TERRAIN ANALYSIS IN PHETCHABUN PROVINCE

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Geology
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การวิเคราะห์ลักษณะภูมิประเทศในจังหวัดเพชรบูรณ์

นายธนพรรษ พิเชฐโสภณ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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ธนพรรษ พิเชฐโสภณ : การวิเคราะห์ลักษณะภูมิประเทศในจังหวัดเพชรบูรณ์. (TERRAIN ANALYSIS IN PHETCHABUN PROVINCE) อ.ที่ปรึกษาหลัก : รศ. ดร.สันติ ภัยหลบลี้

จังหวัดเพชรบูรณ์ ภาคเหนือตอนล่างของประเทศไทย มีโอกาสที่จะเกิดภัยพิบัติหลายรูปแบบ ได้แก่ ดินถล่ม น้ำท่วม ที่สร้างความเสียหายให้แก่ประชาชนและทรัพย์สินได้ นอกจากนั้นยังพบโครงสร้างแนวเส้น ซึ่งเป็นแหล่งกำเนิดของธรณีแปรสัณฐาน ดังนั้นนงานวิจัยนี้จึงเลือกใช้วิธีการวิเคราะห์ลักษณะภูมิประเทศ โดยใช้ข้อมูลแบบจ้าลองระดับสูงเชิงเลข ขนาด 30x30 เมตร เพื่อคำนวณดัชนีธรณีสัณฐานทั้งหมด 5 ชนิด 1) ดัชนีความลาดยาวทางน้ำ 2)ดัชนีความคดโค้งเชิงเขา 3) ดัชนีความสูงสัมบูรณ์ของแอ่ง 4) เส้นโค้งสัดส่วนพื้นโลกและ 5) ดัชนีรูปร่างของแอ่ง ซึ่งมีความเกี่ยวข้องกับกิจกรรมทางธรณีแปรสัณฐาน ทำการวิเคราะห์พื้นที่ที่มีความอ่อนไหวต่อการเกิดภัยพิบัติดินถล่ม โดยใช้ดัชนีสถิติทั้งหมดตัวแปร 6 ตัวแปร และใช้ตัวแปรทั้งหมด 5 ตัวแปร ทำการวิเคราะห์ดัชนีความอ่อนไหวต่อการเกิดภัยพิบัติน้ำท่วม

ผลการศึกษาพบว่าบริเวณที่ค่าดัชนีความลาดยาวทางน้ำที่มีค่าร้อยละ 90-100 เป็นค่าที่มีความผิดปกติ ค่าดัชนีความคดโค้งเชิงเขามีส่วนใหญ่บ่งบอกว่าพื้นที่ที่ระดับธรณีแปรสัณฐานที่ต่ำ, ค่าดัชนีความสูงสัมบูรณ์ของแอ่งที่มีค่าสูงแสดงถึงผลกระทบจากธรณีแปรสัณฐานในระดับต่ำ อยู่บริเวณทางตะวันตกและใต้ของจังหวัดเพชรบูรณ์, เส้นโค้งสัดส่วนพื้นโลกของแอ่งในจังหวัดเพชรบูรณ์ ส่วนใหญ่แสดงลักษณะโค้งเว้า และค่าดัชนีรูปร่างของแอ่ง ส่วนใหญ่แสดงรูปร่างวงรีและมีค่าสูง บ่งบอกว่าเกิดกิจกรรมทางธรณีแปรสัณฐานที่สูง ผลการศึกษาความอ่อนไหวต่อการเกิดภัยพิบัติดินถล่ม สามารถแบ่งออกเป็น 5 ระดับ โดยระดับสูงและสูงมากจะพบบริเวณเทือกเขาทางตะวันออกและตะวันตกของจัหวัดเพชรบูรณ์ และผลการศึกษาความอ่อนไหวต่อการเกิดภัยพิบัติน้ำท่วม สามารถแบ่งได้ 4 ระดับ ซึ่งบริเวณที่มีความอ่อนไหวสูงจะพบทางตอนกลางและใต้ของจังหวัดเพชรบูรณ์

สาขาวิชา	ธรณีวิทยา	ลายมือชื่อนิสิต ....
ปีการศึกษา	2562	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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Tanapat Pichetsopon : TERRAIN ANALYSIS IN PHETCHABUN PROVINCE. Advisor: Assoc. Prof. SANTI PAILOPLEE, Ph.D.

Phetchabun province, lower northern Thailand is vulnerable to geohazards, landslide and flooding with the potential for significant harm to people and property. In addition, Phetchabun province has many lineaments that could be potential source of tectonic activities. In this study, terrain analysis techniques are used through 30 meters resolution Digital Elevation Model (DEM) data in order to determine geomorphic indices related to tectonic activity. The statistic index method (S_i) is calculated in relation of six parameters to indicate landslide susceptible area. and the hydromorphometric contrast index (HCI) is used to identify sensitive area to flooding by evaluating five parameters.

According to the result, the SL index with 90 to 100 percentage was selected to represent anomalous values. The S_{mf} index, most of lineaments has been supported the low to medium active tectonics. The value of HI indicates less impact from tectonic activity. HC show most drainage basins in concave curves. The B_s index, most drainage basins that are related to medium to high tectonic activity. Additionally, the high and very high classes of landslide susceptibility maps have been situated in the eastern and western area. The high class of flood susceptibility map has been shown in the central and southern area.

Field of Study: Geology Student's Signature ....

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Tanapat Pichetsopon

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INTRODUCTION

Background

Phetchabun province, lower northern Thailand is vulnerable to various geohazards, e.g. flood, earthquake, land slide, including debris and earth flow hazards, with the potential for significant harm to people and property. In 2011, a debris flow occurred in Nam Ko sub-district, Phetchabun (Yumuang, 2006), killed 136 people and caused 109 injuries and over US$21 million in property damage. The debris flow rapidly moved into the river channel and flooded over the lowland flat areas. In 2019, Phetchabun also faced severe flooding triggered by heavy rainfall in many districts which are Lom Sak, Wang Pong and Chon Daen. This is one of the most severe natural disasters in the past few decades (Figure 1).

To avoid damage or reduce losses of life and property, this study identified the areas which are subject to active tectonics, landslides and flooding which is the major cause of natural hazards, measuring from low to high. This thesis, therefore, presents the spatial distribution of i) relative tectonic activity, ii) landslide susceptibility map and iii) flood susceptibility map of Phetchabun which can provide planners and decision makers in disaster planning.

In order to analyze hazard and risk assessment for Phetchabun, we used the terrain analysis method via remote sensing and GIS to identify potential vulnerable zones. The method can be divided into 3 indicators: i) geomorphic indices to identify active tectonics, ii) statistical index (Si) (Meinhardt, Fink, and Tünschel, 2015), weighting factors by means of bivariate statistics, to locate landslide susceptibility zones with 88.5% success rate and 88.1% prediction rate and iii) hydromorphometric contrast index (HCI) (García-Rivero et al., 2017) to detect flood susceptibility areas with high accuracy. The hazard map created from digital elevation model (DEM) data as it provides a high accuracy and open access.

Figure 1. Hazard in Phetchabun province (a) landslide at Nam kor Yai village Lom Sak district in 2001 (DMR, 2009), (b) landslide at Muang Phetchabun district in 2000 (DMR, 2009), (c) flood at Lom Sak in 2018 (Khaosod, 2018) and (d) flood at Lom Sak district in 2017 (Thaipbs, 2017).

Study Area

1. Location and accessibility

The study area is the entire of the Pa Sak River basin which is located in the central part of Phetchabun province, Thailand. The GPS coordinates between 16°30’N to 17°20’N and 100°60’E to 100°80’E with a surface area of approximately 12,600 square kilometers (Figure 2), 70 kilometers north of Bangkok. It borders with Loei to the north, Lopburi to the south, Chaiyaphum and Khon Kaen to the east and Phitsanulok, Phichit and Nakhon Sawan to the west.

2. Topography

There is complex mountainous area in the north serves as the catchment basin of the Pa Sak River. It passes through the central Phetchabun as the backbone of the province, flowing north to south along a steep cliff. It has been banked by terraces and a series of hills and is surrounded by mountain ranges running along both the western and eastern sectors. The area mainly composed of hills, strongly incised plateau and piedmont, varying in altitude as from 30 to about 1,760 meters above sea level (Figure 2). The highest area is Phu Thap Boek Mountain. The lowest part of terrain is floodplain where most important hazards has occurred.

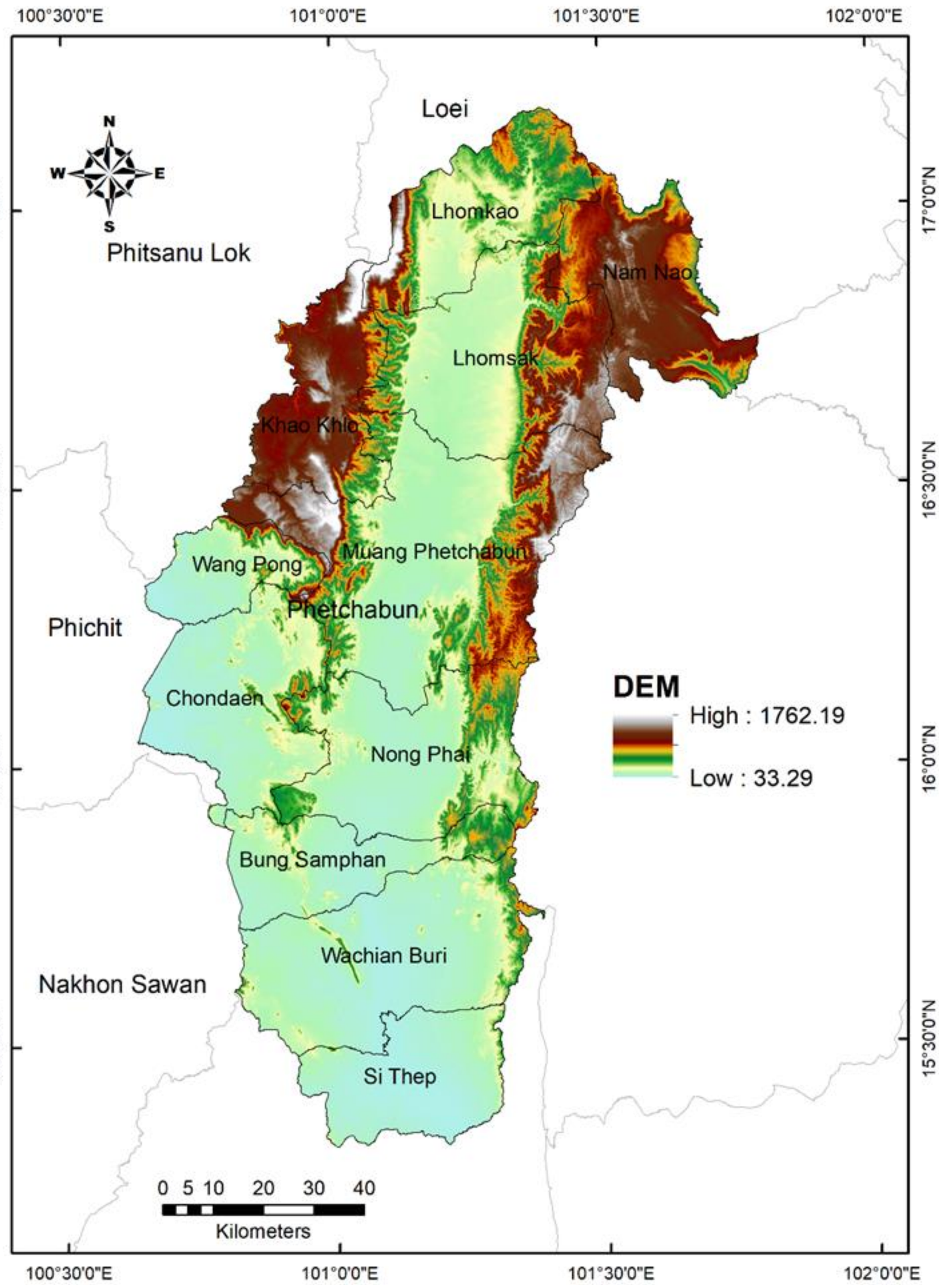


Figure 2. Phetchabun province showing spatial distribution of topography analyzed by Digital Elevation Model (DEM) data.

3. The geological setting

The classification of rocks in Phetchabun is based on lithology, depositional environment and fossils that were found in the Late Paleozoic rocks. In this report, the geological map of Thailand on 1:250,000 scale (Chonglakmani and sattayarak,

1979) is used for relative age of rocks identification. The following are the study area's stratigraphy in order from oldest to youngest (see also Figure 3).

3.1. Carboniferous

The Dok Du Formation represents the Carboniferous strata in Loei-Phetchabun Ranges region which consists of shale, sandstone, siltstone and dark grey limestone. Most parts of limestone melted during the intrusion of igneous rocks and turned into marble. These outcrops are widespread in western mountain area extending from Wang Pong district to Chon Daen district.

3.2. Carboniferous-Late Permian

The Huai Som Formation has been designed for Carboniferous-Late Permian rocks. It is younger than Dok Du Formation consisting of tuffaceous sandstone, tuffaceous siltstone, tuffaceous mudstone, conglomerate and chert with intercalations of lenticular limestone.

3.3. Early Permian-Middle Permian

The Early Permian-Middle Permian rocks in Phetchabun belong to Pha Nok Khao Formation. The main lithologies in ascending order are nodular or layered chert, shale and dark-gray massive too thick-bedded limestone.

3.4. Middle Permian-Mate Permian

Hua Na Kham Formation presents the Middle Permian-Late Permian consisting chiefly of clastic sediments, shale, siltstone and sandstone unit with limestone lenses or beds. Andesite, tuff and agglomerate also can be found in this formation.

3.5. Triassic

The non-marine Triassic rocks belong to Huai Hin Lat Formation of Khorat Group. Reddish-brown basal conglomerates, sub-graywacke, calcarenite and siltstone are the main lithologies of these rocks. Epidote and diopside are also present in calcarenite. Quartzite, metamorphosed by sandstone, can be found in the area that the magma intruded. There are the Triassic igneous rocks indicating magma intrusive.

3.6. Early Jurassic

The Nam Phong and Phu Kradung Formations consist of red-brown micaceous sandstones, siltstones, mudstones and conglomerates. It unconformably overlies the

Late Triassic Huai Hin Lat and older strata. It can be interpreted as having been deposited by meandering and braided rivers in semi-arid to arid conditions.

3.7. Late Jurassic

The Phra Wihan Formation in Khorat Group represents the Late Jurassic. It is composed almost entirely of thick bedded to massive white sandstones which identify that they have been deposited by a stacked series of braided rivers.

3.8. Quaternary

The Quaternary sediments are classified by geomorphology, lithology, depositional environments and fossils. The lowland area and watershed are composed mainly of Quaternary sediments. They are rich in mineral resources and construction materials. It is interpreted that has been deposited 1.6 million years ago to today. The classification of Quaternary sediments can be divided into 2 types.

The first one is terrace gravel which is reserved in the west and the east of Phetchabun basin. Some terraces contain laterite which height approximate 130-190 meters. The terrace gravel forming is related to the Pa Sak River.

The second one is alluvial deposits the main sediments of alluvial deposits are clay sand and silty sand overlying gravels and bed rocks. The major source of sediments is caused by the process of gully erosion which running water through the Pa Sak River cuts new unstable channels into erodible soil and weathered rock.

4. Structural geology

In this study, the Late Paleozoic strata has not been found a cleavage. Also, there is a low dip angle fault. These features indicate that the study area is situated outside the intense folding zones which is caused by plate tectonics. Therefore, the investigation zone shows uncomplicated structural geology especially in comparison to the Phetchabun Folds and Thrust Belts, examined by Helmke et al. (1985), which is located on the opposite side in Phetchabun basin. The following are the summary of the interest area’s structural geology (see also Figure 3).

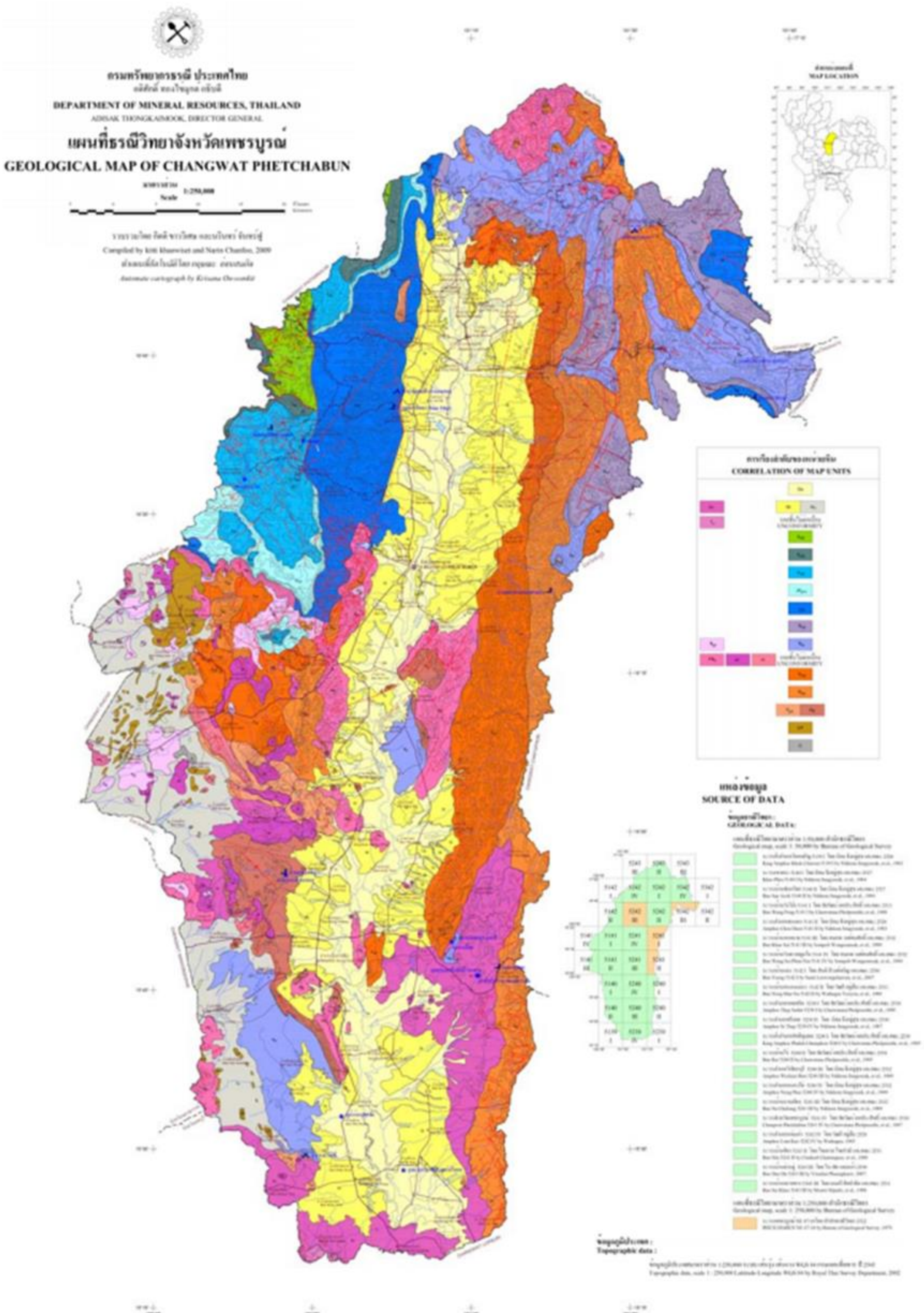


Figure 3 Geological map of Phetchabun province (DMR, 2009).

ตะกอน หินชั้น และหินแปร SEDIMENT, SEDIMENTARY AND METAMORPHIC ROCKS	ชื่อหมวด/กลุ่มหิน FORMATION/GROUP	ยุค PERIOD	อายุ (ล้านปี) AGE (my.)
Qa [illegible] Alluvial deposit : sand, silt, clay and fine-grained gravel. Qt [illegible] Terrace deposits : gravel, sand, silt and clay. Qc [illegible] Colluvial deposits : Gravelly sand to sandy clay, loose bodies of sediment, deposited at the base of mountains or the bottom of slow-grade slope, transported by gravity.		ควอเทอร์นารี QUATERNARY	0.01-1.6
Kkk [illegible] Siltstone interbedded sandstone and intercalated conglomerate ; siltstone : grayish red, reddish brown and pale red, sandstone ; conglomerate : calcareous cement, calcrete.	หมวดหินโคกกรวด กลุ่มหินโคราช KHOK KRUAT Fm., KHORAT Gp.	ครีเทเชียส CRETACEOUS	66.4-140
Kpp [illegible] Pebbly sandstone, gray sandstone, gray, grayish white, medium-to coarse-grained, poor sorted, subangular to subrounded, large scale cross-bedded; siltstone and claystone, gray to dark gray, thin bedded, are intercalated locally; conglomerate, gray, grayish white with pebbles of quartz and cherts, white, dark gray, red and green, volcanic rockfragments and metasandstone, subround, silica cement.	หมวดหินภูพาน กลุ่มหินโคราช PHU PHAN Fm., KHORAT Gp.		
Ksk [illegible] Sandstone, brown, reddish brown, purple and purlish red, fine-to medium-grained, well sorted; siltstone and claystone, reddish brown, purplish red, micaceous.	หมวดหินเสาขัว กลุ่มหินโคราช SAO KHUA Fm., KHORAT Gp.		
JKpw [illegible] Sandstone, white, pink, quartzitic, fine-to coarse-grained, moderately sorted, subrounded; conglomerate and pebbly sandstone, gray with pebbles of quartz and cherts, gray, black, brown, red and quartzite, large scale cross-bedded; siltstone and claystone, gray and dark gray, thin-bedded, are intercalated locally.	หมวดหินพระวิหาร กลุ่มหินโคราช PHRA WIHAN Fm., KHORAT Gp.	ครีเทเชียสถึงจูแรสซิก CRETACEOUS to JURASSIC	66.4-210
Jpk [illegible] Siltstone and claystone, maroon, reddish brown, reddish gray, fine to medium grained, poor sorted interbedded with greenish gray feldspathic medium-grained sandstone.	หมวดหินภูกระดึง กลุ่มหินโคราช PHU KRADUNG Fm., KHORAT Gp.	จูแรสซิก JURASSIC	140-210
TRnp [illegible] Sandstone, reddish brown, reddish gray, fine-to medium-grained, well sorted, subrounded to rounded, thin-to thick-bedded, well laminated, calcrete layers at top of cycles and spot are common, interbedded with reddish brown to dark reddish brown calcareous siltstone; calcareous mudstone, gray, purplish gray; fossils are vertebrates.	หมวดหินน้ำพอง กลุ่มหินโคราช NAM PONG Fm., KHORAT Gp.	ไทรแอสซิก TRIASSIC	210-245
TRhl [illegible] Sandstone, siltstone, conglomeratic sandstone, brownish red, greyish purple ; basal conglomerate, pebbles of quartz chert, volcanic rocks, shale, sandstone and limestone, calcareous cementing and intercalated with shale; fossils are Conchostracans and plant remains.	หมวดหินห้วยหินลาด กลุ่มหินโคราช HUAI HIN LAT Fm., KHORAT Gp.		
Pnd [illegible] Shale, greyish black, brownish red; sandstone, brownish yellow, brownish red, small to medium cross-bedded, highly folded siliceous cementing; limestone lens.	หมวดหินน้ำดุก NAM DUK Fm.	เพอร์เมียน PERMIAN	245-286
Phk [illegible] Shale, gray; sandstone, yellowish-brown and limestone, gray lense or bedded; fossils are fusulinids, brachiopods and corals and plant remains.	หมวดหินหัวนาคำ HUA NA KHAM Fm.		
Ppk [illegible] Limestone, gray, massive and bedded; shale, grey, yellowish brown; and chert, gray; fossils are fusulinids, brachiopods ammonites and corals.	หมวดหินผานกเค้า PHA NOK KHAO Fm.		
Ptf [illegible] Limestone, gray to black, massive to well bedded; chert, black nodular or thin bedded; with intercalations of thin bedded gray shale.	หมวดหินตากฟ้า TAK FA Fm.		
CP [illegible] Sandstone, siltstone shale and mudstone, black to greenish gray, thin to medium bedded; conglomerate bed and slaty shale.		เพอร์เมียนถึงคาร์บอนิเฟอรัส PERMIAN to CARBONIFEROUS	245-360
C [illegible] Slaty shale, gray; shale, brown, brownish-gray; chert, gray; sandstone, brown; and conglomerate.	หมวดหินวังสะพุง WANG SAPHUNG Fm.	คาร์บอนิเฟอรัส CARBONIFEROUS	286-360
หินอัคนี IGNEOUS ROCKS	**ยุค PERIOD**		
[illegible] Basalt, dark gray to black, vesicular and amygdaloidal, with phenocrysts and megacrysts of olivine, pyroxene and spinel locally columnar joints.	เทอร์เชียรี TERTIARY		1.6-66.4
Tv [illegible] Rhyolite mainly lava flows, grayish red to maroon, fine-grained, porphyritic texture, flow over glassy beds and pyroclastic flow; andesite, porphyry, grayish green; rhyolitic tuff, white to grayish white, very fine-grained.			
TRgr [illegible] Biotite granite, tourmaline granite, granodiorite, biotite-muscovite granite, muscovite-tourmaline granite, biotite-tourmaline granite.	ไทรแอสซิก TRIASSIC		210-245
PTRv [illegible] Tuff, andesitic tuff, rhyolitic tuff, greenish-gray, light-gray, white; agglomerate, greenish-gray, rhyolitic white, light gray; and andesite, greenish-gray.	ไทรแอสซิก ถึง เพอร์เมียน TRIASSIC to PERMIAN		210-286
[illegible] Andesite porphyry, grayish green, very fine-grained with hornblended phenocrysts and basalt xenoliths. [illegible] Rhyolite, pale gray, very fine grained porphyritic texture with plagioclase and quartz phenocrysts.	เพอร์เมียน PERMIAN		245-286

Figure 4 Geological map of Phetchabun province (cont.) (DMR, 2009).

4.1. Unconformity

An unconformity is defined as a contact between two strata which the lower unit is much older than the upper unit because of an extended period of buried erosion. There are several causes of unconformity such as by tectonic plate uplifts or by eustatic sea-level fall. An unconformity preserves time missing (hiatus) from the geological record. Thus, the other clues are used to discover the part of the geologic history of the area. In this study, the unconformities are defined by the tectonic event as follows.

4.1.1. Early Triassic

The angular unconformity can be observed as the boundary between the late Paleozoic and Triassic. The Triassic sedimentary rocks cover the Permian-Triassic volcanic rocks directed by a nonconformity. The basal conglomerates that have been found identify the unconformity. The sediment particles depend on their accumulated location and source rocks in the basin.

4.1.2. Late Triassic

The unconformity between the late Triassic-late Jurassic has been found as a disconformity and nonconformity overlying on igneous rocks. A change in the sedimentary rocks is an evidence for this unconformity. The Triassic sedimentary rocks usually formed from the source rocks such as pyroclastic debris and chert debris. While the Jurassic lithologies mostly found quartz from the late Triassic granite weathering.

4.1.3. Early Tertiary

The Phetchabun basin is formed in this period as a result of simple shear tectonics. The movement of tectonic plates caused the unconformity that separates the Tertiary sequence from the Permo-Triassic units.

4.2. Folds

The late Paleozoic fold features open and broad. The axial surfaces have developed paralleling with the current rock layers orientation which is north-south axis with the lower plunge. It formed as a large syncline. The fold axes can be observed in the Triassic sedimentary rocks in Wang Pong district distributing southward to Chon Daen district. The western and eastern outer layers of fold limb is found as the Carboniferous rocks and Permian rocks. There is the north-south direction fault strikethrough the Carboniferous rocks causing subsidence and formed as a basement of Phetchabun basin. In aspect of mesoscopic scale, several small synclines and anticlines are found distributed in the study area.

4.3. Fractures and faults

Data obtained from the aerial photographs and field work showing the fractures and faults occurring in Phetchabun as follows.

4.3.1. NNE-SSW and NNW-SSE faults

The aerial photographs show the trends of these faults which can be clearly seen as large normal faults with the length is longer than 5 to 15 kilometers. These faults have been interpreted to be formed in Pleistocene.

4.3.2. NE-SW and NW-SE faults

These faults seem to be strike slip or oblique slip fault which the displacement of rocks can be observed. They are less marked compared with the previously faults.

4.3.3. E-W faults

They usually appeared as small faults with low displacement. The type of these faults hasn’t defined yet. It is considered to have been formed in the late Triassic related to igneous rock in the area.

Objective and Benefit of the study

1. **Objective**
    - **1.1.** To study the spatial distribution of significant geomorphic indices to the relative tectonic activity.
    - **1.2.** To study landslide susceptibility area in Phetchabun province.
    - **1.3.** To study flood susceptibility area in Phetchabun province.
2. **Benefit of the study**
    - **2.1.** Map of spatial distribution of significant geomorphic indexes to relative tectonic activity
    - **2.2.** Landslide susceptibility map of Phetchabun province.
    - **2.3.** Flood susceptibility map of Phetchabun province.

Structure of The Thesis

This report includes the following seven chapters. The chapter I introduces the topic, geological setting, structural geology and topography of study area. The chapter II mentions the relevant theory, methodology and parameters of terrain analysis which are geomorphic indices, landslide susceptibility and flood susceptibility. Also, the literature review is included in this chapter.

In the chapter III-V, they represent the following three parameters analysis of Phetchabun province with a detailed explanation including data collection method: i) geomorphic indices indicates low to high relative tectonic activity, ii) landslide susceptibility identifies sensitive areas which are subject to landslides and is measured from low to high, and flood susceptibility points out flood-prone areas.

The chapter VI is to focus on the result and discussion on each parameter. The first one is the tectonic analysis using geomorphic indices which is classified into three tectonic activity classes. Secondly, the classification of landslide susceptibility is separated into five classes describing the level of intensity from low to high, respectively. Lastly, the flood susceptibility compared with the flooding history of 2013, 2014 and 2016 in Phetchabun which is ranked into 5 classes as well.

The final chapter VII is the conclusion which summarizes all parameters and issues of various type of hazard obtained from terrain analysis in this study.

CHAPTER II
THEORY

Terrain analysis is a study of characteristics of changing topography which is caused by tectonic and/or geomorphic activity. It is also applied to identify areas where it is sensitive to disaster. In this thesis, there are three methods of terrain analysis that are geomorphic indices, landslide susceptibility and flood susceptibility mapping.

Geomorphic indexing for tectonic activity evaluation

Geomorphic indexing for tectonic activity evaluation is evaluation to index study tectonic activity using digital elevation model (DEM) data. This study concludes 5 indices that are stream-length gradient index (SL), mountain front sinuosity index (Smf), hypsometric integral (HI), hypsometric curve and basin shape index (Thaipbs). There are three types in analysis and four types spatial representation shown in Table 1. Each Analysis type have three types including line-base (segment), polygon-base (area/basin) and cell-base. Also, there are four type of Spatial representation including point, line, cell and polygon/area.

Table 1. Type of geomorphic analysis in this study.

Geomorphic index	Types of geomorphic index	Analysis	Spatial representation
Stream-length gradient index (SL)	Linear parameter	Line-base (segment)	Point
Mountain front sinuosity index (Smf)	Linear parameter	Line-base (segment)	Line
Hypsometric integral (HI)	Area parameter	Polygon-base (area/basin)	Polygon/area
Hypsometric curve (HC)	Relief parameter	Cell-base	Cell
Basin shape index (Bs)	Area parameter	Polygon-base (area/basin)	Polygon/area

1. **Stream-length gradient index (SL)**

In general, the stream has reached equilibrium. Stream-length gradient index (SL) is an indicator to measure changes in river profile (Figure 4). It is sensitive to the river slope. SL changing influences by tectonic activity, erosion resistance, climate and topographic features (Hack, 1973). In other words, a river gradient change produced by tectonic movement increases the value of SL. The SL calculation use the following equation:

$$SL = (\Delta H / \Delta L) * L \qquad \text{Equation (1.1)}$$

where ΔH is the change of elevation (m), ΔL is the length of reach (m) and L is the horizontal length (m) from the midpoint of the reach to river head.

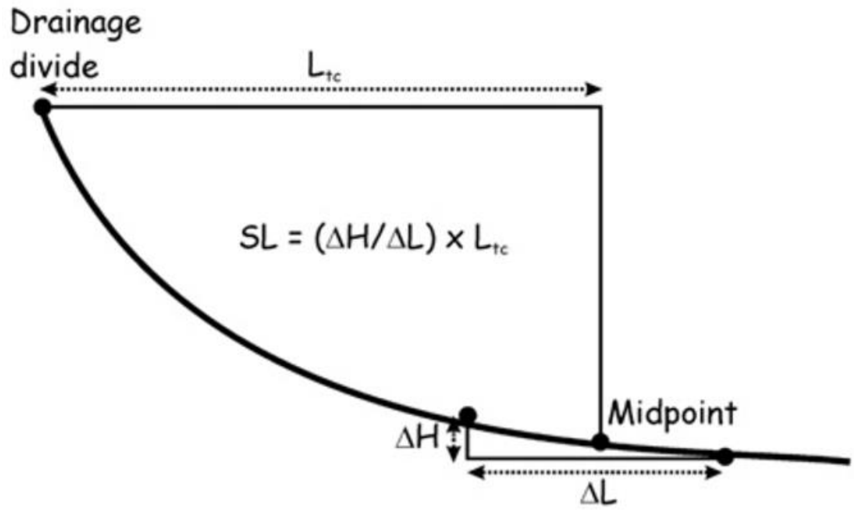


Figure 5. Mechanism of calculation of SL following steam (Hack, 1973).

Sarp et al. (2011) examined the tectonic activities in Yenicaga basin, Turkey by using SL index. The research showed the value of SL from 11-1,780 along the river in the basin meaning of tectonically influence of area by North Anatolian fault zone

The low values are marked as low tectonic activity and the high values present high activity (Figure 5a).

In addition, Mahmood et al. (2011) used SL index to identify susceptible areas of tectonic activities at Hindu Kush located in northern Pakistan and Afghanistan where is junction of three important mountain ranges (Hindu Kush-Karakorum-Himalayas) resulting from the India-Eurasia collision. The study area was classified into 5 classes from low to high tectonic activity (Figure 5b).

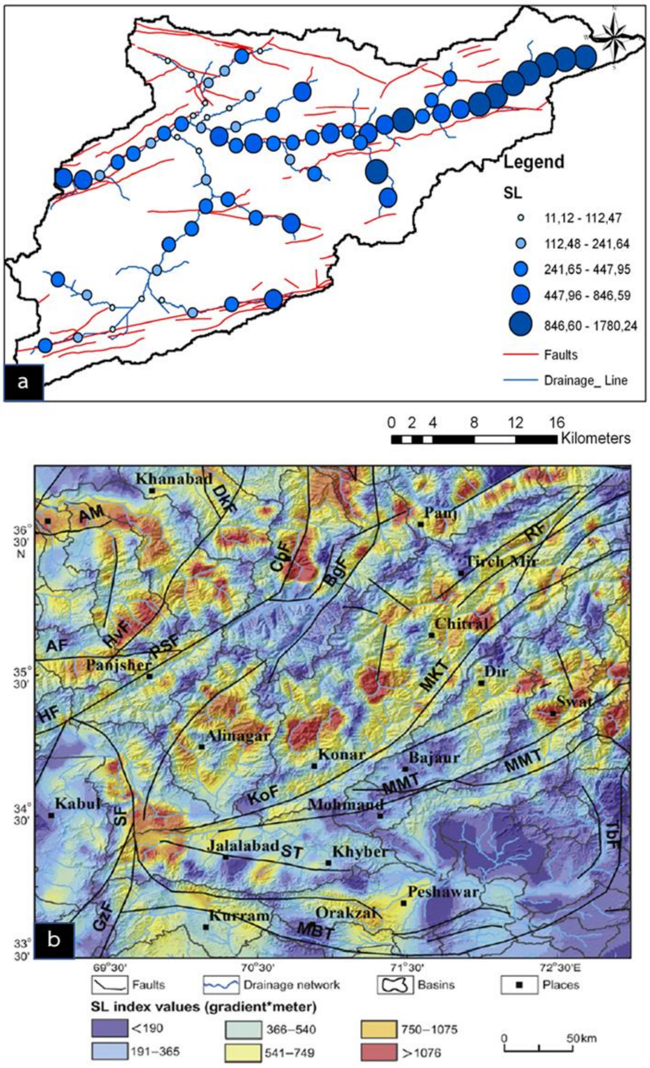


Figure 6. Map of SL showing distribution map of SL: (a) Yenicaga basin in Turkey (small blue point means low value and big blue point means high value) (Sarp et al., 2011). (b) Hindu Kush in NW Pakistan and NE Afghanistan (blue means low value and red means high value) (Mahmood and Gloaguen, 2012).

2. Mountain front sinuosity index (S_{mf})

Mountain front sinuosity index has been used to evaluate relative tectonic activities along mountain front (Keller and Pinter, 2001; Silva et al. (2003). The closer to 1 is an active tectonic uplift which predominates erosional processes shows straight fronts with low values of S_{mf}, while inactive or less active fronts reveals values of S_{mf} is less than 1. The S_{mf} is defined as:

$$S_{mf} = L_{mf} / L_s \qquad \text{Equation (1.2)}$$

where L_{mf} is the straight-line distance along a contour line and L_s is the true distance along the same contour line (Figure 6).

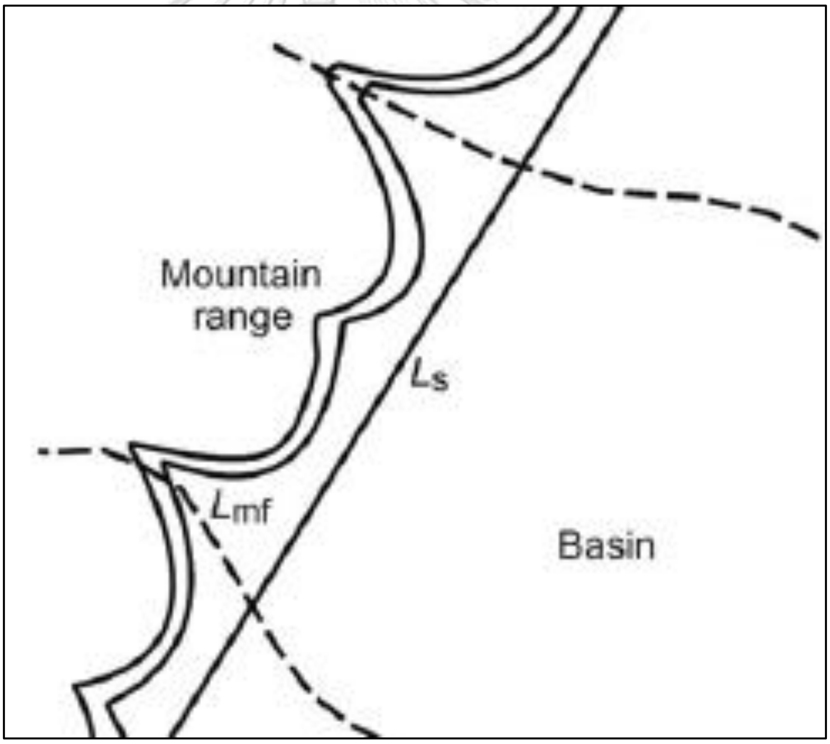


Figure 7. Mechanism of calculation of S_{mf} following mountain rage (Mahmood et al., 2011).

In previous investigation, (Soria-Jáuregui, Jiménez-Cantizano, and Antón, 2018) has measured geomorphic indices including S_{mf} along the mountain front surrounding the Ebro river which total 66 segments. In the South of the river, the highest value is

3.44, the lowest is 1.03 and the mean value is 1.48. While, in the North of the river, S_{mf} values ranged from 1.05 to 1.41 and the mean value is 1.17. The result suggests a mature stage of development and indicates a transient state as a response to tectonic uplift (Figure 7).

