การประยุกต์หลักการรับรู้จากระยะไกลและระบบสารสนเทศภูมิศาสตร์ ในการจัดการที่ดินและน้ำสำหรับการผลิตพืชไร่เศรษฐกิจ: กรณีศึกษาจังหวัดนครราชสีมา ประเทศไทย

นายพิชัย วงศ์สวาสดิ์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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APPLICATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM TO LAND AND WATER MANAGEMENT FOR ECONOMIC CROPS PRODUCTION: CASE STUDY IN NAKHON RATCHASIMA PROVINCE, THAILAND

Pichai Wongsawat

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Geoinformatics

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APPLICATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM TO LAND AND WATER MANAGEMENT FOR ECONOMIC CROPS PRODUCTION: CASE STUDY IN NAKHON RATCHASIMA PROVINCE, THAILAND

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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พิชัย วงศ์สวาสดิ์ : การประยุกต์หลักการรับรู้จากระยะไกลและระบบสารสนเทศภูมิศาสตร์ในการจัดการที่ดินและน้ำสำหรับการผลิตพืชไร่เศรษฐกิจ: กรณีศึกษาจังหวัดนครราชสีมา ประเทศไทย (APPLICATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM TO LAND AND WATER MANAGEMENT FOR ECONOMIC CROPS PRODUCTION: CASE STUDY IN NAKHON RATCHASIMA PROVINCE, THAILAND) อาจารย์ที่ปรึกษา: ผู้ช่วยศาสตราจารย์ ดร.ทรงกต ทศานนท์, 178 หน้า.

ในงานวิทยานิพนธ์ฉบับนี้นำเทคโนโลยีภูมิสารสนเทศมาประยุกต์ เพื่อการวิเคราะห์ความเหมาะสมของที่ดินและประเมินขนาดของสระน้ำที่เหมาะสมและผลของการให้น้ำต่อผลผลิตที่คาดการณ์ของพืชไร่ในพื้นที่ตัวอย่างที่สนใจ สำหรับพื้นที่ศึกษาคือจังหวัดนครราชสีมา โดยพิจารณาพืชไร่ 3 ชนิดคือมันสำปะหลังโรงงาน อ้อยโรงงาน และข้าวโพดเลี้ยงสัตว์ สำหรับหัวข้อศึกษามีทั้งหมด 5 หัวข้อ คือ (1) การสร้างแผนที่การใช้ประโยชน์ที่ดินและสิ่งปกคลุมดิน (LULC map) ระดับจังหวัด (2) การประเมินความเหมาะสมของที่ดิน (3) การจัดการน้ำอย่างมีประสิทธิภาพในพื้นที่เกษตรที่เลือกมา (4) การวิเคราะห์ปฏิทินเพาะปลูกที่มีประสิทธิภาพ (5) ผลของการให้น้ำชลประทานต่อผลผลิตพืชและประสิทธิภาพการใช้น้ำ (WUE) ในงานชิ้นแรก พบว่าพื้นที่เพาะปลูกพืชไร่ทั้ง 3 ชนิดข้างต้นมีประมาณร้อยละ 27.77 ของพื้นที่จังหวัด แยกเป็นร้อยละ 17.72 (มันสำปะหลังโรงงาน) ร้อยละ 4.147 (อ้อยโรงงาน) และร้อยละ 5.93 (ข้าวโพดเลี้ยงสัตว์) ในงานชิ้นที่ 2 พบว่าคุณภาพของที่ดินสำหรับการเพาะปลูกพืชทั้ง 3 ชนิดในจังหวัดอยู่ในระดับปานกลาง โดยอุณหภูมิและความลึกใช้การของดินเป็นปัจจัยที่มีความเหมาะสมมากที่สุด ในขณะที่ปริมาณฝนน้อยทำให้เกิดปัญหากับอ้อยโรงงานเป็นอย่างมาก แต่ค่อนข้างเหมาะสมกับมันสำปะหลังโรงงานและเหมาะสมมากสำหรับข้าวโพดเลี้ยงสัตว์ ส่วนความอุดมสมบูรณ์ของดิน ถือเป็นข้อด้อยสำคัญสำหรับพืชทุกชนิดโดยเฉพาะอ้อยและข้าวโพดเลี้ยงสัตว์ ในงานชิ้นที่ 3 พื้นที่ตัวอย่างที่อุดมสมบูรณ์ซึ่งเลือกมา มีขนาด 176,756 ตร.ม. (หรือ 110.5 ไร่) โดยวางแผนว่ามีสระน้ำขนาด 137x137x3 ลบ.ม. ถูกสมมติว่าสร้างขึ้นในที่ดินดังกล่าว เพื่อเป็นแหล่งน้ำชลประทานให้กับพืชไร่ทั้ง 3 ชนิดข้างต้น โดยขนาดที่เหมาะสมที่สุดของสระจะอิงมาจากความรู้เกี่ยวกับความต้องการน้ำสูงสุดของพืชและปริมาณน้ำฝนในปี ค.ศ. 2001 (ปีที่แห้งแล้งที่สุดระหว่าง ค.ศ. 1977-2006) ของพื้นที่ตัวอย่าง จากการวิเคราะห์ประสิทธิภาพของสระโดยจำลองสถานการณ์ว่ามีการใช้น้ำในระยะยาวพบว่า สระจะล้มเหลวเนื่องจากปริมาณน้ำไม่พอประมาณร้อยละ 54 และร้อยละ 6 สำหรับการให้น้ำอย่างเต็มที่และให้ที่ร้อยละ 75 ตามที่พืชต้องการ แต่ว่าความล้มเหลวจะไม่ปรากฏขึ้นถ้าลดการให้น้ำเหลือเพียงครึ่งเดียวจากค่าที่พืชต้องการ ในงานชิ้นที่ 4 ปฏิทินเพาะปลูกของพืชแต่ละชนิดได้ถูกปรับใหม่ โดย

ให้เดือนที่พืชต้องการน้ำมากที่สุดไปอยู่ตรงกับเดือนที่มีฝนมากที่สุดของพื้นที่ (กันยายน) ส่งผลทำให้สามารถลดปริมาณน้ำชลประทานที่พืชต้องการไปได้ประมาณร้อยละ 4.32 (อ้อยโรงงาน) และร้อยละ 10.90 (ข้าวโพดเลี้ยงสัตว์) โดยไม่มีการเปลี่ยนแปลงปฏิทินเพาะปลูกสำหรับมันสำปะหลังโรงงาน ในงานชิ้นที่ 5 ผลของการให้น้ำชลประทานต่อผลผลิตคาดการณ์ของพืชทั้ง 3 ชนิด และค่า WUE ปรากฏให้เห็นอย่างเด่นชัด แต่ว่าผลดังกล่าวเห็นได้น้อยลงเมื่อปริมาณน้ำชลประทานที่ให้เข้าใกล้จุดที่พืชต้องการมากที่สุด กล่าวโดยสรุป หากเปรียบเทียบระหว่างการมีน้ำฝนอย่างเดียว กับการให้น้ำชลประทานร้อยละ 100 ตามที่พืชต้องการทำให้มีผลผลิตคาดการณ์เพิ่มขึ้นมาร้อยละ 132.8 (มันสำปะหลังโรงงาน) ร้อยละ 50.72 (อ้อยโรงงาน) และร้อยละ 119.17 (ข้าวโพดเลี้ยงสัตว์) ขณะที่ WUE จะเพิ่มขึ้นร้อยละ 117.61 (มันสำปะหลังโรงงาน) ร้อยละ 37.91 (อ้อยโรงงาน) และร้อยละ 93.51 (ข้าวโพดเลี้ยงสัตว์) ตามลำดับ

สาขาวิชาการรับรู้จากระยะไกล ลายมือชื่อนักศึกษา______

ปีการศึกษา 2557 ลายมือชื่ออาจารย์ที่ปรึกษา______

PICHAI WONGSAWAT : APPLICATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM TO LAND AND WATER MANAGEMENT FOR ECONOMIC CROPS PRODUCTION: CASE STUDY IN NAKHON RATCHASIMA PROVINCE, THAILAND. THESIS ADVISOR : ASST. PROF. SONGKOT DASANONDA, Ph.D. 178 PP.

REMOTE SENSING/ GEOGRAPHIC INFORMATION SYSTEM/ WATER MANAGEMENT/ CROPS PRODUCTION

In this thesis, geoinformatics technology was applied to facilitate the soil suitability analysis and the determination of optimum farm pond capacity and its effects on predicted crop yield over an area of interest. The study area was Nakhon Ratchasima Province and the three economic crops under consideration were cassava, sugarcane, and maize. Five main topics were investigated: (1) formulation of the Landsat-based land use/land cover (LULC) map, (2) land suitability evaluation, (3) effective water management for crops in the representative farmland, (4) effective crop calendar analysis, (5) effects of supplementary irrigation on crop yield and water use efficiency (WUE).

In the first task, it was found that, in 2006, the listed crops had occupied about 27.77% of the entire provincial area including cassava (17.42%), sugarcane (4.147%), and maize (5.93%), respectively. In the second task, land quality was found moderately suitable for the planting of all studied crops, where temperature and effective soil depth are the most supportive factors while low rainfall was found most problematic to the sugarcane but this was moderately fine for cassava and very sufficient for maize. Soil fertility was found notably inferior, especially for sugarcane and maize. In the third objective, the representative fertile farmland with a total area of 176,756.0 m^2 (or 110.5 rai) was located and farm pond with size of 137x137x3 m^3 were assumed to be developed therein to supply irrigation water to all the crops found over the area. The optimum pond capacity was determined based on prior knowledge of full demand for the 3 crops and amount of rainfall in 2001 (the driest year during 1977-2006) over the chosen area. The pond efficiency derived from the simulation study suggested that pond should fail on its task at rate of 54% and 6% (in long time operation) when supplying irrigation water at 100% and 75% of net irrigation water requirement respectively but this failure shall not happen if only half of full crop demand was fulfilled. In the fourth task, new crop calendar for each crop was devised by shifting months with its highest need for water to coincide with month of peak rainfall of the area (September). This practice resulted in the reduction of demand for irrigation water of sugarcane and maize by 4.32% and 10.90% respectively (no change was needed for cassava). In the fifth task, effects of irrigation water on predicted crop yield and WUE were strongly evidenced in the positive manner but the effect was less pronounced as amount of the supply water approaching the full demand of each crop. In conclusion, compared to the rainfed situation, the providing of full 100% of crop water demand, the yield was risen by 132.8% (cassava), 50.72% (sugarcane) and 119.17% (maize) while the increases in terms of the WUE are 117.61% (cassava), 37.91% (sugarcane), and 93.51% (maize), respectively.

School of Remote Sensing | Student's Signature ____________

Academic Year 2014 | Advisor's Signature S. Dasananda

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LIST OF ABBREVIATIONS

A_p	=	Pond surface area (m^2)
A_{cas}	=	Cassava area (m^2)
A_{sug}	=	Sugarcane area (m^2)
A_{mai}	=	Maize area (m^2)
AHP	=	Analytical hierarchy process
BC ratio	=	Benefit-cost ratio
C	=	Adjustment factor to compensate for the effect of day and night weather conditions
CI	=	Consistency index
CN	=	Curve number
C_p	=	Pan coefficient
CWR	=	Crop water requirement
DEM	=	Digital Elevation Model
DNs	=	Digital numbers
e_a	=	Saturation vapor pressure at the mean air temperature in °C
e_d	=	Mean actual vapor pressure of air (mbar).
e_d	=	e_aRHmean/100 (mbar).
E	=	Evaporation
E_t	=	Evaporation during the t^{th} period
E_r	=	Reservoir (or on farm pond) evaporation

LIST OF ABBREVIATIONS (Continued)

E_p	=	Pan evaporation
ET_o	=	Reference crop evapotranspiration
ET_{crop}	=	Crop evapotranspiration
or ET_c	=	Crop evapotranspiration
ET_m	=	Maximum evapotranspiration
f (U)	=	Wind related function
F_a	=	Water retention in the watershed
FAO	=	Food and Agriculture Organization of The United Nations
g	=	Unbiased estimate of population skew coefficient
G	=	Number of rainfall station
GIS	=	Geographic information system
HEC-4	=	Hydrologic Engineering Center-4
i	=	Month number
I_a	=	Initial abstraction
I_{gft}	=	Ground water inflow during the t^{th} period
I_{sft}	=	Surface water inflow during the t^{th} period
Isf_t	=	Direct runoff (m^3)
IRR	=	Internal rate of return
IWR_n	=	Net irrigation water requirement
j	=	Station number
k	=	Normal standard deviate

LIST OF ABBREVIATIONS (Continued)

K_c	=	Crop coefficient
$K^{'}$	=	Monthly streamflows logarithm, express as a normal standard deviate
LC	=	Land cover
LU	=	Land use
m	=	Year number
M	=	Rank of data: m = 1, 2,…., N
MADM	=	Multi-attribute decision making
MCDA	=	Multicriteria decision analysis
MCDM	=	Multicriteria decision making
n	=	Not suitable
n	=	Actual mean sunshine hour
n	=	Number of interrelated stations
N	=	Maximum possible sunshine hour
N	=	Sample length
NIWR	=	Net irrigation water requirement (mm)
NPV	=	Net present value
O_{gft}	=	Ground water outflow during the t^{th} period
O_{sft}	=	Surface water outflow during the t^{th} period
Osf_t	=	Supplementary irrigation (m^3)
P	=	Precipitation

LIST OF ABBREVIATIONS (Continued)

Pd	=	Direct rainfall (m^3)
P_e	=	Direct runoff
P_{eff}	=	Effective rainfall
p_g	=	Rainfall at each station
P_t	=	Precipitation during the t^{th} period
P_{tot}	=	Monthly rainfall
$\hat{P}$	=	Areal rainfall
$\overline{P}_f$	=	Probability of failure
q	=	Small increment of streamflow use to prevent infinite logarithm for month of zero flow
Q	=	Monthly recorded streamflow
Q_d	=	Direct runoff (m^3)
Q_A	=	Total daily clear sky radiation at the surface of earth in equivalent to evaporation
r	=	Reflection coefficient
R	=	Multiple correlation coefficient
RH	=	Relative humidity
R_n	=	Net solar radiation in equivalent to evaporation
RS	=	Remote sensing
S	=	Potential maximum retention
S	=	Unbiased estimate of population standard deviate

LIST OF ABBREVIATIONS (Continued)

SAW	=	Simple additive weighting
S_{t+1}	=	Pond storage at the beginning of the $(t+1)^{th}$ period
S_t	=	Pond storage at the beginning of the t^{th} period
S1	=	Highly suitable
S2	=	Moderately suitable
S3	=	Marginally suitable
t	=	Time index
t	=	Pearson Type III standard deviate
T_t	=	Transpiration during the t^{th} period
U_1	=	Wind velocity measured at h m height
U_2	=	Wind velocity measured at 2m height
W	=	Weighting factor for altitude and temperature effect on wind and humidity
MCE	=	Multicriteria evaluation
WUE	=	Water use efficiency
x	=	Logarithm of incremented monthly streamflow
$\bar{x}$	=	Mean logarithm of incremented monthly streamflow
X_i	=	Input variables
Y	=	Crop-water production
Z	=	Random number from normal standard population
β	=	Beta coefficient

LIST OF ABBREVIATIONS (Continued)

$\sum I$	=	$\sum$Inflow
$\sum O$	=	$\sum$Outflow
ΔS	=	Change in storage
σT^4	=	Black surface reflection in equivalent to evaporation

CHAPTER I

INTRODUCTION

1.1 Background and significance of the study

Agriculture can be broadly defined as the cultivation and/or production of crop plants or livestock products which is generally synonymous with “farming”, the field or field-dependent production of food, fodder and industrial organic material (Bareja, 2011). Fundamentally, crop production is critically water-dependent where the quality and quantity of used water are two interrelated properties that control the production capacity of the agricultural land (Tanji and Yaron, 1994). However, while demand for food production is increasing globally to serve the rapid-growing population, amount of the usable water and arable land for the agriculture in many countries are becoming scarce. In this case, development of the new water or land resources along with highly efficient management of the existing (or the newly-developed) ones are tremendously needed (Wallace, 2000; Kampman, Brouwer, and Schepers, 2008; FAO, 2008; 2011). As a result, researches on land suitability assessment for crop farming and water use efficiency improvement in agriculture have been intensified in recent decades, such as FAO (1997); Howell (2001); Deng, Shan, Zhang, and Turner (2006); Lynch and Duke (2007); Kurtener, Torbert, and Krueger (2008); Fang, Ma, Green, Yu, Wang, and Ahuja. (2010); Molden,, Theib, Pasquale, Prem, Munir, and Jacob. (2010); Kang’au, Home, and Gathenya (2011). According to FAO (2011), the capability to locate high-input agriculture on the most suitable lands for cropping shall alleviate pressure on land expansion and limit encroachment on forests and other land uses.

In principle, the assessment of land suitability for crop planning is a complicated task in which comprehensive knowledge on the relationships between plant's specific needs for its proper growth and inherent land qualities is crucially required (Rossiter, 1996). Commonly, standard references on this issue are the FAO frameworks for land evaluation in which guidelines for crop requirements regarding to the land qualities, e.g., topography, climate, soil quality, water supply, are given (FAO, 1976; 1983; 2007). The suitability category for each considered land unit for a particular crop is classified as highly (S1), moderately (S2), marginally (S3), or not suitable (N), e.g., in Paiboonsak and Mong (2007); My Agriculture Information Bank (2011); Paiboonsak and Mongkolsawat (2007); Tienwong, Dasananda, and Navanugrah (2009); Mustafa, Man, Sahoo, Nayan, Manoj, Sarangi, and Mishra (2011); and Elaalem (2012).

Typically, the evaluation of land suitability for crop planting over a particular area of interest is often relied on the systematical combination of the suitability degree of several used factors (both spatial/non-spatial data) under some definite classifying criteria. This working concept allows direct application of the geographic information system (GIS) in the process as the system is prominently capable in dealing with both spatial and non-spatial data under the pre-defined rules of the interaction among them (Rossiter, 1996; Ahamed, Rao, and Murthy, 2000; Malczewski, 2004). This capability is also greatly useful for the hydrological research in which GIS has played major role in development of the preferred hydrologic models to improve in-depth understanding of the hydrological system over a particular area. This knowledge is highly essential for aiding hydrological prediction and effective water resource management, and for assessing impact of the concerned environmental changes (e.g. climate or land use) on runoff yield and distribution within an area (Clark, 1998; Wilson, Mitasova, and Wright, 2000; Daene, McKinneya, and Cai, 2002).

Thailand is considered an agricultural country in tradition where about 38% of the population still live in the agricultural sector recently (Department of Agriculture Extension, 2012). And like many agricultural countries worldwide, it usually has serious problem on the scarcity of arable land and water resources for agriculture, especially in the northeastern part (or the Isan region) where most areas are found not suitable for agriculture due to the relatively poor soil quality and shortage of the large and efficient irrigation systems (Land Development Department, 2010a). These serious shortcomings in land fertility and usable water for agriculture limit productive and sustainable plantation of the economic crops within the area. In this circumstance, knowledge on the suitable crops to be grown on a particular plot of land in association with the introduction of an effective irrigation system shall significantly benefit work of the farmers and reduce burden of the subsidy for these crops by the government.

An efficient management of land and water resources to support sustainable agriculture for local farmers is also an important issue elaborated in the New Theory of Agriculture conceptually initiated by His Majesty the King of Thailand. In this theory, about 30% of farmland is adviced to be reservoir for water reservoir while another 30% is used for rice planting (for household consumption) and another 30% for the production of other crops (for income generation), e.g., orchards or field crops (Royal Irrigation Department, 2012). Furthermore, recently the Thai Government has launched a pilot agricultural economic crops zoning project. Six economic crops, as major contributors to the economy: rice, cassava, sugarcane, oil palm, rubber, and maize, were considered. In this project, formal recommendation of suitable areas for each crop shall be announced (at sub-district level). Farmers included in this project will receive Government incentive (Land Development Department, 2013).

To support the growing need for efficient management of the available land and water resources for agricultural fields in Thailand, this thesis shall demonstrate the systematic applications of advanced geoinformatics technology in the detailed assessment of land suitability for major economic crops in Nakhon Ratchasima Province. And as water storage facilities are scarce the thesis shall also present an effective land and water management strategy for these crops.

Nakhon Ratchasima Province was selected due to its large agricultural land (about 70% of the total area, mostly rice, cassava, sugarcane, and maize). Most of the agricultural areas are rainfed. Irrigation system can serve about 7% of the province as seen in Figure 1.1. Low annual rainfall (Figure 1.2) also causes low crop productivity. In addition, widespread infertile soil makes productive planting of the major economic crops within the province less viable (Nakhon Ratchasima Province Office, 2013).

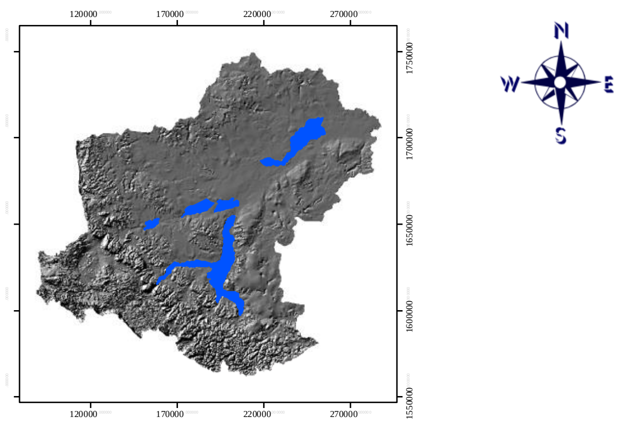


Figure 1.1 Digital elevation model (DEM) of Nakhon Ratchasima Province and irrigation area

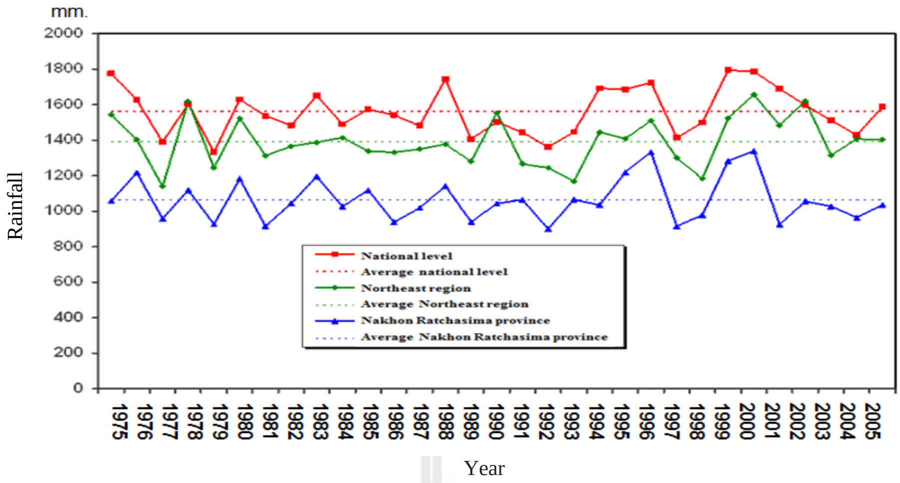


Figure 1.2 Annual rainfall of Nakhon Ratchasima Province compared to the national and regional level (1975-2005).

Source: Chadtabud (2008).

In this study, land suitability maps for three economic crops (i.e., cassava, sugarcane, and maize) are derived using multicriteria decision making (MCDM) scheme and FAO land evaluation guideline for rainfed agriculture. This is followed by the design and performance analysis of a farm pond to harvest the necessary water to produce crops in a given area. It is hoped that this work shall provide understanding on variability of land suitability to aid farmers in the study area. In addition, it is also hoped that knowledge gained from this study shall illustrate the indispensable role of advanced geoinformatics technology in proper management of land and water resource management and emphasize the practicability of His Majesty the King of Thailand New Theory of Agriculture for farmers both in Thailand and elsewhere.

1.2 Research objectives

The main objective of this work is to establish an optimal plan for economic crops production by integrating land and water management under the application of current geoinformatics technology. Details of specific objectives are as follows.

1.2.1 To classify land use/land cover (LULC) characteristics from Landsat-TM images for the identification of the interested economic crop planting areas within Nakhon Ratchasima Province

1.2.2 To evaluate suitable area for the cultivation of the three major economic crops (cassava, sugarcane, and maize).

1.2.3 To investigate a proper water resource development plan, including:

1.2.3.1 To estimate the amount of crop water requirement (CWR) on monthly basis.

1.2.3.2 To determine optimum capacity of the farm pond capable of supplying sufficient water for all three economic crops in an area.

1.2.3.3 To evaluate probability of failure of the pond under different scenarios of supplementary irrigation rate.

1.2.4 To propose a suitable crop calendar for an area based on knowledge of the monthly ET_{crop} data gained from Objective 1.2.3.1.

