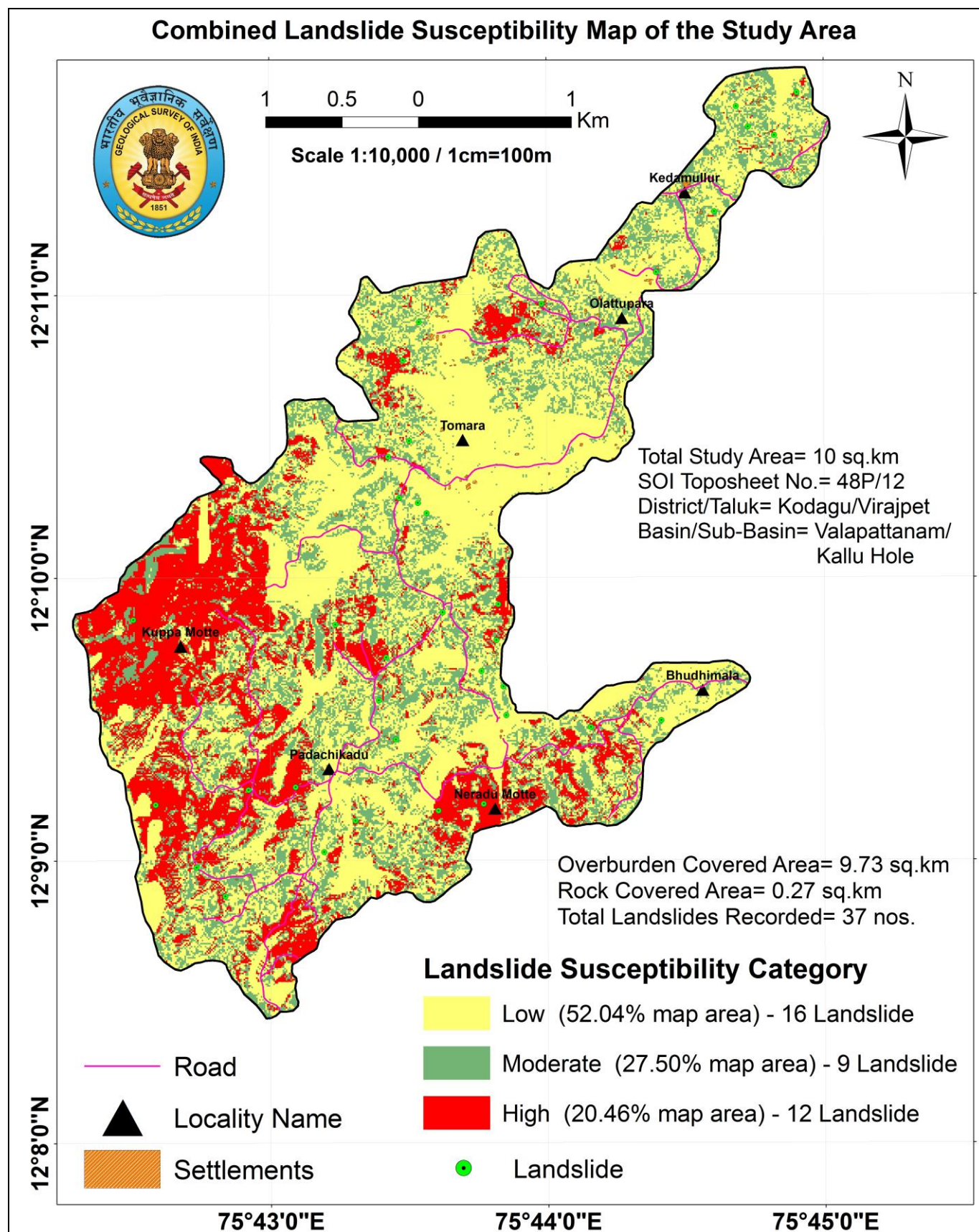
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Not visible
Landuse/Landcover	Forest vegetation
Hydrological Condition	Flowing
Element at Risk	Forest vegetation
Geo-scientific Cause	Toe erosion by stream water action
Remedial Measures	There is need to give toe support to the slope immediately by appropriate concrete measures like erosion resistant retaining wall; there is need to construct proper drainage network along the road on upslope side
Alert	I
Remarks	Both anthropogenic and natural cause



Sl. No.	37
Landslide No.	LS37
Deg.	12°
Min.	10'
Sec.	12.39"
Y	12.17010833
Deg.	75°
Min.	42'
Sec.	51.58"
X	75.71432778
Locality Name	Thomara village, Kodagu district, Karnataka
Length	10m
Width	10m
Height	5m
Area	500m ³
Type of Material	Debris
Type of Movement	Slide
Failure Mechanism	Translational shallow
History	Not known
Lithology	Granite gneiss
Landuse/Landcover	Coffee, jungal wood
Hydrological Condition	Dry
Element at Risk	Cultivation
Geo-scientific Cause	Steep slope angle; incompetent debris material; modified slope
Remedial Measures	Do not remove the slided material; there is need to construct multiple check walls from toe of the slide to upslope side by using wooden logs; adopt the deep root plantation
Alert	III
Remarks	Both anthropogenic and natural cause



Plate-1





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