Mahmood and Gloaguen (2012) evaluated the active tectonics using DEM derive drainage network and geomorphic indices. The S_{mf} values of Eastern Hindu Kush-Karakoram-Himalayas mountain ranges are assigned between 1.04 and 1.38 which provided an average value of 1.12 and evaluated 49 mountain fronts measuring from ASTER GDEM elevation model. They were divided into three classes: class 1 (1.00-1.09), class 2 (1.1-1.16) and class 3 (>1.16). Then, they were combined with an index of relative tectonics (IRAT) that responded to tectonic activity (Figure 8).

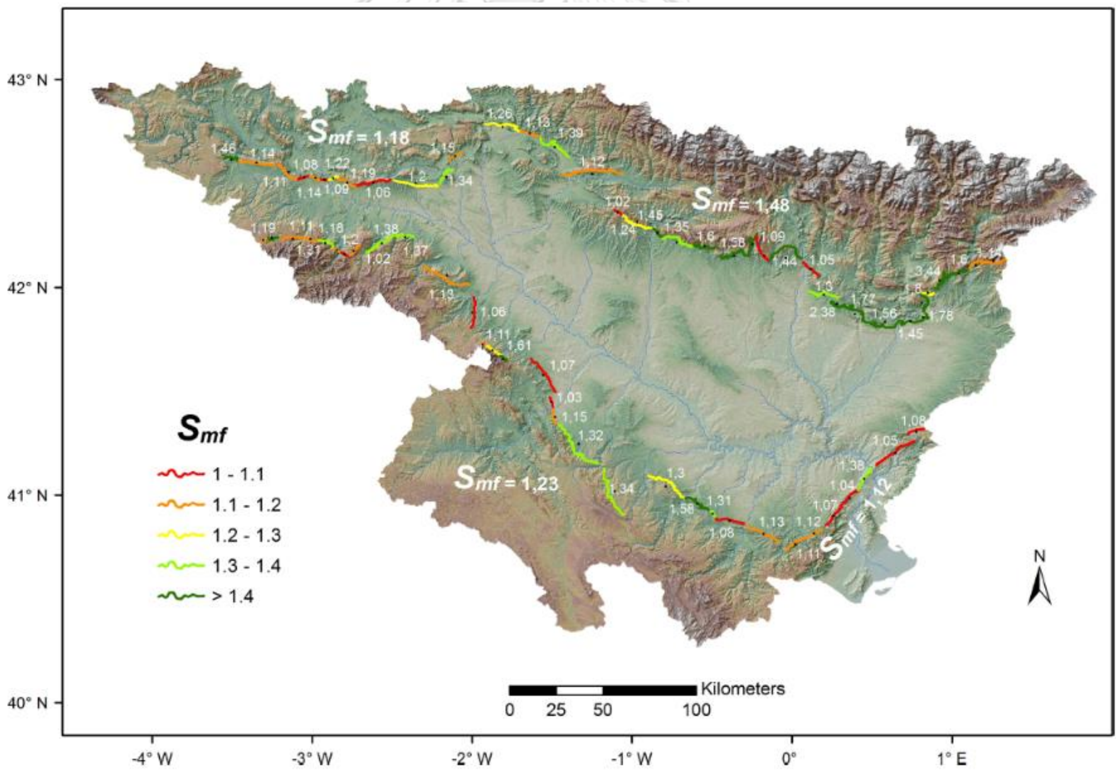


Figure 8. Map of S_{mf} showing distribution 66 segment of S_{mf} (red line means low value and green line means high value) along mountain front around the Ebro river in Iberia (Soria-Jáuregui et al., 2018).

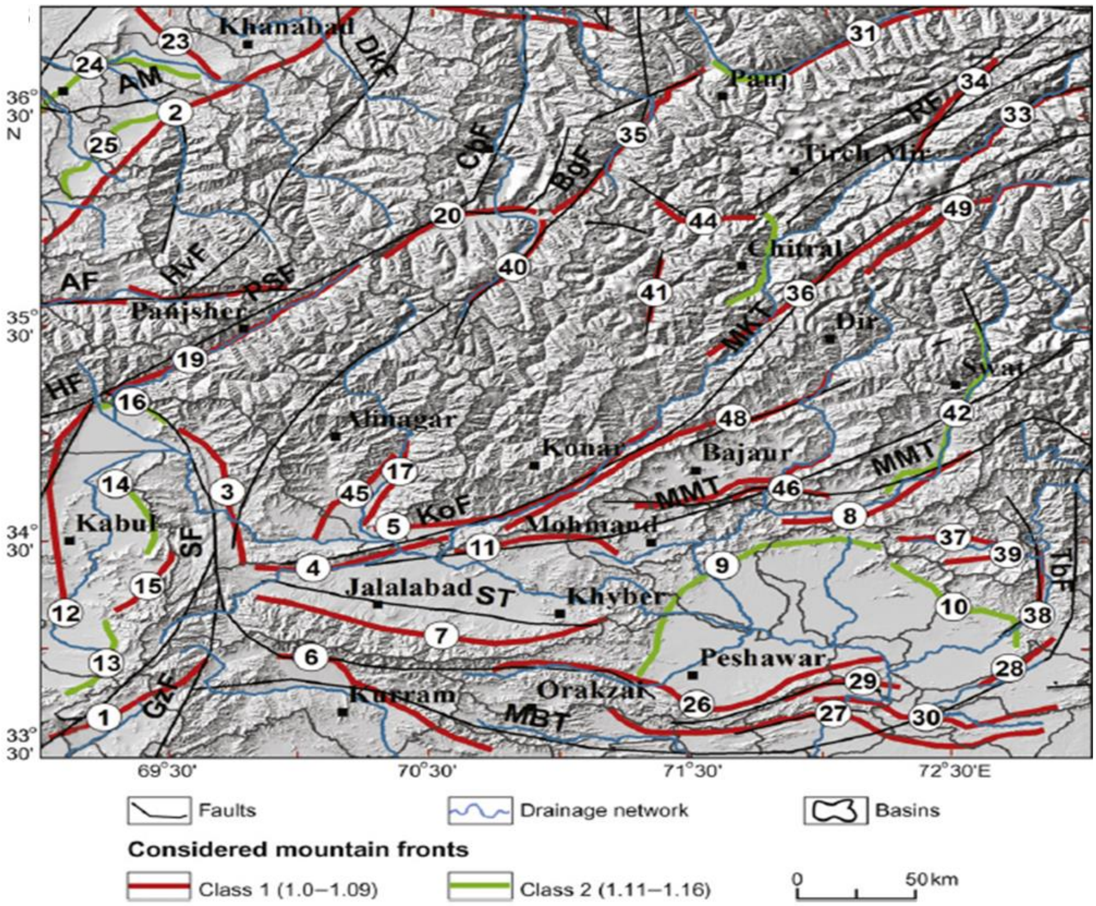


Figure 9. Map of S_{mf} showing distribution 49 mountain fronts (red line means low value and green line means high value) in Hindu Kush in NW Pakistan and NE Afghanistan (Mahmood and Gloaguen, 2012).

3. Hypsometric integral (HI)

The HI is an index that explains the distribution of elevation of area of a landscape, particularly a drainage basin (Strahler, 1952). The index is defined as the area below the hypsometric curve and expresses the volume of the basin that has not been eroded (Dehbozorgi et al., 2010). The equation that calculates the HI index (Mayer, 1990; Keller and Pinter, 2002) is:

$$HI = (Elev_{mean}-Elev_{min}) / (Elev_{max}-Elev_{min}) \quad \text{Equation (1.3)}$$

where $Elev_{max}$ is maximum elevation of drainage basin, $Elev_{mean}$ is mean elevation of drainage basin and $Elev_{min}$ is minimum elevation of drainage basin.

The index similar to the SL index. High values of HI usually mean recent incision into a young landscape, possibly produced by active tectonics where have not been eroded. Low values are related to an older landscape that has been eroded or less active tectonic. In Gao et al. (2013) research, the HI values contained 0.18 to 0.72 and separated into 5 groups following the landscape evolution (Figure 9).

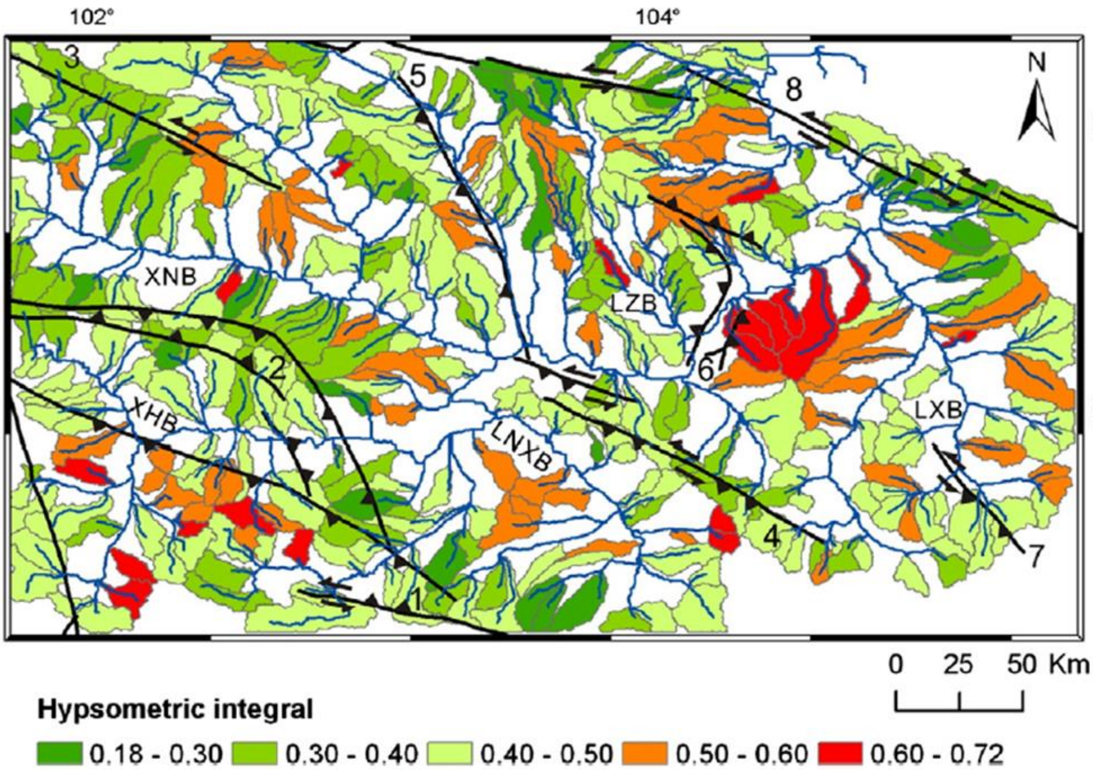


Figure 10. Map of Tibitan plateau, China showing HI distribution (green means low value and red means high value) (Gao et al., 2013).

4. Hypsometric curve (HC)

A hypsometric curve is plotted to measure the distribution of landmass volume in a basin. The curve is determined from selecting area elevation (a), the total area of basin (A), selecting elevation (h) and the highest elevation of basin (H) on every point in basin. Then, plotted the proportion of basin area (a/A) and proportion of total basin elevation (h/H) (Figure 10) into hypsometric diagram (Strahler, 1952). There are 3 classes which are class 1 with concave hypsometric curve, class 2 with concave-convex hypsometric curve and class 3 with convex hypsometric curve.

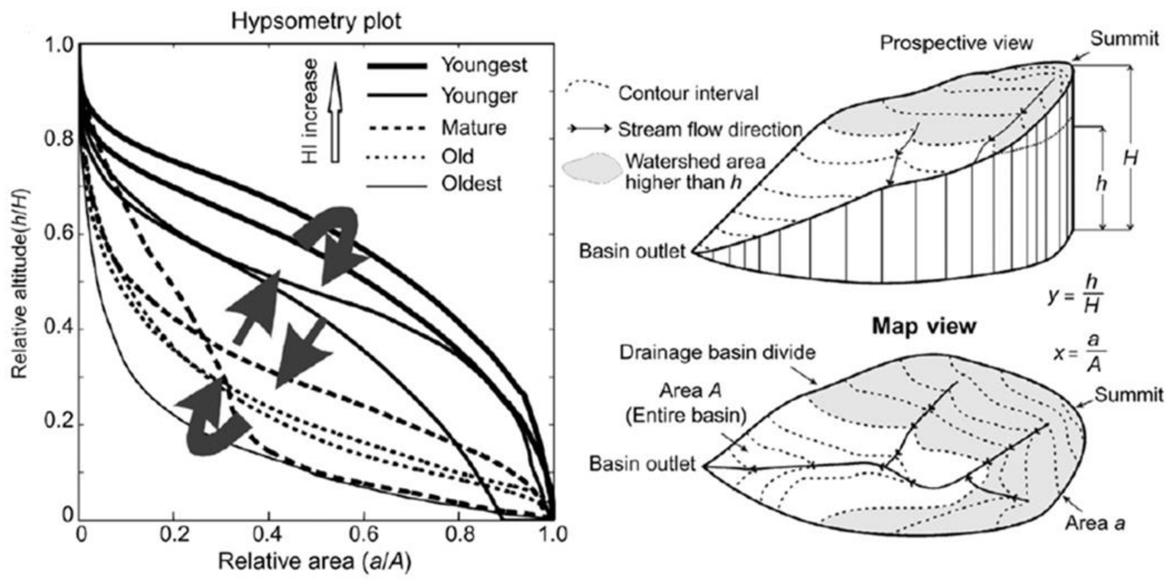


Figure 11. Graph showing measurement of hypsometric curve (Mahmood and Gloaguen, 2012).

(Giaconia et al., 2012) computed the hypsometric curve in the drainage basin of the Sierra Alhamilla. The curves had 4 types that are concave, s-shaped (concave-convex), convex and complex. Some basins showed quite irregular hypsometric curves that cannot be classified into any of the existing shapes that might be due to rejuvenation processes (Figure 11).

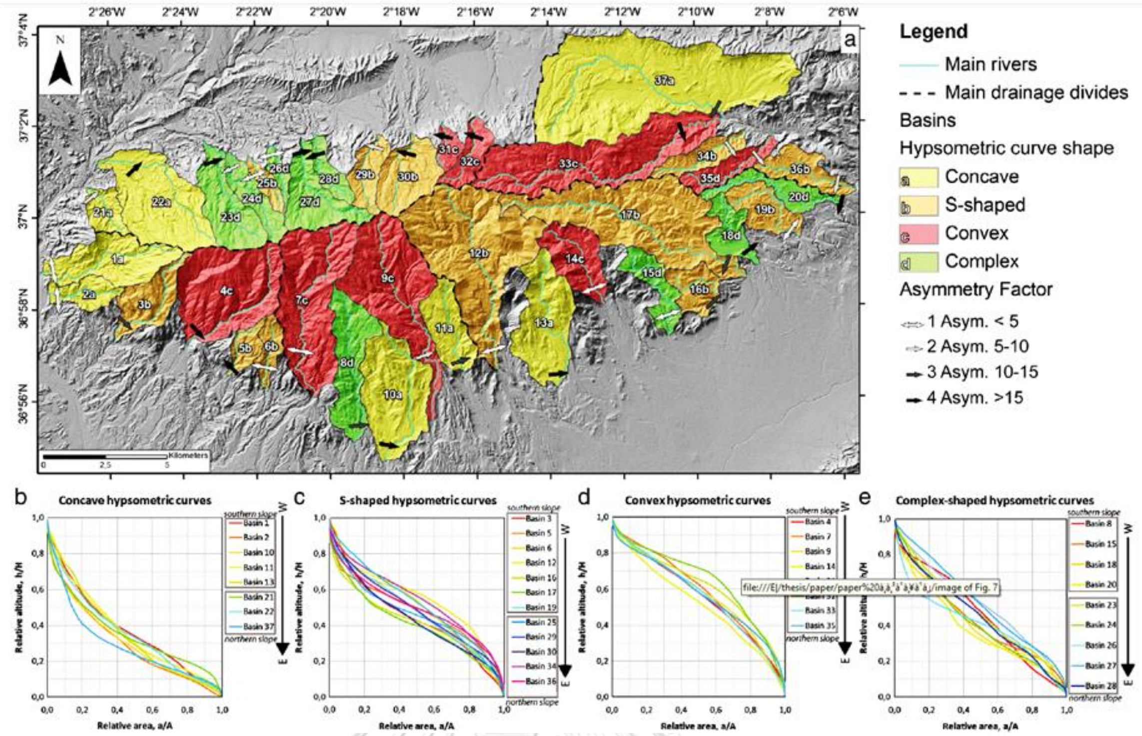


Figure 12. Map of sierra Alhamilla showing (a) distribution of HI (yellow means low value and red means high value) and classification of hypsometric curve (b) concave (c) s-shaped (d) convex (e) complex (Giaconia et al., 2012).

5. Basin shape index (Thaipbs)

Overall, the basin in tectonically active areas has elongation shape and parallel to slope. The elongation shape (Figure 12a) can be transformed into circular shapes (Figure 12b) as the tectonic activity has been slowing down with time and has continued evolution (Bull and MCFadden, 1997). The transformation is caused by the energy of stream that has been directed primarily to downcutting. The horizontal projection may be explained by B_s (Ramírez-Herrera, 1998). The B_s is expressed as:

$$B_s = B_l/B_w \qquad \text{Equation (1.4)}$$

where B_l is the length of the basin measured from headwater to outlet and B_w the width of basin measure at widest point.

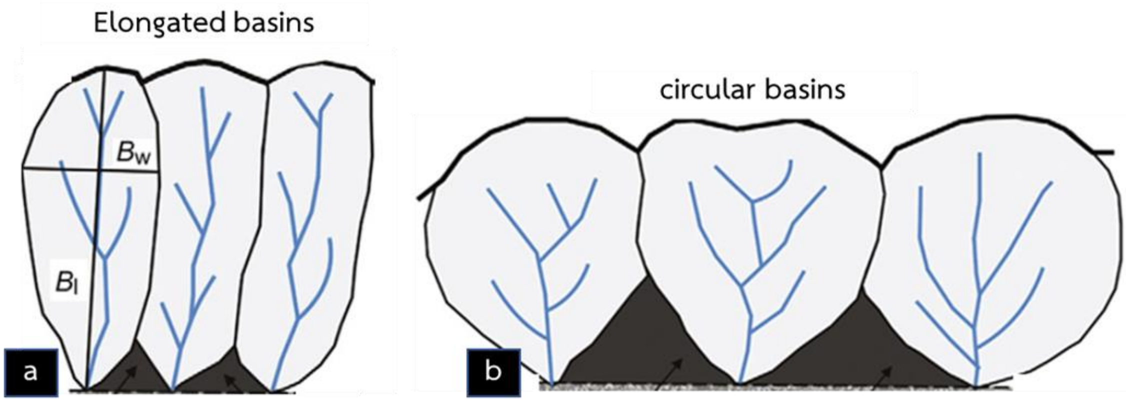


Figure 13. Calculation method of B_s and shape of drainage basin that related to B_s index: (a) elongated basin, (b) circular basin(Mahmood and Gloaguen, 2012).

The high values of B_s indicate elongation basin and the low values of B_s are related to a circular shaped basin which normally associate with low tectonic activity. Therefore, B_s may detect the rate of active tectonic. In Hindu Kush (Figure 13), B_s was classified into three classes: class 1 (1.77-3.22), class 2 (1.21-1.76) and class 3 (1.11-1.20). The class 1 and class 2 are elongated with higher B_s than class 3 with nearly circular shape (Mahmood and Gloaguen, 2012).

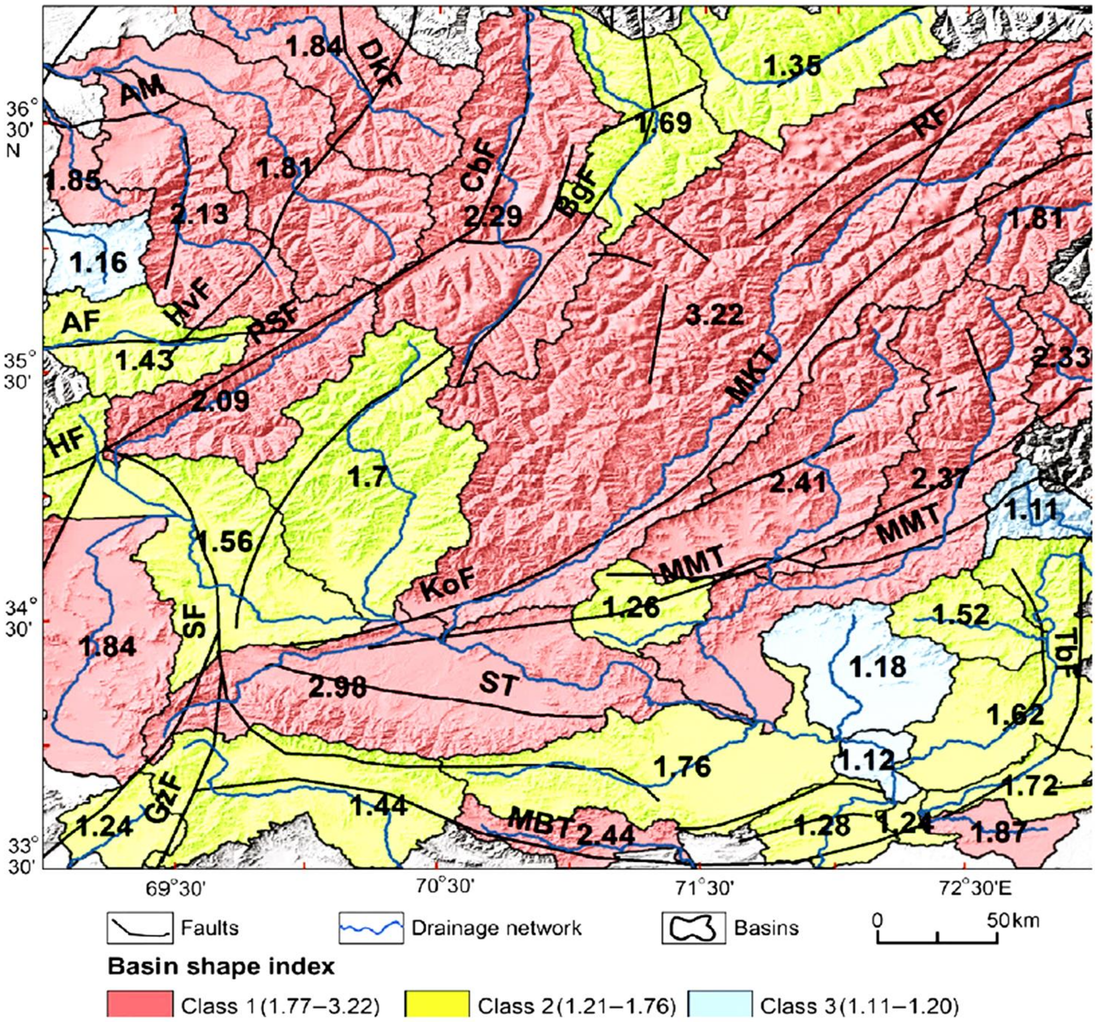


Figure 14. Map of Hindu Kush NW Pakistan and NE Afghanistan showing distribution of B_s with three classification (blue means low value and red means high value (Mahmood and Gloaguen, 2012)

Landslide Susceptibility

1. Landslide

Landslide is the movement of soil or rock following slope gradient that is influenced by gravity. In Thailand, water has always been an important factor of landslides which decreases resistance of soil or rock. Also, water can change the property of soil from solid into liquid.

In previous investigations, there are several methods to indicate the sensitive areas. The first one is studied by (Akkrawintawong, 2008) who conducted landslide susceptibility maps of Nan province using aerial photography, satellite images from Landsat 7 ETM and IKONOS. There are five variables used to analyze in the study which are elevation, slope, land management, contour and geological features. The research determines the relationship between physical, anthropogenic factors and landslide activity using bivariate probability methods and weighting factors. It has been supported that the steep slope areas consist of sandstones and volcanic rocks located near the fault which is sensitive to landslide. Moreover, there are higher probability of landslides occurring in the steep mountains where based on Nan's northern areas; Chaloem Phra Kiat, Song Kwae, Chiang Klang and Pua Districts than the southern areas; Na Noi, Viang Sa and Nan districts.

The second one is a research article by Meinhardt et al. (2015). They conducted landslide susceptibility analysis in central Vietnam using 13 parameters which are slope, aspect, valley depth, profile curvature, plan curvature, topographic wetness index, stream power index, distance to roads, distance to water bodies, land management sediment transport index, lithology group, and precipitation. A probability assessment of landslides is therefore undertaken through the use of bivariate statistics using the basic statistical Index (SI) to evaluate. The method is a calculation of the landslide density were the resulting weights of the factors using the natural logarithm as stated by Pourghasemi et al. (2013) which presented in the central Vietnam landslide susceptibility map.

In addition, Department of Mineral Resources, Thailand (2017) produced the landslide hazard map of Satun Nation Parks using GDEM satellite images from Landsat 8, geological map and topographic map. The method developed in this work is based on the 9 parameters which are slope aspect, profile curvature, elevation, lithology group, distance to water bodies, distance to roads, distance to fault, normalized difference vegetation index (NDVI) and land use. The research studied the relationship of 166 landslide activities based on frequency ratio to evaluate the landslides occurring probability. It has been demonstrated that an area consisting of sandstones, siltstones and shale have a tendency to generate landslides. Also, marl limestone or limestone zone with 300-400 meters of elevation have a high chance to cause landslides. The study found that the anthropogenic activities can lead to landslides especially cutting slopes, removing toe slopes, poorly planning alteration of drainage pattern and agriculture land.

2. Statistic index (Si)

The Statistic index (Si) method in this thesis evaluated and weighted factors which influence landslide occurrence in total 6 parameters that are i) slope, ii) aspect, iii) profile curvature, iv) plan curvature, v) topographic wetness index and vi) stream power index.

When getting the map of factors related to landslide, then will know the number of pixels of each factor. After that, the landslide susceptibility will be determined by overlapping historical landslide map and calculate them into landslide susceptibility (Figure 20) as (Pourghasemi et al., 2013)

$$Si = \ln\left[\left(\frac{Npix(Li)}{Npix(Ni)}\right)/\left(\frac{\sum Npix(Li)}{\sum Npix(Ni)}\right)\right]$$ Equation (1.8)

Where Si is landslide susceptibility, Npix(Li) is the numberof pixels that contain landslide in the parameter class, Npix (Ni) is the number of pixels in the i-th parameter class, ΣNpix(Li) is is the number of pixels with landslides in the study area and ΣNpix(Ni) is is the total number of pixels in the study area.

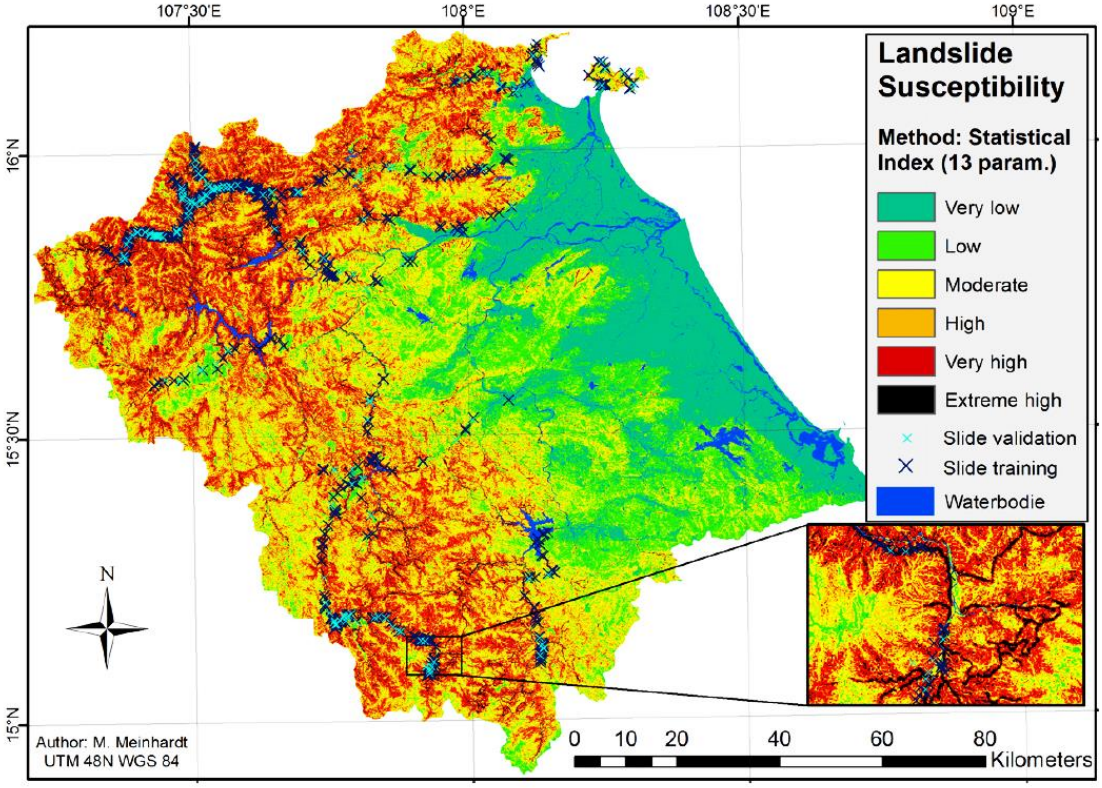


Figure 15. Map of central Vietnam showing landslide susceptibility map using statistical method with 13 parameters (Meinhardt et al., 2015).

2.1. Slope.

The slope is based on elevation data from DEM by calculated elevation of pixel in degree (Figure 14). It can be defined as

Slope in degrees = Atan (√ ([dz/dx]2 + [dz/dy]2)) Equation (1.5)

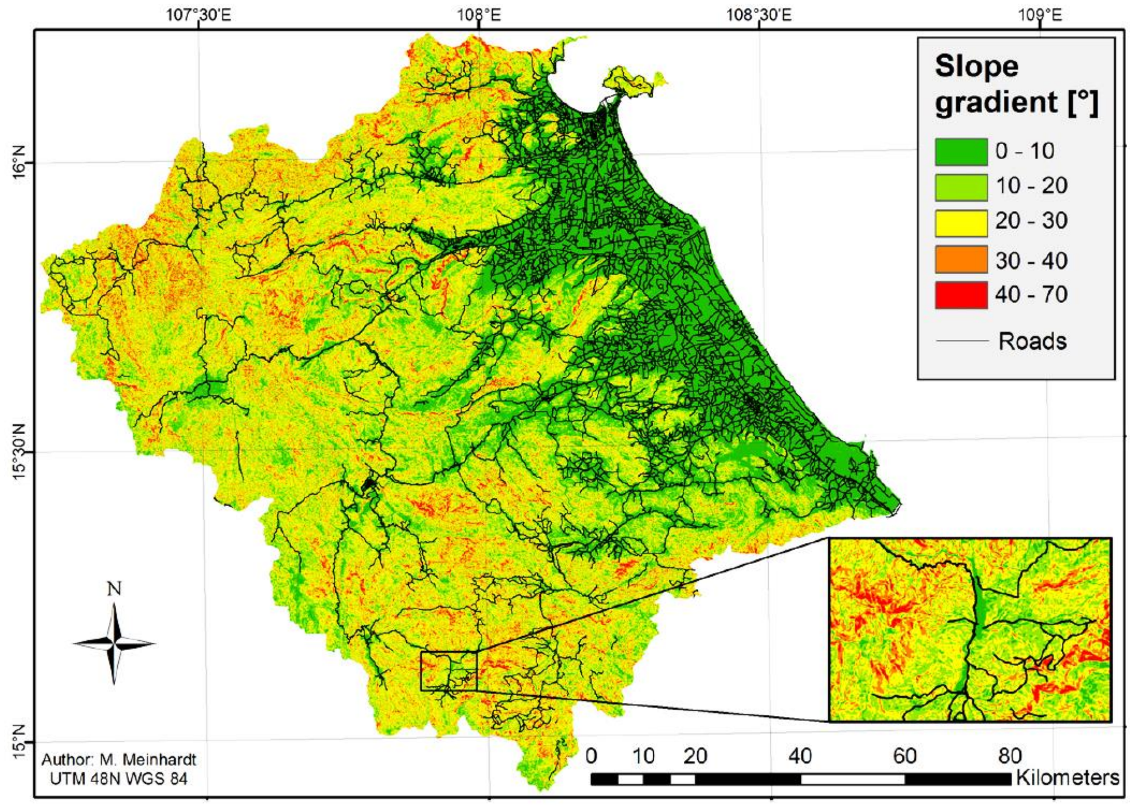


Figure 16. Map of central Vietnam showing slope gradient map in central Vietnam for calculating Si (Meinhardt et al., 2015).

2.2. Aspect.

It is direction of slope which can be grouped into eight main ordinal directions which is North (337.5°-22.5°), Northeast (22.5°-67.5°), East (67.5°-112.5°), Southeast (112.5°-157.5°), South (157.5°-202.5°), Southwest (202.5°-247.5°), West (247.5°-292.5°) Northwest (292. 5°-337.5°) (Figure 15). This parameter interacts like precipitation, wind and insolation that doesn’t influence slope stability directly (Sidle and Ochiai, 2006).

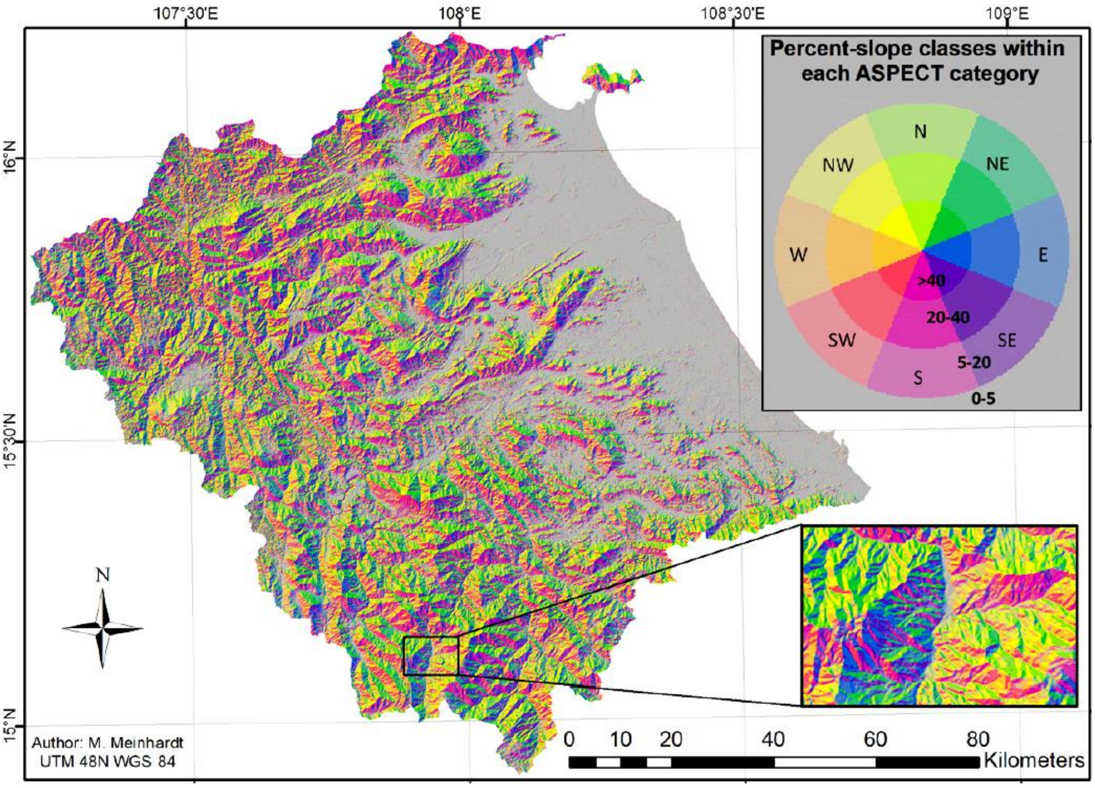


Figure 17. Map of central Vietnam showing aspect in 8 direction (Meinhardt et al., 2015).

2.3. Profile curvature.

The profile curvature is the curvature in the vertical parallel to the highest direction of slope that affects the flow of surface stream, erosion and deposition. A negative value is related to convex meaning slows a flow of stream down. A positive value represents an increase in a stream velocity (Figure 16).

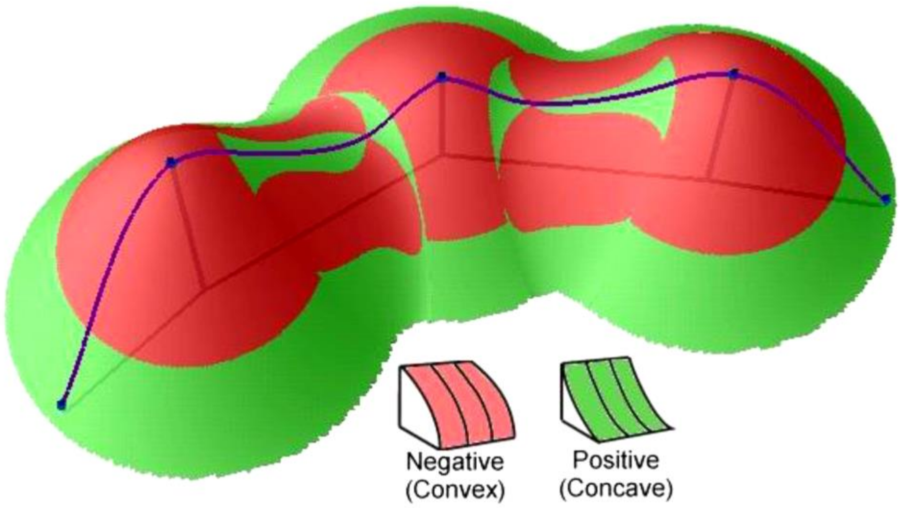


Figure 18. show curvature line parallel with slope direction(Zevenbergen, 1987)

2.4. Plan curvature.

This is curvature of perpendicular to the highest slope direction which is related to in-out of surface flow. A positive value means concave topography. Meanwhile, a negative is convex topography. Also, it can classify the difference of valleys and ridges (Figure 17).

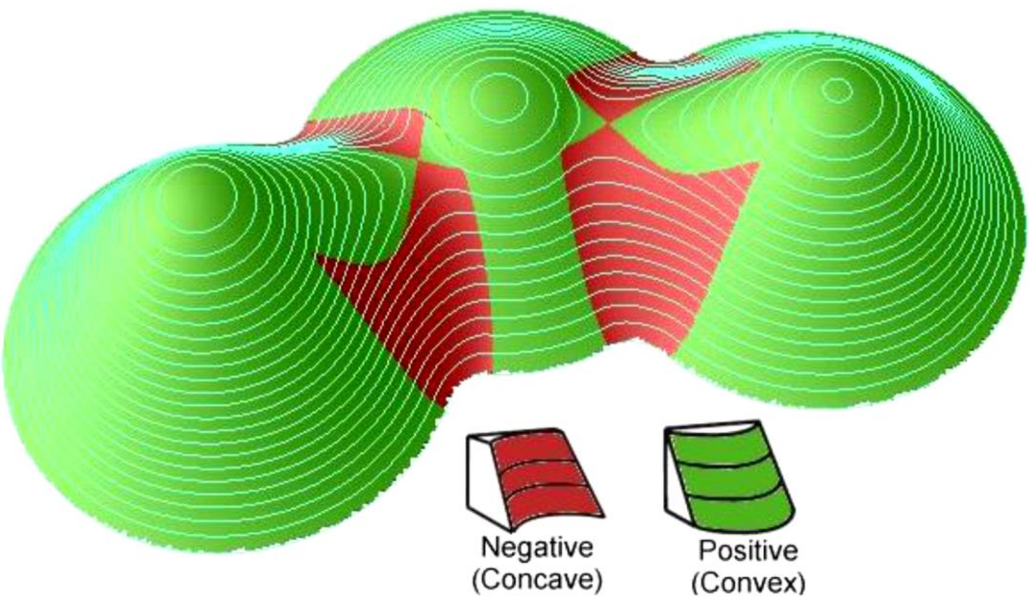


Figure 19. show curvature line preopercular with slope direction (Zevenbergen, 1987).

