GEOSPATIAL MODEL FOR LOCATING POTENTIAL MICRO HYDROPOWER SITES IN UNGAUGED CATCHMENTS

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A Thesis Submitted in Partial Fulfillment of the Requirements for the

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แบบจำลองเชิงพื้นที่สำหรับการกำหนดตำแหน่งศักยภาพโรงไฟฟ้าพลังน้ำขนาดเล็กในพื้นที่รับน้ำที่ไม่มีสถานีตรวจวัด

นายวิภพ แพงวังทอง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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GEOSPATIAL MODEL FOR LOCATING POTENTIAL MICRO HYDROPOWER SITES IN UNGAUGED CATCHMENTS

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วิภพ แพงวังทอง : แบบจำลองเชิงพื้นที่สำหรับการกำหนดตำแหน่งศักยภาพโรงไฟฟ้าพลังน้ำขนาดเล็กในพื้นที่รับน้ำที่ไม่มีสถานีตรวจวัด (GEOSPATIAL MODEL FOR LOCATING POTENTIAL MICRO HYDROPOWER SITES IN UNGAUGED CATCHMENTS) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.สัญญา สราภิรมย์, 155 หน้า.

การขาดแคลนพลังงานมีแนวโน้มกลายเป็นวิกฤตทั้งในท้องถิ่นและภูมิภาค พื้นที่ลุ่มน้ำเข็กในเขตจังหวัดพิษณุโลกและเพชรบูรณ์เป็นพื้นที่ลุ่มน้ำที่มีลักษณะเหมือนกับลุ่มน้ำอื่นของประเทศที่มีลุ่มน้ำย่อยที่มีศักยภาพด้านอุทกวิทยาและมีการจัดเก็บข้อมูลอุทกวิทยาน้อยหรือแทบจะไม่มีข้อมูลสถานีตรวจวัดสำหรับใช้ในการค้นหาตำแหน่งศักยภาพเลยโดยเฉพาะอย่างยิ่งสำหรับการพัฒนาโรงไฟฟ้าพลังน้ำขนาดเล็ก มิใช่เพียงพลังงานทดแทนที่จะถูกพัฒนาจากโรงไฟฟ้าพลังน้ำขนาดเล็ก แต่ยังมีศักยภาพพัฒนาเป็นแหล่งท่องเที่ยวได้อีกด้วย ดังนั้นการวิจัยครั้งนี้จึงมีเป้าหมายรวบรวมและดำเนินการตามแนวคิดและเทคนิคเพื่อค้นหาตำแหน่งศักยภาพสำหรับการพัฒนาโรงไฟฟ้าพลังน้ำขนาดเล็กโดยใช้เทคโนโลยีระบบสารสนเทศภูมิศาสตร์และข้อมูลแบบจำลองระดับสูงเชิงเลข วัตถุประสงค์ของการวิจัยนี้จึงมุ่งเน้นเรื่อง (1) การประเมินคุณภาพของแบบจำลองระดับสูงเชิงเลขที่มีอยู่เพื่อการประยุกต์ใช้ด้านอุทกวิทยา (2) การระบุตำแหน่งทางเลือกด้านหัวน้ำและปริมาณน้ำของโรงไฟฟ้าพลังน้ำขนาดเล็กโดยใช้ดัชนีความชันแบบนอมอลไลซ์และเส้นโค้งเวลาการไหล ณ พื้นที่รับน้ำที่ไม่มีสถานีตรวจวัด (3) การจัดลำดับตำแหน่งทางเลือกตามความสามารถในการผลิตกำลังไฟฟ้าและพัฒนาเป็นแหล่งท่องเที่ยวโดยใช้การวิเคราะห์ตัดสินใจแบบหลายเกณฑ์

การประเมินข้อมูลแบบจำลองระดับสูงเชิงเลขพบว่าค่าแบบจำลองระดับสูงเชิงเลขของกรมแผนที่ทหารมีตำแหน่งทางราบและความสูงของทางน้ำแม่นยำที่สุด ทั้งนี้ความแม่นยำของทางน้ำที่สังเกตได้ต่อลักษณะภูมิประเทศไม่มีความแตกต่างกันอย่างมีนัยสำคัญ

การดำเนินการโดยใช้แบบจำลองระดับสูงเชิงเลขที่ดีที่สุดพบว่ามี 11 ส่วนทางน้ำที่มีความชันผิดปกติจากทั้งหมด 177 ส่วนโดยใช้ดัชนีความชันแบบนอมอลไลซ์ และตรวจพบเพิ่มเติมอีก 3 ส่วนทางน้ำด้วยการใช้เทคนิคการเปลี่ยนแปลงความลาดอย่างฉับพลัน ท้ายที่สุดทั้งหมด 14 ส่วนทางน้ำที่ถูกเลือกเป็นตำแหน่งทางเลือกด้านหัวน้ำ และตำแหน่งดังกล่าวยังคงถูกเก็บไว้เป็นตำแหน่งทางเลือกด้านปริมาณน้ำด้วยเนื่องจากมีกำลังผลิตไฟฟ้าซึ่งถูกประมาณการด้วยเส้นโค้งเวลาการไหลมากกว่า 20 กิโลวัตต์

ในส่วนสุดท้าย ตำแหน่งศักยภาพทั้งหมดถูกจัดลำดับตามเกณฑ์ซึ่งประกอบด้วย ขนาดเนื้อที่ เสถียรภาพด้านสิ่งแวดล้อม สิ่งดึงดูดใจ ความโดดเด่น ศักยภาพการขยายตัวและโอกาสในอนาคต และความสามารถในการผลิตไฟฟ้า ความคิดเห็นของผู้บริหารส่วนท้องถิ่นจากการสัมภาษณ์ถูก

แปลงเป็นค่าคะแนนและน้ำหนักของเกณฑ์โดยใช้ฟังก์ชันภาวะสมาชิกคลุมเครือและวิธีเปรียบเทียบแบบกลุ่มตามลำดับ ค่าคะแนนรวมของแต่ละตำแหน่งทางเลือกถูกรวบรวมโดยใช้กฎการตัดสินใจแบบวิธีรวมน้ำหนักแบบคลุมเครือ หลังจากนั้นคะแนนรวมดังกล่าวจะถูกขจัดความคลุมเครือและจัดลำดับ ซึ่งการจัดลำดับดังกล่าวพบว่าห้าอันดับแรกกระจายตัวอยู่ใกล้กับน้ำตกปอยและน้ำตกวังนกแอ่น นอกจากนี้การวิเคราะห์ความอ่อนไหวถูกใช้เพื่อให้ทราบถึงเกณฑ์ที่มีผลกระทบต่อการจัดลำดับนี้ด้วย

สาขาวิชาการรับรู้จากระยะไกล
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ลายมือชื่อนักศึกษา____________________
ลายมือชื่ออาจารย์ที่ปรึกษา____________________
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม____________________

WIPOP PAENGWANGTHONG : GEOSPATIAL MODEL FOR LOCATING POTENTIAL MICRO HYDROPOWER SITES IN UNGAUGED CATCHMENTS. THESIS ADVISOR : ASST. PROF. SUNYA SARAPIROME, Ph.D. 155 PP.

GEOSPATIAL MODEL / MICRO HYDROPOWER / DEM DATA ASSESSMENT / Q-H-BASED POTENTIAL ALTERNATIVE / TOURIST DEVELOPMENT PRIORITY

Deficiency of energy tends to become critical both in the regional and local areas. Nam Khek watershed in Phitsanulok and Phetchabun resembles several watersheds of the country. It contains catchments having hydrologic potential particularly for micro-hydropower development and being considered as ungauged catchments because of limited information of actual measurements along stream for potential sites searching. Not only is renewable energy developed from locations considered promising in rural area, but it can also contribute to increasing ability of being tourist attraction. This research therefore aimed at gathering and implementing concepts and techniques for searching potential sites for micro-hydropower development using GIS technology and DEM data. The research objectives focused on (1) evaluating the quality of available DEM data for hydrologic applications; (2) identifying Q-H-based potential alternatives of micro-hydropower using a normalized stream steepness index and flow duration curve at ungauged catchments; and (3) ranking the Q-H-based alternatives based on power productivity and ability of being tourist node development using multi-criteria decision analysis.

The assessment of available DEM data provided that the RTSD-DTED2 data having the best accuracy in terms of stream horizontal position and elevation. No significant difference in accuracies according to kinds of terrains was observed.

Working on the best DEM data, 11 stream segments from the total of 177 were identified as having anomaly steepness using k_{sn}. Three additional segments were detected by the use of abrupt-slope-change method. In conclusion, there were totally 14 segments selected as H-based potential alternatives which were kept as Q-H-based potential alternatives because their estimated power outputs through flow duration curve method were more than 20 kW.

Finally, the potential alternatives were ranked based on criteria, including size, environmental stability, attractions and features, distinctiveness, future options/expansion potential, and electric power productivity. The opinions of local administrators from interviews were transformed to criteria scores and weights using fuzzy set membership function and multiple comparison method, respectively. The Fuzzy Additive Weighting decision rule was used to aggregate the overall weight-scores of each alternative. The result was then defuzzified and subsequently ranked. The ranking showed that top five of the ranks distributed near Poy and Wang Nok Aen waterfalls. In addition, sensitivity analyses were performed to obtain which criteria have more effect on the ranking.

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I would like to thank the chairman and other members of this thesis defend committee: Assoc. Prof. Dr. Suwit Ongsomwang, Asst. Prof. Dr. Vicharn Amarakul, Asst. Prof. Dr. Songkot Dasananda, and Dr. Dusdi Chanlikit for all valuable suggestions and critical comments during the proposal and thesis defends.

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LIST OF ABBREVIATIONS

ANUDEM = Australian National University’s Digital Elevation Model algorithm
DEM = Digital Elevation Model
DTED2 = Digital Terrain Elevation Data Level 2
DWR = Department of Water Resources
FDC = Flow Duration Curve
GDEM = ASTER Global Digital Elevation Map
GIS = Geographic Information System
kW = Kilowatt
LDD = Land Development Department
MCDA = Multi Criteria Decision Analysis
MOAC = Ministry of Agriculture and Cooperatives
MWh = Megawatt hours
NEA = National Energy Administration
RID = Royal Irrigation Department
RMSE = Root Mean Square Error
RTSD = Royal Thai Survey Department
SG-DEM = Self-generated Digital Elevation Model
SRTM = Shuttle Radar Topography Mission
PP = Power Productivity

SZ = Size

ES = Environmental Stability

AF = Attractions and Features

DT = Distinctiveness

FE = Future Expansion

CHAPTER I

INTRODUCTION

1.1 Background of the problem

With the energy shortage crisis, there has been an enormous increase in the global demand for energy in recent years as a result of industrial development and population growth. Micro-hydropower is one of renewable and clean energy source that can reduce use and importing of fossil fuel, which depends on the world energy market price. Also, it can lead the way toward energy self-sufficiency and contribute to reducing gaseous pollutants emission into the atmosphere. Therefore, any high potential sites available should be determined, evaluated, and ranked as potential alternatives for feasibility study and even designing stage in the near future.

Nam Khek River is a tributary of Nan River that has high potential enough for producing hydropower from some catchments, particularly run-of-river type of hydropower plants. As the report of National Energy Administration (NEA, 1988a), there were seven investigated sites for run-of-river type small hydropower plant. In addition, the area is rather unstable electrified state because its transmission-line is very long through remote-rural area and the cables can be easily broken by both natural and human-made causes. One solution for both national and local problem is rural electrification development corresponding to physical potential of the area.

Firstly, most of non-forest areas have been used for solely cropping and rangeland which can be changed to value addition. Secondly, it contains the existing tourist activities and attractions such as Nam Khek rafting trip, Phu Hin Rong Kla, Thung Salaeng Luang National Park as well as Kaeng Sopa and Sri Dit waterfalls. Therefore, not only can the micro-hydropower additionally supply the energy to an area, but its potential sites can also be set as a node of existing tourist programs if other criteria correspond with previous studies (Lindberg, Furze, Staff, and Black, 1997; PlanningWA, 2004) are suitable.

Due to lack of gauging stations data in this area, the appropriate locations of micro-hydropower sites deal with ungauged catchments. With reliable techniques, it definitely provides more trustable data of physical characteristics of upstream drainage area, stream layout, and elevation for the estimation of water flow (Q) and head (H). According to previous studies (IEE, 2010; Kupakrapinyo, 2003; Rojanamon, Chaisomphob, and Bureekul, 2009), such parameters at ungauged catchments were estimated based on the calculation starting from digital elevation model (DEM) data. Q at any point from catchment was estimated from the relationship between catchment area and measured discharge from neighboring catchments. The parameters of any ungauged catchments can be more accurately estimated using trustable DEM data. This will be more reliable than the conventional method. Therefore, accurate DEM data should be acquired carefully in aspects of generation and assessment.

According to the study of NEA (1988a), problem of locating H-based potential alternatives along streams by expert decision was overabundant and unstable. They found that there were many unfavorable sites at the early stage during screening of the project selection. In general, their solution methods used conditions e.g. forest restricted area, trivial number of electric power productivity, and even non-perennial stream which did not directly corresponding to their H-based potential (Kupakrapinyo, 2003; NEA, 1988a; Rojanamon, 2009). Therefore, a normalized stream steepness index (Gonga-Saholiariliva, Gunnell, Harbor, and Metering, 2011; Wobus et al., 2006) is proposed in this study because it is suitable for finding stream segments with anomaly steepness and abrupt change in their profiles. The found segments can be considered as the initial H-based potential alternatives because of high relationship between stream steepness and H. The result is considered stable and trustable that any potential sites are not missed.

In order to set up the development priority of the found Q-H-based potential alternatives, they should be evaluated and ranked by using multi-criteria decision analysis (MCDA) according to their power productivity and potential of being tourist node development. Effective multi-criteria selection, evaluation, and analysis are required to serve the purpose.

1.2 Research objectives

The ultimate goal is to assess the feasibility of potential sites of run-of-river micro-hydropower plants in Nam Khek watershed. The specific objectives are:

(1) to evaluate and compare the quality of available DEM data for the hydrologic applications, particularly in terms of parameters related to locating potential sites for micro-hydropower and to estimate their generation ability in the study area;

(2) to identify Q-H-based potential alternatives of micro-hydropower using flow duration curve at ungauged catchments and a normalized stream steepness index; and

(3) to evaluate and rank the Q-H-based alternatives based on power productivity and ability of being tourist node development using multi-criteria decision analysis.

1.3 Conceptual framework and scopes of the study

1.3.1 Conceptual framework of the study

This research attempts to present the procedure for potential site assessment emphasizing on “reinforced.” The processing of “reinforced” herein could be inserted in several parts. First, it aims at accuracy assessment of derived extracted stream from currently available DEM data. Second, it aims at using normalized stream steepness index and estimating flow duration curve (FDC) at ungauged catchments to locate initial Q-H-based potential alternatives. Third, the study covers ranking alternatives using MCDA concentrating more on the ability of being tourist node development. The flow diagram of research conceptual framework shows in Figure 1.1. All parts and their relationships are explained and described in Chapter II-V and are concluded in Chapter VI.

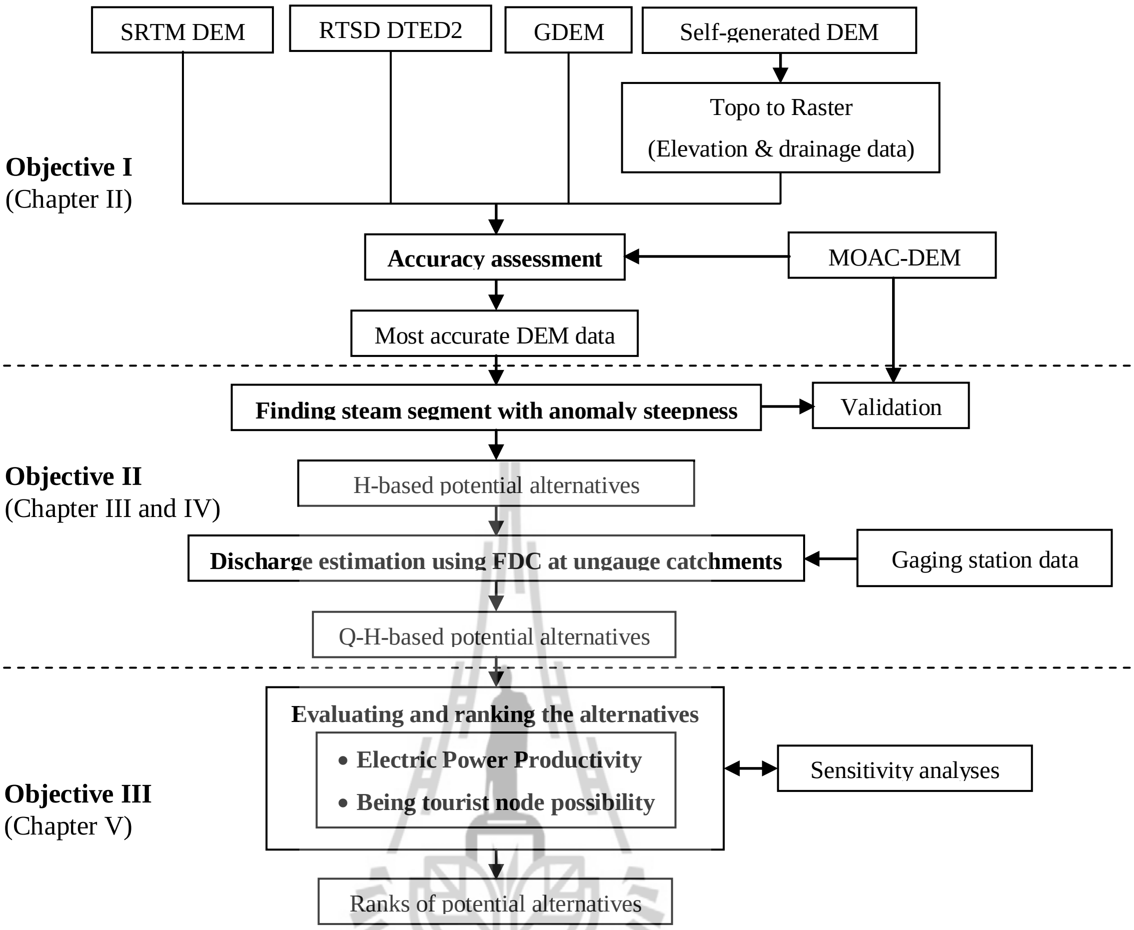

Figure 1.1 Conceptual framework of the study.

1.3.2 Scopes of the study

(1) The topographic data/information in this study was collected from topographic map with 1:50,000 scale which is sufficient to fit for preliminary feasibility study to locate and rank potential sites of micro-hydropower plant. Actual site development of each project requires additional ground survey for design and construction phases.

(2) This study does not emphasize strongly on economic, environmental and social evaluation.

(3) Most accurate DEM data were obtained through an accuracy assessment of extracted stream derived from different data sources and reference DEM data of the MOAC (Ministry of Agriculture and Cooperatives).

(4) The spatial resolution of DEMs was resized to 30 m x 30 m to match the scale of data/information and actual channel width of Nam Khek.

(5) The segment length used in finding anomaly stream steepness implies structural length of water pipe used in plant construction. It was assumed to be 1,000 m in horizontal similar to those of the well known Mae Kam Pong, Mae Ton Luang, and Bo Kaeo micro-hydropower projects (NEA, 1984).

(6) The amount of annual runoff at any Q-based alternatives was calculated based on the relationship between annual runoff and drainage area, as similar to the studies of NEA (1988a), Kupakrapinyo (2003), and Rojanamon et al. (2009), which could be derived from gauged watershed with hydrological observation station namely: N.24, N.36, N.40, N.54, N.55, N.58, N.59, N62, N.66, N.73, and 091603. Two of them are located in the Nam Khek watershed with N.24 and 091603. Others are neighboring watersheds outside of Nam Khek basin.

(7) The magnitude of monthly stream flow at any Q-based alternative was calculated based on the monthly ratio of runoff in a year from the nearest downstream station with data recorded longer than 40 years.

(8) The designed discharge for installed run-of-river hydropower capacity was estimated as a discharge at 30% time of exceedance ($Q_{d(30\%)}$) that is obtained from FDC at ungauged catchment (Kupakrapinyo, 2003; NEA, 1988b; Rojanamon et al., 2009).

(9) Electric power productivity was calculated based on hydropower generation equation of the New Energy Foundation (NEF) (1996; quoted in Rojanamon et al. (2009) and Arruda, Baldwin, and Quinn (2010)). The Q-H-based alternative at each site should have the power output not less than 20 kW because it is less than the demand obtained from the interviews with local administrators.

(10) Evaluation and ranking the Q-H-based alternatives was based on electric power productivity and ability of being tourist node development using MCDA. The data analysis was performed through decision rule of the Simple Additive Weighting.

(11) The evaluation criteria used for potential assessment of being tourist node were referred from previous studies of Lindberg, Furze, Staff, and Black (1997) and PlanningWA (2004). It consisted of size, environmental stability, attractions and features, distinctiveness, and future options/expansion potential. Criteria score and weight were based on the opinions of the local administrators.

1.4 The study area

1.4.1 General data

The Nam Khek Watershed upstream of N.24 (Wang Nok Aen) was chosen as the study area (Figure 1.2). It is located between the northeastern part of Phitsanulok province and the western part of Phetchabun province with latitudes between 16° 22' 32" to 17° 2' 46" N and longitudes between 100° 28' 38" to 101° 5' 7" E with the watershed area of 1,861 square kilometers (km^2). The boundary of this watershed connects to Khwae Noi watershed in the north, to the lower part of Nan river basin in the south, to Pa Sak river basin at Phetchabun province in the east, and to Wang Thong watershed in the west.

The major transportation route in the watershed area of Nam Khek is Asian Highway route 14 (or National Highway route 12, Phitsanulok–Lom Sak), passing through office of Thung Salaeng Luang National Park. Minor highways consist of Highway 2196, Tambon Camp Son–Tambon Thung Samo and Highway 2258, Ban Nong Mae Na-Ban Na Ngua.

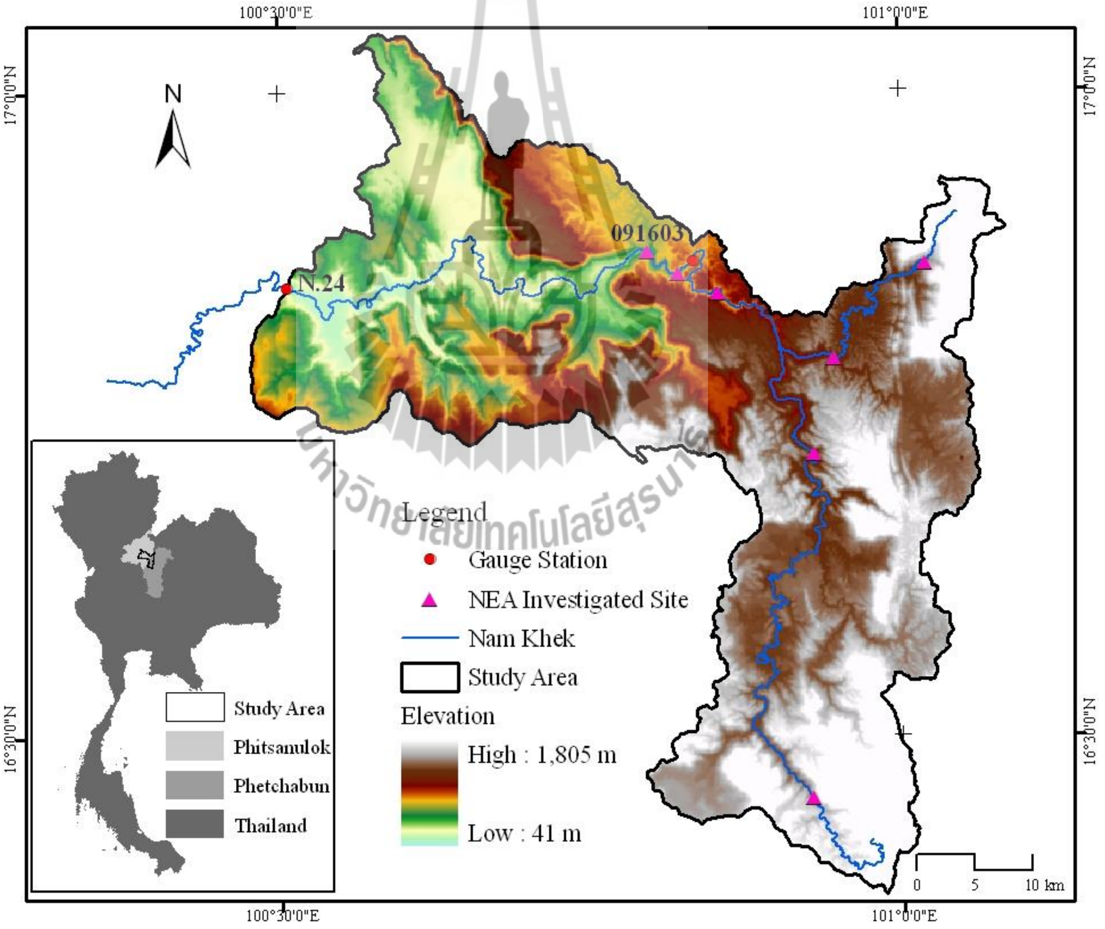

Figure 1.2 Topography of the study area including stream-gauge stations and seven investigated sites for run-of-river small hydropower plant studied by NEA (1988b).

1.4.2 Physical data

(1) Topography

The topography of the area is mainly characterized by high mountain range in the east. Its elevation is between 41 m to 1,805 m above mean sea level (MSL). The terrain altitude gradually decreases to the lower part which is characterized by undulating to rolling surface, alternated with valleys and plains. There are several mountain peaks, e.g. Khao Kho, Khao Ya which are heads of water resource. The tallest peak with elevation of 1,805 m is Khao Tua Khong.

(2) Climate

The climate of the study area was described by คเชนทร์ ไกรสิทธิพงศ์, ภัทรสุดา จันทร์คำ, มาลี นิเวศนา, และ สันติ นามวิเศษ (2543).

The area is located in tropical monsoon region consisting of the Southwest and the Northeast Monsoon including tropical storm from Pacific Ocean. Southwest Monsoon starts from May to October. It usually brings moisture from Indian Ocean that turns into rainfall in this region. The Northeast Monsoon (from October to February) flows through the south of Siberia and passes the Main Land China to Thailand and brings cold climate to the region. The summer of the area is between February to May. Under the influence of Southeast Monsoon, watershed area of Nam Khek receives rainfall starting from May to October when is the rainy season. Also, most of annual rainfalls (~90%) happen during this season (กรมชลประทาน, 2551).

Average annual rainfall of the area and its vicinity is about 1,360 mm. Mean temperature during the rainy season is 28℃ and 30℃ in the summer. During November to December, temperature is 24-27℃ and it can be as low as 2-3℃ during December to January.

Average relative moisture is about 77%. The lowest (59%) is in March and the highest (80%) is in September. Within one year cycle, the water evaporation is about 1,560 mm. The highest monthly evaporation (about 186 mm) is in April and the least (about 110 mm) is in January.

(3) Hydrology

Streams in the Nam Khek watershed show mainly trellis pattern due to their geology characterized by the sequences of fine-coarse grained clastic rocks of the Khorat group. The flow direction of main stream is from south-east to north in Phetchabun province and from east to west in Phitsanulok province as shown in Figure 1.2, respectively. Mostly, the water has flown through for the whole year. According to monthly flow data of N.24 station (กรมชลประทาน, 2555), mean annual runoff and flow is about 822 million cubic meters (MCM) and 26.08 cubic meter per second (m^3/s) respectively. About 80% of its volume is active during June to October.

The study area has two gauge stations namely 091603 (Ban Khek Yai) and N.24 (Ban Wang Nok Aen) shown in Figure 1.2. The first one has been managed by The Department of Water Resources (DWR) and the second one has been managed by The Royal Irrigation Department (RID). Runoff yield of the study area at N.24 was 14.19 L/s/km^2 during 1965 to 2010 while runoff yield of 091603 was 18.66 L/s/km^2.

1.5 Structure of the dissertation

According to the objectives of the research and the conceptual framework, this dissertation can be divided into six chapters.

In the first Chapter, the overview of the study including the background problem, research objectives, conceptual framework and the characteristic of the study area are explained. This Chapter shows the relationship of all parts of the study and it can be the guideline to follow and understand all the next chapters.

In the second Chapter, the DEM data assessment was accomplished to find the most accurate DEM data for identifying Q-H-based potential alternative of micro-hydropower generation. This Chapter describes the whole process starting from the input DEMs data used, accuracy assessment, and the results as comparison accuracy of available DEM data. Additionally, this Chapter provides the output that meets the most accurate DEM data. This result was used to confirm trustfulness of most accurate DEM data used as the input of the further processes in the next chapter.

The third Chapter attempts to identify H-based potential alternatives of micro-hydropower which was divided into two parts. The first one identifies H-based potential alternatives using normalized steepness indexing and abrupt slope change techniques. The second one is the validation using MOAC-DEM data as reference. The results were used as input for identifying the Q-H-based alternatives in the fourth Chapter.

The fourth Chapter attempts to identify Q-H-based potential alternatives of micro-hydropower which was divided into three parts. The first one estimates mean annual runoff at ungauge catchment using relationship between annual runoff (Q_m) and drainage area (A) derived from chosen gauge station. The second one constructs

FDC of an ungauged catchment. Both drainage areas of ungauged catchments derived from GIS technique and monthly ratio of runoff in a year from two gauge station were used as input parameters of the construction. The last one calculates theoretical power productivity and ranks the Q-H-based alternatives using equation 4.2 and parameters derived from GIS techniques. The results were used as inputs for evaluating and ranking the alternatives in the fifth Chapter.

The fifth Chapter presents the multi-criteria decision analysis process. On one hand, the research presents the establishment of the development priority of the found Q-H-based potential sites. On the other hand, the research attempts to investigate which criteria can be typical characteristics of the area influencing potential alternatives ranking

The final Chapter entails the conclusion and recommendation. The research results of all parts were concluded and recommended for further research.

1.6 Synthesis for the research approach

The result of the literature review can be concluded and used as a guide to establish the research procedure for potential assessment of micro-hydropower sites. The procedure will be focused on accuracy assessment of extracted stream derived from DEM data, sieving Q-H-based potential alternatives along the main streams and ranking them by integrating criteria into the decision making process. The conclusion from the review and the proposed research approach can be discussed.

(1) Accuracy assessment of currently available DEM data includes SRTM DEM, RTSD-DTED2 (DEM 30 m from RTSD), GDEM and the self-generated DEM using contour and stream information from RTSD 1:50,000 scaled topographic map through

Topo to raster tool were performed and compared. The one that provides the most accurate stream position was further used for analysis to locate anomaly steepness stream segments.

(2) Alternatives of micro-hydropower sites can be determined by various methods varying from an expert manual to universal searching using each pair of contour interval along a stream. The later method can result in a huge number of alternatives which will be sorted using other specifications later. From the literature review, it is very interesting to note that potential alternatives determined using anomaly steepness stream segment characteristic can provide better and more accurate results. This method has been proved to be appropriate for identifying knick points or points with abrupt change of the stream gradient. Those points further imply the locations of waterfalls and rock boundary. This method will be selected for sieving the potential alternatives. The result can be expected as an input for further estimation of discharge and water head which in turn are for power productivity estimation. Also, it will result in a trustable number of alternatives showing high potential.

(3) Instead of ranking significance of alternatives based only on engineering, economic, environmental, and public participation criteria as always carried out in previous studies, this research will focus basically on evaluating and ranking alternatives based on their power productivity and opportunity of being a node of tourist which is active and popular in the area and in the vicinity.

(4) Sensitivity analysis is applied to investigate which criteria can be typical characteristic of the area influencing potential alternatives.

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CHAPTER II

DEM DATA ASSESSMENT

2.1 Abstract

Hydrologic applications, i.e. locating potential sites for micro-hydropower generation, require parameters extracted from DEM data. These parameters include stream position, elevation, and slope. They are parameters required for estimations, for example, area upstream and channel parameters for run-off and water-head estimation. More accurate DEM data can provide more accurate parameters. DEM data available in Thailand comes from several sources, i.e. SRTM-DEM, GDEM, RTSD-DTED2, and self-generated DEM (SG-DEM), which are different in acquiring methods, spatial resolution, spatial position and elevation accuracy. From different sources, DEM data can be normally generated from sets of remotely sensed data with different sets of control points and geometric correction methods. Therefore, their accuracy can affect the parameters which in turn will affect the applications. The purpose of the study is to assess the data quality and suitability of available DEM in Thailand for hydrologic applications at the scale of 30 m cell size fit to preliminary feasibility study in Nam Khek watershed. The Nam Khek watershed is characterized by mountainous area with main streams providing potential for micro-hydropower generation, tourist attraction and activities. Accuracy of the parameters in the area extracted from available DEM data is assessed based on reference data. Matching ratio, omission and commission errors for stream position and root mean square error for stream elevation are estimated and compared.

Keywords: DEM data assessment, DEM data accuracy, Hydrologic application.

2.2 Introduction

2.2.1 Background problem

Due to limited number of gauge stations available in the study area, any hydrological applications, for example site suitability assessment of micro-hydropower, deal specifically more with data from ungauged catchments. With reliable GIS techniques, it can definitely provide more trustable data of physical characteristics, particularly upstream drainage area, stream position, and elevation for discharge and water-head estimation. According to the previous studies (IEE, 2010; Rojanamon, Chaisomphob, and Bureekul, 2009), such parameters at ungauged sites were estimated based on calculations starting from grid DEM data. For example, discharge estimation at ungauged point along the stream is more accurately estimated using its relationship to the catchment area upstream from that point (Sarapirome, Teaumroong, Kulworawanichpong, Ongsomwang, and Paengwangthong, 2010; ประกอบ วิโรจนกูฏ และ ฤกษ์ชัย ศรีวรมาศ, 2543). Identification of anomaly steepness stream segments can be carried out using relationship of slope of stream segment and catchment area upstream as well (Gonga-Saholiariliva, Gunnell, Harbor, and Metering, 2011; Wobus et al., 2006). To achieve the accurate catchment area upstream of any point along the stream, the accumulation of cells in raster-based sub-watershed is started from the most upstream cell down to the cell at that point. If the cell is shifted apart from the stream position only 1 or 2 cells, the accumulation of upstream cells or the catchment area upstream of the cell can be deviated more than several hundred times. This will greatly cause adverse effect to further analysis using this parameter. Therefore, apart from using effective and appropriate GIS techniques, parameters of any ungauged points can be more accurately estimated using trustable DEM data. The result will be more reliable than the conventional method.

DEM data available in Thailand come from several sources, i.e. SRTM, GDEM, RTSD-DTED2, and SG-DEM. They are different in acquiring methods, spatial resolution, and position and elevation accuracy. These DEM data are low cost or are distributed for free. Therefore, before using DEM data for hydrological applications they should be selected, acquired, or generated, and assessed carefully to ensure that their accuracy fits for a certain level of applications.

The objective of the study is to compare the quality of DEM data available in Thailand for the hydrologic applications, particularly in terms of parameters related to locating potential sites for micro-hydropower and to estimate their generation ability in the study area. Horizontal and vertical accuracy of all kinds of DEM data mentioned above were assessed with reference DEM data of the MOAC (Ministry of Agriculture and Cooperatives). These MOAC-DEM data have the highest spatial resolution and are distributed with very high cost. Due to very limited study budget, only several comparatively tiny areas of MOAC-DEM data supported by the Land Development Department (LDD) were employed as reference data (Figure 2.1). The matching ratio was used to assess agreement between the extracted and the reference stream position while the root mean square error is for assessing elevation accuracy along reference streams. The results of assessment can be used to compare which DEM data are more suitable for further applications.

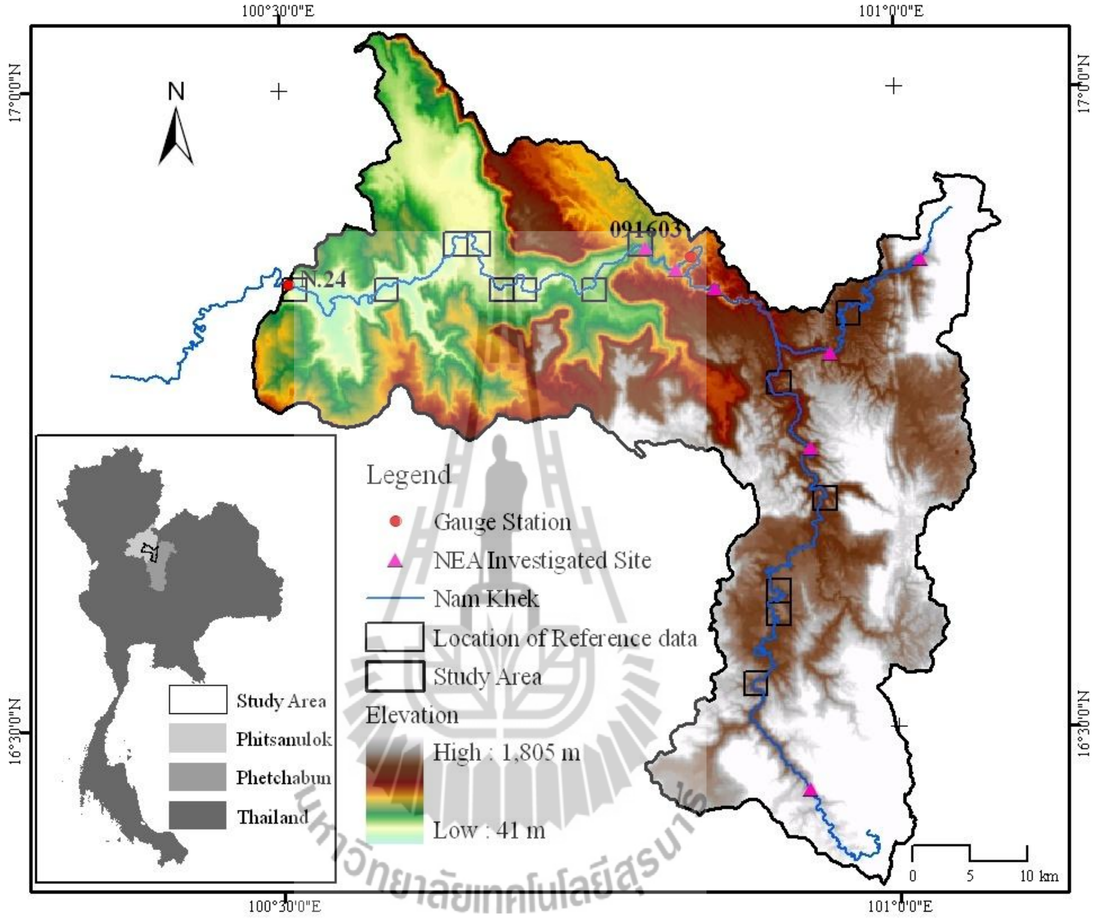

Figure 2.1 Location of reference data.