1.2.5 To predict the yields of each crop under the effect of each irrigation rate.

1.3 Scope and limitations of the study

1.3.1 The study area is Nakhon Ratchasima Province and the major economic crops of interest are cassava, sugarcane, and maize.

1.3.2 LULC classification is processed based on the Landsat-TM imagery data in 2006 along with land information from field surveys.

1.3.3 Land suitability evaluation for each concerned crop is carried out based on the guidelines issued by the FAO for rainfed agriculture (FAO, 1983) and by the Land Development Department (Tansiri and Saifauk, 1996).

1.4 Study area

The study area, Nakhon Ratchasima Province, also known as Khorat, situates in the Korat plateau in the northeastern part (or Isan region) of Thailand (Figure 1.3) whose details of general characteristics are as follows [summarized from the information illustrated in Nakhon Ratchasima Province Office (2013)]. At present, Nakhon Ratchasima province comprises 32 districts (287 sub-districts) with a total population of about 2.59 million in 2012 and total area of about 20494 km^2 (or 12.81 million rai), which makes it the largest province in Thailand. The province is regarded as being a capital of southern Isan due to its official roles as a center for both economic development and administrative organization of the area. It is generally known as the hub (or gateway) for the transportation to the Isan region as well as for its richness in cultural and historical sites (dated back to the glorious period of the ancient Khmer empire). The province also produces great amount of the economic crop production each year, which are mostly rice, cassava, sugarcane, and maize.

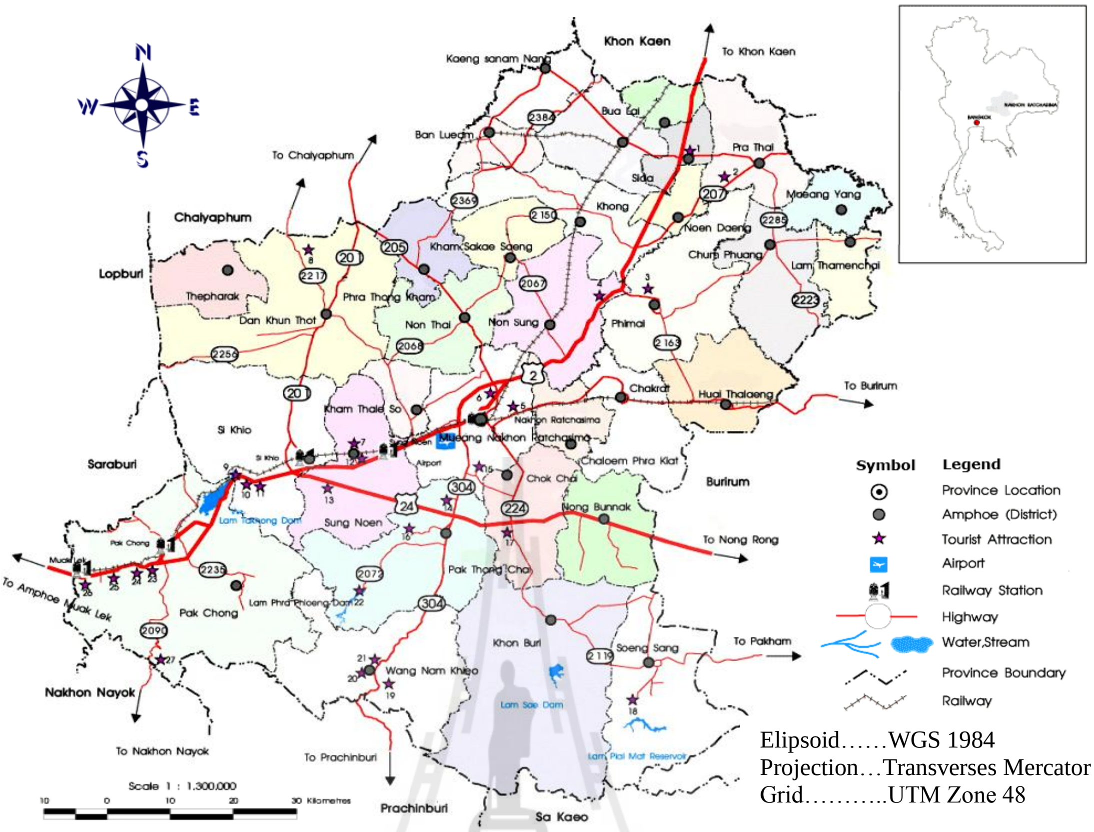


Figure 1.3 Map of Nakhon Ratchasima Province. (See appendix a for information at district level).

Source: http://www.novabizz.com/Map/img/map-36-Nakhonratchasima.gif

Topography of the province is dominated by a vast flat plain integrating with shallow undulations in the middle and northern parts and high mountain ranges in the southern part, which gives rise to several major rivers of the area, e.g. Mun, Lam Phra Phloeng, or Lam Takhong. Average elevation is about 187 meters above mean sea level. At present, about 70% of the total areas are used for agriculture while forest covers about 18%, urban/build-up zone takes up about 6%, the remaining 6% is water body. Though, being renowned for its expansive agricultural sector, most farm areas are still rain-fed. The current irrigation system, comprises five large reservoirs, which can serve about 7% of the cultivated area, mostly to support the paddy field situated in the lowland downstream of these reservoirs.

In addition, low annual rainfall (averaged about 1020 mm/year) and widespread infertile soil (mostly from salinity and low soil quality) make productive planting of crops in the province become less viable. Majority of soil formed in the area is of the sandy-loam type which usually possesses low nutrient and water holding capacity. This makes it difficult for growing most prominent cash crops. Now, only about 30% of the province is classified by the authorities as sufficiently suitable for productive cultivation. This situation requires the wise use and management of land and water resources for achieving productive and sustainable agriculture. To fulfill this desire, this thesis shall demonstrate the application of advanced geoinformatics technology (remote sensing and GIS in particular) in the evaluation of land suitability for three major economic crops (cassava, sugarcane, maize) along with the planning of a farm pond capable of supplying irrigation for the crops.

1.5 Benefits of the study

1.5.1 LULC map for the year 2006 and land suitability maps for the three crops.

1.5.2 Optimum pond capacity for servicing crops in the representative area.

1.5.3 Knowledge of simulation method for reliability analysis.

1.5.4 An alternative crop calendar more responsive to the rainfall pattern.

1.5.5 Effects of the supplementary irrigation on the crop yield.

CHAPTER II

LITERATURE REVIEW

Essential information and relevant theories and researches are reviewed in this chapter with emphasis on the five main topics of interest, which are, (1) land suitability evaluation, (2) crop evapotranspiration, (3) water harvesting for crop production, (4) crop water requirement, and (5) review of relevant researches and comments. Detail on each topic follows.

2.1 Land suitability evaluation

Typically, productivity of crop cultivation over a particular agricultural area depends on five main controlling factors: environment conditions, soil qualities, water availability, crop variety and agricultural practices. Among these, the first three factors are related directly to the quality of the land. Therefore, land suitability evaluation is essential for maximizing productive and sustainable use of existing land. According to FAO (1983), the principal objective of land evaluation is to identify optimum land use for each defined land unit, taking into account both the physical and socio-economic considerations and the conservation of environmental resources for future use. Land evaluation concept supports many other disciplines and users for many purposes, e.g. land use planning, sustainable land management and land degradation control (FAO, 2007).

2.1.1 Multicriteria decision analysis

Land suitability analysis is a multicriteria decision analysis (MCDA) in nature as it involves a comparative judgment on several individual factors to find best solution under the predefined criteria. Critical aspect of spatial multicriteria analysis is that it involves evaluation of geographical events based on the criterion values and the decision maker's preferences with respect to a set of the evaluation criteria. This implies that the result of the analysis depends not only on the geographical distribution of events (attributer) but also on the value judgments involved in the decision-making process, consequently, the combination of GIS capabilities with MCDM is a decision maker supporting tool in achieving greater effectiveness and efficiency of decision making while solving spatial decision problems (Malczewski, 1999) (Figure 2.1).

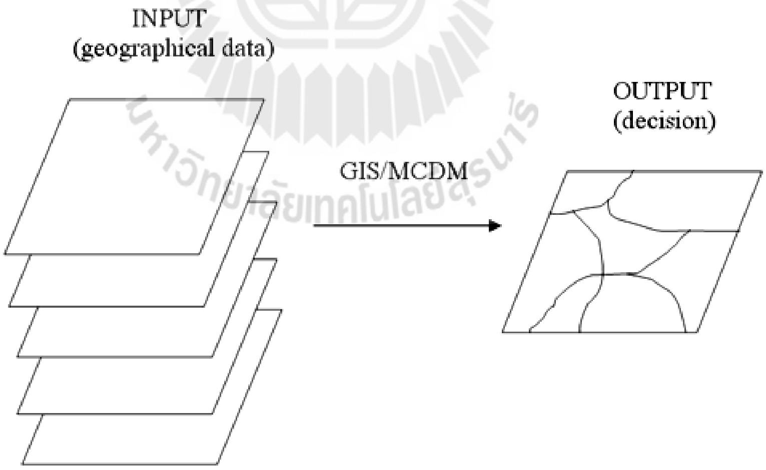


Figure 2.1 Spatial multicriteria decision analysis (MCDA): input-output perspective. **Source**: Malczewski (1999).

2.1.1.1 Evaluation criteria. Whenever a decision problem is identified, the spatial multicriteria analysis focuses on the set of evaluation criteria (objective and attribute). Step of evaluation criteria involves specifying (1) a comprehensive set of the objectives that reflects all concerns associated to the decision problem, and (2) measures for achieving those objectives by using attribute. The evaluation criteria are associated with geographic entities and relationship between entities, therefore, can be shown in form of maps. These maps also referred to as attribute maps (or thematic maps or data layers in GIS field) can be used to generate inputs to spatial multicriteria decision analysis.

2.1.1.2 Criteria selection. The set of criteria can be selected depending on particular system being analyzed or problem specificity, for example, the criteria used for evaluating sites of nuclear plant will be different from those in a school location problem. And the numbers of evaluation criteria selected depends on the characteristics of the decision problem. These sets of evaluation criteria for a particular decision problem may be developed through an examination of the relevant literature, analytical study, and opinion.

2.1.1.3 Decision rules analysis. Following generic classification of MCDA, the decision rules analysis can be divided into 2 categories: (1) multi-attribute spatial decision rule, e.g., simple additive weighting (SAW), analysis hierarchy process (AHP), fuzzy additive weighting and (2) multi-objective spatial decision rules, e.g., goal programming. Ultimate aim of the analysis is to combine major elements (evaluation criteria, alternatives, and decision-maker preferences) using multicriteria decision rules to provide basis for ordering the decision alternative and for choosing most preferred alternatives (Malczewski, 1999).

2.1.2 Theory of land evaluation for rainfed agriculture

The increasing demand for intensification of existing cultivated land and opening up of new land can only be satisfied without damaging the environment if land is classified according to its suitability for different kinds of use (FAO, 1983). Land quality is a group of attributes of land which influences the suitability of the land for a specific kind of use. Examples of land qualities that are widely applicable to rainfed cropping are temperature regime, moisture availability, drainage, nutrient supply, rooting condition, potential for mechanization. Within each land quality there are a number of characteristics. Some characteristic may be used to distinguish land of differing suitability levels. Examples of land characteristics are mean annual rainfall, slope angle, soil drainage class, and effective depth.

Land suitability evaluation for a particular crop is an attempt to match the requirements of the crop to the qualities of the land. There are two types of land suitability evaluation: qualitative and quantitative. Qualitative suitability evaluation processes both cardinal and ordinal values of land qualities to arrive at a final suitability value which is then grouped into suitability classes (usually 4 to 5). This method is appropriate for low-intensity surveys of large regions. Qualitative evaluation can be used for many general planning purposes, e.g. the identification of areas for particular crops for future project feasibility studies. Furthermore, qualitative evaluation has a relatively long term validity, that is, the results remain valid for a number of years. This study will emphasize qualitative suitability evaluation.

2.1.2.1 Qualitative land suitability evaluation

1) Selection of land qualities. Land qualities should be selected on the basis of known effect upon the crops or kind of land use under consideration. In

one category of land quality there may be more than one type of land characteristics representing quality. FAO guideline for land evaluation has established 25 land qualities for rainfed agriculture. Meanwhile the Land Use Planning Division (LDD) has chosen 13 land qualities for Thailand (Tansiri and Saifauk, 1996) (Appendix B).

2) Selecting diagnostic factors (or diagnostic criteria). As mentioned earlier, in some cases, a land quality might be satisfactorily described using a single land characteristic, whilst in others, a number of characteristics are necessary. In land evaluation procedure, appropriate land characteristics are used as diagnostic factors (or diagnostic criteria) (FAO, 1983).

Tansiri and Saifauk (1996) selected 12 land qualities and 23 diagnostic factors, Charuppat (2002) selected 8 land qualities and 13 diagnostic factors, and Albab (1995) selected 7 land characteristics and 8 diagnostic factors to carry out land evaluation for cassava, sugarcane, and maize cultivation.

3) Land use requirement. The requirements for each land use type for its successful operation are known as the "land use requirements". Land use requirements related to the efficient functioning of land utilization type consist of three sets: crops requirement, management requirement, and conservation requirement. These land use requirements are later matched with land qualities to determine the suitability of a particular land unit which can be demarcated on a map.

4) Factor ratings. Factor ratings are sets of values which indicate how well each land use requirement is satisfied by particular conditions of the corresponding land quality, in other words, the suitability of the land quality for the specific land use. Factors rating are often expressed in four or five classes, such as, high (S1), moderate (S2), marginal (S3), not suitable (N). Each factor rating may be assessed

in two ways, in terms of a reduced yield or production caused by deficiencies of the requirement under consideration, or in terms of an input or additional cost needed to avoid such reduction by counteracting this deficiency. Guidelines for definitions of factor rating classes in terms of crop yields and of inputs are illustrated in Table 2.1.

Table 2.1 Guidelines for definitions of classes for factors rating.

Factor rating Class*	**Definition in terms of yields****: Expected crop yields, as a percentage of yields under optimal conditions, in the absence of inputs specific to the land quality considered.	**Definition in terms of inputs:** Inputs or management practices, specific to the land quality considered, necessary to achieve yields of 80% of those under optimal conditions.
Highly Suitable (S1)	More than 80%	None
Moderately Suitable (S2)	40-80%	Inputs needed, which are likely to be both practicable and economic
Marginally Suitable (S3)	20-40%	Inputs need, which are practicable but only economic under favorable circumstances
Not suitable (N)	20%	Limitation can rarely or never be overcome by inputs or management practices

Notes: *These classes refer to a single land quality, rated with respect to a specified crop or land utilization type.

**Yield percentages are given as an example, and can vary according to economic conditions; thus a yield reduction to 40% of the optimum might still be acceptable to a subsistence farmer but not to a competitive commercial enterprise.

However, the factor rating values will usually require adjustment, or calibration in relation to crop yields (FAO, 1983).

5) Matching of land use requirements with land qualities. Matching is a necessary component in any kind of land evaluation method. In qualitative suitability classification, the requirement of each land use type is matched with the land qualities of each mapped land unit, then the factor rating is read off. This matching procedure will lead to a fairly close approximation to the final land suitability.

6) Combining individual rating into an overall suitability. The factor rating layer for each diagnostic criterion (criterion map) can be combined to get final suitability map using five methods: subjective, combination, limiting condition, arithmetic procedures, modeling.

2.1.2.2 Arithmetic procedures. Individual assessments, expressed numerically, can be combined by addition or by multiplication. In this study, the multiplication method was used to combine criterion map. Because, a number of studies demonstrated that good correlations have been obtained between overall suitability ratings obtained by this method and observed crop yields if transferred from one area to another.

For the multiplication method, the factor rating values for each criterion map are multiplied to each other (related criterion map) to obtain the overall suitability rating. Each overall suitability rating is then grouped into four land suitability classes: (1) high (S1), (2) moderate (S2), (3) marginal (S3), and (4) not suitable (N). Detailed procedures are described in FAO (1983).

2.2 Crop evapotranspiration

Crop evapotranspiration (ET_{crop}) is a vital mechanism that can determine both crop growth and crop yield for a particular agricultural area. Therefore, knowledge on this process is essential to support the development of effective and sustainable crop production in both short-term and long-term basis.

2.2.1 Basic knowledge

Evapotranspiration (ET) process is an essential part of the water cycle (Figure 2.2) referring to the combination of two distinct processes of vaporization, i.e., evaporation (from land/water surface) and transpiration (from crop leaf surface). Typically, over the cropped land, these two processes occur simultaneously and very difficult to distinguish them from one another. In general, when the crop is still small (i.e. in its initial stage), water is predominantly lost by soil evaporation process, which is controlled mostly by amount of water availability and supporting climate, but once crop is growing, transpiration process shall be gradually more important and become a main process when it reaches maturity state and covers whole area (Figure 2.3).

The amount of ET depends on several factors: weather parameters, crop characteristics, and management/environmental aspect (FAO, 1998). The main weather parameters referred to are solar radiation, air temperature, humidity and wind speed, whereby, the evaporation power of the atmosphere is represented by the reference crop ET (ET_o) from a standardized vegetated surface. The essential crop factors are its type, variety, development stage. While management and environmental conditions include soil salinity, land fertility, soil structure, watering system, plant density, etc.

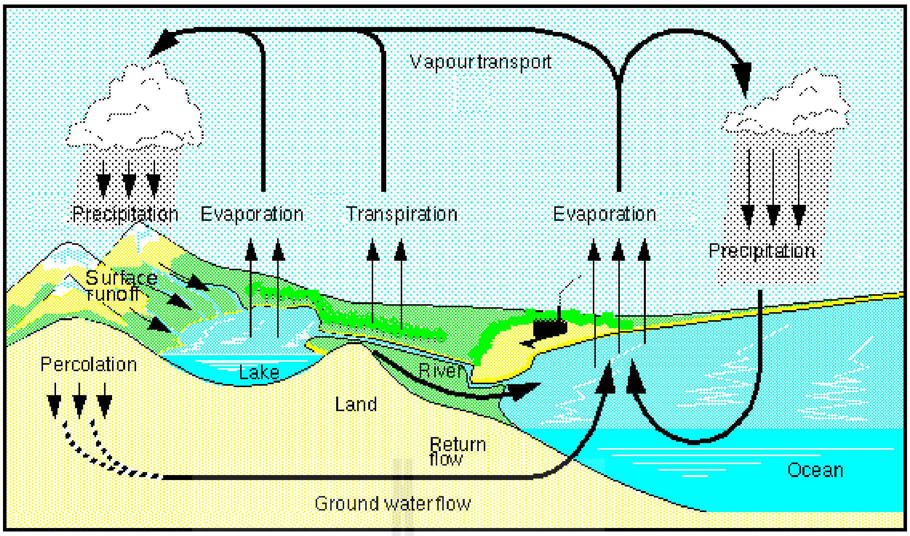


Figure 2.2 Main components of the global water cycle.

Source: http://wwwk12.atmos.washington.edu/k12/pilot/water_cycle/

where_the_water_goes.html.

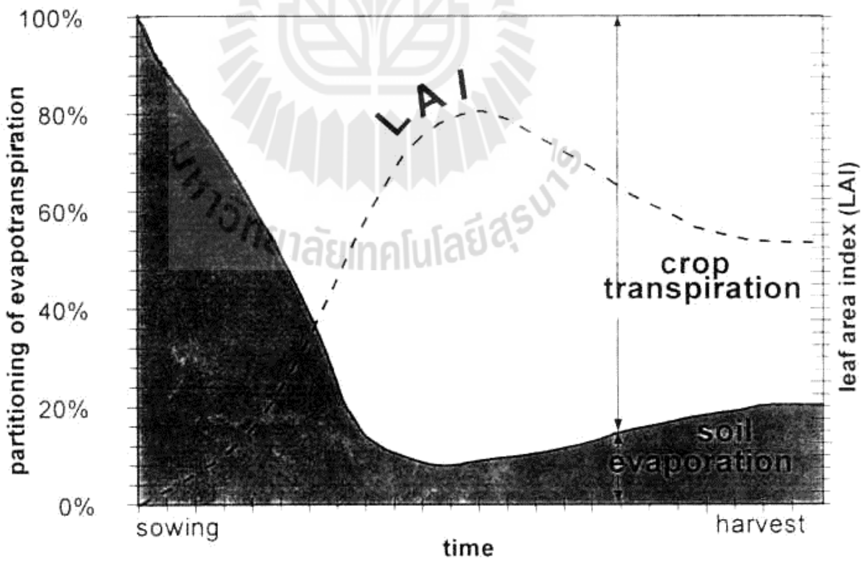


Figure 2.3 The partitioning of evapotranspiration into evaporation and transpiration over the growing period for an annual field crop.

Source: FAO (1998).

In principle, ET and crop water requirement (CWR) are greatly identical because CWR refers to the amount of water required by the crop, while crop ET refers to the amount of water being lost through the process. The sources of water supply to fulfill daily CWR are precipitation and irrigation. As such, supplementary irrigation can be defined as the difference of CWR (or crop ET) and effective precipitation.

Standard definition of the ET_{crop} (or ET_c) is as follows:

$$ET_{crop} = K_c ET_o \tag{2.1}$$

where ET_o is the reference crop ET (in unit of mm/day) conventionally determined by using the modified Penman or Penman-Monteith methods (FAO, 1998) and K_c is crop coefficient (dimensionless) whose certain values were carefully assessed and reported for a large number of crops worldwide.

Definition of ET_{crop} given above is for the use in standard condition, i.e., having disease-free, well-fertilized, large fields, under optimum soil water conditions, and achieving full production under specific climatic conditions. From this definition, effect of various weather conditions on daily crop ET is conceptually integrated into the ET_o factor while those of the crop characteristics is inherited in the K_c coefficient. However, for crop evapotranspiration under non-standard conditions ($ET_{crop\text{-}adj}$), i.e., crops grown under the management and environmental conditions that differ from the standard conditions, the actual crop ET in the area may be different from the standard ET_{crop} due to non-optimal conditions such as the presence of pests and diseases, soil salinity, marginal soil fertility, water shortage or waterlogging. This situation might lead to the improper plant growth, low plant density, and might reduce the observed ET rate below that of ET_{crop}.

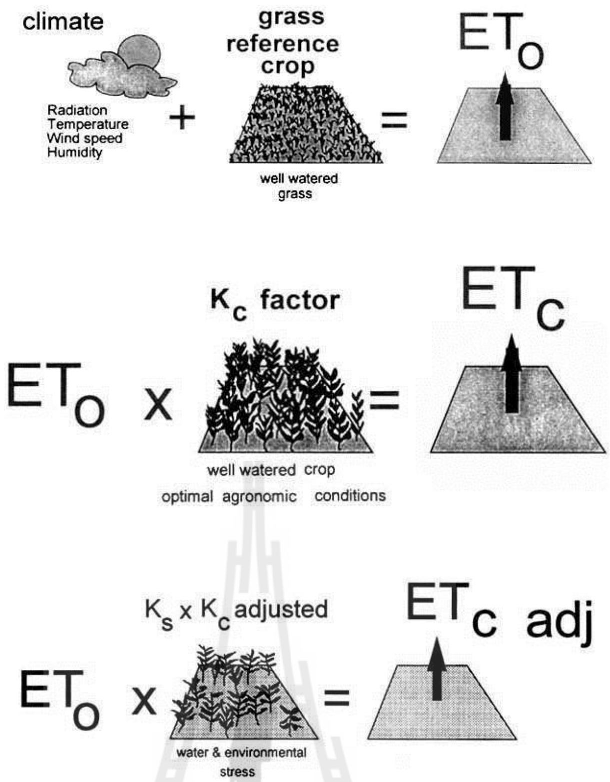


Figure 2.4 Reference crop ET (ET_o), ET under standard condition (ET_{crop}) and non-standard condition ($ET_{crop\text{-}adj}$).

Source: FAO (1998).

In this case, the ET under non-standard condition can be calculated using a water stress coefficient K_s (that reflect effects of the encountered conditions) and/or by adjusting K_c for all kinds of other stresses and environmental constraints on crop evapotranspiration process (Figure 2.4) (FAO, 1998)

According to the presented knowledge about ET_{crop}, typical calculation procedure for ET_{crop} is as follows:

1) Identifying crop growth stages and selecting the corresponding K_c;

2) Adjusting the selected K_c coefficients to suit the environment;

3) Constructing the crop coefficient curve; and

4) Calculating ET_{crop} as the product of ET_o and K_c (Eq. 2.1).

2.2.2 Determination of the reference crop ET

From its formal definition given in Eq. 2.1, determination of the ET_{crop} over an agricultural area of interest principally depends on knowledge of the reference ET on the area (ET_o) that must be quantified beforehand. In theory, ET_o represents ET rate of a reference grass under well-watered condition. This process can be directly measured on the reference grass field using proper instrument or theoretically derived by means of the process-based method (like the Penman-Monteith method). ET_o was found to be between 1 to 9 mm/day globally (Table 2.2).