2.5. Topographic wetness index (TWI).

The index is a measure of soil moisture content which is controlled by topography (Figure 18). It controls the flow direction of soil and groundwater (Rodhe and Seibert, 1999). The equation is:

$$TWI = \ln(a/\tan B) \quad \text{Equation (1.6)}$$

where a is catchment area and B is slope gradient.

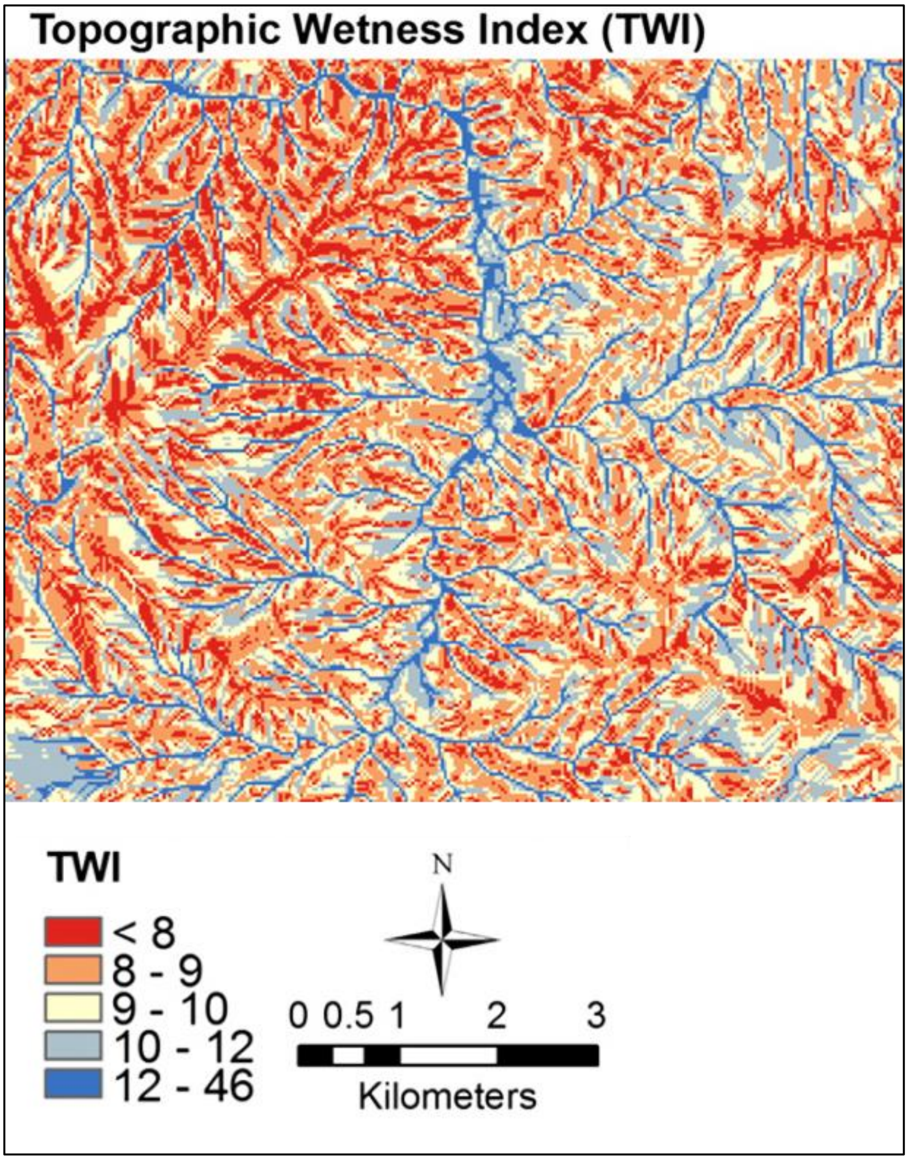


Figure 20. Map of showing distribution map of TWI (red color means low value and blue means high value) in central Vietnam (Meinhardt et al., 2015).

2.6. Stream power index (SPI).

The SPI is used to describe the erosion of flow that may occur at point of terrain surface (Figure 19) which can be calculated from the equation:

$$SPI = \ln (a^* \tan B) \qquad \text{Equation (1.7)}$$

where a is catchment area and B is slope gradient.

The SPI can describe the flow velocity and the slope erosion risk. Moreover, it can define the locations proning to gully erosion which could also trigger landslides (Dai and Lee, 2002).

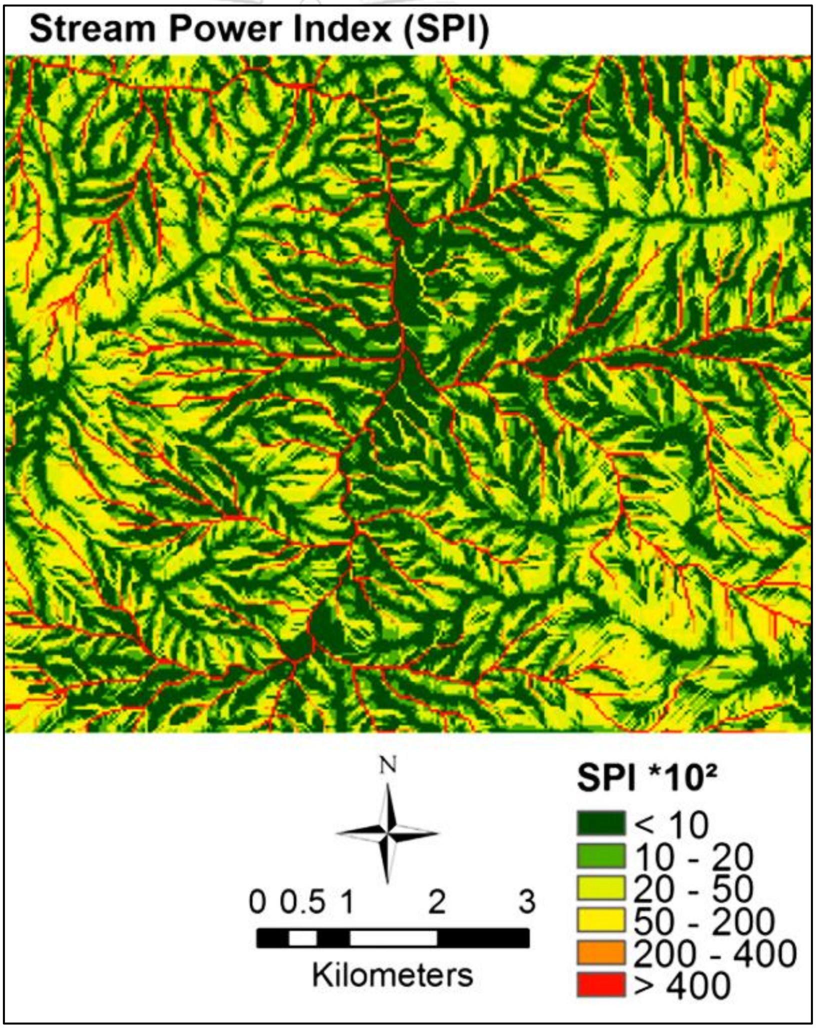


Figure 21. Map of central Vietnam showing distribution map of SPI (dark green color means low value and red color means high value) in central Vietnam (Meinhardt et al., 2015)

Flood susceptibility

1. **Flood**

Flood is a top natural disaster that causes damage to the top of Thailand and occurs throughout a year. It sometimes causes enormous damage that immediately becomes a disaster. The causes of flooding occur both by nature and human activities. The main causes of flooding are as follow; The natural causes include low pressure, Tropical cyclones, Monsoon trough or low-pressure, trench, southwest monsoon, northeast monsoon and Dam breaks. The human activities include: Deforestation which caused sudden floods, Land encroachment and modification Disposal of waste into the canal.

2. **Flood susceptibility**

Recently, there are many methods and tools that give a complete conceptual representation of all the hydrological and hydraulic processes involved in fluvial floods. In the 1960s, Crawford and Linsley's Stanford Watershed Model emerged in 1996 to model various aspects of the hydrological cycle. Nowadays, there is an important range of ways of implementing several methods in free software which identify floodable areas in QGIS which runs on the HEC-RAS model. A great part of the GIS is to complete modules for hydrological work such as SAGA-GIS. A GIS platform dedicated spatial analysis with high speed to calculation procedures.

Kazakis, Kougias, and Patsialis (2015) conducted a study of assessment of flood hazard areas at a regional scale using Flood Hazard Index (FHI) to analyze and define flood exposure. The work evaluated by 7 parameters which are rainfall intensity, slope, flow accumulation, elevation, distance from drainage network, land uses and geology. The methodology weighted each factor to determine its role in the result called FIGUSED. This work has been compared with the records of historical floods in the fieldwork which is confirmed the highly accurate result of FIGUSED method.

García-Rivero et al. (2017)performed the investigation of flood risk assessment in Madre de Dios, Peru using Hydromorphometric Contrast Index (HCI) to evaluate and discover the flood hazard zones. The study focuses on geomorphological and hydrological factors. The geomorphological parameter contains 2 indices that are vertical distance from the drainage network and closed depression. While, the hydrological parameter consists of 3 indices which are surface runoff, topographic wetness index, and modified catchment area. This information can define the space delineation of flood scenarios and classify the flood susceptibility levels.

The methodology applied in this work based on the DTM with the techniques and tools of SAGA that obtains the flood susceptibility mapping on the study areas (García-Rivero et al., 2017). The following are the criteria using to calculate and identify the highest susceptibility flooding areas:

The criteria as mentioned above, Geomorphological criteria have 2 indices for evaluating based on García-Rivero et al. (2017) including: Close depression (CD), It is the flat or non-flat area that is below elevation of nearly areas where prolonged precipitations accumulate runoff waters (Figure 21a). Vertical distance from the drainage network (VD), It can be measured from the drainage network to adjacent height in vertical distance that is related to floodplains and reach water in riverbeds (Figure 21b).

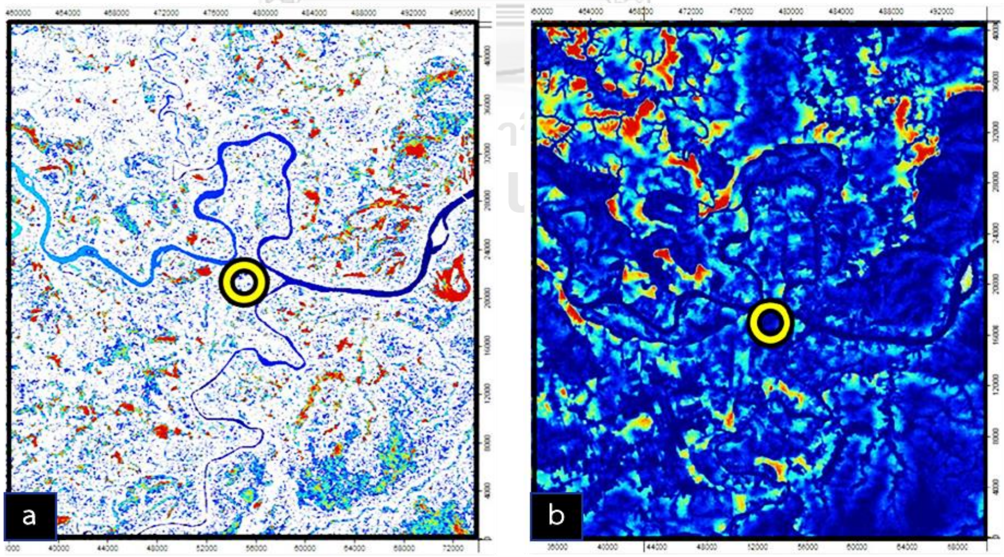
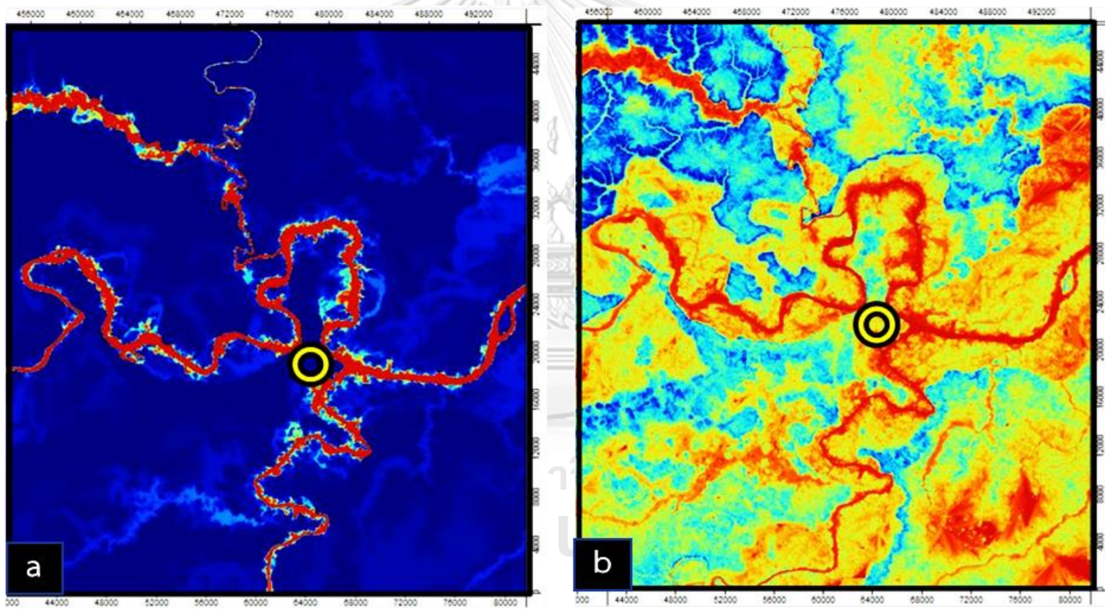


Figure 22. Map of Madre de Dios, Peru showing distribution maps of parameter (a) CD (blue means low value and red means high value) (b) VD (blue means low value and red means high value) to calculate flood susceptibility map (García-Rivero et al., 2017).

Moreover, Hydrological criteria were computed for flood susceptibility map based on García-Rivero et al. (2017) and they contain 3 indices. Modified catchment area (MCA), This area receives an amount of flow that accumulates and is an important factor for describing flood (Figure 22a). Runoff-overland flow (D8), It is a relevance of slope and the direction of the slope, affecting the direction of flow from high to low area which is formed when precipitation is superior to the capacity of infiltration of ground due to high humidity of ground. Topographic wetness index (TWI), The TWI is related to the production of runoff that originates in the presence of water situation in soil. This condition is due to the presence of extreme hydrometeorological phenomena with prolonged rainfall (Figure 22b).



. **Figure 23**. Map of Madre de Dios, Peru showing distribution maps of parameter (a) MCA (blue means low value and red means high value) (b) TWI (blue means low value and red means high value) to calculate flood susceptibility map (García-Rivero et al., 2017).

With all maps of the types factors, the map of Hydromorphometric Contrast Index (HCI) (Figure 23) is obtained from its weighted linear sum as:

$$HCI = (CD+MCA+D8+TWI-VD) \quad \text{Equation (1.9)}$$

where CD is close depression, VD is vertical distance to drainage network, MCA is Modified catchment area, D8 is runoff-overland flow and TWI is topographic wetness index. Each of them is determined the statistical parameters being classified to the following expression:

$$\text{Typified value} = (Vi-\mu)/\sigma \qquad \text{Equation (1.9)}$$

where Vi is the value of each raster map cell, μ is arithmetic mean of values of all raster map cells and σ is standard deviation of the values of all raster map cells.

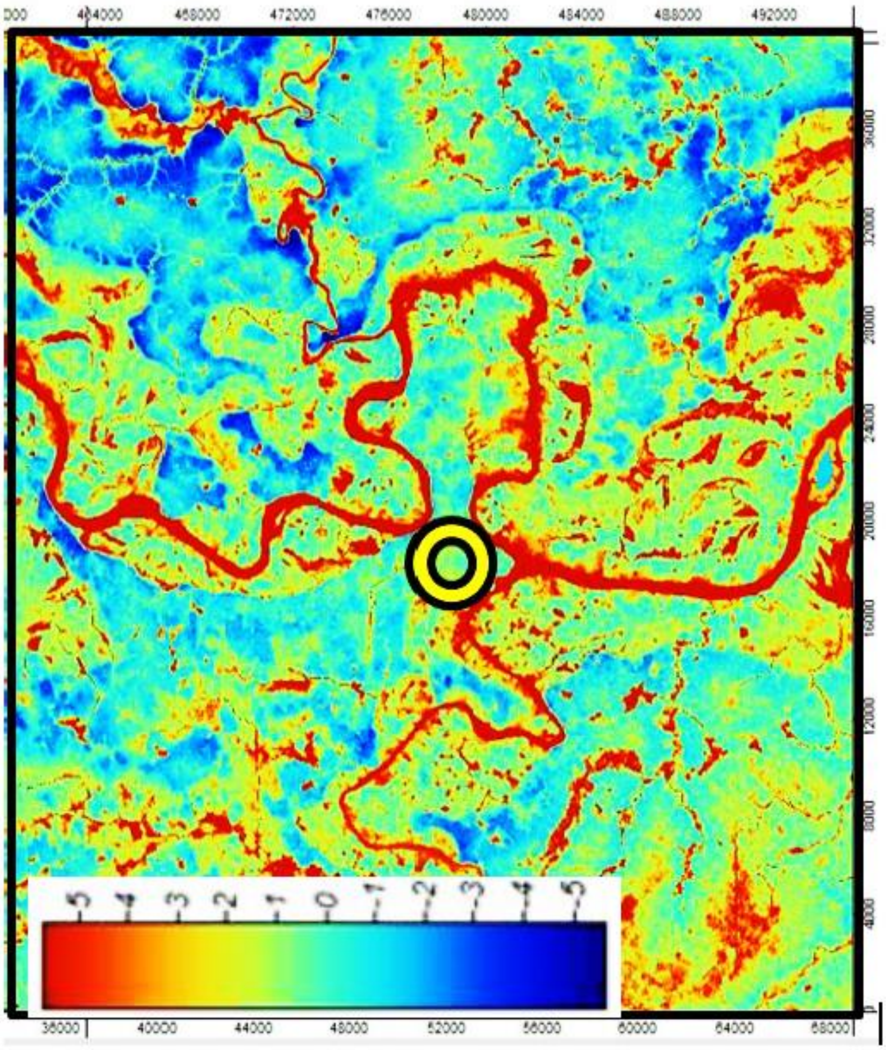


Figure 24. Map of Madre de Dios, Peru showing HCI distribution (blue means low value and red means high value) (García-Rivero et al., 2017).

Based on theory compilation and literature review as mentioned above, this study applied totally 7 indices for analysis. 5 indices called geomorphic index were calculated to identify tectonic activity including: SL is an indicator to measure along river profile and detected tectonic activity along stream, S_{mf} is along mountain fronts, HI, HC and B_s were computed for detect tectonics, erosional processes also age of drainage basin. Si is value to locate area that sensitive landslide occurrence. It combines 6 parameters slope, aspect, profile curvature, plan curvature, TWI and SPI. And the last index, HCI was evaluated for showing flood susceptibility map which contain 6 indices CD, VD, MCA, D8 and TWI.

CHAPTER III
GEOMORPHIC INDEX FOR TECTONIC ACTIVITY EVALUATION

In this study, the analysis of geomorphic indices of drainage basin allows us to detect tectonic activity and uplifting. As rivers are sensitive to change in control slope gradient and mountain front are continuously changing due to lineament and erosion. Moreover, elevation and basin shape can affect drainage basin. Therefore, five geomorphic indices were selected and evaluated in this thesis: SL, S_{mf}, HI, HC and B_s.

Methodology

Figure 24 is the flowchart that represents the methodology used to count on DEM data in correspondence with the required work scale. To understand how geomorphic indices can be used to evaluate the level of relative tectonic activity in the drainage basin, it is necessary to gather data of factors affecting the occurrence of floods. The first one is drainage basin characterization that was extracted from the DEM data. This study analyzed 38 drainage basins that were obtained using the ArcGIS ArcHydro toolbox. Then, lineament data were derived from Google Earth software.

Three geomorphic indices were calculated including the HI, the HC and the B_s for each drainage basin. In addition, SL and S_{mf} are also generated to detect the anomaly of slope and erosion along with tectonic activity of mountain front respectively.SL is analyzed from stream and stream order and S_{mf} is generated from lineament.

Finally, it has provided the three geomorphic indices maps for each drainage basin which include HI, HC, and B_s values. These values indicate the comparatively low-high tectonic activity. Apart from that, another two geomorphic indices, SL and S_{mf}, are shown in maps that are also demonstrate comparatively low-high tectonic activities. However, SL and S_{mf} depend on the stream and sinuosity of mountain front respectively instead of characteristics of drainage basin.

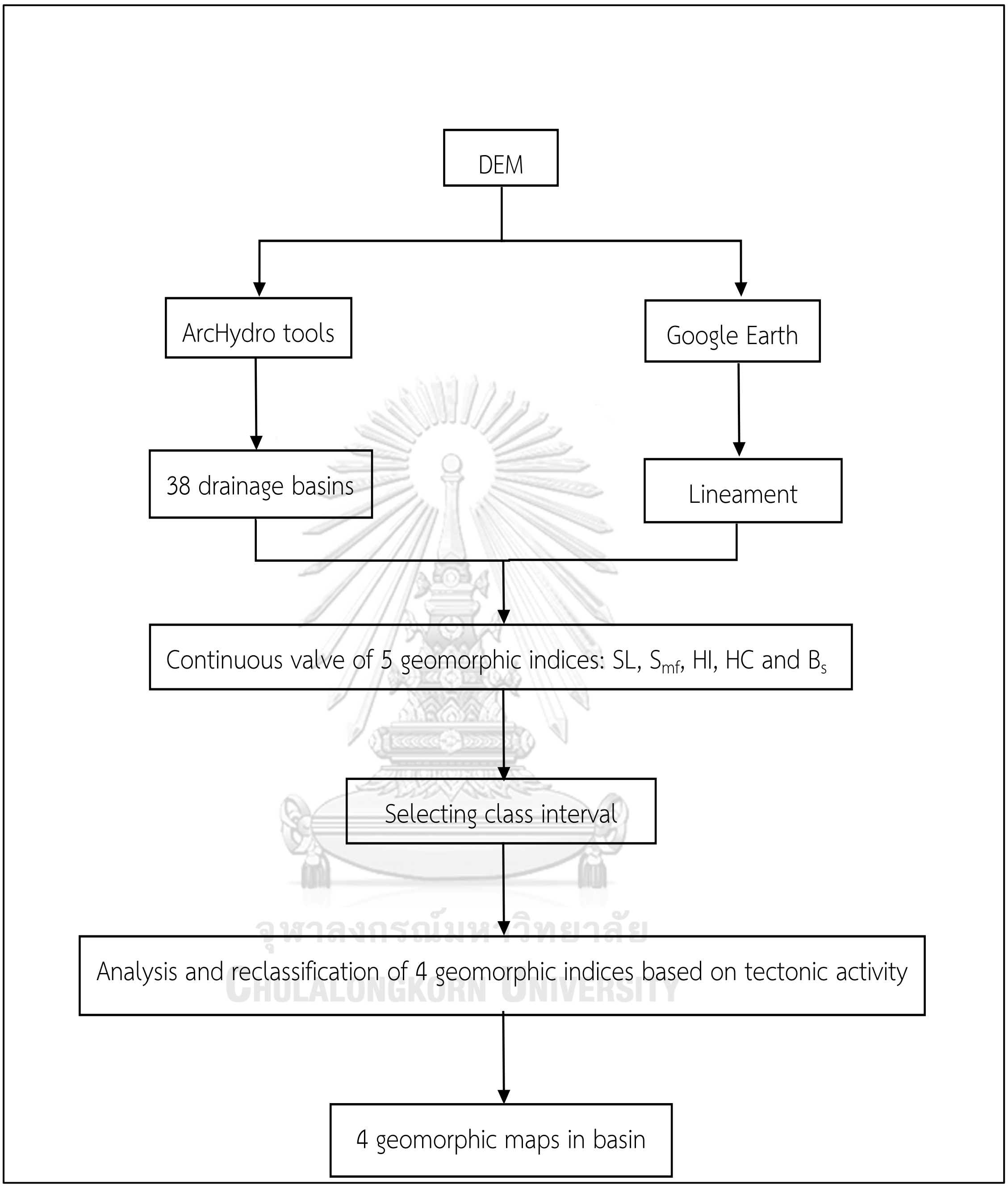


Figure 25. Flowchart showing methodology of geomorphic indexing in this study.

Result of Geomorphic Indexing

1. Stream length gradient index (SL)

The SL analysis allows us to identify anomalous points along streams that are related to tectonic activity. Phetchabun province can be divided into 6 orders, which contain an enormous number of points to the point that it is impossible to calculate (Figure 25). Hence, this study plots the histogram for choosing the suitable interval to create a map. Finally, this study selects a range of SL values to be in the 90-100 normalized percentage due to the aberrant interval observed from SL histogram in that particular range.

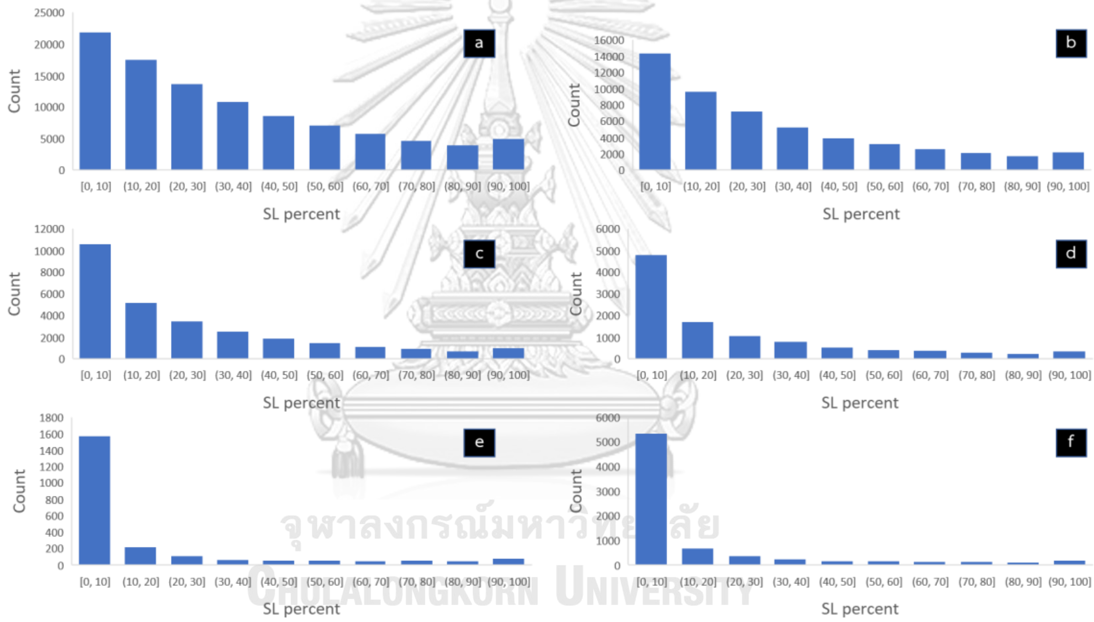


Figure 26. Histogram showing SL percentage (10 interval) in Phetchabun province following stream order, a) order 1, b) order 2, c) order 3, d) order 4, e) order 5., and f) order 6 obtain from this study.

From the above paragraph, the high value points in the 90-100 range represent high tectonic activity causing by fault, lineament and local uplifting. The high value of SL appearing on the map following stream order can be divided to six orders. There are a total 6,120 points of SL value in the 90-100 percentage range (Figures 26-31).

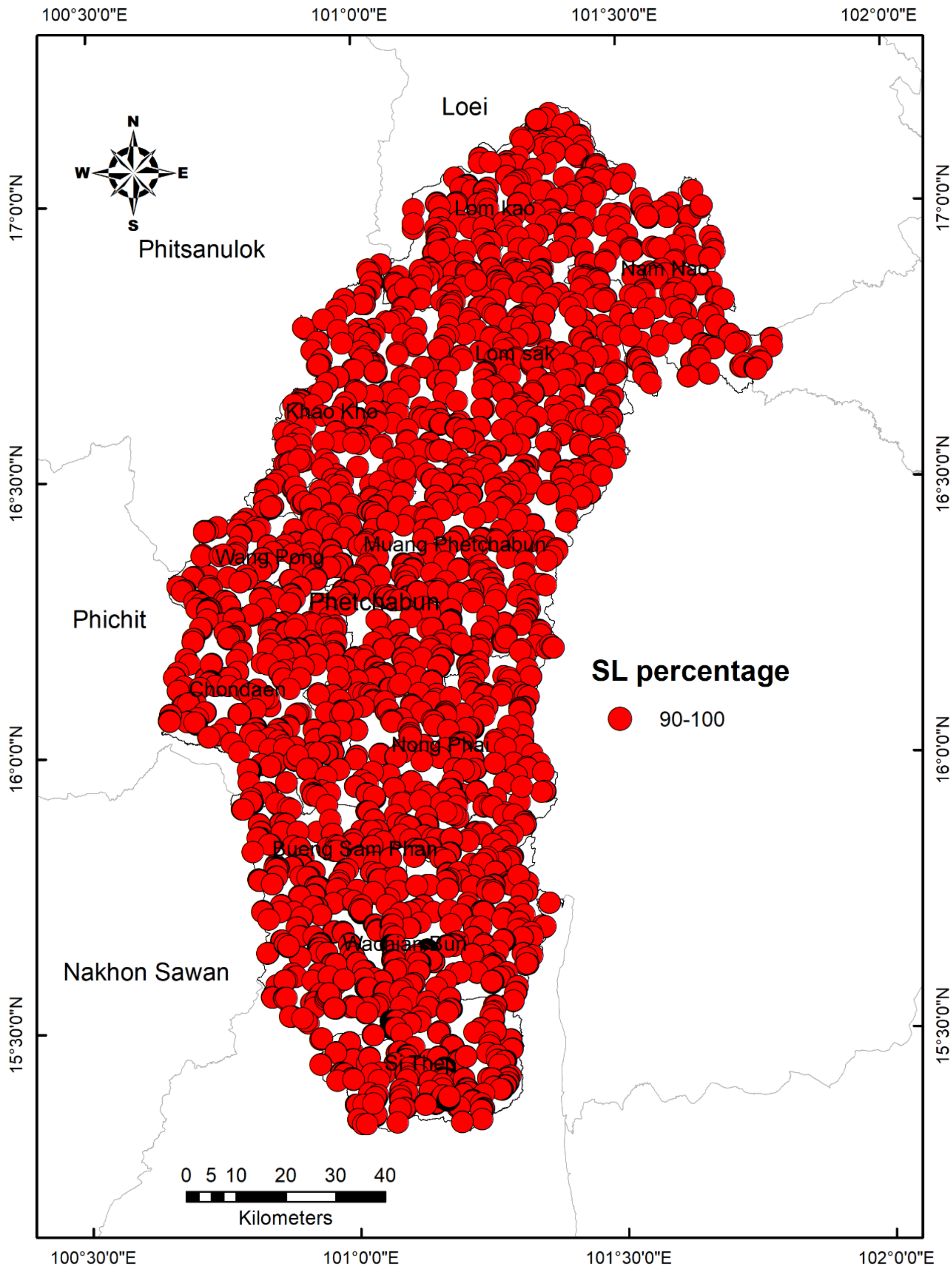


Figure 27. Map of Phetchabun province showing distribution map of SL following stream order 1 obtain from this study.

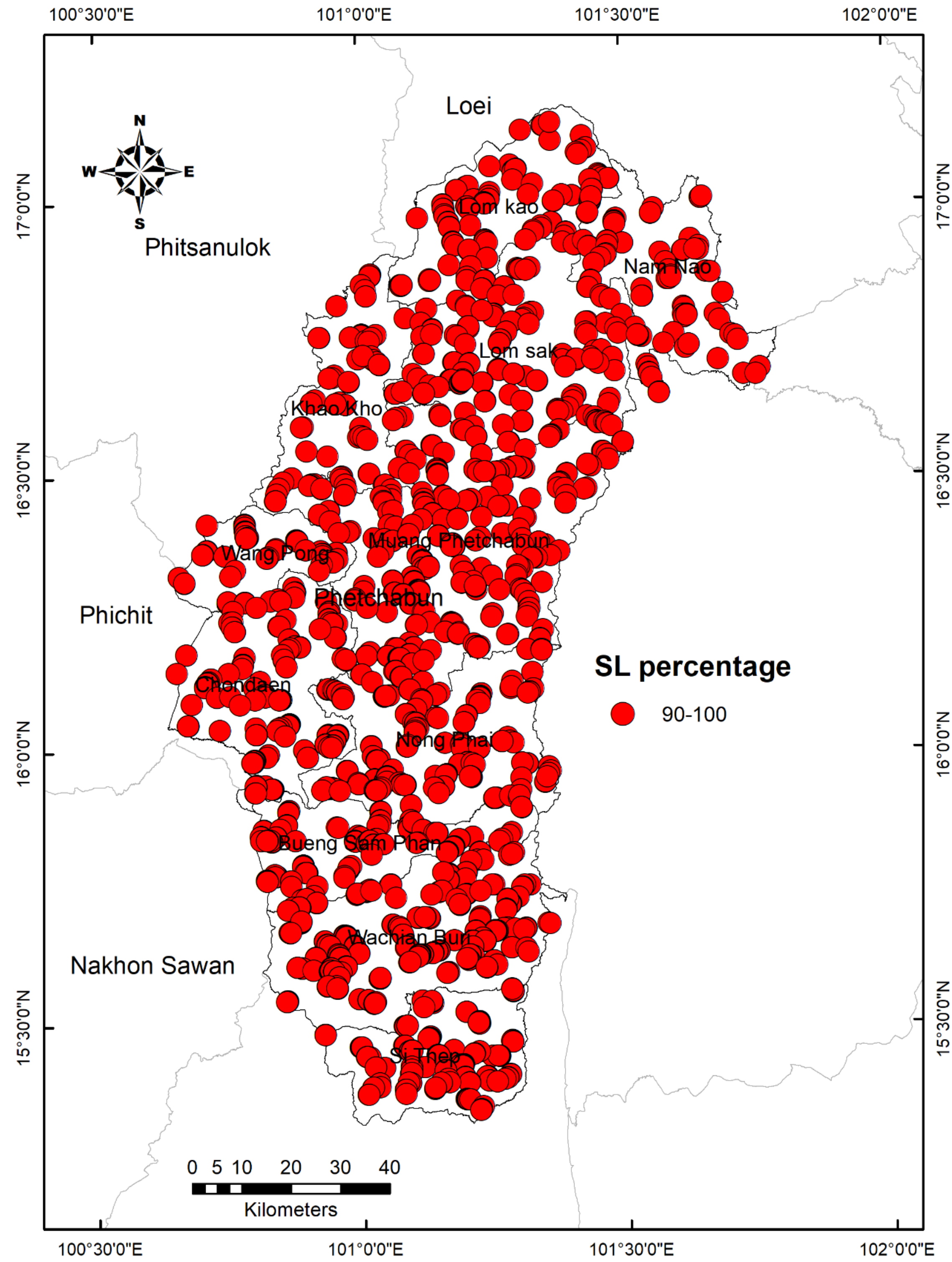


Figure 28. Map of Phetchabun province showing distribution map of SL following stream order 2 obtain from this study.

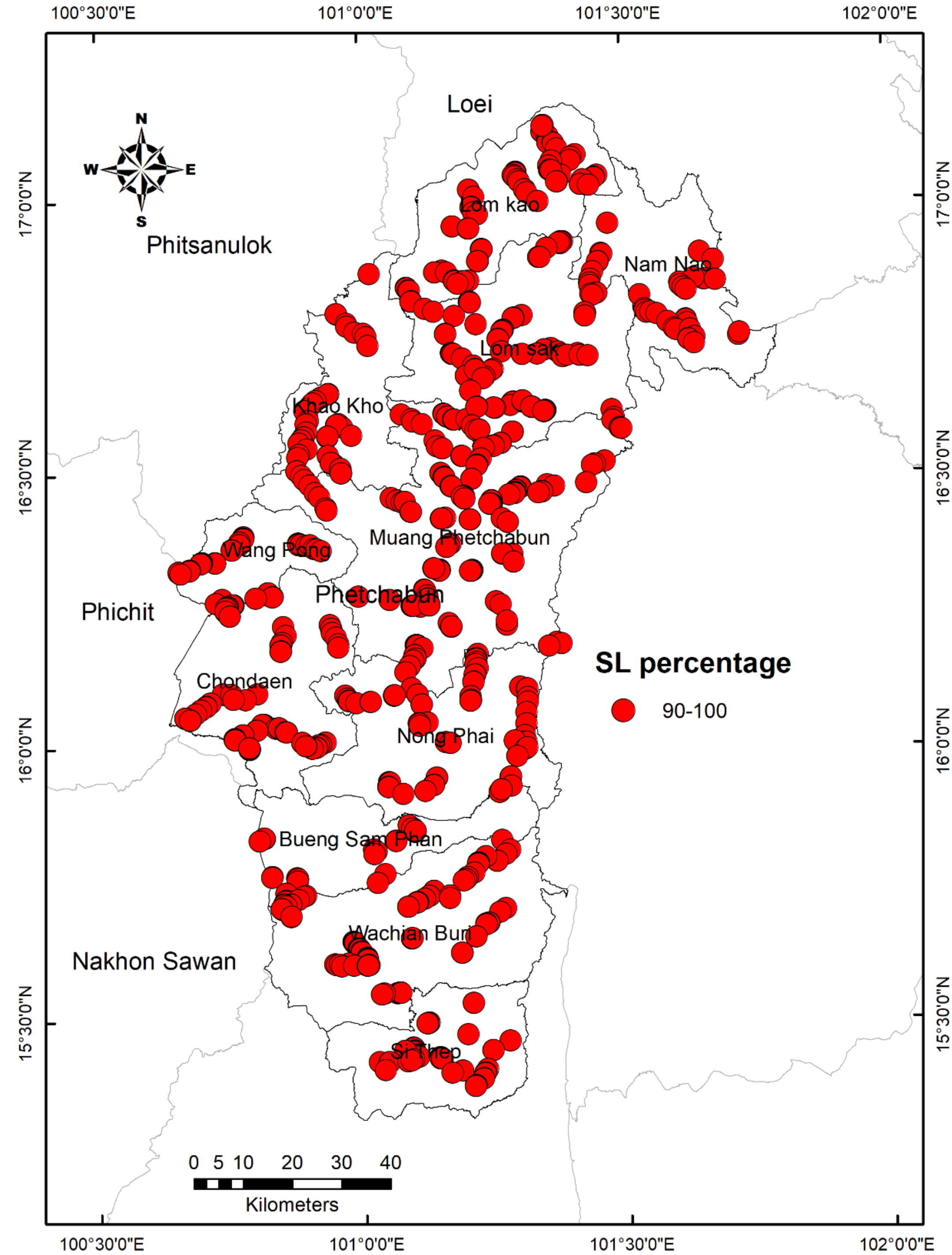


Figure 29. Map of Phetchabun province showing distribution map of SL following stream order 3 obtain from this study.