2.2.2 Available DEM data and their acquiring methods

As mentioned above, DEM data recently available in Thailand are obtained from several sources. Their acquiring methods are different and result in various resolutions. Their sources, resolutions, and acquiring methods can be concluded in Table 2.1.

Table 2.1 Characteristics of available DEM data in Thailand.

Data	Spatial resolution	Presented vertical resolution	Acquiring method
MOAC-DEM	5 m	1 mm	Digital photogrammetry of aerial photo.
SG-DEM	30 m	1 m	Interpolation of contour data (RTSD 1:50,000 topographic map).
RTSD-DTED2	30 m	1 m	SAR interferometry.
GDEM	30 m	1 m	Digital photogrammetry of ASTER image with additional improvement techniques.
SRTM-DEM	90 m	1 m	SAR interferometry with additional improvement techniques.

(1) MOAC-DEM: According to LDD (2004), the detail sets of point data, the product of digital photogrammetry operated on color air-photos (at the referred scale of 1:4,000), were converted to grid DEM and contours of 2, 5 and 10 m interval for flat and mountainous areas respectively. Their vertical accuracy was estimated at 2 m and 4 m (95% confidence interval) for flat (slope < 35%) and mountainous areas (slope > 35%).

(2) SG-DEM: The grid DEM data was generated using Topo to Raster interpolation function of ArcGIS^{TM} version 9.x, with default parameters setting. The input vector data obtained from the RTSD are spot heights, 20 m interval contour lines, and stream center lines of 1:50,000 topographic map.

(3) RTSD-DTED2: According to Slater et al. (2006) and ศุภฤกษ์ ชัยชนะ (2549), the SRTM project produced the grid DEM at one-arcsecond (approximately

30 m) intervals in latitude and longitude using SAR interferometry. The RTSD procured these data from the National Imagery and Mapping Agency (NIMA).

(4) GDEM: The GDEM data were generated using stereo pairs of ASTER images. Currently, they have been improved in processing i.e. water masking, smaller correlation kernel size, and bias removal (Tachikawa et al., 2011).

(5) SRTM-DEM: Primarily, the SRTM-DEM data have been produced based on radar images from NASA's shuttle as well as the RTSD-DTED2. Before distributing them via internet, their spatial resolution was reduced to 90 m. Currently, the latest version has been improved using new interpolation algorithms and better auxiliary DEMs (Jarvis, Rubiano, Nelson, Farrow, and Mulligan, 2004).

2.3 Literature review

2.3.1 Self-generated DEM using Topo to Raster tool

Topo to Raster tool is a DEM data generation program which is based on Australian National University's Digital Elevation Model algorithm (ANUDEM). It incorporates process between interpolation of regular grid DEM and drainage enforcement algorithm (Hutchinson, 1988). The related substance of DEM data generation can be mentioned as follows.

2.3.1.1 DEM generation

The DEM generation method consists of an iteration technique which employs a nested grid strategy. This technique starts from an initial coarse grid and successively calculates grids at finer resolution. It halves the cell size until the final user defined resolution is obtained. The initial values for the first coarse grid are calculated by using the heights of local maxima based on the surrounding contour height information since no other information on the maximum height is available. The following finer grid resolutions are based on linear interpolation from the preceding coarser grid (Manuel and Maidment, 2004; Asserup and Eklof, 2000 (quoted in Bergström and Malmros, (2005)).

Drainage enforcement algorithm of *Topo to Raster* tool is designed to remove all unidentified sinks because they are not found at general landscape. In addition, the program has a side conditions that is also set for each stream line. This ensures that the stream line acts as a break-line for the interpolation conditions and simultaneously ensures that each stream line lies at the bottom of its accompanying valley. Corresponding with the concept stated that flow of water is primary erosive force to determining the general shape of most landscapes.

The result of the example interpolation done with the input data shown in Figure 2.2 can be seen in Figure 2.3. Topo to Raster tool generates inferred ridges and streamlines from points of locally maximum curvature on contour lines. This permits interpolation of the fine structure in contours across the area between them. The derived contours also show a close match with the contours in the input data in Figure 2.2.

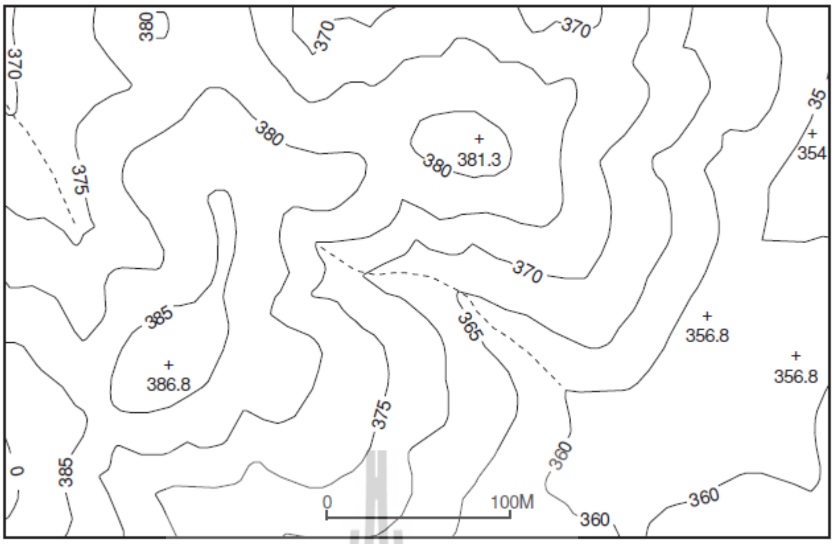

Figure 2.2 Contour 5 m interval, stream line, and point elevation data.

Source: Hutchinson (2008)

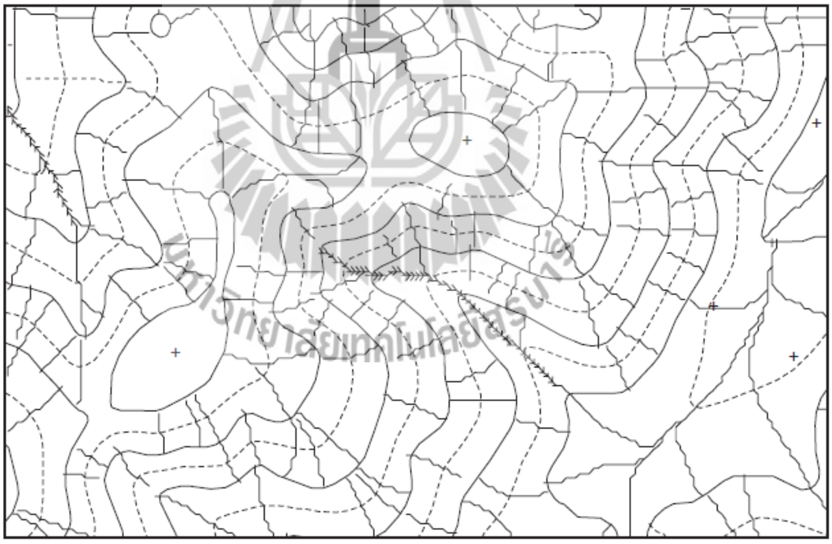

Figure 2.3 Inferred stream and ridge lines are generated automatically by ANUDEM. All contours are derived from the interpolated DEM. Dashed lines are shown at elevations midway between the data contour elevations.

Source: Hutchinson (2008)

2.3.1.2 Implementation

For the DEM data generation using *Topo to Raster* tool, there is a set of tolerances used to adjust the smoothing of input data and the removing of sinks in the drainage enforcement process. These tolerances are as follows:

Tolerance number one reflects the accuracy and density of the elevation points. Data points which block drainage by no more than this tolerance, are removed. In other words, the tolerance adjusts the strength of drainage enforcement in relation to both the accuracy and density of the input elevation data. In addition, it is also used to prefer drainage enforcement via saddle points with elevation data points over saddle points that do not have an associated data point. Therefore, this should be set to one-half of the contour interval when using contour data (Bergström and Malmros, 2005; Hutchinson, Stein, Stein, Society, Hamish, and Phil, 2008).

Tolerance number two represents the amount of error inherent in the process of converting point, line, and polygon elevation data into a regularly spaced grid. It is scaled by the program depending on the local slope at each data point and the grid cell size. Larger values will cause more data smoothing, resulting in a more generalized output grid. Smaller values will cause less data smoothing, resulting in a sharper output grid which is more likely to contain spurious sinks and peaks. Also, such tolerance is used to prevent drainage clearance through unrealistically high barriers (Bergström et al., 2005; Hutchinson et al., 2008).

2.3.1.3 Default and optimized algorithm parameter

Interpolation with optimized key parameters is regarded as it is a careful method to generating DEM data. The key parameters are composed of spatial resolution, number of iterations, and the roughness penalty that the process of defining optimal value for them according to the study of Yang, Niel, McVicar, Hutchinson, and Li. (2005). However, a previous study (Yang, McVicar, Vanniel, Hutchinson, Li, and Zhang, 2007) showed that the validation between default and optimize algorithm parameters was not extremely different when all among them was compared with the known point of drainage area.

Generated DEM using the default parameters setting was suggested by Hutchinson et al. (2008) that generating DEM data by using default parameters was very robust and had been tested with a wide variety of data sources. If the result of interpolation is inferior, it should be solved by checking errors in the input data before changing the default values (Johnston, Hoef, Krivoruchko, and Lucas, 2001). As mentioned earlier, this study let the tolerances be default except for the first tolerance, which is set to 10 meters, half the input data contour interval.

2.3.2 Previous studies

Manuel and Maidment (2004) evaluated the influence of DEM interpolation method in drainage analysis: Inverse Distance Weighted; radial basic functions; ordinary Kriging; and TOPOGRID (command in ArcInfo based on ANUDEM version 4.6.3). The small watersheds in the Eastern Andean cordillera of Ecuador were selected as the study area: the upper Oyacachi River basin and the Upper Chalpi River basin. The synthetic stream network and contour line were compared with the digitized stream from topographic maps (“true data”). The comparison was made by using a visual qualitative evaluation and a quantitative measure. With a quantitative measure to quantify the level of agreement between the synthetic and the reference stream networks, the Kappa coefficient of agreement (K_{hat}) was calculated for each synthetic stream network using the error matrix. The writers explained about visual qualitative evaluation that the DEM generated using TOPOGRID allowed a much more accurate delineation of the stream network, particularly the DEM created using drainage enforcement was the best overall. For quantitative measure of the level of agreement between the synthetic and the true data, they found that the highest level of agreement for the raw DEMs was attained by using the TOPOGRID surfaces. In addition, the result with a hydrological standpoint concluded that the best interpolator technique analysed was TOPOGRID.

Yang et al. (2007) improved the quality of the DEM by reducing source data errors and optimizing ANUDEM (Version 5.1) algorithm parameters in the Loess Plateau, China. The improvement was assessed by using higher accuracy independent validation of 32 contributing areas and 1,474 spot heights and visual comparison of DEM derivatives produced from default parameter ANUDEM and Triangular Irregular Network (TIN) algorithms. Improvement in the default ANUDEM DEM over the default TIN DEM was shown where the percentage of the total absolute difference in contributing areas reduced and the bias between the spot heights and DEM elevations also reduced. In addition, large improvement in DEM quality was gained by using ANUDEM instead of TIN, with smaller improvement gained by fixing source data errors and optimizing ANUDEM parameters.

Davies, Lagueux, Sanderson, and Beechie (2007) demonstrated methods for deriving synthetic stream networks via GIS across large and diverse basin using drainage-enforced DEMs, along with technique for estimating channel widths and gradient on the reach scale. The two-step drainage enforcement method (by coupling the TOPOGRID to the AGREE.aml) produced synthetic stream networks that displayed a high degree of positional accuracy relative to the true streams. The accuracies of their estimated channel parameters were assessed with field data, predictions of bankfull width, wetted width, and gradients were strongly correlated with measured values (r^2 = 0.92, r^2 = 0.95, r^2 = 0.88, respectively). In addition, the result also revealed that TOPOGRID added more positional accuracy of synthetic stream than original DEM without any modification.

Callow, Van Niel, and Boggs (2007) found that there was as impact of drainage enforcements which commonly used hydrological correction methods (stream burning, Agree.aml, ANUDEM *v*4.6.3, and ANUDEM *v*5.1). There is an overall nature of a DEM, finding that different methods produce non-convergent outcomes for catchment parameters (such as catchment boundaries, stream position, and length) using comparison with the original DEM without any modification. The writers explained that these increased catchment slope and no single method performs best across all categories. However, the result also revealed that no different replicating known hydrological conditions and catchment parameters between both versions of ANUDEM with default parameters.

2.4 Research methods

2.4.1 Research procedure

The conceptual framework of this part is displayed in Figure 2.4. All data preparations and assessments were operated on raster-based GIS data. The details of each step can be explained as the following framework.

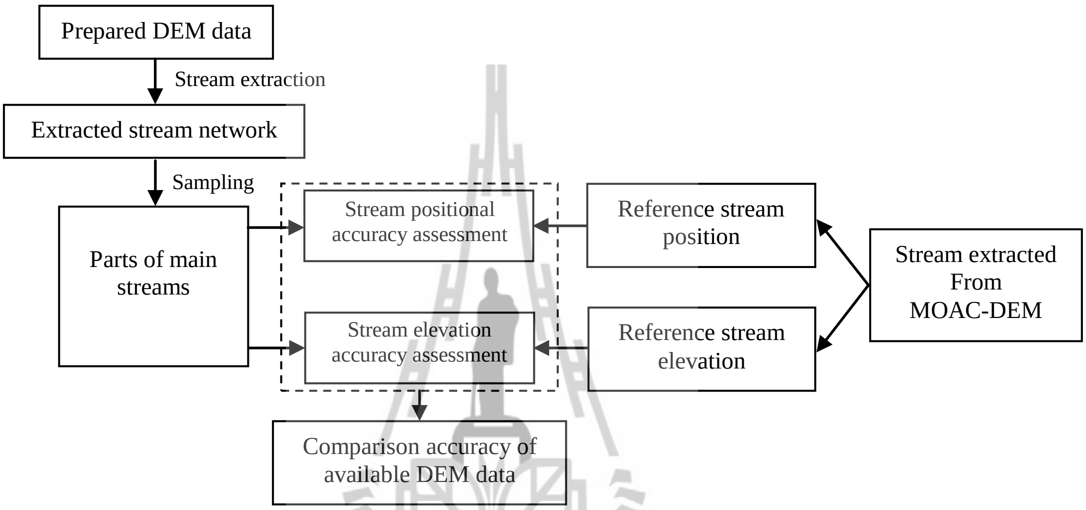

Figure 2.4 Conceptual framework of the DEM data assessment.

2.4.2 Self-generating DEM data

Topo to Raster interpolation, a tool of ArcGIS^{TM} version 9.x which uses ANUDEM method, is selected for DEM data generation. According to Manuel and Maidment (2004), the ANUDEM method was claimed to be a DEM-data interpolation tool that provides more accurate stream location than other techniques. In practice, the data are firstly prepared appropriately before the input process. The steps include (Figure 2.5):

(1) separating the stream and lake into different layers and removing man-made canals;

(2) adjusting the stream network in form of single lines;

(3) checking correctness of stream lines with connection and flow direction;

(4) running the Topo to raster tool over the study area using elevation (contour and point) and drainage data as the input;

(5) correcting error of input according to messages obtained from the inspection of diagnostic files, e.g. sink and stream flow direction;

(6) identifying and correcting mislabeled and misplaced spot heights using visual checking on the slope surfaces and hillshade layers; and

(7) rerunning the Topo to raster tool using corrected input data.

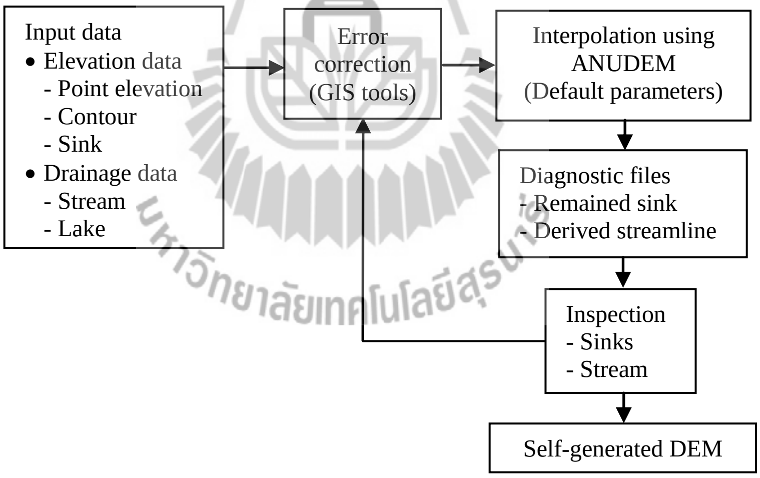

Figure 2.5 The flow of self-generating DEM data using Topo to Raster interpolation.

2.4.3 Available DEM data assessment

A number of 14 sheets of MOAC-DEM data was used as reference for accuracy assessment of stream position and elevation in other DEM data. The most accurate DEM data were selected based on relative position accuracy of synthetic streams which were compared with reference vector data. The size of a sheet is 2 km x 2 km. Seven of them fall into mountainous terrain while 4 in hilly and undulating, and 3 in narrow valley flat (see Figure 2.1). All DEM data were prepared in common characteristics for fair assessment. Steps of the procedure are as follows:

(1) resampling cell size of all DEM data to be 30 m x 30 m, which approximately matches the actual channel width of the Nam Khek River;

(2) extracting stream networks from all DEM data using flow accumulation process of Hydrology function in Spatial Analyst Tools of ArcMAP^{TM};

(3) reclassifying attributes of grid cells corresponding to stream network to be 2 for MOAC-DEM, 1 for other DEMs, and 0 for all non-stream cells;

(4) overlaying stream layers extracted from other DEMs, one at a time, with stream data sheets extracted from MOAC-DEM; and

(5) assessing accuracy of stream position and elevation based on reference streams extracted from 14 sheets of MOAC-DEM. Two groups of sampling sheets of reference data (MOAC-DEM) were used for different purposes. All sheets were for assessment in all kinds of terrain. Seven sheets of them were for mountainous terrain. The latter group was emphasized in mountainous terrain because the site suitability for micro-hydropower was concentrated more in this type of terrain. Corresponding to Paengwangthong and Sarapirome (2012), matching ratio, omission and commission errors were used for assessing stream position accuracy whereas root mean square error (RMSE) was for stream elevation. The details of each indicator can be explained here.

(5.1) Estimating matching ratio, overlay analysis by means of summation was operated. Resulting cells with score of 3 and 2 represented matching and non-matching cells of reference stream respectively. The matching ratio can be expressed as ((matching cells)/(matching cells + non-matching cells)). Any DEM data providing the higher matching ratio have more accurate stream position.

(5.2) Calculating omission and commission error, overlay analysis by shortest distance between stream cells of reference and other DEM data was operated using spatial join process of Overlay function in Analysis Tools of ArcMAP^{TM}. Resulting cells with score of 2 and 1 with distance more than 42.42 m represented omission and commission error cells respectively. The omission and commission errors can be expressed as ((omission error cells)/(reference stream cells)) and ((commission error cells)/(extracted stream cells)), respectively. The former indicated the probability of reference stream cells which were not extracted whereas the later indicated the probability of wrong extraction.

(5.3) Comparing elevation of cells along reference streams, RMSE of matching stream cells from each DEM were calculated by use of equation 2.1 (ASPRS, 1990). Any DEM data providing the higher RMSE have less elevation accuracy or depict the higher difference in elevation when compared to reference data:

$$RMSE = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}\left(Z_i - \acute{Z}_i\right)^2\right]}, \qquad (2.1)$$

where n represents a number of cells of reference streams, Z_i for cell elevation of reference data, $\acute{Z}_i$ for cell elevation of other DEM.

2.5 Results and discussion

2.5.1 Stream position accuracy

Examples of extracted streams of all DEM data in 3 sheets of MOAC-DEM are displayed in Figure 2.6 and others are shown in Appendix A.1. From visual observation, the stream extracted from GDEM shifts away from the reference stream, followed by the one from SRTM-DEM. The rests agree more with the reference. Matching ratios in mountainous and all kinds of terrains are shown in Table 2.2.

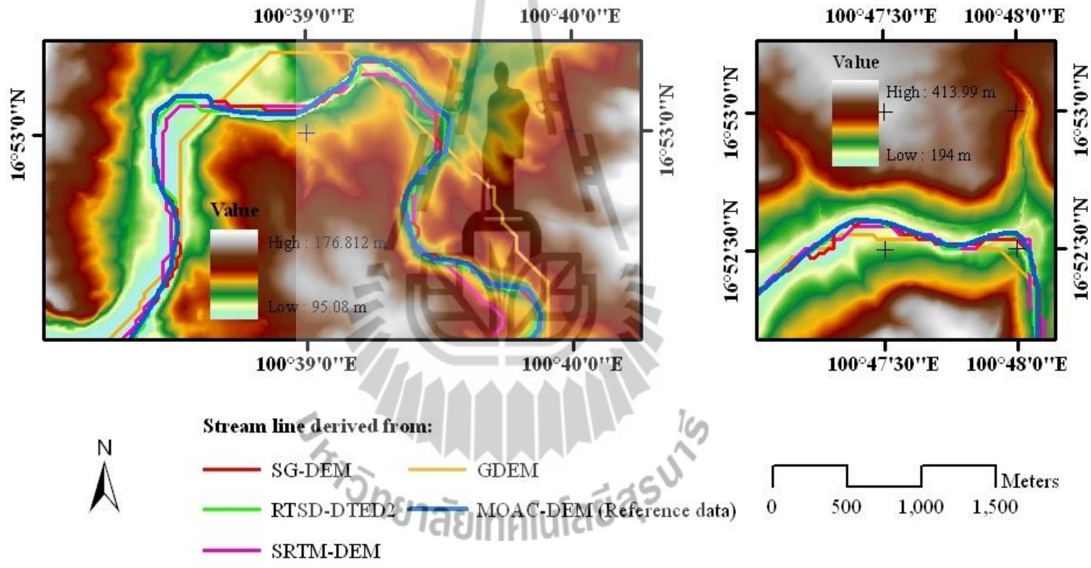

Figure 2.6 Examples of extracted streams of all DEM data in 3 sheets of the reference data.

Table 2.2 Comparative stream position accuracy (cell by cell) of all DEM data in mountainous and all kind of terrains.

	Total stream cells	All terrains		Mountainous terrain	
		n	Matching %	n	Matching %
MOAC-DEM	1,340	1,340	100	776	100
SG-DEM	1,340	652	49	360	46
RTSD-DTED2	1,268	551	41	305	39
SRTM-DEM	1,114	218	16	112	14
GDEM	1,044	63	4	43	5

Among available DEM data, it is obvious that DEM data of SG-DEM provide the best stream position accuracy. Their matching ratio in percentages with reference data are 46 and 49 in mountainous and all kinds of terrains respectively. The accuracies of RTSD-DTED2 are lower (39 and 41) but not much different from the SG-DEM's. GDEM data provide the least stream accuracy. The SRTM is poor in accuracy as compared to ones of the SG-DEM and RTSD-DTED2.

Table 2.3 Relative positional accuracy of extracted streams derived from four different DEM data compare with reference stream data.

		Relative Positional Accuracy (Cell)							
		All terrain				Mountainous			
		SG-DEM	DTED2	SRTM	GDEM	SG-DEM	DTED2	SRTM	GDEM
Shortest distance from reference stream (m)	0	652	551	218	63	360	305	112	43
	>0,≤ 30	529	630	350	99	333	340	194	72
	>30,≤ 42.42	45	38	105	52	25	28	55	34
Total	Cell matching	1,226	1,219	673	214	718	673	361	149
	Extracted stream cells	1,340	1,268	1,114	1,044	783	713	597	547
Stream position accuracies (%) with acceptable error with one nearby cell	Matching percentage	91	91	50	16	93	87	47	19
	Omission error	9	9	5	84	7	13	53	81
	Commission error	9	4	40	80	8	6	40	73

Note: Cell indicates length of extracted stream occurring within each class of shortest distance from reference stream. Total stream length sampled was more than 25 km. In addition, stream position accuracies (%) of each DEM data were calculated by acceptable error at one nearby cell.

As seen on Tables 2.2 and 2.3, even if the matching percentages of SG-DEM are higher than RTSD-DTED2 but its stream position accuracies are not better, particularly when the stream position can be acceptable accuracy at error of one nearby cell according to previous study of Manuel et al. (2004). The stream position of RTSD-DTED2 is the best. Also, this is acceptable in preliminary feasibility study at 1:50,000 map scale.

In this case, it is obvious that DEM data of both SRTM and GDEM provided poor stream accuracy. This could be the result of their characteristics on spatial resolution and acquiring methods. For the first one, their spatial resolution was reduced to 90 m before distributing via internet. This certainly affected their accuracy. The last one was generated using stereo pairs of ASTER multispectral images. The data were classified as a digital surface model that can be affected from tree canopy (Tachikawa et al., 2011).

2.5.2 Stream elevation accuracy

The stream elevation accuracy in mountainous and all kinds of terrains of each available DEM, in term of RMSE, is reported in Table 2.4. The DEM data of RTSD-DTED2 provide the best stream elevation accuracy. Their RMSEs are 4.69 m and 3.66 m in mountainous and all kinds of terrains. For this assessment, SRTM-DEM data carry the high RMSEs which are as high as 22.84 m and 18.46 m. These RMSE are not much different from the ones of GDEM (16.11 m and 18.83 m.). The elevation accuracies of SG-DEM (18.95 m and 15.96 m) are not much better than those of GDEM and SRTM-DEM.

Table 2.4 RMSE of elevation of each DEM in mountainous and all kinds of terrains as compared to elevation of reference streams.

	All terrains						**Mountainous terrain**					
	n	**Min**	**Max**	**Ave**	**SD**	**RMSE**	**n**	**Min**	**Max**	**Ave**	**SD**	**RMSE**
MOAC-DEM	1340	40.84	698.22	390.18	261.40	0.00	776	193.00	698.22	590.60	145.87	0.00
SG-DEM	652	40.84	686.54	372.08	256.05	15.96	360	189.78	686.54	586.51	122.49	18.95
RTSD-DTED2	551	39.00	703.00	370.54	259.81	3.66	305	193.00	703.00	578.99	152.61	4.69
SRTM-DEM	218	55.00	726.00	343.10	243.96	18.46	112	211.00	726.00	549.93	170.21	22.84
GDEM	63	56.00	727.00	340.11	234.78	18.83	43	208.00	727.00	450.53	203.90	16.11

2.6 Conclusion

Related to hydrological applications, the accuracies in terms of stream position and elevation of recently available DEM data in Thailand were assessed by comparing to the MOAC-DEM data which are claimed to be the best reference. The results can be concluded that DEM data of RTSD-DTED2 provide the best accuracies. Of SG-DEM data are relatively moderate. SRTM-DEM and GDEM data express the lowest accuracies in both terms. No significant difference in accuracies according to kinds of terrains is observable.

However, to achieve the conclusive results, more sampling areas and other regions including kinds of terrain are suggested. With different purpose of applications, assessment methods and results can be varied as well.

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CHAPTER III

H-BASED POTENTIAL ALTERNATIVES LOCATION FOR MICRO-HYDROPOWER DEVELOPMENT

3.1 Abstract

The steepness of the stream segments is one of the important characteristics, particularly when it is assigned as H-based potential location for stream water management e.g. locations for micro-hydropower plants, weir sites, and gateway for irrigation canals. This study aims at locating anomaly steepness stream segments using normalized steepness indexing and abrupt slope change techniques through medium-scale (1:50,000) DEM data of Nam Khek watershed. The indexing applies the slope-area relationship to identifying stream segments with anomaly steepness. The relationship is expressed in terms of steepness (k_s) and concavity indexes (θ) at the mid-point of each stream segment. These indexes are normalized by the referent concavity index and result in normalized steepness index(k_{sn}). Any stream segment which has the ratio in percentage more than 110% of its average is the segment having anomaly steepness. The 39 anomaly steepness segments result from total 177 segments. A number of anomaly segments with index less than natural break is further cut off to assure that the rests have actually a high potential for stream water management. This results in 11 stream segments. The abrupt-slope-change stream segments are additional detected based on the least slope change of big waterfalls within the study area. Finally, there are 14 segments selected as potential alternatives. These anomaly segments are validated using slope of stream segments extracted from MOAC-DEM and existing waterfalls within the study area.

Keywords: Slope-Area relationship, Normalized stream steepness Index, Medium-scale DEM data.

3.2 Introduction

One of the essential issues that run-of-river micro-hydropower planner was facing with difficulty in locating H-based potential sites, particularly in large mountainous area. In general, factors used for screening are forest restricted area, trivial number of electric power productivity, and even non-perennial stream (NEA, 1988a; Kupakrapinyo, 2003; Rojanamon, 2009) which are not directly corresponding to that potential. However, that screening sometimes can end up with no potential site. Therefore, this chapter attempts to explain the appropriate methods for determining the H-based potential alternatives from ordinary segments. The normalized stream steepness index and abrupt slope change detection were applied to identifying stream segments with anomaly steepness.

3.3 Literature reviews

3.3.1 Normalized stream steepness index

3.3.1.1 Slope-area relationship

This study applied the slope-area relationship based on assumption of longitudinal bedrock channel profile evolution. In other words, the changing rate of river-bed elevation (dz/dt) uses the competition uplift and erosion from a concept of mass conservation (Howard, Dietrich, and Seidl, 1994):

$$\frac{dz}{dt} = U - E = U - KA^{m}S^{n}, \tag{3.1}$$

where U is the rock uplift rate relative to base level, E is erosion rate of bedrock channel, K is erosion coefficient, A is drainage area, S is local slope, and m and n are a positive constants relative to area and slope, respectively. The channel profile is a steady-state $(dz/dt = 0)$ landscape. The above equation can be solved for equilibrium slope (S_{e}):

$$S_e = (U/K)^{1/n} A^{-m/n}, \tag{3.2}$$

where U and K are uniform, m/n dictates concavity of the equilibrium profile, and $(U/K)^{1/n}$ dictates steepness of the equilibrium profile. So the Equation (3.2) is similar to the relation between slope and area by Hack (1957; quoted in Duvall, Kirby, and Burbank, 2004; Harkins, Kirby, Heimsath, Robinson, and Reiser, 2007):

$$S = k_s A^{-\theta}, \tag{3.3}$$

where k_s equal to $(U/K)^{1/n}$, θ equal to m/n. Also, the parameters of concavity (θ) and steepness (k_s) index are calculated directly from the regression analysis of drainage area (A) and channel slope (S) (Harkins et al., 2007; Lee and Tsai, 2010; Sklar and Dietrich, 1998).

Theoretically, steepness and concavity index can be attributes of either combined or separated stream segments. In this sense, when they are in transient states, any segment may have a knick-point that separates old and new equilibrium states, or it is the equilibrium profile that crosses from uplift regime to another. As seen on Figure 3.1, all cases find no statistically significant difference in the concavity index of channel in the high and low uplift rate zones (Wobus et al., 2006) but apparently high at the border. Steepness index along the entire channel segment should be spatially uniformed (Duvall et al., 2004).

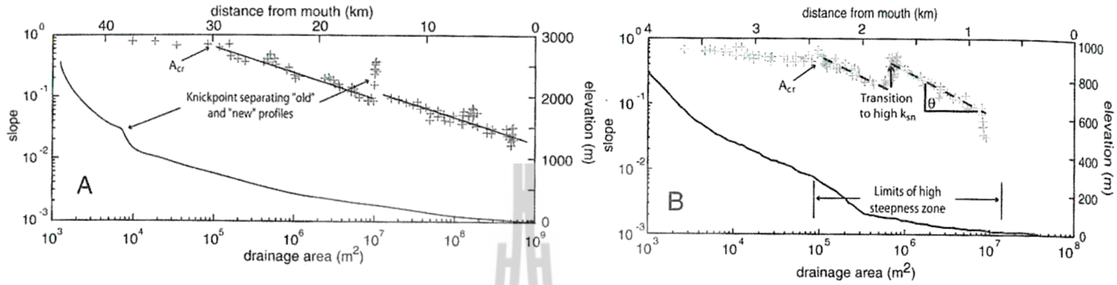

Figure 3.1 Schematic longitudinal profile plots comparing transient and steady-state systems, and corresponded slope-area relationship plots in log-log space.

(A) Transient long profile showing short over steepened reach separating old and new equilibrium states.

(B) Profile crossing from one uplift regime to another, showing channel reaches with constant k_s values is separated by a high or low concavity transition zone in between. Note that A_{cr} marks transition to fluvial channel.

Source: Wobus et al. (2006)

Steepness and concavity index of each stream segment reveals a characteristic of longitudinal profile that is changing throughout the considered streamline. For concavity index, on the one hand, when it is a changing rate of uplift or a knick-point, nearby downstream segment has been decreasing of concavity index value. In other words, graph of slope-area relationship is begun to toe due to abrupt change in decreasing of river-bed elevation while increasing rate of drainage area is small. On the other hand, nearby upstream segment has been spatially uniform of concavity index value when comparing with increasing rate of drainage area (Figure 3.2A).

In case of steepness index, it is a function of rock uplift rate, lithology, and climate. Also, it indicates the relationship between concavity and rock uplift rate. In general, channel profile data are consistently composed of parallel slope–area arrays with different intercepts, in different uplift rate as well as similar climate and lithology (Figure 3.2B) (Lee and Tsai, 2010).

In general, if considered stream segments are not abrupt knick-point, Whipple (2004) stated that they are uniform substrate exhibit smoothly concave up profiles and display concavity indices consistent with theoretical values. Also, characterized concavity (θ) can be divided into four types:

(1) low concavities (<0.4) are associated either with short, steep drainage influenced by debris flow or with downstream increase in either incision rate or rock strength, commonly related to knick-points;

(2) moderate concavities (0.4-0.7) are associated with actively uplifting bedrock channels in homogenous substrates experiencing uniform (or close to uniform) rock uplift;

(3) high concavities (0.7-1.0) are associated with downstream decreases in rock uplift rate or rock strength; downstream transitions to fully alluvial conditions and disequilibrium conditions resulted from a temporal decline in rock uplift rate; and

(4) extreme concavities (<0 or >1) are associated with abrupt knick-points owing either to pronounced along-stream changes in substrate properties

or to spatial or temporal differences in rock uplift rate, including transitions from incisive to depositional conditions.

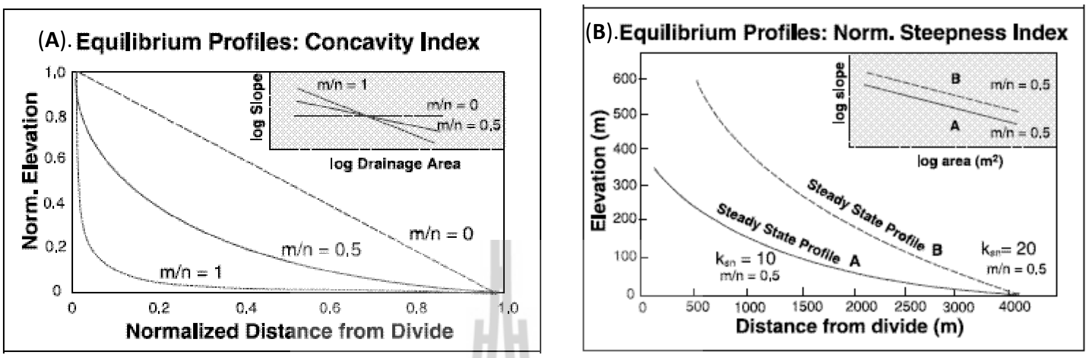

Figure 3.2 Schematics of key parameters derived from equilibrium longitudinal profiles.

(A) Longitudinal stream profile concavity is set by *m/n* ratio (concavity index). The upper inset shows different *m/n* values in slope-area space that is corresponding to three ratios in the main graph.