Table 2.2 Average ET_o for different agroclimatic regions in mm/day.

Regions		Mean daily temperature (°C)		
		Cool ~10°C	Moderate 20°C	Warm > 30°C
Tropics and subtropics	humid and sub-humid	2-3	3-5	5-7
	arid and semi-arid	2-4	4-6	6-8
Temperate region	humid and sub-humid	1-2	2-4	4-7
	arid and semi-arid	1-3	4-7	6-9

Source: FAO (1998).

ET_o can also be estimated from the reference pan evaporation rate. Here, actual water loss (evaporation) from the pan can be applied in conjunction with the empirical coefficients to find ET_o. However, special precautions and management must be used as the method is sensitive to microclimatic conditions during operation and rigor of station maintenance. The ET_o is usually used to calculate ET for different crop at different regions.

2.2.3 The FAO modified penman method

In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed (Jacobs, 2001). FAO had adopted this concept and modified in some parts to make it agree better with the reference grass surface before introducing in the FAO Irrigation and Drainage Paper No. 24 released in 1977. This method uses mean daily climatic data, with an adjustment for day and night time weather conditions. The main climate data needed for the calculation are radiation (sunshine period and daily net radiation), air temperature, air humidity (daily actual vapour pressure) and wind speed (at 2-m above ground level or an equivalent value at 2-m height) (Doorenbos and Pruitt, 1977).

In this work, the modified Penman method was applied to estimate ET_o. This method gives a satisfactory estimate of ET_o since it accounts for all the weather factors affecting ET_{crop} and was proved to have wide applicability in an arid, semi-arid, humid, or sub-humid conditions. And it was also found complementing effectively in Thailand (Chiang Mai University, Civil Engineering Department, 1994).

As detailed in Putthakunjarean (2003) and Rao, Devi, and Hemalatha, (2010), ET_o can be estimated by the relationship:

$$ET_o = C \cdot [WR_n + (1-W) \cdot f(U) \cdot (e_a-e_d)] \qquad (2.2)$$

where C is an adjustment factor to compensate for an effect of day and night weather conditions (dimensionless),

W is weighting factor related to altitude and temperature effect on wind and humidity (dimensionless), f(U) is a wind related function, R_n is net solar radiation in equivalent to evaporation (mm/day),

e_a is the saturation vapor pressure at the mean air temperature in ^oC (mbar),

e_d is actual vapor pressure of air (mbar).

Specific relationships of e_d, f(U), and R_n are as follows:

$$e_d = \frac{e_a \cdot RH_{mean}}{100} \tag{2.3}$$

where RH is the relative humidity,

$$f(U) = 0.27 \cdot \left(1 + \frac{U_2}{100}\right) \tag{2.4}$$

where U_2 is wind velocity measured at elevation 2m (km/day). However, if no data of the wind velocity at elevation 2m is available, U_2 shall be estimated by:

$$U_2 = U_1 \cdot \frac{\log 2}{\log h} \tag{2.5}$$

where U_1 is wind velocity measured at height h in meters (km/day),

$$R_n = Q_A(1-r)(0.26+0.50\frac{n}{N}) - \sigma T^4\,[0.56-0.0797(e_d)^{1/2}\,](0.10+0.90\frac{n}{N}) \tag{2.6}$$

where Q_A is the total daily clear sky radiation data at the earth's surface in equivalent to evaporation (mm/day),

r is the reflection coefficient, n is actual mean sunshine hour (hr/day),

N is a maximum possible sunshine hour (hr/day),

σT^4 is black-body surface reflection in equivalent evaporation (mm/day)

2.2.4 Determination of crop coefficient (K_c)

Original concept of crop coefficient (K_c) was initiated by Jensen (1968) and further developed and implemented by the other researchers afterward. Basically,

K_c acts like being an ET measurement for a specific crop if compared to the reference ET (or ET_o) for grass. $K_c > 1$ (or < 1) means that crop has higher (or lower) ET rate than the reference value of grass under the defined condition mentioned earlier. As ET consists of two main mechanisms; evaporation (mostly by soil) and transpiration (by plant), variation in these data during different crop growing stages shall indicate ultimate value of K_c for each crop. According to FAO standard, the growing period of plant can be divided into four distinct growth stages (Figure 2.5) (FAO, 1998):

1) Initial period which runs from planting date to an approximately 10% ground cover by green vegetation. At this stage, ET is mostly dominated by the soil evaporation which leads to rather low K_c of about 0.3-0.7 for most crops (except rice).

2) Crop development period which runs from about 10% ground cover to effective full cover. An effective full cover for many crops occurs at the initiation of flowering. At this stage, role of soil evaporation is gradually limited from apparent crop growth and an increase in plant transpiration is highly evidenced. This situation leads to a rapid rise of the K_c to stand at about 1.0-1.2 for most crops (at full cover).

3) Mid-season period which runs from effective full cover to beginning of maturity, often indicated by the starting of the ageing, yellowing or senescence of leaves, leaf drop, or the browning of fruit to the degree that the crop ET is reduced relative to the reference ET_o. The mid-season stage is the longest stage for perennials and for many annuals, but it may be relatively short for vegetable crops, with K_c data constantly stand at about 1.0-1.2, the peak values of the growth cycle.

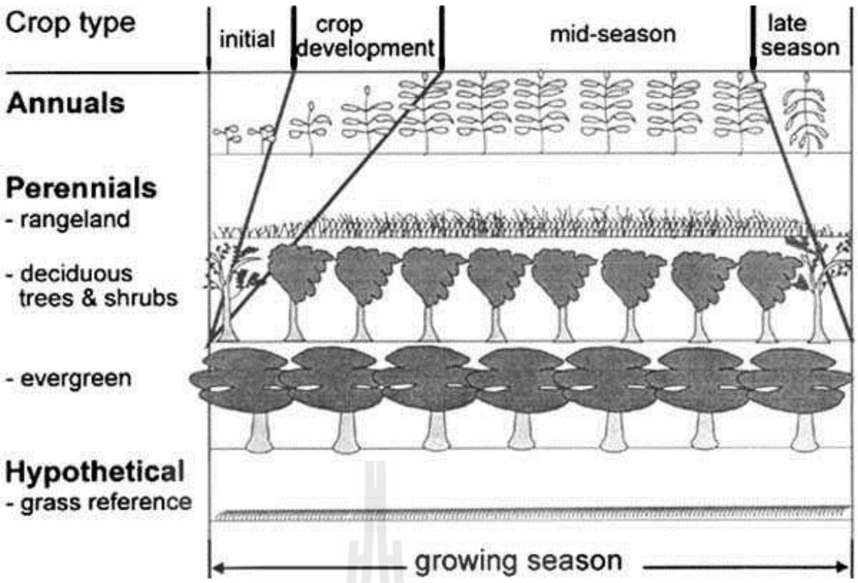


Figure 2.5 Crop growth stages for different types of crops.

Source: FAO (1998).

In calculating K_c, not only crop structural conditions but also the climatic conditions and crop height should be included in the analysis, especially for areas in the arid or semi-arid region. Normally, more arid climates and conditions of greater wind speed shall result in higher value for $K_{c\ mid}$. More humid climates and conditions of lower wind speed shall lower these values.

4) Late season which lasts from the beginning of maturity to harvest (or full senescence). The calculation for K_c and ET_{crop} is presumed to terminate when the crop is harvested, dries out naturally, reaches full senescence, or experiences the leaf drop. At this stage, K_c value mainly reflects crop and water management practices, from which the K_c value is high if crop is frequently irrigated until harvested fresh. Typical values of K_c data at this stage stand at about 0.7-0.95.

In conclusion, typical ranges expected in K_c for the four growth stages are illustrated in Figures 2.6 and 2.7, respective.

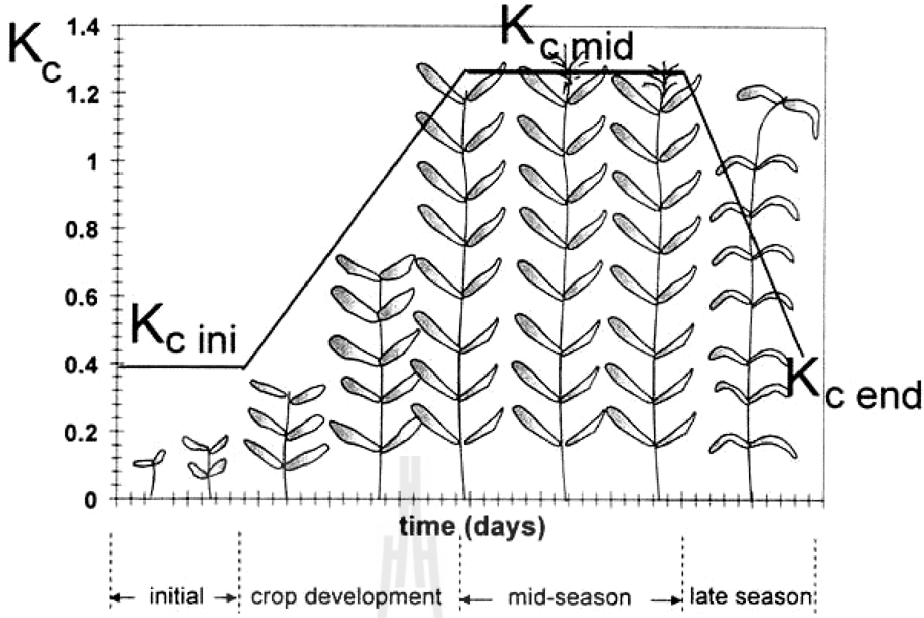


Figure 2.6 Variation of K_c with crop growth stages.

Source: FAO (1998).

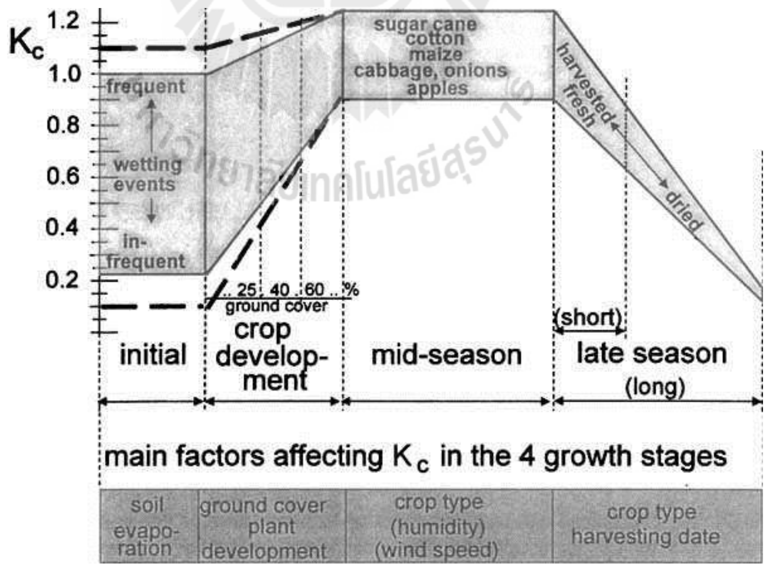


Figure 2.7 Typical ranges expected in K_c for the four growth stages.

Source: FAO (1998).

2.3 Crop yield and water requirement

It is widely known that water is critically essential factor for the proper growth and fertile yield of all crops. However, the relationship of water and crop yield is a complicated subject which attracts researchers worldwide in recent decades. Some issues are discussed here.

2.3.1 Crop yield response to water

Relationship between crop yield and crop water consumption (in terms of the crop evapotranspiration) has been a subject of great interest for long time and is called crop water production function. Results were reported for a variety of plants so far. Based on extensive researches, the Food and Agriculture Organization (FAO) had proposed a rather simple formula to explain the relationship as follows (FAO, 2012):

$$1-\frac{Y_a}{Y_x}=K_y\left(1-\frac{ET_a}{ET_x}\right), \tag{2.7}$$

or,

$$Y_a=\left[1-K_y\left(1-\frac{ET_a}{ET_x}\right)\right]\cdot Y_x \tag{2.8}$$

where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual ET, and K_y is a yield response factor representing the effect of a reduced ET. This is a standard equation for the yield in response to reduction in evapotranspiration (ET). This equation is applicable to all agricultural crops, i.e., herbaceous, trees and vines (FAO, 2012).

The total amount of actual ET (ET_a) depends on the available water in the soil, and also on the response of crop growth to water availability (K_y) at each crop growing stage. If sufficient water is provided to the crop at all time (ET_a = ET_x), the maximum yield can be reached regardless of the K_y factor. The yield response factor

(K_y) is a specific constant for each crop at each growing stage resulted from the complex interaction of crop production and the used water in which several biological, physical and chemical processes are related. This factor was extensively quantified for the use as a standard reference for the study of crop growth worldwide (see Table 2.3 for examples). Here, $K_y > 1$ means crop response is very sensitive to the water deficit with proportional larger yield reductions when water use is reduced. For $K_y < 1$, crop is more tolerant to water deficit in such situation while for $K_y = 1$, it means yield reduction is directly proportional to reduced water use.

Table 2.3 Seasonal K_y values of some well-known crops/plants.

Crop	K_y	Crop	K_y	Crop	K_y
Alfalfa	1.1	Onion	1.1	Spring wheat	1.15
Banana	1.2-1.35	Peas	1.15	Sugarcane	1.2
Cotton	0.85	Potato	1.1	Sunflower	0.95
Maize	1.25	Soil bean	0.85	Tomato	1.05

Source: FAO (2012).

In general, yield response to water deficit will differ largely depending on growing stage that the water stress occurs. Typically, flowering and yield formation stages are most sensitive to stress, while stress occurring during the ripening phases usually has a limited impact, as in the vegetative phase, provided the crop is able to recover from stress in subsequent stages.

According to Eq. 2.8, the actual crop yield Y_a can be found by following the four-step procedure detailed below (FAO, 2012):

1) Estimate maximum yield (Y_x), or yield under the excellent condition in which the agronomic factors (e.g., water, fertilizers, pest and diseases) are assumed not

limiting. This can be obtained by using the proper crop-growth model or extracting from the local data for maximum crop yields.

2) Calculate maximum ET (ET_x) based on some proper methodologies considering that the crop-water requirements are fully met. In this case, it is typically assumed that $ET_x = ET_{crop}$ which can be defined as follows:

$$ET_x = K_c ET_o \tag{2.9}$$

where ET_o is the reference-crop ET (mm/day) and K_c is crop coefficient (dimensionless) which is available for a large number of crops. Here, influence of climate data on crop water need is mostly integrated into the ET_o estimate while K_c depends predominately on specific crop characteristics and only to a limited extent with climate.

3) Determine actual crop ET (ET_a) under known specific situation, as determined by the available water supply to the crop using the daily water balance model. If soil water is sufficient, then $ET_a = ET_x$ and the crop shall have maximum yield under the stated condition.

4) Evaluate actual yield (Y_a) based on information of the estimated Y_x and the calculated ET_x and ET_a along with proper selection of the response factor (K_y) for the full growing season or over the different growing stages.

2.3.2 Water use efficiency

The importance of the consumed water and eventual crop yield is quite well comprehended for long time, but in a water-limited condition, the low efficiency in water use by crops is also a prominent concern to the agronomists. The crop water use efficiency (WUE) can be defined as follows (FAO, 1997):

$$\mathrm{WUE} = \frac{\mathrm{CP}}{\mathrm{WU}} \tag{2.10}$$

where CP is a certain type of crop product (e.g., grain yield, dry biomass, marketable yield) and WU is a certain type of the water use (e.g. total water, irrigation water, or ET_{crop}) (Boutraa, 2010). The usual goal is to maximize WUE which is very essential in water-limited areas where agricultural water is relatively scarce. In more detail, WUE can be expressed as:

$$\mathrm{WUE} = \frac{\mathrm{CP}}{R + D + E_p + E_s + T_w + T_c} \tag{2.11}$$

where R is the volume of water lost by runoff from the field, D is the volume drained below the root zone (deep percolation), E_p is the volume lost by evaporation during the conveyance and application to the field, E_s is the volume evaporated from the soil surface (mainly between the rows of crop plants), T_w is volume transpired by weeds, and T_c is the volume transpired by the crop (all these volumes pertain to the same unit area). This means that only a fraction of the applied water is actually absorbed and utilized by the crop (T_c). Therefore, to maximize WUE, the usual loss through runoff, seepage, evaporation and transpiration by weeds must be minimized and the planting of high-yielding crop varieties must be promoted.

This also includes the changes in cropping practices to optimize growing conditions like finding proper timing for planting and harvesting, tillage, fertilization and pest control. In short, raising water use efficiency requires good farming practices from start to finish which could greatly increase crop production efficiency compared to the low efficiency characteristics of traditional practice. Summary of the effective ways to improve water use efficiency is presented in Table 2.4.

Table 2.4 Summary of the ways to improve water use efficiency.

Conservation of water	
1.	Reduce conveyance losses by lining channels or, preferably, by using closed conduits.
2.	Reduce direct evaporation during irrigation by avoiding midday sprinkling. Minimize foliar interception by under-canopy, rather than by overhead sprinkling.
3.	Reduce runoff and percolation losses due to over-irrigation.
4.	Reduce evaporation from bare soil by mulching and by keeping the inter-row strips dry.
5.	Reduce transpiration by weeds, keeping the inter-row strips dry and applying weed control measures where needed.
6.	Irrigate at high frequency and in the exact amounts needed to prevent water deficits, taking account of weather conditions and crop growth stage.
Enhancement of crop growth	
1.	Select most suitable and marketable crops for the region.
2.	Use optimal timing for planting and harvesting.
3.	Use optimal tillage (avoid excessive cultivation).
4.	Use appropriate insect, parasite and disease control.
5.	Apply manures and green manures where possible and fertilize effectively (preferably by injecting the necessary nutrients into the irrigation water).
6.	Practice soil conservation for long-term sustainability.
7.	Avoid progressive salinization by monitoring water-table elevation and early signs of salt accumulation, and by appropriate drainage.

Source: FAO (1997).

2.3.3 Irrigation and crop water requirements

As stated earlier, knowledge of the ET_{crop} (in Eq. 2.1) is important for the determination of daily crop-water requirements during the crop growing period. This is because about 99% of the daily water uptake by most plants from the soil shall be lost in form of the ET, which makes it a good predictor for full demand of water by a specific crop each day. As a result, in order to prevent unwanted underestimation or overestimation of crop water consumption, knowledge of water loss through actual ET is necessary for the development of a sustainable water management system over an area of interest. Therefore, data of ET_{crop} can support the efficient water resource management by being the necessary information for the proper supplying of irrigation to meet crop requirements the most on daily basis (Lazzara and Rana, 2010).

In most agricultural areas, two main sources of the usable water supply are precipitation and irrigation, whereas, in the tropical zone, precipitation is usually in the form of rain. As a consequence, the net irrigation water requirement (IWR_n) for each crop over a specific area was determined based on the following formula:

$$IWR_n = ET_{crop} - P_{eff} \tag{2.12}$$

where IWR_n is total irrigation water requirement for a certain time period, e.g., day, month (in mm), ET_{crop} is the total crop ET (mm) in that period and P_{eff} is the defined effective rainfall of the same time period (mm) as detailed below:

$$P_{eff} = 0.6P_{tot} - 10 \quad (\text{for } P_{tot} \leq 70 \text{ mm/month}) \tag{2.13a}$$

$$P_{eff} = 0.8P_{tot} - 24 \quad (\text{for } P_{tot} > 70 \text{ mm/month}) \tag{2.13b}$$

where P_{tot} is the total rainfall. These formulas were empirically derived for arid and sub-humid climates by the FAO (FAO, 1985; Burton, 2010).

The concept of effective rainfall was introduced because not all rainfall on a field can be utilized by crops. Some may run off and enter the drainage system, while rainfall that exceeds the storage capacity in the crop's root zone is not available to crop, and will thus not be effective in contributing to the actual crop's water needs.

The irrigation water supply forms a basic condition for plant production. In order to ensure optimum production, an adequate water supply should be provided. The quantity needed is determined by the type of crop grown, its stage of growth, the length of the growing season, and crop evapotranspiration values (ET_{crop}) collected for effective rainfall and irrigation efficiency is needed to evaluate irrigation water supplies. And then, peak values are used to determine design capacity of the irrigation system in need (ILACOB, 1981).

In Asia, it was found that yields from most crops increase by 100-400% after irrigation. The irrigation also allows double cropping and decrease the uncertainty of water supply by rainfall (Karina and David, 2007). In other words, the proper irrigation can improve crop yield and/or yield quality (James, 1988). The relationship between crop yield and total seasonal irrigation, is often called crop-water production function (CWPF), which is a considerably useful tool for irrigation planning purposes. With this function decision, farmers can effectively assess irrigation water needed to meet the production targets or, conversely, estimate likely crop production for fixed volumes of water. Typical pattern of the CWPF is shown in Figure 2.8 (Brumbelow and Georgakakos, 2007). From this information, it is obvious that effects of irrigation water on crop yield shall be eminent at the very first stage but this shall be gradually declined with increase in the irrigation supply until reaching the saturation period.

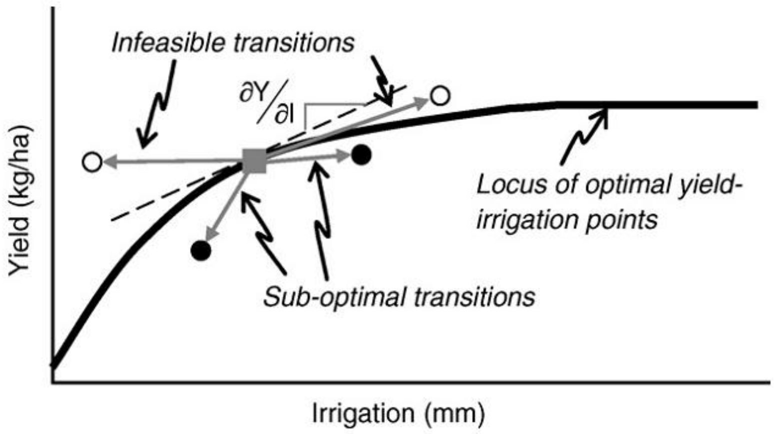


Figure 2.8 Example of the crop-water production function (CWPF)

Source: Brumbelow and Georgakakos (2007).

The used crop-water production function might be derived theoretically (process-based approach) or derived from actual data gained from field experiments or from available records (data-based approach). Figure 2.9 presents crop production function of maize reported in the work of Kipkorir, Raes, and Massawe (2002).

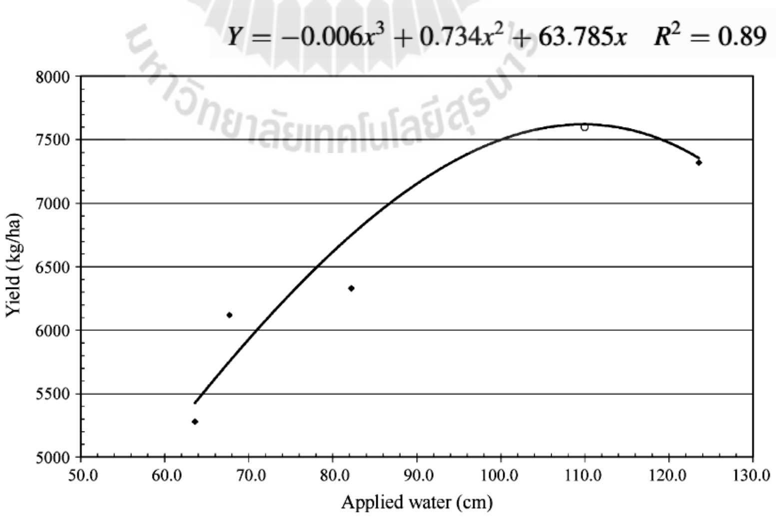


Figure 2.9 Water production function for maize, based on seasonal water supply (including rainfall)

Source: Kipkorir, Raes, and Massawe (2002).

2.4 Water harvesting for crop production

Water harvesting is the direct capturing and utilizing of the runoff on-site. In some applications, water harvesting collects water both direct rainfall and overland flow in a constructed pond and supplies water for the needed irrigation (Ferguson, 1998). As far as possible, the pond should be located in the lower patch of the field (or watershed) to maximize runoff catchment. Farm ponds may be circular, square, or rectangular.

The optimum volume of the on farm pond is the maximum difference between the cumulative supply and demand during the period of the driest year of the available records (Patra, 2008). Successive end of month storage can be determined by using the water balance equation. And the life cycle of a pond is between 50 to 100 years (Abdel-Magid, Mohammed, and Rowe, 1996; Chaitham, 1999).