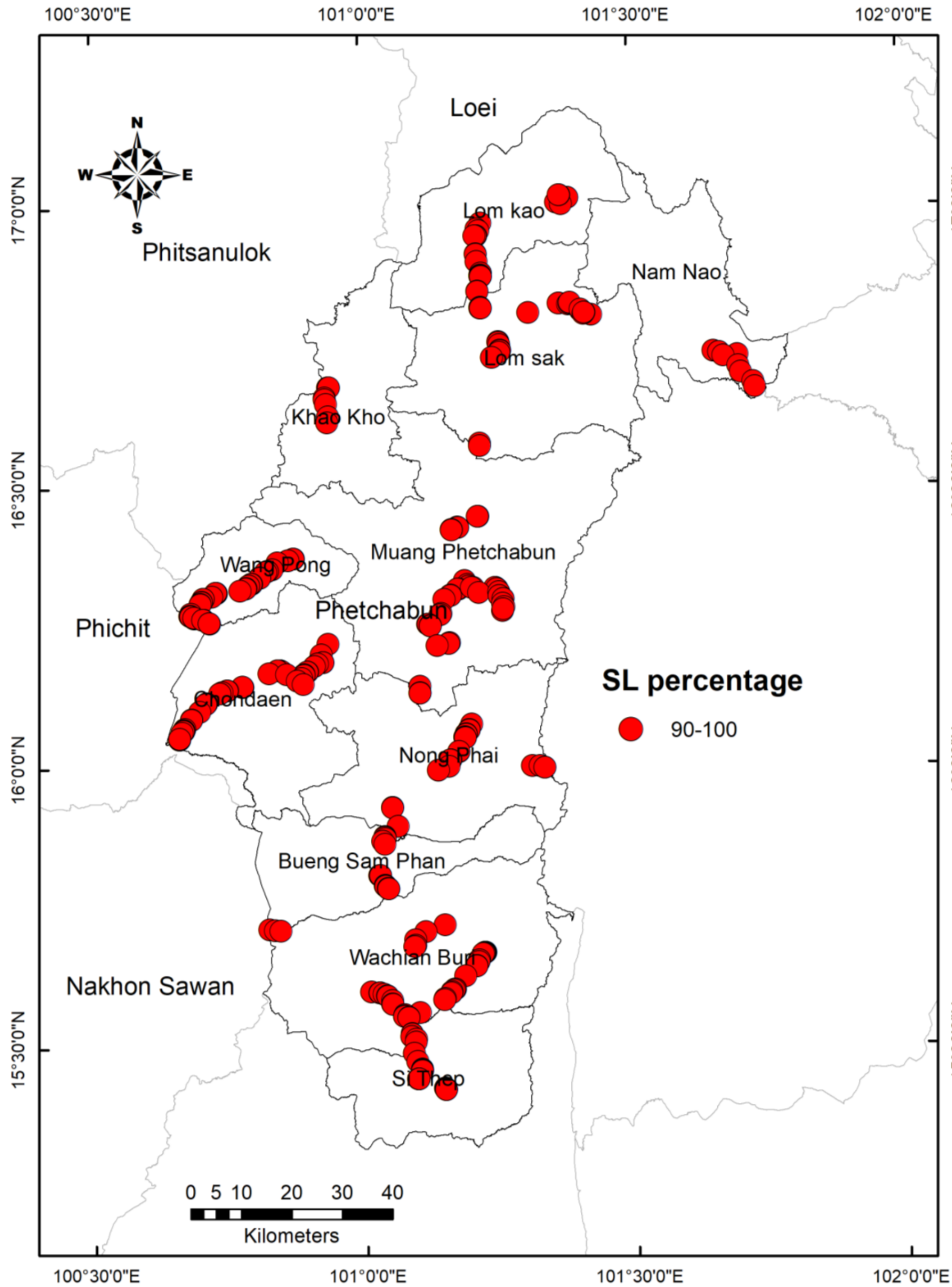


Figure 30 Map of Phetchabun province showing distribution map of SL following stream order 4 obtain from this study.

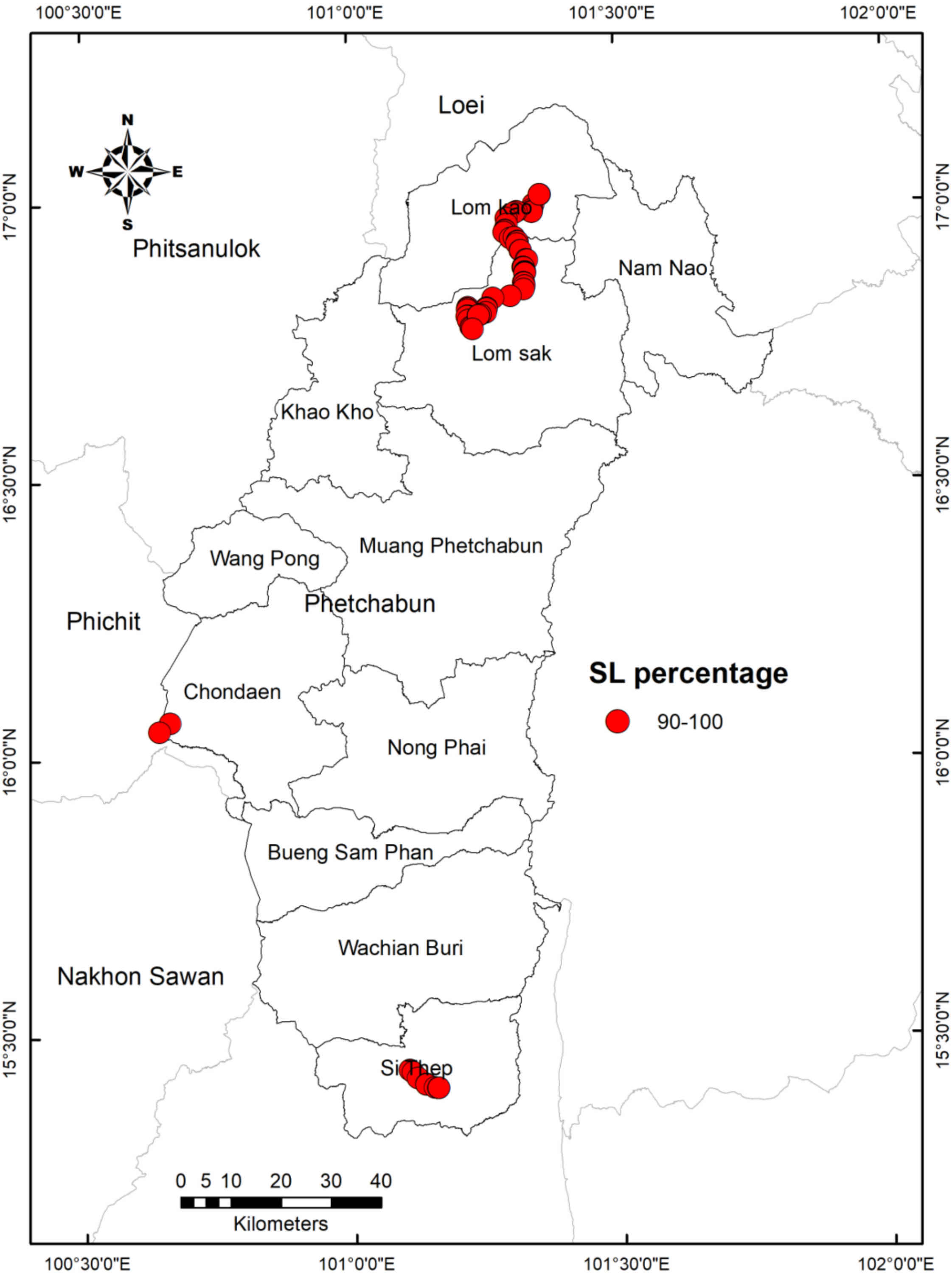


Figure 31. Map of Phetchabun province showing distribution map of SL following stream order 5 obtain from this study.

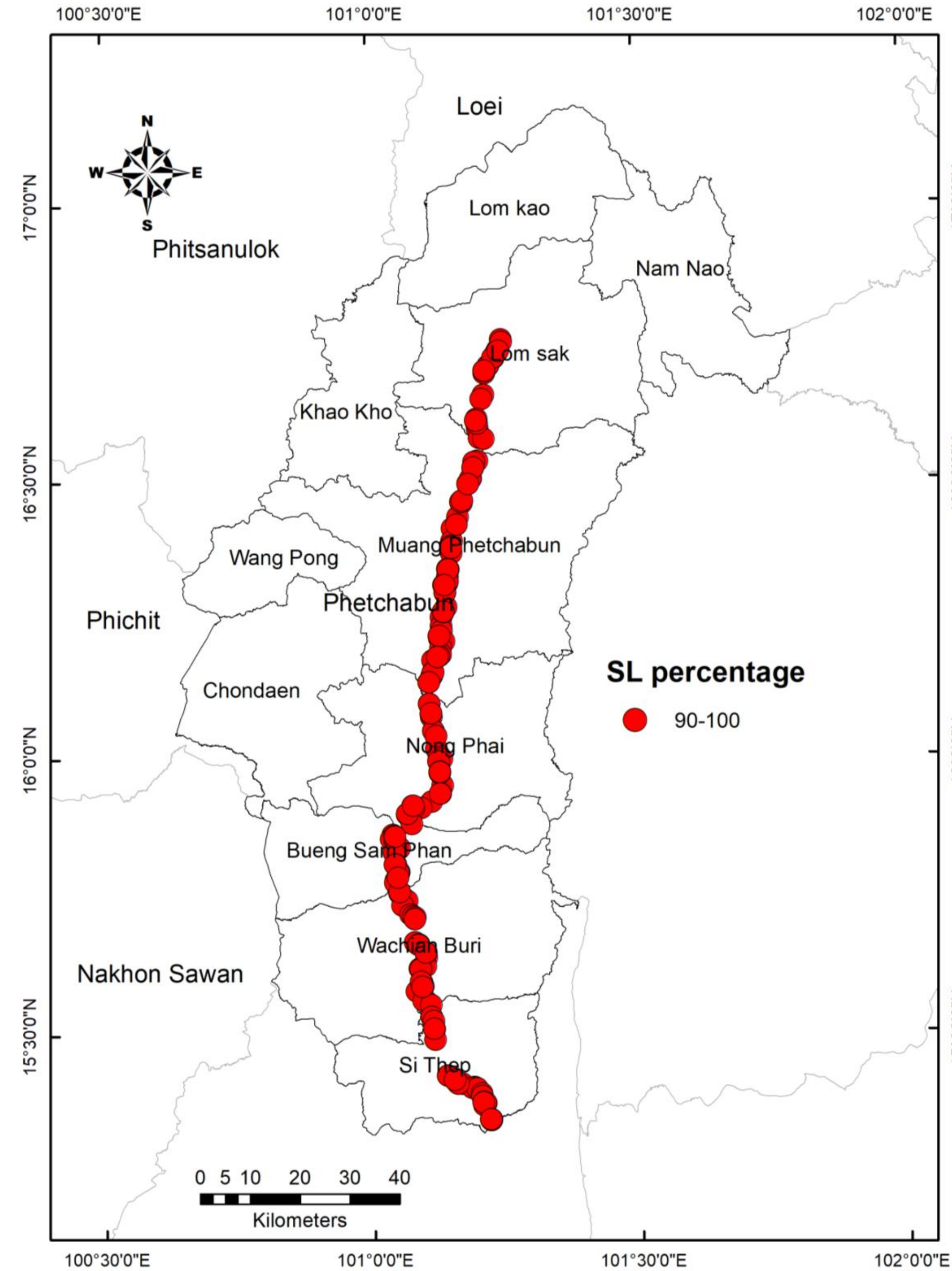


Figure 32. Map of Phetchabun province showing distribution map of SL following stream order 6 obtain from this study.

The high value of SL distributes along streams in Phetchabun province are as follows: order 1 with 3395 points (Figure 26), order 2 with 1349 points (Figure 27), order 3 with 1015 points (Figure 28), order 4 with 205 points (Figure 29), order 5 with 77 points (Figure 30) and order 6 with 79 points (Figure 31). Points of order 1, 2 and 3 are thoroughly distributed over the study area. However, points of order 6 are distributed in a straight manner from center of Lom Sak district to center of Si Thep district from North to South direction.

2. Mountain front sinuosity index (S_{mf})

The S_{mf} was evaluated by lineament which extracted data from Google Earth software and 20 meters interval contour line generated by ArcGIS software. In general, lineament and contour lines have a tendency to be equal distance. However, the calculation has suggested that the streams that flow out from the mountain create a concave in the contour line, causing errors in the S_{mf} calculation.

In Phetchabun province, there are total 207 lineaments (Figure 32). The result of the S_{mf} values range from 1.02 to 6.92 (Figure 33). According to the investigation of Keller and Pinter, 1996, if S_{mf} is close to 1, then mountains fronts show straight lines corresponding to lineament. Referring to this mention, the result has been demonstrated that the central and northeast Phetchabun indicate high recent tectonic. Since it expresses low S_{mf} value. Mostly of this zone situated in mountain area.

In contrast, the S_{mf} value for eastern and southern Phetchabun, mostly located in the plain area, indicate high tectonic activity due to its low S_{mf} value. Therefore, it means that there are higher tectonic and more erosion in the central and northeast area than eastern and southern of study area.

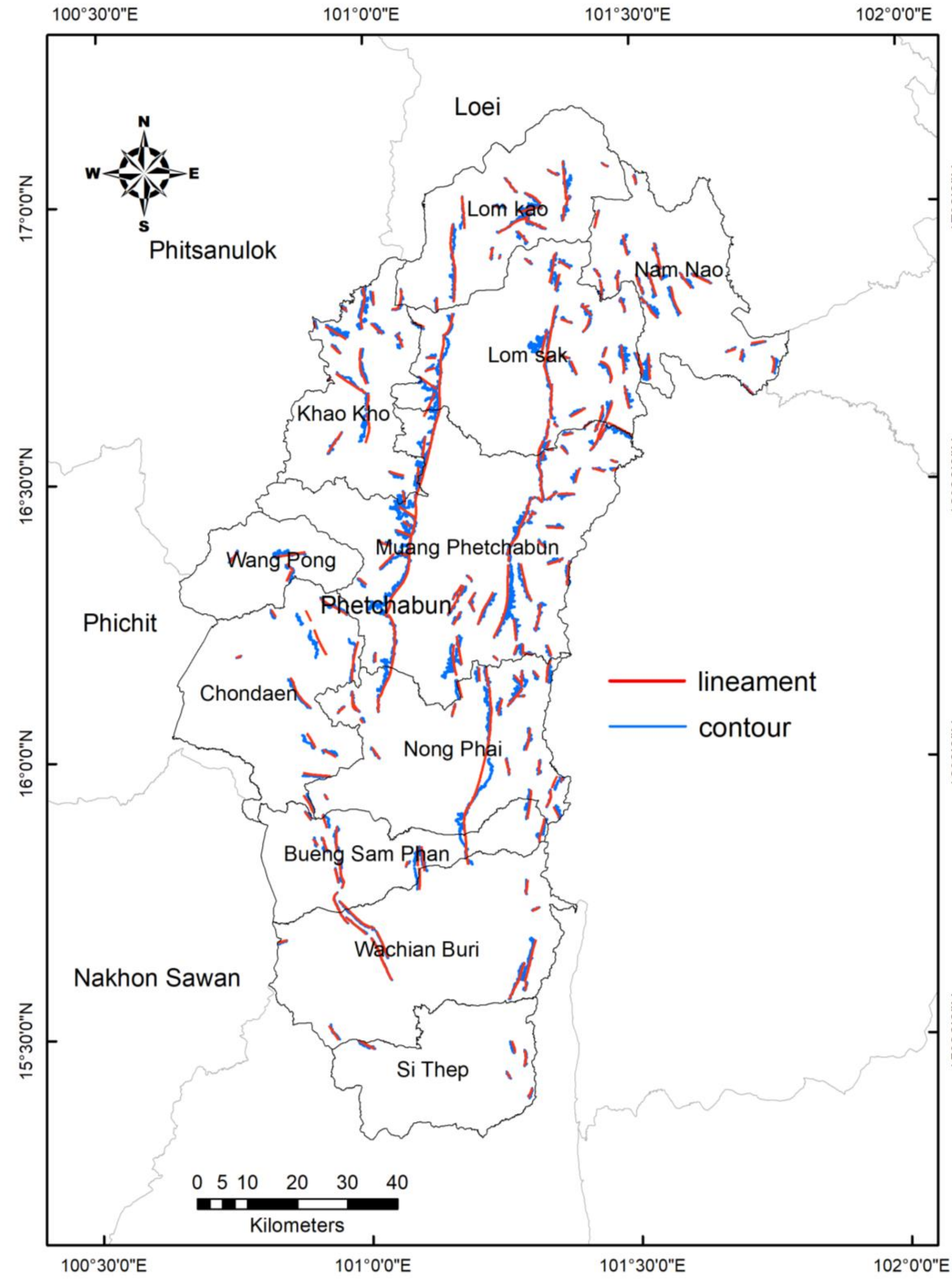


Figure 33. Map of Phetchabun province showing lineament and contour line map (20 meters interval) obtain from this study to calculate S_{mf} (red line is lineament and blue line is contour line).

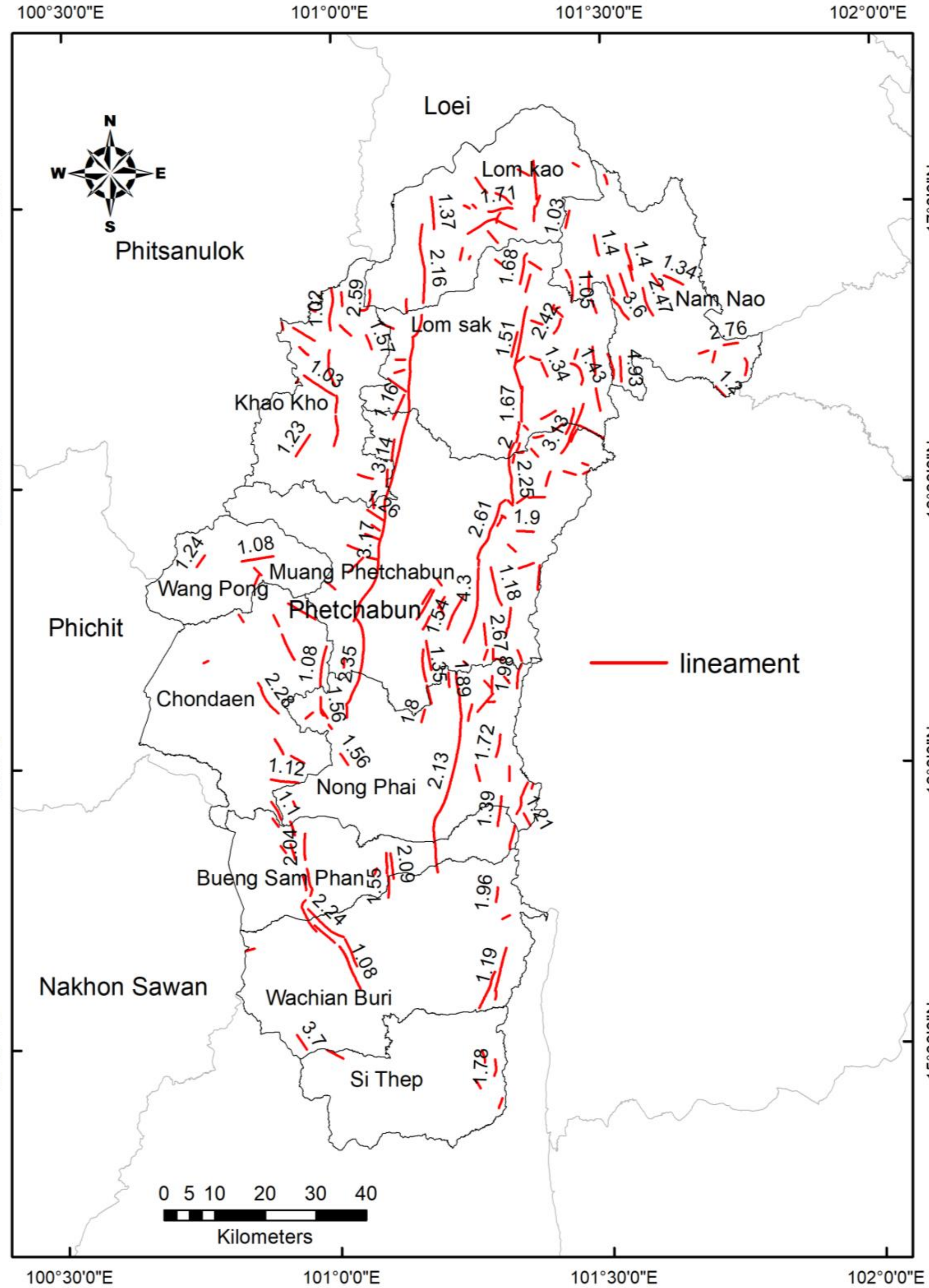


Figure 34. Map of Phetchabun province showing S_{mf} distribution obtain from this study.

3. Hypsometric integral (HI)

The HI values in Phetchabun province range from 0.05 to 1.00 (Figure 34) which related to tectonic activity, actively uplifting and age of drainage basins. If the HI value is near to 1, then that corresponding drainage basins are young and relate to active tectonic activity.

Most basins have quite low HI value in which the lowest value is 0.05 in the Southern area. Meaning that, drainage basins in Phetchabun province have been more eroded and less impacted by active tectonics especially in western and Southern areas than eastern areas which have high value from 0.48-1. Therefore, the HI value can be interpreted that Western and Southern area have low tectonic activity and are older when compared to Eastern of study area.

4. Hypsometric curve (HC)

The hypsometric curve is related to the HI that the area below the hypsometric curve defines tectonic activity and age of the drainage basin as HI value. The curve can be divided into 3 classes: i) concave hypsometric curve, ii) concave-convex hypsometric curve and iii) convex hypsometric curve. Concave hypsometric curve or low HI can be interpreted as older drainage basins which were eroded and less impacted by tectonic activity (Figure 35c). The concave-convex is an s-shaped graph indicating that these drainage basins are relatively stable called mature drainage basins (Figure 35a).

However, they are still a developing landscape. Convex hypsometric curves indicate that the drainage basins have been highly impacted by tectonic activity and are young drainage basins (Figure 35b). In the study area of 38 drainage basins, there are 31 basins identified as Concave HC, 6 basins identified as Concave-convex HC, and one basin identified as convex HC.

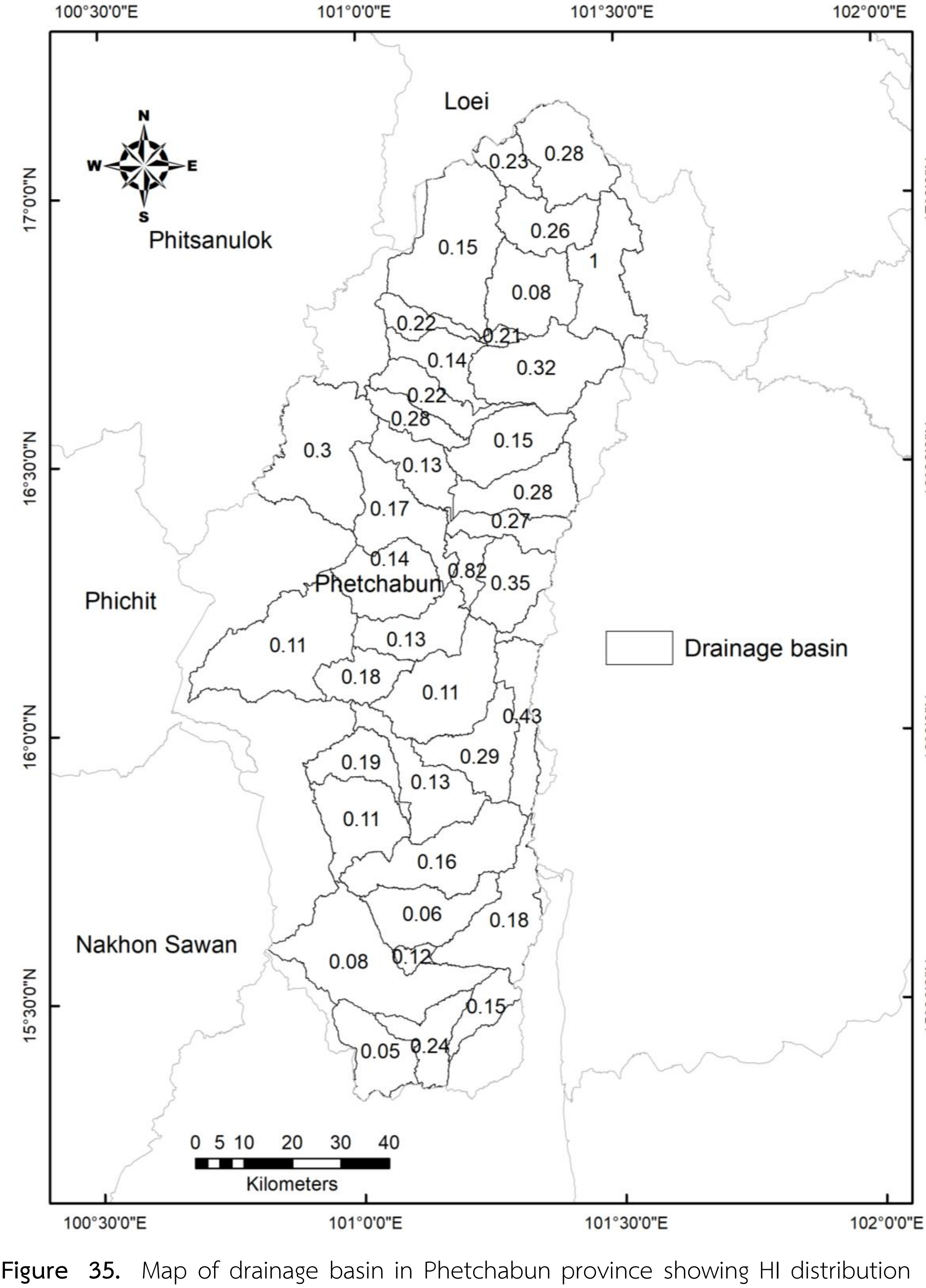


Figure 35. Map of drainage basin in Phetchabun province showing HI distribution obtain from this study.

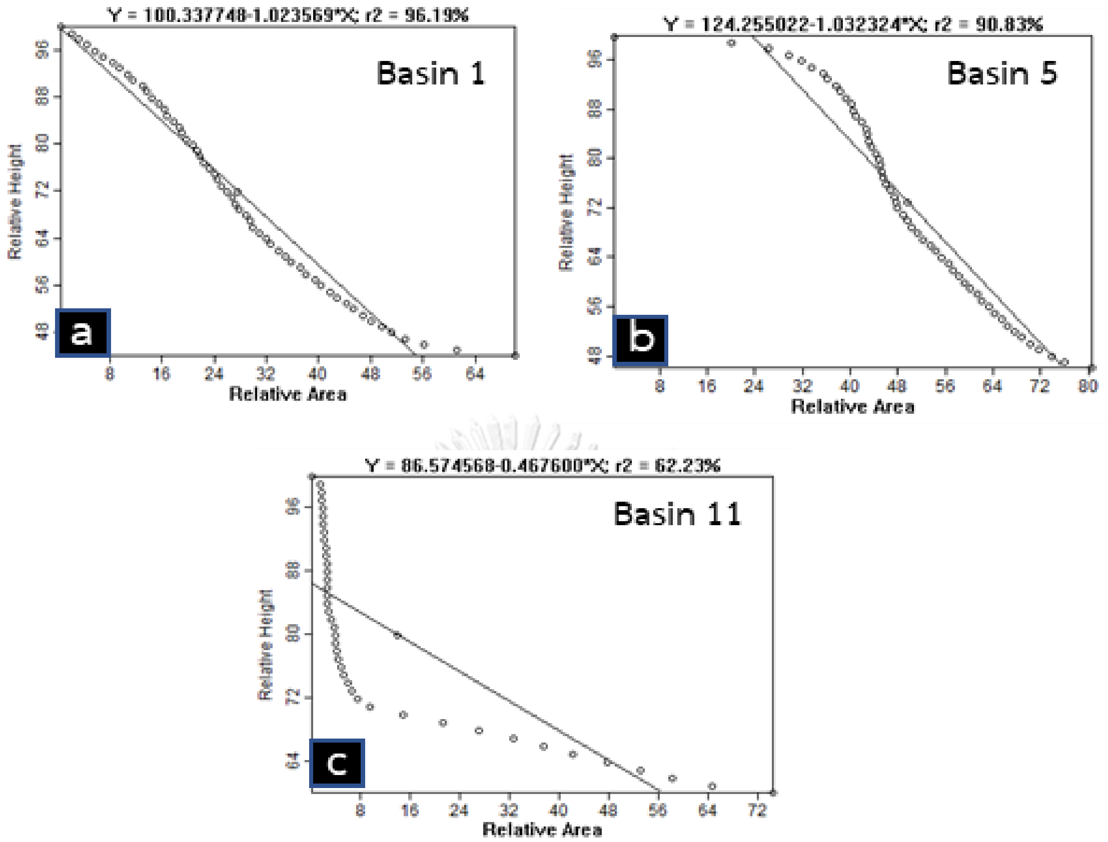


Figure 36. Graph of drainage basin in Phetchabun province showing classification of hypsometric curve obtain from this study a) concave-convex curve, b) convex curve and c) concave curve.

5. **Basin shape index (Thaipbs)**

Generally, the low B_s value indicates circular shape of drainage basins and low active tectonic activity and high value relate to a narrow and long shape drainage basin that the potential of tectonic activity is high. Results of the B_s in Phetchabun province have the value range from 0.31 to 5.80 (Figure 36). High B_s value is shown in Central Phetchabun, ranging from 1.37 to 3.06. Other parts show low B_s value around 1 and the lowest value is 0.31. From this result, this study can conclude that most drainage basins in Phetchabun province indicates comparatively high tectonic activity or high activity of erosion process.

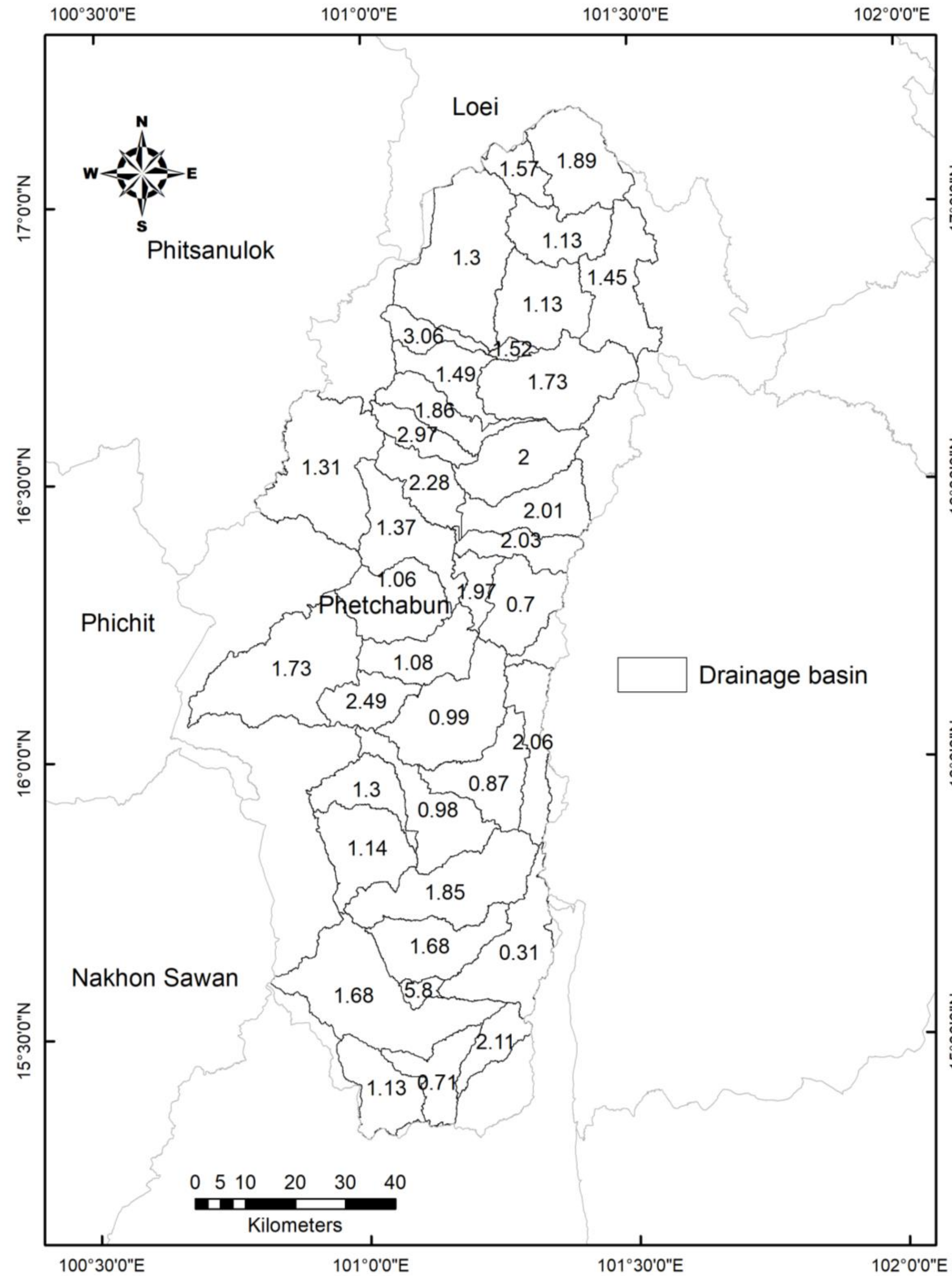


Figure 37. Map of drainage basin in Phetchabun showing distribution of B_s obtain from this study.

CHAPTER IV

LANDSLIDE SUSCEPTIBILTIY

Methodology

Figure 37 is the flowchart that shows the methodology used to count on DEM in correspondence with the required work scale. The evaluation of landslide was based on slope, aspect, profile curvature, plan curvature, TWI and SPI which were extracted from the DEM. The slope, aspect and curvature were obtained from ArcGIS software. The TWI and SPI were earned using SAGA software. Then, six parameters were reclassified and divided them following (Meinhardt et al., 2015). Next, the classified parameters were intersected with historical landslide that obtain from department of mineral resource (DMR) (Figure. 38) before calculated for Si value of parameter class (Table 2.) and linear sum of that. Consequently, these are selected class from Si interval (Table 1.) and categorized into five classes including very low, low, medium, high and very high, and generated into a landslide susceptibility map according to Meinhardt et al., (2015).

Table 2. Classification of landslide susceptibility in this study.

Class of landslide susceptibility	Interval of landslide susceptibility
Very low	-10.50 to -7.30
Low	-7.30 to -3.20
Medium	-3.20 to -1.4
High	-1.40 to 2.69
Very high	2.69 to 7.99

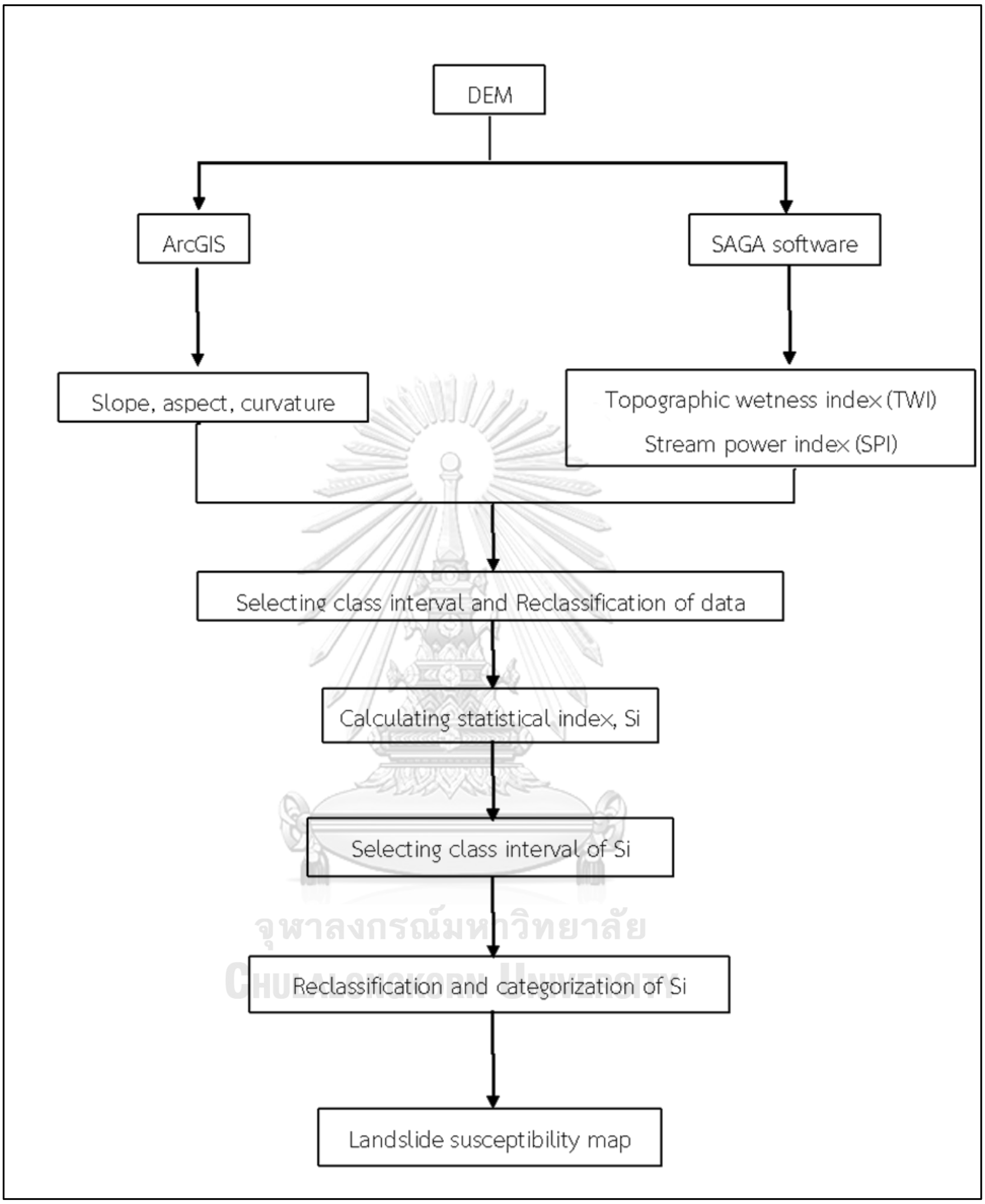


Figure 38. Flowchart showing methodology of landslide susceptibility map in this study.