(B) Two profiles with varying normalized stream steepness indices are presented. Note that although stream B is twice as steep as stream A, they have the same concavity.

Source: Duvall et al. (2004)

3.3.1.2 Data handling

(1) Elevation smoothing and channel slope calculation

Once the elevation and drainage area data are compiled, the next step is to calculate local slopes to be used in slope-area plots. However, if we use built-in ArcGIS functions that compute a slope values from 3x3 moving window across entire DEM, high slopes on channel walls will cause significant upward bias in channel slopes, particularly at large drainage area in narrow bedrock canyons (Wobus et al., 2006). Therefore, this solution is used only raw pixel-to-pixel slopes from the channel itself (rise/run).

In addition, spatial resolution and vertical accuracy of DEM are directly affected to calculating both steepness and concavity indexes. For low resolution and accuracy, synthetic stream often short-circuit meander bends in a river profile, resulting in an overestimate of local channel slope, typically in floodplains at large drainage area (Wobus et al., 2006).

Moreover, zero channel slope value is avoided to regressing of slope-area relation in power law. As aforementioned, the solution is smoothing elevation values which will also be predictable. A popular technique of most research is moving average. It has affect to both concavity and normalized steepness index values which will typically fall within ~10% of other wide range of smoothing windows as seen on Figure 3.3 (Wobus et al., 2006).

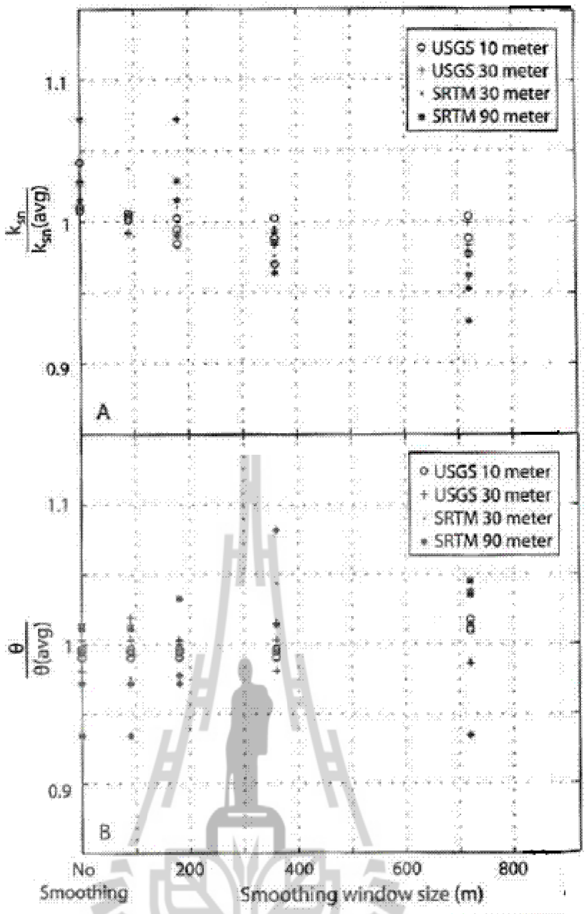

Figure 3.3 Effects of smoothing on longitudinal profile data, from San Gabriel Mountains in southern California.

(A) Plot of k_{sn}, normalized to average value of each group, versus smoothing window.

(B) Plot of θ, normalized to average value of each group, versus smoothing window. Note that steepness and concavity indices for any data set are consistent within ~10%, regardless of the choice of smoothing window size.

Note: Both concavity and normalized steepness indexes are derived based on U.S. Geological Survey (USGS) 10 and 30 m DEM, Shuttle Radar Topography Mission (SRTM) 30 and 90 m DEM, respectively.

Source: Wobus et al. (2006)

(2) Drainage areas above a critical threshold and steepness and concavity indexes calculation

Due to application of slope-area relationship must base on only bedrock channel, the drainage areas above critical threshold (A_{cr}) have commonly been neglected in detachment-limited bedrock erosion models because they are assumed that large flood events are responsible for most bedrock erosion and that in these events the boundary shear stress is much greater than the minimum value for incision (Duvall et al., 2004). In other words, A_{cr} is variably interpreted as the transition from divergent to convergent topography or from debris-flow to fluvial processes (Tarboton, Bras, and Rodriguez-Iturbe, 1989).

Therefore, defining critical threshold (A_{cr}) is based on specified topographic of each study area that may consider plotting slope-area relationship in log-log space (as seen on Figure 3.1) or field survey data. As noted by many researchers, slope-area data often exhibit a pronounced break in scaling at $A_{cr} \leq 10^6 \mathrm{m}^2$ (Whipple and Tucker, 1999; Wobus et al., 2006), which in unglaciated environments may represent the transition from debris-flow-dominated to stream-flow-dominated fluvial channels (Table 3.1).

However, with the potential site assessment, defining critical threshold is not crucial because the sufficient streamflow to generate electrical power of micro-hydropower is usually more than 20 km^2 (NEA, 1984).

Table 3.1 Critical drainage area statistics in other researches.

Study area	A_{cr} (10^5 m^2)
King Range, California (high uplift rate)	0.59 ± 0.20
King Range, California (low uplift rate)	0.72 ± 0.22
Central Range, Taiwan (high uplift rate)	1.40 ± 0.48
San Garbriel Mountains, California (high uplift rate)	0.6-8.9
San Garbriel Mountains, California (low uplift rate)	0.25 ± 0.17

Source: Whipple (2004); Whipple and Tucker (1999).

For steepness and concavity index calculation, they could be attributes of either all streams combined or stream segments. In defining segment length case, it is no art to where to pick regression bounds (Whipple, Wobus, Crosby, Kirby, and Sheehan, 2007). The concavity index may be sensitive to the choice of regression limits, while steepness index appears to be robust across a broad range of data quality and user-chosen regression limits. Thus the regression bound depends on researcher who tries out with various values. However, oversampling leads to decreasing of ability in detecting the change of slope-area relationship. In other words, small knick-point is not detected since its magnitude to regression is reduced.

(3) Normalized stream steepness index and finding stream segments with anomaly steepness

Normalized stream steepness index (k_{sn}) is valued based on the comparison between concavity index of each considered segment and reference concavity (θ_{ref}). It is required for interpretation of steepness values, because k_s and θ as determined by regression analyses are, of course, strongly correlated. In practice, θ_{ref} is usually taken as the regional means to observe θ values in undisturbed stream segments (i.e. those exhibiting no known knick-points, uplift rate gradients, or changes in rock strength along stream), and can be estimated from a plot superimposing all of the data from a catchment. Typically, reference concavities fall in the range of 0.35-0.65 (Hu, Pan, Kirby, Li, Geng, and Chen, 2010; Kirby, Whipple, Tang, and Chen, 2003; Snyder, Whipple, Tucker, and Merritts, 2000). In general, 0.45 has been applied.

As mentioned above, there are stream segments which are used with a referred parameter value. Thus individual segment with k_{sn} allows inter-comparison among difference segments in the same stream and basin (Foster, 2010; Gonga-Saholiariliva, Gunnell, Harbor, and Metering, 2011). Accordingly, the individual segment and the midpoint value for the segment analysed are:

$$k_{sn} = k_s A_{cent}^{(\theta_{ref}-\theta)}, \tag{3.4}$$

and

$$A_{cent} = 10^{(\log A_{max} + \log A_{\min})/2}, \tag{3.5}$$

where k_s and θ are determined by regression, A_{min} and A_{max} bound the segment of the profile analysed, and A_{cent} is the midpoint value for the segment analysed. In practice, equation 3.4 is found to match calculation by regression analysis to within ~10%. Where the difference between θ and θ_{ref} is large, however, (>0.2), the k_{sn} value is meaningful only over a short range of drainage area near A_{cent}.

Due to the affect of smoothing elevation to both concavity and normalized steepness index, it is expected that stream segments with normal steepness will typically fall within 10% from their average. Therefore the segment with k_{sn} above the range is considered as the anomaly steepness segment.

3.3.2 Previous studies

Gonga-Saholiariliva et al. (2011) used normalized stream steepness index to compare with their automated method for locating knick points and knick zones based on local slope gradient and curvature attributes, particularly any areas that could not be surveyed due to inaccessibility. The accuracy of their method is tested on two digital elevation grids, SRTM DEM (ground resolution of 90 m, resample to 75 m) and the GDEM (DEM 15 m from ASTER) in the Sierra Nacimiento (New Mexico, USA). The writer explained that out of every 10 gradient anomalies detected by the SRTM-derived numeric routine, up to 8 are certifiable knick points recognized among a population of geo-referenced occurrences surveyed in the field. Moreover, the approach also revealed that normalized stream steepness index is a popular method to study the river gradient variation and even the abrupt change in longitudinal stream profile. For the aster DEM, the writer stated that it has a lower performance because of topographic attributes derived from elevation data that are dependent on initial DEM quality and accuracy.

Hu et al. (2010) used a normalized stream steepness index to extract information about the spatial patterns of differential rock uplift along the northern Qilian Mountain. The SRTM DEM, stream segment length of 1,000 m, and reference concavity of 0.45 were chosen for the study. Analysis of the longitudinal profiles of bedrock channels revealed systematic differences in the channel steepness index along trend of the frontal ranges. Local comparisons of channel steepness also revealed that lithology and precipitation have limited influence on channel steepness. In addition, the results revealed that the index could show a difference between high and low rock uplift rate.

Shahzad, Mahmood, and Gloaguen (2007) analysed stream longitudinal profile and neotectonic of Hazara Kashmir Syntaxis. The study focused on Kunhar River, Kishanganga River and their 95 contributing streams. Stream network has been extracted from SRTM DEM using D8 Algorithm. ASCII files of contributing area, elevation, downstream distance, and spatial locations were prepared for all streams. Steepness and concavity indices were calculated from stream power law. The writer stated that stream power law gives useful information for understanding the tectonics of the study area. In addition, both index values over a region can be used for investigating spatial variation of bedrock uplift and detecting geological boundaries among different rocks types; for instance, sand stone, silt stone, limestone, and the like.

Wobus et al. (2006) described in detail a method for exploiting slope-area relationship in which both steepness and concavity indices of longitudinal profile shape and character are derived from DEM data. The description of the method is followed by three case studies from varied tectonic settings. The case studies illustrate the power of stream profile analysis in delineating spatial patterns of, and in some cases, temporal changes in rock uplift rate. Moreover, the writer also stated that slope-area data in log-log space would exhibit considerable scatter, which may be obscure natural breaks in scaling along the profile. However, further smoothing of the slope data greatly aids identification of scaling breaks without influencing their position and with predicting effects on the values of both indices. The effects on concavity values will also be predictable, but will depend on the relative position of outliers in a particular profile: If the data contain spikes high in the profile, it can anticipate the concavities to decrease with increased smoothing as the regression pivots counterclockwise (flattens). On the contrary, it will be true for data containing spikes near the toe of the channel. Despite these systematic and predictable biases, it should be noted that steepness and concavity values will typically fall within ~10% of one another for a wide range of smoothing windows.

3.4 Research methods

3.4.1 Research Procedure

The main steps of this part are displayed in Figure 3.4. All data preparations and analyses were operated on raster-based GIS data and Microsoft Excel table data.

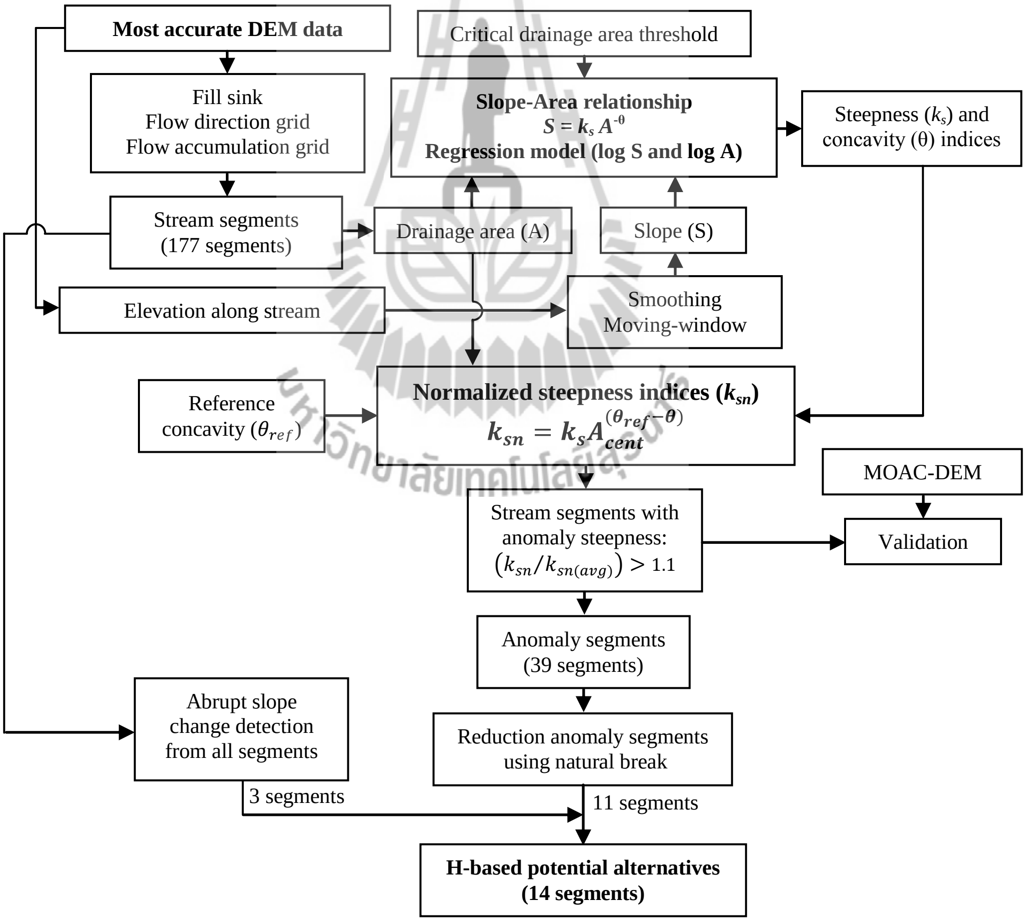

Figure 3.4 Process of finding H-based potential alternatives.

3.4.2 Finding stream segments with anomaly steepness and H-based potential alternative

3.4.2.1 Calculation of normalized stream steepness index

The main steps of the calculation of normalized stream steepness index are displayed in Figure 3.4.

(1) Extracting the synthetic stream network from the most accurate DEM data after fill sinks, flow direction, and flow accumulation array analyses in Hydrology, a tool in Spatial Analyst of ArcGIS^{TM} version 9.

(2) Separating the synthetic stream network into consecutive segments without stream conjunction. However, the segments with drainage area less than critical threshold value were removed.

(3) Converting ordered pairs between the drainage areas of flow accumulation layer and elevation values of unfilled DEM to Microsoft Excel table.

(4) Smoothing elevation values along stream by moving average of 30 pixels (approximately 1,000 m).

(5) Calculating slope of each cell along a stream using smoothed elevation data.

(6) Calculating steepness and concavity indices of each stream segment using equation 3.3 with slope and area upstream from every cell of a segment. However, the ordered pairs with slope value equal to zero were removed from that calculation.

(7) Calculating normalized stream steepness index by using concavity reference and drainage area at midpoint of each segment.

(8) Identifying anomaly steepness segment by filtering using >1.1 of $k_{sn}/k_{sn}(avg)$ as a filter.

(9) Sieving outstanding H-based potential alternatives by cutting off a number of identified anomaly steepness segments of which their k_{sn}values were less than the selected natural break.

3.4.2.2 Additional anomaly segments by abrupt slope change detection

To cover missing anomaly segments due to rather small working scale of DEM data and ambiguity of proper segment length, the abrupt-slope-change stream segments were additionally picked up based on the least slope change of 4 big water falls within the study area, Kaeng Sopa, Poy, Kaeng Song, and Wang Nok Aen (Figure 3.10). They have relief higher than 10 m. Some of the results can be repetitive with the results of normalized stream steepness indexing.

3.4.3 Validation

The resulting anomaly steepness stream segments can be validated as the following steps:

(1) random comparison of the anomaly steepness stream segments with well-known waterfalls by image visualization; and

(2) random comparison of the sampled slope from MOAC-DEM data.

3.5 Results and discussion

3.5.1 Anomaly steepness stream segment

Normalized steepness index of each stream segment was calculated based on RTSD-DTED2 DEM data with cell size 30 m x 30 m, which were proved to be most acceptable among available DEM data (see details in Chapter II). In addition, flow direction analysis and flow accumulation were used for creating extracted stream. Also, the moving average was 1 km of smoothing window and referent concavity was 0.45 while stream segment length was 1 km. By applying slope-area relationship to finding stream segments with anomaly steepness, it results in 39 anomaly segments from the entire 177 segments as shown in Figures 3.5 and 3.6. The k_s, θ, and k_{sn}values of each stream segment were shown in Appendix B.1.

Due to the medium scale of elevation data used and improper segment length identified, k_{sn} application based on slope-area relationship was brought to help identify the anomaly stream segments. For example, in case that segments have the same slope profile while using the medium scale elevation data and improper segment length, they can have the same degree of anomaly steepness. But in fact some of them can have anomaly steepness different from others if their watershed areas obviously reduced. It means that the obvious area reduction help indicate the anomaly steepness of segments which cannot be detected using the general profiles of segments. Also it was confirmed that medium scale DEM data have more acceptable spatial resolution and can be used to partially cover their low vertical resolution.

As a result, a number of anomaly segments seems to be too big. This might be because of the improper use of referent concavity and k_{sn} filtering. They might be appropriate in other areas, according to the previous studies, but do not fit to this area. Therefore, this study proposed sieving those anomaly steepness segments by few methods to assure that a proper number of outstanding H-based potential alternatives were picked up.

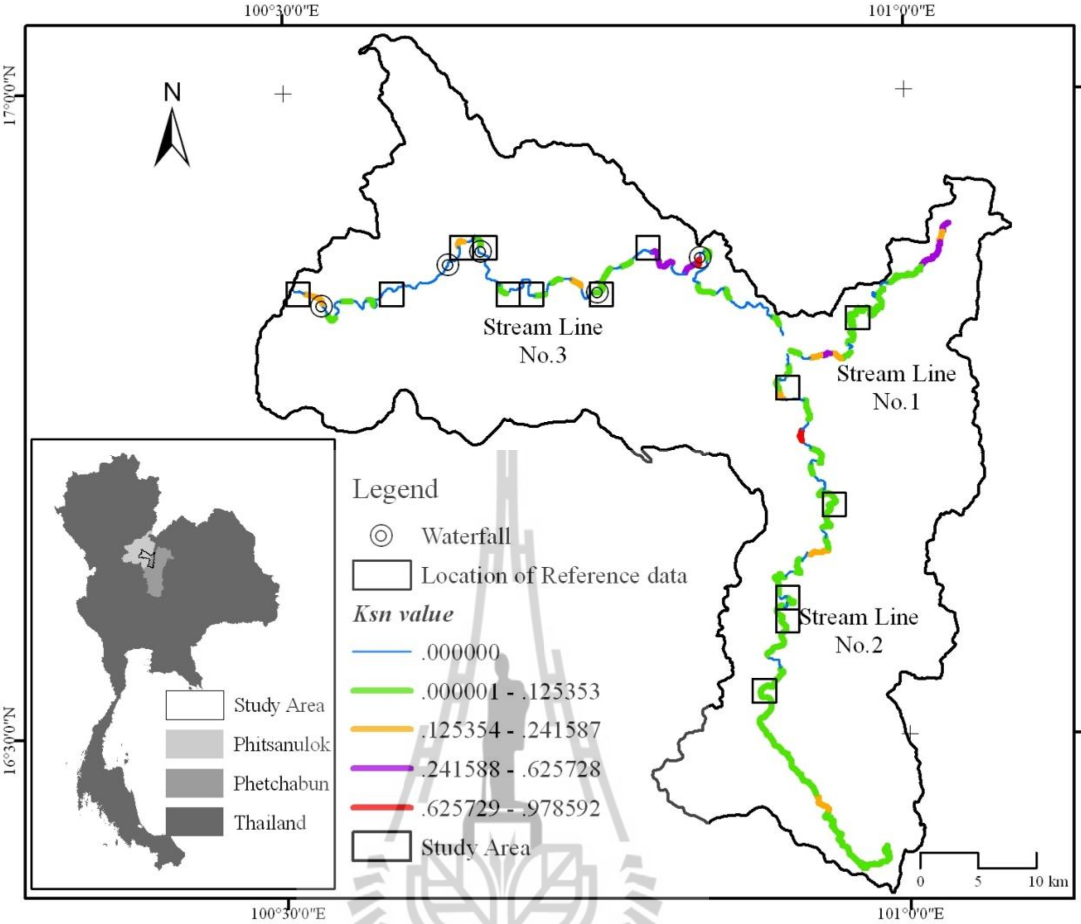

Figure 3.5 The k_{sn} values of every stream segment.

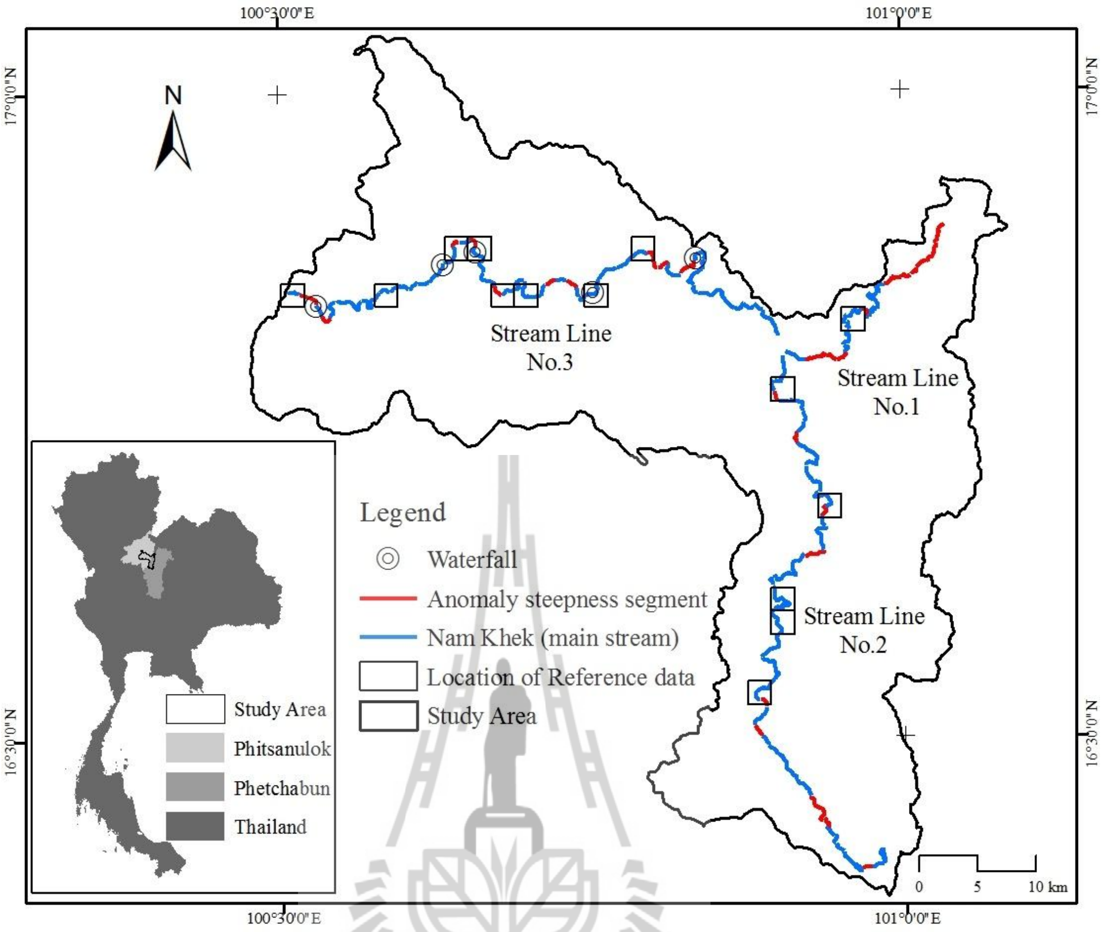

Figure 3.6 Anomaly steepness segments along Nam Khek for every stream line.

3.5.2 Outstanding H-based potential alternatives

To sieve the actually high anomaly segments resulting in outstanding H-based potential alternatives, natural break of k_{sn} frequency curve was a possible technique.

With natural break method (Figure 3.7), if the breaks were at k_{sn} 0.276 and 0.540, a number of outstanding segments were 11 and 3 respectively. The result of cut off by using SD (0.153) was 20 segments (Figures 3.8-3.10). A number of outstanding segments extracted from both methods were not much different. The method using natural break cut off at 0.276 was then selected to use.

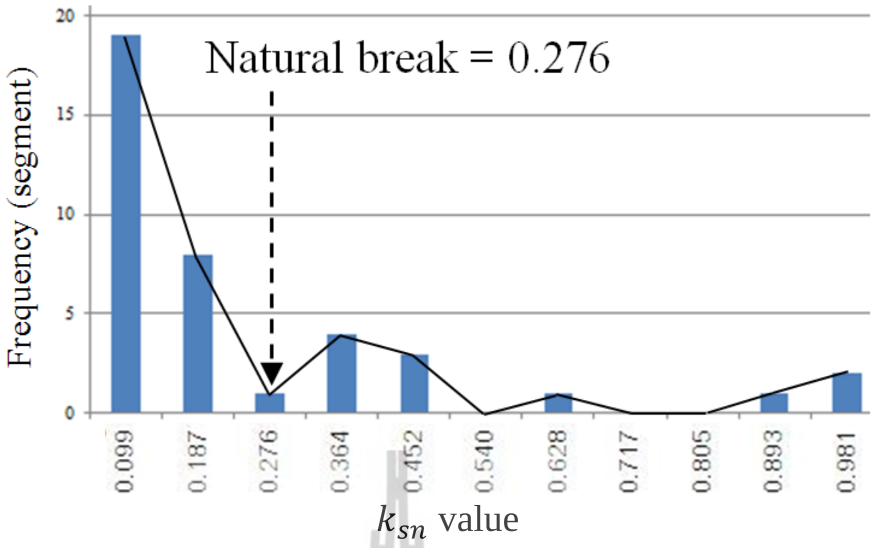

Figure 3.7 k_{sn} frequency distribution of anomaly steepness segments.

From Figures 3.8-3.10, the anomaly segments detected cannot actually correspond with all obvious big waterfalls in the area. Three big waterfalls cannot be detected. Therefore, abrupt-slope-change detection was applied to cover the missing ones.

3.5.3 Anomaly segments by abrupt-slope-change detection

The abrupt slope change of each consecutive segment was applied to 177 original stream segments using the least slope change (0.0038) of 4 big waterfalls (mentioned above) existing within the study area. It resulted in 28 segments as shown in Figures 3.8-3.10 and Appendix B.1. Some of them were repetitive to the anomaly ones sieved from steepness index. They can be described as follows: 6 out of 28 segments were repetitive with anomaly segments selected by k_{sn} . There was only 1 of these 6 segments corresponding with Poy waterfalls; and 22 out of those 28 segments were associated with normal segments and 2 big waterfalls (Wang Nok Aen and Kaeng Song). Therefore, all 3 big waterfalls were recovered. Only 20 in a group of normal segments were not big waterfalls. Using this techniques, knick points at the border of segments can be detected even though the upstream segment is rather flat. Remarkably, additional field investigation or using DEM data with higher spatial and vertical resolutions to check those 20 segments found in a group of normal ones was strongly recommended. However, it was unfortunate that accessibility of these segments was too difficult together with unavailable MOAC-DEM in hand. Therefore, in this study only 14 segments were considered as potential alternatives for further consideration in terms of additional Q-based potential and power productivity. The maps of their location were shown in Appendix B.2.

3.5.4 Validation

3.5.4.1 Validation with well-known waterfalls

Longitudinal stream profiles of 3 streamlines in the study area were displayed in Figures 3.8-3.10. Four big waterfalls with relief higher than 10 m were used for validation. Without the result from the abrupt slope change detection, there were 3 segments containing actual big waterfalls mismatched with anomaly segments extracted by indexing. When the additional abrupt change detection was applied, there were no missing waterfalls. It was very interesting to note that the furthermost downstream waterfalls not associated with any selected anomaly segment might be because of their oversize drainage area compared to their slope. This came up with limitation of the indexing ability when dealing with oversize drainage area in the most downstream part.

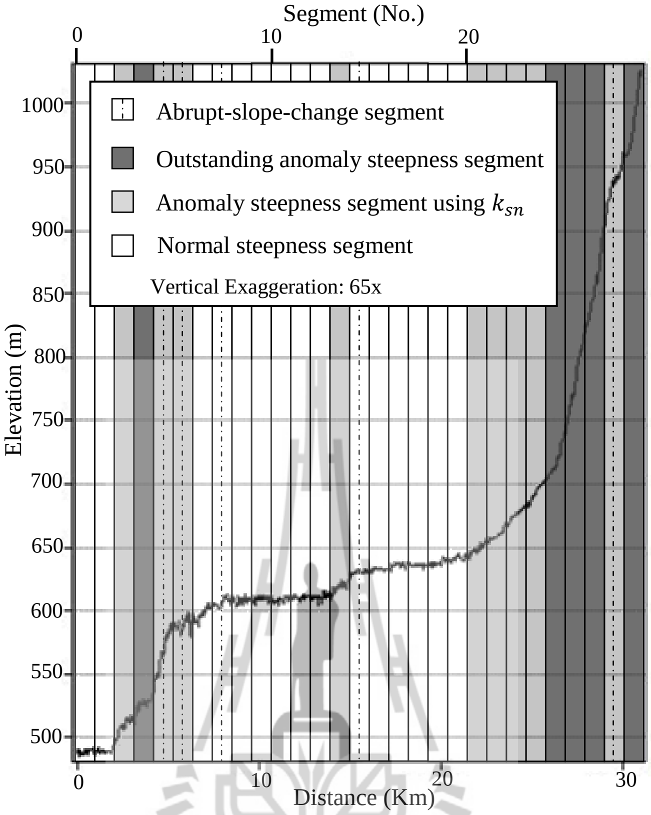

Figure 3.8 Longitudinal profile of stream line no.1.

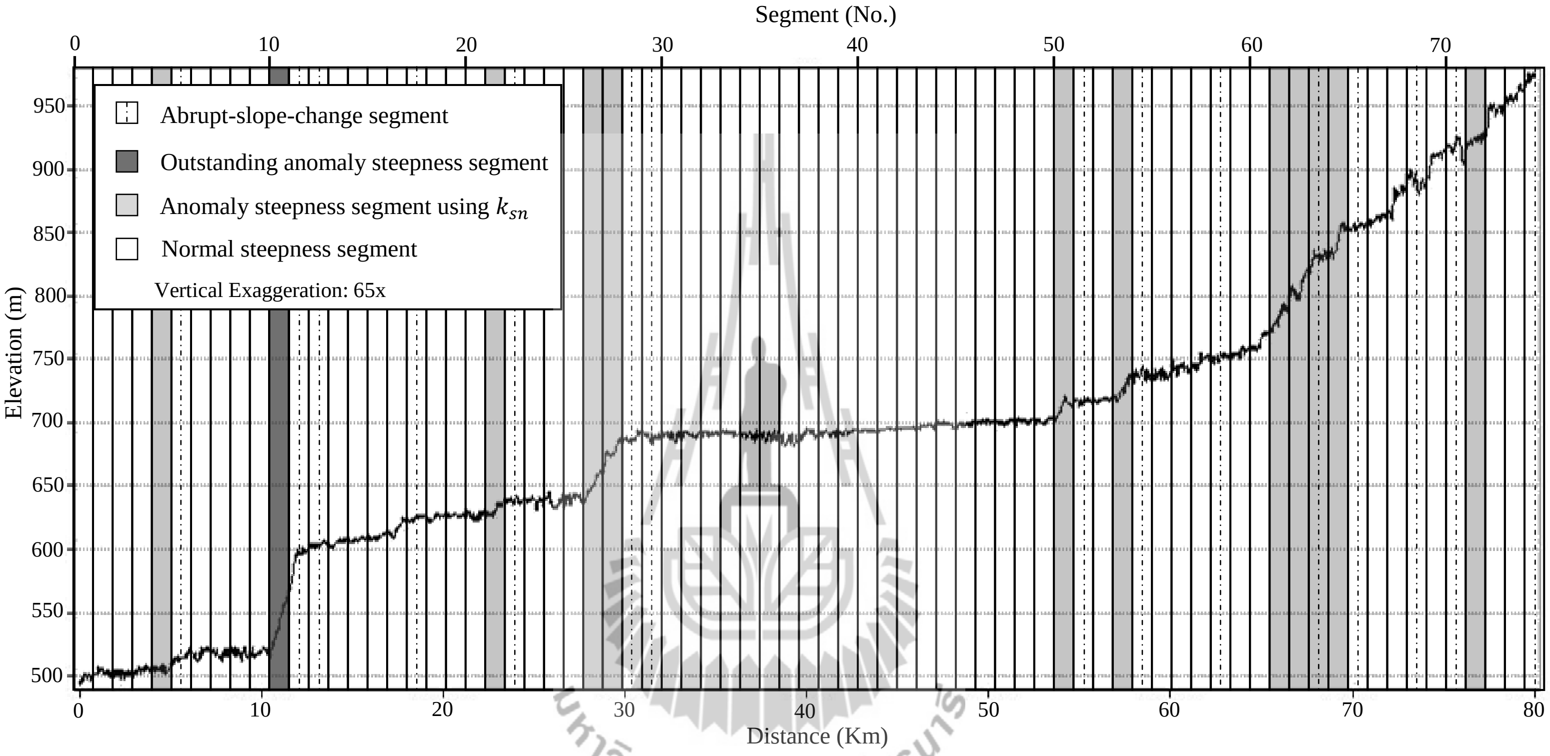

Figure 3.9 Longitudinal profile of stream line no.2.

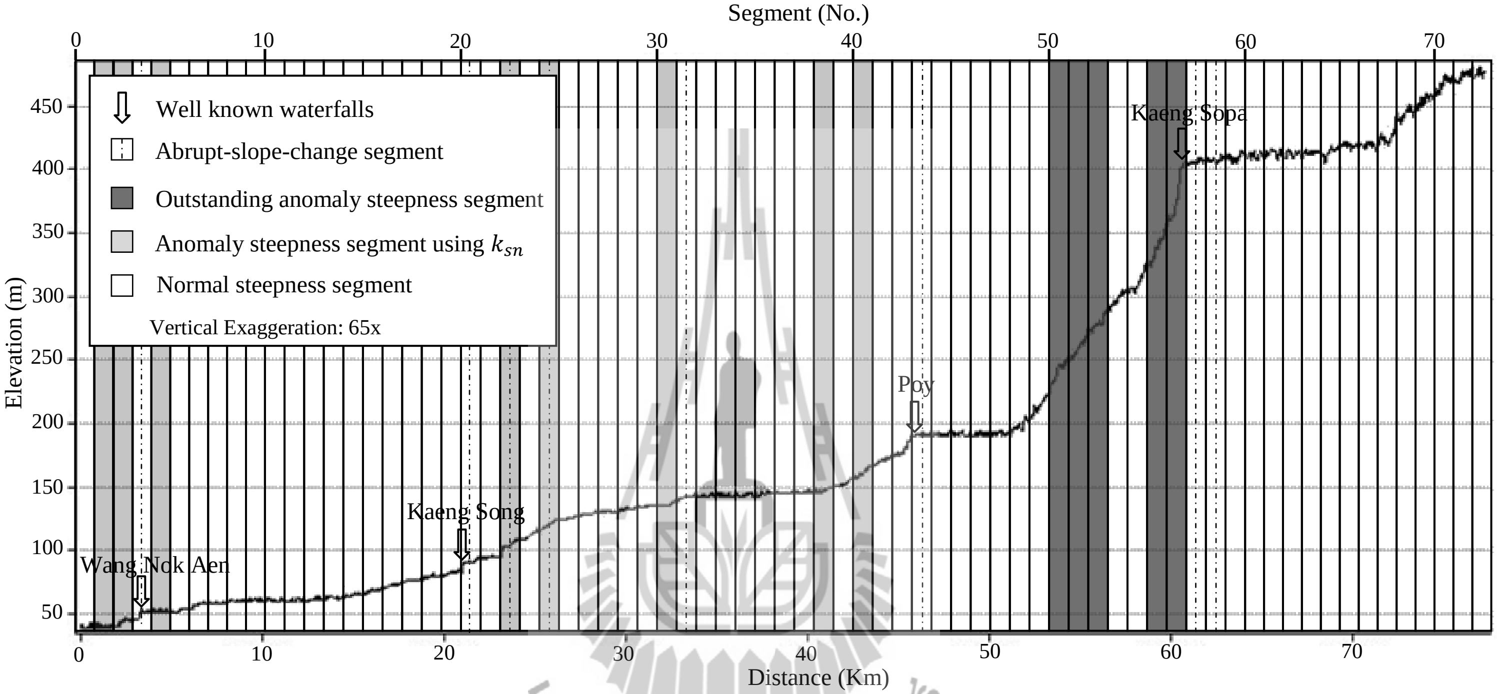

Figure 3.10 Longitudinal profile of stream line no.3 including waterfalls positions.