2.4.1 Water balance equation

In quantitative terms the hydrologic cycle can be represented by a closed equation which represents the principle of conservation of mass, often referred to in hydraulics as a continuity equation. The terms of this “water balance equation” may be expanded or lumped by subdividing, consolidating, or eliminating some of the terms, depending on the purpose of computation (Gupyai, 2008). Water balance or water budget method accounts for all the incoming, outgoing and stored water in a lake or reservoir which is assigned as a control volume over a period of time:

$$\text{Change in pond storage} = \sum \text{Inflow} - \sum \text{Outflow} - \text{Evaporation loss} \quad (2.14)$$

or,

$$\Delta S = \sum I - \sum O - E \quad (2.15)$$

Here, the two sources of inflow are the runoff yield over an area and the direct rainfall over the pond area, while the sole outflow is the irrigation to crop cultivation area.

It can be generalized by taking all the factors of inflow and outflow and transformed into a more useable form for practical application. The above equation can be rewritten as:

$$\Delta S = S_{t+1} - S_t = (P_t + I_{sft} + I_{gft}) - (O_{sft} + O_{gft} + T_t) - E_t \qquad (2.16)$$

where [all factors are in unit of volume (m^3)]

S_{t+1} = Pond storage at the beginning of the $(t+1)^{th}$ period

S_t = Pond storage at the beginning of the t^{th} period

P_t = Precipitation during the t^{th} period (in terms of areal rainfall)

I_{sft} = Surface water inflow during the t^{th} period (e.g. as direct run off.)

I_{gft} = Ground water inflow during the t^{th} period

O_{sft} = Surface water outflow during the t^{th} period (e.g. irrigation water)

O_{gft} = Ground water outflow during the t^{th} period in unit of volume (m^3)

T_t = Transpiration during the t^{th} period (may be neglected)

E_t = Evaporation during the t^{th} period

t = Time index

For gauged watershed, measurement of these quantities is possible except I_{gf}, O_{gf}, and T since ground water inflow and outflow are very difficult to measure for a lake or reservoir (Patra, 2008; Fredrich, 1975; Gyasi-Agyei, 2003).

2.4.1.1 Areal rainfall. Normally, the measurement of precipitation is a point sampling procedure. The quantity of precipitation over an area (called areal rainfall or areal precipitation) has to be estimated from these point data for the hydrological study. The arithmetic mean is one of many methods used to calculate this average rainfall over an area of interest. The arithmetic mean method gives a very satisfactory measure of the areal rainfall under the following conditions:

1) The catchment area is equipped by many uniformly spaced rain gauges.

2) The area has no marked diversity in topography and the range in altitude is small. Hence, variation in rainfall amounts is minimal.

The relationship is expressed as:

$$\hat{P} = \frac{1}{G} . \sum_{g=1}^{G} p_g \tag{2.17}$$

Where $\hat{P}$ is areal rainfall (mm), G is number of rainfall stations, p_g is rainfall at each station (mm) (Dingman, 2002) The stations are usually those inside the catchment area, but neighboring gauges in the vicinity might be included to facilitate continuous distribution of areal rainfall over an area (Shaw, 1994).

2.4.1.2 Direct runoff. The U.S. Department of Agriculture Soil Conservation service (SCS) (1972), now the National Resources Conservation Service (NRCS), developed a rainfall-runoff relation for ungauged watersheds (Chaitham, 1999). The depth of excess precipitation or direct runoff (P_e) is always less than or equal to depth of precipitation (P). Likewise, after runoff begins, the additional depth of water retained in the watershed (F_a), is less than or equal to some potential maximum retention (S). There is some amount of rainfall (I_a; initial abstraction) for which no runoff will occur, so the potential runoff is P - I_a.

The SCS method assumes that the ratio of the two actual to the two potential quantities are equal, that is:

$$\frac{Fa}{s} = \frac{Pe}{P - Ia} \tag{2.18}$$

From continuity equation:

$$P = P_e + I_a + F_a \tag{2.19}$$

Combining two above equations and solving for P_e gives

$$P_e = (P - I_a)^2/(P - I_a + S) \tag{2.20}$$

From the study of several small experimental watersheds, an empirical relation was developed for I_a is, $I_a = 0.2S$.

Amount of the surface runoff available within an area was then calculated using the SCS-CN method, as detailed below:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2.21}$$

where P_e is the direct runoff over an area (mm), S is potential maximum retention of land (mm), P is the total precipitation over an area (mm). Referred empirical analyses suggested that S could be approximated by the following relation:

$$S = 254\left(\frac{100}{CN} - 1\right) \tag{2.22}$$

where CN is curve number (dimensionless) whose value depended on several factors, e.g., hydrologic soil group, LULC, and hydrologic condition. CN has a range from 30 to 100; higher numbers mean higher potential for having runoff. Impervious and water surface CN = 100, for natural surfaces CN < 100.

Curve number has been established by the SCS on the basis of hydrologic soil group and land use. The four hydrologic soil groups are described as:

Group A: Deep sand, deep loess, aggregated silts.

Group B: Shallow loess, sandy loam.

Group C: Clay loams, shallow sandy loam, soil low in organic content, and soils usually high in clay.

Group D: Soils that swell significantly when wet, heavy plastic clays, and certain saline soils (Mays, 2005).

2.4.1.3 Evaporation. The evaporation loss from the reservoir (or on farm pond) is estimated from evaporation pan data based on the principle that the pan coefficient (C_p) is the ratio of annual reservoir evaporation (E_r) to annual pan evaporation (E_p). This relation can be expressed in equation as follows:

$$E_r = C_p E_p \tag{2.23}$$

where E_r is the pond evaporation (mm), E_p is the reference pan evaporation (mm), and C_p is pan coefficient (dimensionless) taken to be 0.70 from the U.S. Weather Bureau standard for the class-A pan coefficient (Leewatjanakul, 2006)

2.4.2 Reservoir operation

The allocation of storage space for various uses is done by reservoir operation study (Patra, 2008). The established operation rules (policies) are used to specify how water is managed in a reservoir and throughout a reservoir system. These operation rules may be designed to vary seasonally in response to the seasonal demands for water and the stochastic nature of reservoir supplies and perhaps a forecast of future expected inflows (or supplies) to the reservoir also. Normally, the operation rules are often established on a monthly basis. There are three basic methods that have been used in planning, design, and operation of reservoir systems:

1) Simplified methods. These are often used for analyzing systems involving one reservoir with one purpose, using data for only a critical flow period.

2) Simulation models. These models can handle much more complex system configurations and can preserve much more fully stochastic, dynamic characteristics of reservoir systems. These models are able to search for an optimum alternative of operating policies and system reliability in an efficient manner.

3) Optimization models. These may have a greater number of assumptions and approximations than the simulation models. They are often needed to make the model mathematically tractable. The combined use of simulation and optimization models can overcome this difficulty (Mays and Tung, 1992; Mays, 1996; 2005).

2.4.3 Reservoir simulation

Reservoir simulation is the numerical representation of sequences (numerical sequential simulation) of events that could occur in real life. Since the key factor in hydrology is variability in time, therefore, the operation of the system is simulated in time by using sequences of observed data, or sequences of generated data but realistic hydrological data as system (or model) inputs (Carr and Underhill, 1974).

The sequences of system (or model) inputs play extremely important role in simulation studies. In reality, these inputs are usually continuous functions of some variables like instantaneous rainfall. However, to provide data series for a simulation study these continuous functions are aggregated over discrete intervals, for example, daily or monthly recorded rainfall, daily or monthly recorded stream flow.

In order to obtain a representative sample of the possible system behavior, the input series used in a simulation study should be at least as long as the anticipated life of the proposed project. If very long records are available then it would be possible to simulate the response of the proposed system over a number of equally likely samples of the stochastic model inputs, each corresponding in length to the design life of the project. Such multiple simulations would allow a number of independent assessments to be made of system performance under equally likely conditions. Hence, probability of experiencing specified frequencies of system shortfall could be assessed.

In reality, it is rare to find records of length similar to the project life span and it would be very unusual to find records that approached designed length for multiple simulation. However, alternative stochastic methods of extending length of available records seek to overcome the problem of short historical series of data by generating long hydrologic sequences which are equally likely samples of possible data series to be used as the model inputs (Carr and Underhill, 1974).

The operation study of reservoir to be previously reviewed dealt with many uncertain variables, especially, the problem of stochastic nature of reservoir supplies. And the simulation model which is used to study the operation of reservoir can preserve the stochastic of reservoir systems, also this model is able to search for an optimum alternative of operating policies and system reliability in an efficient manner. According to this context, Monte Carlo simulation is an efficient method which can well be applied to the “stochastic problem” (Sherider, 1966) and used in uncertainty analysis (Kentel and Melih, 2008).

2.4.4 Monte Carlo simulation method

Monte Carlo simulation is mathematical technique to be used to evaluate the behavior of a system connected with uncertainty variables (Ayyub and McCuen, 2002) for comparing alternative designs (or policies) by applying the series of random variables, so called a stochastic process (Jensen and Bard, 2003; Cassady and Nachlas,

2008) to deterministic functional relationship (Ganoulis, 2009).

Each evaluation (or the simulation cycle) is based on a certain randomly selected series of conditions for the input parameters of a system. Certain analytical tools are used to assure random selection (or random generation) of input parameters according to their respective probability distribution function (PDF). Hence, several predictions of behavior (or possible outcomes) are obtained. Then statistical methods are used to evaluate the moments and distribution type for the behavior of the system.

The analytical and computational steps that are needed for performing Monte Carlo Simulation are (Ayyub and McCuen, 2002; Blanchard, 2006):

1) definition of the system using a model,

2) determining a distribution function to represent all input variables,

3) generation of random variables,

4) evaluation of the model to obtain the possible outcomes distribution,

5) statistical analysis of the resulting behavior

2.4.1.1 Generation of synthetic rainfall. The process of generating a random variable from its probability density function can be viewed as a sampling procedure with a sample size N, when N are the number of simulation cycles (or equally likely series) (Ayyub and McCuen, 2002).

HEC-4 Monthly Streamflow Simulation, is one of the generalized computer programs developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers (US Army Corps of Engineers, 1971) and has become the most widely used model for multisite synthetic streamflow generation (Jothiprakash, Devamane, and Mohan, 2006). This program will analyze monthly rainfall or streamflows at a number of interrelated stations to find their statistical characteristics and will generate a sequence of hypothetical streamflows of any designed length with those characteristics. It will reconstitute missing streamflows on the basis of concurrent flows observed at other locations and will obtain maximum and minimum quantities for each month and for specified duration in the recorded, reconstituted and generated flows.

Conceptually, HEC-4 assumes that recorded monthly rainfall statistics can be explained by a Log-Pearson Type III (or gamma) distribution, which is often used to calculate the frequency of extreme events when the distribution of all events (both big and small) is log-normally distributed, as follows:

$$x_{i,m} = \log(Q_{i,m}) + q_i \tag{2.24}$$

and

$$t_{i,m} = \frac{(x_{i,m} - \bar{x}_i)}{S_i} \tag{2.25}$$

where $x_{i,m}$ is logarithm of the incremented monthly rainfall for the i^{th} month of the m_{th} year, Q is the monthly recorded rainfall (mm), q is the small increment of the rainfall used to prevent infinite logarithm for months with zero rainfall (mm), t is the Pearson Type III standard deviation, $\bar{x}$ is the mean logarithm of incremented monthly rainfall (mm), and S is the unbiased estimate of the population standard deviation.

The obtained data from the assumed Log-Pearson Type III distribution were then transformed into a presumed normal distribution using the Wilson–Hilferty transformation equation as follows:

$$K_{i,m} = \frac{6}{g_i}\left[\left(\left(\frac{g_i \cdot t_{i,m}}{2}\right)+1\right)^{1/3} - 1\right] + \frac{g_i}{6} \tag{2.26}$$

where K is the normal standard deviation and g is the unbiased estimate of population skew coefficient. The $K_{i,m}$ data were approximated as follows:

$$K'_{i,j} = \beta_1 K'_{i,1} + \beta_2 K'_{i,2} + \ldots + \beta_{j-1} K'_{i,j-1} + \beta_j K'_{i-1,j} + \beta_{j+1} K'_{i-1,j+1} + \ldots + \beta_n K'_{i-1,n} + (1-R^2_{i,j})^{1/2} Z_{i,j} \tag{2.27}$$

where $K'_{i,j}$ is the monthly rainfall logarithm for the i^{th} month of the j^{th} station, B is the beta coefficient determined from a correlation matrix, n is a number of interrelated stations, R is the multiple correlation coefficient, and Z is a random number from the normal standard population. The synthetic monthly rainfall data obtained through this equation were then converted to Log-Pearson Type III variant as follows:

$$t_{i,m} = \left[\left(\left(\frac{g_i}{6}\right)\cdot\left(K'_{i,m} - \frac{g_i}{6}\right) + 1\right)^3 - 1\right]\cdot\frac{2}{g_i} \tag{2.28}$$

The $t_{i,m}$ data at this stage were then transformed to its equivalent monthly rainfall data ($Q_{i,m}$) through the use of Eqs. 2.24 and 2.25.

Not only the monthly streamflow generation, HEC-4 model can be efficiently utilized for generating other variables, e.g., rainfall, evaporation, and water requirements, alone or in combination (US Army Copes of Engineers, 1971; 1985).

As reviewed above, the synthetically generated series can be obtained by means of a stochastic model fitted to the observed series, such that the generated series resemble, in a statistical sense (such as probability density function), the observed ones. Thus, each generated series can be considered as one of the possible series (equally likely series or independent series) that maybe occur in the future. As a consequence, the data resulting can be seen as a large sample from the population of all the possible system behaviors in the future (Monte Carlo simulation). Then, probability features (for example, probability of failure) of the consequences of drought or water shortage can be assessed by performing a statistical analysis of the results of simulation by using generated series as a model input (Bonaccorso, Cancelliere, Nicolosi, Rossi, and Cristaudo, 2014).

2.4.4.2 Estimation of probability of failure. The estimation of probability of failure was particularly crucial in the assessment of reliability analysis. Various methods can be applied to evaluate the probability of failure, like the first order second moment method (FOSM), the first order reliability method (FORM), and the direct Monte Carlo simulation method (MC-Direct). In this study, MC-Direct method was used to calculate the pond probability of failure. The direct Monte Carlo simulation method needs to define a performance function (M) of a stochastic system based on the specified mission as followed:

M = performance limit-response indicator

(or given criterion limit) = $g(x_1), g(x_2), \ldots, g(x_n)$

where

$x_1, x_2, \ldots, x_n$ = "n" basic random variables generated from probability density function (PDF)

$g(x_1), g(x_2), \ldots, g(x_n)$ = functional relationship between basic random variables and the failure of the system

From the above performance function, the limit state (or failure surface) which represented the boundary between "safety state" and "failure state" was identified by M = 0. The failure state was defined as the space where M < 0, and safety state was defined as the space where M > 0.

According to the performance function, the probability of failure can be estimated through a direct Monte Carlo simulation method with x_i (i = 1, 2, …, n) generated from probability density function (f(x)) as followed:

$$\overline{P}_f = \frac{\sum_{i=1}^{N} N_f(i)}{N} \tag{2.29}$$

where N_f is number of equally likely series (or simulation cycle) resulting in failure (in which $g(x_i) < 0$) and N is total number of equally likely series (or simulation cycle) throughout the simulation run. Note that, if N approaches infinity, $\overline{P}_f$ shall approach the true probability of failure (Cardoso, Almeida, Dias, and Coelho, 2008; Devictor, 2014; Guillaumat, Dau, Cocheteux, and Chauvin, 2007; Guérin, Barreau, Charki and Todoskoff, A. 2007).

In this study, the MC-Direct method was used to calculate pond probability of failure where the performance function, limit state, safety state, and failure state were expressed as follow:

Performance function: $S_{t+1} = S_t + \Sigma(\text{Inflow})_t - \Sigma(\text{Outflow})_t$

Limit state: $S_{t+1} = S_t + \Sigma(\text{Inflow})_t - \Sigma(\text{Outflow})_t = 0$

Remark: Limit state represented boundary between “safety state” and “failure state”

Safety state: $S_{t+1} = S_t + \Sigma(\text{Inflow})_t - \Sigma(\text{Outflow})_t > 0$

Failure state: $S_{t+1} = S_t + \Sigma(\text{Inflow})_t - \Sigma(\text{Outflow})_t < 0$

So, pond probability of failure can be expressed as:

$$\overline{P}_f = \frac{\text{Number of equally likely series resulting in failure}}{\text{Total number of equally likely series throughout the simulation run}} \times 100\% \quad (2.30)$$

In irrigation schemes, crops, ideally, do not suffer from water shortages: irrigation water is applied before the crops are under drought stress. However, it may not be possible to apply the irrigation water exactly in the case of unexpected or sometimes even planned. For example, in a dry year the pond may not have enough water to irrigate all the fields on time. In general, crops grown for their fresh leaves or fruits are more sensitive to water shortages than those grown for their dry seeds or fruits. From all 3 economic crops, sugarcane is highly sensitive to water shortage follows by maize (medium-to-high) and cassava is least sensitive to water shortage. In case of sugarcane, it is very sensitive to water shortages. This means that if it suffers, even little, water shortage its yield will be reduced considerably. Such water shortages must be avoided (Brouwer, Prins, and Heibloem, 1989).

Consequently, in this study, the characteristic of sugarcane was used as the criterion to suggest failure outcome (or the series which results in failure) as follow:

Suggestion of possible definition for a failure outcome:

1) A series which results in monthly storage between 0 and negative C m^3 for two or more consecutive months.

2) A series which results in monthly storage less than negative C m^3 in any month.

C being some numerical value to be discussed below**.** Consider when the crops need supplementary irrigation, the whole cultivated area served by the pond will require at least 1 mm of water. The total volume will be 157987*1/1000 m^3

(A being the area in m^2). Therefore C can be taken as 160.0 m^3 approximately.

2.4.5 Crop calendar

Farmers usually follow the traditional crop calendar which indicates the planting/sowing time of a locally adapted crop in the region. This crop calendar can be tuned in relation to the long term climate prediction (or the next possible climate phenomenon) under relatively confident quantity of this climate (Las, Unadi, Sosiawan, and kartiwa, 2007; Mengistu and Mekonnen, 2011).

The confident quantity of this climate can be calculated by using any probabilistic methods to identify probability of event being equaled or exceeded. The probability "*p*" of the event being equaled or exceeded is calculated by any of the plotting position formula given in Table 2.5 (Patra, 2008).

Table 2.5 Plotting position formulas.

No.	Formula name	Probability *p* of the event
1	California (1923)	m/N
2	Hazen (1914)	(m – 0.5)/N
3	Weibull (1939)	m/(N+1)
4	Beard (1943)	(m-0.31)/(N+0.38)
5	Chegodayev (1955)	(m-0.3)/(N+0.4)
6	Blom (1958)	(m-3/8)/(N+1/4)
7	Tukey (1962)	(3m-1)/(3N+1)
8	Gringorten (1963)	(m-0.44)/(N+0.12)
9	Cunnane (1978)	(m-0.4)/(N+0.2)
10	Adamowski (1981)	(m-1/4)/(N+1/2)

Source: (Patra, 2008).

Note: m is rank of data: m = 1, 2,…., N; N = sample length

2.5 Review of relevant researches

Plenty of researches related to main topics discussed in this chapter were found during the literature review process and some of these works are reported here to provide background for further work in this thesis.

2.5.1 Research on land suitability evaluation

Kolat, Vedat, Can, and Mehme (2006) evaluated suitability area for the new residential location in Eskisehir downtown, Turkey using six factors: slope, soil, depth to water table, swelling potential, flood susceptibility, and liquefaction potential. The weight and rank values were estimated by using two methods, namely, Simple Additive Weighting (SAW) and Analytic Hierarchy Process (AHP). Finally, total score was calculated by means of linear combination to obtain two output maps. As a result, the accordant classification category in comparison of two output maps was found to be 98.38% of total study area.

To evaluate the suitable land for maize, cassava, sugarcane, soybean, pineapple, forage, mango, and para rubber in Pakchong District, NE Thailand, Albab (1995) selected 8 appropriate land characteristics to be used as the diagnostic criteria from 6 land qualities (temperature regime, moisture availability, rooting condition, oxygen availability to roots, nutrient availability, and erosion hazard). Soil series map was utilized as the based map to establish the criterion maps. The linear combination method was exploited to do the overlay operation (integrated) of all criterion maps. It was found that, the suitability classes S1, S2, S3, and N for maize were 9.08%, 57.7%, 0.0%, and 33.22% respectively, the suitability classes S1, S2, S3, and N for cassava were 21.23%, 35.75%, 9.86%, and 33.16% respectively, the suitability classes S1, S2, S3, and N for sugarcane were 23.73%, 43.09%, 0.02%, and 33.16% respectively.

Eiumnoh, Shrestha, Baimoung, Kesawapitak, and Noomhorm (1995) chose cassava productivity factors: soil texture, moisture availability, soil drainage, effective soil depth, organic matter, base saturation, cation exchange capacity, mineral reserve, and fertility level together with related land-use requirements to prepare criterion maps in vector based data. These criterion maps were integrated by means of the limitation concept combined with parametric approach to evaluate cassava land suitability in Nakhon Ratchasima Province. The final suitability map was found to be 14.8 percent, 16.73 percent, and 4.09 percent under most suitable, moderately suitable, and marginally suitable respectively.

Multicriteria evaluation (MCE) was applied to evaluate land suitability for the cultivation of maize and potato in central Mexico. For crop maize, the relevant criteria and constraints, also, crop requirement or land use requirement and suitability level for the criteria were established based on expert opinion. Criterion maps were then constructed in the form of raster layer and the weight of each criterion map was calculated using a pairwise comparison matrix according to the process of analytical hierarchy process (AHP), after that, consistency index (CI) was tested. The criterion maps were integrated by using weight linear combination. In the final suitability map, the area for very high suitability, high suitability, medium suitability, low suitability, and very low suitability were 11,713 ha, 121,067 ha, 110,549 ha, 7193 ha, and 29 ha respectively (Ceballos-Silva and López-Blanco, 2003).

In case of the suitable land for crop planting, Charuppat (2002) exploited FAO procedure and GIS functions to evaluate suitable land for major crop in Lam Phra Phloeng watershed, NE Thailand. The eight biophysical factors such as temperature and rainfall between crop growing season, soil-water holding capacity were used as important land qualities together with the economic factor which was marketing price/rai. The multiplication method was used to integrate all diagnostic criterion maps to obtain final suitability map. As a result, the land was suitable for six economic crops (maize, cassava, sugarcane, rubber, mango, tamarind).

Ten chosen factors were exploited to evaluate suitable land for sugarcane and cassava cultivation in Kanchanaburi Province, western Thailand. The relative important values, in terms of proportion number obtained from the comparing between these factor pairs, were derived from expert opinion by means of the questionnaires. These relative important values were then used to calculate factor weight and classes weights (or factor rating) of each factor through the pairwise comparison method in context of analytic hierarchy process (AHP). Each factor layer, that contained classes weights, were combined using simple additive weighting (SAW) method. The results of suitability maps indicated that the highly suitable area for sugarcane and cassava were 6.87% and 21.52%, respectively (Tienwong, 2008).

From the above, it is evident that the FAO principle, GIS methodology and MCDM method are efficient tools for suitability land evaluation. Therefore suitability land evaluation for the three major economic crops in Nakhon Ratchasima province shall be implemented through the use of FAO principle incorporated with GIS techniques and MCDM method.

2.5.2 Research on crop yield and water use

Oweis, Hachum, and Kijne (2000) estimated optimum input factors of wheat yield production and WUE in rainfed and irrigated conditions in the northern Syria using experimental design. Wheat yield and its water use efficiency (WUE) in rainfed agricultural areas were found generally low and variable due to low amount and normally poor distribution of rainfall. The treatments consisted of 3 sowing dates (November, December, and January) and 4 supplementary irrigation (SI) rates (full SI, 2/3 SI, 1/3 SI and rainfed condition). The highest WUE was found at 2/3 SI for early sowing date (Nov) and at 1/3 SI for normal and late sowing date (Dec/Jan).

From the above useful research, the principle of water use efficiency derived from field experiment (crop water production function) was used to predict economic crop yield under the different rate of supplementary irrigation in Nakhon Ratchasima province.

Dogan, Clark, Rogers, Martin, and Vanderlip (2006) studied relationship between "relative net irrigation ratio: RI" (RI = net applied irrigation amount/net required irrigation amount) and the response of maize yield. Seven field experiments were implemented in Kansas State for a period of 3 years (1999, 2000, and 2001). Four treatments of supplementary irrigation (50%, 65%, 75%, and 100% of reference crop evapotranspiration from Perman-Montieth equation) were applied in each experimental field and the net applied irrigation amount was measured and recorded at each treatment. The net required irrigation amount was derived by multiplying the adjusted crop coefficient with the reference crop evapotranspiration. Plotting the graph between RI and maize it was found that the greatest yield occurred at a relative net irrigation value of 1.0 (full irrigation).