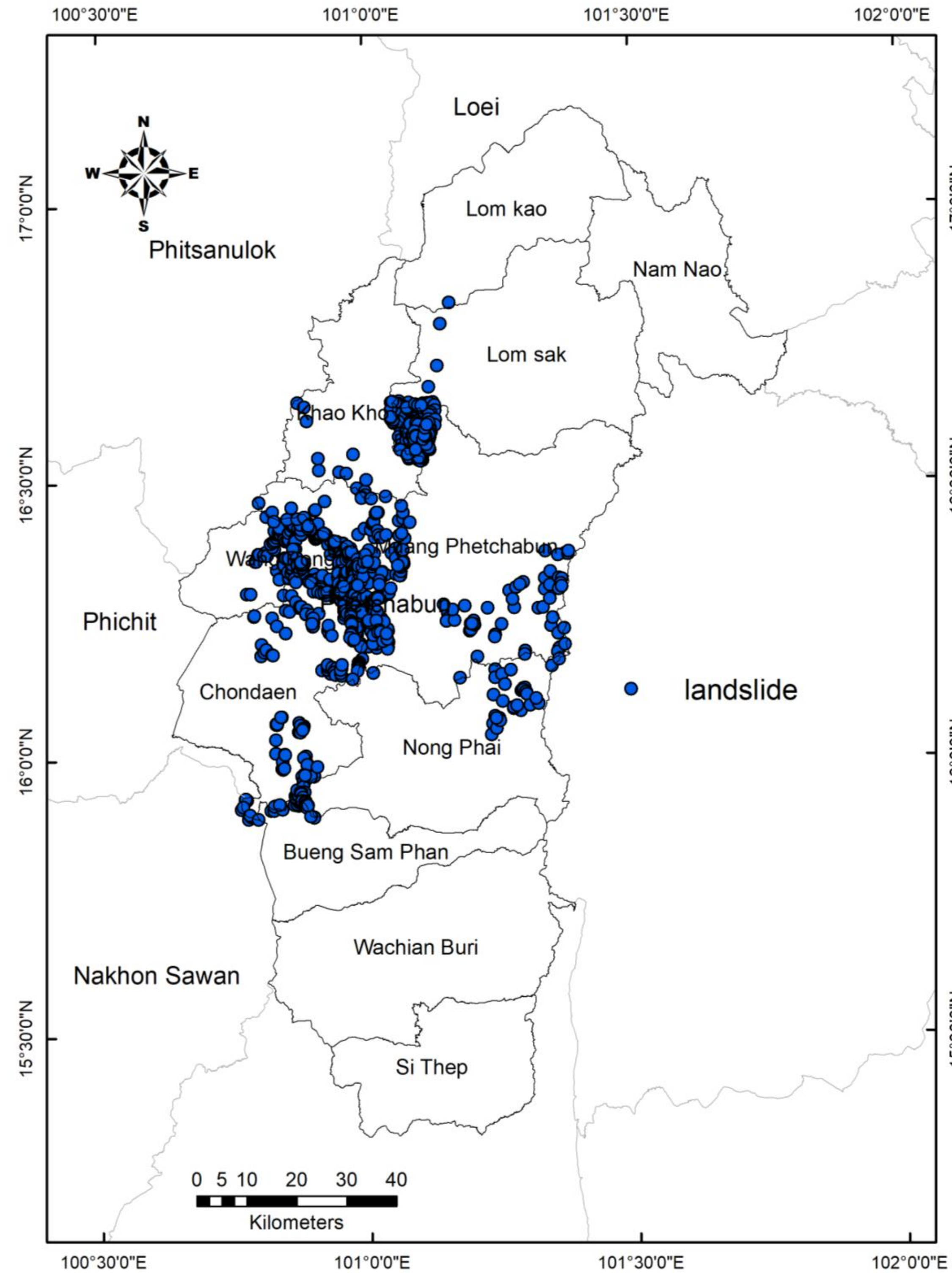


Figure 39 Map of Phetchabun province showing historical landslide map obtain from department of mineral resource (DMR).

Result of Landslide susceptibility

1. **Parameters on occurrence of the landslide.**

1.1. Slope gradient.

Slope gradient in Phetchabun province (Figure 39) range from 0°-70°. Most areas show average slope gradient with 10°-20°. The maximum is shown in western Phetchabun with 70° which situated in western of Lom Sak and Muang Phetchabun district. The minimum found in southern of Phetchabun where Bung Samphan, Wichian Buri and Si Thep are with 0°-10°.

Before landslide susceptibility calculation, this investigation can divide slope gradient into 5 classes; class 1 (0°-10°), class 2 (10°-20°), class 3 (20°-30°), class 4 (30°-40°), and class 5 (40°-70°). Class 1 and 2 are mostly located in the central and southern Phetchabun area. Other classes are located in eastern and western 7Phetchabun which is mountain range.

1.2. Aspect.

Aspect (Figure 40) can be grouped into eight classes following eight slope directions including north, northeast, east, southeast, south, southwest, west, and northwest. The evaluation suggests that most of study areas represent the north direction with 1,406,496 pixels. The second one is west direction with 220,517 pixels. Besides, the direction that have found the lowest number of pixels is northeast direction (Figure 39).

1.3. Profile curvature.

Profile curvature (Figure 41) is the curvature in vertical parallel to the highest direction of slope. It can be divided into three classes including: concave, plain, and convex areas. They are related to stream velocity from slow to fast with the positive and negative value respectively.

The analysis showed that the concave with positive values covers the least area in Phetchabun province equivalent to 288,710 pixels. The plain covers most areas in Phetchabun province with 751,497 pixels. The next is the convex with negative values covering 331,860 pixels. For that reason, it has been presented that the most areas in Phetchabun Province revealed low velocity of stream (Figure 40).

1.4. Plan curvature.

Plan curvature (Figure 42) is the curvature of perpendicular to the highest slope direction. It can be divided into three classes including: concave, plan, and convex area. They can identify an in-out of surface flow following negative to positive values.

The findings indicated that the concave with negative values extends over the least area in Phetchabun province with only 259,752 pixels. In contrast, most of the fieldwork in Phetchabun province is covered by plan with 783,376 pixels. In addition, the convex with positive values cover 329,119 pixels in Phetchabun (Figure 41).

1.5. Topographic wetness index (TWI).

TWI in Phetchabun province (Figure 43) range from 0.00-46.00. Most areas show an average TWI at 0.00-8.00. The maximum index is 46. It has been found in central and southern Phetchabun area including: central of Lom Sak, central of Muang Phetchabun, Nong Phai, Bung Samphan, Wichian Buri and Si Trep. Besides, the minimum TWI has been shown in eastern and western of Phetchabun which defines mountain range at 0.00-8.00.

Before landslide susceptibility calculation, we can divide TWI to five classes following Meinhardt et al., (2015); class 1 (0.00-8.00), class 2 (8.00-9.00), class 3 (9.00-10.00), class 4 (10.00-12.00) and class 5 (12.00-46.00). The class 1 and class 2 have been mostly located in eastern and western Phetchabun area. While the other classes have been situated in central and southern Phetchabun which is a plain area (see also Figure 43).

1.6. Stream power index (SPI).

SPI in Phetchabun province (Figure 44) range from 0-2,578. Most areas imply an average SPI with 0-50. The minimum SPI has been found in central and southern Phetchabun area with 0.00-150.00. On the other hand, the maximum SPI has been shown in eastern and western of Phetchabun which indicates a mountain range at 2,578.

Before landslide susceptibility calculation, SPI can be separated into six classes including: class 1 (0.00-50.00), class 2 (50.00-150.00) class 3 (150.00-272.00), class 4 (272.00-414.00) and class 5 (414.00-636.00), and class 6 (636.00-2,578.00) (see also Figure 44). The class 1, class 2 and class 3 have been mostly located in central Lom Sak, Lom Kao, Muang Phetchabun, Nong Phai, Chondaen, Wang Pong, Bung Samphan, Wichian Buri and Si Thep districts. Besides, the rest classes located in eastern and western Phetchabun. Those zones are eastern of Lom Sak, Muang Phetchabun and Khao Khlo districts (Figure 44).

Table 3. Landslide susceptibility of 5 parameters in this study.

Index	Class	Area (pixel)	Landslide in class (pixel)	Si
slope	1	9,396,520	137	-1.83
	2	2,453,338	336	0.41
	3	1,437,932	448	1.23
	4	390,719	263	2.00
	5	42,179	60	2.75
Aspect	North	1,406496	151	0.169
	Northeast	1,430,041	136	0.05
	East	1,770,540	116	-0.32
	Southeast	1,587,838	137	-0.05
	South	1,734,356	161	0.02
	Southwest	1,983770	203	0.12
	West	2,205,177	193	-0.04
	Northwest	1,601,538	147	0.01
Profile curvature	Concave	2,887,102	504	0.66
	Plan	7,514,768	163	-1.43
	Convex	3,318,608	577	0.65
Plan curvature	Concave	2,595,723	578	0.89
	Plan	7,833,768	133	-1.68
	convex	3,291,197	533	0.58
TWI	1	5,005,972	1132	0.94
	2	3,084,300	58	-1.57
	3	3,254,988	16	-2.91
	4	2,317,956	7	-3.40
	5	57,472	1	-1.65
SPI	1	8,812,907	124	-1.86
	2	2,315,693	453	0.77
	3	1,465,918	332	0.92
	4	747,250	156	0.83
	5	318,387	107	1.31
	6	60,533	72	2.57

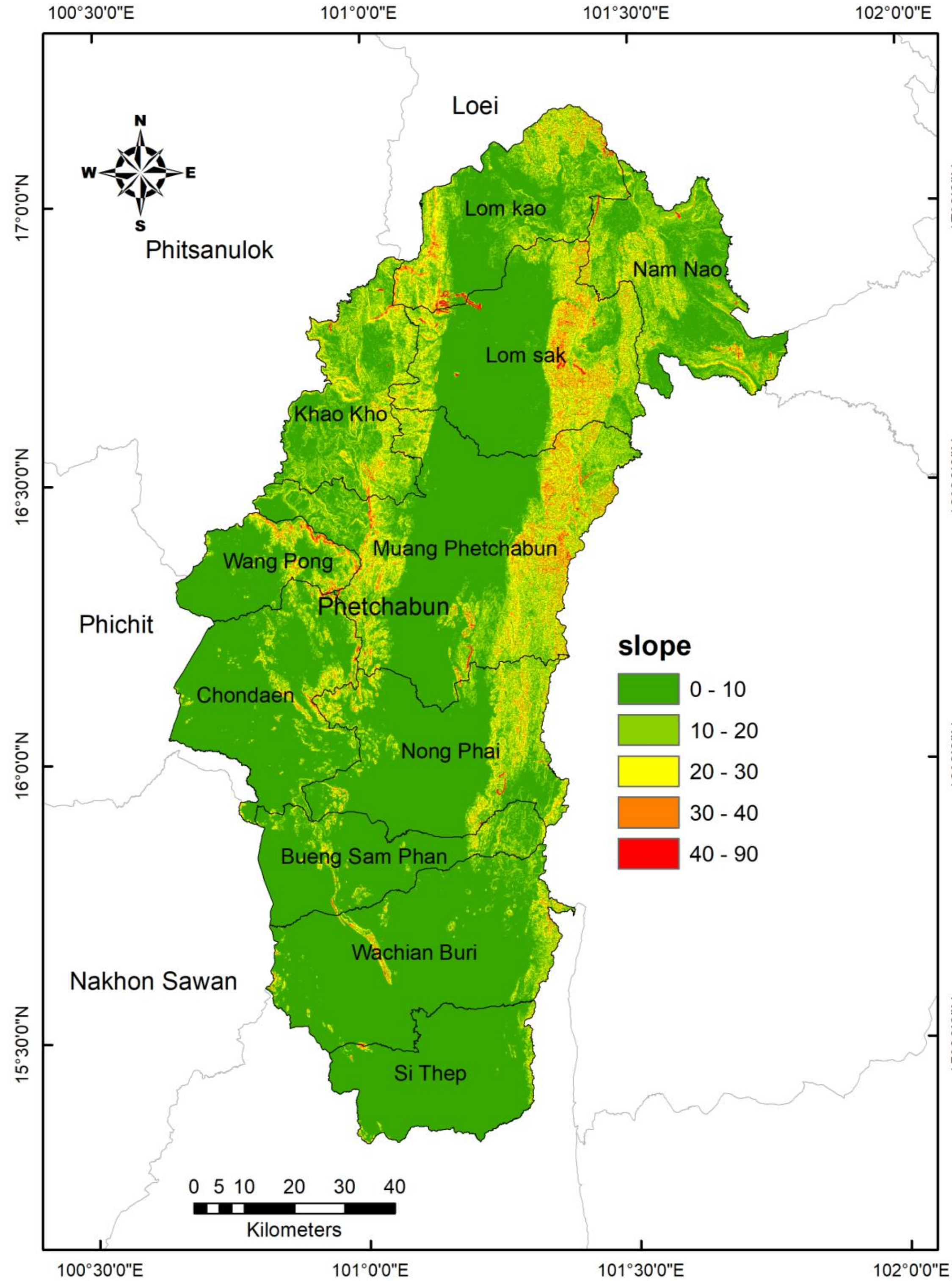


Figure 40. Map of Phetchabun province showing slope gradient (in degree) that is parameter on occurrence of landslide obtain from this study.

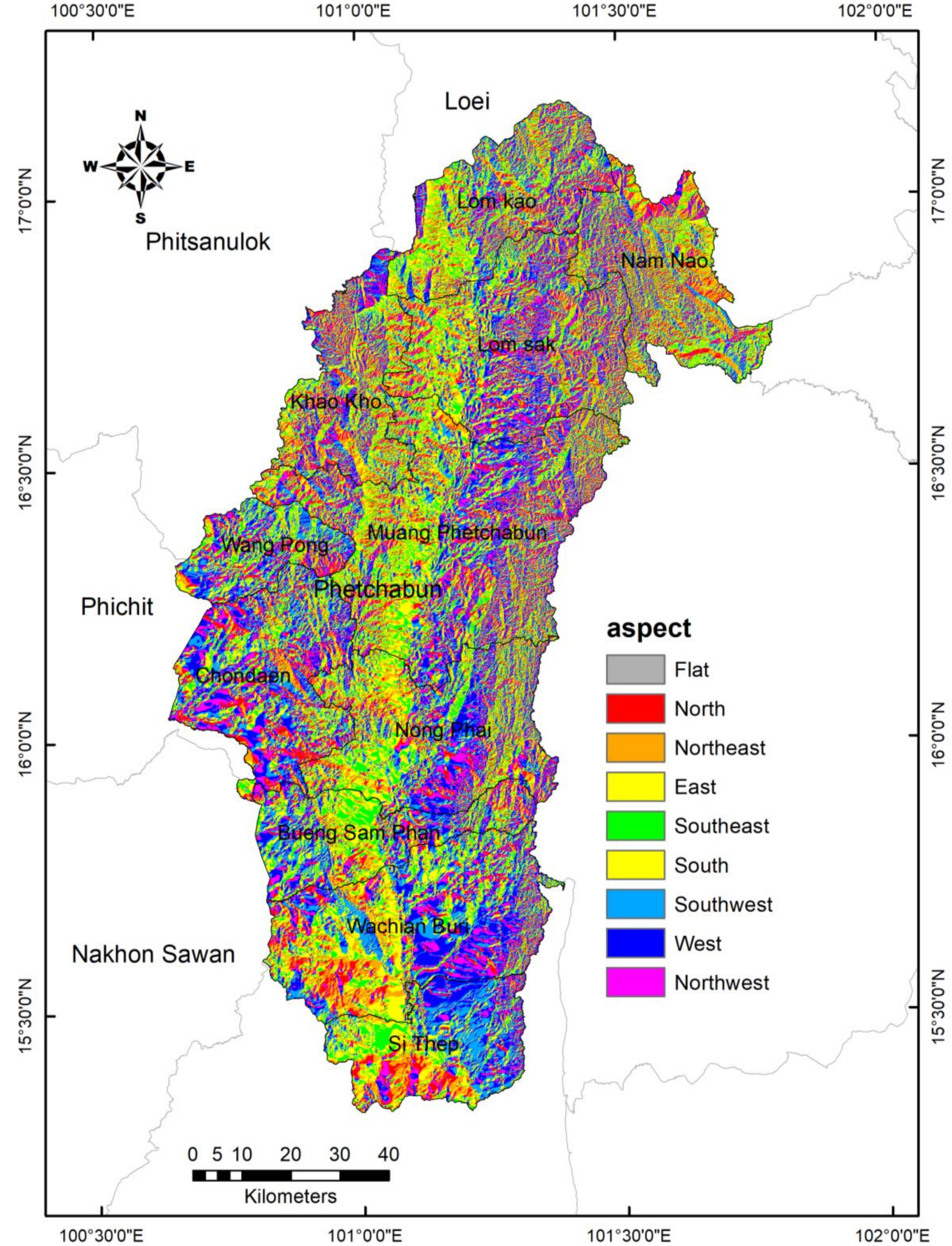


Figure 41. Map of Phetchabun province showing aspect that is parameter on occurrence of landslide obtain from this study.

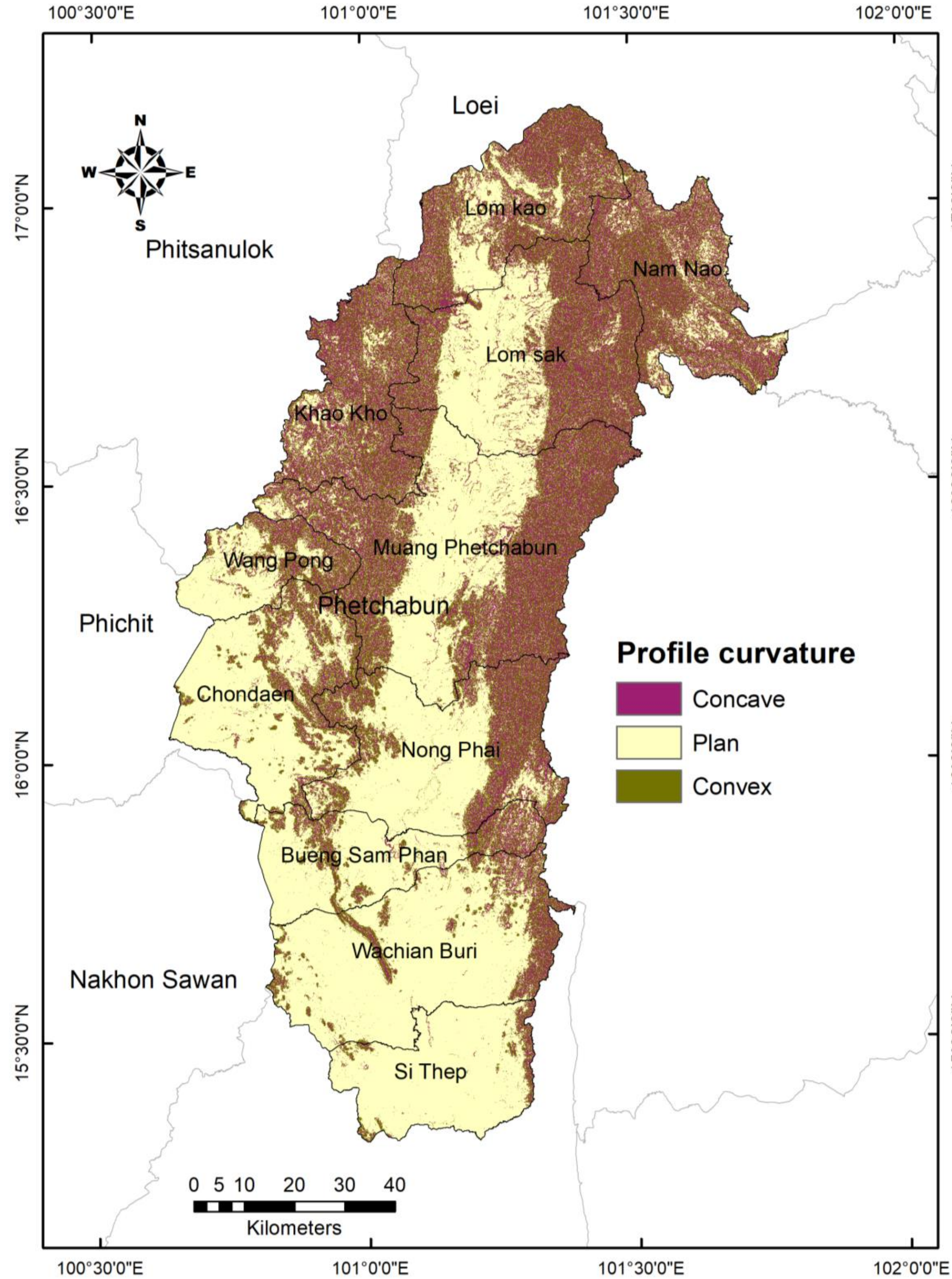


Figure 42. Map of Phetchabun province showing profile curvature that is parameter on occurrence of landslide obtain from this study.

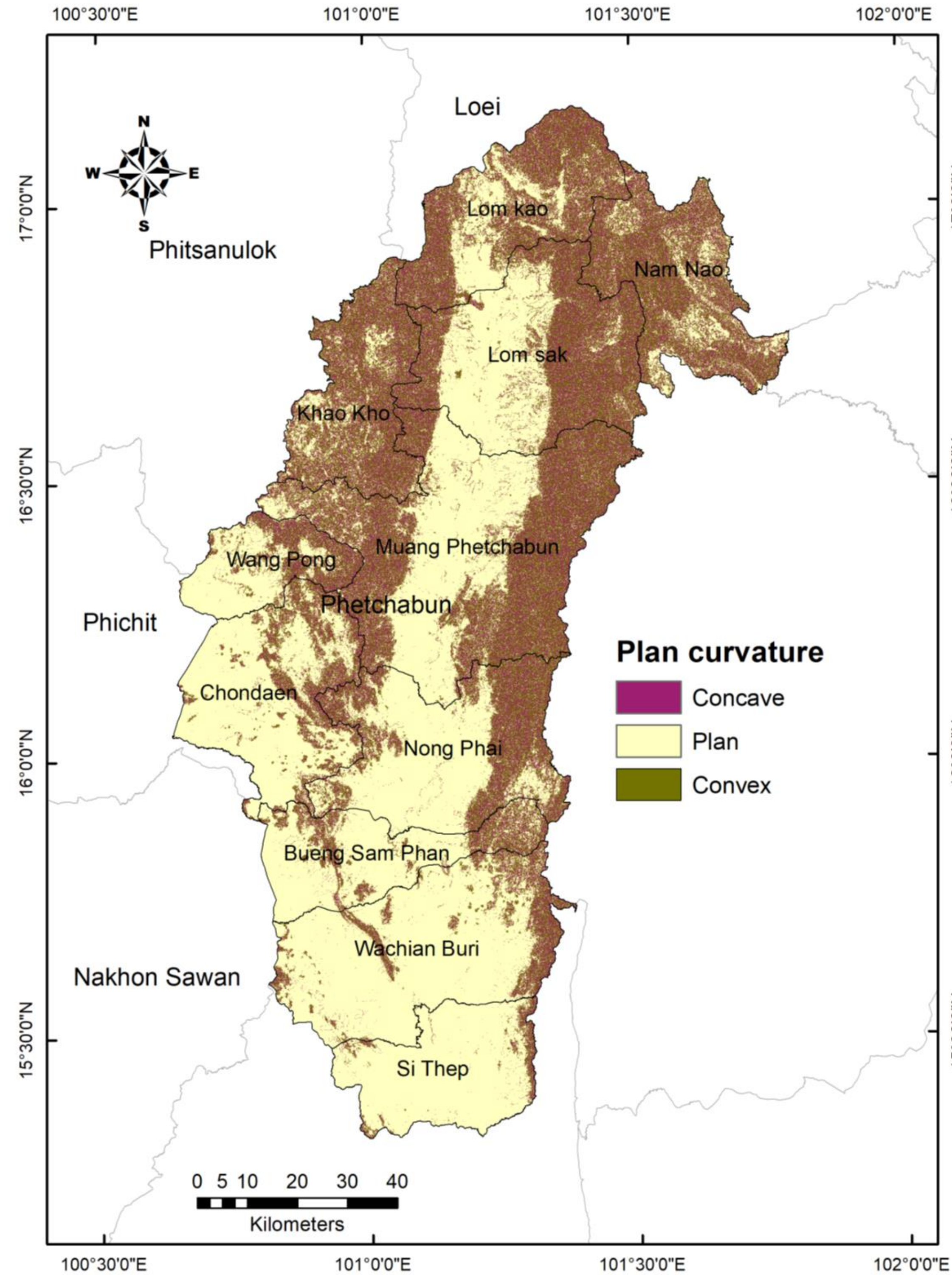


Figure 43. Map of Phetchabun province showing plan curvature that is parameter on occurrence of landslide obtain from this study.

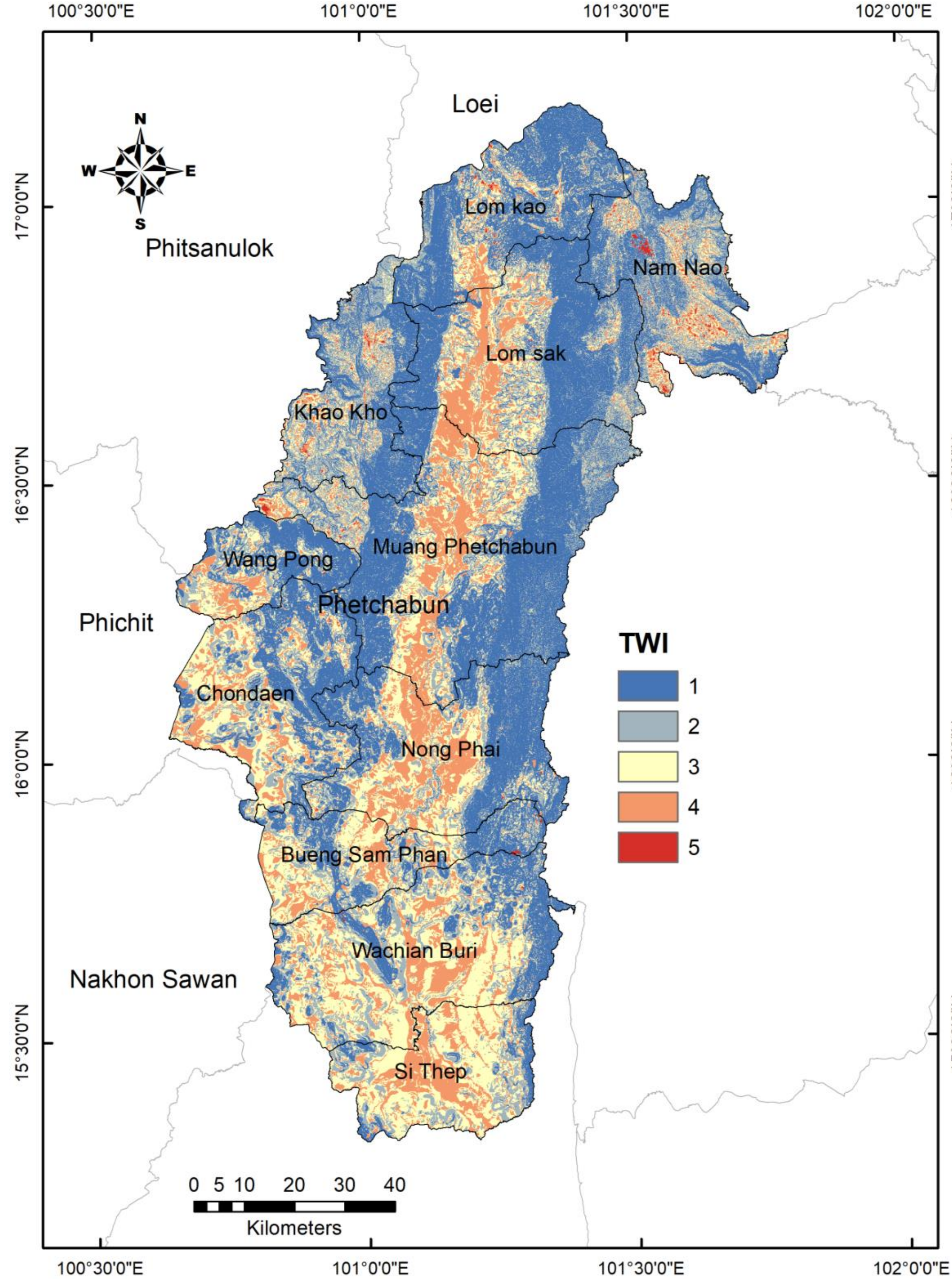


Figure 44. Map of Phetchabun province showing TWI that is parameter on occurrence of landslide obtain from this study.

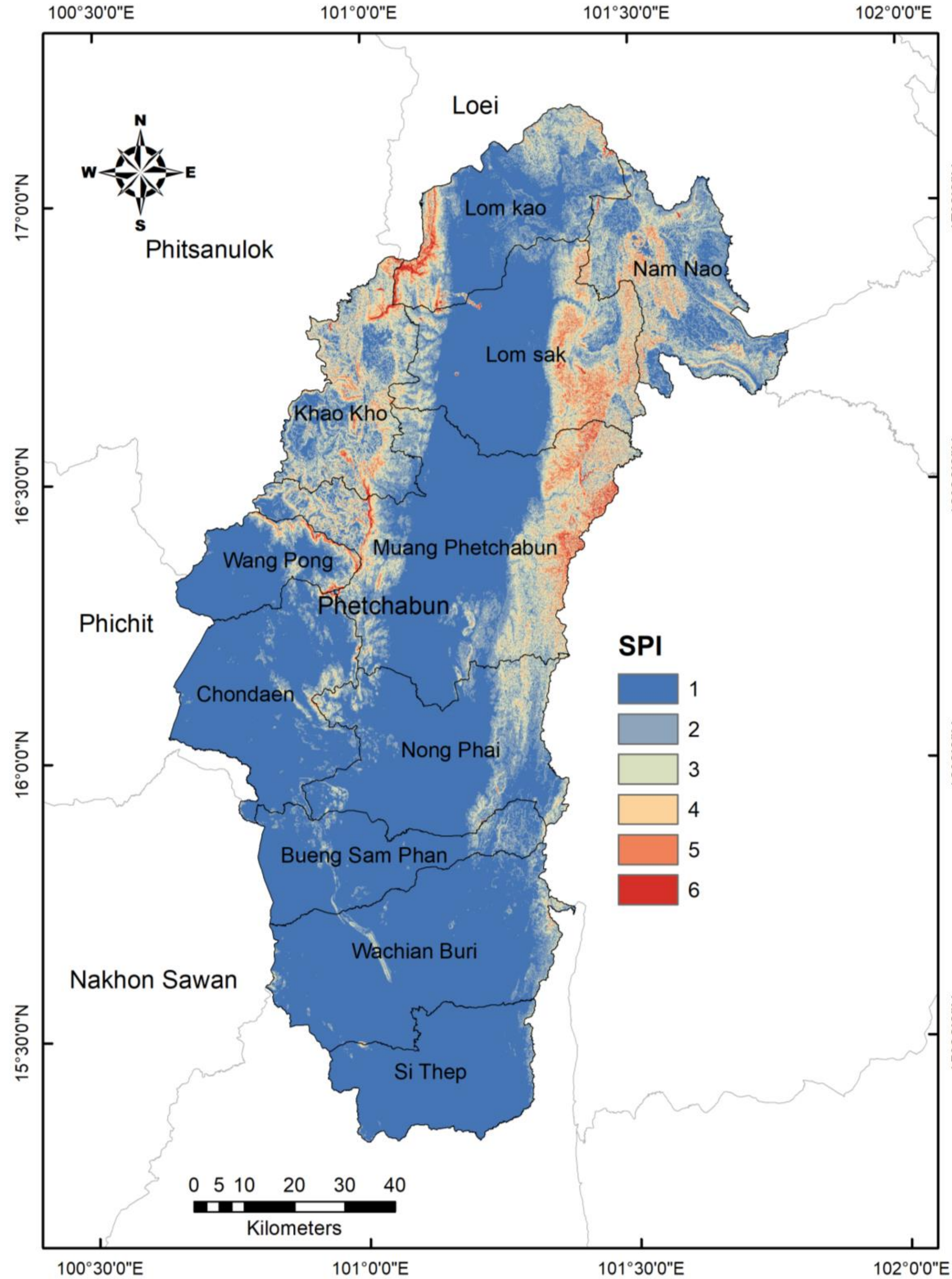


Figure 45. Map of Phetchabun province showing SPI that is parameter on occurrence of landslide obtain from this study.

2. Landslide susceptibility map

The result of landslide susceptibility in Phetchabun province is shown in Figure 45. The level of landslide susceptibility assessment can be divided into five groups that are classified by table 1: class 1 very low (-10.50 to -7.30), class 2 low (-7.30 to -3.20), class 3 medium (-3.20 to -1.40), class 4 high (-1.40 to 2.69) and class 5 very high (2.69 to 7.99). The area quantity can be sorted in descending order as follows: class 1 covers 5,887 km^2, class 5 covers 2,753 km^2, class 2 covers 1,618 km^2, class 3 covers 1,075 km^2 and class 4 covers the least area of 1,015 km^2 as shown in the table 3.

The analysis indicated larger part of Phetchabun province has been defined to be a very low susceptibility area. It includes central Lom Sak, central Muang Phetchabun and Nong Phai districts in central Phetchabun, Wang Pong and Chon daen districts in western Phetchabun, Bung Samphan, Wichian Buri and Si Thep districts in southern Phetchabun.

On the other side, the other areas that did not mention above are considered to be a very high susceptibility area. These zones consist of Lom Kao district in northern Phetchabun, Khao Kho and Wang Pong districts in western Phetchabun, both of eastern and western Lom Sak, Muang Phetchabun and eastern Nong Phai district. Additionally, these high susceptibility areas are located on Phetchabun mountain range.

Table 4. The total area for each class of landslide susceptibility map.

Class of landslide susceptibility	Area (Km^2)
very low	5,886
low	1,618
medium	1,074
high	1,015
very high	2,752

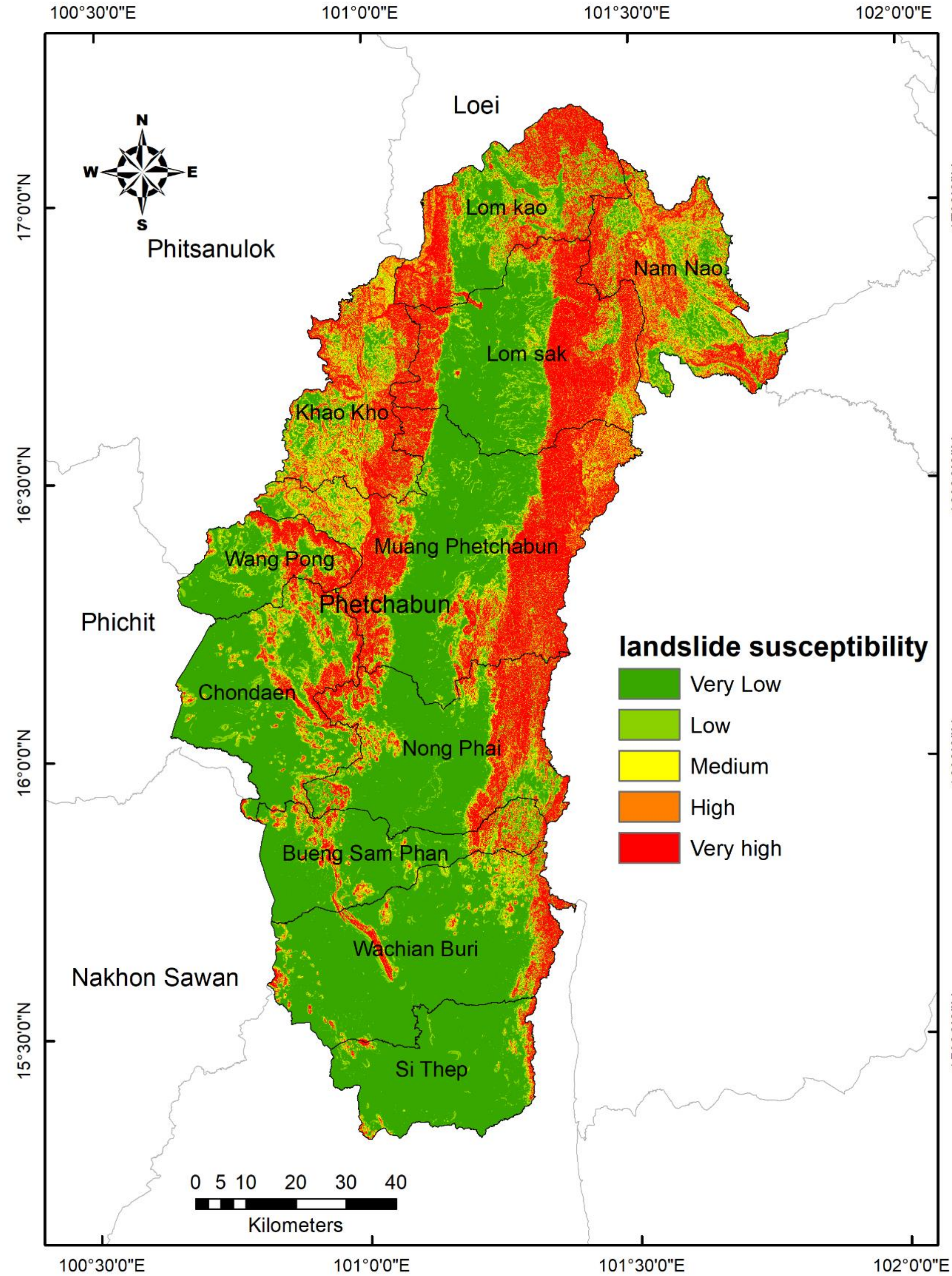


Figure 46. Map of Phetchabun showing landslide susceptibility map (green indicates very low and red indicates very high) obtain from this study.

CHAPTER V
FLOOD SUSCEPTIBILITY

Methodology

Figure 46 is the flowchart which presents the methodology used to count on DEM data in correspondence with required work scale. The assessment of flood susceptibility was based on a geomorphological and hydrological index which was extracted from DEM. These were obtained using SAGA software. Geomorphological index contains CD and VD also; hydrological index has MCA, D8 and TWI respectively. Before HCI calculation, the parameters must be normalized (equation 1.10). Then, this study classifies the calculated HCI using standard deviation methods in five intervals (Table 4). Finally, these intervals were reclassified and categorized into five classes including: none, low, medium, high, and very high so flood susceptibility map is obtained from this methodology.

Table 5. Classification and category of flood susceptibility in this study.

Category of susceptibility to floods	Category rank		Calculation formula
	From	To	
none	-	-	-
Low	Minimum value (Vmin)	Mean value (μ) + one standard deviation (σ)	Vmin to μ + σ
Medium	Mean value (μ) + one standard deviation (σ)	Mean value (μ) + two standard deviation (2σ)	μ + σ to μ + 2σ
High	Mean value (μ) + two standard deviation (2σ)	Mean value (μ) + three standard deviation (3σ)	μ + 2σ to μ + 3σ
Very high	Mean value (μ) + three standard deviation (3σ)	Maximum value (Vmax)	μ + 3σ to Vmax

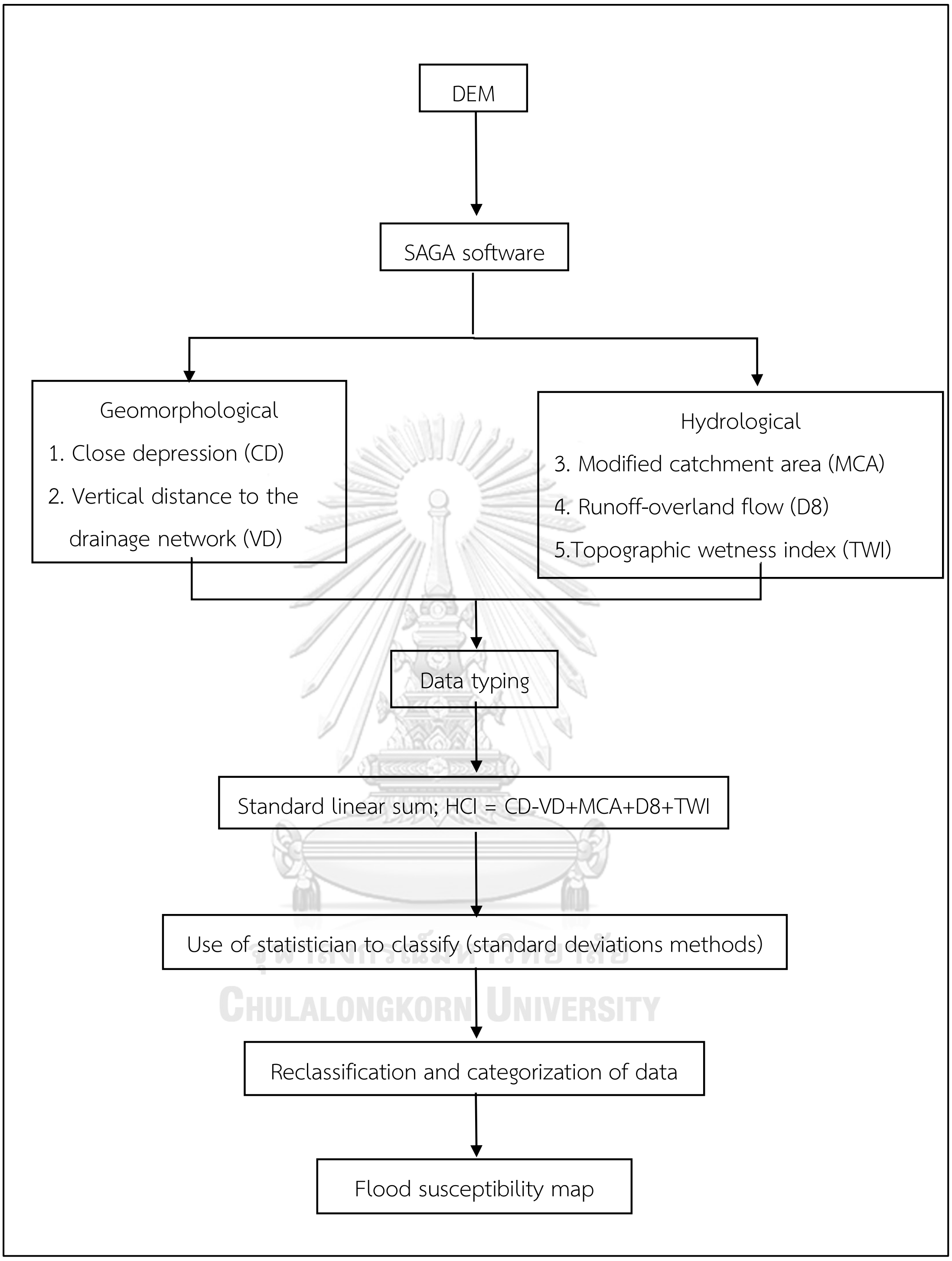


Figure 47. Flowchart showing methodology of flood susceptibility map in this study.