3.5.4.2 Validation with slope from MOAC-DEM data

Correlating 6 samples of anomaly segment slopes and k_{sn} with corresponding segment slopes were derived from the MOAC-DEM data, their correlation coefficients were 0.81 and 0.92 respectively. The graphs of their relationship were shown in Appendix B.3.

As seen in Table 3.2, it was observable that minimum, average and maximum slopes of anomaly segments derived from MOAC-DEM data well corresponded to the ones of normal segments. The maximum slopes of the anomaly ones were obviously higher than the normal ones. Considering the statistics slopes derived from the RTSD-DTED2 DEM data, the order seemed to be acceptable but all slopes of the normal segments were observably higher than the ones of anomaly segments. It indicated that the medium scale DEM data used provided more chances of wrong selection of the anomaly segments when only the slopes were considered. When considering the k_{sn} values, their statistics of anomaly ones were entirely and obviously different from the normal ones which carried not more than 0.0597.

Table 3.2 Characteristics of both group anomaly and normal segment.

Source	**Statistical**	**Anomaly**	**Normal**
Slope MOAC-DEM	Max	0.0221	0.0124
	Average	0.0064	0.0024
	Min	0.0001	0.0000
Slope RTSD-DTED2	Max	0.0198	0.0221
	Average	0.0087	0.0032
	Min	0.0040	0.0004
k_{sn} value	Max	0.4483	0.0597
	Average	0.1807	0.0151
	Min	0.0910	0.0000

3.6 Conclusion

Related to conventional method for locating the H-based alternatives, the trustfulness in terms of stability of result was improved by using normalized steepness index together with abrupt-slope-change detection. It can be concluded that the k_{sn}index and abrupt-slope-change detection allow the sieving effectively H-based potential alternatives. From the validation, the result covers all potential sites. There were 4 big waterfalls associated with the segments selected by those two methods. Comparing slope of anomaly segments and k_{sn} with referent slopes derived from MOAC-DEM data, the correlation coefficient was 0.81 and 0.92 respectively. Therefore, it can be concluded that the methods used were helpful and efficient in sieving H-based alternatives.

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CHAPTER IV

Q-H-BASED POTENTIAL ALTERNATIVES LOCATION FOR MICRO-HYDROPOWER DEVELOPMENT

4.1 Abstract

The method used for locating potential sites of run-of-river type micro-hydropower plant in this study was Flow Duration Curve (FDC) constructing at ungauge catchment for stream flow behavior representation. The process of construction was accomplished based on the relationship between annual runoff and drainage area. Monthly runoff data at gauge station within the study area and the vicinity were used as input data for that process. The relationship between annual runoff and drainage area of this area was presented with R^2 = 0.91. The process resulted in $Q_{monthly}$ of each exceeding percentage at each H-based potential alternative. In addition, other parameters participated with theoretical power calculation were collected using GIS techniques i.e. the structural length of water pipe, and water-head. They were calculated together with $Q_{monthly}$ for power productivity estimation of each alternative. Finally 14 H-based potential alternatives were kept as Q-H-based potential alternatives because their estimated power through flow duration curve method were more than 20 kW.

Keywords: Flow duration curve, discharge estimation, power productivity.

4.2 Introduction

For run-of-river type micro-hydropower projects, NEA (1988) stated that the flow for power generation is not regulated but is equal to the streamflow. As the head for power generation is more or less constant, the flow normally plays a single role controlling the level of generation. Therefore, the knowledge of river behavior is important for determining the expected power productivity of each alternative. The favorite method to estimate discharge for that type is a flow duration curve (FDC).

This study estimated FDC at ungauge catchments using both the relationship between annual runoff and drainage area and the ratio of runoff water in different months during a year of กรมชลประทาน (2551). This method also resembled the studies of NEA (1988), Kupakrapinyo (2003), Chaisomphob et al. (2009), and Rojanamon (2009). The study area was surrounded by their study areas. At the same time the study area can also be assumed as a hydrological homogeneous region because it was only an element within sub-region divided by the previous relevant literatures (Chaisomphob et al., 2009; สัจจะชาญ พรัดมะลิ, 2544). In addition, slope values of all 3 existing streamlines derived from RTSD-DTED2 (Appendix B.1) were not much different i.e. by average 0.006 - 0.019 and by S.D. 0.008 - 0.025. Therefore, it was considered reasonable that the area had the homogeneous characteristic which can be represented by a single relationship between annual runoff and drainage area for the FDC estimation of this study.

On the other way, daily or monthly flow simulation methods have been developed such as Hydrological Model Application System (HYMAS) software or Agro hydrological (ACRU) model as well as the Soil Conservation Service Curve Number (SCS-CN) method or Soil and Water Assessment Tool (SWAT) which can be estimate based on rainfall event in a particular area. However, the successful application of these methods is dependent on an adequate quantification of model parameter values and the availability of reliable rainfall input data. The conventional method, particularly FDC, is sometimes hampered by a lack of knowledge on physiographic characteristics of the drainage basins while the latter (simulation) methods are not always available in study area. Smakhtin, Hughes, and Creuse-Naudin (1997) also suggested that the regionalization technique may be preferable in small-scale water projects because of its cost and time saving.

As previously stated, the objective of this chapter was to sieve Q-H-based potential alternatives using FDC and power productivity at ungauge catchment. The result was used as input for ranking the alternative in the next chapter.

4.3 Literature reviews

4.3.1 Discharge estimation using FDC at ungauge catchment

4.3.1.1 Relationship between annual runoff and drainage area

The relationship between annual runoff and drainage area (Q-A) have mostly been used for stream flow estimation in ungauge catchment by many researches (Kupakrapinyo, 2003; NEA, 1988; Rojanamon, Chaisomphob, and Bureekul, 2009; Sarapirome, Teaumroong, Kulworawanichpong, Ongsomwang, and Paengwangthong, 2010; กรมชลประทาน, 2551; ประกอบ วิโรจนกูฏ และ ฤกษ์ชัย ศรีวรมาศ,

2543). It was useful for the derivation of flow duration curve for run-of-river type projects as stated in the previous section, due to lack of actual measured flow data at each site selection. However, application of the relationship can be extrapolated in this study area because of those watersheds having similar topography to the upstream gauged catchments. The plots of both Q-A and FDC used observed data from gaging station measured by both RID and DWR.

The relationship determination was obtained using chosen gauge stations with hydrological similarity. This is an approach adopted for determining the values of a and b from logarithm scales. Annual runoff and drainage area relationship: a regression analysis is performed as straight line in log-scale. The drainage area is an independent variable whereas the mean annual runoff is a dependent variable. Therefore, the values of coefficients in a relationship (Equation 4.1) are fixed for the particular river basin:

$$Q_m = aA^b, \tag{4.1}$$

where Q_m is mean annual runoff (Million Cubic Meters/MCM); A is drainage area (km^2); a is a constant; and b is a slope of line in power linear regression.

The data are used from the stations within the particular basin. This approach is employed in case that there are at least 5 stations used. Thus, a correlation coefficient can also be known. Also, it will be possible to cooperate with FDC to interpolate streamflow values using the ratio of drainage areas of the respective catchments basins (Biedenharn et al., 2000; Rojanamon, 2009). Therefore when we use their talent to extrapolate in power generated calculation, basic assumption from limit of their period of record cannot be avoided.

4.3.1.2 Flow Duration Curve

Basically, FDC illustrates the relationship between the frequency and magnitude of streamflow for only gauge site (Castellarin, Galeati, Brandimarte, Montanari, and Brath, 2004). With Biedenharn et al. (2000) stated that there are two possible methods of estimating a FDC for ungauge catchments. The first method is by using the longest possible common period of records from nearby gauge stations within the same drainage basin (called drainage area-flow duration curve method). This method relies on the availability of gaging station data at a number of sites on the same river as the ungauged location. FDCs for each gauge station are derived. Provided that there is a regular downstream decrease in the discharge per unit watershed area, a graph of discharge for a given exceedance duration against upstream drainage area will produce a power function with virtually no scatter about the best-fit regression line. For example, Figure 4.1 shows the relationship of the River Wye, UK (Hey, 1975; quoted in Biedenharn et al., 2000).

The second method develops a regionalized flow-duration curve (called regionalized duration curve method). This method is based on data from watersheds with similar characteristics. A dimensionless index (the ratio of discharge to bankfull discharge) is to transfer flow duration relationships among basins with similar characteristics. In addition, such a dimensionless discharge index can be used to transfer a flow duration relationship to an ungauged site from a nearby gauge site.

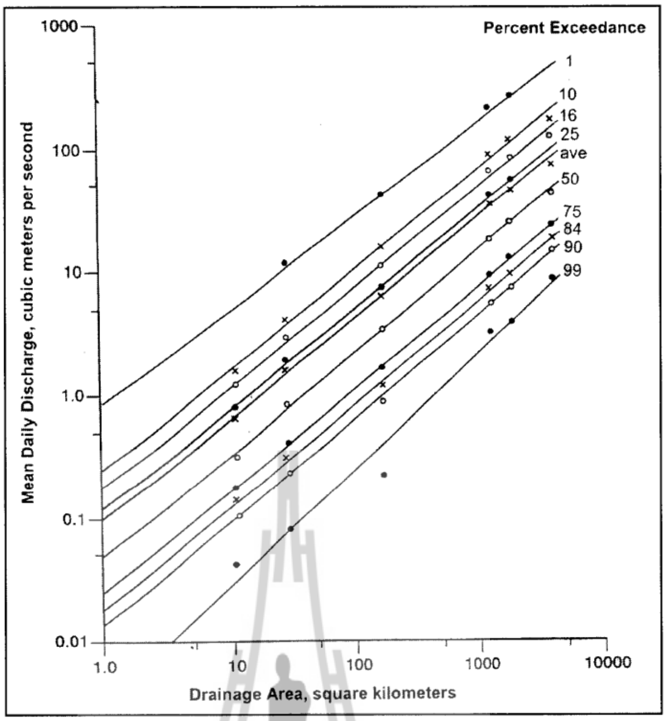

Figure 4.1 Example of flow duration curves for the River Wye, UK.

Source: Hey (1975)

As for FDC, Davie (2003) stated that an understanding how much water is flowing down a river is fundamental to hydrology. In particular, interest for both flood and low flow hydrology is the question of how representative a certain flow is. This can be addressed by looking at the frequency of daily flows and some statistics derived from the frequency analysis. The culmination of the frequency analysis is a FDC. It is concerned with the amount of time that a certain flow is exceeded. The data most commonly used are daily mean flows and the average flow for each day. To derive a FDC the daily mean flow data are required for a long period of time, in excess of five years. However, to determine generated power and energy, NEA (1988) stated that monthly data was sufficient for the desk study level as shown in Figure 4.2.

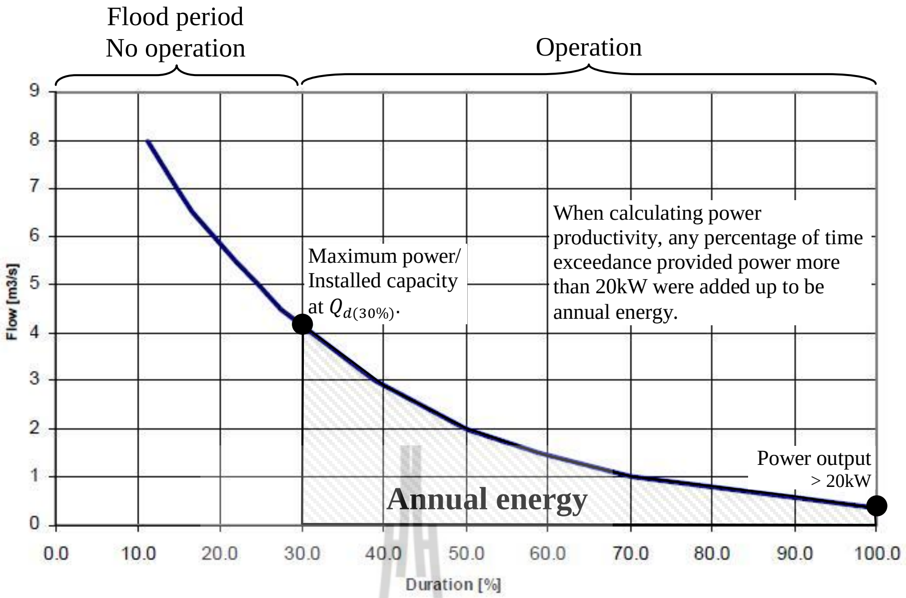

Figure 4.2 Example of a flow duration curve derived from monthly stream flow data and annual energy calculation.

Source: ESHA (2004)

4.3.2 Micro-hydropower computational design

There are many studies and guides on small hydropower design; for instance, NEF (1996), Rojanamon et al. (2009), and Arruda et al. (2010), providing theoretical power calculation generated at a plant as the product of H, Q, and parameters (i.e. gravity, turbine and generator efficiency, length of headrace and penstock). An equation derived for power generated by a run-of-river type micro-hydropower plant in the study is:

$$P = \mathrm{g}\eta_t\eta_\mathrm{g}Q_d\left(H_d - \left(0.001L_h + 0.005L_p\right)\right), \qquad (4.2)$$

where P is power generated from a plant in kW; g is the specific gravity (9.81 m/s^2); η_t is the turbine efficiency (0.88); η_g is the generator efficiency (0.96); Q_d is the design discharge (m^3/s); $H_d$is the gross head (the different elevation at a weir and a power house); L_h is the length of headrace (m); and L_p is the length of penstock (250 m) follow through the previous study (Sarapirome et al., 2010; มหาวิทยาลัยเทคโนโลยีสุรนารี, 2552). In addition, the expression of $(0.001L_h + 0.005L_p)$ represents the loss head that is incurred when transferring the water from intake entrance to turbine. The parameters of this computational design can be displayed in Figure 4.3.

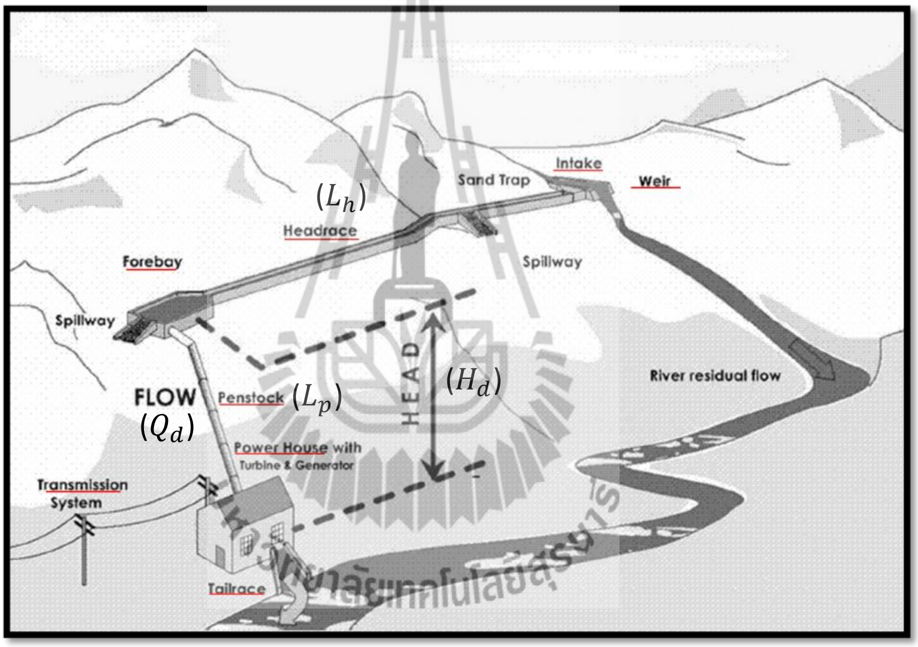

Figure 4.3 Typical components and related parameters of run-of-river micro-hydropower.

Source: NREL (2001).

The variables required for power productivity estimation at each alternative site which can be obtained by the use of Geographic Information System (GIS) techniques are H_d, Q_d, and a straight distance of alternatives along the same stream which reflects the structural length of water pipe. Based on practical experiences mentioned in NEA (1988), the maximum Q_d was set at $Q_{d(20\%)}$ for economic reason. In general, the Q_d for the potential sites varied mainly between $Q_{d(20\%)}$ and $Q_{d(50\%)}$. However, previous relevant studies (Kupakrapinyo, 2003; Rojanamon, 2009) around this study area mostly set the design discharge as $Q_{d(30\%)}$ because any flows greater than this was expected to occur during flood periods. Therefore, in this study, the Q_d of discharge at 30% time of exceedance was used to estimate the installed capacity.

4.3.3 Previous studies

NEA (1988) developed master plan of mini hydropower development for the whole country of Thailand. The study based on engineering and economical criteria. There were three categories of project considered i.e. run-of-river, reservoir, and irrigation storage dam. With run-of-river type, the study could sieve potential alternatives using engineering criteria and then ranked the feasible projects by using economical criteria. In addition, the writer stated that there was a very high number of sites to be investigated; there was a need to streamline the project appraisal. So, initial screening criteria were consequently developed for rejecting surely-unfeasible sites at the early stage. The screening criteria were as follows: (1) the sites had not to be located in the forest restricted area; (2) the installed capacity had to be in the range of 200 to 6,000 kW; and (3) the project's initial economic rate of return (EIRR), calculated based on initial project layout and benefit, had to be less than 8 per cent and technically unfeasible of constructions.

Kupakrapinyo (2003) used GIS techniques and synthesis flow duration curve to study site selection on run-of-river type small hydropower plant in Changwat Maehongson. Similar to the study of NEA (1988), his study could sieve weir and power house using engineering criteria and then ranked the potential area by using economical criteria. However, the possible location for weir site was chosen by the specialist from the candidate areas selected by two criteria i.e. concentrate on perennial stream and a flat area where the slope was less than 1 degree. After site selection by the expert, additional factors or criteria were needed for analysis such as runoff river flow at the weir site, head, distance from weir to power house (not more than 5 km) and electric power productivity (usually use between 1,000 to 6,000 kW) respectively. The result showed that there were 22 potential small-scale hydropower plants considered in this study. Among these, 15 plants were justified economically feasible.

Sarapirome et al. (2010) located potential alternatives for run-of-river micro-hydropower plants along stream within low-relief area of Mun river basin. The researchers aimed at developing a web-based tool applying GIS data and techniques to locate the water-head-based potential alternatives for that plant. Intersecting points of main streams and contour lines with varying intervals were regarded as preliminary alternatives with varying water heads for plant locations. The straight distance between two intersecting points implied length of water pipe used in plant construction. Drainage area of each intersecting point (sites) could be determined using GIS hydrological techniques operating on DEM. Using the typical relationship between the surface runoff and the area upstream which was unique for any basin, the runoff of each intersecting point could be estimated. Water head and runoff discharge achieved through GIS were mainly utilized to anticipate power and straight distances or pipe length at points. They were employed as conditions to interactively query in order that any alternatives met with the specific requirements and constraints could be selected. In addition, the researchers stated that result of the study could be further used for other detailed selection processes with additional techniques such as MCDA which can include socio-economic and environmental impact factors into consideration.

4.4 Research methods

The locating Q-H-based potential alternative can be divided into 2 parts, which consist of estimation of FDC at ungauge catchments and ranking Q-H-based potential alternatives of selection sites.

4.4.1 Discharge estimation using flow duration curve at ungauge catchment

The main steps of the discharge estimation using flow duration curve at ungauge catchment are displayed in Figure 4.4.

(1)Based on the relationship between observed annual runoff (Q_m) and drainage area (A) derived from chosen gaging stations, mean annual runoff at ungauged catchment was estimated based on measured drainage area, and flow accumulation was determined using GIS techniques on DEM data.

(2) Mean monthly runoff per unit area from measured gaging station was constructed. An ungauged catchment was estimated based on monthly ratio of runoff in a year from the nearest downstream station with data recorded longer than 40 years. It was converted to the monthly flow ($Q_{monthly}$) in the unit of cubic meters per second.

(3)Flow duration curve (FDC) of an ungauged catchment was constructed by putting $Q_{monthly}$ in descendent order together with the accumulated percentage of time in a year with the flow rate not less than it.

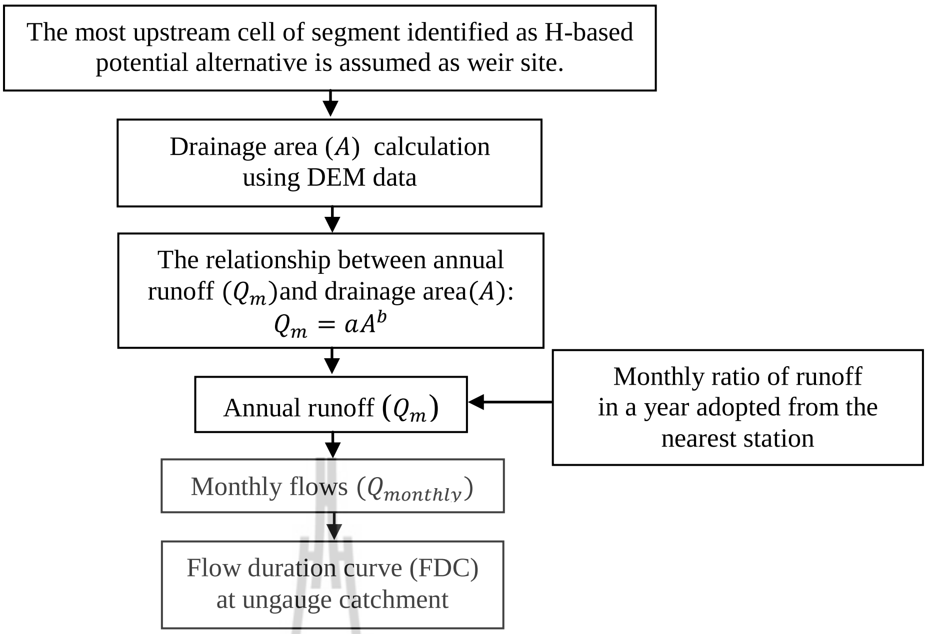

Figure 4.4 Process of construction of flow duration curve at ungauge catchment.

4.4.2 Locating and ranking Q-H-based potential alternatives using their power productivity

To locate Q-H-based potential alternatives, outstanding H-based alternatives with known Q were inputs for the power productivity estimation using equation 4.2. Any percentage of time exceedance providing power productivity more than 20 kW were added as annual electric energy (see example in Figure 4.2). The rank of potential alternatives relied on the annual electric energy at the sites. The site with a higher energy exhibited the higher rank of potential. The flow of operations can be displayed in Figure 4.5.

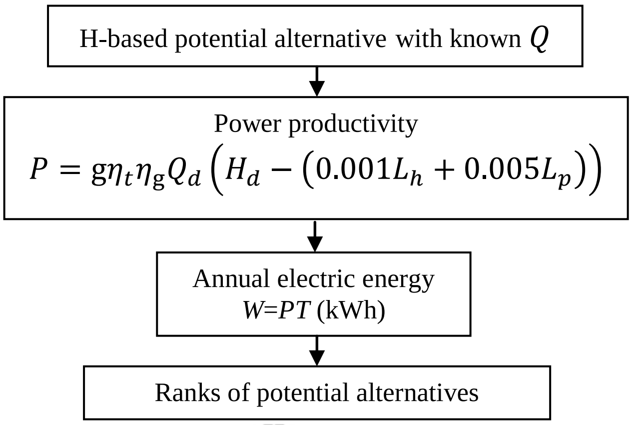

Figure 4.5 Locating and ranking Q-H-based potential alternatives using their power productivity.

4.5 Results and discussion

4.5.1 Discharge estimation

4.5.1.1 Relationship between annual runoff and drainage area

As previously stated in the introduction, the amount of annual runoff at any Q-based alternatives can be calculated based on the relationship between annual runoff and drainage area. The relationship can be estimated using existing input data which were annual runoff data and watershed areas of small-watershed gauge stations with hydrological similarity in the study area and the vicinity i.e. N.24, N.36, N.40, N.54, N.55, N.58, N.59, N62, N.66, N.73, and 091603. Their characteristics, location, and monthly runoff distribution were shown in Table 4.1 and Appendix C respectively. The resulting relationship showed high coefficient of determination ($R^2 = 0.91$) which was acceptable for preliminary feasibility study. The relationship can be expressed as Equation 4.3:

$$Q_m = 0.9325A^{0.9137}. \tag{4.3}$$

The graph and equation of the relationship were displayed in Figure 4.6. With input of watershed area of each H-based alternative, the mean annual runoff of each alternative can be estimated using the relationship in Equation 4.3. The map of mean annual runoff at each alternative was ungauged as shown in Figure 4.7. It was generated using the equation.

Table 4.1 Chosen gauge stations for the relationship determination and their characteristics.

No.	Code	Name	Position		Duration Record	Length (Year)	Drainage area (Km^2)	Mean annual runoff (MCM)
			Latitude	Longitude				
1	N.66	Huai Om Sing at Ban Noen Phoem	17° 07' 17"N	100° 53' 51"E	1998-2011	14	152	68.37
2	N.54	Khlong Wang Pong at Ban Wang Pong	16° 19' 34"N	100° 48' 28"E	1999-2011	13	185	128.20
3	N.73	Nam Khek-Ban Tantawun	16° 34' 08"N	100° 53' 30"E	2002-2011	10	210	233.21
4	N.58	Nam Fia at Ban Kok Muang	17° 08' 33"N	100° 56' 06"E	1998-2011	14	322	110.55
5	N.62	Nam Klueng at Ban Huai Tha Nua	17° 14' 25"N	100° 33' 11"E	1998-2011	14	350	146.44
6	N.59	Nam Kan at Ban Na Pho Na Chan	17° 01' 43"N	100° 50' 44"E	1998-2011	14	405	209.95
7	N.55	Nam Phak at Ban Tha Sakae	17° 15' 10"N	100° 37' 51"E	1994-2011	18	697	514.29
8	091603	Nam Khek at Ban Khek Yai	16° 52 '00"N	100° 50' 00"E	1967-2009	43	993	584.20
9	N.36	Mae Nam Kwaenoi at BanNonggataow	17° 04' 59"N	100° 49' 55"E	1970-2011	42	1651	869.29
10	N.24	Nam Khek-Ban wang nok aen	16° 50' 35"N	100° 31' 20"E	1965-1987,1989-2011	46	1861	832.94
11	N.40	Mae Nam Kwaenoi-BanNongbon	17° 13' 14"N	100° 21' 10"E	1977-2011	35	4340	1,837.31

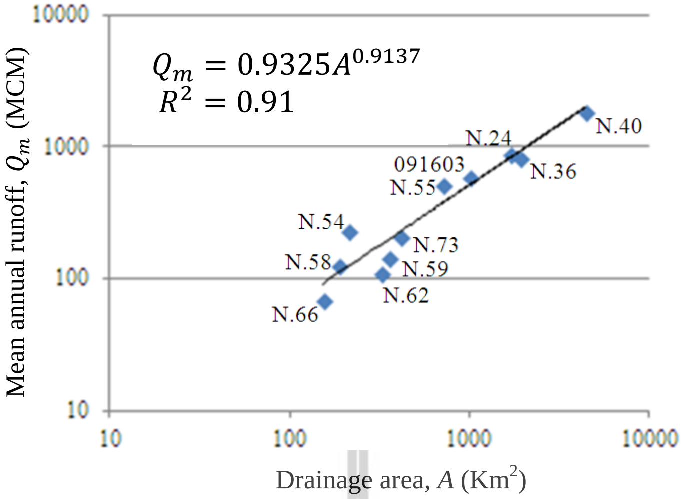

Figure 4.6 Relationship of annual runoff and drainage area from 11 gaging stations.

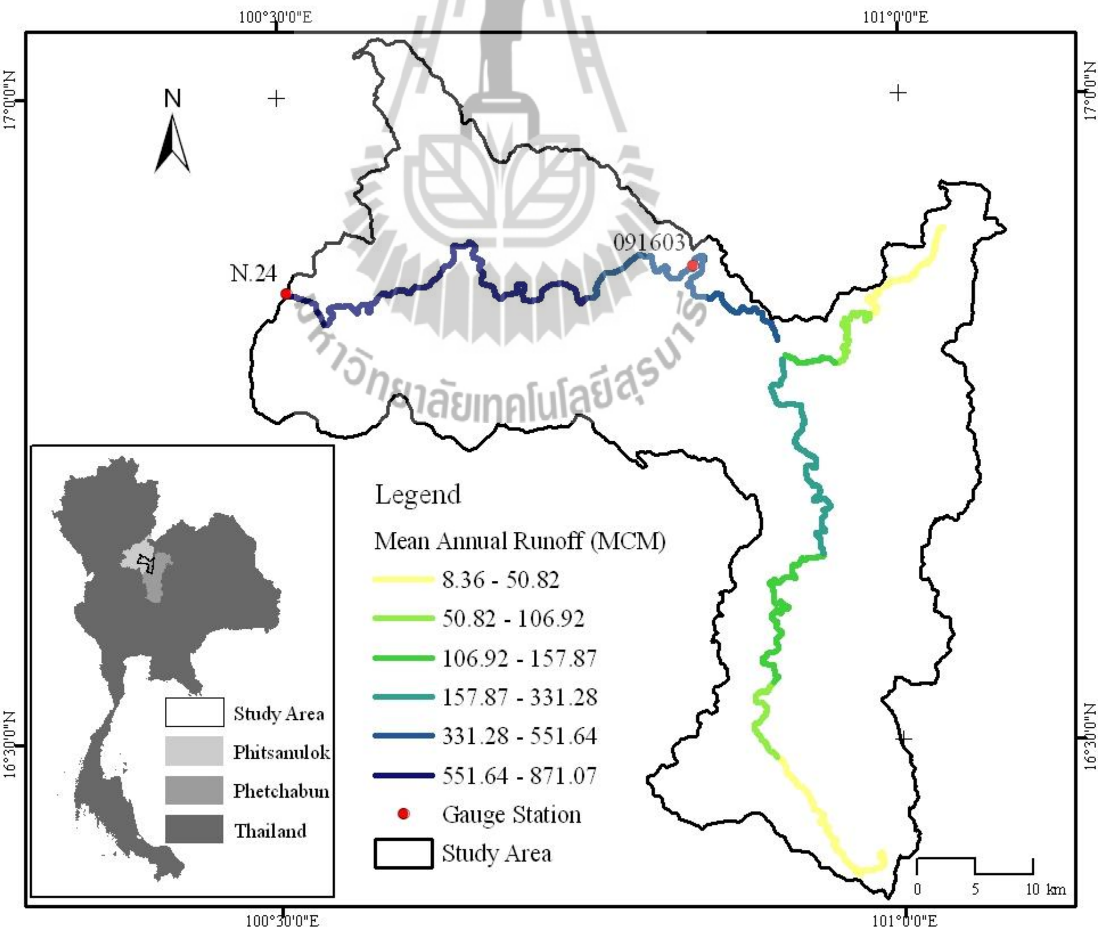

Figure 4.7 Mean annual runoff at ungauged catchment.

4.5.1.2 Flow duration curve

The monthly runoff at an ungauge catchment was the product of the multiplication of its mean annual runoff (Q_m) and the monthly ratio of runoff in a year from the nearest downstream gaging station. The ratios of 2 gauged stations available in the study area were shown in Tables 4.2, 4.3 and Figure 4.8. After that they were converted to the monthly flow ($Q_{monthly}$) in cubic meters per second as shown in Table 4.4. The $Q_{monthly}$ was arranged in descendent order. The accumulated percentage of time or month (in this case) in a year was calculated. The relation curve between arranged $Q_{monthly}$ and the accumulated percentage of time of each potential alternative were estimated and displayed in Table 4.5 and Appendix C.3.

Table 4.2 Monthly ratios of runoff in a year at 091603 gauge station.

Year	Runoff (MCM)												
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
1967	3.31	7.43	12.10	19.70	57.97	108.86	46.40	11.49	5.96	4.93	2.86	1.60	282.53
1968	3.02	25.23	78.71	137.38	101.95	64.11	58.06	13.22	6.00	2.57	1.14	1.58	493.34
1969	1.22	3.69	14.34	39.74	50.11	146.88	69.90	25.23	8.99	3.65	2.42	2.28	368.06
1970	2.81	6.77	37.07	51.67	128.74	112.32	44.76	17.28	7.88	4.75	2.25	2.33	419.04
1971	2.69	8.22	23.59	48.47	88.99	121.82	67.13	13.13	6.96	4.66	3.12	2.95	392.26
1972	2.88	3.08	14.60	29.64	71.54	85.97	86.05	23.33	9.16	3.91	2.79	2.26	335.23
1973	2.63	7.61	26.87	68.26	80.61	123.55	50.46	11.32	5.69	4.78	2.32	4.58	388.80
1974	4.29	9.85	18.58	34.73	101.09	75.77	45.27	34.56	10.97	3.49	2.71	3.11	344.74
1975	4.15	12.44	54.52	63.50	108.00	160.70	82.68	19.44	8.99	6.99	3.59	4.35	529.63
1976	2.58	30.84	27.65	64.11	155.52	199.58	134.78	46.66	13.31	5.20	5.21	3.08	687.74
1977	4.62	16.16	9.68	27.82	72.75	243.65	61.60	14.95	7.78	6.63	3.38	3.30	472.61
1978	5.37	19.70	16.93	123.55	200.45	261.79	133.06	23.41	9.68	6.66	4.63	3.17	807.84
1979	4.54	13.22	74.56	29.55	140.83	130.46	39.57	11.58	6.50	6.99	4.30	2.87	464.83
1980	3.65	12.36	86.40	103.68	132.19	256.61	67.39	20.56	9.50	3.88	2.35	3.42	701.57
1981	5.93	22.72	49.68	113.18	210.82	81.39	46.92	21.34	9.16	4.99	3.27	3.03	571.97
1982	4.32	6.72	18.84	37.50	83.20	245.38	104.54	35.34	16.50	6.36	3.57	3.27	565.06
1983	1.53	12.96	41.39	55.64	126.14	134.78	95.04	39.48	15.12	9.42	5.06	3.02	540.00
1984	5.12	24.45	139.97	91.58	107.14	171.07	183.17	43.11	16.68	9.24	7.25	5.20	803.52
1985	4.72	14.26	57.80	94.18	95.04	131.33	122.69	52.88	19.96	8.58	5.07	3.88	610.85
1986	9.07	80.44	72.23	93.31	111.46	94.18	52.01	24.62	11.49	9.76	5.29	3.91	567.65
1987	3.96	11.23	21.43	13.31	97.63	190.08	108.00	32.31	13.31	6.02	3.31	4.78	504.58
1988	7.40	45.19	35.60	83.64	119.23	107.14	142.56	36.89	13.74	7.66	6.32	4.21	608.26
1989	3.45	61.60	66.01	58.84	38.62	72.75	68.08	21.17	9.68	8.27	4.22	3.68	416.45
1990	2.13	63.50	154.66	127.87	75.08	108.86	91.58	40.52	13.48	5.32	2.28	10.63	696.38
1991	6.13	30.67	48.56	25.75	285.98	205.63	88.99	22.20	10.89	6.98	3.84	2.96	739.58
1992	1.97	4.12	13.91	15.64	102.82	92.45	66.79	14.26	7.65	9.42	4.86	3.28	337.82
1993	6.54	25.49	28.94	24.19	47.00	145.15	49.42	12.10	7.07	5.74	3.09	3.98	358.56
1994	5.70	47.61	127.01	108.86	219.46	223.78	65.06	19.18	13.31	4.34	3.49	8.81	846.72
1995	7.68	25.49	26.09	100.22	192.67	213.41	88.13	23.16	10.89	7.40	4.60	2.60	702.43
1996	8.81	42.34	91.58	46.83	102.82	260.93	100.22	39.83	17.02	6.94	5.04	4.30	727.49
1997	8.40	4.96	5.48	46.92	74.91	129.60	115.78	20.39	9.76	8.49	4.67	5.45	434.59
1998	5.19	26.61	33.70	114.05	125.28	112.32	49.68	17.88	8.90	5.73	3.65	2.32	505.44
1999	12.70	69.29	92.45	73.09	121.82	168.48	70.59	36.37	14.26	5.65	3.39	2.09	670.46
2000	34.21	116.64	129.60	139.97	95.04	209.09	119.23	41.13	16.24	7.17	7.14	4.28	924.48
2001	5.65	42.60	75.60	90.72	152.06	108.86	51.06	17.37	9.24	8.08	4.95	10.20	576.29
2002	5.07	36.37	88.13	61.60	201.31	304.99	116.64	49.16	27.39	6.78	2.61	2.63	907.20
2003	9.33	11.84	59.27	79.32	96.77	140.83	60.83	21.43	5.49	13.65	7.66	12.27	518.40
2004	6.17	42.08	151.20	75.08	101.09	124.42	47.43	15.29	8.18	8.15	11.58	4.08	594.43
2005	6.96	22.38	41.47	95.04	108.86	173.66	61.69	32.14	15.38	6.17	3.35	2.55	569.38
2006	12.61	58.67	63.68	144.29	105.41	256.61	223.78	39.31	18.32	9.59	6.38	6.25	941.76
2007	9.16	40.52	52.53	55.81	158.11	211.68	255.74	31.71	14.77	6.81	2.59	2.22	841.54
2008	20.39	38.53	80.78	87.26	139.97	211.68	109.73	65.49	21.34	7.49	5.99	2.03	790.56
2009	9.68	49.25	37.24	56.42	49.25	139.97	158.98	27.13	13.05	9.24	5.49	5.29	560.74
Average	6.46	29.19	55.82	70.97	117.11	159.59	90.73	27.43	11.76	6.71	4.26	4.05	584.20
S.D.	5.62	24.12	39.94	36.35	51.50	62.15	47.99	12.86	4.72	2.14	1.89	2.36	176.49
Ratio	0.01	0.05	0.10	0.12	0.20	0.27	0.15	0.05	0.02	0.01	0.01	0.01	1.00
Maximum	34.21	116.64	154.66	144.29	285.98	304.99	255.74	65.49	27.39	13.65	11.58	12.27	941.76
Minimum	1.22	3.08	5.48	13.31	38.62	64.11	39.57	11.32	5.49	2.57	1.14	1.58	282.53
Mean Q ($m^3/s/km^2$)	0.0025	0.0110	0.0217	0.0267	0.0440	0.0620	0.0341	0.0107	0.0044	0.0025	0.0018	0.0015	0.0187

Table 4.3 Monthly ratios of runoff in a year at N.24 gauge station.