This research showed that ET_c defines the irrigation rate. This study will use ET_c for supplementary irrigation.

The response of maize yields, according to its varieties and plant densities, to different supplementary irrigation rates were studied at National Corn and Sorghum Research Center, Nakhon Ratchasima province during December, 1974 to

April, 1980. The split-split plot experimental design was applied with 3 supplementary irrigation rates (77.1 mm/m, 38.6 mm/m, and 25.7 mm/m and 6 different treatments were undertaken for each supplementary irrigation rate), 2 plant densities (6836 and 9615 plant/rai), and 3 maize varieties. Results of the study demonstrated that the average maize yield was significantly increased by 0.4 ton/rai, 0.78 ton/rai, and 0.90 ton/rai at the supplementary irrigation rates of 25.7 mm/m, 38.6 mm/m, and 77.1 mm/m respectively (Onvimala, 1981).

The effects of non-irrigated (rainfed agriculture) and irrigated conditions on sugarcane yield were studied at Banglen Project, Nakhon Pathom Province. To avoid the bias of difference soil type and soil texture, the continuously homogeneous 24 sugarcane planting plots were utilized as the representative area and were divided into 2 groups. The 12 plots of each group were also put into 3 categories of sugarcane (newly, first ratoon, and second ratoon). The first group (12 sugarcane plots) received only rainfall (rainfed agriculture), meanwhile, the second group (12 sugarcane plots) received rainfall with supplementary irrigation throughout the experimental period (during 2001 and 2002). Each category in the second group was supplied by each supplementary irrigation rate in each year. The study results found that the newly sugarcane which received supplementary irrigation at 55.86 mm/m in the year 2002 had substantially increased average yield from 10.31 ton/rai (rainfed agriculture) to 14.66 ton/rai and received supplementary irrigation by 21.48 mm/m in the year 2001 caused the average yield substantially increased from 9.74 ton/rai (rainfed agriculture) to 13.90 ton/rai. The first ratoon sugarcane yield substantially increased from 8.00 ton/rai (rainfed agriculture) to 13.78 ton/rai in the year 2002 and substantially increased from 9.98 ton/rai (rainfed agriculture) to 16.23 ton/rai in the year 2001 when received supplementary irrigation by 60.74 mm/m and 21.23 mm/m respectively. For the second ratoon sugarcane, the yield substantially increased from 9.52 ton/rai (rainfed agriculture) to 15.71 ton/rai when received supplementary irrigation equal to 52.19 mm/m in the year 2002 and the yield substantially increased from 8.86 ton/rai (rainfed agriculture) to 12.17 ton/rai when received supplementary irrigation equal to 19.11 mm/m in the year 2001 (Jitpratug, 2004)

Effect of different supplementary irrigation rates on cassava yield were studied at Khon Hin Son Research Station, Chachongsao Province during period of May 2005 to May 2006. A randomized complete block design (RCBD) was used with 3 replicates. The rates of supplementary irrigation (30 mm/m, 45 mm/m, and 60 mm/m.) were set according to the minimum value of evapotranspiration between 2 consecutive seasons (rainy season to dry season) obtained from the study in Northeast region, Thailand (i.e. 2 mm/day in rainy season, 1.5 mm/day between 2 seasons (end of rainy to starting of dry season), and 1mm/day in dry season) (Watanabe, Kawata, Sudo, Sekiyama, Inaoka, Bae, and Ohtsuka, 2004) and the controlled treatment was performed under rain-fed condition. Final results demonstrated that the cassava yields were significantly increased by 8.37 ton/rai, 8.92 ton/rai, and 9.11 ton/rai in relation to the supplementary irrigation rates of 30 mm/m, 45 mm/m, and 60 mm/m respectively, meanwhile, the cassava yield obtained under controlled treatment was 5.23 ton/rai (Samutthong, 2007).

These field experiments provided useful crop water production function. Table 2.6 concludes main results reported in these works.

Table 2.6 Effects of the supplementary irrigation on the increase of crop yields based on field experiment in Thailand (SIR = supplementary irrigation rate).

Cassava		Sugarcane		Maize	
SIR (mm/m)	Yield (ton/rai)	SIR (mm/m)	Yield (ton/rai)	SIR (mm/m)	Yield (ton/rai)
0 (rainfed)	5.23	0 (rainfed)	10.31	0 (rainfed)	0.36
30	8.37	21.48	13.90	25.7	0.40
45	8.92	55.86	14.66	38.6	0.78
60	9.11	-	-	77.1	0.90

Source: Samutthong (2007). (cassava); Jitpratug (2004). (sugarcane); and Onvimala (1981). (maize).

2.5.3 Research on water resource development

Cracium, Haidu, and Bilasco (2007) utilized Soil Conservation Service Curve Number (SCS-CN) method and GIS process to determine surface runoff at different moisture condition in Hydrographical Basin of vale Mare, Romania. Land use layer was produced by digitizing from original maps taken from different sources. The soil layer was also arranged by dividing into 4 hydrological soil groups including sandy, loamy, sandy clay loam, and clay soil. The two layers were merged by vector data manipulation (e.g. intersection). The combined layer was a map which contained land use together with the hydrological soil groups, then CN values could be assigned into all polygons in the combined layer. Potential maximum retention (S) and surface runoff volume (Q) were calculated to make map which indicated runoff volume in the study area.

Cereal crop productivity in the African continent heavily depended on rainfed agriculture. A dry spell in this continent, occurred about 2 or 3 weeks, caused a significant crop yield reduction. To overcome this problem, Senay and Verdin (2004) estimated the number of small capacity ponds throughout the African continent. The seasonal average of cereal crop evapotranspiration in most places in the continent during a growing season was approximately 4.5 mm per day. For this crop evapotranspiration value, a small pond capacity of 1000 m^3 was assumed to be sufficient for supplying full supplementary irrigation during a dry spell event. The full production was obtained at full supplementary irrigation and was enough to feed an average farm family in Africa. Annual rainfall, which was the major variables in rainfed agriculture, from 1998 to 2002 was derived from satellite and its ground station. The surface runoff produced from each catchment area (corresponding to each pond) was calculated by using the SCS-CN method. The required size of catchment area to fill up the 1000 m^3 of water (or to produce 1000 m^3 of surface runoff) into the used pond was also estimated. The number of (1000 m^3 capacity) ponds in each watershed were estimated by dividing the watershed area with upstream catchment area.

For demand and supply analysis, Zacharias, Dimitriou, and Koussouris (2003) established five scenarios in order to reduce water level fluctuation and keep soil moisture condition in Trichonis Lake, Western Greece. The aerial photos were put into RS process to provide present land use map. Crop areas from the LULC map were multiplied by irrigation rate to quantify water demand for all irrigation crops. Finally, the water balance model was used to calculate changing volume in the lake. The results indicated that, the best scenario was selected for practice.

Rainfed rice and mustard in the eastern India suffered frequent moisture stress leading to severe yield reduction due to uncertainty of rainfall and inadequate field level rainwater conservation structure (on farm reservoir: OFR). Therefore, to increase rice and mustard yield in rainfed agricultural area, the optimum sizing of OFR was estimated to harvest rainwater and surface runoff and provide supplementary irrigation (SI) to rice-mustard crop rotation in the same cultivation area. The OFR water balance simulation for 22 years (1977-1998) was utilized to determine the optimum sizing of OFR by accounting for all components (direct rainfall, surface runoff, evaporation, percolation, supplementary irrigation) which influenced upon the OFR storage. Farm area of 800 m^2 was used as the representative area for simulation study. Rice-mustard crop rotation system in representative area received 5 cm. of SI from OFR, or actual available water in the OFR, to irrigate rice during reproductive stage when the crop root zoon was 20% depletion of soil moisture content from saturate level. While, the other stages of rice were kept in rainfed condition without SI.

For mustard, if some water is left in OFR, the SI from OFR was applied as the pre-sowing irrigation for seed germination to raise the current soil moisture status to 75% available soil moisture content. In other stages of mustard, the SI was applied when actual evapotranspiration is less than the potential evapotranspiration. The initial OFR sizing tried in the simulation process began from 6% of farm area up to 20% of farm area (6, 8, 10, 12, 14, 16, 18, and 20% of farm area) until OFR was not dry during any year of simulation run time span. Then, the simulation procedure was terminated when the OFR storage was able to meet the pre-assigned irrigation demand of rice and mustard as described earlier. The present worth economic efficiency indices (net present value, benefit-cost ratio, internal rate of return, and payback period) were also studied for deciding the optimum sizing of OFR. The study revealed that the OFR of 2 m. depth, requiring 12% of farm area was the optimum sizing that gave the maximum values of NPV, BCR, IRR, and provided a minimum value of PBP, particularly this sizing of OFR can substantially increased rice and mustard yield in the studied area (Panigrahi, Panda, and Agrawal, 2005).

Design of irrigation system for lowland rice in Mudd Irrigation Scheme, Malaysia relied on many agricultural factors. One of the most important agricultural factors concerned with the designing of irrigation system was cropping calendar which highly depended on rainfall pattern. To ensure the efficient design of irrigation system for a long-term stability and satisfactory functioning, the cropping calendar should be adjusted in accordance with rainfall pattern. The historical monthly rainfall amount based on 80 percent probability of rainfall exceedence was derived by means of plotting position method to compare to traditional calendar. The results indicated that the rainfall distribution appeared in bimodal model with the first peak and second peak in May and October respectively. Consequently, the cropping calendar was then shifted for adjusting the crop growth period to coincide with the first peak or the second peak (Thavaraj, 1978).

From the above useful research, the principle of plotting position analysis can be applied to improve cropping calendar of other economic crops in rainfed agricultural areas. Nevertheless, monthly crop evapotranspiration should be calculated using long term climatic data to compare against the results from plotting position analysis. The wettest month obtained from plotting position analysis should be coincided with the month that had the maximum crop evapotranspiration for the efficient use of rain water.

For water investment projects in rain-fed agriculture, the measurement of economic efficiency associated with irrigation water policy options is one of the most important activities for determining whether the project is worth or not. The most used criteria for measuring economic efficiency are benefit-cost ratio (BC ratio), net present value (NPV), and internal rate of return (IRR) (The Netherlands ministry of agriculture and fisheries, 1989) and (Mays, 1996; Sharma and Charma, 2008). A BC ratio ≥ 1.0 indicates that the project evaluated is economically advantageous (Blank and Tarquin, 1989). The commission in India has laid down the standard benefit-cost ratio criterion of 1.5 for the irrigation project located in normal rainfall areas and 1.0 for drought prone areas (Sharma and Charma, 2008). These economic efficiencies are useful when making plan and finding potential alternatives (Kay and Williams, 1994).

For example, to find out the effects of irrigation schedule on the yield and the benefit-cost ratio of cassava production, the experiment was implemented in a split plot design with the four levels of irrigation at 598 mm, 639 mm, 660 mm, and 702 mm over all the cropping cycle. As a results, cassava yield increased according to the increasing of irrigation levels. Nevertheless, at the level of 702 mm the yield was slightly decreased. The benefit-cost ratio at each irrigation level were 2.78, 3.03, 3.04, and 2.95 in which more than 1.00 of all. The benefit-cost ratio values indicated that all four irrigation levels were worth for investment (Amanullah, Somasundaram, Alagesan, Vaiyapuri, Pazhanivelan, and Sathyamoorthi, 2006).

For maize, Karim and Alam (2010) randomly selected 120 farmers from 4 districts for interviewing about economic data of hybrid maize cultivation in their irrigation areas and, then, the benefit-cost ratio was calculated. The result found that the average benefit-cost ratio of all 4 districts was 1.89. It was indicated that the irrigation project for hybrid maize cultivation was worth for investment.

It was demonstrated that water can be harvested using pond to collect runoff from a proper size of catchment. To provide water for other nearby areas more ponds of the same size may be used for similar size catchments. However, for ponds with unknown and variable demand other methods such as simulation may be used in conjunction with SCS-CN and water balance equations. The SCS-CN method was demonstrated to be an efficient procedure for surface runoff estimation in ungauge catchment. These principles will be utilized as the fundamental concept to determine the optimum volume and reliability of farm pond under the different rates of supplementary irrigation by means of simulation procedure. The simulation procedure can be carried out by extending of rainfall sequence (synthetic series of rainfall) based on its probability density function which can provide long enough input data to predict the extreme probability of failure.

2.5.4 Research on the application of Monte Carlo simulation

The application of Monte Carlo simulation in water balance analysis was previously reported in the work of Nelson, Fundingsland, Hazen, and Hight (2009) to determine effectiveness of acid rock drainage (ARD) from a waste goldmine site. The exceeded ARD volume may be required extra storage and/or treatment pump to prevent any uncontrolled release. Monte Carlo simulation was carried out for the mine pit water balance to determine possible outcomes of the ARD volume at site. Recorded inflow data (yearly ARD yield which highly depended on precipitation) and recorded outflow data (discharge capacity of mine site water treatment pump) during 1999 to 2007 were utilized to define their probability density functions. Ten thousands values of each variable were created by random sampling from each of corresponding probability density function. All synthetic inflow and outflow values were considered as input data for the mine pit water balance model to produce the possible outcomes of stored ARD volume. The simulated ARD volume was then compared to the available ARD storage capacity to estimate the probability that the storage capacity is exceeded. It was found that the cumulative probability that the ARD volume will be less than maximum ARD capacity (961 million liters) was 99%. This probability indicated that an uncontrolled release has a small chance to occur (1%), as a result of the insufficient ARD storage and treatment pump capacity at site. So, to reduce the risk of ARD uncontrolled release, an extra storage and/or a higher treatment pump capacity should be prepared.

The above research applied Monte Carlo simulation method to water balance model by using mine pit as a control volume. This efficient procedure can be applied to other systems such as farm pond to simulate the storage change under different water demand. For a given capacity the possible pond storage under different supplementary irrigation rates can be analyzed to study the risk of failure.

Limaye, Paudel, Musleh, Cruise, and Hatch (2014) proposed a farm pond to harvest water for the production of 3 crops (corn, cotton, and peanut) for farmers in Henry County, Alabama. The objective was to maximize the economic returns (price of crop multiplied by the total yield minus all related costs) of the 3 crops. Pond water balance model, crop yield-soil moisture production function, and Monte Carlo simulation method were used to simulate yield of all 3 crops according to weekly soil moisture content. The soil moisture content in each week was estimated from irrigation rate and direct rainfall that occurred during the week. Weekly surface runoff and direct rainfall were generated for entire project life of 62 years to provide inflows to pond. The pond surface area was varied (the depth was fixed at 10 ft.) and the corresponding irrigation for all 3 crops determined using pond water balance equation. The objective function of return (price of crop multiplied by the total yield minus all related cost) was then calculated for each pond size. The above procedures (from varying pond size to calculating the total rate of returns) were run for several hundred thousand iterations each pond size.

It was found that pond size of 40 acres and 20 acres (with 10 ft. depth) could maintain the maximum possible rate of returns for the 3 crops under the simulation condition for up to 700 acres and 400 acres of planted land respectively (Limaye, Paudel, Musleh, Cruise, and Hatch, 2014).

From the above, Monte Carlo simulation method can be applied to pond water balance equation to determine the pond size that maximizes total rate of returns. The performance of farm pond should be examined using probability of failure for the entire project life.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Conceptual framework

This research consists of three main parts in accordance with the objectives stated earlier in Section 1.2 (see work flowchart in Figure 3.1). The first part involves a comprehensive evaluation of land suitability for each economic crop in Nakhon Ratchasima Province (cassava, sugarcane, maize) using the FAO land evaluation guideline for rainfed agriculture (FAO, 1983). The results are presented in the form of land suitability map (for each crop) with four classes of land suitability: highly (S1), moderately (S2), marginally (S3), and not (N) suitable. Also, a composite (or integrated) suitability map from all the three crops is also produced to provide comparative suitability. This information will aid farmers in selecting crops which best suit their land regarding its quality. In addition, a map-based comparison between actual crop planted (from classified LULC map in 2006) and the developed land suitability maps for each crop is also presented.

In the second part, the conceptual design of a farm pond to harvest water for production of the three economic crops over a representative land is demonstrated based on the recorded rainfall and crop water requirement.

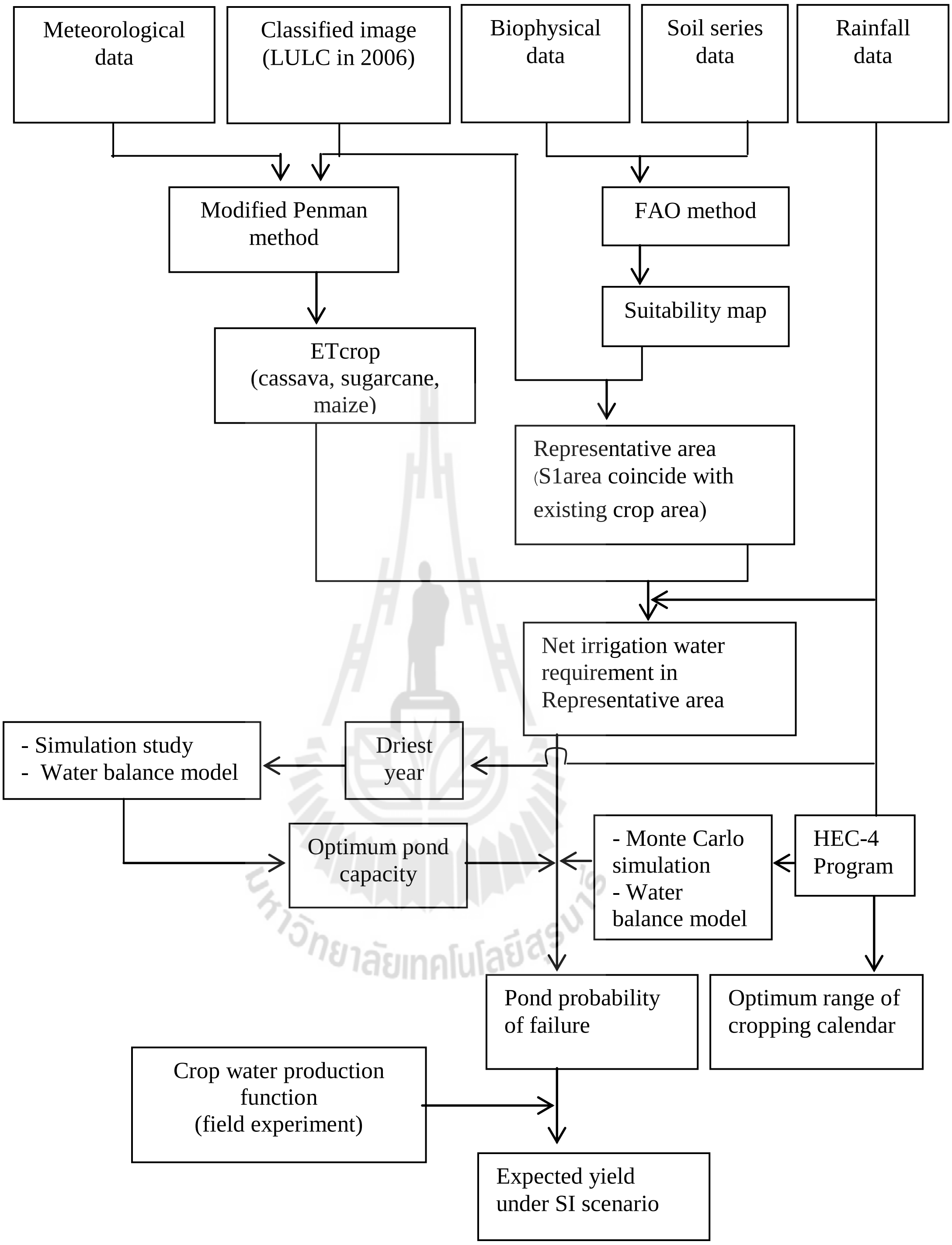


Figure 3.1 Flowchart of the study.

To achieve this task, the amount of crop water requirement (CWR) on monthly basis is determined first based on ET_{crop} [or maximum evapotranspiration (ET_m)] calculated from the standard FAO modified Penman method described in Chapter II. To assess risk of failure of the proposed pond, Monte Carlo simulation was used to determine water shortage probability at three different supplementary irrigation rates (100%, 75%, and 50% IWR_n).

In the third part, the effect of the supplement water on the eventual crop yield is assessed. This part includes two tasks. The first one is the development of suitable crop calendar for each listed crop based on monthly water need during the growth period, and the long-term rainfall pattern within the area. In theory, the month with highest need for water (for each concerned crop), based on the known monthly ET_{crop} gained earlier, should coincide with the month of peak rainfall. The second task is the assessment of yield increase in response to given water, and water use efficiency (WUE), comparing to that found under actual rainfed condition, based on field experiments.

3.2 Land use land cover (LULC) classification

The LULC map for the study area was obtained through the following procedure:

1) Landsat TM data in the visible and NIR/MIR regions (Band 1, 2, 3, 4, 5, 7) taken in November 2006 over the Nakhon Ratchasima Province were acquired from the Geo-informatics and Space Technology Development Agency (GISTDA).

2) Original images were processed to reduce geometric and radiometric errors. The geometric correction was carried out using reference ground control points (GCP)

extracted from a topographic map (used as base map) along with the information from field surveys. To aid automatic classification and also the visual interpretation for vegetation component, the false-color infrared composite image was produced from the combination of TM data in NIR (Band 4), Red (Band 3) and Green (Band 2) expressed in the format of RGB = 432 (Figure 3.2).

3) The LULC was classified using hybrid classification method in which the unsupervised classification (by Isodata clustering algorithm) was applied first to separate image data into several distinct groups in the spectral space followed by the supervised classification (by maximum likelihood algorithm) to group into the corresponding LULC classes based on the information of the LULC data in the training area collected from the field surveys. The results were reported in the forms of table and map in which seven main LULC groups were exhibited: cassava, sugarcane, maize, forest, urban/built-up, water, and others.

4) Accuracy of the resulting LULC map was assessed using the reference LULC data gathered from the field surveys at random locations (cluster sampling) and reported in the form of standard error matrix.

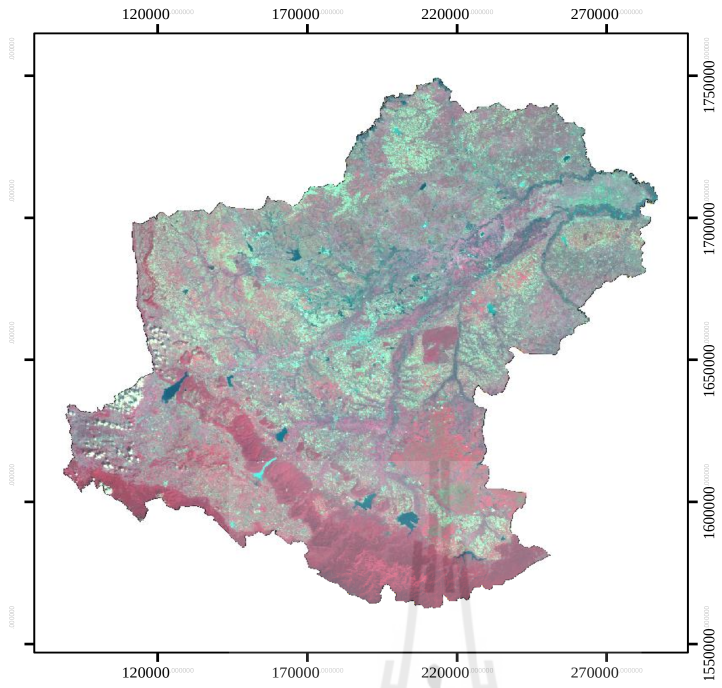


Figure 3.2 False-color composite image of the Nakhon Ratchasima Province derived from the Landsat-5 TM data (RGB = 432) in November 2006.

3.3 Land suitability analysis

The evaluation of land suitability for crop cultivation in the province was conducted for the three major crops based on guideline given by the FAO for rainfed agriculture (FAO, 1983) and knowledge of major land quality requirements of each crop (as described in Tables 3.1-3.3) which was collected from many sources described therein (see Appendix B for more data on the FAO guideline). Some areas, e.g. forest reserve, urban/built up, salt farm were excluded from the analysis based on the LDD guideline. The work procedure is as follows.

1) The necessary land quality attributes for suitability evaluation process and their representative characteristics (or diagnostic factors) were collected from the responsible agencies as illustrated in Tables 3.1-3.3.

Table 3.1 Land use requirement for cassava.