Result of flood susceptibility

1. **Parameter on occurrence of flood.**

   1.1. **Close depression (CD)**

CD in Phetchabun province (Figure 47) range from 3.18×10^{-6} to 410.51 average CD is 1.61. The maximum index is 410.51 located in northeast and eastern of Phetchabun province including Nam Nao, eastern of Nong Phai and eastern of Bung Samphan districts. The minimum CD has been shown in central Phetchabun including central Lom Sak, central of Muang Phetchabun and central of Wichian Buri.

These indices have indicated flat type morphologies sunken the above general level and the presence of intense or prolonged precipitation, results in the accumulation runoff water. That means a low CD value determines the flat or intense precipitation accumulation areas. For that reason, Phetchabun province has presented flat type morphologies and high intense precipitation in central Phetchabun.

   1.2. **Vertical distance from the channel network (VD)**

VD in Phetchabun province range (Figure 48) from 0 to 346.45. Most areas have provided an average VD of 3.00. The maximum index has been located in eastern and western of Phetchabun province. The zones include northern Lom Sak, western of Nam Nao, eastern and western of Lom Sak, eastern and western Muang Phetchabun and Khao Khlo districts. The minimum VD has been shown in central, western and southern of Phetchabun province including central of Lom Sak, central of Muang Phetchabun, central of Nong Phai, western of Chondaen, Bung Samphan, Wichian Buri, Si Thep districts.

This index related to the difference between pixel elevation and channel network base level, meaning that a high VD value indicates high elevation from channel network base level and a low VD value indicates low elevation. Consequently, most areas in Phetchabun province has shown low elevation from channel network base level.

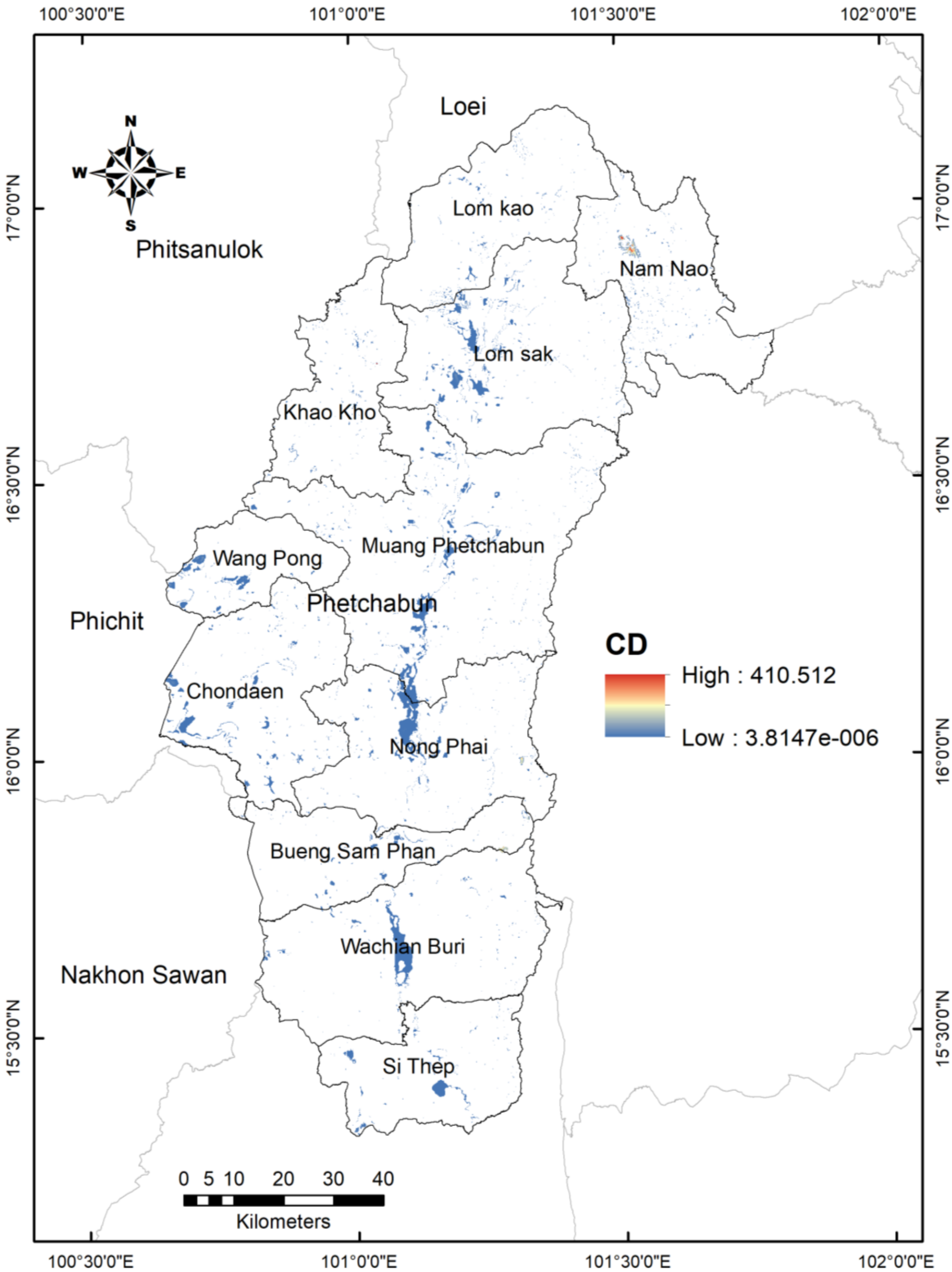


Figure 48. Map of Phetchabun province showing CD that is parameters on occurrence of flooding obtained from this study.

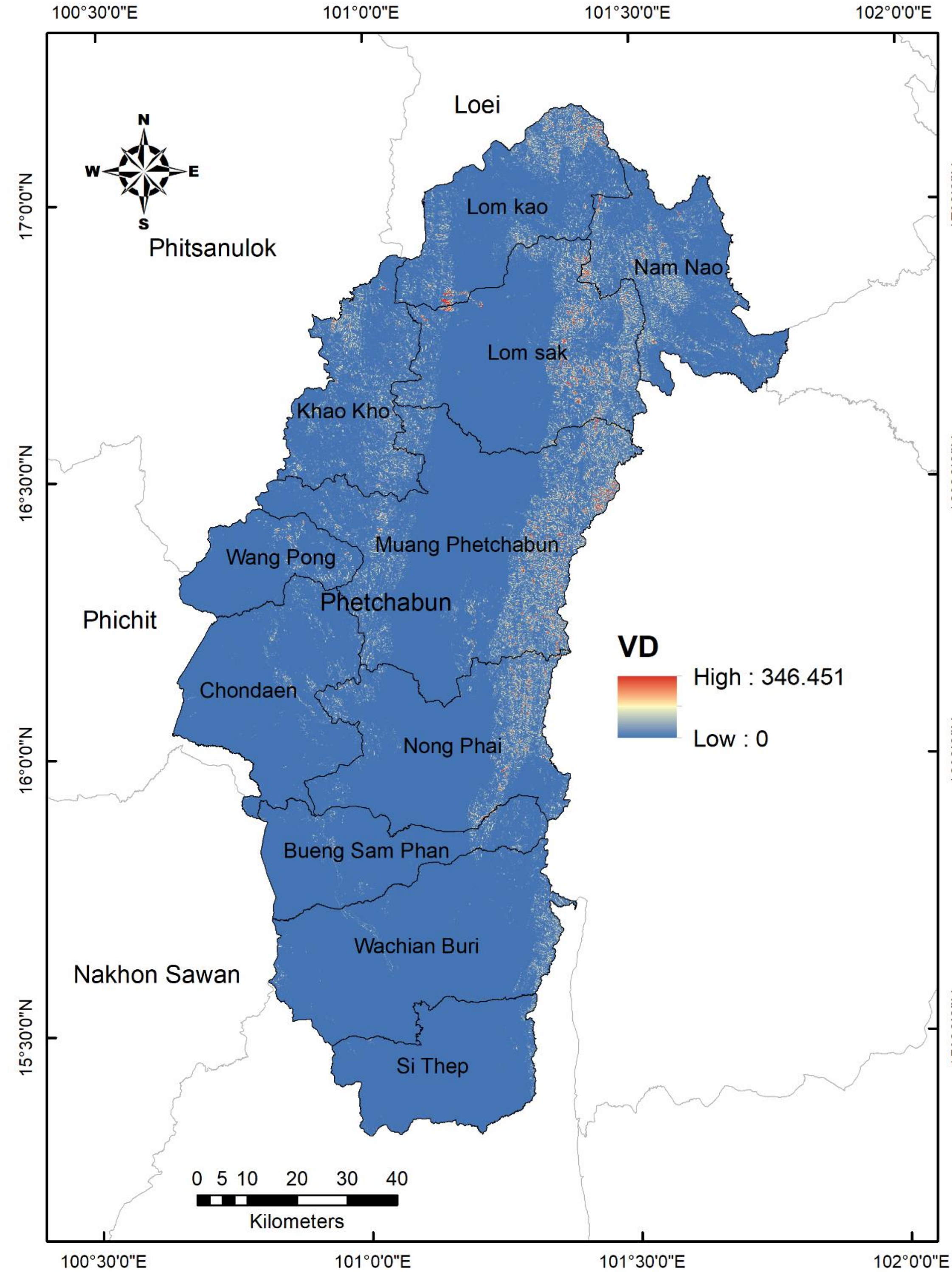


Figure 49. Map of Phetchabun province showing VD that is parameters on occurrence of flooding obtained from this study.

1.1. Runoff-overland flow (D8)

D8 in Phetchabun province (Figure 49) range from 9.42×10^{-10} to 6,696.60. Most areas have provided an average D8 of 6.48. The maximum index 6,696.60 has been found in some areas in Phetchabun which is distributed following an amount of precipitation. The minimum D8 is shown in most areas in Phetchabun province. The D8 is related to slope gradient and slope direction. These affect to flood hazard and water flow from high elevation to low elevation.

1.2. Modified catchment area (MCA)

MCA in Phetchabun province (Figure 50) range from 900.00 to 3.18×10^{8}. Most areas show average MCA. The maximum index is 3.18×10^{8} which has been found in central and southern of Phetchabun province including: central of Muang Phetchabun, central of Nong Phai, central of Wichian Buri and central of Wichian Buri and central of Si Thep. The minimum MCA is 900.00 which cover most of study areas, especially eastern and western of Phetchabun province which is mountain range.

This index is a related area that received an amount of flow that accumulated per unit area. The high MCA determines an area at high an amount of flow accumulation. In contrast, the low MCA indicates an area at low flow accumulation. Therefore, Phetchabun province has shown a high amount of flow accumulation in the central area.

1.3. Topographic wetness index (TWI)

TWI in Phetchabun province (Figure 51) range from 0.76 to 14.30. Most areas show an average TWI with 7.36. The maximum index is 14.3 located in central and southern Phetchabun area. It consists of central of Lom Sak, central of Muang Phetchabun, Nong Phai, Bung Samphan, Wichian Buri, Si Thep and western of Chondaen districts. The minimum TWI has been shown in eastern and western of Phetchabun which is mountain range. The zones include Nam Nao, eastern of Lom Sak, eastern and western of Muang Phetchabun, Khao Khlo and northern of Lom Kao. The TWI relate to soil moisture content, flow direction of soil and groundwater which is controlled by topography

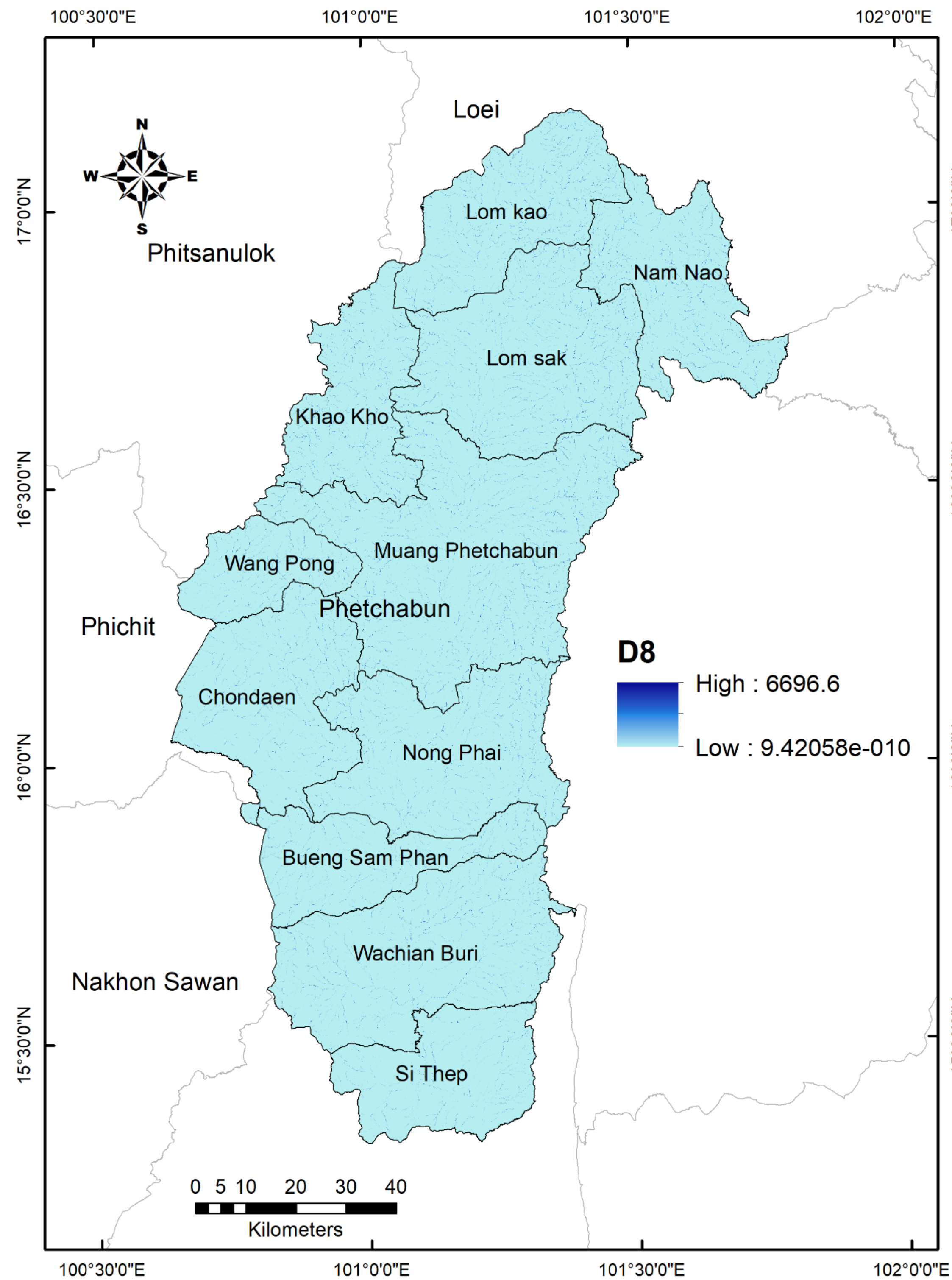


Figure 50. Map of Phetchabun province showing D8 that is parameters on occurrence of flooding obtained from this study.

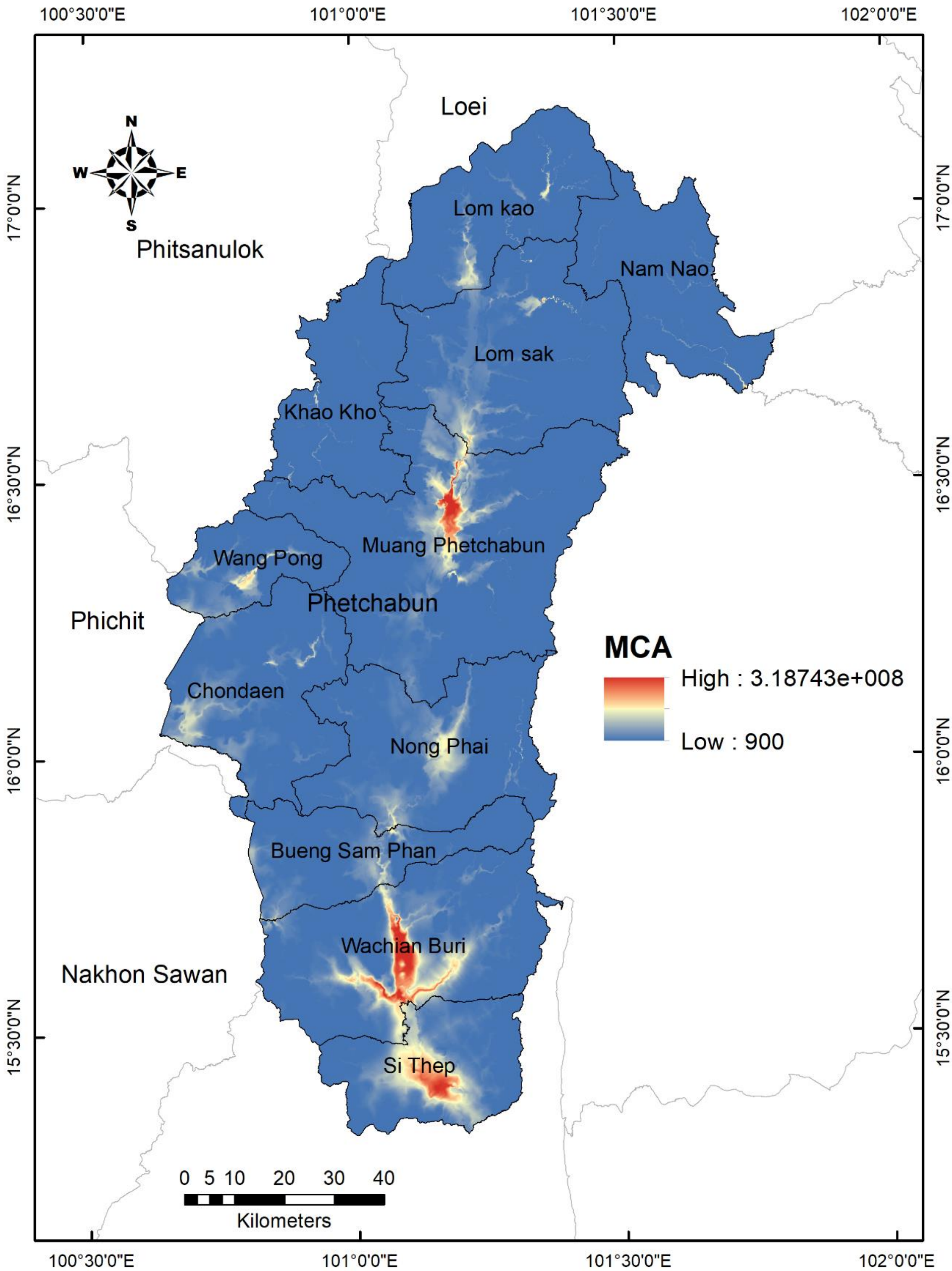


Figure 51. Map of Phetchabun province showing MCA that is parameters on occurrence of flooding obtain from this study.

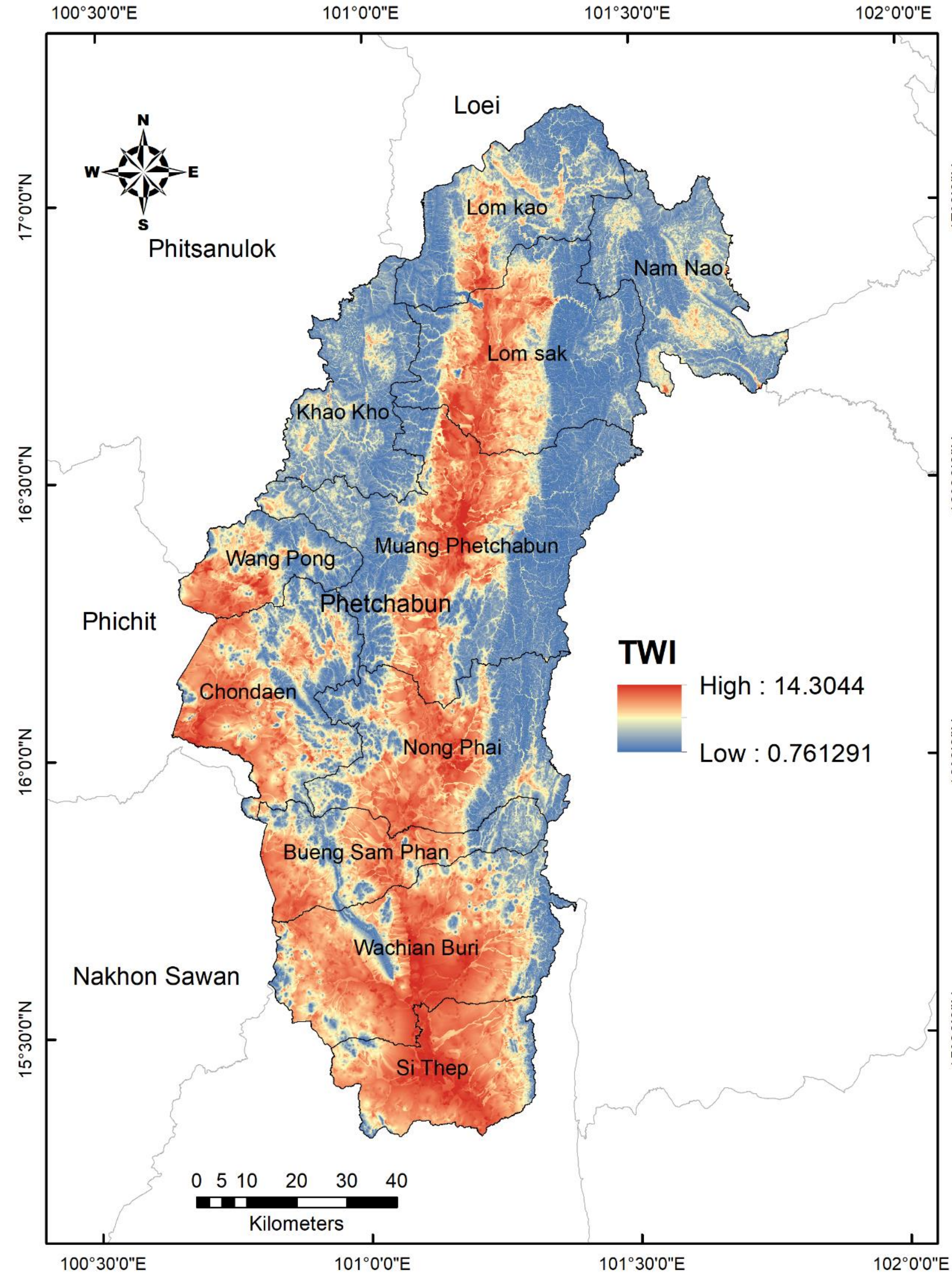


Figure 52. Map of Phetchabun province showing TWI that is parameters on occurrence of flooding obtain from this study.

2. Flood susceptibility map

The result of flood susceptibility in Phetchabun province is shown in Figure 52. The evaluation can be divided into five groups that are classified by table: class 1 none, class 2 low, class 3 medium, class 4 high and class 5 very high. The area quantity of each class can be sorted in descending order as follows: class 1 covers the most area of 244.35 km^2, class 3 covers 28.65 km^2, class 2 covers 20.71 km^2, and class 4 covers the least area of 2.09 km^2. It contributes to 2.33% of Phetchabun province as shown in the table 5.

Overall area of Phetchabun province has been presented to be a non-susceptibility area. These zones that referred to are located in southern Phetchabun including central of Wichian Buri and central of Si Thep districts. Next, the medium susceptibility area has been found in central and western Phetchabun including central of Muang Phetchabun, central of Wang Pong and western of Chondaen districts. Then, the high susceptibility area has distributed all over Phetchabun province especially central of Lom Sak, central of Muang Phetchabun, western of Chondaen and western of Wong Pong districts. Ultimately, the analysis suggested the very high susceptibility area distributing all over Phetchabun province as well, especially Khao Kho and Nam Nao districts.

Table 6. The total area for each class of the flood susceptibility map.

Class of flood susceptibility	Area (Km^2)
low	244
medium	20
high	28
very high	2

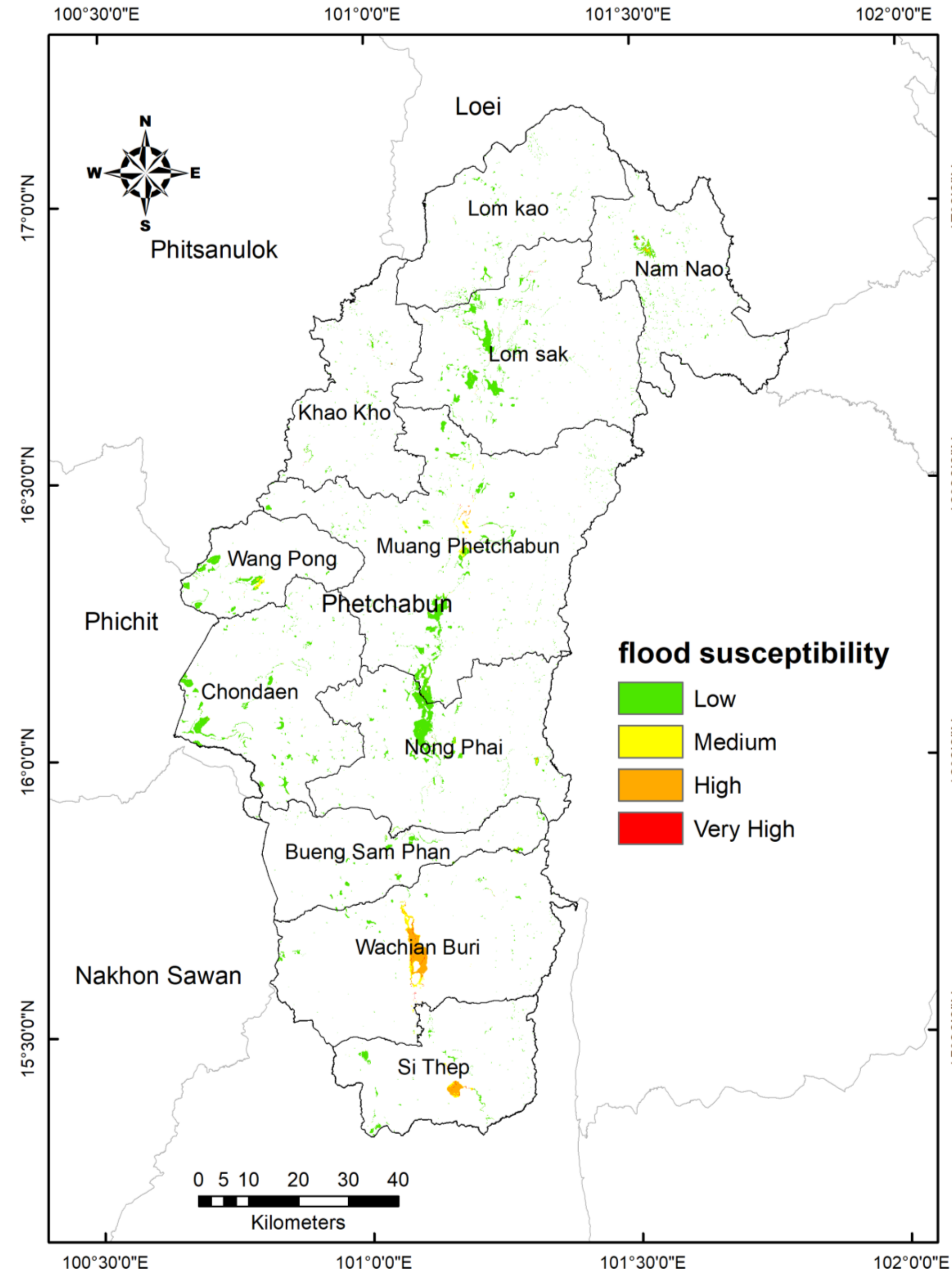


Figure 53. Map of Phetchabun province showing flood susceptibility map (green means low susceptibility and red means very high susceptibility) obtain from this study.

CHAPTER VI
DISCUSSION

Comparatively Geomorphic index

The main reason this project use comparatively Geomorphic index is because this study uses new analysis methods which is not been previously used on this area before. Henceforth, it is necessaries to use previous works to identify and detect low-high tectonic activities in the area. This study uses three previous works to create each type of classification of geomorphic index. This method used is called "Comparatively geomorphic index".

1. **Stream length gradient index (SL)**

From the result, SL map can be classified into three types: type 1 (Cheng et al., 2016), type 2 (Mahmood and Gloaguen, 2012) and type 3 (Sarp et al., 2011). However, in this study decide to classify only the stream order 5 and order 6 as they provide the obviously anomalous values of SL which can indicate the tectonic activity of the main stream in Phetchabun province.

The type 1 can be divided into five classes: class 1 (<25.00), class 2 (25.00-75.00), class 3 (75.00-200.00), class 4 (200.00-400.00) and class 5 (≥400.00). The type 2 has six classes: class 1 (<190.00), class 2 (191.00-365.00), class 3 (366.00-540.00), class 4 (541.00-749.00), class 5 (750.00-1,075.00) and class 6 (≥1,076.00). The type 3 has five classes: class 1 (<112.47), class 2 (112.48-241.64), class 3 (241.65-447.95), class 4 (447.6-846.59) and class 5 (846.60-1,780.24).

The SL map of the order 5 can be classified by type 1 to 3 as shown in a Figure 53 to 55. It has been presented 2,230 points in class 1, 59 points in class 2 and 28 points in class 3 (Figure 53). Then, the type 2 shows 2,316 points in class 1 and 1 point in class 2 (Figure 54). Lastly, the type 3 displays 2,306 points in class 1 and 16 points in class 2 (Figure 55). This has been demonstrated SL in stream order 5 with three classifications indicating low tectonic activities along stream. It also related to rock types.

The SL map of the order 6 can be classified by type 1 to 3. It has been presented 7,389 points in class 1, 98 points in class 2 and 28 points in class 3 (Figure 56). The type 2 only shows 7,515 points in class 1 (Figure 57). The type 3 displays 7,511 points in class 1 and 4 points in class 2 (Figure 58). So that means SL in stream order 6 with 3 classifications can indicate low tectonic activities along stream. Also, it related to rock types.

According to the 3 types of classification of the stream order 5 and 6, SL in Phetchabun province has been supported low tectonic activities along stream and related to rock types.

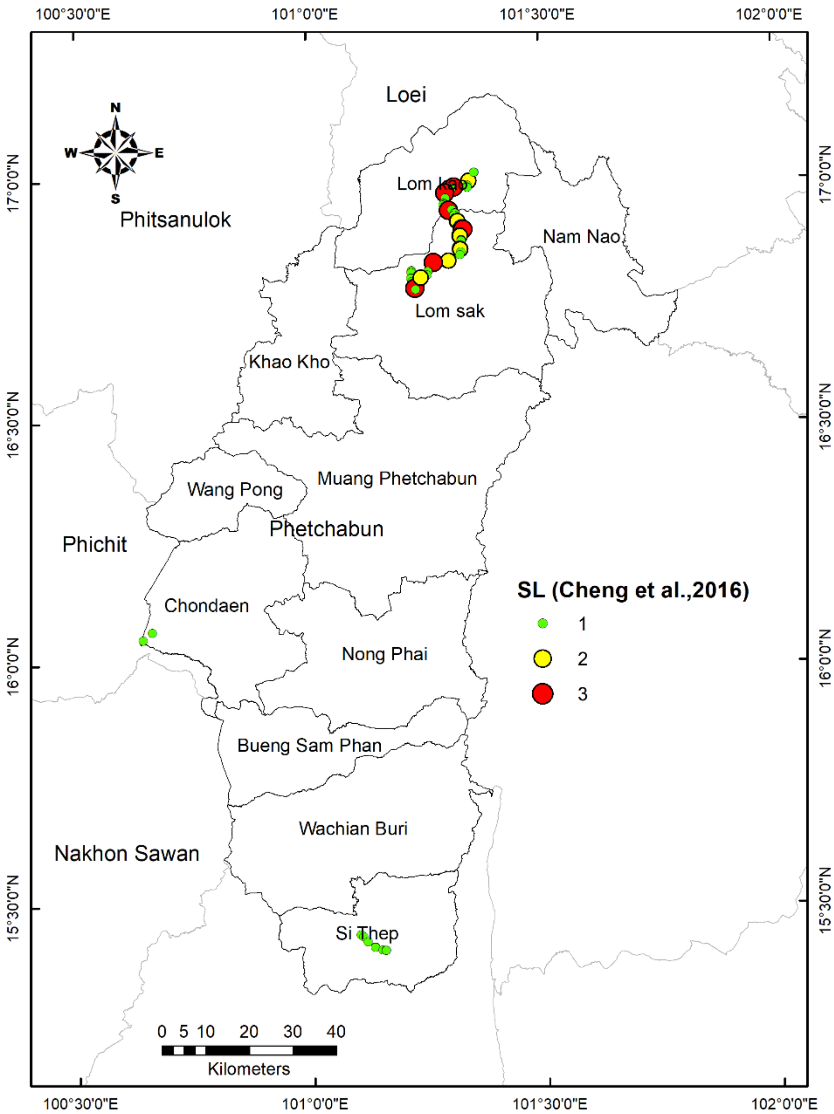


Figure 54. Map of Phetchabun province showing types 1 (Cheng et al., 2016) classification of SL in stream order 5.

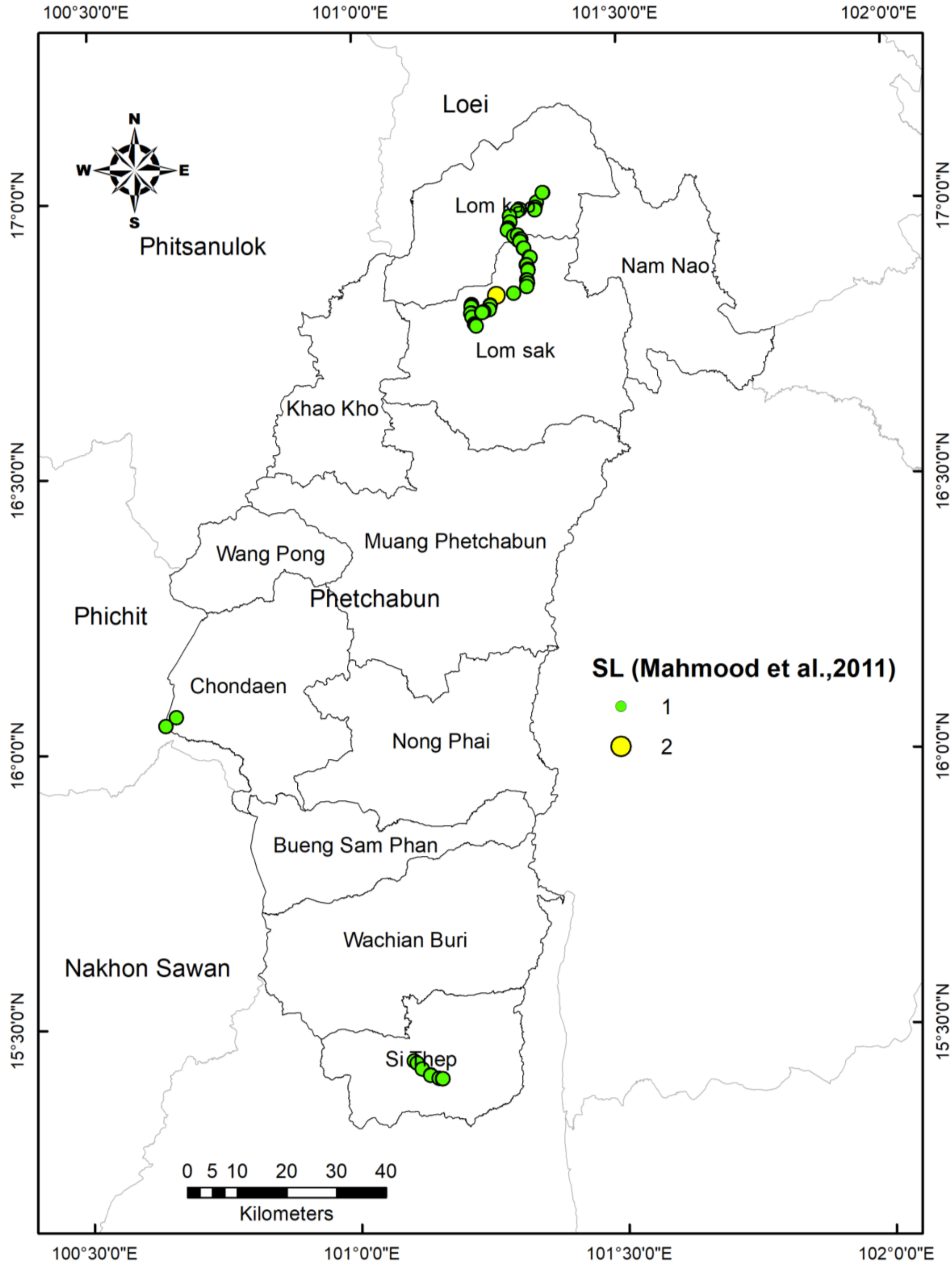


Figure 55. Map of Phetchabun province showing types 2 (Mahmood and Gloaguen, 2012) classification of SL in stream order 5.