Year	Runoff (MCM)												
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
1965	3.60	18.30	78.00	52.40	153.00	193.00	78.00	31.00	10.40	4.90	2.80	1.90	627.30
1966	1.30	15.00	60.50	68.10	285.00	242.00	60.60	26.90	12.00	5.20	2.60	1.70	780.90
1967	2.20	6.20	9.20	20.00	61.70	187.00	74.40	14.20	6.20	2.70	1.30	1.30	386.40
1968	5.80	28.30	90.10	178.00	128.00	87.40	93.90	17.90	6.00	4.20	2.30	1.50	643.40
1969	1.00	3.30	20.20	65.00	87.30	283.00	128.00	48.20	14.00	6.80	3.20	2.00	662.00
1970	2.20	8.30	54.00	110.00	285.00	220.00	101.00	45.10	18.40	8.10	3.70	3.00	858.80
1971	1.90	11.40	39.10	68.50	122.00	171.00	83.10	19.10	7.70	3.12	1.40	1.20	529.52
1972	1.50	1.50	20.00	33.70	74.90	95.50	117.00	32.90	10.50	3.20	1.00	2.50	394.20
1973	1.20	6.70	43.60	70.10	118.00	183.00	86.40	20.40	7.10	2.50	1.10	1.30	541.40
1974	3.40	11.30	21.70	43.90	121.00	96.80	66.50	52.50	12.90	9.50	4.00	4.00	447.50
1975	3.40	18.90	62.20	71.00	170.00	330.00	190.00	47.30	17.80	9.50	8.20	3.40	931.70
1976	2.20	35.30	31.30	87.50	251.00	289.00	238.00	82.10	24.40	11.20	5.00	3.80	1060.80
1977	5.30	17.30	9.90	27.80	96.50	321.00	109.00	30.60	12.40	6.80	3.70	3.50	643.80
1978	4.80	17.70	17.10	135.00	265.00	367.00	246.00	44.10	18.20	9.20	4.80	2.90	1131.80
1979	4.30	20.30	119.00	50.00	159.00	192.00	75.20	18.00	7.60	4.30	2.50	3.10	655.30
1980	3.80	20.30	116.00	156.00	194.00	406.00	127.00	43.40	17.30	8.90	4.80	4.00	1101.50
1981	9.00	30.80	62.90	148.00	289.00	119.00	78.20	34.00	14.90	7.30	3.40	1.90	798.40
1982	4.10	6.50	20.50	38.00	90.60	356.00	171.00	49.10	21.40	11.00	4.50	2.00	774.70
1983	1.00	10.50	39.80	64.50	177.00	237.00	178.00	67.70	23.00	13.70	9.50	6.60	828.30
1984	5.30	18.50	62.00	134.00	160.00	242.00	287.00	155.00	49.10	22.50	13.00	9.40	1157.80
1985	13.80	115.00	87.70	106.00	152.00	136.00	62.20	29.40	15.00	8.00	4.10	6.00	735.20
1986	3.50	10.30	23.50	10.30	106.00	260.00	140.00	39.20	14.30	6.90	4.50	2.60	621.10
1987	4.60	56.80	35.00	85.30	131.00	116.00	199.00	40.80	13.20	6.30	3.50	2.70	694.20
1989	2.40	58.80	80.10	68.20	51.00	106.00	95.80	29.00	11.30	5.60	2.20	13.90	524.30
1990	5.00	87.00	154.30	187.80	103.00	159.80	125.20	42.50	21.20	12.10	5.80	3.10	906.80
1991	8.60	22.20	36.60	22.40	361.50	264.80	149.40	33.40	20.20	16.80	11.20	9.70	956.80
1992	3.30	5.25	20.50	25.70	133.89	121.90	84.30	19.20	10.50	6.80	4.40	4.70	440.44
1993	6.30	24.92	35.41	25.95	47.60	203.78	67.48	13.09	6.77	4.97	3.82	7.14	447.22
1994	6.60	78.58	205.40	133.75	327.46	367.57	103.68	35.22	25.76	13.70	10.40	6.25	1314.38
1995	5.49	28.72	27.77	114.71	261.74	378.45	137.39	32.28	11.48	5.78	3.75	3.45	1011.01
1996	11.80	68.90	179.40	62.20	168.30	505.00	200.66	68.50	22.10	10.70	5.37	5.22	1308.14
1997	10.14	6.81	6.89	50.33	101.43	208.23	181.33	23.69	8.35	3.89	2.75	0.39	604.23
1998	5.15	29.52	30.54	167.81	134.02	133.12	78.98	26.19	12.17	7.13	4.08	2.97	631.68
1999	46.56	84.59	117.85	81.33	202.58	276.27	113.58	53.04	15.79	7.07	5.37	2.69	1006.72
2000	24.17	133.85	161.21	193.60	130.30	401.47	187.68	35.27	20.84	14.89	9.41	13.14	1325.82
2001	6.70	59.30	104.10	114.40	262.50	147.70	107.40	35.20	16.50	8.40	2.40	1.90	866.50
2002	5.27	27.61	88.50	60.08	413.60	626.31	177.27	55.71	31.57	18.98	14.50	15.14	1534.53
2003	15.64	19.86	54.84	79.24	120.02	232.61	78.77	23.97	14.17	9.64	12.30	4.49	665.54
2004	7.92	38.34	202.60	88.86	127.41	205.30	55.68	21.99	15.12	9.48	3.80	3.48	779.98
2005	12.31	14.37	42.85	103.14	130.94	246.71	73.58	35.65	23.94	12.27	3.93	4.36	704.05
2006	11.38	51.42	87.44	164.44	152.37	308.56	200.28	38.28	18.10	10.15	5.82	5.75	1053.99
2007	11.0	53.2	78.2	80.3	159.7	368.3	350.8	47.5	21.4	11.7	10.4	6.0	1198.4
2008	15.8	46.1	74.7	119.9	174.0	299.2	137.3	100.4	30.6	19.6	13.4	13.4	1044.3
2009	5.9	60.4	67.6	93.7	77.0	194.6	251.8	52.9	16.6	0.6	0.0	0.0	821.1
2010	0.0	3.5	6.0	52.6	218.4	306.1	190.4	49.7	20.5	0.0	0.0	5.7	852.9
2011	8.9	103.6	114.1	124.0	247.0	482.4	155.4	40.2	16.7	8.6	5.7	3.9	1310.5
Average	7.08	34.68	67.40	87.77	169.19	253.78	136.83	41.34	16.64	8.58	5.12	4.55	832.94
S.D.	7.63	31.88	51.54	48.18	83.84	117.72	66.83	24.41	7.86	4.83	3.65	3.58	281.79
Ratio	0.01	0.04	0.08	0.11	0.20	0.30	0.16	0.05	0.02	0.01	0.01	0.01	1.00
Maximum	46.56	133.85	205.40	193.60	413.60	626.31	350.80	155.00	49.10	22.50	14.50	15.14	1,534.53
Minimum	0.00	1.50	6.00	10.30	47.60	87.40	55.68	13.09	6.00	0.00	0.00	0.00	386.40
Mean Q ($m^3/s/km^2$)	0.0015	0.0067	0.0138	0.0174	0.0336	0.0516	0.0274	0.0086	0.0033	0.0017	0.0011	0.0009	0.0140

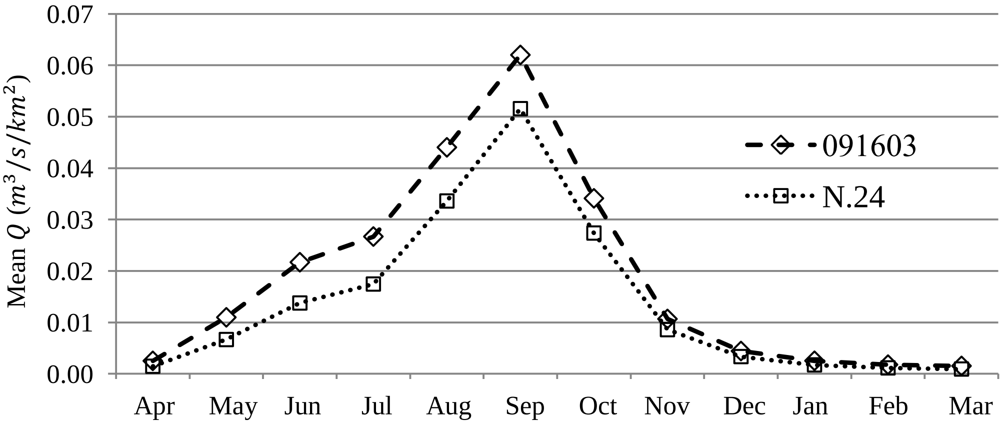

Figure 4.8 Mean monthly runoff distribution of two gauged stations available in the study area.

Table 4.4 Mean annual runoff (Q_m) and monthly discharge (Q) of the alternatives.

Site	Stream No.	Segment ID	Catchment area (km^2)	Q_m (MCM)	Mean monthly discharge (m^3/s)											
					Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1	1	4	253.28	146.50	0.62	2.73	5.39	6.64	10.99	15.45	8.49	2.66	1.10	0.63	0.44	0.38
2	1	25	38.69	26.32	0.11	0.49	0.97	1.19	1.97	2.78	1.52	0.48	0.20	0.11	0.08	0.07
3	1	26	27.86	19.50	0.08	0.36	0.72	0.88	1.46	2.06	1.13	0.35	0.15	0.08	0.06	0.05
4	1	27	22.45	16.00	0.07	0.30	0.59	0.73	1.20	1.69	0.93	0.29	0.12	0.07	0.05	0.04
5	1	29	16.97	12.40	0.05	0.23	0.46	0.56	0.93	1.31	0.72	0.22	0.09	0.05	0.04	0.03
6	2	11	570.90	307.84	1.31	5.74	11.34	13.96	23.09	32.46	17.83	5.58	2.31	1.32	0.93	0.79
7	3	4	1,767.48	864.48	2.90	12.75	28.42	34.21	67.01	98.42	51.45	16.54	6.52	3.55	2.32	1.84
8	3	21	1,488.72	739.00	2.48	10.90	24.29	29.25	57.28	84.14	43.98	14.14	5.57	3.04	1.99	1.57
9	3	44	1,080.99	551.64	1.85	8.14	18.13	21.83	42.76	62.80	32.83	10.56	4.16	2.27	1.48	1.17
10	3	51	959.09	494.51	1.66	7.29	16.25	19.57	38.33	56.30	29.43	9.46	3.73	2.03	1.33	1.05
11	3	52	956.57	493.32	1.66	7.28	16.22	19.52	38.24	56.16	29.36	9.44	3.72	2.03	1.33	1.05
12	3	53	954.02	492.12	1.65	7.26	16.18	19.48	38.14	56.03	29.29	9.42	3.71	2.02	1.32	1.05
13	3	56	947.05	488.83	1.64	7.21	16.07	19.35	37.89	55.65	29.09	9.35	3.69	2.01	1.31	1.04
14	3	57	946.40	488.53	2.08	9.11	17.99	22.15	36.65	51.52	28.30	8.86	3.66	2.09	1.47	1.26

4.5.2 Theoretical power productivity of the alternatives and their ranking

The power productivity of each alternative was calculated based on Equation 4.2 using several parameters i.e. discharge obtained from FDC, water-head and structural length of water pipe obtained using GIS techniques. To estimate the installed capacity or the maximum productivity, the Q_d was assumed as a discharge at 30% time of exceedance, denoted as $Q_{d(30\%)}$(Table 4.5). For the annual electric energy of each alternative, it was calculated by the multiplication between its power (>20 kW) and operation time derived from FDC. The power productivity was derived from a discharge at any percentage of time of exceedance as shown in Table 4.6. This result was used as one of the criteria in ranking the potential alternatives discussed in the next chapter.

Table 4.5 FDC and installed capacity of Q-H-based alternatives.

Site.	Stream No.	Segment ID	Q_m (MCM)	Percent of Time Exceedance 10	20	30	40	50	60	70	80	90	100	H_d (m)	L_h (m)	Power (kW) at $Q_{d(30\%)}$
1	1	4	146.50	14.56	9.99	7.38	5.64	2.73	2.34	0.91	0.63	0.48	0.38	23	568.84	1,448.29
2	1	25	26.32	2.62	1.79	1.33	1.01	0.49	0.42	0.16	0.11	0.09	0.07	34	698.68	379.64
3	1	26	19.50	1.94	1.33	0.98	0.75	0.36	0.31	0.12	0.08	0.06	0.05	72	598.53	591.37
4	1	27	16.00	1.59	1.09	0.81	0.62	0.30	0.26	0.10	0.07	0.05	0.04	76	638.43	511.86
5	1	29	12.40	1.23	0.85	0.62	0.48	0.23	0.20	0.08	0.05	0.04	0.03	75	615.33	391.45
6	2	11	307.84	30.59	20.99	15.51	11.86	5.74	4.93	1.91	1.31	1.00	0.79	44	620.00	5,735.55
7	3	4	864.48	92.14	60.78	41.11	29.58	12.75	11.50	5.33	3.16	2.44	1.84	6	743.63	2,216.54
8	3	21	739.00	78.76	51.96	35.14	25.28	10.90	9.83	4.56	2.70	2.08	1.57	3	650.50	1,048.26
9	3	44	551.64	58.79	38.79	26.23	18.87	8.14	7.34	3.40	2.02	1.56	1.17	10	641.96	2,306.05
10	3	51	494.51	52.71	34.77	23.51	16.92	7.29	6.58	3.05	1.81	1.39	1.05	28	428.82	5,616.49
11	3	52	493.32	52.58	34.69	23.46	16.88	7.28	6.56	3.04	1.80	1.39	1.05	16	568.84	3,242.92
12	3	53	492.12	52.45	34.60	23.40	16.84	7.26	6.55	3.04	1.80	1.39	1.05	19	663.89	3,798.38
13	3	56	488.83	52.10	34.37	23.24	16.72	7.21	6.50	3.02	1.79	1.38	1.04	30	704.83	5,884.16
14	3	57	488.53	48.54	33.31	24.61	18.82	9.11	7.82	3.04	2.08	1.59	1.26	29	407.95	6,086.15

Table 4.6 Power productivity at any percentage of time exceedance and annual energy of Q-H-based alternatives

Site.	Stream No.	Segment ID	power productivity (kW) at any percentage of time exceedance (%)								Annual Energy (MWh)	Ranking number
			30	40	50	60	70	80	90	100		
1	1	4	1,448.29	1,107.67	536.05	460.05	178.64	122.68	93.74	74.22	3,522.70	9
2	1	25	379.64	290.35	140.51	120.59	46.83	32.16	24.57	19.46*	906.35	14
3	1	26	591.37	452.28	218.88	187.85	72.94	50.09	38.27	30.31	1,438.39	11
4	1	27	511.86	391.48	189.45	162.59	63.14	43.36	33.13	26.23	1,245.01	12
5	1	29	391.45	299.38	144.88	124.34	48.28	33.16	25.33	20.06	952.12	13
6	2	11	5,735.55	4,386.62	2,122.88	1,821.91	707.46	485.84	371.21	293.94	13,950.66	2
7	3	4	2,216.54	1,594.74	687.45	620.27	287.51	170.45	131.49	99.20	5,087.50	8
8	3	21	1,048.26	754.20	325.11	293.34	135.97	80.61	62.18	46.92	2,406.02	10
9	3	44	2,306.05	1,659.14	715.21	645.32	299.12	177.34	136.80	103.21	5,292.95	7
10	3	51	5,616.49	4,040.91	1,741.92	1,571.70	728.52	431.91	333.18	251.37	12,891.21	4
11	3	52	3,242.92	2,333.19	1,005.77	907.49	420.64	249.38	192.37	145.14	7,443.29	6
12	3	53	3,798.38	2,732.83	1,178.05	1,062.92	492.69	292.10	225.32	170.00	8,718.20	5
13	3	56	5,884.16	4,233.49	1,824.94	1,646.60	763.24	452.49	349.06	263.35	13,505.57	3
14	3	57	6,086.15	4,654.77	2,252.65	1,933.28	750.71	515.54	393.91	311.91	14,803.44	1

Note: * Unused for the annual energy calculation.

4.6 Conclusion

Due to having limited number of gauge stations in the area, the location of micro-hydropower sites deals specifically more with data from ungauged catchments. As of stream flow behavior estimation, the study area was a small catchment which can be assumed as a hydrological homogeneous region. This study used the FDCs to estimate discharge in percentage exceedance at each ungauged catchment or alternative based on both the relationships between annual runoff and drainage area and monthly runoff data of gauge station within the study area and the vicinity. The coefficient of determination of the relationship (R^2) is 0.91.

The power productivity of each alternative was calculated using several parameters i.e. the structural length of water pipe, water-head, and $Q_{monthly}$ of each exceeding percentage. They are obtained from several techniques. The first one was

GIS technique for calculating the structural length of water pipe and water-head. The last one was FDC construction for estimating the discharge of ungauged catchments or alternatives. The results are further used as one of the criteria in Multi-criteria Decision Analysis to rank the development priority of potential alternatives.

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CHAPTER V

EVALUATION AND RANKING THE ALTERNATIVES FOR MICRO-HYDROPOWER DEVELOPMENT

5.1 Abstract

A potential run-of-river micro-hydropower project should be located in remote, or rural, and mountainous area where electricity cannot be connected from the main grid. Most projects available in Thailand are located in areas which are surrounded by forests, natural resources, tourist attractions and even resorts. With different Q-H-based alternatives along Nam Khek, development priority of all 14 alternatives can be varied to their power productivity and potential of being tourist node. The evaluation and ranking of alternatives were performed using MCDA. The criteria with fuzzy scores used for evaluation were size, environmental stability, attractions and features, distinctiveness, future options/expansion potential and electric power productivity. The opinion of local administrators through multiple comparison method which remarked multi-decision makers was applied to weighting the criteria. The Fuzzy Additive Weighting (FAW) method was used to aggregate the overall weight-scores of criteria of each alternative. The result was then defuzzified by center-of-area technique and subsequently ranked. The ranking showed that most suitable alternatives distributed along stream no.3 near Poy and Wang Nok Aen waterfalls.

In addition, sensitivity analyses were performed to obtain the criteria which have more effect on the ranking.

Keywords: Micro-hydropower, Tourist development priority, Fuzzy data, MCDA.

5.2 Introduction

In general, the criteria used in alternative ranking decision were adopted from the previous studies. By pragmatic consideration, an important by-product of micro-hydropower development in this study area is a node of tourism because they are always surrounded by mountainous areaa, forest and natural resources, for example, the well-known Mae Kam Pong micro-hydropower project in Chiangmai and Pha Bong project in Maehongson. Both of them have been promoted as nodes or highlights of tourist programs. At the Mae Kam Pong project, not only supply energy to the community operating it but the project can also supply surplus electricity for nearby villages. Therefore, in order to point out how appropriate the potential site is, among criteria, high annual energy and potential to be tourist nodes were set up to be high preference criteria. However, the preference determination of criteria by stake holders can be fuzzy due to characteristics of the criteria. To cope with this difficulty, evaluating and ranking of alternatives were then performed using MCDA-FAW decision rule. Practically, effective multi-criteria selection, analysis, evaluation, and ranking were required to serve the purpose.

5.3 Literature reviews

The review includes concepts, theories and previous studies involved in this study as discussed below.

5.3.1 Multi criteria decision analysis (MCDA)

In general, decision maker has a lot of useful information for making a decision. It is important to have an advance technique to handle the information. One interesting technique is MCDA which Triantaphyllou, Shu, Sanchez, and Ray (1998), Malczewski (1999), and Doumpos and Zopounidis (2002) explained that MCDA is a set of procedures to analyse complex decision problems involving non-commensurable, conflicting criteria on the basis of which alternative decisions are evaluated. The two board classes of MCDA can be distinguished as Multi Attribute Decision Making (MADM) and Multi Objective Decision Making (MODM). The main difference between MADM and MODM approach was concluded by Malczewski (1999). On the one hand, the MADM approach consists of a finite number of alternatives, explicitly known in the beginning of the solution process in which each alternative is represented by its performance in multi criteria. The approach may be defined as the best alternative for decision making. On the other hand, when dealing with MODM problems, the alternatives are not explicitly known. An alternative can be found by solving a mathematical model. The number of alternatives is either infinite and not countable or typically very large if countable.

5.3.1.1 Criteria scoring

The criteria attributes of the potential sites or alternatives in this study were not completely commensurable. They were thus collected as linguistic variables and converted to fuzzy numbers using fuzzy set membership. This corresponds to the previous works of Chen and Hwang (1992; quoted in Malczewski, J. (1999)); Casola, Preziosi, Rak, and Troiano (2005), and Kabir and Hasin (2011). Criteria attributes can be many classes, for example, medium and high for 2 classes and low, medium, and high for 3 classes. Each class is represented by 4 elements of a trapezoidal/triangle form as *a*, *b*, *c*, and *d* as seen in Figure 5.1.

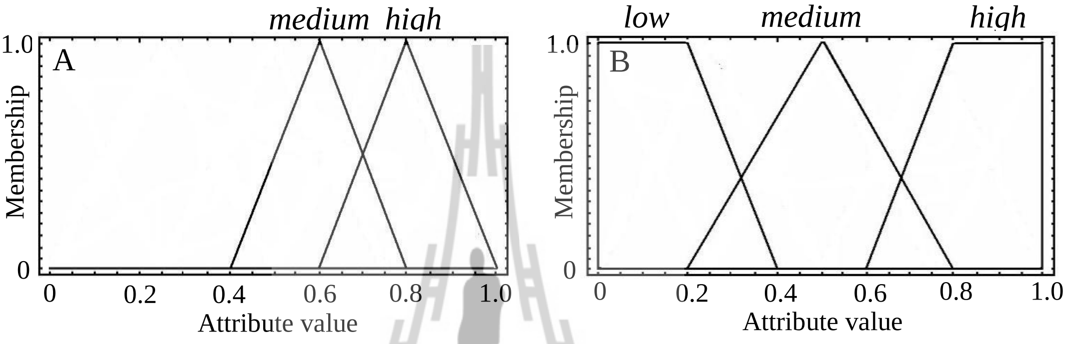

Figure 5.1 The fuzzy number of each criterion with two (a) and three (b) linguistic classes.

Source: Chen and Hwang (1992; quoted in Malczewski, J. (1999)) and Casola et al., (2005)

5.3.1.2 Criteria weighting

For the criteria weighting, this study selected the multiple comparison method for weight estimation due to having multi decision makers. Conceptually, a number of decision makers who preferred a given criterion to another recognized the degree of importance of that criterion. The assumption of individual decision makers was cooperated as a team (Malczewski, 1999). The weights were also normalized to between 0 and 1, and summed up to 1.

5.3.1.3 Decision rule

This study applied the concept of Fuzzy Additive Weighting (FAW). It is superficially similar to the conventional Simple Additive Weighting (SAW) method. Theoretically, due to total score of each alternative is calculated by the summation of multiplying the weights and scores (attributes) of criteria, there are two strong assumptions i.e. the linearity and additivity of criteria attributes. The former assumption assumes that the relationship between attributes is linear, while the latter concludes that there is no interaction effect between criteria attributes (Malczewski, 1999). Lastly, when the total score is obtained and defuzzified, the highest score is the best alternative.

5.3.1.4 Defuzzification

With defuzzification, the center-of-area method (Ross, 1995) was applied to convert the degrees of trapezoidal fuzzy numbers into a single numeric value (x^*). Conceptually, the defuzzification tries to define the border line of left and right sides of a convex based on equal area. Its *x*-intercept is a defuzzified value of that convex (or here: a trapezoidal/triangle). It determines an actual scores of each potential site as expressed in Figure 5.2.

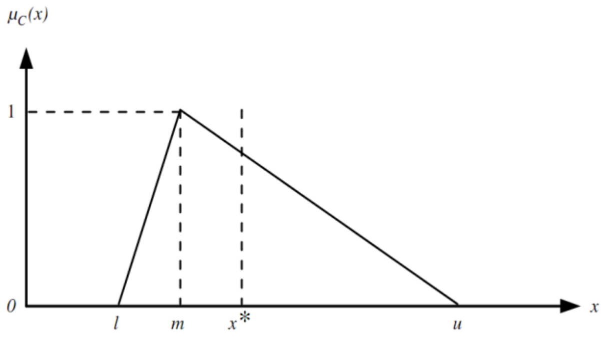

Figure 5.2 Center-of-area method for defuzzifying a triangular fuzzy number.

Source: Vahidnia, Alesheikh, and Alimohammadi (2009).

5.3.2 Sensitivity analyses

Sensitivity analysis was selected for this study corresponding with previous studies of Babiker, Mohamed, Hiyama, and Kato, 2005; Sarapirome and Majandang, 2008; and Majandang, 2011. The map removal sensitivity analysis was adopted and modified to fit the study. The method is one way to acknowledge uncertainty in criterion estimation by observing changes of overall scores while using different sets of criteria and can help to determine the most influential criterion on the priority development ranking of the potential alternatives. It is important both for the experts that implement a MCDA and for the users of the ranking result. The former can use sensitivity analysis for consistency evaluation of the analytical results. They can select the criteria which are more critical for the analysis and require more detailed information and accuracy on them. These will imply that which criterion could provide more effect to the decision analysis result.

5.3.3 Previous studies

Rojanamon et al. (2009) proposed a method to select feasible sites of small run-of-river hydropower projects using GIS technique. The selected study area was the upper Nan river basin. A combination of engineering, economic, environmental criteria, and social impact was employed. With the engineering criteria, the project locations were found by the use of GIS techniques in visual basic platform, and then economic evaluations of the selected projects were performed. The environmental parameters were used to rank the projects by total weighted scores. Finally, a social impact study at the potential sites was conducted which also involved public participation process, i.e. questionnaire survey and focus group discussions.

มหาวิทยาลัยเชียงใหม่ (2549; quoted in Rojanamon, 2009) studied about small hydropower development plan in the Ping river basin by considering engineering, economic, environmental, and socio-economic criteria. In the study, multi-criteria decision making method was applied to rank the potential sites. There were 64 projects which were collected to analyse from 6 sources i.e., (1) the projects situated in the Ping River, (2) the projects sited at existing of irrigation dam and reservoirs, (3) the projects obtained from previous study, (4) the projects attained from the prior master plan report, (5) the RID and DWR development plan projects, and (6) the proposed projects by considering the different heads. The selected criteria were composed of generating electricity, engineering and economic, socio-economic, environmental, and public participation. By expert system for ranking significance, the criteria could be ranked from the highest to the lowest weighted scores.

มหาวิทยาลัยเทคโนโลยีสุรนารี (2552) studied on the potential for developing hydropower with electric power in Mun river basin. The evaluation criteria comprised electricity generation, engineering, economics, socio-economic and environment with stakeholders involvement. The major and minor criteria weighting were determined by pairwise comparison. The results showed that there are 35 potential projects and the top three with the highest potential such as Lamtakhong-Dam, Huay Jarake Mak reservoir, and Huay Talad reservoir. The overall electricity potential was about 16.112 MW with annual power generation about 12,990 MW. The investment cost could range from 4.69 - 318.38 million baht. In addition, the stakeholders survey showed that they had positive attitude towards the project.

5.4 Research methods

5.4.1 Research procedure

Nature of the decision making process in this study, to rank the Q-H-based potential alternatives of micro-hydropower projects, was the MADM because all alternatives were already known. The flow of the process was displayed in Figure 5.3. It consists of criteria selection, criterion scoring and weighting, weight-score aggregation, defuzzification, and ranking.

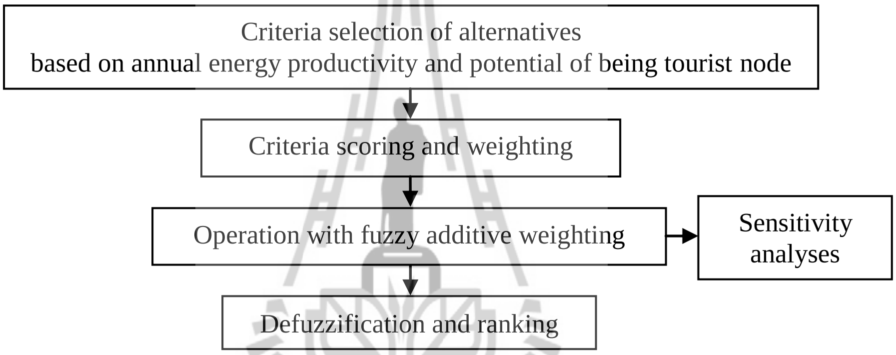

Figure 5.3 Process of evaluation and ranking the alternatives.

5.4.2 Evaluation criteria and input data

Apart from *electric power productivity* in term of annual energy considered as the primary important characteristic of an alternative, being tourist node was another important criterion has to be involved in ranking the potential sites.

According to Lindberg, Furze, Staff, and Black (1997) and PlanningWA (2004), criteria involving in being tourist node could be size, environmental stability, attractions and features, distinctiveness, and future options/expansion potential as described below.

(1) *Size* is considered as a land area of sufficient scale and configuration to accommodate the designated level of sustainable tourism.

(2) *Environmental stability* includes soils, biological composition, visual landscape, and ecological land systems. They were considered in aspect of being stable and sustainable change without unacceptable loss of value.

(3) *Attractions and features* are considered in terms of a land area with an attractive appeal due to the presence of a number of special sites or attractions of biological, social, cultural, visual or historical significance.

(4) *Distinctiveness* is particular uniqueness of sites due to natural elements, proximity to features of node, historical land uses, and landscape characteristics or particular attractions.

(5) *Future options/expansion potential* is considered in aspect of suitability for expansion or upgrading of sites.

The first criterion, power productivity, was derived from Q-H-based alternatives (see details in Chapter III and IV), while others were collected from the interview with chief executives of sub-district administration organization (Appendix D.1). The script of the interview used is detailed in Appendix D.2. The criteria and their attributes classification are listed in Table 5.1.

Table 5.1 Set of criteria and their attributes.

No.	Criterion	Abbreviation	Attributes		
1	Power productivity	PP	Megawatt-hour (MWh)		
2	Size	SZ	Limited	Adequate	Expansive
3	Environmental stability	ES	Sensitive	Acceptable	Stable
4	Attractions and features	AF	Few		Numerous
5	Distinctiveness	DT	Low	Moderate	Exceptional
6	Future expansion	FE	Limited	Moderate	Exceptional

5.4.3 Scoring and weighting criteria

(1) Score of power productivity

Even though characteristic of power productivity is ratio-scale, the lower limit concluded from the interview is recommended to be regarded for satisfied development with fuzzy number of 1. Any alternatives with lower productivity might be able to be accepted with lower preference assigned as fuzzy numbers between 0 and 1.

(2) Criteria scores of being potential tourist node

According to Figure 5.1, criterion with two classes of “medium” and “high” will be represented by sets of fuzzy numbers as (0.4, 0.6, 0.6, 0.8) and (0.6, 0.8, 0.8, 1), respectively. For the criterion attribute with three linguistic classes, their sets of fuzzy numbers will be: “low” = (0, 0, 0.2, 0.4), “medium” = (0.2, 0.5, 0.5, 0.8), and “high” = (0.6, 0.8, 1, 1).

(3) Criteria weighting

The multiple comparisons provide preferences for all criteria by the ratio of rank/range. The rank of a certain criterion was determined from the summation of the total of decision makers who preferred that criterion to another. The range could be determined from $nk - k$, where n is the number of criteria, k is the number of decision makers. The ratio of rank/range was later normalized to between 0 and 1.

5.4.4 Weight-score aggregation

Weight-score aggregation was achieved using FAW decision rule. It can be written in the form:

$$F_i = \sum_j w_j x_{ij}^{-} , \tag{5.1}$$

where F_i is the overall score of each trapezoidal fuzzy number (i.e. *a*, *b*, *c*, and *d*) which obtained by multiplying the score and weight. x_{ij}^{-} is the score of the *i*th alternative with respect to the *j*th attributes through membership functions (*a*, *b*, *c*, *d*). The weight w_j is a normalized weight of each attribute.

5.4.5 Defuzzification

The center-of-area defuzzification was applied to convert the overall score of all the elements into a single numeric value (x^*). It represents the degree of development priority of each alternative. The center of area of any fuzzy number ($\tilde{c}$) is defined by:

$$x^* = \frac{\int \mu_{\tilde{c}}(x)dx}{\int \mu_{\tilde{c}}dx} . \tag{5.2}$$

The ranks of alternatives were subsequently assigned based on the defuzzified values. The alternative with a higher value exhibited the higher rank of potential.

5.4.6 Sensitivity analyses

The process of map removal (Lodwick, Monson, and Svoboda (1990; quoted in Napolitano and Fabbri, 1990)) adopted in this study removes one criterion at a time for testing the effect of that criterion to the overall score. The purpose of the analysis is to identify which one(s) of criteria can be removed and it will not affect much on the score. The ones show more effect on the total score are considered very important and have to be serious when collecting them. The map removal can be calculated by the formula:

$$S = \left[\frac{\left| \frac{V}{N} - \frac{\acute{V}}{n} \right|}{V} \right] \times 100, \tag{5.3}$$

where S is the sensitivity measurement expressed in terms of variation index, V and $\acute{V}$ are the unperturbed and the perturbed overall scores respectively, and N and n are the numbers of criteria used to compute V and $\acute{V}$. This operation is the alternative-based or site-based analysis. An alternative with very high or very low score of a removed criterion will show much effect on the variation index. According to Babiker et al. (2005), a variation index in terms of the normalized mean difference of each criterion removal will be used to indicate which criterion can be less effect to a certain site. Any criterion with lower normalized value indicates the less effect.

5.5 Results and discussion

5.5.1 Scoring and weighting criteria

5.5.1.1 Score of power productivity

From the interview with local administrators, it was found that the means of preferred degree of power productivity were at 5,000 MWh. Thus, the annual energy of each alternative (listed in Appendix D.3) was converted to standardized (fuzzy) score. The conversion method could be presented by graph of the trapezoidal fuzzy number as shown in Figure 5.4. The result of each alternative from the process is shown at column PP in Table 5.2.

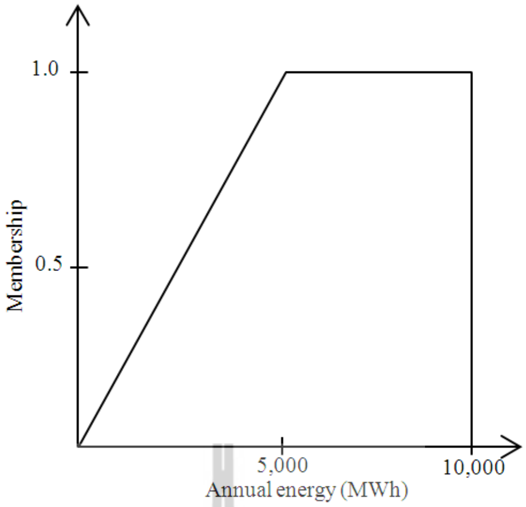

Figure 5.4 Generating fuzzy score of power productivity.

5.5.1.2 Scoring of criteria for being potential tourist node

The opinions of the informants on a set of criteria were collected as linguistic terms (Appendix D.3) and converted to the trapezoidal fuzzy number represented by a score of each element (i.e. *a*, *b*, *c*, and *d*). The scores of every informant with the same criterion were averaged as the criterion score of each potential alternative. The results are shown in the form of trapezoidal fuzzy number in Table 5.2.

Table 5.2 Criteria values of the potential sites in form of trapezoidal fuzzy number.