Land use requirement			Factor rating				Source
Land quality	Diagnostic factor	Unit	Highly suitable (S1-1.0)	Moderately suitable (S2-0.8)	Marginally suitable (S3-0.6)	Not suitable (N-0.4)	
Temperature	Annual mean temperature	^{o}C	25-30	31-33 24-14	34-36 13-10	> 36 < 10	2,3,5
Moisture availability	Annual rainfall	mm	1200-1500	1500-2500 900-1200	2500-4000 500-900	> 4000 < 500	2,3,5
Oxygen availability	Soil drainage	class	5,6	3,4	2	1	1,3,5
Nutrient availability	Soluble Phosphorus (P)	ppm	> 60	30-60	< 30	-	1,3,5
	Soluble Potassium (K)	ppm	> 15	10-15	< 10	-	1,3,5
	Organic matter (OM)	%	> 1.0	0.9-0.5	< 0.5	-	1,2,3,4
Nutrient retention	C.E.C	meq/ 100g	> 15	3-15	< 3	-	1,3,4,5
	B.S	%	> 75	35-75	< 35	-	1,3,5
Rooting condition	Effective soil depth	cm.	> 100	50-100	25-50	< 25	1,2,3
Potential for mechanization	Slope gradient	%	0-8	8-16	16-30	> 30	1,3,6

Source: Navanugraha (2002); Office of Agricultural Economics, Nakhon Ratchasima (2005); Tansiri and Saifauk (1996); Ilaco(1981); Charuppat (2002); and Albab (1995).

2) Soil data were obtained from soil series map of scale 1:50000 contributed from the Land Development Department (1980).

3) Climate data during 1977-2006 were obtained from the Thai Meteorological Department (TMD).

Table 3.2 Land use requirement for sugarcane.

Land use requirement			Factor rating				Source
Land quality	Diagnostic factor	Unit	Highly suitable (S1-1.0)	Moderately suitable (S2-0.8)	Marginally suitable (S3-0.6)	Not suitable (N-0.4)	
Temperature	Annual mean temperature	^{o}C	24-27	28-31 19-23	32-35 15-18	> 35 < 15	3,5
Moisture availability	Annual rainfall	mm	1600-2500	1200-1600 2500-3000	900-1200 3000-4000	< 900 > 4000	3,5
Oxygen availability	Soil drainage	class	5,6	3,4	2	1	1,3,5
Nutrient availability	Soluble Phosphorus (P)	ppm	> 45	25-45	3-25	< 3	1,3,5
	Soluble Potassium (K)	ppm	> 60	30-60	< 30	-	1,3,5
	Organic matter (OM)	%	> 1.0	0.9-0.5	< 0.5	-	1,3,4
Nutrient retention	C.E.C	meq/100g	> 15	10-15	5-9	< 5	1,3,4,5
	B.S	%	> 75	35-75	< 35	-	1,3,5
Rooting condition	Effective soil depth	cm	> 100	50-100	25-50	< 25	1,3
Potential for mechanization	Slope gradient	%	0-8	8-16	16-35	> 35	1,3,6

Table 3.3 Land use requirement for maize.

Land use requirement			Factor rating				Source
Land quality	Diagnostic factor	Unit	Highly suitable (S1-1.0)	Moderately suitable (S2-0.8)	Marginally suitable (S3-0.6)	Not suitable (N-0.4)	
Temperature	Annual mean temperature	^{o}C	25-30	31-32 20-24	33-35 16-19	> 35 < 16	2,3,5
Moisture availability	Annual rainfall	mm	> 500	400-500	300-400	< 300	2,3,5,7
Oxygen availability	Soil drainage	class	5,6	4	3	1,2	1,3,5
Nutrient availability	Soluble Phosphorus (P)	ppm	> 45	25-45	3-25	< 3	1,2,3,5
	Soluble Potassium (K)	ppm	> 60	30-60	< 30	-	1,2,3,5
	Organic matter (OM)	%	> 1.0	0.9-0.5	< 0.5	-	1,2,3,4
Nutrient retention	C.E.C	meq/ 100g	> 15	10-15	3-9	< 3	1,3,4,5
	B.S	%	> 75	35-75	< 35	-	1,3,5
Rooting condition	Effective soil depth	cm	> 100	50-100	25-50	< 25	1,2,3
Potential for mechanization	Slope gradient	%	0-5	5-16	16-30	> 30	1,2,3,6

4) The total suitability score for a specific crop plantation over a unit of land was assessed by multiplying the specific suitability score for a particular land unit (i.e., S1-1.0, S2-0.8, S3-0.6, N-0.4), or,

$$TSC = SC_1 \text{ x } SC_2 \text{ x } SC_3 \text{ x } SC_4 \text{ x } SC_5 \text{ x } SC_6 \tag{3.1}$$

where TSC is a total suitability score for each defined land unit (TSC = 0-1), and SC_i is the corresponding land suitability score for factor *i* as detailed in the FAO land evaluation guideline (given in Tables 3.1-3.3). In this study, six FAO recommended factors were taken into account, which are, annual mean temperature, annual rainfall, oxygen availability (soil drainage), soil fertility (as a combination of nutrient availability and nutrient retention as recommended in the LDD land evaluation guideline), effective soil depth, and slope gradient.

Each member of the original TSC from Eq. 3.1 is then converted to a modified total suitability score (MTSC) for each land unit which shall be used to prepare the resulting suitability map (for each crop) as follows:

$$MTSC_i = \frac{TSC_i}{TSC_{max}} \tag{3.2}$$

Where $MTSC_i$ is the modified TSC for the i^{th} land unit under consideration and TSC_{max} is the maximum TSC encountered in the used TSC dataset. The obtained MTSC data are then grouped into 4 classes, which are, highly (S1, MTSC = 0.8-1.0), moderately (S2, MTSC = 0.6-0.8), marginally (S3, MTSC = 0.4-0.6), and not suitable (N, MTSC = 0.0-0.4), to produce the final land suitability map.

5) The composite (or integrated) land suitability map for all the three crops was produced using the matrix method. A particular plot of land would have different

suitability level for each of the three crops, the crop with the highest suitability should be selected (FAO, 1983).

6) In addition, the combination between mapped crop planting pattern in 2006 of the province (derived from classified LULC map obtained in the earlier work) and composite (or integrated) land suitability map for all the three crops was carried out by overlaying the classified crop map in 2006 and land suitability maps. This map indicated overlap areas (or coincided areas) between existing cassava, sugarcane, and maize planting areas in 2006 and their suitability classes (for example, cassava coincided with marginally suitable for cassava etc.). These overlap areas (or coincide areas) obtained from composition of classified crop map in 2006 and land suitability maps were then utilized to investigate the proper used of land in planting the suitable crop in the year 2006 and, also, taken as the case study (or model) for predicting potential yield under the effect of different supplementary irrigation rate in the whole of Nakhon Ratchasima Province.

3.4 Water management

As stated earlier, work in this part shall deal mainly with the conceptual design of an optimum capacity of farm pond, to supply water at full need of the chosen crops planting over a farmland of interest, based on monthly record of rainfall data in the driest year ever experienced in the area during 1977-2006 (which in this case is 2001) and knowledge on monthly amount of total water required by all the three considered crops. Detailed procedure of the works in this part are as follows.

3.4.1 Crop water requirement (CWR)

The monthly crop water requirement (CWR) or ET_{crop} [or maximum evapotranspiration (ET_m)] was estimated from the FAO modified Penman method described in Chapter II under standard condition of the study area. The equation for ET_{crop} is:

$$ET_{crop} = K_c ET_o \tag{3.3}$$

Where ET_{crop} and ET_o are in unit of mm/month, and K_c is dimensionless. The ET_o data were determined based on the Modified Penman method and the long-term average (1977-2006) climate data (on monthly basis) measured at the Nakhon Ratchasima meteorological station. These include mean temperature, relative humidity, sunshine duration, wind velocity, and cloudiness. The relationship is expressed as:

$$ET_o = C \cdot [WR_n + (1-W) \cdot f(U) \cdot (e_a - e_d)] \tag{3.4}$$

where C is an adjustment factor to compensate for the effect of day and night weather conditions (dimensionless), W is a weighting factor for altitude and temperature effect on wind and humidity (dimensionless), f(U) is a wind related function, R_n is net solar radiation in equivalent to evaporation (mm/day), e_a is the saturation vapor pressure at the mean air temperature in ^oC (mbar), and e_d is actual vapor pressure of air (mbar). Specific definitions of e_d, f(U), and R_n are as follows:

$$e_d = \frac{e_a \cdot RH_{mean}}{100} \tag{3.5}$$

where RH is the relative humidity,

$$f(U) = 0.27 \cdot \left(1 + \frac{U_2}{100}\right) \tag{3.6}$$

where U_2 is wind velocity measured at 2m height (km/day). However, if no data of the wind velocity at 2m high is available, U_2 shall be estimated by:

$$U_2 = U_1 \cdot \frac{\log 2}{\log h} \tag{3.7}$$

where U_1 is wind velocity measured at height h in meters (km/day),

$$R_n = Q_A\,(1-r)(0.26+0.50\,\frac{n}{N}) - \sigma T^4\,[0.56-0.0797(e_d)^{1/2}\,](0.10+0.90\,\frac{n}{N}) \tag{3.8}$$

where Q_A is the total daily clear sky radiation data at the earth's surface in equivalent to evaporation (mm/day), r is the reflection coefficient, n is actual mean sunshine hour (hr/day), N is a maximum possible sunshine hour (hr/day), σT^4 is Black-body surface reflection in equivalent to evaporation (mm/day).

The derived monthly ET_{crop} were then summed up for the entire growing season for each crop. The references Kc data are presented in Table 3.4 while the crop calendar for the area is shown in Table 3.5.

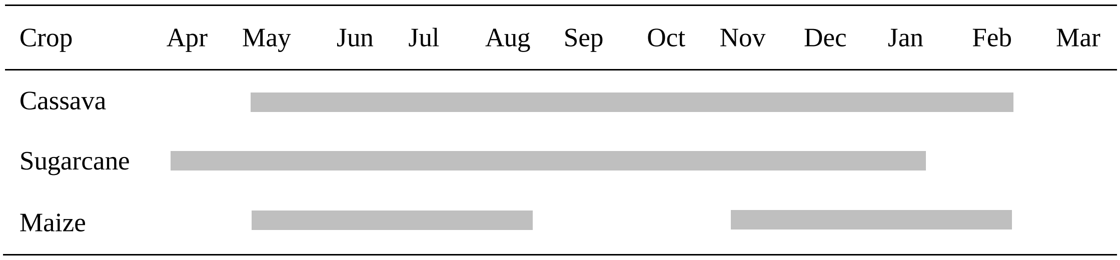
Table 3.4 Information of crop coefficient (K_c) for the studied crops.

Crop	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Cassava	-	0.67	0.74	0.61	0.68	0.88	0.84	0.64	0.44	0.47	0.43	-
Sugarcane	0.47	0.68	0.85	1.03	1.20	1.00	0.86	0.65	0.50	0.42	-	-
Maize	-	0.70	1.29	1.10	0.63	-	-	0.80	1.33	1.20	0.70	-

Source: Royal Irrigation Department (2012).

Note: Maize is cultivated 2 times per year as illustrated in Table 3.5.

Table 3.5 Traditional crop calendar in the study area.



Source: Land Development Department (2010b).

3.4.2 Optimum pond capacity

Work in this stage was devoted to the conceptual design of a sustainable farm pond to supply necessary water for all crops cultivated over a representative land of interest. The detailed work procedure is as follows.

1) A representative land was identified based on four specific requirements: a) having all the three crops planted, b) classified as highly suitable region (S1) for all these crops, c) bounded by a small watershed (based on a standard topographic map of 2m contour, or DEM), d) being a rainfed agricultural area outside irrigation zone (based on the irrigation map).

2) Potential location of the required farm pond was subsequently placed at the downstream end of the selected area where all (or most) of the run-off (along the stream network) over the selected area can be harvested. The initial surface area of the pond was set to be about 10-15% of the representative area as suggested by the Land Development Department (2005). Proper depth of the pond was determined later to suit the required optimum pond capacity.

3) From the location map of rain-gauge stations within Nakhon Ratchasima Province relevant stations located in the vicinity of the selected area are

to be selected. Monthly rainfall data for the period 1977 to 2006 for these stations were collected. The data were tested for consistency using the double mass curve method. Areal rainfall for the area was calculated as follows:

$$P = \frac{1}{N} \cdot \sum_{i=1}^{N} p_i \tag{3.9}$$

where P is the areal rainfall data (mm), N is the number of rainfall stations in use, and p_i is the rainfall data at the i^{th} station (mm).

4) Amount of the surface runoff produced from the area was calculated using the SCS-CN method, as detailed below:

$$Q_d = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3.10}$$

where Q_d is the direct runoff from the area, S is potential maximum retention of land, P is the total precipitation over an area, all quantities are in mm. Calculation was performed on a monthly basis. The results of experiments suggested that S could be approximated by the following relation:

$$S = 254\left(\frac{100}{CN} - 1\right) \tag{3.11}$$

where CN is curve number (dimensionless) whose values depended on several factors, e.g., hydrologic soil group, LULC, and hydrologic condition. CN has a range from 30 to 100; higher numbers mean higher potential for having runoff. All runoff yield from the area was assumed to flow into the pond.

5) The water balance model for the pond was used to find successive end-of-month storage as described below (Figure 3.3):

Change in pond storage = ∑Inflow - ∑Outflow - Evaporation loss (3.12)

or, $$\Delta S = \sum I - \sum O - E \quad (3.13)$$

Here, the major sources of inflow to the pond are direct runoff from the area and direct rainfall over the pond, while, the major sources of outflow are evaporation, supplementary irrigation to crop cultivation area, and spill (whenever pond capacity is exceeded).

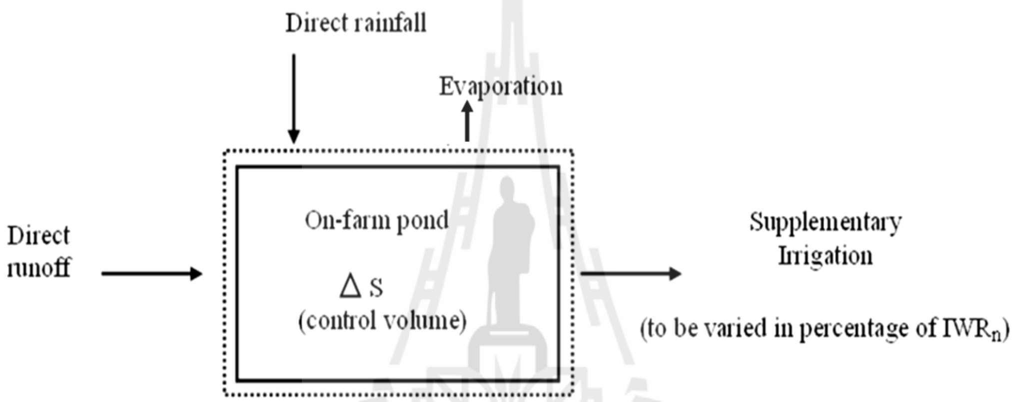


Figure 3.3 Water balance components of the assumed pond.

Eq. 3.13 can be rewritten as:

$$\Delta S = S_{t+1} - S_t = (Pd_t + Isf_t) - (Osf_t + E_t) \quad (3.14)$$

where S_{t+1} and S_t are pond storages at the beginning of the $(t+1)^{th}$ and t^{th} period in unit of volume (m^3), Pd_t is the direct rainfall during the t^{th} period (m^3), Isf_t is the runoff yield during the t^{th} period (m^3) based on Eq. 3.10, Osf_t is the supplementary irrigation for crops during the t^{th} period (m^3), E_t is evaporation during the t^{th} period (m^3). Note that, the ground water and deep percolation components were assumed negligible in this study. For simplicity, the pond's horizontal cross-section was assumed to be rectangular and constant at every depth.

Direct rainfall was calculated using:

$$P_t = P*A_p \tag{3.15}$$

where P is the areal rain (mm), A_p is the pond surface area (m^2) and P_t is the direct rainfall (m^3)

6) Optimum pond capacity was set as that which hold sufficient amount of water to sustain the driest year data (2001). This was obtained as follows:

The net irrigation water requirement (IWR_n) per month for each crop is the crop water requirement less the effective rainfall:

$$NIWR = ET_{crop} - P_{eff} \tag{3.16}$$

where NIWR is the net irrigation water requirement for a specific month (mm), ET_{crop} is the crop evapotranspiration for that month based on Eq. 3.3, and P_{eff} is the effective rainfall of the same month which can be determined as follows:

$$P_{eff}=0.6P_{tot} - 10 \quad (\text{for } P_{tot} \leq 70 \text{ mm/month}) \tag{3.17a}$$

$$P_{eff}=0.8P_{tot} - 24 \quad (\text{for } P_{tot} > 70 \text{ mm/month}) \tag{3.17b}$$

where P_{eff} (effective rainfall) and P_{tot} (areal rainfall) are in mm/month.

NIWR can be calculated for each crop from Eq. 3.16.

The monthly evaporation of pond's water was calculated using the following relation:

$$E_r = C_pE_p \tag{3.18}$$

where E_r is the pond evaporation (mm), E_p is the reference pan evaporation (mm), and C_p is pan coefficient (dimensionless) taken to be 0.70 as suggested by the U.S. Weather Bureau standard for the class-A pan coefficient. The E_p data were obtained from the records at Nakhon Ratchasima meteorological station during period 1977-

2006. Note that, in this study, these mean monthly pond evaporation were used throughout the process of Monte Carlo simulation.

The total irrigation requirement, IWR_n, for all three crops, is thus:

$$\text{Total NIWR} = NIWR*A_{cas}+NIWR*A_{sug}+NIWR*A_{mai} \tag{3.19}$$

where A_{cas} is cassava area, A_{sug} is sugarcane area, and A_{mai} is maize area, all quantities are in m^2.

Setting the initial pond storage as zero and using the driest year rainfall as input successive end-of-month pond storages were calculated from Eq. 3.14 $[S_{t+1} = S_t + (P_t + I_{sft}) - (O_{sft}+ E_t)]$

The maximum storage deficit (negative storage) was taken as an optimum pond capacity that shall ensure no shortage of water for crop needs in any month even in the driest year.

3.4.3 Determination of pond probability of failure

The optimum pond capacity when operated over very long years may encounter shortage. Considering the variation of the rainfall data over an area in a longer time span, e.g., 100 or 1000 years, the pond might fail to deliver the needed water in some extremely dry years or two or more consecutive dry years. In this part, the risk of failure was estimated by simulating its performance under 100 equally likely series of 50-year (synthetic) data. Three scenarios of supplementary irrigation were explored, i.e., 100%, 75%, and 50% of total IWR_n.

As reviewed in Chapter II, synthetically generated series can be obtained by means of a stochastic model fitted to the observed series, such that the generated series resembles, in a statistical sense (such as probability density function), the observed series. Thus, each generated series (equally likely series or independent series) can be considered as possible outcome that may occur in the future. Consequently, such series can be considered as a sample from the population of all the possible system states in the future (Monte Carlo simulation). Probability features (for example, probability of failure) of water shortage can be assessed by performing a statistical analysis of the results of simulation by using generated series as a model input. Detailed work procedure of this task is as follows:

1) Input the recorded rainfall data of 30-year period (1977-2006) of the 8 selected stations into the HEC-4 Monthly Streamflow Simulation Program. HEC-4 automatically calculates the relevant statistics and distribution of the data.

2) Use HEC-4 to generate 100 equally likely series of 50-year rainfall data at each selected rainfall station and, then, calculated areal rainfall using equation 3.9.

3) Input each series derived from step (2) into SCS runoff equation (Eq. 3.10), direct rainfall equation (Eq. 3.15), and water balance equation (Eq. 3.14) to obtain end-of-month storage. Start the Monte Carlo simulation from the tenth month of year 1 in the series, assuming an initial storage of full capacity. And run the simulation till the end month of the series.

Repeat step (3) for each of the 100 equally likely series. This completes the run for one irrigation rate (Figure 3.4).

Vary the irrigation rate (75%, and 50% of the total IWR_n) and repeat.

4) Define failure as an outcome which has

(a) storage between 0 and -160 m^3 in any two consecutive months or more

(b) storage less than -160 m^3 in any month

Count the number of series which results in failure. Calculate the pond probability of failure:

$$\overline{P}_f = \frac{\text{Number of equally likely series resulting in failure}}{\text{Total number of equally likely series throughout the simulation run}} \times 100\% \quad (3.20)$$

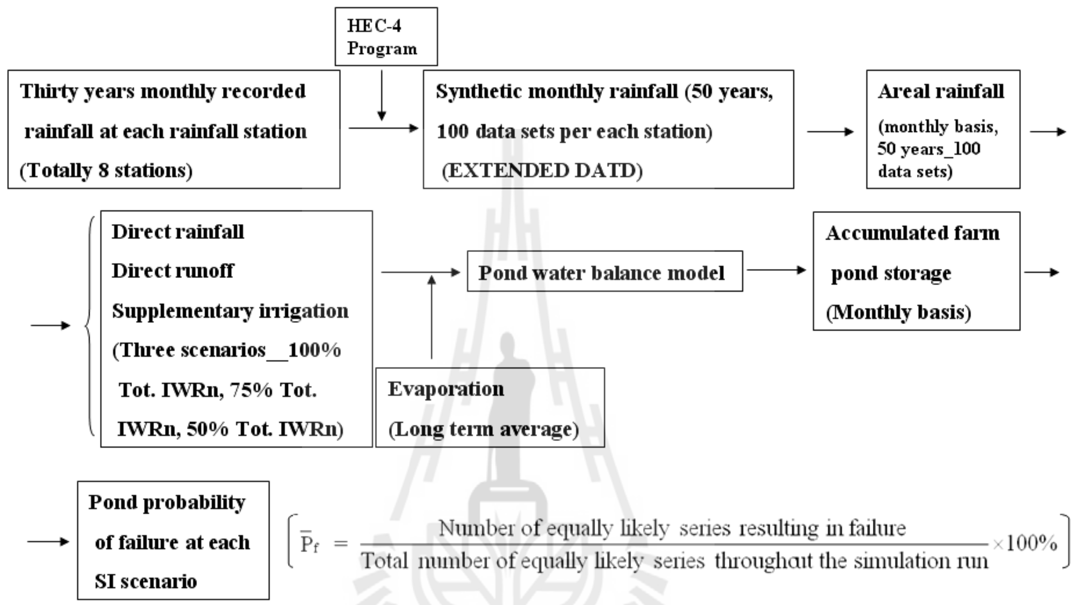


Figure 3.4 Flowchart of the Monte Carlo simulation method.

3.5 Development of proper crop calendar

As reviewed in section 2.4.3 a crop calendar may be tuned to the local climate or change in climate. Since rainfall is the most critical climate for crop production a crop calendar should be assessed in relation to the long-term rainfall pattern and water requirement of the particular crop.

The cumulative water deficit ($\Delta W = ET_{crop}$-P_{eff}) resulting from using a particular crop calendar may be used as a performance indicator. The performance of a traditional crop calendar can then be evaluated and compared to that of an alternative crop calendar. The calendar with a lower cumulative water deficit should be preferred.

Areal synthetic rainfall data of 100 equally likely series of 50-year were used to calculate the 80% exceedance probability annual rainfall pattern. For each month of the year the 5000 monthly rainfalls were ranked in descending order. Using Weibull's plotting position, the 80% exceedance rainfall is the 4001th value. P_{eff} for each month was calculated from equations 2.13a&b.

For any crop calendar, ET_{crop} could be calculated for the entire growing season. The cumulative water deficit for each crop calendar was calculated. For each crop, two calendars were evaluated and compared: traditional and alternative (peak crop water requirement matched with second rainfall peak).

3.6 Effects of supplementary irrigation on crop yield and water use efficiency

In this part, effect of supplement water on potential crop yield was considered based on some prior assumptions concluded from several relevant previous works on relationships of average yield of the interested crop with the provided supplementary water discussed in Chapter II. In this case, increase of yield productivity from rainfed condition (of each considered crop) and crop's associated water use efficiency (WUE) were assumed to be influenced mainly by amount of the gained supplementary water and the classified land quality (i.e., S1, S2, S3, and N). According to relevant previous works on this issue found in Thailand, effects of supplementary irrigation on observed yields of three interested crops (from field experiments) are as described in Table 2.6

and all these findings were assumed to be applicable for the respective crop plantation in NakhonRatchasimaProvince as well. Details of work in this part are as follows:

1) Relationship between average crop yield and amount of the supplementary water for each target crop at each interval of the reported amount of the water supply was derived in a presumed linear form. Rate of increase in crop yield per unit of water use (irrigated water) at each referred interval of used water supply was then identified. These rates simply indicates crop's water use efficiency (WUE) at different amount of the provided supplementary irrigated water, or WUE (SI), which were further used as reference data for the study in Nakhon Ratchasima Province later on.

2) Crop yield was predicted at each specified values of the known total IWR_n (e.g., 100%, 75% or 50% of the net IWR for each crop obtained from the earlier work (in Section 3.3.2) based on knowledge of WUE (SI) data gained in the previous work in step (1), for each studied crop.