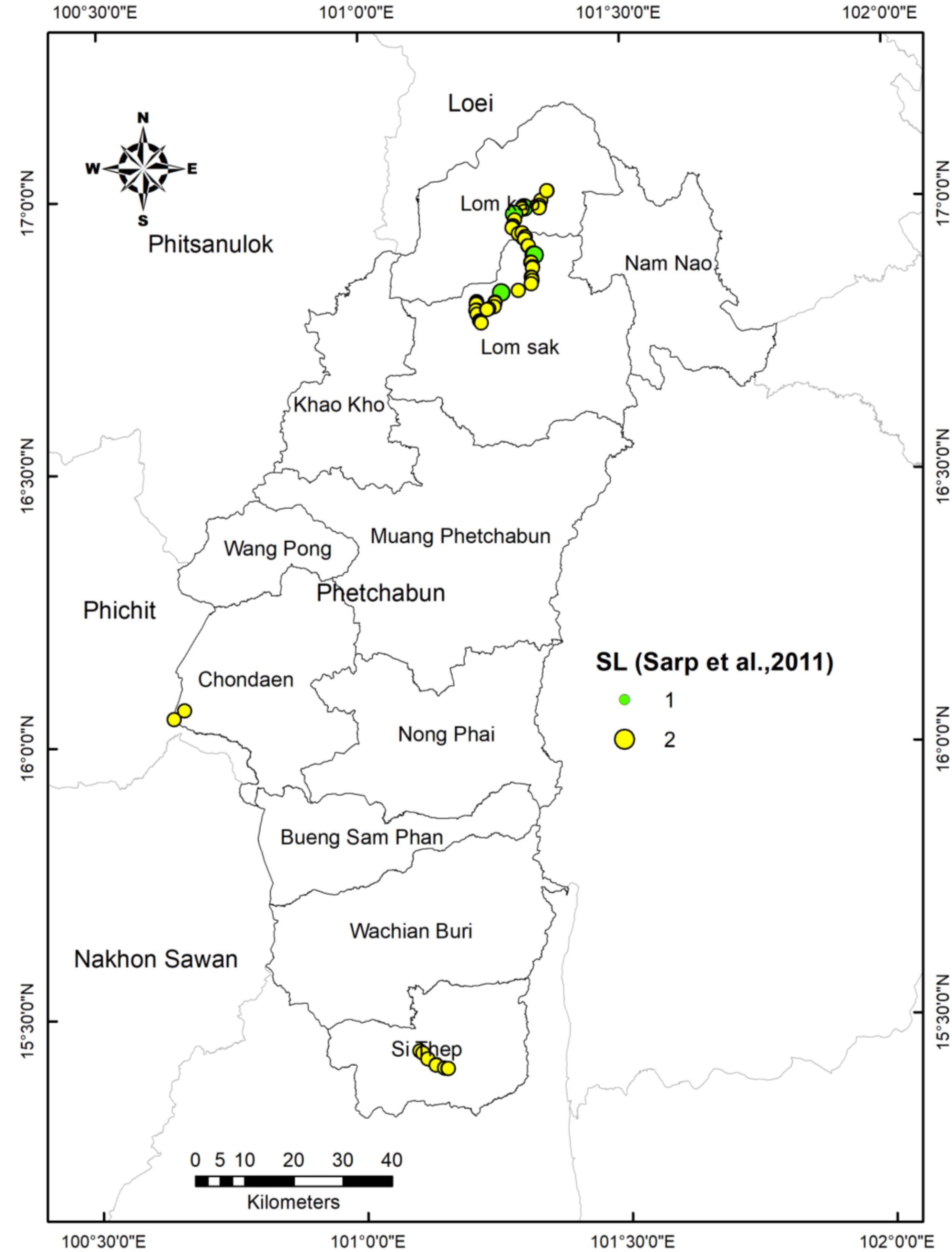


Figure 56. Map of Phetchabun province showing types 3 (Sarp et al., 2011) classification of SL in stream order 5.

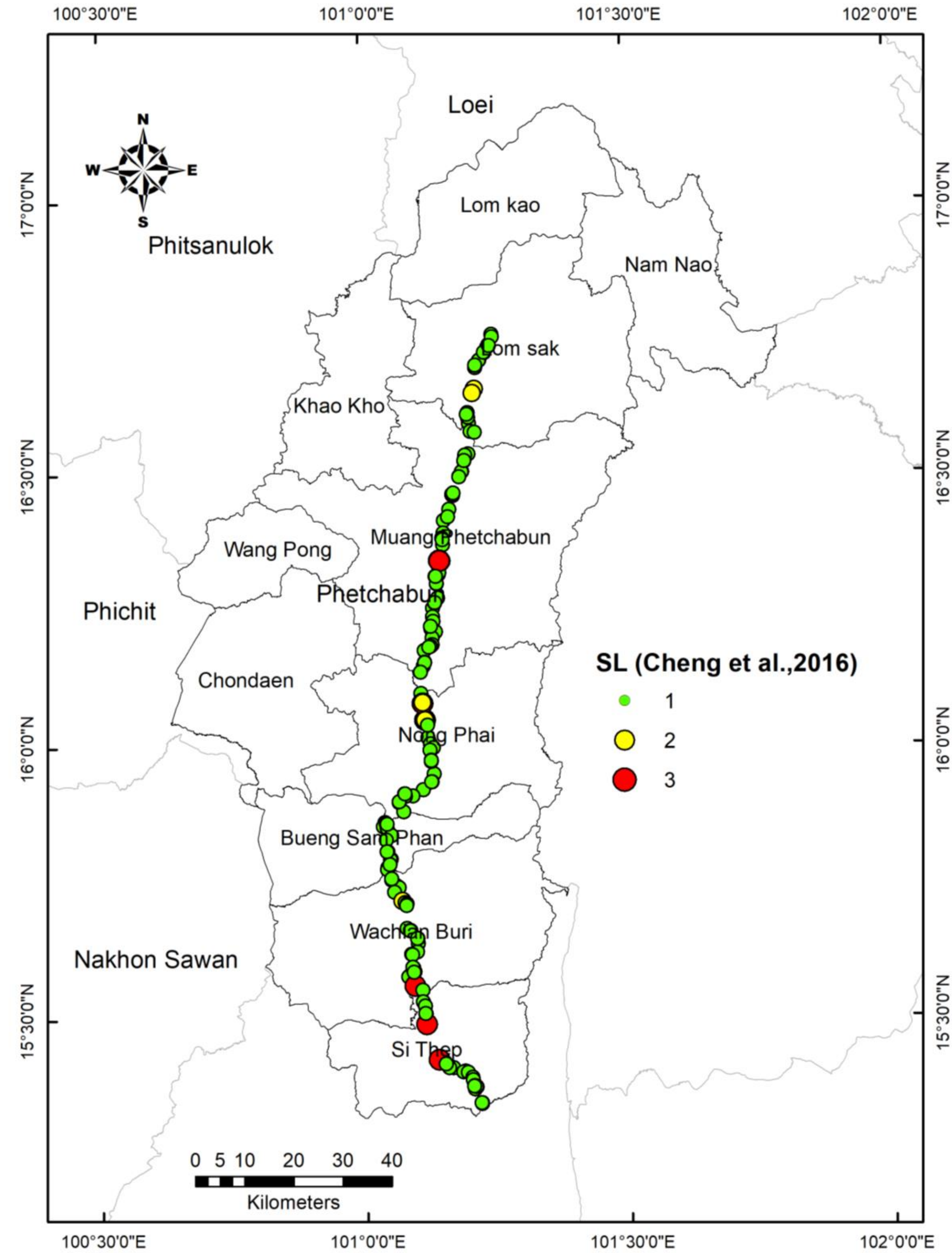


Figure 57. Map of Phetchabun province showing types 1 (Cheng et al., 2016) classification of SL in stream order 6.

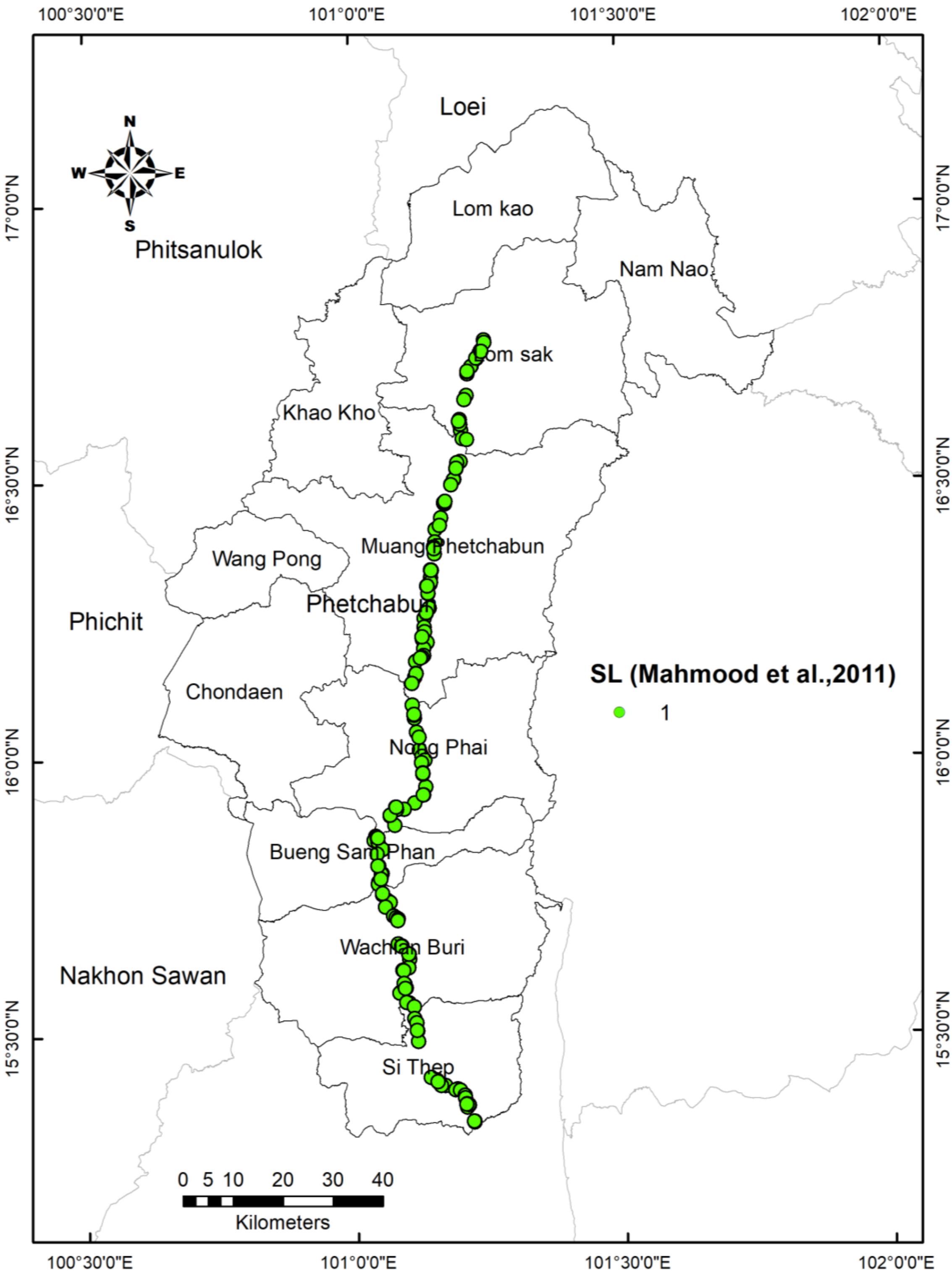


Figure 58. Map of Phetchabun province showing types 2 (Mahmood and Gloaguen, 2012) classification of SL in stream order 6.

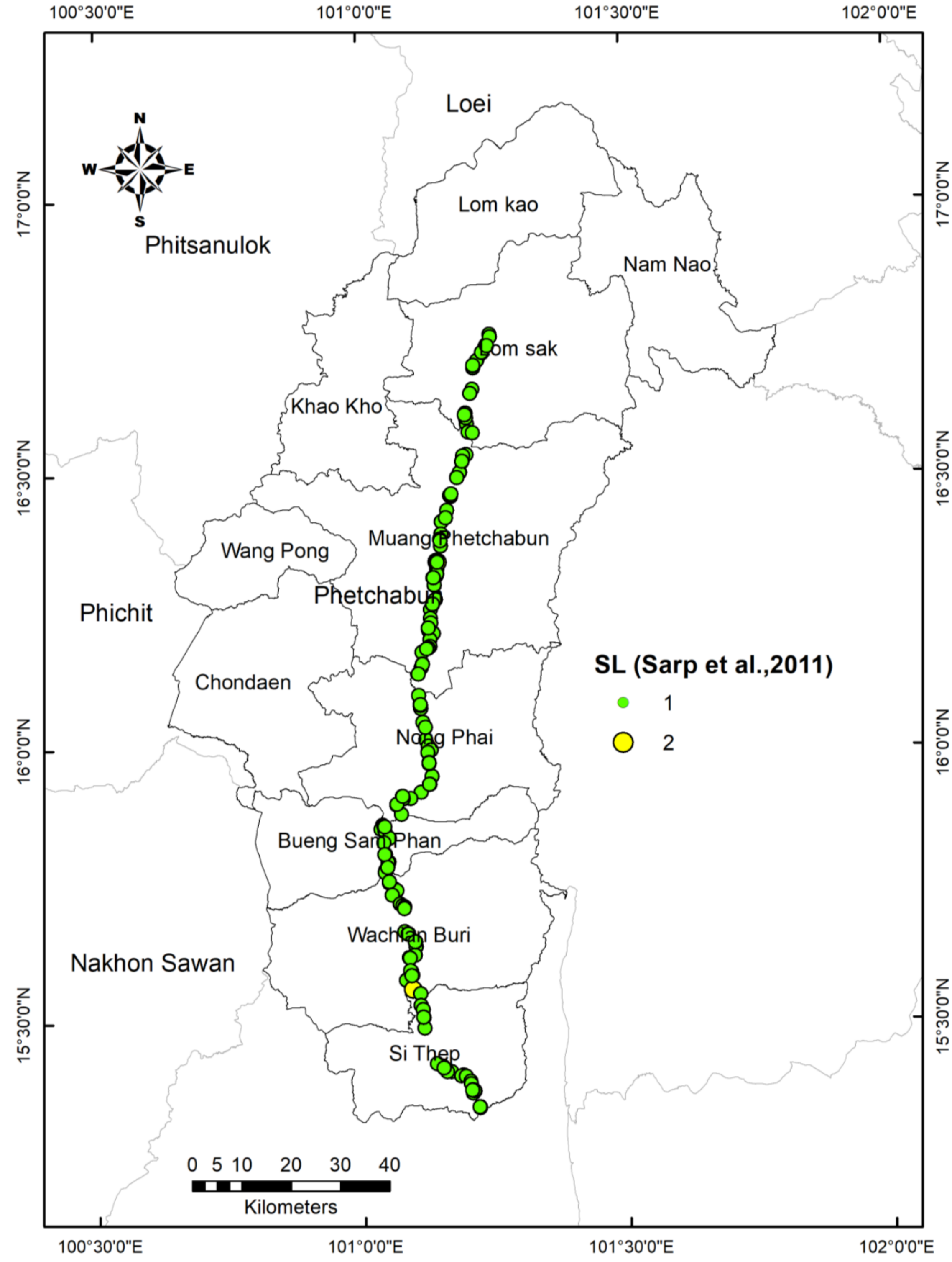


Figure 59. Map of Phetchabun province showing types 3 (Sarp et al., 2011) classification of SL in stream order 6.

2. Mountain front sinuosity (S_{mf})

From S_{mf} in the result, it can be classified into three types: type (Mahmood and Gloaguen, 2012), types 2 (Partabian, Nourbakhsh, and Ameri, 2016) and type 3 (Ntokos, Lykoudi, and Rondoyanni, 2016). The type 1 has three classes: class 1 (1.00-1.09), class 2 (1.10-1.16) and class 3 (>1.16). The type 2 has three classes: class 1 (1.00-1.10), class 2 (1.10-1.50) and class 3 (>1.50). The type 3 has three classes: class 1 (1.00-1.40), class 2 (1.40-3.00) and class 3 (>3.00).

According to the type 1 (Figure 59), all classes imply an active tectonic uplifting, which predominates erosional processes to less or inactive fronts which low erosional processes respectively. The S_{mf} map in this study can be categorized by the type 1 which shows 12 lineaments in class 1, 10 lineaments in class 2 and 185 lineaments in class 3. For this reason, the lineament in Phetchabun province presents less or inactive fronts and low erosional processes.

Then, all classes of the type 2 (Figure 60) indicate an active tectonic uplifting which predominates erosional processes to less or inactive fronts which low erosional processes respectively. The S_{mf} map in this study classified with type 2 shows that 13 lineaments in class 1, 5 lineaments in class 2 and 189 lineaments in class 3. Therefore, it means lineament in Phetchabun province present less or inactive fronts and low erosional processes.

Finally, the type 3 (Figure 61), class 1 to class 3 indicate an active tectonic uplifting which predominates erosional processes to less or inactive fronts which low erosional processes respectively. The S_{mf} map in this study classified with type 3 shows that 70 lineaments in class 1, 121 lineaments in class 2 and 16 lineaments in class 3. For this reason, the lineament in Phetchabun province present active to less fronts and medium to high erosional processes.

Two types of classification (type 1-2) in S_{mf} along the mountain front show less or inactive mountain front and low erosional processes. However, type 3 indicates an active or less mountain front. Then, the type 3 provide difference classification which is medium active mountain front and medium erosion process. So, mountain front in study area indicate low to medium tectonic activities and low to medium erosion process.

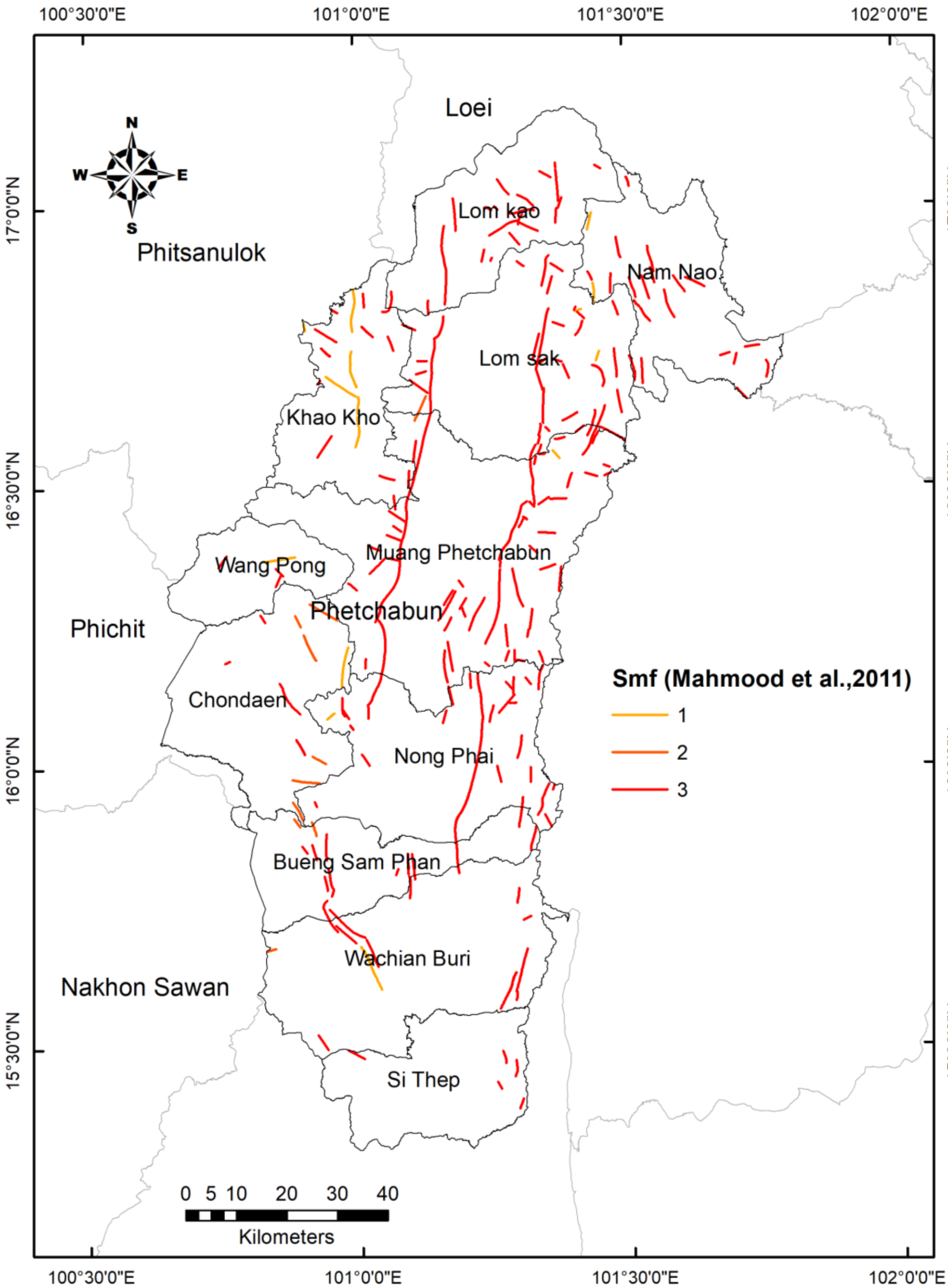


Figure 60. Map of Phetchabun province showing type 1 (Mahmood and Gloaguen, 2012) classification of S_{mf}.

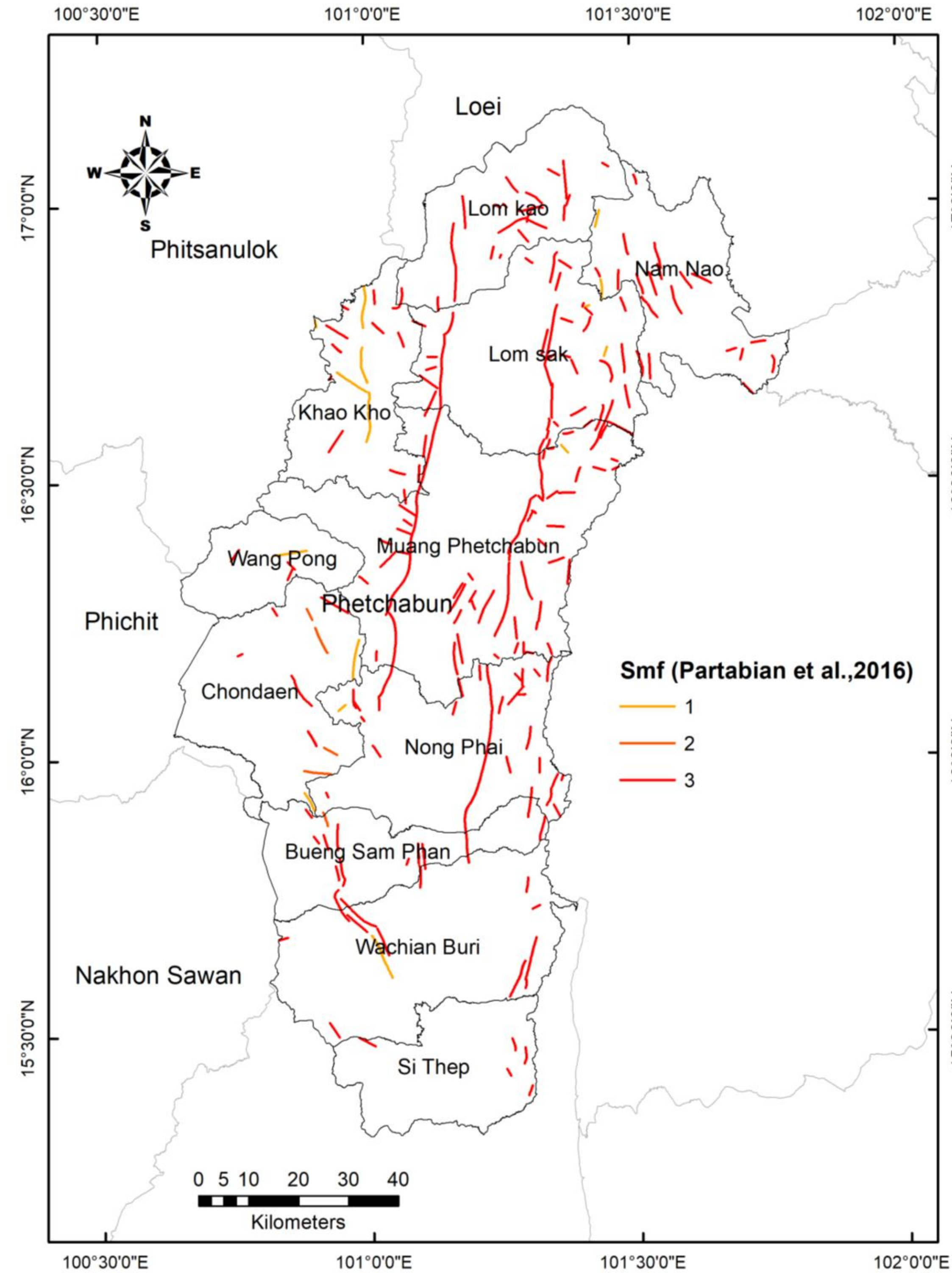


Figure 61. Map of Phetchabun province showing type 2 (Partabian et al., 2016) classification of S_{mf}.

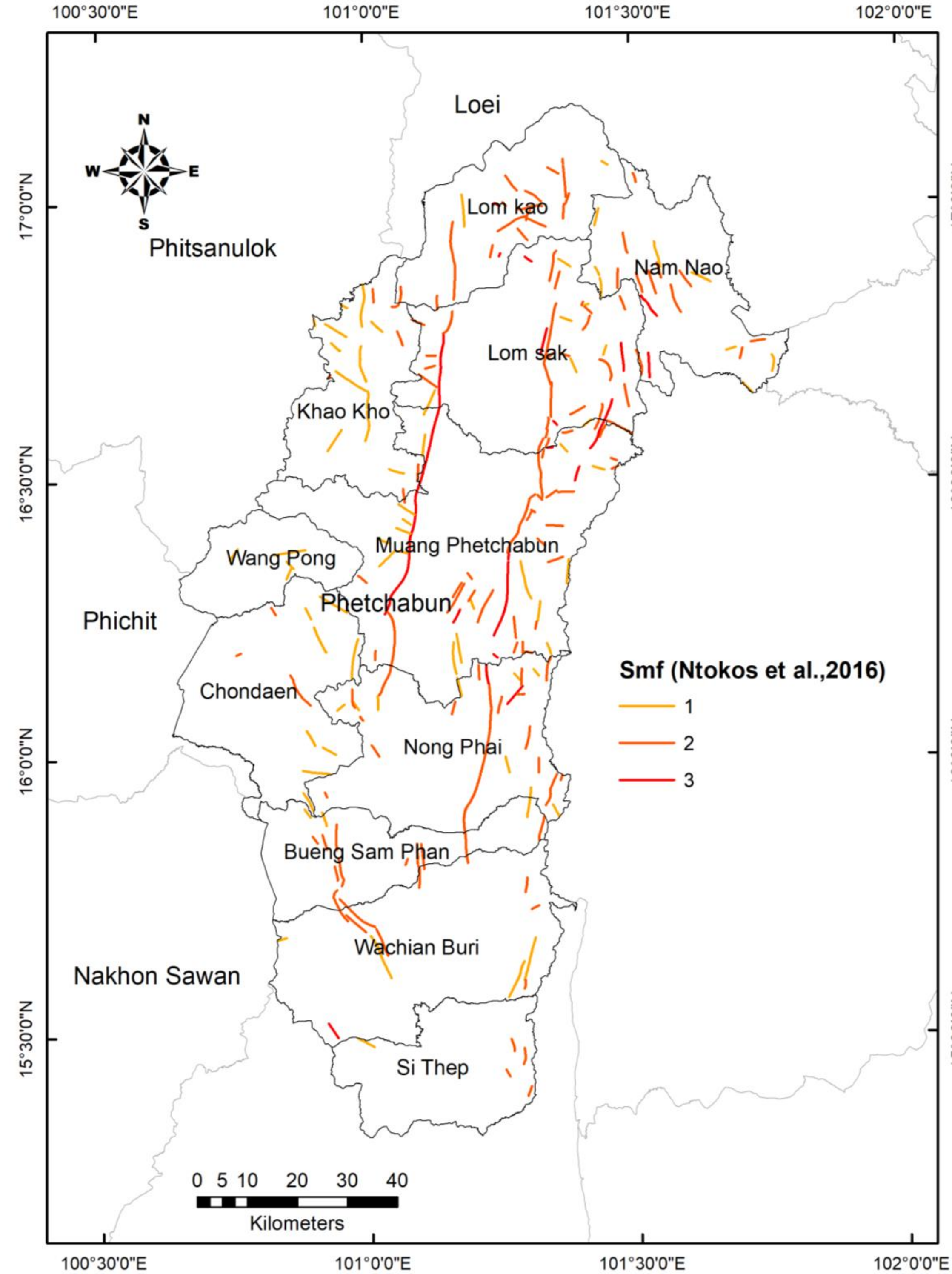


Figure 62. Map of Phetchabun province showing type 3 (Ntokos et al., 2016) classification of S_{mf}.

3. Hypsometric integral (HI)

According to the result of HI ma, it can be divided into three types: type 1 (Mahmood and Gloaguen, 2012), types 2 (Cheng et al., 2016) and type 3 (Nikoonejad et al., 2015). Type 1 has three classes: class 1 (<0.37), class 2 (0.37-0.50) and class 3 (0.51-1.00). Type 2 has five classes: class 1 (<0.3), class 2 (0.3-0.4), class 3 (0.4-0.5), class 4 (0.5-0.6) and class 5 (≥0.6). Type 3 has three classes: class 1 (<0.4), class 2 (0.4-0.5) and class 3 (>0.5).

First, all classes of the type 1 (Figure 62) indicate old age drainage basins that have been more eroded and less impacted by recent active tectonics to young drainage basins that are active tectonic activities and less erosional process respectively. The HI map in this study classified with type 1 show that 35 drainage basins in class 1, where are located most area in Phetchabun province, 1 drainage basins in class 2 where is shown in Nam Nao and Muang Phetchabun districts and 2 drainage basins in class 3 found in Nong Phai district. Therefore, it means most drainage basins with type 1 in Phetchabun province show old age drainage basins, low tectonic activities and low erosional intensity.

Then, class 1 to class 5 of the type 2 (Figure 63) determine old age drainage basins that have been more eroded and less impacted by recent active tectonics to young drainage basins that are active tectonic activities and less erosional process respectively. The HI map in this analyze can be classified by the type 2. It shows that class 1 has 32 drainage basins which are located in most area in Phetchabun province. While, class 2 has 3 drainage basins placed in Lom Sak and Khao Khlo district. Furthermore, there are 1 drainage basin in class 3 found in Nong Phai district, 1 drainage basin in class 4 situated in Muang Phetchabun district, and 1 drainage basin in class 5 discovered in Nam Nao and Lom Sak districts. So that means, the most drainage basins with type 2 in Phetchabun province present old age drainage basins, low tectonic activities and low erosional intensity.

Lastly, the type 3 (Figure 64), class 1 to class 3 indicate old age drainage basins that have been more eroded and less impacted by recent active tectonics to young drainage basins that are active tectonic activities and less erosional process respectively. The HI map in this study classified with type 3 show that 35 drainage basins in class 1 found in most area in Phetchabun province, 1 drainage basin class 2 placed in Nong Phai district and 2 drainage basins in class 3 found in Lom Sak, Nam Nao and Muang Phetchabun districts. So that means most drainage basins with type 3 in Phetchabun province present old age drainage basins, low tectonic activities and erosional intensity.

From three types classification with HI. Most drainage basins in Phetchabun province indicate area that are less impacted by active tectonic, old age drainage basin and low erosional processes.

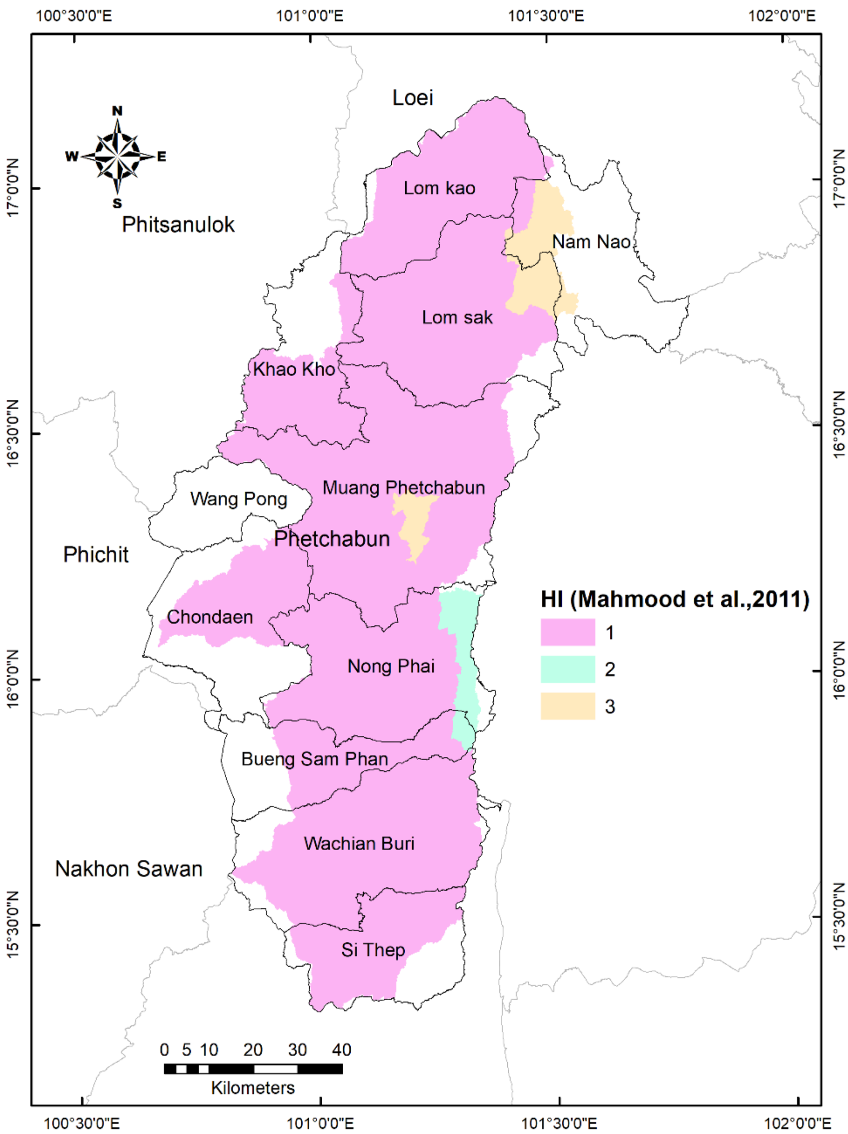


Figure 63. Map of Phetchabun province showing type 1 (Mahmood and Gloaguen, 2012) classification of HI.

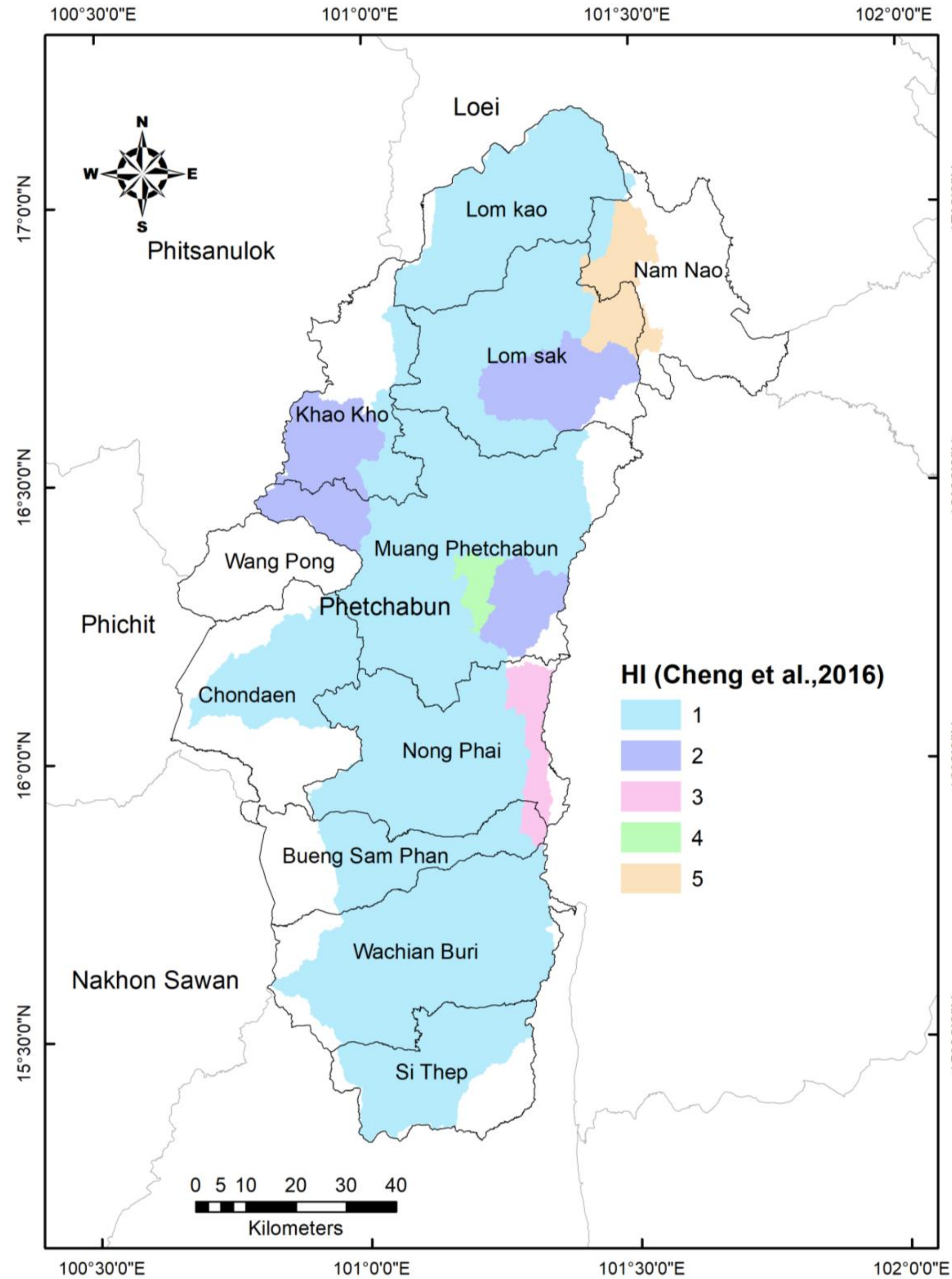


Figure 64. Map of Phetchabun province showing type 2 (Cheng et al., 2016) classification of HI.

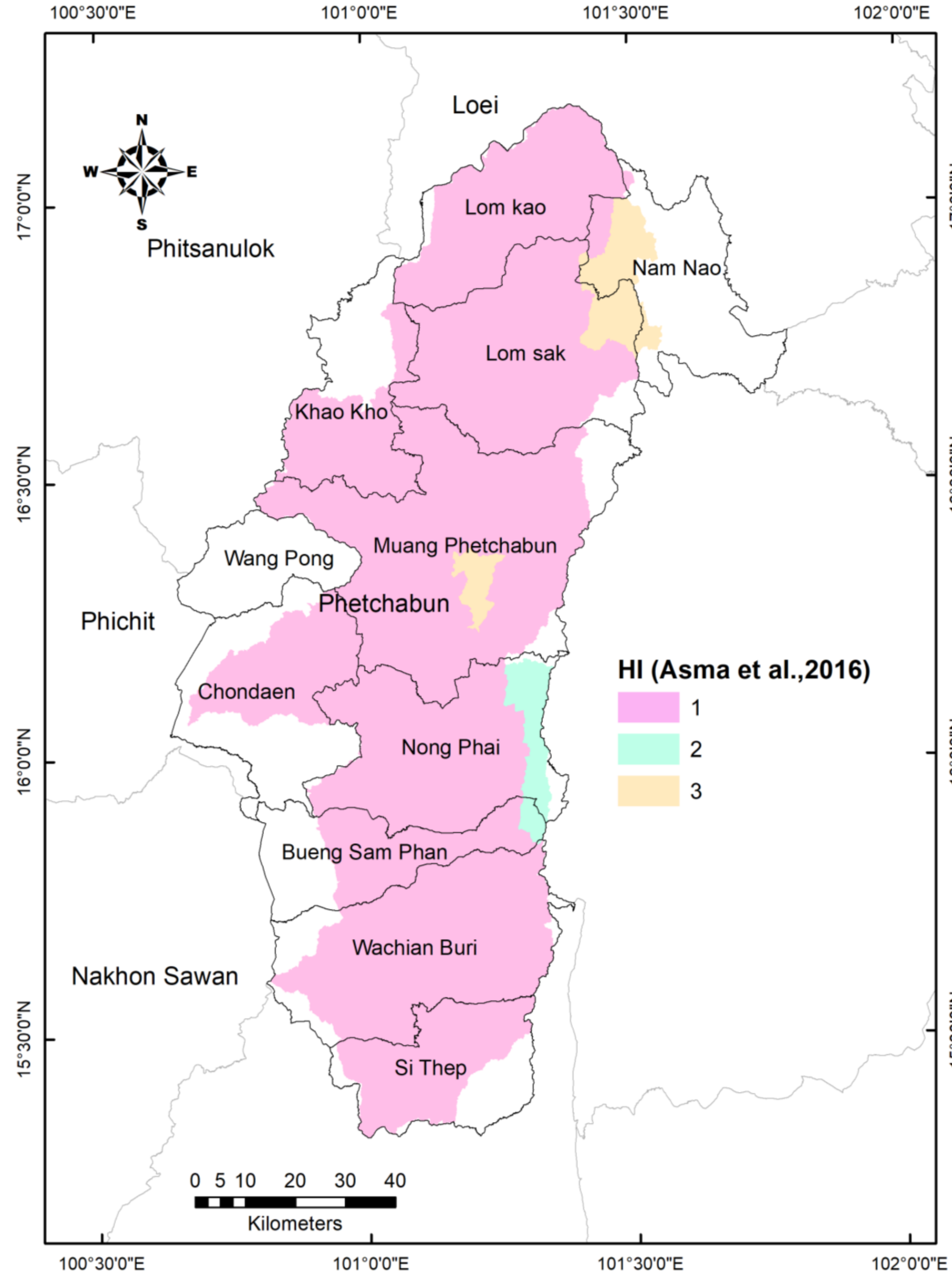


Figure 65. Map of Phetchabun province showing type 3 (Nikoonejad et al., 2015) classification of HI.