Site.	Criteria																				
	PP	SZ				ES				AF				DT				FE			
		a	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*
1	0.705	0.033	0.083	0.250	0.467	0.067	0.167	0.300	0.533	0.467	0.667	0.733	0.867	0.000	0.000	0.200	0.400	0.000	0.000	0.200	0.400
2	0.181	0.033	0.083	0.250	0.467	0.100	0.250	0.350	0.600	0.400	0.600	0.600	0.800	0.167	0.300	0.433	0.633	0.133	0.333	0.400	0.667
3	0.288	0.033	0.083	0.250	0.467	0.100	0.250	0.350	0.600	0.400	0.600	0.600	0.800	0.233	0.350	0.517	0.667	0.133	0.333	0.400	0.667
4	0.249	0.033	0.083	0.250	0.467	0.067	0.167	0.300	0.533	0.400	0.600	0.600	0.800	0.100	0.250	0.350	0.600	0.067	0.167	0.300	0.533
5	0.190	0.033	0.083	0.250	0.467	0.033	0.083	0.250	0.467	0.400	0.600	0.600	0.800	0.100	0.250	0.350	0.600	0.000	0.000	0.200	0.400
6	1.000	0.000	0.000	0.200	0.400	0.000	0.000	0.200	0.400	0.400	0.600	0.600	0.800	0.000	0.000	0.200	0.400	0.000	0.000	0.200	0.400
7	1.000	0.467	0.700	0.833	0.933	0.533	0.750	0.917	0.967	0.600	0.800	1.000	1.000	0.600	0.800	1.000	1.000	0.533	0.750	0.917	0.967
8	0.481	0.267	0.550	0.583	0.833	0.600	0.800	1.000	1.000	0.600	0.800	1.000	1.000	0.533	0.750	0.917	0.967	0.067	0.167	0.300	0.533
9	1.000	0.600	0.800	1.000	1.000	0.600	0.800	1.000	1.000	0.600	0.800	1.000	1.000	0.533	0.750	0.917	0.967	0.600	0.800	1.000	1.000
10	1.000	0.100	0.250	0.350	0.600	0.333	0.600	0.667	0.867	0.600	0.800	1.000	1.000	0.200	0.500	0.500	0.800	0.067	0.167	0.300	0.533
11	1.000	0.000	0.000	0.200	0.400	0.333	0.600	0.667	0.867	0.467	0.667	0.733	0.867	0.200	0.500	0.500	0.800	0.000	0.000	0.200	0.400
12	1.000	0.000	0.000	0.200	0.400	0.333	0.600	0.667	0.867	0.467	0.667	0.733	0.867	0.200	0.500	0.500	0.800	0.000	0.000	0.200	0.400
13	1.000	0.000	0.000	0.200	0.400	0.333	0.600	0.667	0.867	0.500	0.700	0.800	0.900	0.200	0.500	0.500	0.800	0.000	0.000	0.200	0.400
14	1.000	0.000	0.000	0.200	0.400	0.333	0.600	0.667	0.867	0.567	0.767	0.933	0.967	0.467	0.700	0.833	0.933	0.000	0.000	0.200	0.400

Note: PP = Power productivity, SZ = Size, ES = Environmental stability, AT = Attractions and features, DT = Distinctiveness, FE = Future expansion

5.5.1.3 Criteria weighting

The process and result of the weight determination is shown in Table 5.3. Among assigned criteria weights, it is obvious that weight of *size* was assigned the highest value at 0.27. The weight of *power productivity* is high (0.24) and not much different from the *size*. *Attractions and features* were assigned to be moderately important. Weight of both *distinctiveness* and *future expansion* was the lowest.

Table 5.3 Weights determination using multiple comparison method.

Step I Results of pairwise comparisons of the six evaluation criteria by 6 decision makers.

Criterion	PP	SZ	ES	AF	DT	FE
PP	-	4	2	2	0	0
SZ	2	-	2	2	0	0
ES	4	4	-	4	2	2
AF	4	4	2	-	1	2
DT	6	6	4	5	-	2
FE	6	6	4	4	4	-
Rank	22	24	14	17	7	6

Note: PP = Power productivity, SZ = Size, ES = Environmental stability, AT = Attractions and features, DT = Distinctiveness, FE = Future expansion

Step II Assessing weights by multiple comparison.

Criterion	Rank	Rank/Range	Weight
PP	22	0.73	0.24
SZ	24	0.80	0.27
ES	14	0.47	0.15
AF	17	0.57	0.19
DT	7	0.23	0.08
FE	6	0.20	0.07
Total		3.00	1.00

n = number of criteria,
k = number of decision maker,
range = *nk* - *k* = 30

5.5.2 Weight-score aggregation (FAW) and Defuzzification

The result of multiplication of the criteria scores and weights (shown in Appendix D.4) was aggregated according to FAW decision rule. The aggregation results remained in the form of trapezoidal fuzzy number. They were defuzzified using center-of-area method. Alternatives were subsequently ranked according to these defuzzified values as shown in Table 5.4 and Appendix D.5. The higher value indicated the higher priority of an alternative to be developed.

It was interesting to note that this ranking did not correspond to the ranking evaluated based solely on *power productivity* (see details in Table 4.6), even though it was considered as the most sensitive criterion. Ranking based on the *power productivity* alone, the actual productivity of alternatives were considered. They were converted to be standard score or equal to 1 when they were over 5,000 MWh while they were incorporated with other criteria in MADM. This caused scoring of *power productivity* of many alternatives becoming the same as 1 even their actual scores were different. Finally, this led to difference in ranking.

Table 5.4 Potential alternatives and their overall scores of each element of the trapezoidal fuzzy number, defuzzified scores, and ranks.

Site	**Overall score of each element of the trapezoidal fuzzy number**				**Defuzzified score**	**Rank**
	a	***b***	***c***	***d***		
1	0.277	0.343	0.451	0.600	0.418	10
2	0.166	0.265	0.340	0.509	0.320	12
3	0.197	0.294	0.372	0.537	0.350	11
4	0.167	0.253	0.335	0.503	0.315	13
5	0.144	0.215	0.307	0.470	0.284	14
6	0.316	0.354	0.468	0.620	0.440	9
7	0.645	0.810	0.937	0.975	0.842	2
8	0.439	0.608	0.707	0.795	0.637	4
9	0.691	0.844	0.993	0.997	0.881	1
10	0.452	0.601	0.686	0.823	0.640	3
11	0.395	0.497	0.587	0.735	0.553	7
12	0.395	0.497	0.587	0.735	0.553	8
13	0.401	0.503	0.600	0.741	0.561	6
14	0.435	0.532	0.652	0.764	0.596	5

5.5.3 Sensitivity analyses

By applying the map removal to sensitivity analysis, the result can be shown in Table 5.5. From the table, the general view of all alternatives obviously expresses that the *power productivity* extremely affects the evaluation result. Its mean value of variation index is highest as 3.12%. The criteria show the mean of variation indices in order from low to high as *Environmental stability* (0.63%), *size* (1.15%), *distinctiveness* (1.82%), *attractions and features* (2.19%), and *future expansion* (2.52%), respectively. In addition, the results also indicate that for each alternative which criterion expresses the most effect to the evaluation result. For example, the *power productivity* of alternative number 6 shows the most effect while alternative number 5 shows the lowest. Therefore, the score of criteria with highly variation at a given alternative should be acquired carefully in aspects of estimation and assessment. For example, *power productivity* expresses the high effect to alternatives 6, 11, 12, and 13 while *attractions and features* shows the high effect to alternatives 5, 4, 2, and 3.

Table 5.5 Variation index of the sensitivity assessment.

Site	**Parameter Removed**					
	PP	**SZ**	**ES**	**AF**	**DT**	**FE**
1	4.76	0.64	1.42	2.88	2.76	2.83
2	0.61	0.18	0.29	3.79	1.42	1.66
3	0.61	0.12	0.55	3.18	1.32	1.80
4	0.46	0.24	0.79	3.91	1.68	2.15
5	0.11	0.63	1.13	4.70	1.50	2.59
6	7.59	1.49	2.31	1.85	2.79	2.86
7	2.37	1.37	0.51	0.50	1.72	2.02
8	0.29	1.40	0.67	1.74	1.35	2.75
9	2.11	1.87	0.44	0.33	1.90	1.98
10	4.16	0.59	0.44	1.71	2.08	2.75
11	5.34	1.87	0.01	1.36	1.89	2.95
12	5.34	1.87	0.01	1.36	1.89	2.95
13	5.22	1.89	0.04	1.58	1.91	2.96
14	4.72	1.97	0.23	1.82	1.36	2.98
Mean	3.12*	1.15	0.63	2.19*	1.82	2.52*
Minimum	0.11	0.12	0.01	0.33	1.32	1.66
Maximum	7.59	1.97	2.31	4.70	2.79	2.98
S.D.	2.46	0.72	0.63	1.30	0.47	0.48

Note: * = Highly variation, PP = Power productivity, SZ = Size, ES = Environmental stability, AT = Attractions and features, DT = Distinctiveness, FE = Future expansion

5.6 Conclusion

The main objective in this chapter is to rank the 14 potential alternatives corresponding to research objective 3 based on two major groups of criteria: annual energy and potential of being tourist node. The annual energy of alternatives was estimated according to their Q-H-based potential described in Chapter 4. The criteria and their scores used for being tourist node assessment were adapted from previous studies and collected by interviews with local administrators. The fuzzy set membership was applied to convert linguistic terms of criteria attributes to numeric scores. The multiple comparison method was applied to weighting criteria. The FAW was used to aggregate weight-score of each alternative. These ranks expressed the development priority of each potential site. The result revealed that most of highly suitable sites were distributed along stream no.3 near Poy, and Wang Nok Aen waterfalls.

In addition, the parameter removal sensitivity analyses based on average variation index showed that the environmental stability was lowly sensitive whereas power productivity, future expansion, attractions and features, distinctiveness, and size were in order from highly to lowly sensitive. It also expressed which criterion provided the most effect for an alternative. The result implied that in this area the aforementioned 5 criteria could influence the ranks of potential sites. Therefore, their criteria scores should be acquired carefully in aspects of estimation and assessment.

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CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The result of the study can be concluded and used as a prototype to establish the procedure for potential assessment of run-of-river micro-hydropower sites. The procedure was focused on accuracy assessment of available DEM data and extracted anomaly stream segments derived from DEM, sieving Q-H-based potential alternatives along the main streams, and ranking them by integrating criteria into the decision making process. The conclusion and the recommendation of the result can be discussed in the following.

6.1 Conclusions

The conclusion herein is described and discussed in the following to response the objectives of the study.

6.1.1 DEM data assessment

According to the first objective, accuracy assessment of currently available DEM data i.e. SRTM DEM, RTSD-DTED2, GDEM and the self-generated DEM (SG-DEM) using spot height, contour and stream information from RTSD 1:50,000 scaled topographic map through *Topo to raster* tool were performed and compared. Their accuracy was assessed by comparing to the referent MOAC-DEM data which are claimed to be the best available data. The assessment consisted of stream position and elevation accuracy. The result concludes that DEM data of RTSD-DTED2 provides the best accuracies. As to SG-DEM; the data are moderate. SRTM-DEM and GDEM data express the lowest accuracies in both terms. No significant difference in accuracies according to kinds of terrains is observed.

6.1.2 H-based potential alternatives

Alternatives of micro-hydropower sites can be determined by various methods varying from manual pointing out by an expert to universal searching using each pair of contour interval along a stream. The later method can result in a huge number of alternatives which will be sorted using other specifications later. For this study, the trustfulness in terms of stability of result was improved by using normalized steepness index (k_{sn}) together with abrupt-slope-change detection. By using this index, 39 anomaly steepness segments were extracted from the total of 177 segments. They were further cut off when their indexes were less than the selected natural break which resulted in 11 stream segments left. The abrupt-slope-change stream segments were additionally applied to detect 3 more potential segments based on the least slope change of big waterfalls within the study area. Finally, there were totally 14 segments selected as H-based potential alternatives. Four big waterfalls were associated with the anomaly segments selected by those two methods. Comparing slope of anomaly segments and k_{sn} with referent slopes derived from MOAC-DEM data, the correlation coefficients were 0.81 and 0.92, respectively. Therefore, it can be concluded that the methods used were helpful and efficient in sieving H-based alternatives.

6.1.3 Q-H-based potential alternatives

Due to having limited number of gauge stations in the study area, the searching for potential locations of micro-hydropower sites deals specifically more with data from ungauged catchments. For stream flow behavior estimation, the study area is considered as a small catchment which can be assumed as a hydrological homogeneous region. This study uses the FDCs to estimate discharge in percentage exceedance at each ungauged catchment or alternative based on both the relationship between annual runoff and drainage area and monthly runoff data of gauge station within the study area and the vicinity. The coefficient of determination of the relationship (R^2) is 0.91. In addition, the power productivity of each alternative was calculated using several parameters i.e. the structural length of water pipe, water-head, and $Q_{monthly}$ of each exceeding percentage. They were obtained from several techniques. The first one was acquired using GIS technique to calculate the structural length of water pipe and water-head. The FDC construction of ungauged catchments or alternatives was applied to estimate the last one. The results were further used as one of the criteria in multi-criteria decision analysis to rank the development priority of 14 potential alternatives. All of them were kept as potential alternatives because their lowest power outputs were more than 20 kW. The result is evident the successfulness of the second research objective.

6.1.4 Evaluation and ranking the alternatives

Instead of ranking significance of alternatives based on only engineering, economic, environmental, and public participation criteria as always carried out in previous studies. This research focused basically on evaluating and ranking alternatives based on their power productivity and opportunity of being a node of tourist activity which is active and popular in the area and the vicinity. The criteria and their scores were adapted from previous studies and opinions of the chief executives of sub-district administration organization. The fuzzy set membership was applied to converting linguistic terms of criteria attributes to ratio scores. Due to several decision makers, the multiple comparison method was applied to weighting criteria. The FAW was used to aggregate weight-score of all criteria of the alternatives. These ranks expressed the development priority of each potential site. The result revealed that the top 5 of the ranks were distributed along stream no.3 near Poy, and Wang Nok Aen waterfalls. In addition, the parameter removal sensitivity analyses based on variation index showed that environmental stability was lowly sensitive whereas power productivity, size, distinctiveness, attractions and features, and future expansion were highly sensitive. The result implied that in this area the highly sensitive criteria could influence the ranks of potential sites. Therefore, their criteria values should be acquired carefully in aspects of estimation and assessment.

6.2 Recommendations

From the experience gained through the study, the recommendations for further study that could guide to yield better results are attainable by the following means.

(1) As far as the DEM data assessment is concerned, due to the limited number of referent DEM data, the assessment only emphasized on stream position and elevation accuracy. Even though it could be used to imply the accuracy of upstream watershed area derived from DEM data, its actual assessment should be performed if the referent data are sufficiently available. This is because it was an important parameter to estimate Q of the ungauged catchment and could provide more accurately. Therefore, with the additional assessment, the better result could be expected.

(2) The estimated k_s index (or y-intercept of slope-area relationship) of a segment can be very high which exceeds the limit of Microsoft excel. This may affect the normalized steepness index of segments. Therefore, the higher performance computing tool is required to obtain more stable results.

(3) A length of penstock at 250 m was assumed to be appropriate for power productivity calculation. If the length varies, it may affect the ranking of development priority of alternatives. Therefore, the development of algorithm using GIS-technique allowing automation of the length adjustment and result observation could provide the better result of ranking.

(4) Due to limited time and budget, the scoring and weighting criteria were generated based on only 6 opinions of decision makers. Therefore, the more reliable result could be expected if higher number of decision makers is incorporated in the process.

(5) Q-H-based potential alternatives and their ranking of development priority resulted from the study can fit to preliminary feasibility study. Therefore, further site development requires additional ground survey for designing and construction phases.

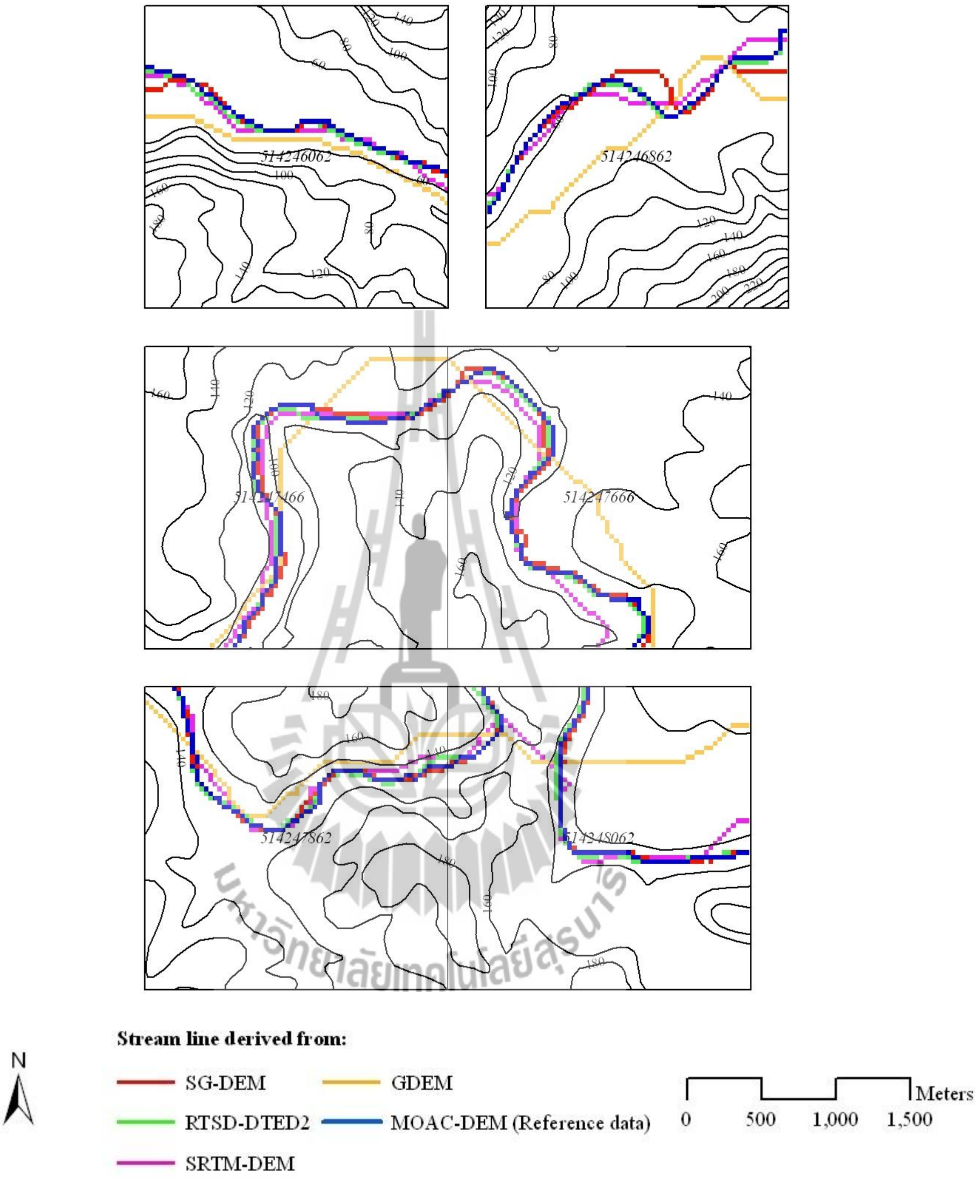
(6) The more reliable result of this study could be expected if the DEM data of MOAC-DEM and even Laser Imaging Detection and Ranging (LIDAR) are employed. However, recently their costs have been extremely high.

APPENDICES

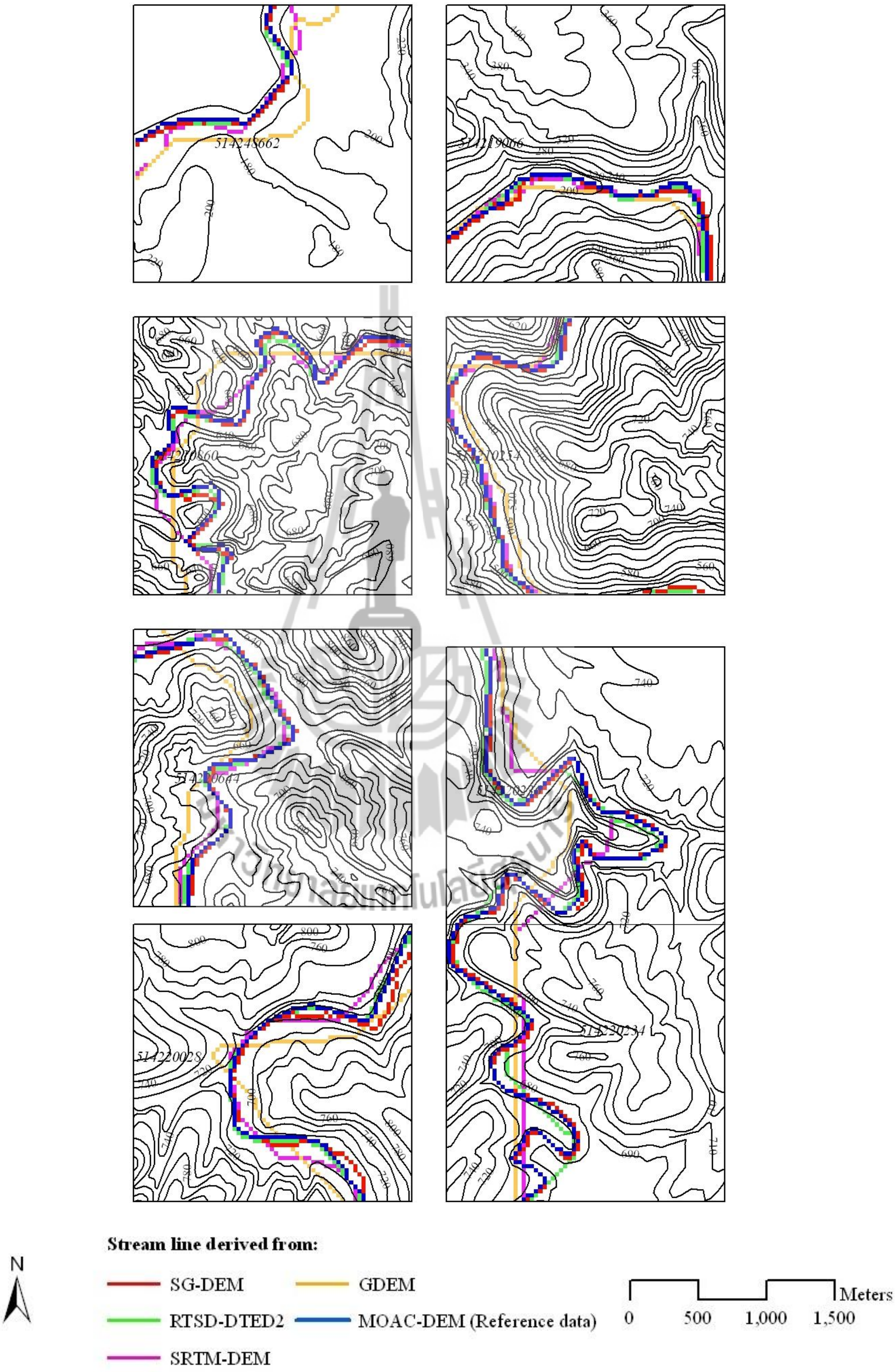
APPENDIX A

EXTRACTED STREAMS OF ALL DEM DATA

A.1 Comparing extracted streams of all DEM data with reference data.



A.1 (Continued).



APPENDIX B

THE k_s, θ, k_{sn} AND RELATED PARAMETERS VALUE OF STREAM SEGMENTS

B.1 k_s, θ, k_{sn} values and related parameters of stream segments.

No.	Stream No.	Segment No.	Rise (m)	Run (m)	k_s	θ	A_{cent}	k_{sn}	k_{sn}/k_{sn}(avg)	Stream Steepness	Outstanding anomaly	Additional anomaly	Slope from RTSD-DTED2	Slope from MOAC-DEM	Big waterfalls
1	1	1	0.80	1019.12	1.08E+90	38.39	260.06	0.026	0.37	Normal	-	-	0.000785	-	-
2	1	2	18.17	994.26	2.00E+307	151.67	258.26	0.000	0.00	Normal	-	-	0.018271	-	-
3	1	3	15.57	1019.12	2.05E-04	-0.78	256.62	0.188	2.69	Anomaly	-	-	0.015275	-	-
4	1	4	35.57	994.26	7.31E+192	80.77	254.56	0.432	6.17	Anomaly	Outstanding	-	0.035772	-	-
5	1	5	25.50	1056.40	3.77E-130	-53.25	249.75	0.206	2.95	Anomaly	-	Additional	0.024139	-	-
6	1	6	8.90	1081.25	4.49E-01	0.76	173.96	0.091	1.30	Anomaly	-	Additional	0.008231	-	-
7	1	7	8.90	1043.97	0	-156.81	122.59	0.000	0.00	Normal	-	-	0.008525	-	-
8	1	8	1.83	981.84	4.46E-34	-14.79	121.05	0.025	0.36	Normal	-	Additional	0.001867	-	-
9	1	9	1.40	1043.97	1.93E-31	-13.53	119.20	0.021	0.30	Normal	-	-	0.001341	-	-
10	1	10	1.40	1031.54	5.88E-80	-38.25	100.58	0.019	0.27	Normal	-	-	0.001357	0.000776	-
11	1	11	1.93	1006.69	6.53E-64	-30.36	98.68	0.018	0.26	Normal	-	-	0.001920	0.003149	-
12	1	12	0.60	981.84	3.10E-35	-15.99	96.82	0.014	0.19	Normal	-	-	0.000611	0.000570	-
13	1	13	6.90	1106.10	2.46E+13	7.89	94.34	0.050	0.72	Normal	-	-	0.006238	0.007549	-
14	1	14	11.67	981.84	2.15E-54	-26.33	92.25	0.091	1.30	Anomaly	-	-	0.011882	-	-
15	1	15	2.70	1019.12	7.04E-41	-19.36	88.56	0.027	0.38	Normal	-	Additional	0.002649	-	-
16	1	16	3.10	1043.97	6.35E+08	5.96	82.30	0.018	0.26	Normal	-	-	0.002969	-	-
17	1	17	1.50	1043.97	6.37E-54	-26.64	78.32	0.013	0.18	Normal	-	-	0.001437	-	-
18	1	18	1.13	1106.10	2.00E+307	5304.51	76.92	0.000	0.00	Normal	-	-	0.001025	-	-
19	1	19	3.60	1081.25	2.14E-69	-35.16	76.27	0.023	0.33	Normal	-	-	0.003329	-	-
20	1	20	5.57	1019.12	2.00E+307	378.52	75.69	0.000	0.00	Normal	-	-	0.005462	-	-
21	1	21	11.13	1043.97	9.88E-37	-18.17	74.90	0.078	1.12	Anomaly	-	-	0.010664	-	-
22	1	22	15.03	994.26	2.98E+08	5.60	71.12	0.086	1.22	Anomaly	-	-	0.015120	-	-
23	1	23	16.17	1019.12	1.66E-01	0.58	54.14	0.098	1.41	Anomaly	-	-	0.015863	-	-
24	1	24	22.90	1043.97	1.77E+11	7.93	42.36	0.122	1.74	Anomaly	-	-	0.021936	-	-
25	1	25	54.40	1056.40	2.22E+17	11.58	40.14	0.315	4.50	Anomaly	Outstanding	-	0.051496	-	-

B.1 (Continued).

No.	Stream No.	Segment No.	Rise (m)	Run (m)	k_s	θ	A_{cent}	k_{sn}	k_{sn}/k_{sn}(avg)	Stream Steepness	Outstanding anomaly	Additional anomaly	Slope from RTSD-DTED2	Slope from MOAC-DEM	Big waterfalls
26	1	26	70.97	1031.54	1.61E-02	-0.43	32.83	0.346	4.94	Anomaly	Outstanding	-	0.068797	-	-
27	1	27	80.37	994.26	6.25E-03	-0.80	25.00	0.348	4.97	Anomaly	Outstanding	-	0.080830	-	-
28	1	28	48.40	1068.82	6.02E+04	4.63	21.31	0.171	2.44	Anomaly	-	Additional	0.045283	-	-
29	1	29	95.43	1031.54	4.28E-01	0.53	18.49	0.340	4.86	Anomaly	Outstanding	-	0.092515	-	-
30	2	1	3.60	919.71	0	-268.28	619.54	0.000	0.00	Normal	-	-	0.003914	-	-
31	2	2	0.90	1031.54	8.99E-31	-9.81	615.51	0.037	0.53	Normal	-	-	0.000872	-	-
32	2	3	2.27	981.84	0	-421.50	611.83	0.000	0.00	Normal	-	-	0.002309	0.001864	-
33	2	4	1.07	1068.82	1.51E-57	-19.44	608.92	0.038	0.54	Normal	-	-	0.000998	0.001965	-
34	2	5	9.37	994.26	4.60E+123	45.21	603.55	0.161	2.30	Anomaly	-	-	0.009421	0.000131	-
35	2	6	2.50	932.13	0	-331.68	599.94	0.000	0.00	Normal	-	Additional	0.002682	-	-
36	2	7	2.30	919.71	2.00E+307	392.51	598.68	0.000	0.00	Normal	-	-	0.002501	-	-
37	2	8	0.97	932.13	2.27E+70	26.29	593.58	0.048	0.68	Normal	-	-	0.001037	-	-
38	2	9	1.47	1043.97	1.65E+05	2.83	582.77	0.044	0.63	Normal	-	-	0.001405	-	-
39	2	10	13.57	1081.25	2.00E+307	310.23	573.96	0.000	0.00	Normal	-	-	0.012547	-	-
40	2	11	49.93	1019.12	4.26E+61	22.83	571.50	0.851	12.15	Anomaly	Outstanding	-	0.048997	-	-
41	2	12	18.67	1093.68	0	-851.98	570.16	0.000	0.00	Normal	-	Additional	0.017068	-	-
42	2	13	2.13	1081.25	4.16E-21	-6.44	565.84	0.039	0.56	Normal	-	Additional	0.001973	-	-
43	2	14	2.53	919.71	4.19E-155	-55.24	557.91	0.038	0.54	Normal	-	-	0.002755	-	-
44	2	15	1.77	981.84	2.00E+307	134.05	552.90	0.000	0.00	Normal	-	-	0.001799	-	-
45	2	16	3.23	956.98	2.38E+21	8.73	543.68	0.052	0.75	Normal	-	-	0.003379	-	-
46	2	17	10.00	1043.97	2.00E+307	117.94	534.67	0.000	0.00	Normal	-	-	0.009579	-	-
47	2	18	2.00	1031.54	0	-499.11	533.44	0.000	0.00	Normal	-	Additional	0.001939	-	-
48	2	19	1.87	1031.54	4.65E+28	11.53	529.94	0.031	0.44	Normal	-	-	0.001810	-	-
49	2	20	0.43	1043.97	2.43E+205	76.48	526.69	0.030	0.43	Normal	-	-	0.000415	0.000996	-
50	2	21	2.30	1056.40	9.95E+18	7.99	508.00	0.040	0.57	Normal	-	-	0.002177	0.000824	-

B.1 (Continued).

No.	Stream No.	Segment No.	Rise (m)	Run (m)	k_s	θ	A_{cent}	k_{sn}	k_{sn}/k_{sn}(avg)	Stream Steepness	Outstanding anomaly	Additional anomaly	Slope from RTSD-DTED2	Slope from MOAC-DEM	Big waterfalls
51	2	22	9.00	1118.53	4.80E-20	-6.40	489.69	0.125	1.79	Anomaly	-	-	0.008046	0.001019	-
52	2	23	1.27	1006.69	1.45E+241	90.72	488.30	0.028	0.40	Normal	-	Additional	0.001258	-	-
53	2	24	2.27	944.56	1.73E-124	-45.19	484.06	0.059	0.84	Normal	-	-	0.002400	-	-
54	2	25	1.50	1043.97	2.00E+307	214.91	479.01	0.000	0.00	Normal	-	-	0.001437	-	-
55	2	26	3.60	1006.69	2.16E-01	0.64	458.37	0.066	0.94	Normal	-	-	0.003576	-	-
56	2	27	20.13	969.41	3.08E+02	1.67	347.76	0.242	3.45	Anomaly	-	-	0.020769	-	-
57	2	28	19.87	981.84	3.67E-258	-104.86	273.76	0.181	2.59	Anomaly	-	-	0.020234	-	-
58	2	29	6.73	1106.10	0	-530.80	272.25	0.000	0.00	Normal	-	Additional	0.006087	-	-
59	2	30	1.50	969.41	3.12E+02	2.09	266.22	0.033	0.46	Normal	-	Additional	0.001547	-	-
60	2	31	0.57	1031.54	6.39E-33	-12.24	259.64	0.027	0.39	Normal	-	-	0.000549	-	-
61	2	32	0.97	1056.40	0	-230.65	258.09	0.000	0.00	Normal	-	-	0.000915	-	-
62	2	33	1.43	1031.54	3.86E-35	-13.16	257.09	0.024	0.34	Normal	-	-	0.001390	-	-
63	2	34	0.73	1031.54	1.58E-09	-2.51	252.42	0.020	0.29	Normal	-	-	0.000711	-	-
64	2	35	2.20	932.13	4.17E-272	-112.29	248.04	0.037	0.53	Normal	-	-	0.002360	-	-
65	2	36	1.47	1093.68	2.00E+307	145.10	247.24	0.000	0.00	Normal	-	-	0.001341	-0.000539	-
66	2	37	2.73	1081.25	2.21E+56	24.62	242.59	0.050	0.71	Normal	-	-	0.002528	-0.000111	-
67	2	38	4.37	1031.54	0	-580.25	238.30	0.000	0.00	Normal	-	-	0.004233	0.001503	-
68	2	39	0.73	1106.10	6.99E-86	-34.71	237.12	0.022	0.32	Normal	-	-	0.000663	0.000678	-
69	2	40	2.10	1081.25	9.57E+78	34.47	234.45	0.023	0.33	Normal	-	-	0.001942	0.000731	-
70	2	41	0.53	1155.81	1.41E+04	3.03	230.14	0.012	0.17	Normal	-	-	0.000461	-0.000208	-
71	2	42	1.13	1043.97	2.53E-45	-17.70	227.08	0.015	0.21	Normal	-	-	0.001086	-	-
72	2	43	1.07	1006.69	6.23E+18	9.23	224.30	0.015	0.21	Normal	-	-	0.001060	-	-
73	2	44	1.87	1068.82	7.00E-06	-1.03	209.16	0.019	0.27	Normal	-	-	0.001746	-	-
74	2	45	1.10	981.84	2.00E+307	579.59	196.98	0.000	0.00	Normal	-	-	0.001120	-	-
75	2	46	1.63	932.13	2.00E+307	201.41	196.65	0.000	0.00	Normal	-	-	0.001752	-	-

B.1 (Continued).

No.	Stream No.	Segment No.	Rise (m)	Run (m)	k_s	θ	A_{cent}	k_{sn}	k_{sn}/k_{sn}(avg)	Stream Steepness	Outstanding anomaly	Additional anomaly	Slope from RTSD-DTED2	Slope from MOAC-DEM	Big waterfalls
76	2	47	1.13	1068.82	2.58E-17	-6.03	192.33	0.017	0.24	Normal	-	-	0.001060	-	-
77	2	48	0.67	1118.53	1.54E+13	7.06	184.18	0.016	0.23	Normal	-	-	0.000596	-	-
78	2	49	0.53	1031.54	4.35E-243	-106.37	178.70	0.016	0.23	Normal	-	-	0.000517	0.000019	-
79	2	50	1.23	932.13	3.06E+29	14.43	172.19	0.017	0.24	Normal	-	-	0.001323	0.000011	-
80	2	51	12.20	1006.69	9.79E-94	-40.94	167.60	0.114	1.63	Anomaly	-	-	0.012119	-	-
81	2	52	2.13	1081.25	2.75E-19	-7.16	165.83	0.022	0.31	Normal	-	Additional	0.001973	-	-
82	2	53	1.50	1006.69	6.21E-03	0.23	136.25	0.018	0.26	Normal	-	-	0.001490	-	-
83	2	54	13.20	1081.25	1.30E+278	136.64	112.19	0.086	1.22	Anomaly	-	-	0.012208	-	-
84	2	55	5.20	1081.25	8.57E-66	-30.68	107.80	0.016	0.23	Normal	-	Additional	0.004809	-	-
85	2	56	3.17	1106.10	3.82E+79	40.74	103.29	0.027	0.39	Normal	-	-	0.002863	-	-
86	2	57	3.30	1043.97	9.95E-09	-2.81	89.22	0.023	0.33	Normal	-	-	0.003161	-	-
87	2	58	6.80	994.26	8.95E+22	13.34	76.80	0.044	0.63	Normal	-	-	0.006839	-	-
88	2	59	1.93	1068.82	9.22E+16	10.62	72.58	0.011	0.16	Normal	-	Additional	0.001809	-	-
89	2	60	4.57	1031.54	1.00E+09	6.19	68.49	0.030	0.42	Normal	-	-	0.004427	-	-
90	2	61	12.53	1043.97	1.06E+28	16.71	64.40	0.042	0.60	Normal	-	-	0.012005	-	-
91	2	62	21.67	1006.69	3.87E+08	5.79	59.60	0.129	1.84	Anomaly	-	-	0.021523	-	-
92	2	63	23.43	1093.68	8.77E+01	2.06	51.16	0.155	2.22	Anomaly	-	-	0.021426	-	-
93	2	64	14.60	1043.97	1.24E-13	-6.72	40.67	0.979	13.98	Anomaly	-	Additional	0.013985	-	-
94	2	65	18.93	1006.69	5.01E+06	5.42	35.75	0.097	1.38	Anomaly	-	-	0.018808	-	-
95	2	66	5.83	1130.95	1.14E-33	-19.86	34.57	0.020	0.29	Normal	-	Additional	0.005158	-	-
96	2	67	8.30	1056.40	4.90E+01	2.63	31.28	0.027	0.38	Normal	-	-	0.007857	-	-
97	2	68	21.37	1068.82	1.40E-05	-2.16	26.89	0.076	1.09	Normal	-	-	0.019991	-	-
98	2	69	8.23	1056.40	8.13E+09	8.68	23.95	0.037	0.52	Normal	-	Additional	0.007794	-	-
99	2	70	18.50	1093.68	5.15E-08	-4.18	21.11	0.070	1.00	Normal	-	-	0.016915	-	-
100	2	71	2.17	1106.10	1.16E-09	-5.08	18.79	0.013	0.18	Normal	-	Additional	0.001959	-	-

B.1 (Continued).