3) Crop yield at a specific value of IWR_n for different class of land suitability was assessed by multiplying a suitability factor (C) to that of the yield found in the earlier step (for a particular land unit) as follows:

$$\text{Crop Yield} = C_i Y_o \tag{3.21}$$

Where C_i is a proper constant defined for each crop based on the land suitability class i (S1, S2, S3, and N) of a considered land unit and a land suitability class identified for Y_o, and Y_o is the original value of the crop yield predicted beforehand based solely on amount of the supplementary water detailed in the previous work. For examples,

If Y_o is assumed to be for class S1 then values of C_{S1} = 1.0, C_{S2} = 0.8, C_{S3} = 0.6, C_N = 0.4 and if Y_o is for class S2 then values of C_{S1} = 1.25, C_{S2} = 1.0, C_{S3} = 0.75 and

C_N = 0.5. This resulted value of C was based on suitability score defined for each class by FAO, i.e., S1 =1.0, S2 = 0.8, S3 = 0.6, S4 = 0.4. Here, the appropriate land suitability class given for the Y_o case is one that contains average recorded crop yield that matches the most with observed yield in the Y_o case for rainfed condition.

CHAPTER IV

RESULTS AND DISCUSSION

This chapter presents main results obtained from all works described in Chapter III along with relevant discussions. The overall content is separated into six sections corresponding to the section 3.1 to 3.6 of Chapter III.

4.1 Land use land cover map

The first task achieved in this study was the formulation of the needed LULC map of Nakhon Ratchasima Province from the Landsat-TM imagery taken in November 2006.

This map was synthesized to have seven main LULC classes of interest present therein at spatial resolution of 25 meters as shown in Figure 4.1. Among these seven LULC types, out of 100% (or 20,699.02 km^2) of the total provincial area, the three economic crops of interest, i.e., cassava, sugarcane, and maize, have taken up the area percentage of 17.42%, 4.147%, and 5.93%, respectively (27.77% in total) scattering throughout the province. Large portions of the cassava field were clearly apparent in the southeastern districts. Another 49.58% of the total area was classified as being other agricultural lands (mostly paddy field in the lowland plain). Forest land stands at about 17.39% of the area, mostly over the lower south which is dominated by high mountains. In addition, urban and built-up for the particular period had a relatively small proportion of 3.92% and water body was found to cover just less than 1% of the total area (Table 4.1).

For comparison, the information of LULC classes in the production year of 2006/2007 from Land Development Department indicated that cassava, sugarcane, and maize covered 17.93%, 4.45%, and 5.57% of the province respectively. Other agricultural lands and forest land covered 45.66%, and 18.38% respectively. Urban and built-up covered 5.90% and water body 2.11% of total area (LDD, 2007).

Table 4.1 Proportion of land for each classified LULC types presented in Figure 4.1.

	LULC	CAS	SGC	MAZ	OTH	FOR	U/B	WAT	Total
Area	km^2	3,606.66	987.99	1,227.97	10,262.62	3,598.64	810.52	204.62	20,699.02
	%	17.42	4.77	5.93	49.58	17.39	3.92	0.99	100.00

Note: 1. CAS ≡ Cassava, SGC ≡ Sugarcane, MAZ ≡ Maize, OTH ≡ other agricultural lands, FOR ≡ Forest, U/B ≡ Urban/Built-up, WAT ≡ Water body

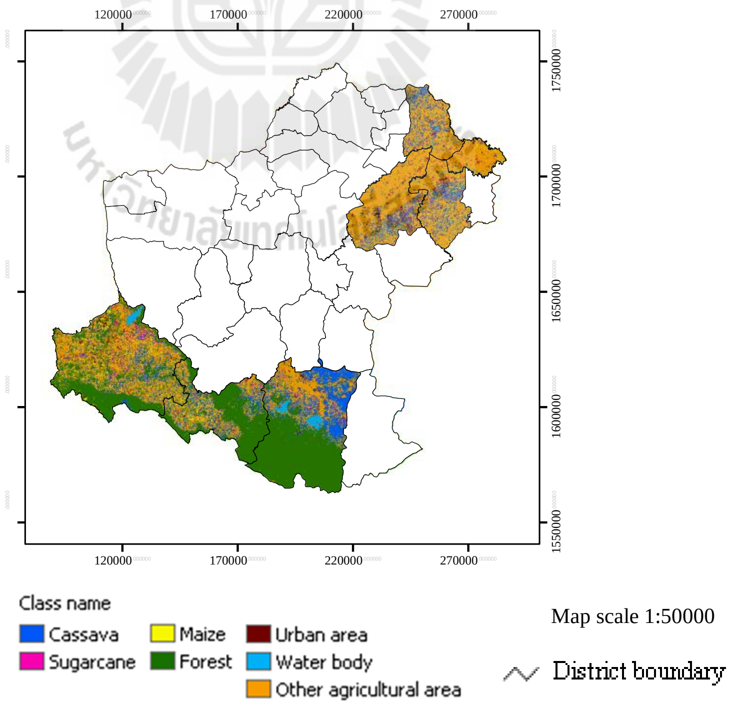


Figure 4.1 Classified LULC map of Nakhon Ratchasima Province in November 2006.

The derived LULC map (Figure 4.1) was then validated for its accuracy by using reference LULC data collected from 1,012 locations spreading throughout the study area and in all classes of LULC categories. The result was presented as standard error matrix (Table 4.2). The overall accuracy is 86.36% and Kappa coefficient 0.83 which were considered fairly satisfactory for further use. Note that, most errors occurred in the classification of cassava, sugarcane, and maize from one another (as mixed cultivation of this three listed crops was prevalent in the area), and between the forest and other agricultural lands (likely along the boundary of these two classes).

Table 4.2 Error matrix of the LULC map in Figure 4.1.

LULC Class		Classified data							Total (pixel)	Accuracy	
		CAS	SGC	MAZ	OTH	FOR	U/B	WAT		EO	PA
Reference data	CAS	194	14	16	4	-	2	-	230	15.65	84.35
	SGC	10	126	12	6	1	-	-	155	18.71	81.29
	MAZ	4	13	104	2	1	1	-	125	16.80	83.20
	OTH	11	3	4	221	2	-	-	241	8.30	91.70
	FOR	5	2	-	19	56	1	-	83	32.53	67.47
	U/B	-	-	-	1	-	95	-	96	1.04	98.96
	WAT	-	-	-	4	-	-	78	82	4.88	95.12
Total (pixel)		224	158	136	257	60	99	78	1,012	-	-
Accuracy	EC	13.39	20.25	23.53	14.01	6.67	4.04	0.00	-	-	-
	CA	86.61	79.75	76.47	85.99	93.33	95.96	100	-	-	-

Remark: Overall accuracy = 86.36% and Kappa coefficient = 0.83

Note: 1. EO ≡ Error of omission, EC ≡ Error of commission, CA ≡ Consumer accuracy, PA ≡ Producer accuracy.

4.2 Land suitability assessment and mapping

The necessary land quality data were prepared as individual thematic maps as portrayed in Figures 4.2a-f, respectively. These are temperature (from mean temperature during growing season) (Figure 4.2a), moisture availability (from total rainfall during growing season) (Figure 4.2b), oxygen availability (from soil drainage) (Figure 4.2c), soil fertility (from combination between nutrient availability and nutrient retention) (Figure 4.3d), rooting condition (from effective soil depth) (Figure 4.3e), and potential for mechanization (from slope gradient) (Figure 4.3f). Among these, only temperature was rather homogenous, only small variation was noticed throughout the entire area (from 26.97 to 28.39^{o}C), the rest are rather outstandingly heterogeneous.

In terms of moisture availability (rainfall), most areas have rather low rainfall of less than 1100 mm/year and the lowest region is the western part of the province while rainfall was found most abundant in the far southern part (close to the mountainous region). For the oxygen availability (soil drainage), most areas have moderate to high levels of soil drainage except for those in lowland area close to the main rivers which experienced rather low soil drainage (due to relatively high soil water saturation). For soil fertility, most provincial areas had marginal to moderate fertility level with only small portion of the land that contains high fertility. And for effective soil depth, most areas are in the deep to very deep class (> 100 mm) and for the mechanization, most areas had rather flat or gentle slope (< 3 degree).

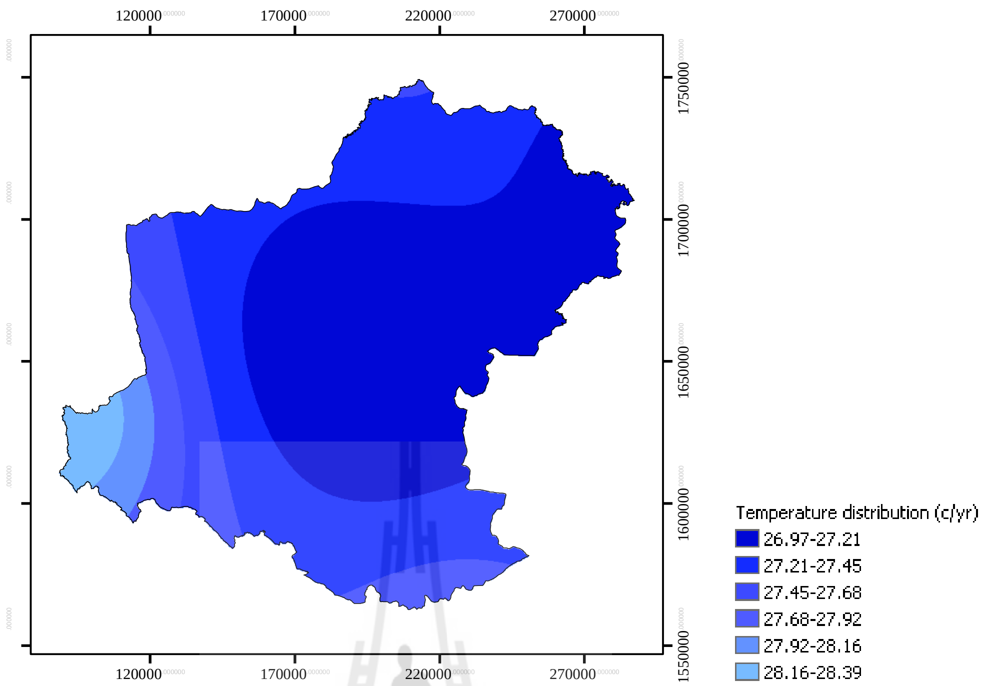


Figure 4.2a Temperature map.

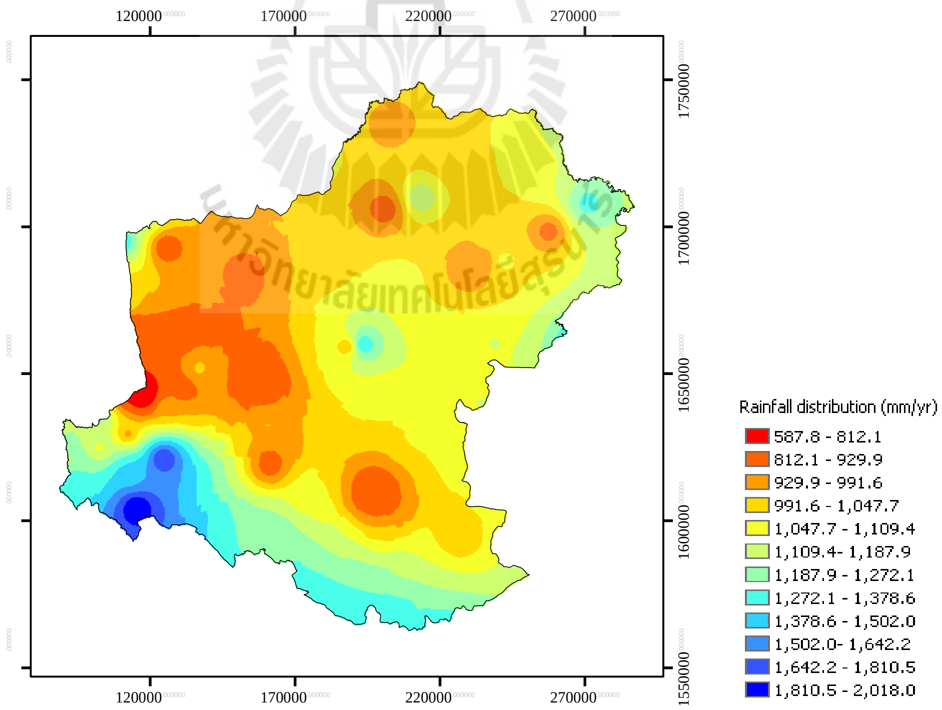


Figure 4.2b Moisture availability.

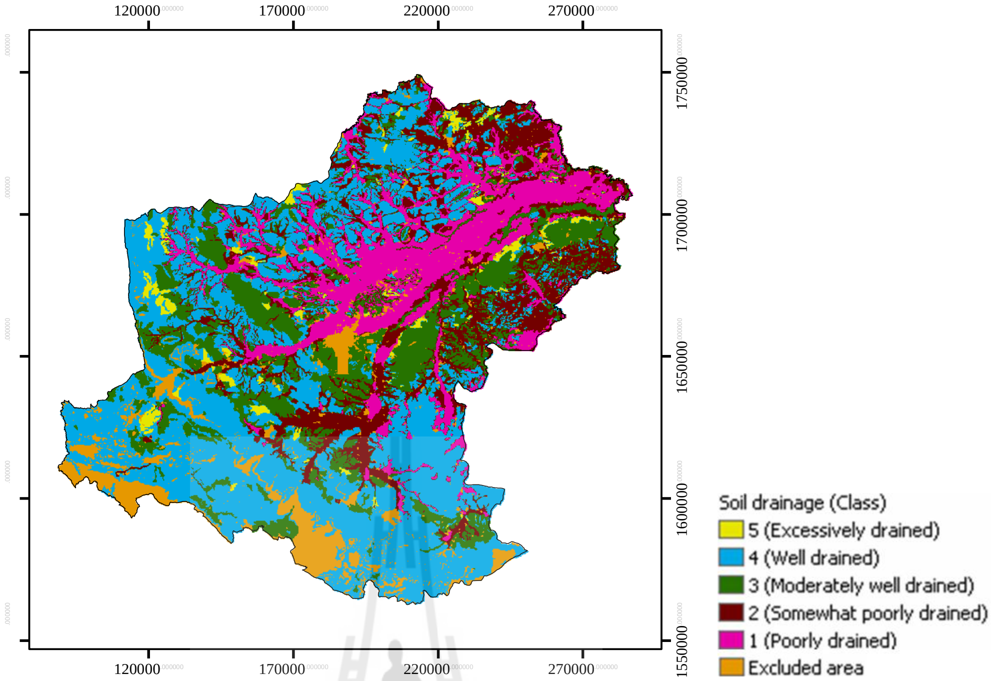


Figure 4.2c Oxygen availability map.

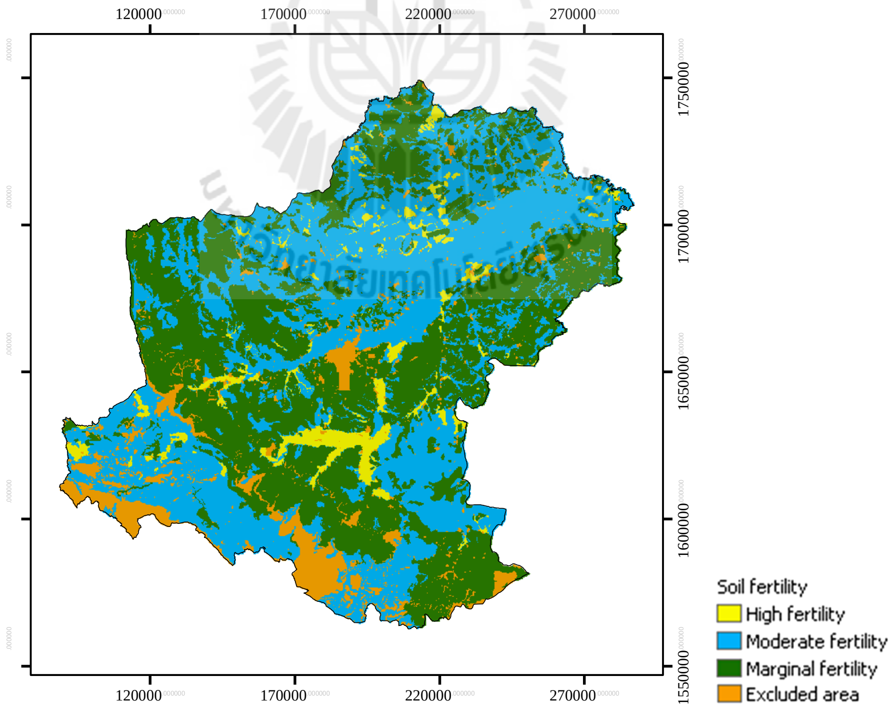


Figure 4.2d Soil fertility map.

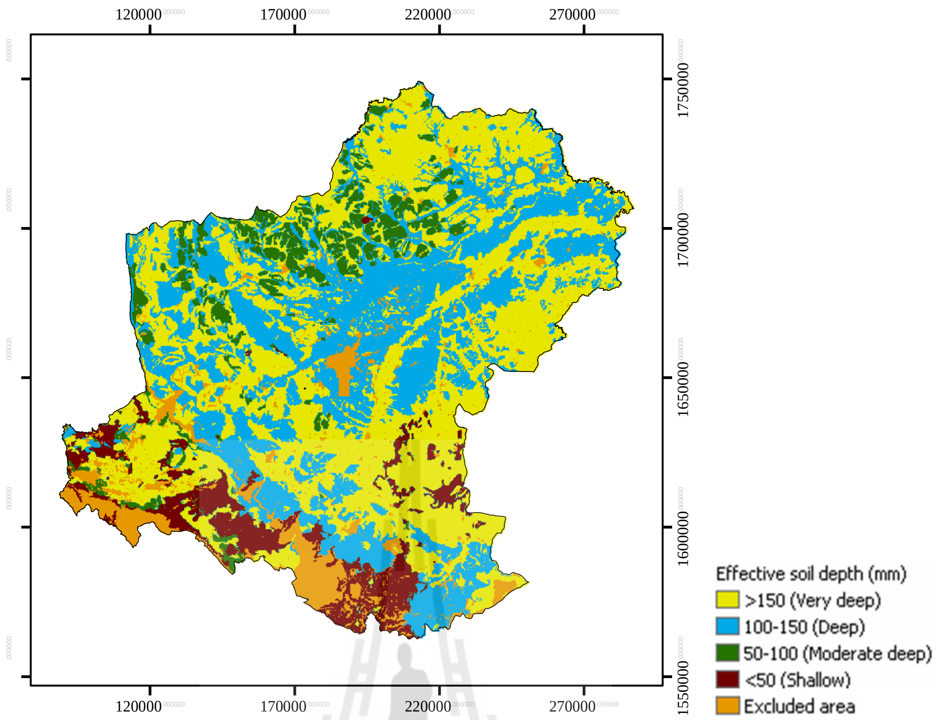


Figure 4.2e Rooting condition map.

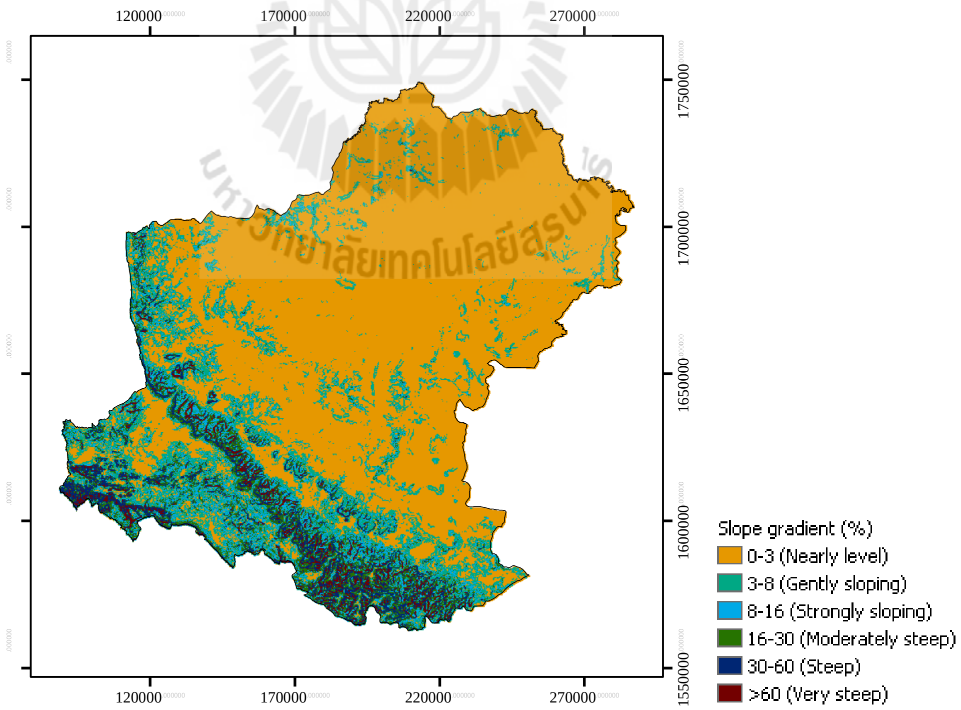


Figure 4.2f Potential for mechanization map.

4.2.1 Construction of the criterion map

The aforementioned land quality maps portrayed in Figures 4.2 (a)-(f) were then used as a reference for the determination of the land suitability level at each unit area (i.e., a pixel with size of 25x25 m^2) for each crop. The criterion maps (in raster format) for cassava, sugarcane and maize were presented in Figures 4.3-4.5, respectively. These maps were constructed by comparing the specific requirements of each crop to land quality characteristics (as detailed in Tables 3.1-3.3). The suitability conditions were taken to be S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable) as suggested by the FAO land evaluation guideline stated earlier in Chapter 3. Systematic combination of the suitability degree from each relevant factor indicates suitability level of the study area.

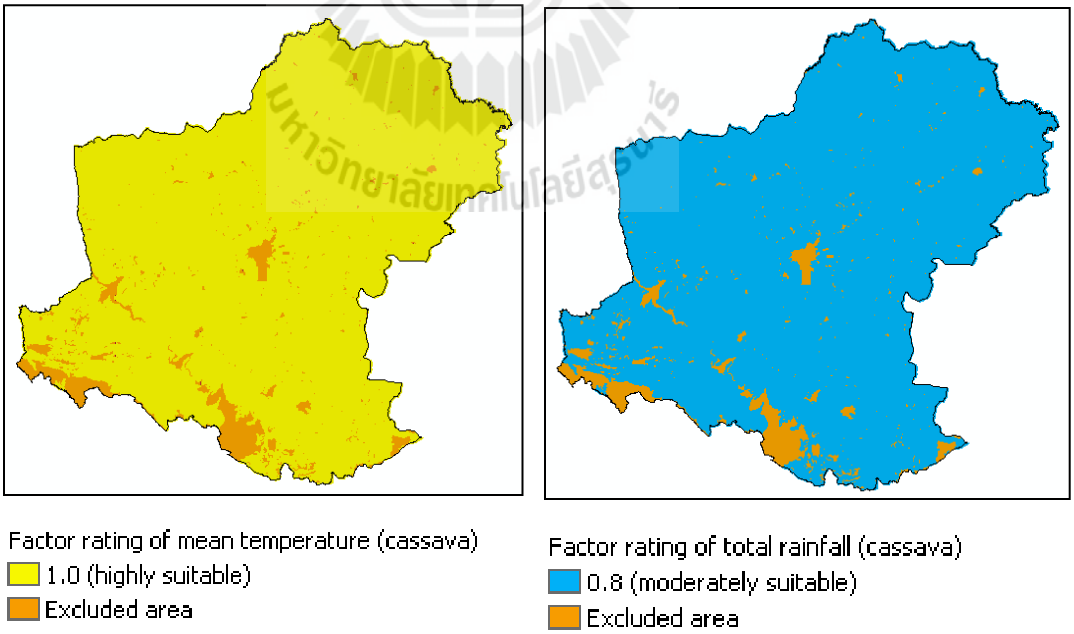


Figure 4.3 Criterion maps for land suitability assessment for cassava.