4. Hypsometric curve (HC)

HC map in the result, it can be classified into three classes: class 1 concave HC, class 2 concave-convex HC and class 3 convex. HC Phetchabun province show 31 drainage basins in class 1 that indicate old age and less or inactive tectonic activities, 6 drainage basins in class 2 which represent mature age and still develop to landscape and class 3 has 1 drainage basin which show the youngest drainage basin and active tectonics (Figure 65). Therefore, drainage basins in Phetchabun province in HC present that most drainage basins are old age and less or inactive tectonics.

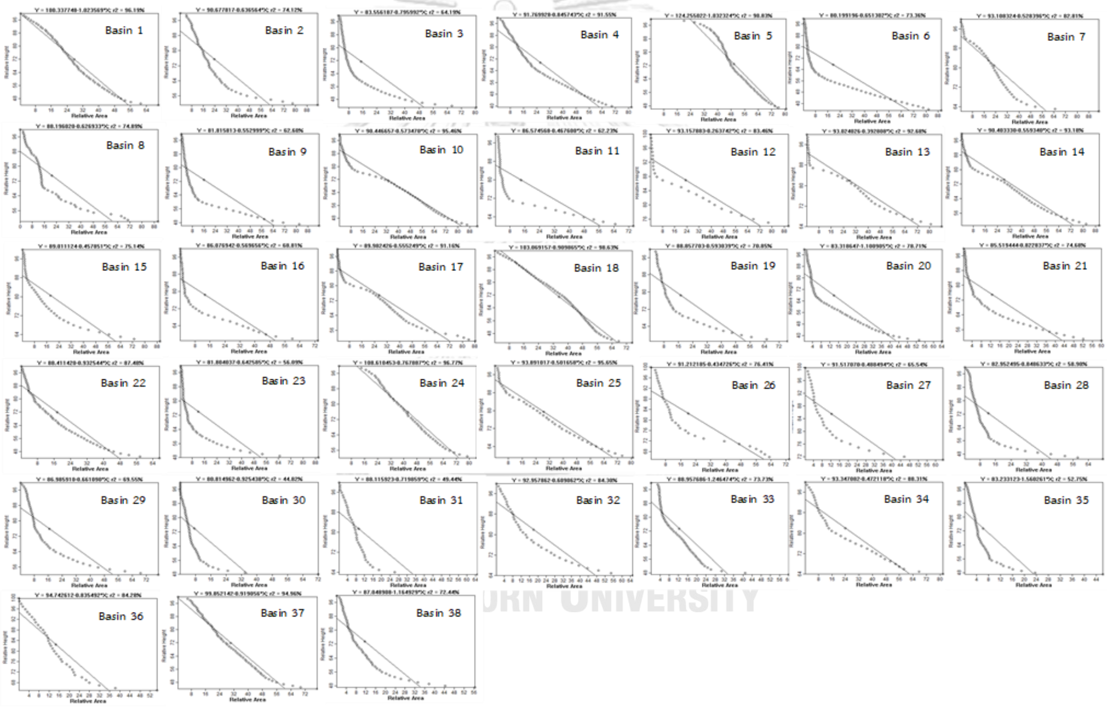


Figure 66. Graph of drainage basins in Phetchabun province showing HC obtain in this study.

5. Basin shape index (Thaipbs)

According to the result from B_s map, the B_s value is closer to 1 that present more circular basin shape and low tectonic activity. In contrast, high value show elongation basin shape and high tectonic activity. it can be classified into three types: type 1 (Mahmood et.al, 2011), types 2 (Cheng et.al., 2016) and type 3 (Partabian et.al.,2016). Type 1 has three classes: class 1 (1.11-1.20), class 2 (1.21-1.76) and class 3 (1.77-3.22). Type 2 has five classes: class 1 (<0.20), class 2 (0.20-0.40), class 3 (0.40-0.80), class 4 (0.80-1.20) and class 5 (≥1.20). Type 3 has three classes: class 1 (<3.00), class 2 (3.00-4.00) and class 3 (≥4.00).

All classes of the type 1 (Figure 66) indicate circular drainage basin with low tectonic activities to elongated drainage basin with high tectonic activities respectively. The B_s map in this study classified with type 1 show that 12 drainage basins in class 1 located in northern of Lom Sak, southern of Muang Phetchabun, Nong Phai, Bung Samphan and Si Thep districts, 12 drainage basins in class 2 placed in Lom Kao, Lom Sak, Khao Kho, Chondaen, Wichian Buri districts and 14 drainage basins in class 3 situated in northern of Muang Phetchabun, northern of Wichian Buri. Therefore, drainage basins with type 1 in Phetchabun province show elongated shape drainage basin and high tectonic activities more than circular drainage basin with low tectonic activities.

The type 2 (Figure 67), class 1 to 5 indicate circular drainage basin with low tectonic activities to elongated drainage basin with high tectonic activities respectively. The B_s map can be classified by type 2. There is no drainage basin in class 1. There are 1 drainage basin in class 2 located in eastern of Wichian Buri, 2 drainage basins in class 3 found in Muang Phetchabun, Si Thep districts, 9 drainage basins in class 4 situated Lom Sak, Muang Phetchabun, Nong Phai, Bung Samphan, Si Thep districts and 26 drainage basins in class 5 discovered most area in Phetchabun province . Thus, most drainage basins that type 2 classified in Phetchabun province present elongated shape drainage basin and high tectonic activities.

Finally, the type 3 (Figure 68), class 1 to 3 indicate circular drainage basin with low tectonic activities to elongated drainage basin with high tectonic activities respectively. B_s map in this study classified with type 2 show that 36 drainage basins in class 1 located in most area in Phetchabun province, 1 drainage basin in class 2 found in Lom Sak district and 1 drainage basin in class 3 situated in Wichian Buri district. Therefore, most drainage basins with type 3 in Phetchabun province show circular drainage basin and low tectonic more than elongated shape drainage basin with high tectonic activities.

From two types classification (type 1-2) with B_s. Most drainage basins in Phetchabun province indicate elongated shape drainage basins that are highly active tectonic. Then the type 3 shows difference classification which has been supported circular shape drainage basins and low tectonic activities therefore drainage basins calculated by B_s show low to high tectonic activities.

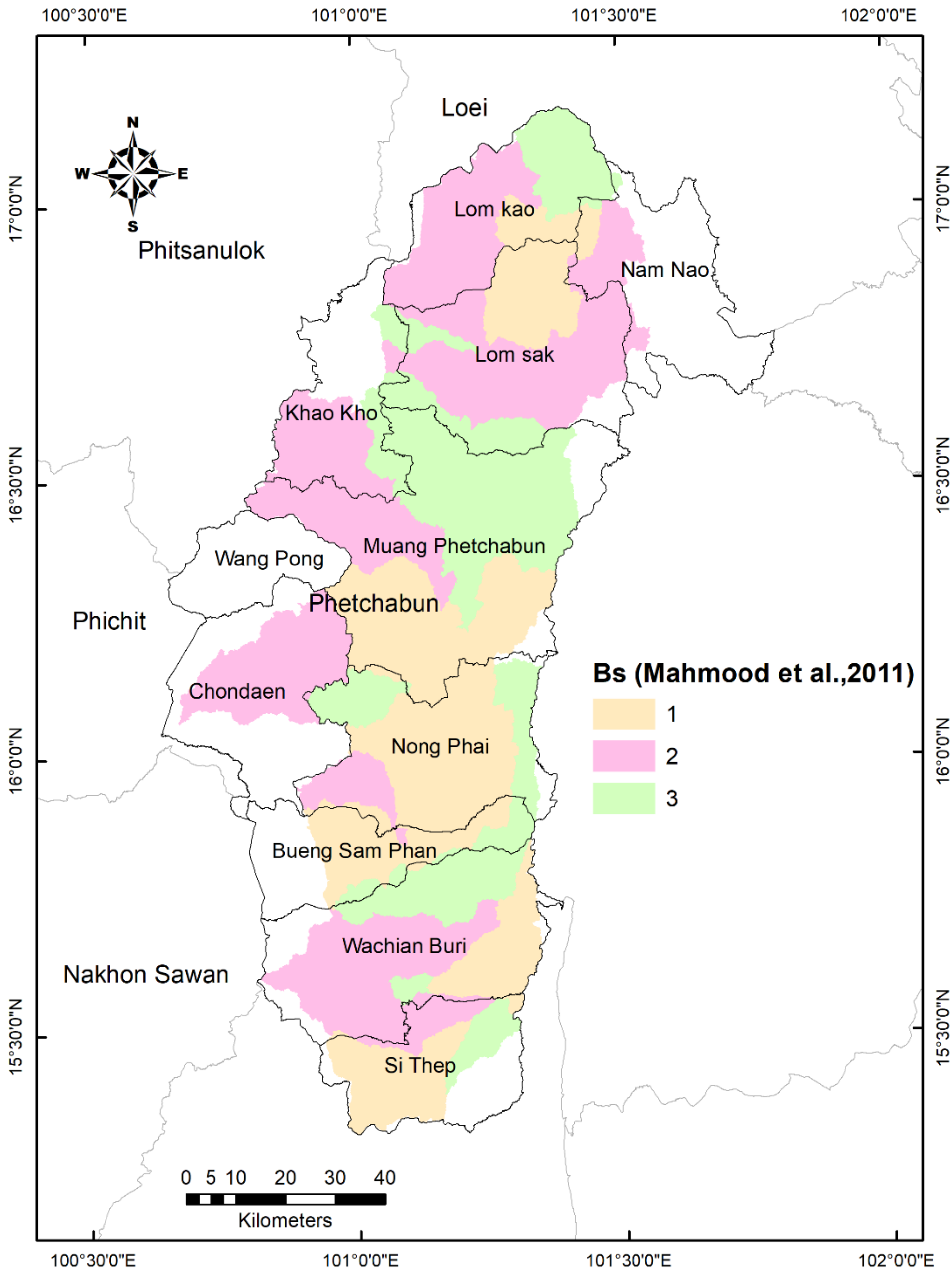


Figure 67. Map of Phetchabun province showing type 1 (Mahmood and Gloaguen, 2012) classification of B_s.

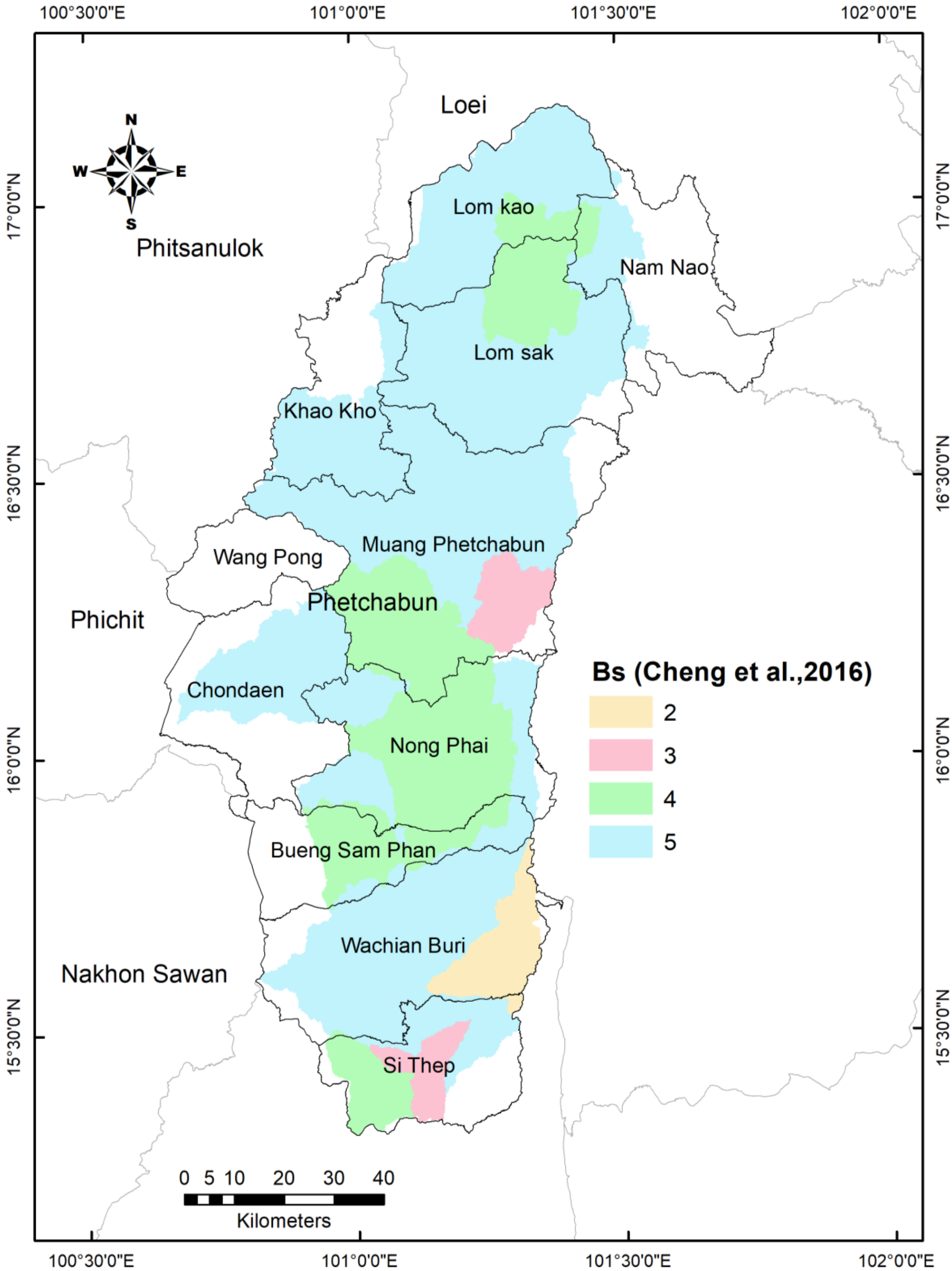


Figure 68. Map of Phetchabun province showing type 2 (Cheng et al., 2016) classification of B_S.

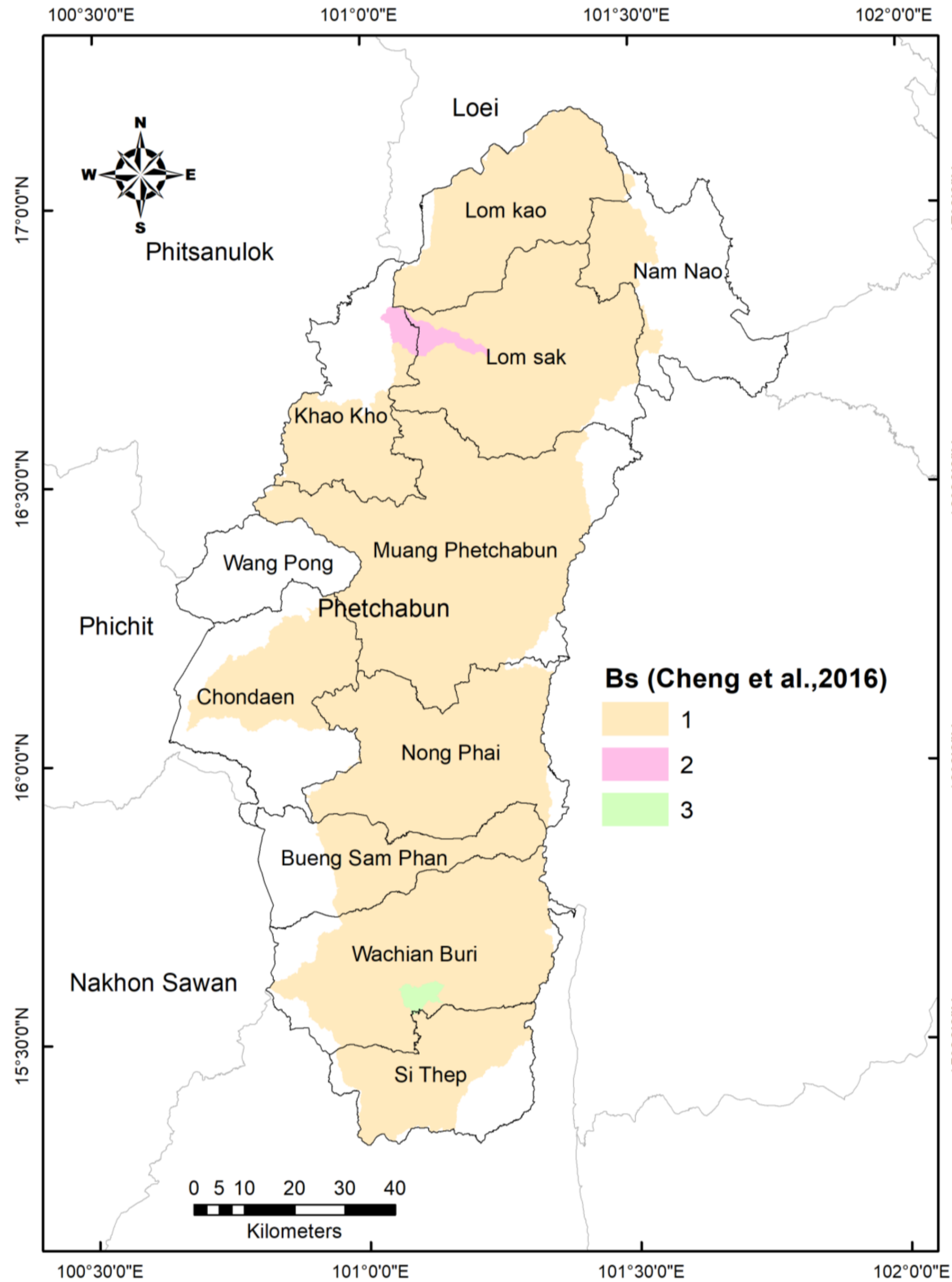


Figure 69. Map of Phetchabun province showing type 3 (Partabian et al., 2016) classification of B_s

In conclusion of comparatively geomorphic index to evaluation tectonic activity in study area show all comparatively classification of geomorphic index by class 1 indicates low tectonic activity and class 5 means high tectonic activity (Table 6.).

Table 7. Classification of each geomorphic index.

Classification types	Class Geomorphic index				
	SL	S_{mf}	HI	HC	B_s
Sarp et al., 2011	1	-	-	-	-
Mahmood and Gloaguen, 2012	1	3	1	-	3
Nikoonejad et al., 2015	-		1	-	
Cheng et al.,2016	1		1	-	5
Partabian, Nourbakhsh, and Ameri, 2016	-	2	-	-	1
Ntokos, Lykoudi, and Rondoyanni, 2016	-	2	-	-	-
Tectonic activities	Low	Low to Medium	Low	Low	Low to High

Geomorphic index and geological setting

Hack (1973) and (Harkins et al., 2014); Harkins, Anastasio, and Pazzaglia (2005) suggested that lithological differences influence SL. According to this study, it has 8 periods following the geological time scale. There are Quaternary, Tertiary, Cretaceous to Jurassic, Jurassic, Triassic, Permian, Permo-Triassic and Carboniferous. Most SL points are shown in Quaternary (5,013 points) (Figure 69c) In addition, there are 13 rock units in the eight following periods, in order from the oldest to the youngest periods.

1. Carboniferous

The Carboniferous (C) mainly contains sedimentary rocks that are conglomerates, sandstones, slaty shales, grey shales and gray cherts.

2. Permian - Triassic

In the Triassic (TR_{np}), there are Triassic reddish-brown sandstones with calcrete layers at top of cycle and interbedded with reddish brown calcareous siltstones and calcareous mudstones. The Triassic (TR_{hl}) consists of brownish-red siltstones, sandstones, conglomeratic sandstones and basal conglomerates. Granites and granodiorites are found in the Triassic (TRgr). In addition, there are fossiliferous limestones, cherts, pillow basalts and serpentinites (Ps), tuffs, rhyolitic tuffs and andesite tuffs in the Permo-Triassic (pTR_v).

3. Cretaceous - Jurassic

There are siltstones interbedded sandstones and intercalated conglomerates in the Cretaceous (K_{kk}). Moreover, there are white and pink sandstones, conglomerates and pebble sandstones, gray siltstones and claystone in the Cretaceous to Jurassic (JK_{pw}). The Jurassic (J_{pk}) consists of reddish-brown siltstones and claystone.

4. Tertiary

The Tertiary period found semi-consolidated claystone; red siltstones, ignites and mudstones in the Tertiary (T) and dark gray to black basalts in the Tertiary (Thaipbs).

5. Quaternary

The Quaternary period can be separated into two units that are alluvial deposit in the Quaternary (Q_a) and terrace deposit in the Quaternary (Q_t).

Moreover, most SL points in the study area are found on Qt (2,620 points), Q_a (1,513 points), Ps (1,125 points), pTR_v (839 points), TR_{hl} (815 points), bs (659 points), JK_{pw} (514 points), J_{pk} (258 points), TR_{np} (213 points), K_{kk} (87 points), TR_{gr} (76 points), C (35 points) and T (1 points). Thus, the rock unit that shows the most SL point is Qt that is gravel sand and clay (Figure 69a).

As reported by Pedrera et al. (2009), the SL is sensitive to active folds where the hard rocks are outside. However, it is insensitive in the sedimentary rocks because of erosional processes on easily erodible sediment. Sedimentary-metamorphic rocks and igneous rocks cover most area in this study. Therefore, most SL points are found on the sedimentary-metamorphic rocks (7,315 points) and igneous rocks (1,574 points) respectively (Figure 69b).

This study has three types of lineament as follows; i) NNE-SSW and NNW-SSE fault which is normal fault with long length called Phetchabun fault, ii) NE-SW which is strike slip fault or oblique slip fault and iii) NW-SE fault and E-W fault that are small fault.

The S_{mf} value obtained from the mountain front. The HI value, HC and B_s gained from drainage basin in this study. They seem to be related to the occurrence of tectonic activities and represent erosional processes. The S_{mf} value and HC showed the low tectonic activities because sediment erosion is important for the length of mountain front, relative area and relative altitude to calculation of S_{mf} and HC respectively.

In general, the erosional process simply occurred on the sedimentary rocks more than metamorphic or igneous rocks both performed by water and by wind. However, it depend on many factor in study area such as rock types, rock strength etc. The erosional processes and low tectonic activities in the result has supported the high S_{mf} values and concave HC from mountain front and HC from drainage basin. In addition, sedimentary rocks as mentioned above have covered most areas of Phetchabun. However, the B_s show high tectonic activities and elongated drainage basin shape. It will be affected by lineament as mentioned and folds a large syncline with north-south axis in the Triassic sedimentary rocks.

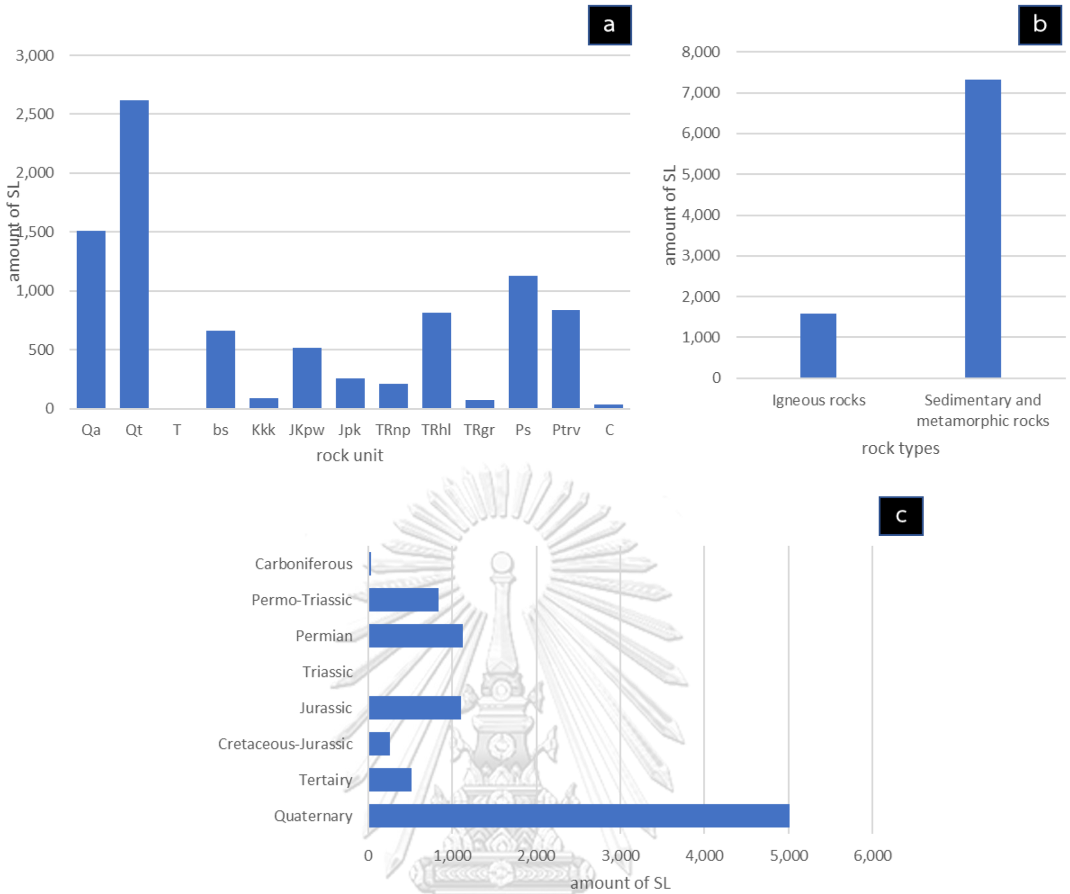


Figure 70. graph of SL showing (a) amount of SL points and rock unit, (b) amount of SL point and rock types and (c) amount of SL point and period of geological time scale obtain from this study.

Landslide susceptibility map

1. **Landslide susceptibility map and landslide hazard map.**

The landslide susceptibility map (Figure 70a) in this study can be grouped into five classes including very low, low medium, high and very high. In the central and southern Phetchabun province, which is plain, represented very low to low classes. While, the eastern and western, which is mountain range, presented high to very high classes.

The Landslide hazard map (Figure 70b) obtained from the department of mineral resources (2010) can be grouped into three classes containing low, medium and high. In the central and southern of Phetchabun province, it indicates none risks occurring landslide. However, the eastern and western has been shown medium to high risk to occur landslide.

From two maps as mentioned above, they show that none risk class of landslide hazard map has very low and low classes of landslide susceptibility map. They are located in central of and southern of Phetchabun province including central of Lom Sak, central of Muang Phetchabun, Nong Phai, Wichian Buri, Si Thep, Chon Daen and Wong Pong districts. A low risk class of landslide hazard map has medium to high classes of landslide hazard map. These consist of Nam Nao, eastern of Lom Sak, western of Muang Phetchabun and western of Khao Kho districts.

In addition, Medium risk class of landslide hazard map has medium to very high class of landslide susceptibility map which contain eastern of Lom Kao, eastern of Lom Sak, central of Khao Kho, eastern of Muang Phetchabun and high risk class of landslide hazard map has high to very high classes of landslide susceptibility map. There are in northern Lom Kao, western of Lom Sak, western of Muang Phetchabun, eastern of Nong Phai, eastern of Bung Samphan district especially, mountain range. From the above there is a discrepancy which may be caused by calculations using different parameters. However, the statistic index is a method to indicate landslide susceptibility area with high accuracy.

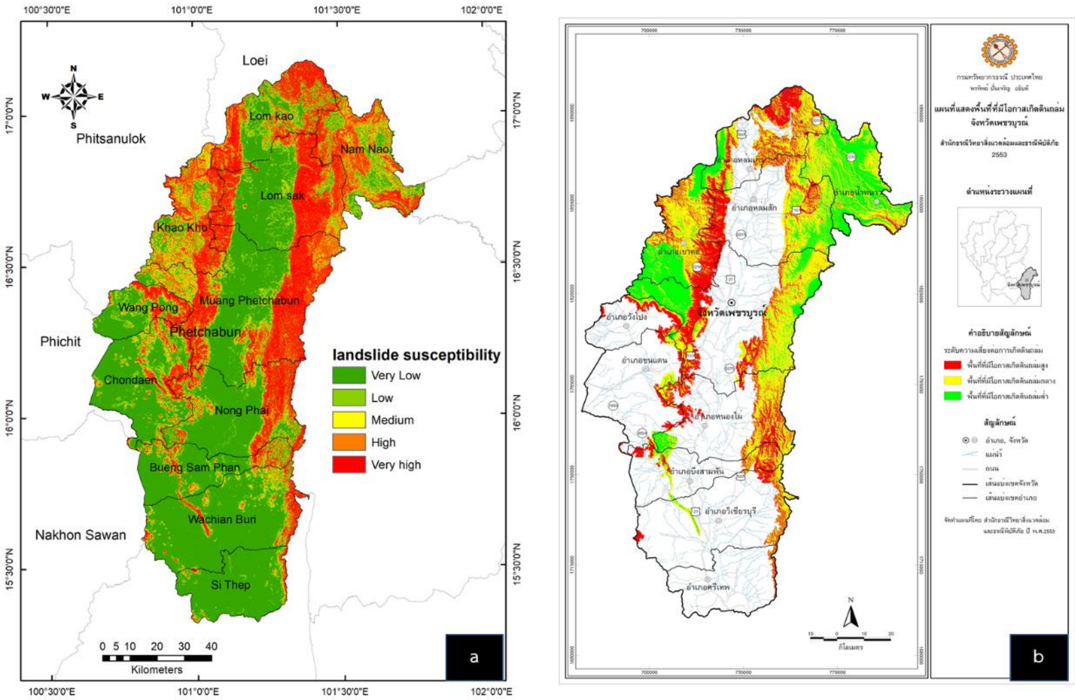


Figure 71. Map of Phetchabun province showing (a) landslide susceptibility map obtained from this study (dark green means very low and red means very high), (b) landslide hazard map obtained from DMR (2010) (green means low risk and red means high risk).

Flood susceptibility map

1. Comparison of flood susceptibility map and historical flood

From the result, we compare the flood susceptibility map (Figure 71a) and historical flood map from Geo-Informatics and Space Technology Development Agency (GISTDA) in 2013 (Figure 71b), 2014 (Figure 71c) and 2016 (Figure 71d). The comparison found that areas of flood susceptibility map similar to historical flood maps in 3 periods. However, some areas show over susceptibility, caused error calculation or they will be found flooding in the future.

The flood susceptibility map (Figure 71a) in this study shows four classes low to medium in the central Phetchabun and high to very high in southern Phetchabun. Consequently, the total area occurring flood hazard is central and southern Phetchabun.

To check the level for accuracy, next is the comparison of landslide susceptibility map that all classes intersect with historical flood maps. The analyze use the records of 2013, 2014 and 2016 flood areas intersect in the central and southern Phetchabun. If the areas do not intersect, it will show an error calculation of ArcGIS software or SAGA software. However, most areas are overlaid. Therefore, that means the HCI method is high accuracy.

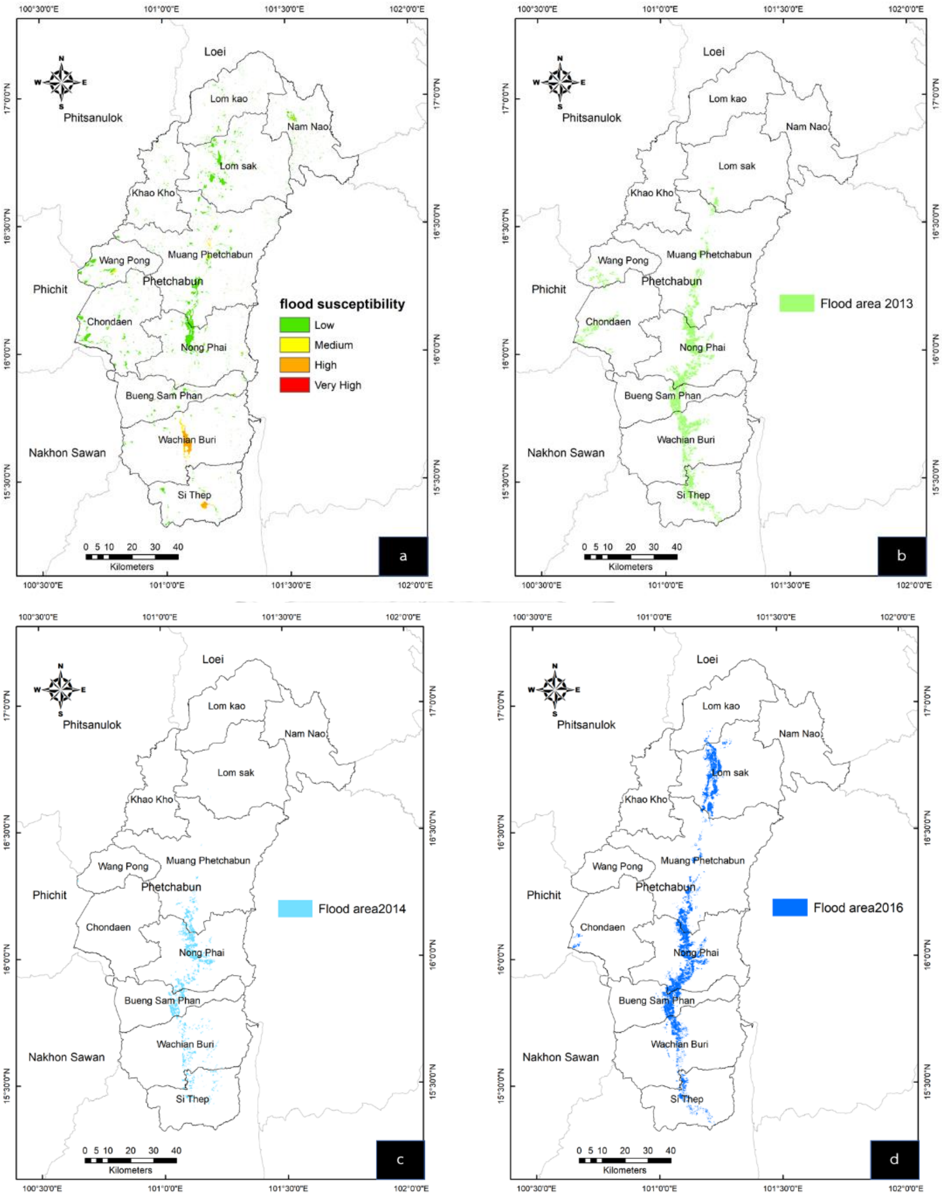


Figure 72. Map of Phetchabun province showing (a) flood susceptibility map obtained from this study, (b) flood area in 2013, (c) flood in 2014 and flood area in 2016 obtain from Geo-Informatics and Space Technology Development Agency (GISTDA).

2. **Characteristics of flood hazard in Phetchabun province.**

There are 3 types of flood hazard characteristics containing flash flood, river flood and drainage flood. A flash flood often occurs on flat or plain near upstream mountains because of heavy rains over mountains for a long time. The amount of water accumulated heavily. A ground and trees cannot absorb fast enough that causes a water flow to flat or plain area and become a flash flood. A river flood occurs from large amount of water due to continuous heavy rain that flows into the stream until it does not drain or reach to the top of drainage basins. Roads and bridges can be damaged and transport routes are cut off. A drainage flood occurs from the large amount of accumulated water that flows horizontally from high to low elevation. Most areas in Phetchabun are plain near upstream mountain. Therefore, most flood susceptible areas in Phetchabun are plain or flat. If the study area occurs flood hazard, it can be a flash flood or a drainage flood (Figure 73).

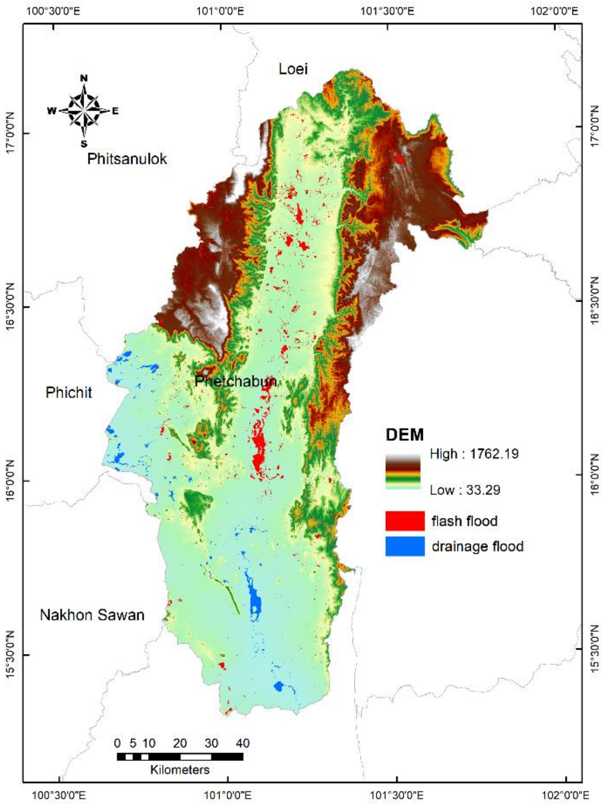


Figure 73. Map of Phetchabun province showing DEM overlay with flood susceptible area (blue circle means flood susceptible area may occur a flash flood and red circle means flood susceptible area may occur drainage flood).

CHAPTER VII
CONCLUSION

The geomorphic indices are effective tools for evaluating the influence of tectonic activities. These indices can be used as surveying instruments to detect the geomorphic anomalies related to tectonic activity. The method is valuable to Phetchabun province which is available for active tectonics based on absolute dating. We evaluated the relative active tectonics using DEM data with 30 resolution.

This study acquired the drainage network and five geomorphic indices which are SL, S_{mf}, HI, HC, and B_s. The statistic index (Si) method used to calculate value of six parameters: slope gradient, aspect, profile curvature, plan curvature, TWI, and SPI. These values called a landslide susceptibility value that can be categorized into five classes with respect to degree of susceptibility. Additionally, the flood susceptibility map evaluated hydromorphometric contrast index (HCI) containing five parameters: CD, VD, D8, MCA, and TWI. These values called a flood susceptibility value that can be classified into four classes.

The values of SL percentage have been found to be anomalies along the stream that was related to the influence of tectonic activity. The values of S_{mf} proposed that the majority of the mountain fronts are tectonically low to medium active. The values of HI and HC for drainage basin determine high tectonic activity and young stage. Moreover, most drainage basins show the high value of B_s that indicate elongated shape drainage basin that represents tectonically active.

The high and very high classes (class 4 and class 5) of landslide susceptibility has been found in a mountain range NE-SW direction where is located in the eastern and southern Phetchabun province, while the central and southern of Phetchabun province have low and very low classes of class 1 to class 2 respectively.

The flood susceptibility has been presented the low class of class 1 in the central, northern and western of Phetchabun which can cause flash floods. While, the high class of class 4 has been found in the southern of Phetchabun which can lead to drainage floods.

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