No.	Stream No.	Segment No.	Rise (m)	Run (m)	k_s	θ	A_{cent}	k_{sn}	k_{sn}/k_{sn}(avg)	Stream Steepness	Outstanding anomaly	Additional anomaly	Slope from RTSD-DTED2	Slope from MOAC-DEM	Big waterfalls
101	2	72	16.83	969.41	5.84E+12	11.96	15.83	0.091	1.30	Anomaly	-	-	0.017364	-	-
102	2	73	16.33	1019.12	4.52E-20	-15.40	13.42	0.034	0.49	Normal	-	-	0.016027	-	-
103	2	74	14.70	1068.82	2.82E+03	4.92	12.20	0.039	0.56	Normal	-	-	0.013753	-	-
104	2	75	4.50	994.26	2.83E-22	-18.21	11.30	0.013	0.18	Normal	-	Additional	0.004526	-	-
105	3	1	0.77	994.26	2.00E+307	489.40	1783.12	0.000	0.00	Normal	-	-	0.000771	0.000795	-
106	3	2	4.67	969.41	1.79E+234	72.79	1777.08	0.148	2.12	Anomaly	-	-	0.004814	-	-
107	3	3	5.73	1031.54	1.62E+232	72.18	1770.59	0.165	2.36	Anomaly	-	-	0.005558	-	-
108	3	4	1.10	1068.82	0	-1932.88	1768.36	0.000	0.00	Normal	-	Additional	0.001029	-	Wang Nok Aen
109	3	5	2.47	1081.25	1.54E+52	16.91	1719.61	0.083	1.19	Anomaly	-	-	0.002281	-	-
110	3	6	3.63	1019.12	0	-1805.76	1672.28	0.000	0.00	Normal	-	-	0.003565	-	-
111	3	7	1.27	981.84	2.00E+307	287.98	1669.59	0.000	0.00	Normal	-	-	0.001290	-	-
112	3	8	0.73	932.13	2.49E-13	-2.99	1657.13	0.031	0.44	Normal	-	-	0.000787	-	-
113	3	9	0.27	1081.25	0	-184.85	1645.80	0.000	0.00	Normal	-	-	0.000247	-	-
114	3	10	0.23	1068.82	0	-114.33	1641.12	0.000	0.00	Normal	-	-	0.000218	-	-
115	3	11	0.53	932.13	7.15E+36	12.29	1637.00	0.064	0.91	Normal	-	-	0.000572	-	-
116	3	12	0.80	1019.12	2.00E+307	205.70	1635.51	0.000	0.00	Normal	-	-	0.000785	-	-
117	3	13	1.43	1081.25	0	-407.43	1633.11	0.000	0.00	Normal	-	-	0.001326	-	-
118	3	14	2.63	1043.97	2.00E+307	144.05	1628.17	0.000	0.00	Normal	-	-	0.002522	0.000479	-
119	3	15	3.33	1031.54	2.00E+307	285.44	1623.55	0.000	0.00	Normal	-	-	0.003231	0.001832	-
120	3	16	4.63	1031.54	2.00E+307	425.32	1622.08	0.000	0.00	Normal	-	-	0.004492	-	-
121	3	17	3.10	1081.25	0	-165.24	1515.01	0.000	0.00	Normal	-	-	0.002867	-	-
122	3	18	2.30	944.56	2.00E+307	362.05	1510.90	0.000	0.00	Normal	-	-	0.002435	-	-
123	3	19	5.20	1106.10	2.00E+307	212.64	1506.94	0.000	0.00	Normal	-	-	0.004701	-	-
124	3	20	7.37	1056.40	0	-184.41	1497.86	0.000	0.00	Normal	-	-	0.006973	-	-
125	3	21	3.23	1019.12	2.00E+307	501.68	1490.52	0.000	0.00	Normal	-	Additional	0.003173	-	Kaeng Song

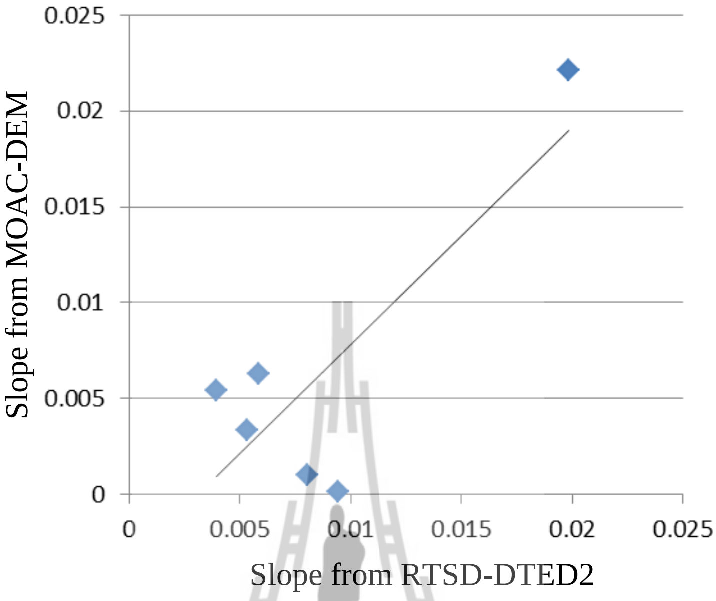
B.1 (Continued).

No.	Stream No.	Segment No.	Rise (m)	Run (m)	k_s	θ	A_{cent}	k_{sn}	k_{sn}/k_{sn}(avg)	Stream Steepness	Outstanding anomaly	Additional anomaly	Slope from RTSD-DTED2	Slope from MOAC-DEM	Big waterfalls
126	3	22	10.30	994.26	0	-267.64	1487.73	0.000	0.00	Normal	-	-	0.010359	0.006608	-
127	3	23	5.60	956.98	3.29E+126	40.59	1485.30	0.160	2.28	Anomaly	-	Additional	0.005852	0.006322	-
128	3	24	8.67	969.41	0	-876.56	1482.99	0.000	0.00	Normal	-	-	0.008940	0.006880	-
129	3	25	4.23	1068.82	4.32E-20	-5.36	1417.48	0.091	1.30	Anomaly	-	Additional	0.003961	0.005417	-
130	3	26	3.23	994.26	0	-347.28	1354.72	0.000	0.00	Normal	-	-	0.003252	0.003027	-
131	3	27	1.23	1081.25	0	-173.47	1352.80	0.000	0.00	Normal	-	-	0.001141	-	-
132	3	28	2.63	1068.82	2.00E+307	167.08	1349.09	0.000	0.00	Normal	-	-	0.002464	-	-
133	3	29	1.50	1031.54	0	-207.96	1346.08	0.000	0.00	Normal	-	-	0.001454	-	-
134	3	30	1.50	1006.69	2.00E+307	315.78	1341.40	0.000	0.00	Normal	-	-	0.001490	-	-
135	3	31	5.40	1019.12	4.53E-137	-42.90	1324.62	0.099	1.42	Anomaly	-	-	0.005299	0.003336	-
136	3	32	1.20	1056.40	2.00E+307	615.80	1311.21	0.000	0.00	Normal	-	Additional	0.001136	0.002281	-
137	3	33	0.60	1031.54	0	-867.79	1310.41	0.000	0.00	Normal	-	-	0.000582	0.002782	-
138	3	34	0.40	956.98	2.00E+307	114.41	1307.59	0.000	0.00	Normal	-	-	0.000418	-	-
139	3	35	0.77	969.41	2.00E+307	414.82	1304.51	0.000	0.00	Normal	-	-	0.000791	-	-
140	3	36	1.20	969.41	0	-518.17	1302.50	0.000	0.00	Normal	-	-	0.001238	0.000299	-
141	3	37	0.30	944.56	1.00E+51	17.33	1294.60	0.029	0.41	Normal	-	-	0.000318	-	-
142	3	38	1.37	1019.12	2.00E+307	441.71	1293.30	0.000	0.00	Normal	-	-	0.001341	-	-
143	3	39	3.83	1019.12	3.14E+273	88.71	1288.91	0.096	1.37	Anomaly	-	-	0.003761	-	-
144	3	40	6.63	919.71	2.00E+307	435.50	1284.78	0.000	0.00	Normal	-	-	0.007212	-	-
145	3	41	9.70	1068.82	1.33E-94	-29.55	1281.92	0.226	3.23	Anomaly	-	-	0.009075	-	-
146	3	42	6.27	969.41	0	-372.42	1278.88	0.000	0.00	Normal	-	-	0.006464	-	-
147	3	43	13.63	1068.82	2.00E+307	292.92	1277.48	0.000	0.00	Normal	-	-	0.012755	-	Poy
148	3	44	2.83	981.84	1.30E-41	-12.47	1174.67	0.060	0.85	Normal	-	Additional	0.002886	0.008820	-
149	3	45	0.60	1043.97	8.48E-70	-21.84	1078.67	0.034	0.48	Normal	-	-	0.000575	-	-
150	3	46	0.40	1118.53	1.53E-122	-39.23	1074.42	0.028	0.40	Normal	-	-	0.000358	-	-
151	3	47	0.17	944.56	2.00E+307	107.46	1069.93	0.000	0.00	Normal	-	-	0.000176	-	-

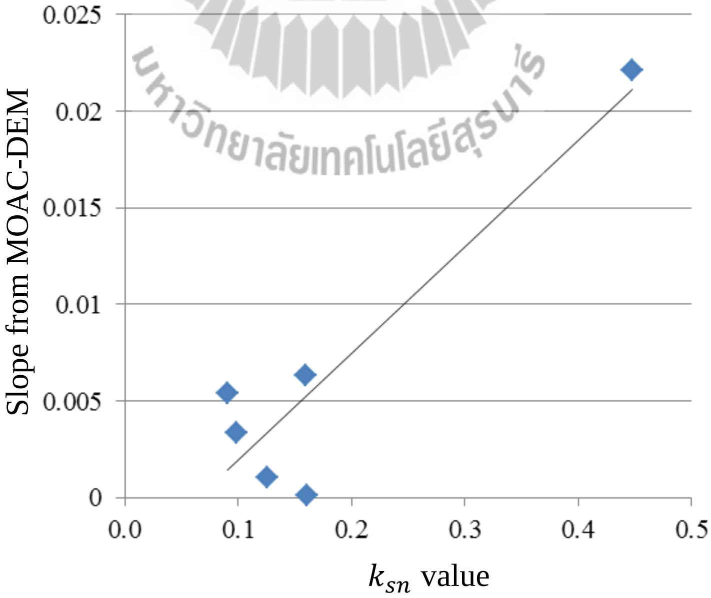
B.1 (Continued).

No.	Stream No.	Segment No.	Rise (m)	Run (m)	k_s	θ	A_{cent}	k_{sn}	k_{sn}/k_{sn}(avg)	Stream Steepness	Outstanding anomaly	Additional anomaly	Slope from RTSD-DTED2	Slope from MOAC-DEM	Big waterfalls
152	3	48	2.07	1068.82	5.72E-199	-64.63	1065.09	0.059	0.85	Normal	-	-	0.001934	-	-
153	3	49	13.80	1155.81	2.00E+307	272.96	1059.75	0.000	0.00	Normal	-	-	0.011940	-	-
154	3	50	21.93	994.26	2.00E+307	489.95	1057.38	0.000	0.00	Normal	-	-	0.022060	0.012401	-
155	3	51	18.97	956.98	6.41E-18	-5.16	1006.49	0.448	6.40	Anomaly	Outstanding	-	0.019819	0.022101	-
156	3	52	19.07	969.41	4.14E+281	95.03	957.82	0.456	6.51	Anomaly	Outstanding	-	0.019668	-	-
157	3	53	17.20	1081.25	1.29E+69	23.79	955.29	0.358	5.12	Anomaly	Outstanding	-	0.015908	-	-
158	3	54	15.67	1056.40	0	-1447.37	953.52	0.000	0.00	Normal	-	-	0.014830	-	-
159	3	55	15.87	932.13	2.00E+307	275.03	950.55	0.000	0.00	Normal	-	-	0.017022	-	-
160	3	56	30.20	1068.82	1.60E-43	-13.86	947.53	0.626	8.94	Anomaly	Outstanding	-	0.028255	-	-
161	3	57	44.20	969.41	1.15E+282	95.22	946.72	0.979	13.98	Anomaly	Outstanding	-	0.045595	-	Kaeng Sopa
162	3	58	9.10	1019.12	0	-1446.11	945.27	0.000	0.00	Normal	-	Additional	0.008929	-	-
163	3	59	1.10	1043.97	2.57E-283	-94.09	941.42	0.035	0.51	Normal	-	Additional	0.001054	-	-
164	3	60	1.97	994.26	0	-150.91	937.97	0.000	0.00	Normal	-	-	0.001978	-	-
165	3	61	1.43	1068.82	2.00E+307	174.82	937.02	0.000	0.00	Normal	-	-	0.001341	-	-
166	3	62	1.70	1056.40	0	-203.36	935.18	0.000	0.00	Normal	-	-	0.001609	-	-
167	3	63	1.03	969.41	1.62E+22	8.34	925.06	0.065	0.92	Normal	-	-	0.001066	-	-
168	3	64	1.03	932.13	4.22E-78	-25.25	915.88	0.057	0.81	Normal	-	-	0.001109	-	-
169	3	65	5.03	1081.25	2.00E+307	447.23	913.78	0.000	0.00	Normal	-	-	0.004655	-	-
170	3	66	1.33	1068.82	2.31E-91	-29.70	910.01	0.037	0.53	Normal	-	-	0.001247	-	-
171	3	67	2.67	1143.38	2.00E+307	416.14	906.85	0.000	0.00	Normal	-	-	0.002332	-	-
172	3	68	14.73	1019.12	2.00E+307	148.73	902.42	0.000	0.00	Normal	-	-	0.014457	-	-
173	3	69	13.87	1118.53	0	-220.75	898.51	0.000	0.00	Normal	-	-	0.012397	-	-
174	3	70	12.33	1081.25	2.00E+307	265.73	897.31	0.000	0.00	Normal	-	-	0.011407	-	-
175	3	71	7.60	981.84	0	-720.08	895.81	0.000	0.00	Normal	-	-	0.007741	-	-
176	3	72	4.27	1031.54	1.1E-142	-47.29	891.24	0.077	1.10	Normal	-	-	0.004136	-	-
177	3	73	1.40	981.84	2.00E+307	110.65	885.64	0.000	0.00	Normal	-	-	0.001426	-	-

B.2 The relationship between anomaly segment slopes derived from RTSD-DTED2 and MOAC-DEM data.



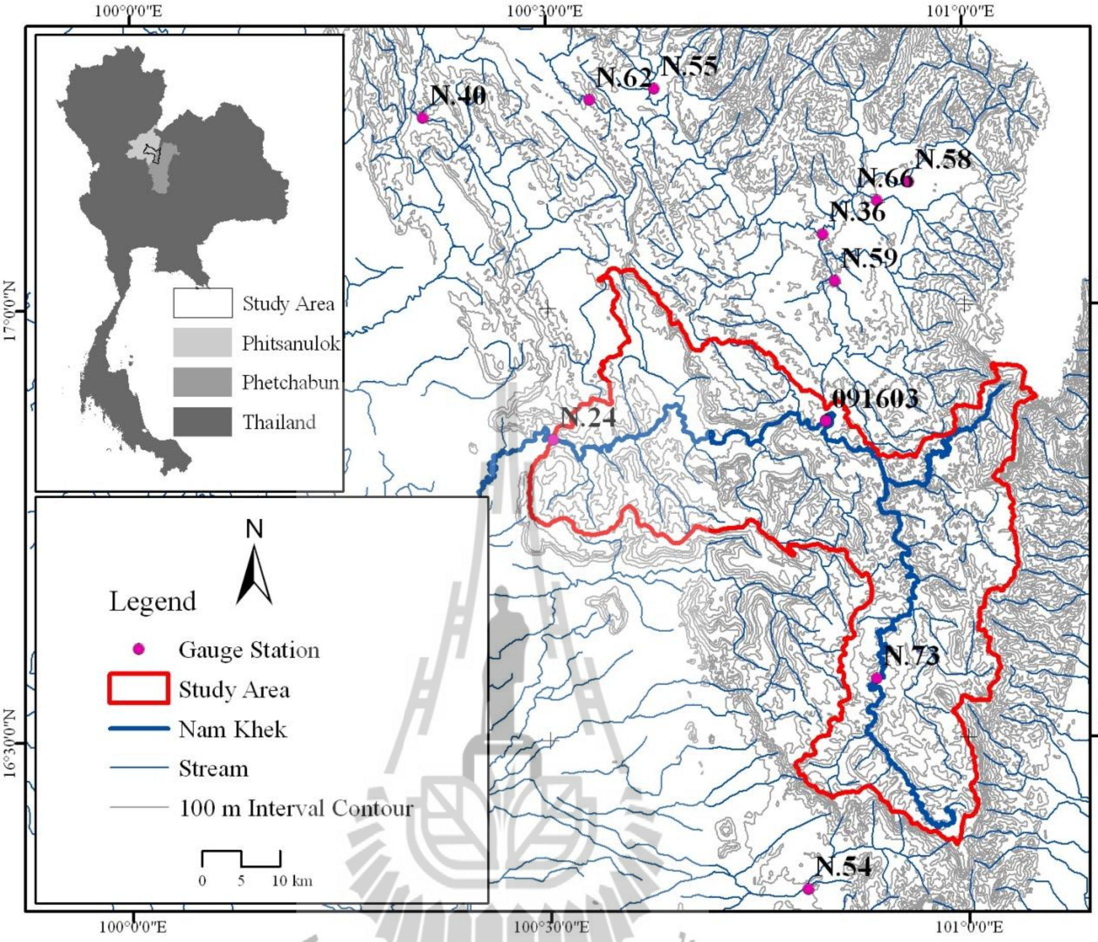
B.3 The relationship between k_{sn} value and anomaly segment slopes derived from MOAC-DEM data.



APPENDIX C

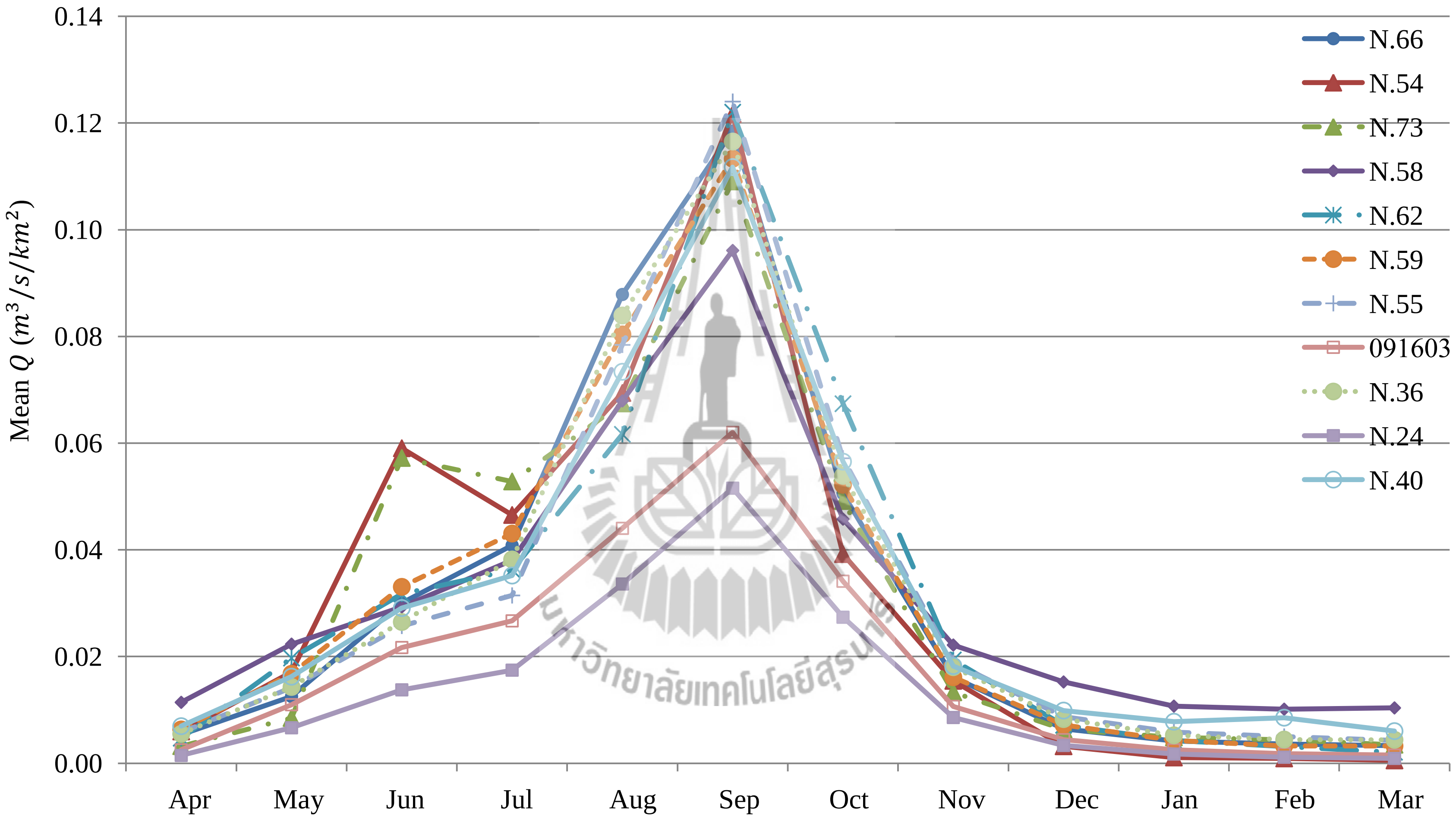
LOCATION, MONTHLY RUNOFF DISTRIBUTION, AND FDC OF 11 GAGING STATIONS

C.1 Location of 11 gaging stations.

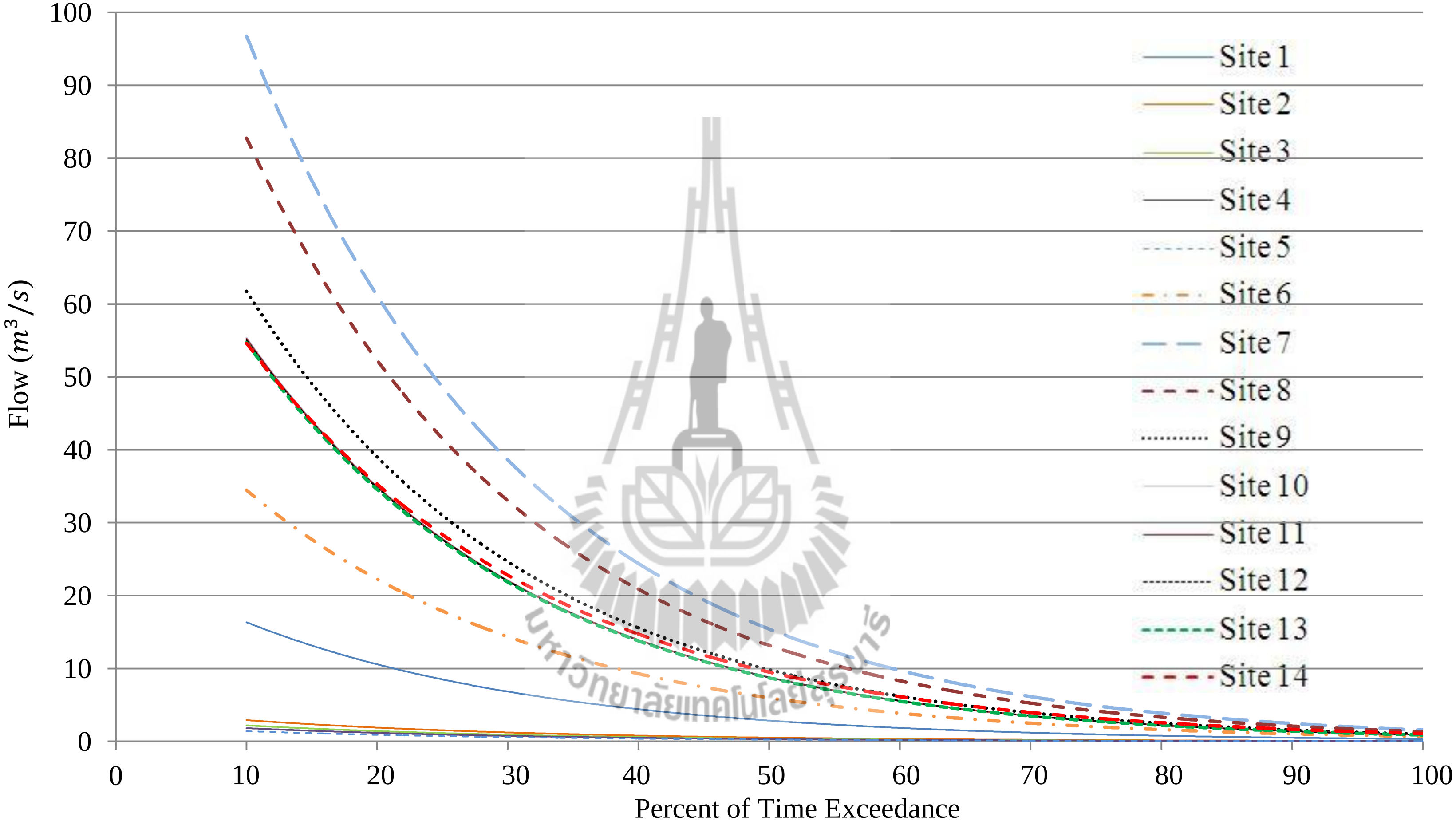


Note: N.73 was a gaging station with missing data records.

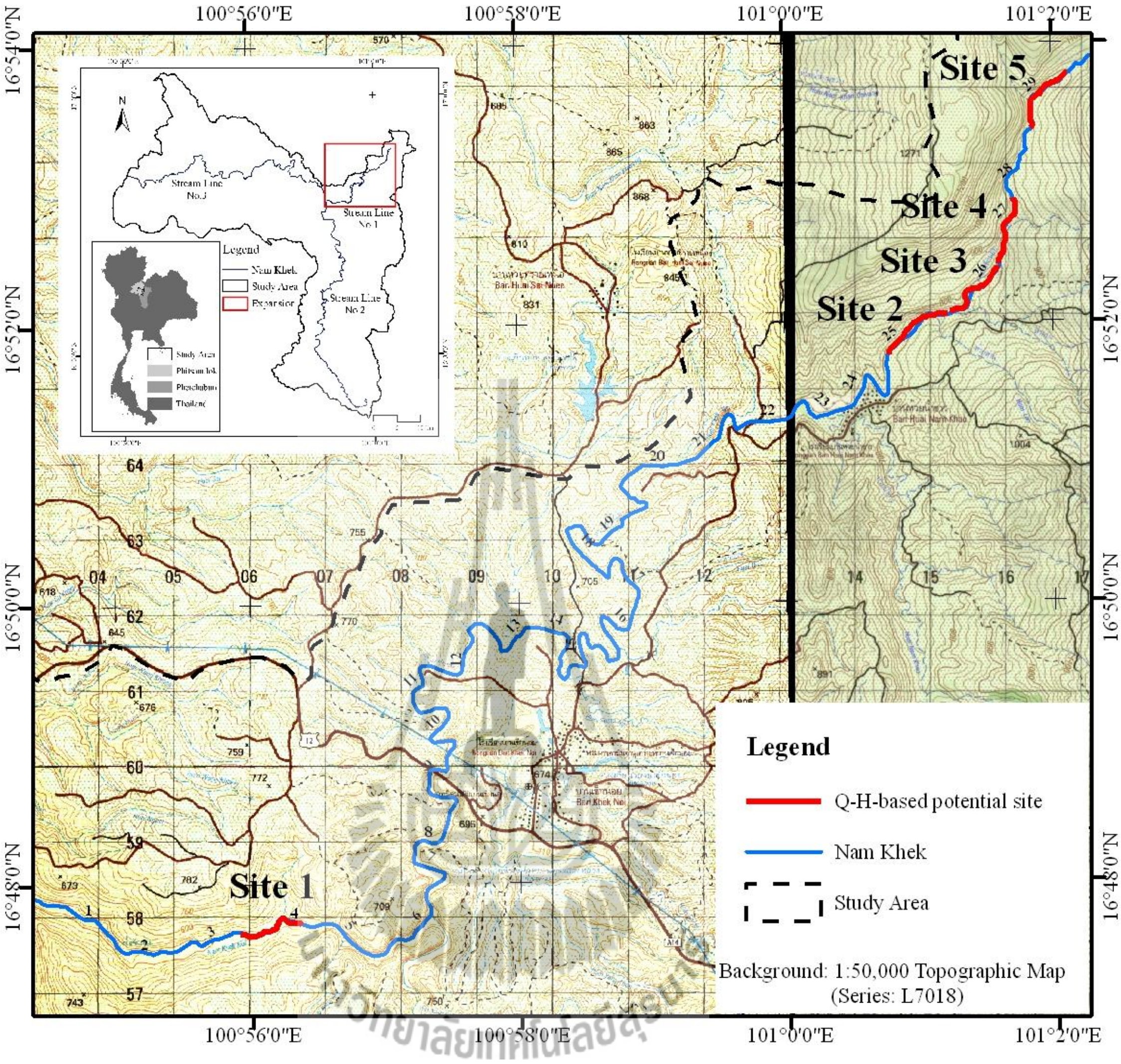
C.2 The monthly runoff distribution of 11 gaging stations.



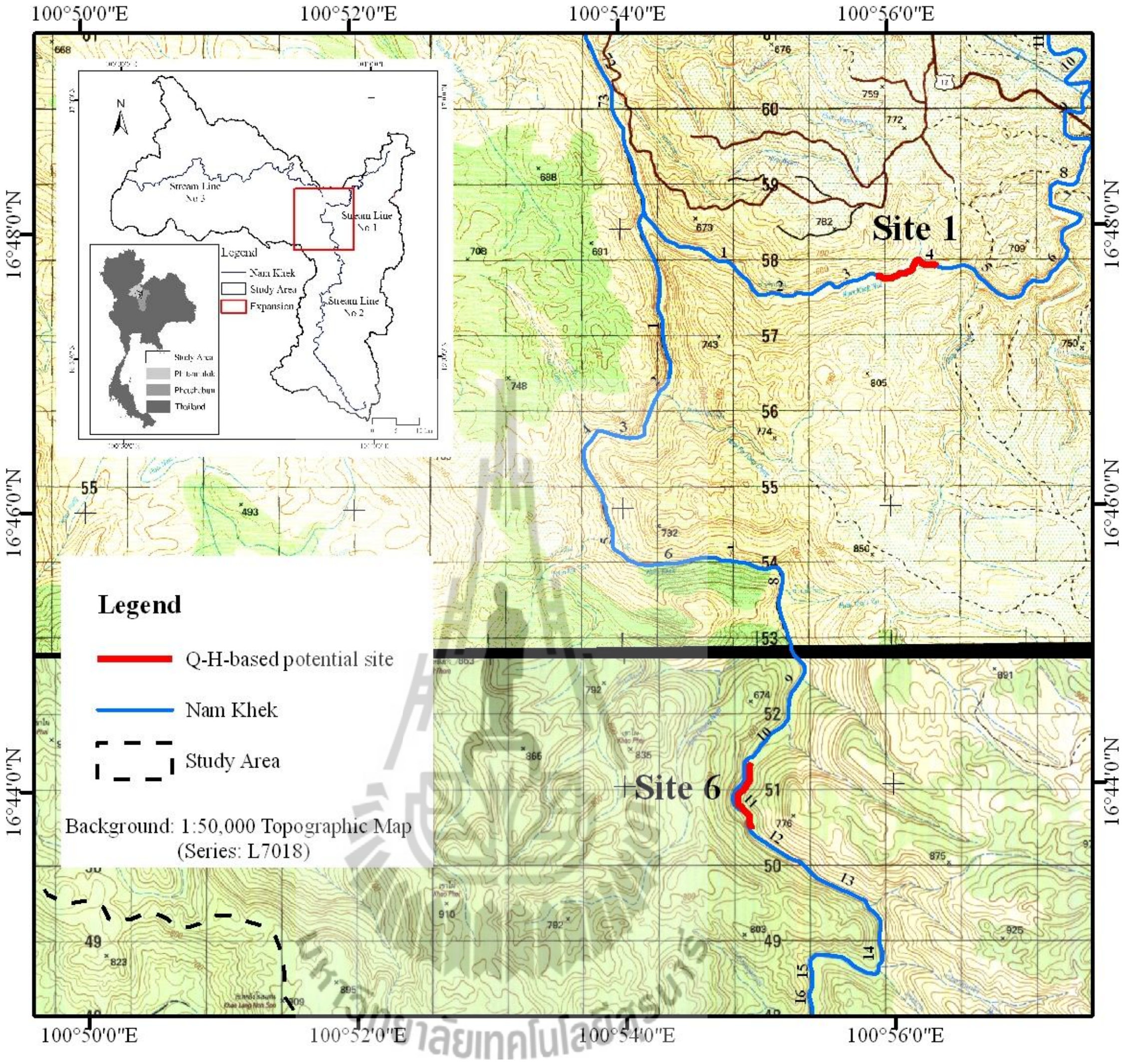
C.3 FDC of the Q-H-based potential alternatives.



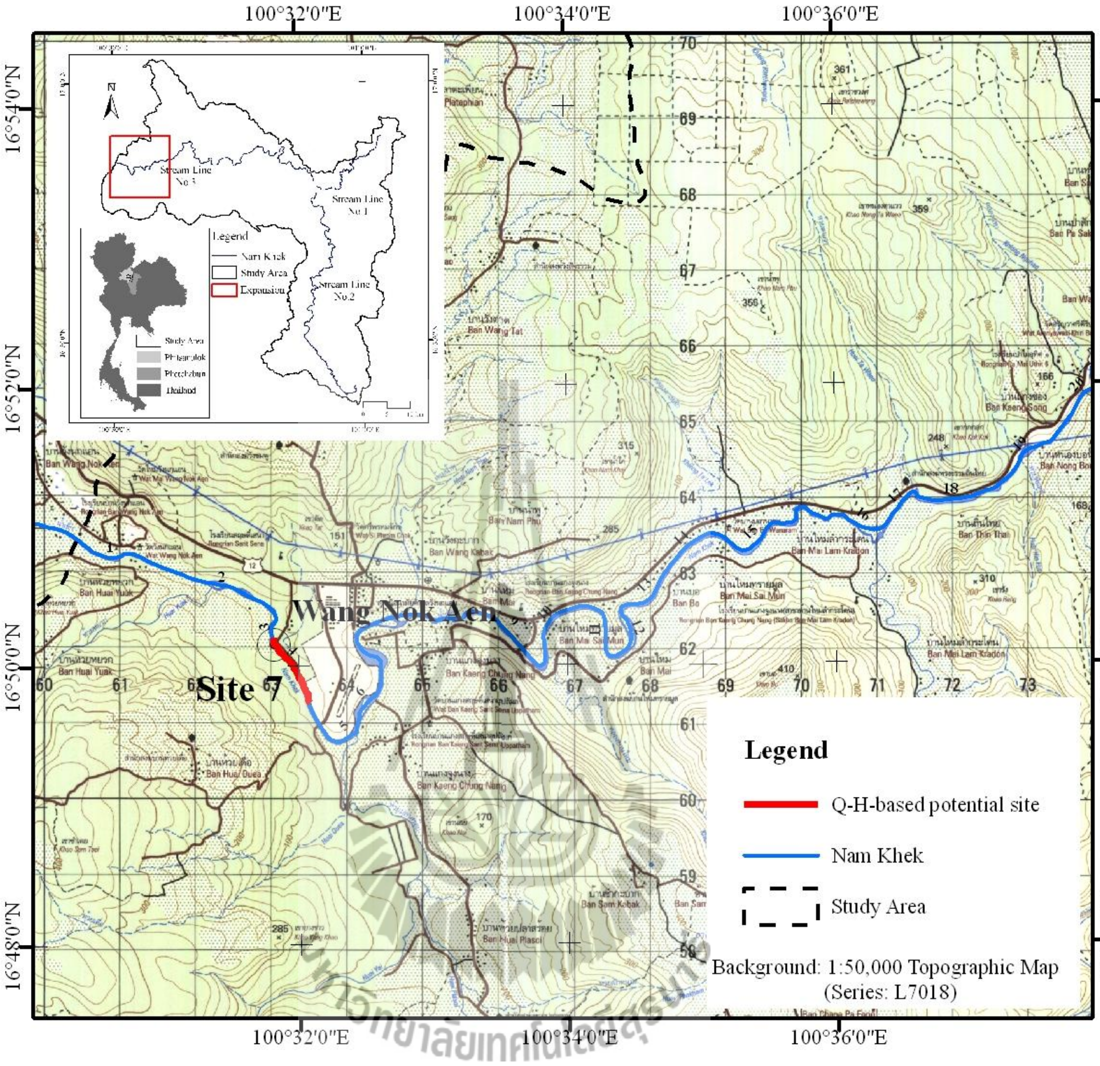
C.4 Location of the Q-H-based potential alternatives.



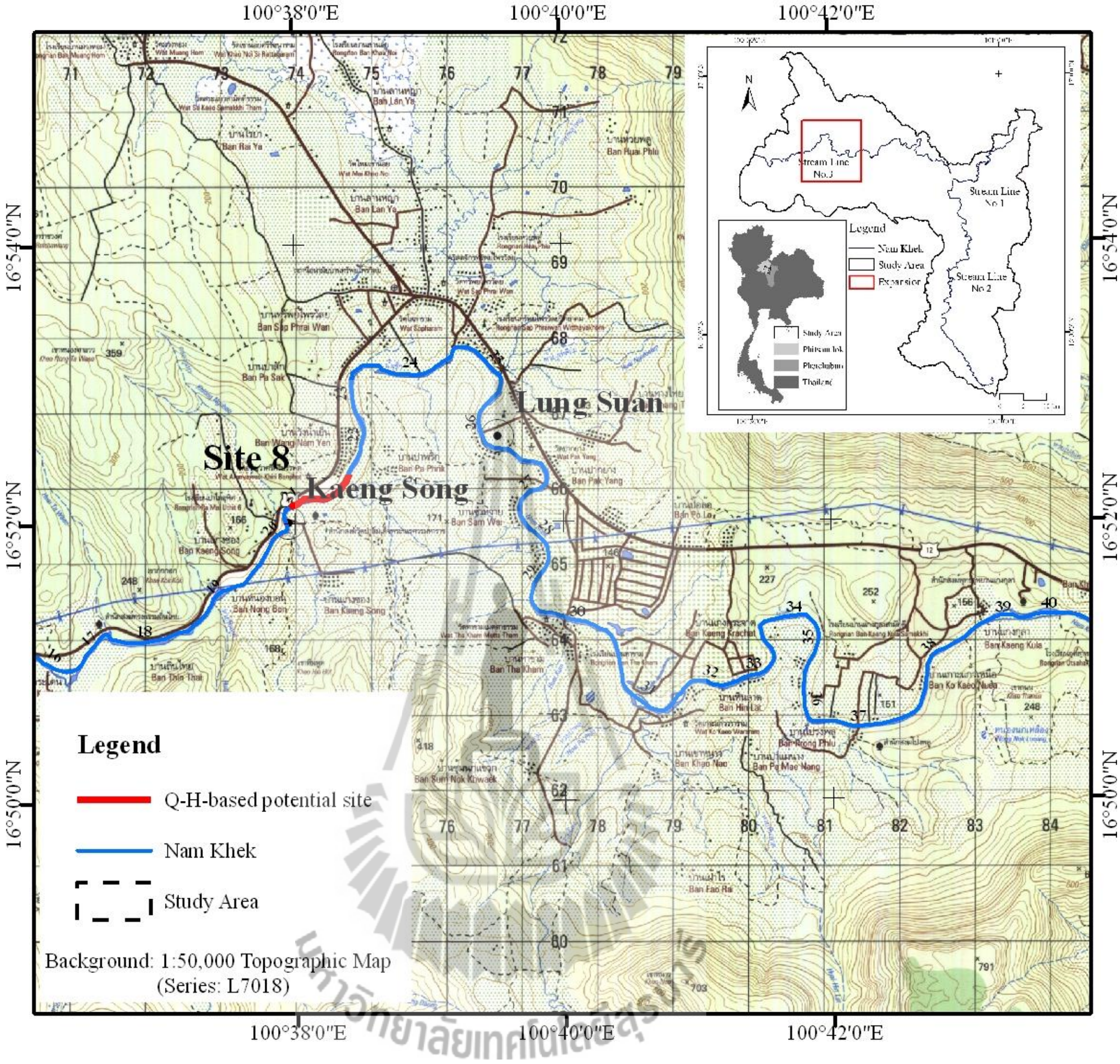
C.4 Location of the Q-H-based potential alternatives (Continued).



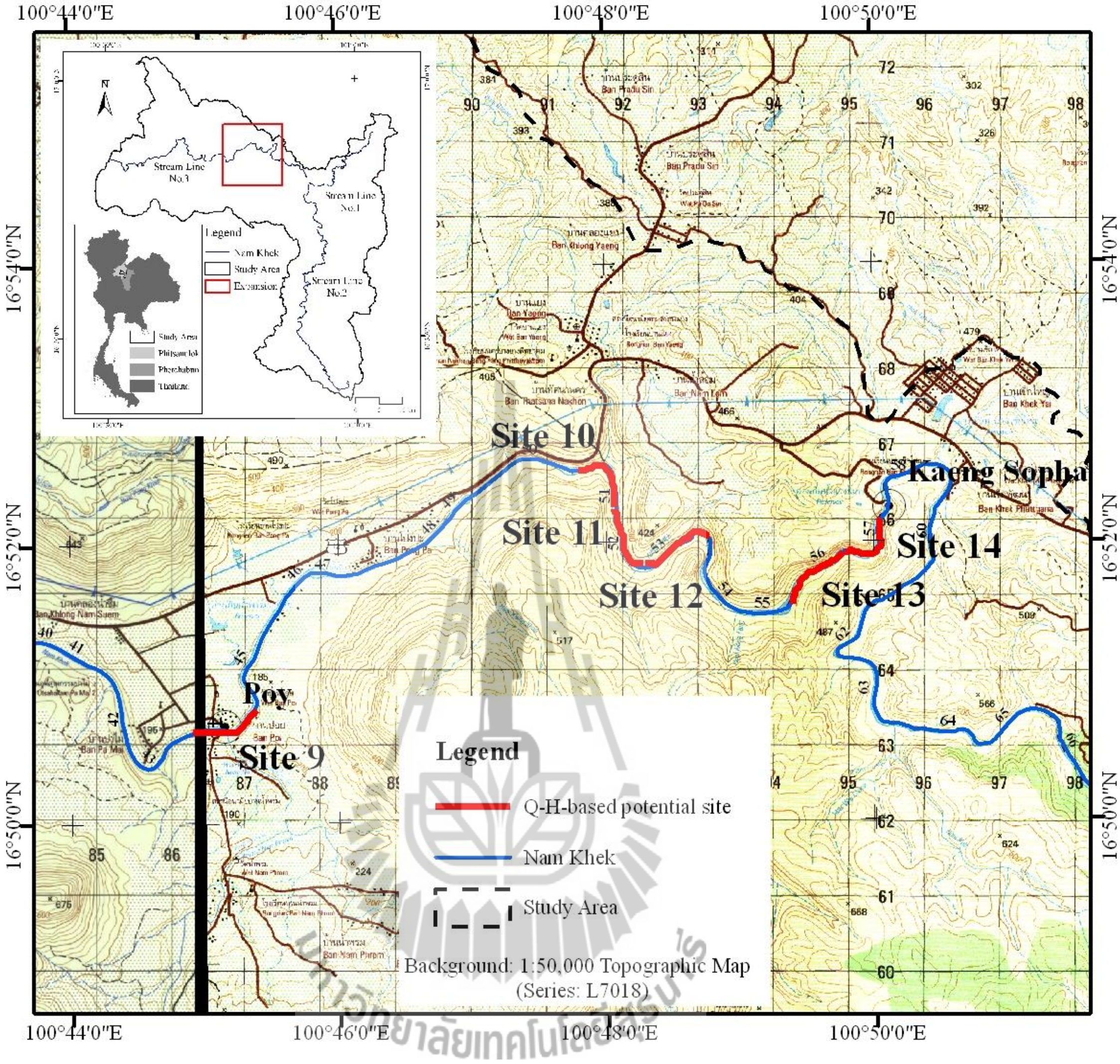
C.4 Location of the Q-H-based potential alternatives (Continued).



C.4 Location of the Q-H-based potential alternatives (Continued).



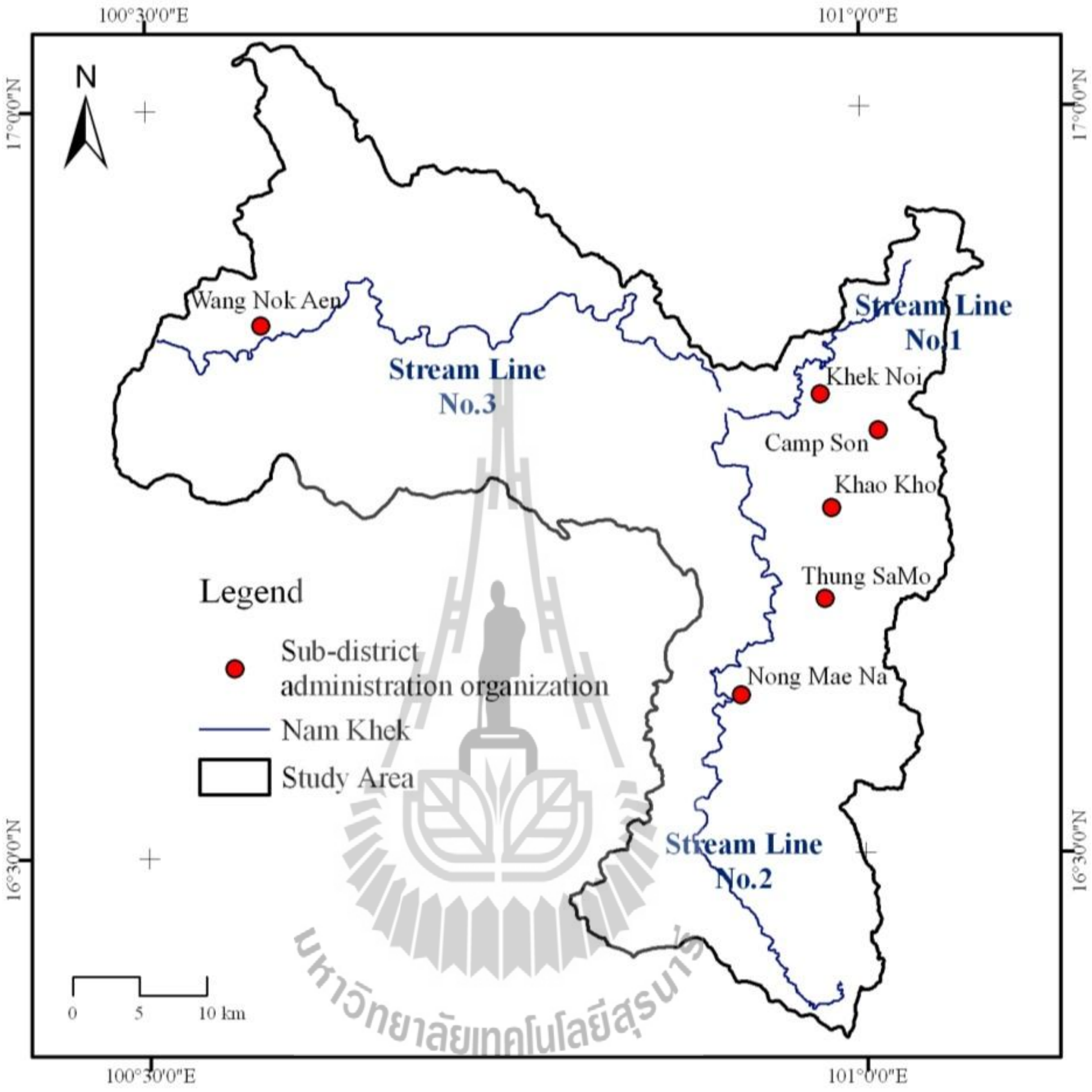
C.4 Location of the Q-H-based potential alternatives (Continued).



APPENDIX D

SCRIPT OF INTERVIEW, THE SCORE AND WEIGHT OF CRITERIA, SOME INTERVIEW WORK & FIELD SURVEY, AND DEFUZZIFICATION

D.1 Some interview work.



Nong Mae Na

Khao Kho

D.2 Script of interview.

แบบสัมภาษณ์ความคิดเห็นของผู้นำท้องถิ่น
เรื่อง การวิเคราะห์ค่าน้ำหนักของปัจจัยที่ใช้ประเมิน
ลำดับการพัฒนาตำแหน่งศักยภาพโรงไฟฟ้าพลังน้ำขนาดเล็ก

1. ข้อมูลทั่วไปของผู้ให้สัมภาษณ์

ภูมิลำเนา:หมู่ที่.............บ้าน.......................ตำบล..........................อำเภอ.......................
ตำแหน่ง/หน้าที่/อาชีพ..
ระยะเวลาการอยู่อาศัยในท้องถิ่น...

2. กรุณาเรียงลำดับความสำคัญของปัจจัยที่ใช้จัดลำดับการพัฒนาตำแหน่งศักยภาพโรงไฟฟ้าพลังน้ำขนาดเล็ก (มากไปหาน้อย)

ปัจจัย	**ลำดับความสำคัญ**
พลังงานไฟฟ้าที่ผลิตได้	
เนื้อที่ใช้ประโยชน์	
เสถียรภาพของสิ่งแวดล้อม	
จำนวนแหล่งท่องเที่ยวใกล้เคียง	
ความโดดเด่นของที่ตั้ง	
ศักยภาพต่อการขยายตัวในอนาคต	

3. กรุณาเปรียบเทียบปัจจัยด้านซ้ายกับปัจจัยด้านขวาของตารางทีละคู่ เพื่อกำหนดว่าปัจจัยใดมีความสำคัญกว่ากัน

ตัวอย่าง หากท่านคิดว่าปัจจัยด้านขนาดเนื้อที่ใช้ประโยชน์มีความสำคัญกว่าปัจจัยด้านพลังงานไฟฟ้าที่ผลิตได้ ให้ท่านวงกลมที่ “ใช่” ในช่องปัจจัยหลังสำคัญกว่าปัจจัยแรก

คู่ที่	ปัจจัยแรก	ปัจจัยหลัง	ปัจจัยแรกสำคัญกว่าปัจจัยหลังในระดับ	เท่ากัน	ปัจจัยหลังสำคัญกว่าปัจจัยแรกในระดับ
1	พลังงานไฟฟ้าที่ผลิตได้	ขนาดเนื้อที่ใช้ประโยชน์	ใช่	ใช่	[✓ ใช่]

กรุณาทำเครื่องหมายลงในตารางเพื่อเปรียบเทียบปัจจัยแต่ละคู่ต่อไปนี้

คู่ที่	ปัจจัยแรก	ปัจจัยหลัง	ปัจจัยแรกสำคัญกว่าปัจจัยหลังในระดับ	เท่ากัน	ปัจจัยหลังสำคัญกว่าปัจจัยแรกในระดับ
1	พลังงานไฟฟ้าที่ผลิตได้	ขนาดเนื้อที่ใช้ประโยชน์	ใช่	ใช่	ใช่
2	พลังงานไฟฟ้าที่ผลิตได้	เสถียรภาพด้านสิ่งแวดล้อม	ใช่	ใช่	ใช่
3	พลังงานไฟฟ้าที่ผลิตได้	จำนวนแหล่งท่องเที่ยวใกล้เคียง	ใช่	ใช่	ใช่
4	พลังงานไฟฟ้าที่ผลิตได้	ความโดดเด่นของที่ตั้ง	ใช่	ใช่	ใช่
5	พลังงานไฟฟ้าที่ผลิตได้	ศักยภาพต่อการขยายตัวในอนาคต	ใช่	ใช่	ใช่
6	ขนาดเนื้อที่ใช้ประโยชน์	เสถียรภาพด้านสิ่งแวดล้อม	ใช่	ใช่	ใช่
7	ขนาดเนื้อที่ใช้ประโยชน์	จำนวนแหล่งท่องเที่ยวใกล้เคียง	ใช่	ใช่	ใช่
8	ขนาดเนื้อที่ใช้ประโยชน์	ความโดดเด่นของที่ตั้ง	ใช่	ใช่	ใช่
9	ขนาดเนื้อที่ใช้ประโยชน์	ศักยภาพต่อการขยายตัวในอนาคต	ใช่	ใช่	ใช่
10	เสถียรภาพด้านสิ่งแวดล้อม	จำนวนแหล่งท่องเที่ยวใกล้เคียง	ใช่	ใช่	ใช่
11	เสถียรภาพด้านสิ่งแวดล้อม	ความโดดเด่นของที่ตั้ง	ใช่	ใช่	ใช่
12	เสถียรภาพด้านสิ่งแวดล้อม	ศักยภาพต่อการขยายตัวในอนาคต	ใช่	ใช่	ใช่
13	จำนวนแหล่งท่องเที่ยวใกล้เคียง	ความโดดเด่นของที่ตั้ง	ใช่	ใช่	ใช่
14	จำนวนแหล่งท่องเที่ยวใกล้เคียง	ศักยภาพต่อการขยายตัวในอนาคต	ใช่	ใช่	ใช่
15	ความโดดเด่นของที่ตั้ง	ศักยภาพต่อการขยายตัวในอนาคต	ใช่	ใช่	ใช่

4. ระดับความสามารถในการผลิตไฟฟ้าที่ท่านพึงพอใจของตำแหน่งศักยภาพฯ ขั้นต่ำควรอยู่ที่ระดับ ....หน่วย/เดือน/หลังคาเรือน

5. ความสามารถในการรองรับผู้ใช้ไฟฟ้าของตำแหน่งศักยภาพโรงไฟฟ้าพลังน้ำขนาดเล็กควรอยู่ที่ระดับ ....หลังคาเรือน

6. กรุณาประเมินคุณลักษณะของเกณฑ์ที่ใช้ในการจัดลำดับการพัฒนาของแต่ละตำแหน่งศักยภาพโรงไฟฟ้าพลังน้ำขนาดเล็ก การพิจารณาดังกล่าวอ้างอิงค่าคุณลักษณะในแต่ละเกณฑ์ดังนี้

No.	**Criterion**	**Abbreviation**	**Attribute (score)**		
1	Size	SZ	Limited (1)	Adequate (2)	Expansive (3)
2	Environmental stability	ES	Sensitive (1)	Acceptable (2)	Stable (3)
3	Attractions and features	AF	Few (1)	Numerous (2)	
4	Distinctiveness	DT	Low (1)	Moderate (2)	Exceptional (3)
5	Future expansion	FE	Limited (1)	Moderate (2)	Exceptional (3)

Site.	**Criterion**				
	SZ	**ES**	**AF**	**DT**	**FE**
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					

7. ความคิดเห็นเพิ่มเติม

D.3 The raw score of criteria.

Site	PP	Informant I					Informant II					Informant III					Informant IV					Informant V					Informant VI				
		SZ	ES	AF	DT	FE	SZ	ES	AF	DT	FE	SZ	ES	AF	DT	FE	SZ	ES	AF	DT	FE	SZ	ES	AF	DT	FE	SZ	ES	AF	DT	FE
1	3,522.70	1	1	2	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1
2	906.35	1	2	1	3	2	1	2	1	2	2	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	2	2	1	2	2
3	1,438.39	1	2	1	3	2	1	2	1	3	2	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	2	2	1	2	2
4	1,245.01	1	1	1	2	2	1	2	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	2	1
5	952.12	1	1	1	2	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	2	1
6	13,950.66	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	5,087.50	3	2	2	3	2	3	3	2	3	3	3	3	2	3	3	2	3	2	3	3	3	3	2	3	3	2	3	2	3	3
8	2,406.02	2	3	2	2	1	3	3	2	3	2	2	3	2	3	2	2	3	2	3	1	2	3	2	3	1	2	3	2	3	1
9	5,292.95	3	3	2	2	3	3	3	2	3	3	3	3	2	3	3	3	3	2	3	3	3	3	2	3	3	3	3	2	3	3
10	12,891.21	2	2	2	2	2	2	3	2	2	2	2	3	2	2	1	1	2	2	2	1	1	2	2	2	1	1	2	2	2	1
11	7,443.29	1	2	2	2	1	1	3	2	2	1	1	3	1	2	1	1	2	1	2	1	1	2	1	2	1	1	2	1	2	1
12	8,718.20	1	2	2	2	1	1	3	2	2	1	1	3	1	2	1	1	2	1	2	1	1	2	1	2	1	1	2	1	2	1
13	13,505.57	1	2	2	2	1	1	3	2	2	1	1	3	1	2	1	1	2	2	2	1	1	2	1	2	1	1	2	1	2	1
14	14,803.44	1	2	2	2	1	1	3	2	3	1	1	3	2	3	1	1	2	2	3	1	1	2	1	2	1	1	2	2	3	2

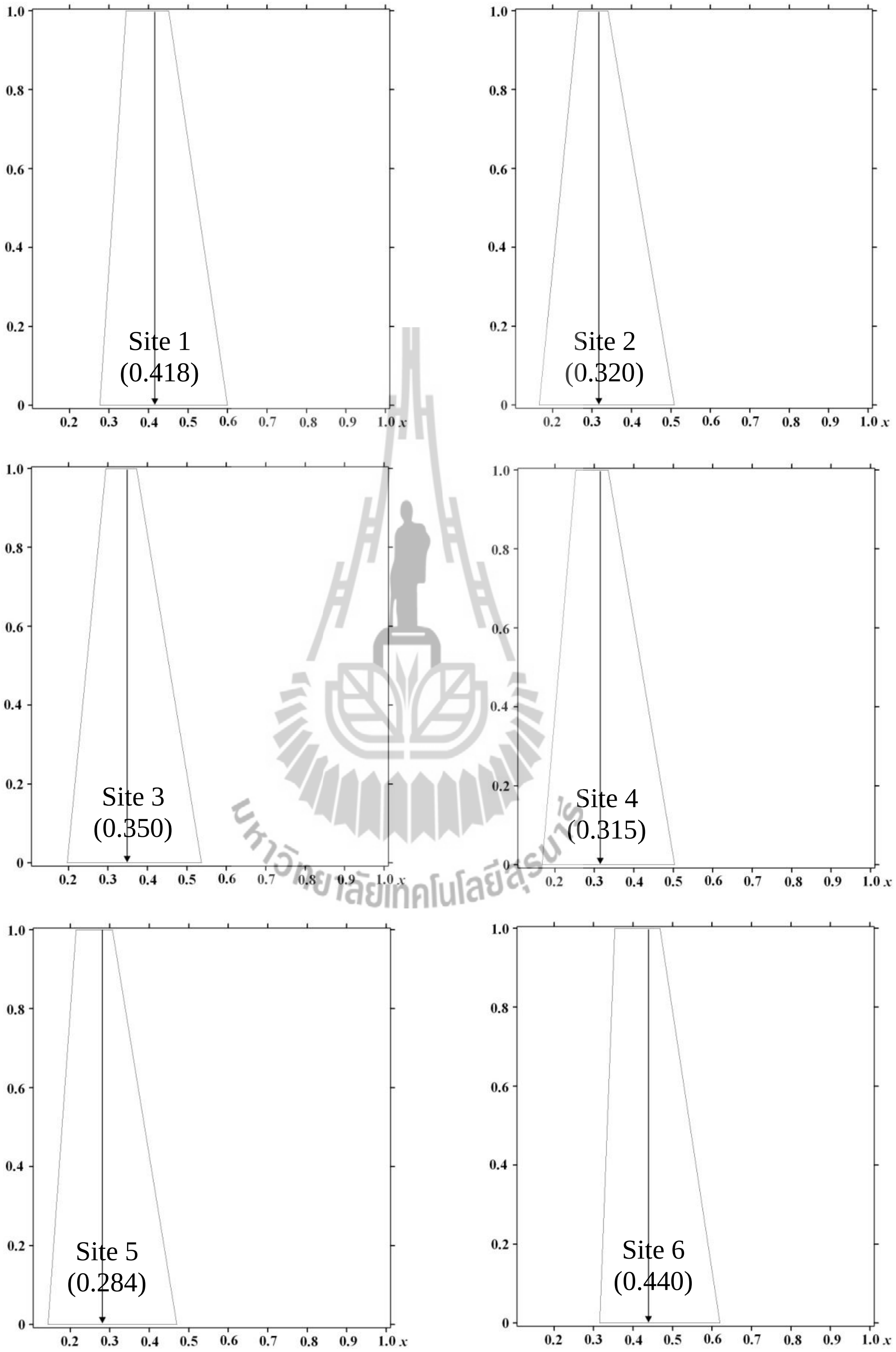
Note: PP = Power productivity, SZ = Size, ES = Environmental stability, AT = Attractions and features, DT = Distinctiveness, FE = Future expansion

D.4 The results of multiplication between a trapezoidal fuzzy number and their weights.

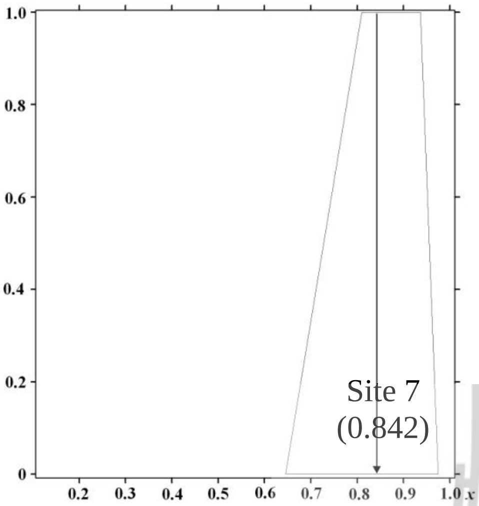
Site.	Criteria																				
	PP	**SZ**				**ES**				**AF**				**DT**				**FE**			
		a	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*
1	0.169	0.009	0.023	0.068	0.126	0.010	0.025	0.045	0.080	0.089	0.127	0.139	0.165	0.000	0.000	0.016	0.032	0.000	0.000	0.014	0.028
2	0.044	0.009	0.023	0.068	0.126	0.015	0.038	0.053	0.090	0.076	0.114	0.114	0.152	0.013	0.024	0.035	0.051	0.009	0.023	0.028	0.047
3	0.069	0.009	0.023	0.068	0.126	0.015	0.038	0.053	0.090	0.076	0.114	0.114	0.152	0.019	0.028	0.041	0.053	0.009	0.023	0.028	0.047
4	0.060	0.009	0.023	0.068	0.126	0.010	0.025	0.045	0.080	0.076	0.114	0.114	0.152	0.008	0.020	0.028	0.048	0.005	0.012	0.021	0.037
5	0.046	0.009	0.023	0.068	0.126	0.005	0.013	0.038	0.070	0.076	0.114	0.114	0.152	0.008	0.020	0.028	0.048	0.000	0.000	0.014	0.028
6	0.240	0.000	0.000	0.054	0.108	0.000	0.000	0.030	0.060	0.076	0.114	0.114	0.152	0.000	0.000	0.016	0.032	0.000	0.000	0.014	0.028
7	0.240	0.126	0.189	0.225	0.252	0.080	0.113	0.138	0.145	0.114	0.152	0.190	0.190	0.048	0.064	0.080	0.080	0.037	0.053	0.064	0.068
8	0.115	0.072	0.149	0.158	0.225	0.090	0.120	0.150	0.150	0.114	0.152	0.190	0.190	0.043	0.060	0.073	0.077	0.005	0.012	0.021	0.037
9	0.240	0.162	0.216	0.270	0.270	0.090	0.120	0.150	0.150	0.114	0.152	0.190	0.190	0.043	0.060	0.073	0.077	0.042	0.056	0.070	0.070
10	0.240	0.027	0.068	0.095	0.162	0.050	0.090	0.100	0.130	0.114	0.152	0.190	0.190	0.016	0.040	0.040	0.064	0.005	0.012	0.021	0.037
11	0.240	0.000	0.000	0.054	0.108	0.050	0.090	0.100	0.130	0.089	0.127	0.139	0.165	0.016	0.040	0.040	0.064	0.000	0.000	0.014	0.028
12	0.240	0.000	0.000	0.054	0.108	0.050	0.090	0.100	0.130	0.089	0.127	0.139	0.165	0.016	0.040	0.040	0.064	0.000	0.000	0.014	0.028
13	0.240	0.000	0.000	0.054	0.108	0.050	0.090	0.100	0.130	0.095	0.133	0.152	0.171	0.016	0.040	0.040	0.064	0.000	0.000	0.014	0.028
14	0.240	0.000	0.000	0.054	0.108	0.050	0.090	0.100	0.130	0.108	0.146	0.177	0.184	0.037	0.056	0.067	0.075	0.000	0.000	0.014	0.028

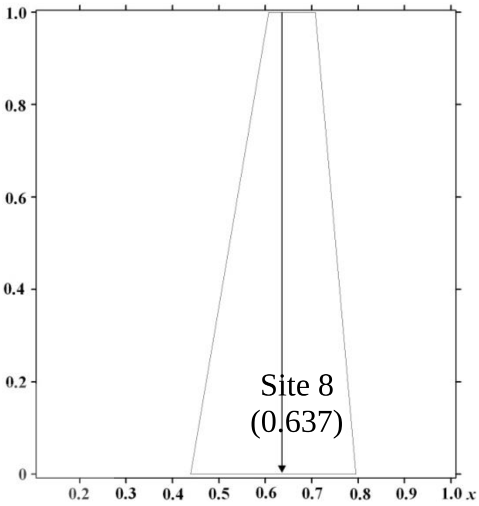
Note: PP = Power productivity, SZ = Size, ES = Environmental stability, AT = Attractions and features, DT = Distinctiveness,
FE = Future expansion

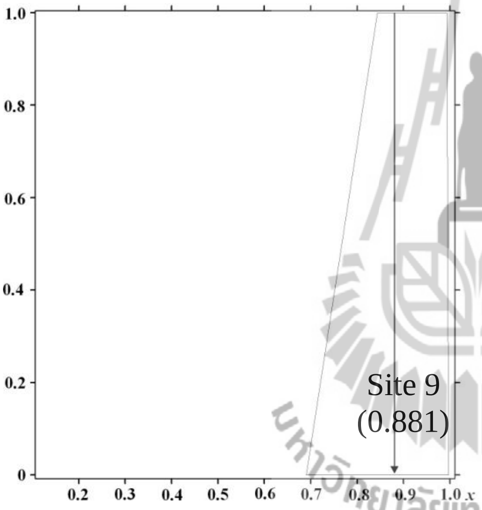
D.5 Defuzzification.

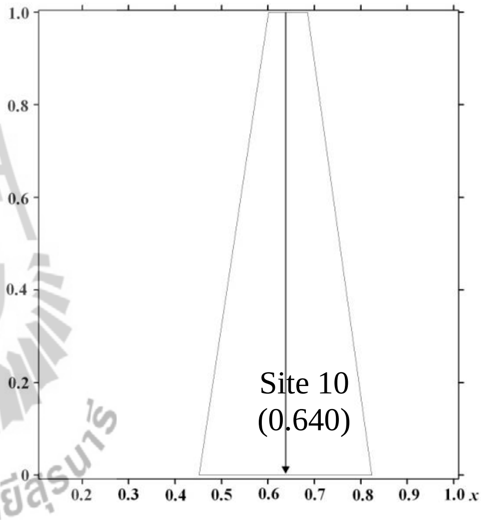


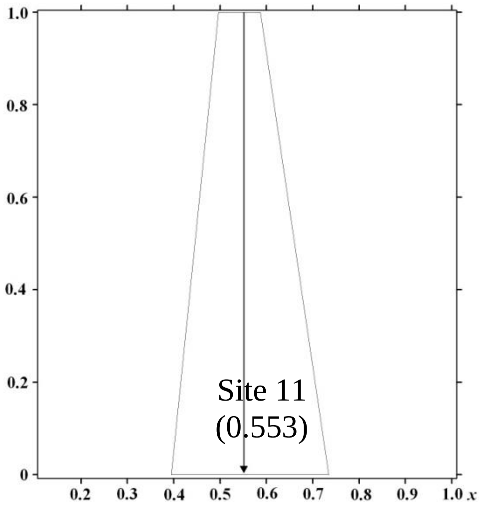
D.5 Defuzzification (Continued).

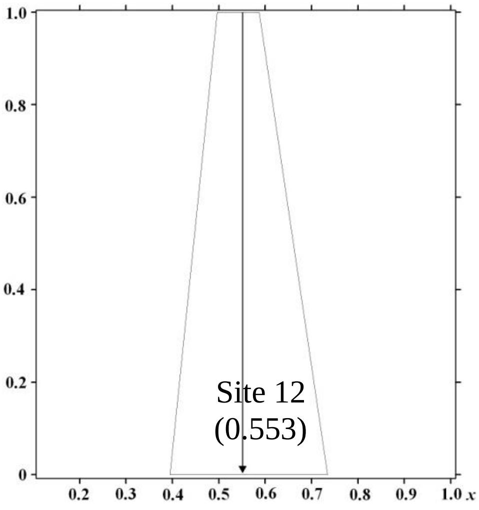




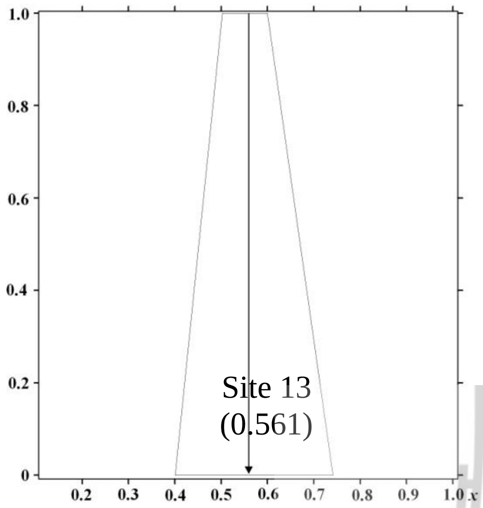


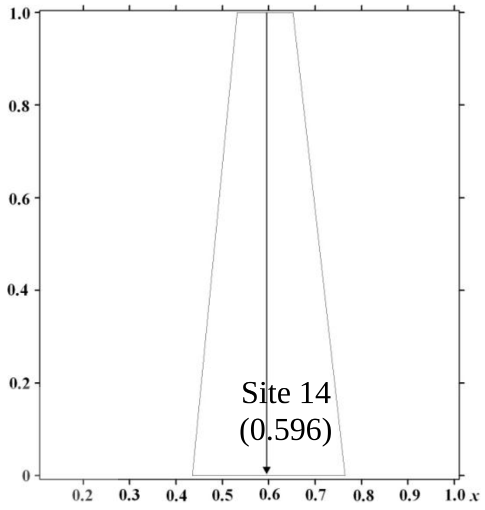




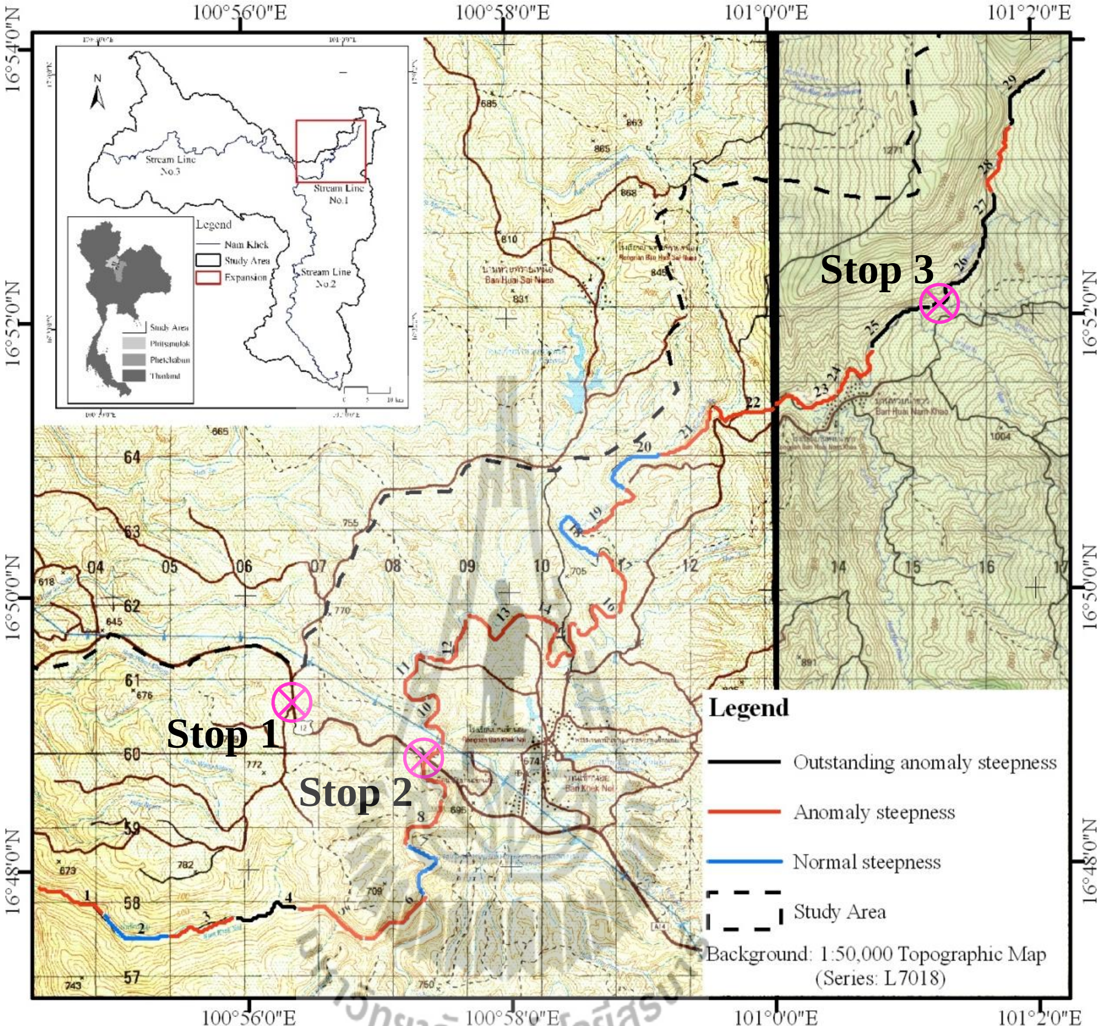


D.5 Defuzzification (Continued).





D.6 Some field survey.



Stop 1 and 2

Stop 3

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