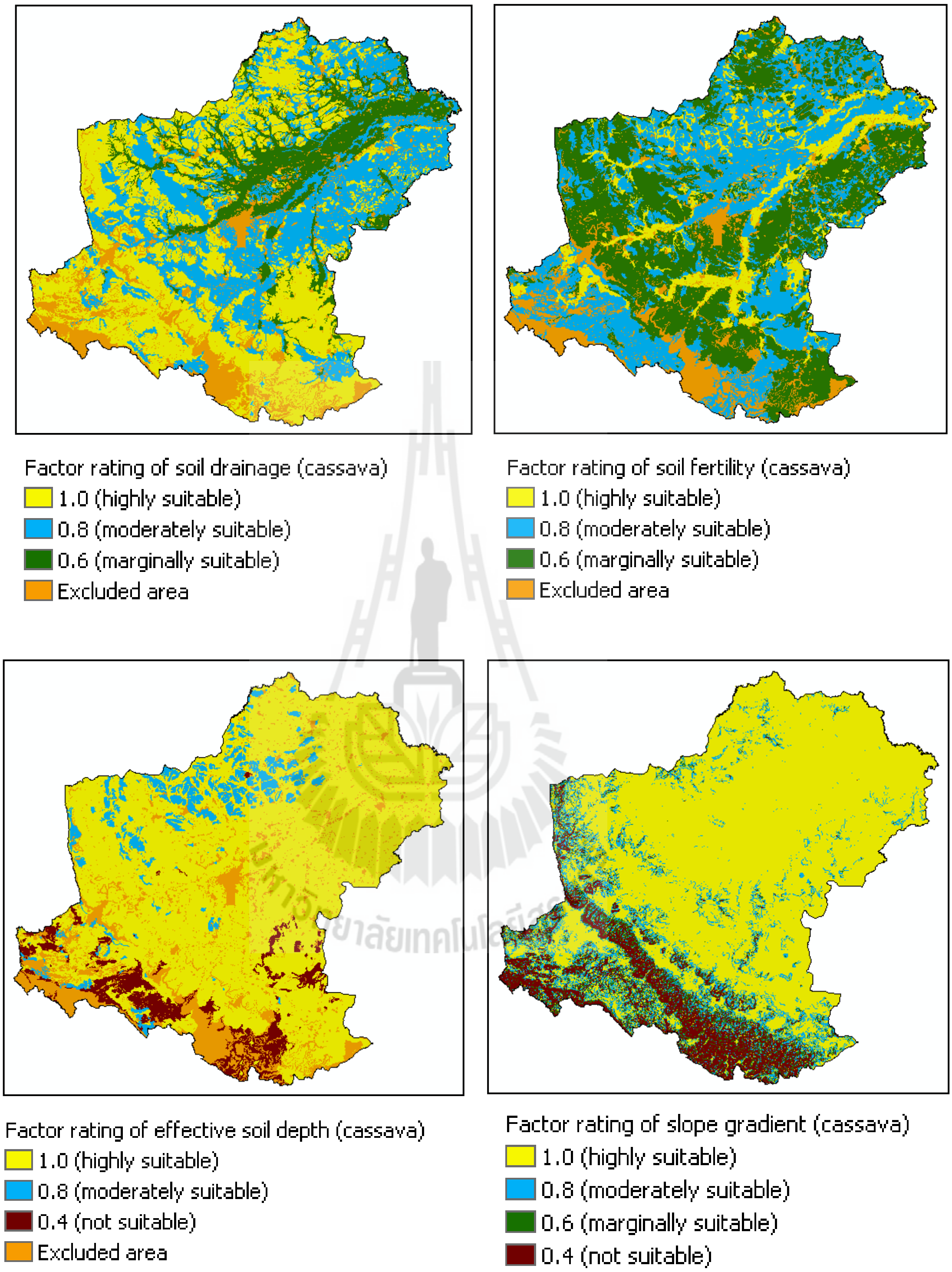


Figure 4.3 (Continued).

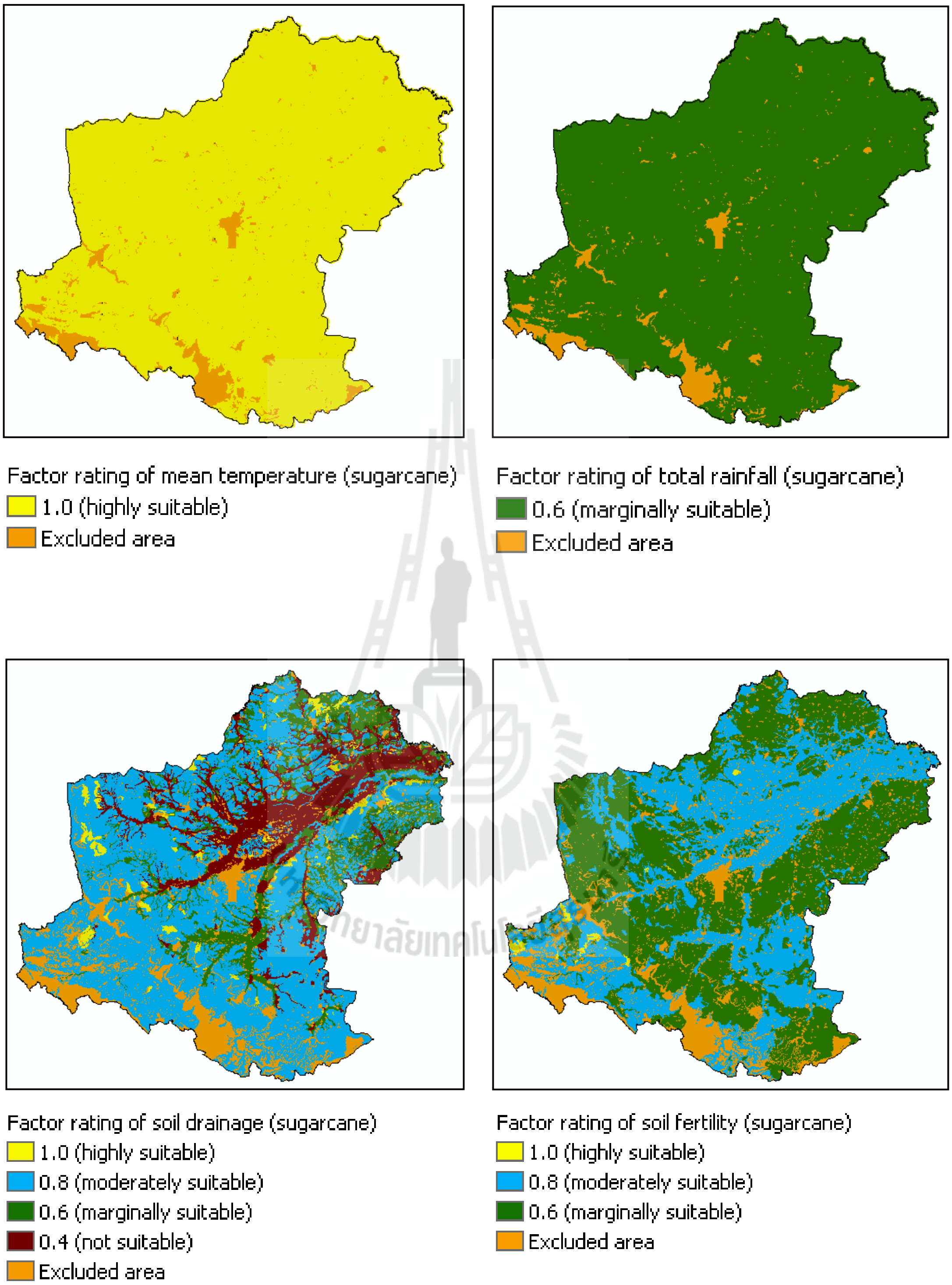


Figure 4.4 Criterion maps for land suitability assessment for sugarcane.

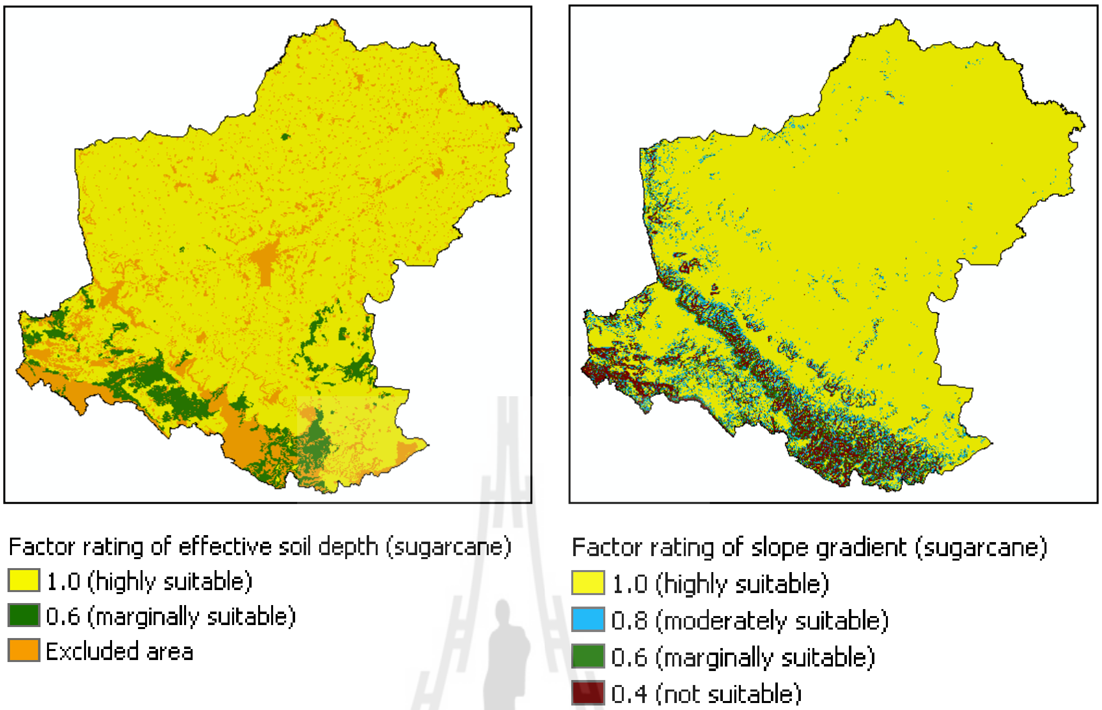


Figure 4.4 (Continued).

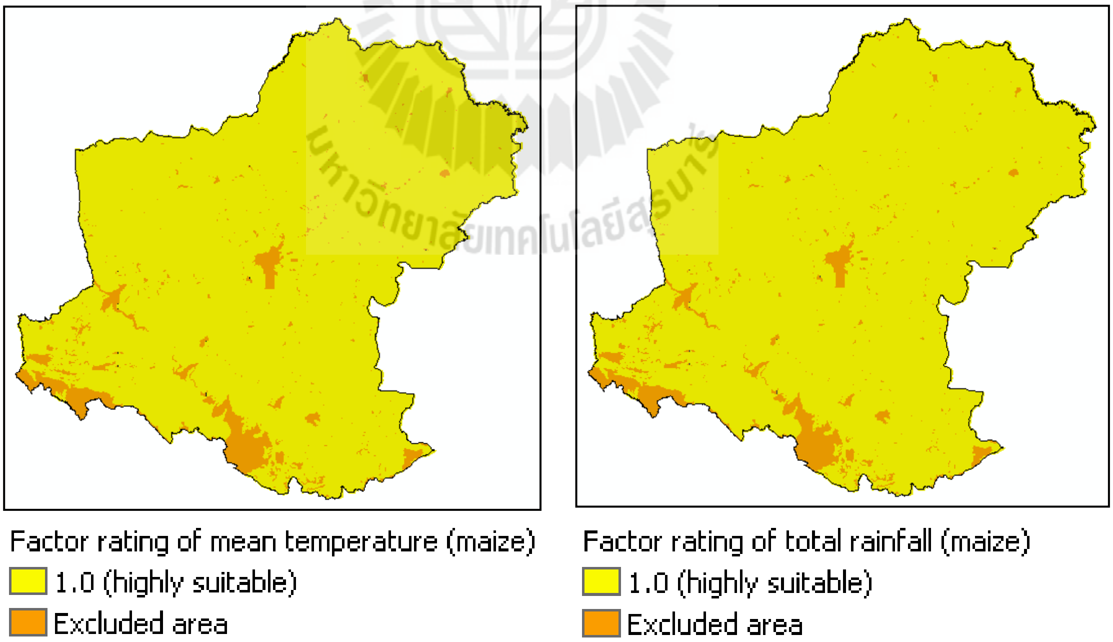


Figure 4.5 Criterion maps for land suitability assessment for maize.

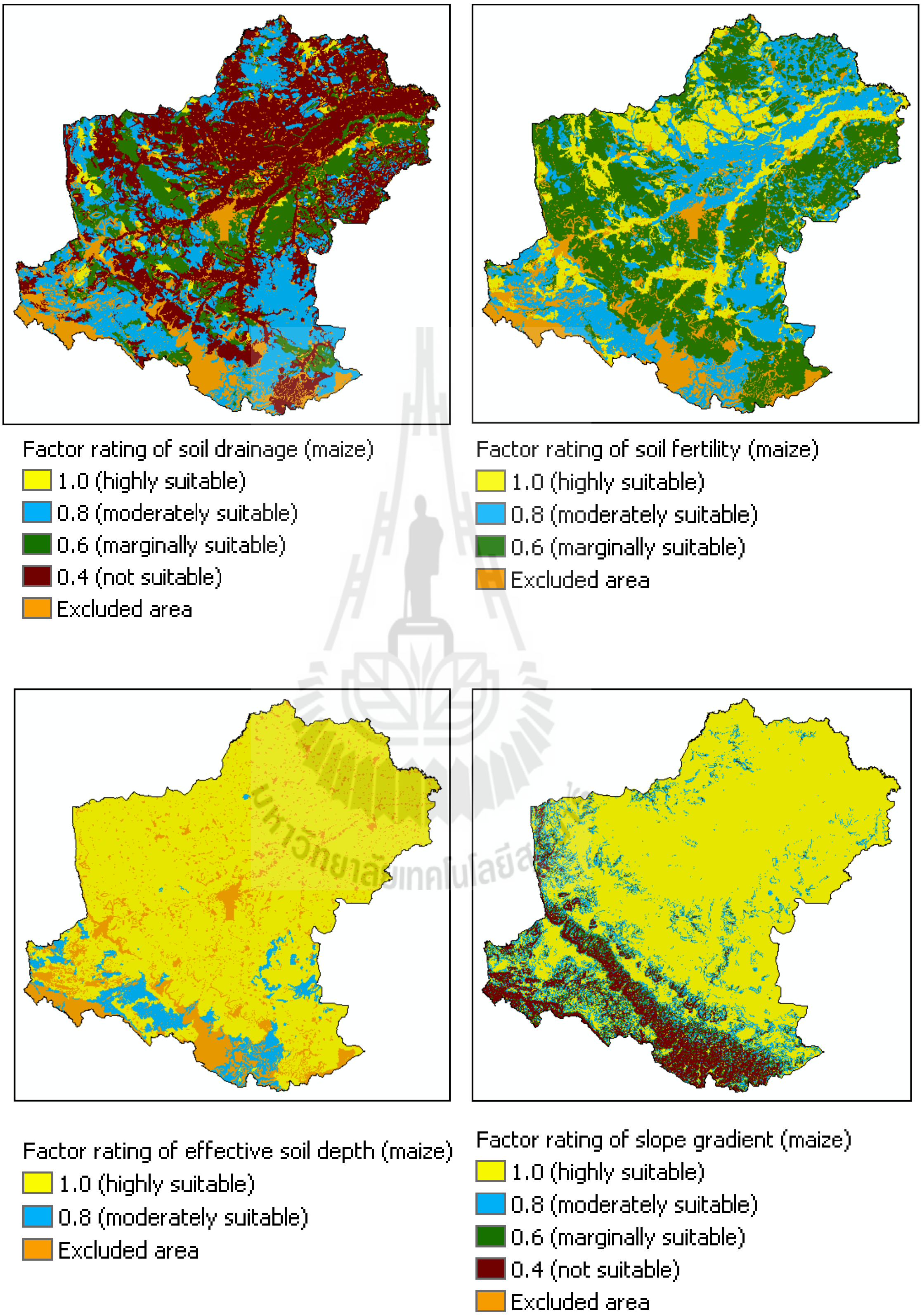


Figure 4.5 (Continued).

Table 4.3 Main components of land suitability for each crop.

Crop	Considered factor					
	Temperature	Rainfall	Soil drainage	Soil fertility	Effective soil depth	Slop gradient
Cassava	S1	S2	S1/S2/S3	S1/S2/S3	S1	S1/N
Sugarcane	S1	S3	S2/N	S2/S3	S1	S1/N
Maize	S1	S1	S2/S3/N	S1/S2/S3	S1	S1/N

From the result in Table 4.3, it can be concluded that temperature and effective soil depth are most suitable for cultivating all three crops in the province while slope gradient is also a most supportive factor in general except over relatively high area in the vicinity of the mountains ranges in the lower south which was found not suitable (N) for planting the crops. Shortage of rainfall causes problem for sugarcane the most (S3) and for cassava to a lesser degree (S2) but it is not a cause for concern for maize (S1). The other two factors, soil drainage and soil fertility, are the main limiting resources for all three crops in most areas (S2/S3/N). Here, soil drainage was a main concern for the growing of all three crops over some particular area (S3/N) especially in the lowland close to major rivers, which could be most detrimental to the growing of maize. Similarly, low soil fertility was also a problem for all crops (S2/S3) only in some parts were found most suitable to grow maize (and cassava) (S1). This conclusion supports the perception that agricultural land in the province still needs more improvement in terms of its essential quality to support sustainable and productive cultivation of the concerned economic crops in long-term basis, especially, water and soil fertility.

4.2.2 Land suitability map

From the land suitability determination process described in Section 3.2, the modified total suitability score (or MTSC as defined in Eq. 3.2) for each individual land unit (pixel-based) was calculated and the final land suitability map for each particular crop was produced as presented in Figures 4.6 (cassava), 4.7 (sugarcane), and 4.8 (maize), respectively. Table 4.4 provides proportion for each suitability category for each crop at provincial level, while this information at the district level is reported in Appendix C. It was found that, out of 17,758 km^2 of provincial area, sugarcane is the most grown crop with highest percentage of land in both high (S1) and moderate (S2) suitability classes (at 19.94% and 44.23%), and cassava is the second favorite crop with percentage in S1 and S2 classes of 15.44% and 30.87%. Maize is the least grown crop with highly suitable land covers just 7.49% while 51.76% was classified as marginally suitable. Comparing the suitability results from this study with results from Albab (1995) in Pak Chong district, Nakhon Ratchasima Province, the maximum of highly suitable area was sugarcane (23.73% of the district) followed by cassava (21.23% of the district) and the least was maize (9.08% of the district). Similar result was found in this study, sugarcane had the maximum highly suitable area (47.33% of the district) followed by cassava (23.16% of the district) and maize had the least amount (15.73% of the district). In case of moderately suitable area, maize had the maximum of moderately suitable area (57.70% of the district) followed by sugarcane (43.09% of the district) and the least was maize (35.75% of the district). While, in this study, sugarcane had the maximum of marginally suitable area (36.58% of the district) followed by maize (31.67% of the district) and the least was cassava (22.80%).

Table 4.4 Classified suitability land for cassava, sugarcane, and maize.

Suitability class	MTSC score range	Cassava		Sugarcane		Maize	
		km^2	%	km^2	%	km^2	%
High (S1)	0.8-1.0	2,742.23	15.44	3,540.95	19.94	1,329.98	7.49
Moderate (S2)	0.6-0.8	5,482.24	30.87	7,853.72	44.23	3,271.56	18.42
Marginal (S3)	0.4-0.6	6,406.09	36.07	5,518.04	31.07	9,191.64	51.76
Not suitable (N)	0.0-0.4	3,127.63	17.61	845.48	4.76	3,965.01	22.33
Total area		17,758.19	100.00	17,758.19	100.00	17,758.19	100.00
Average suitability (cassava)		(1.0)·(0.1544) + (0.8)·(0.3087) + (0.6)·(0.3607) + (0.4)·(0.1761) = 0.6882					
Average suitability (sugarcane)		(1.0)·(0.1994) + (0.8)·(0.4423) + (0.6)·(0.3107) + (0.4)·(0.0476) = 0.7587					
Average suitability (maize)		(1.0)·(0.0749) + (0.8)·(0.1842) + (0.6)·(0.5176) + (0.4)·(0.2233) = 0.6221					

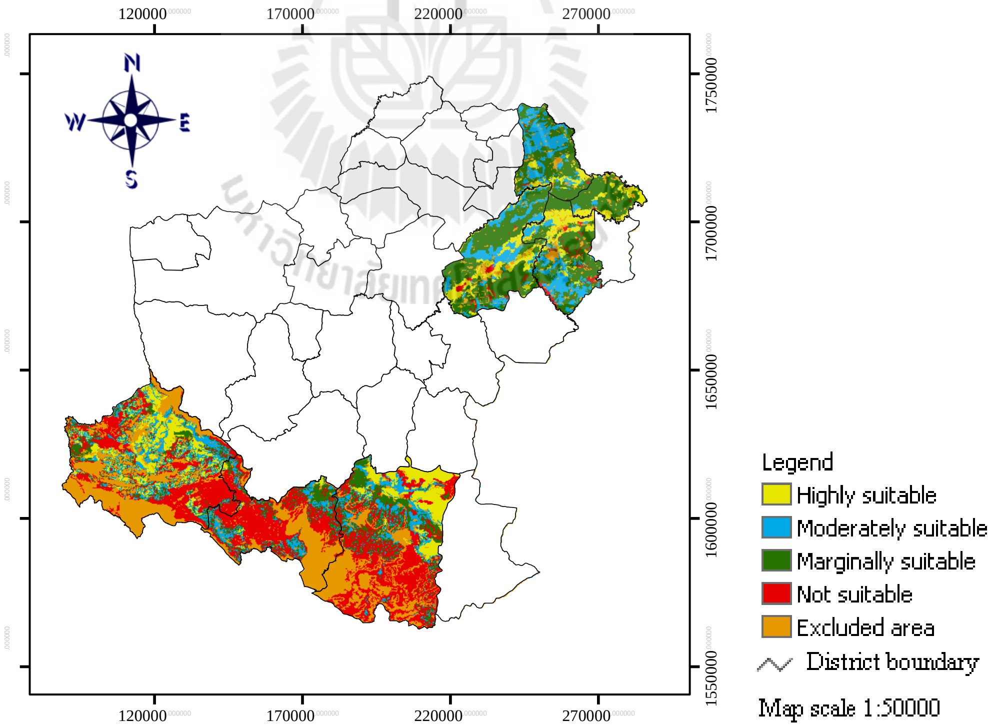


Figure 4.6 Land suitability map for cassava cultivation.

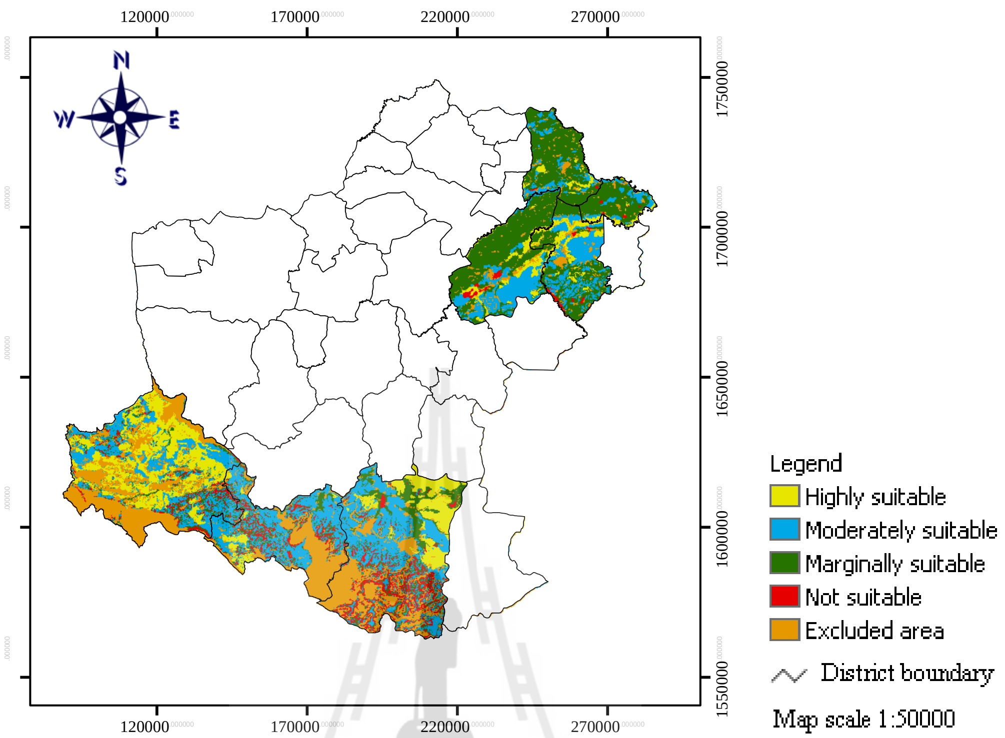


Figure 4.7 Land suitability map for sugarcane cultivation.

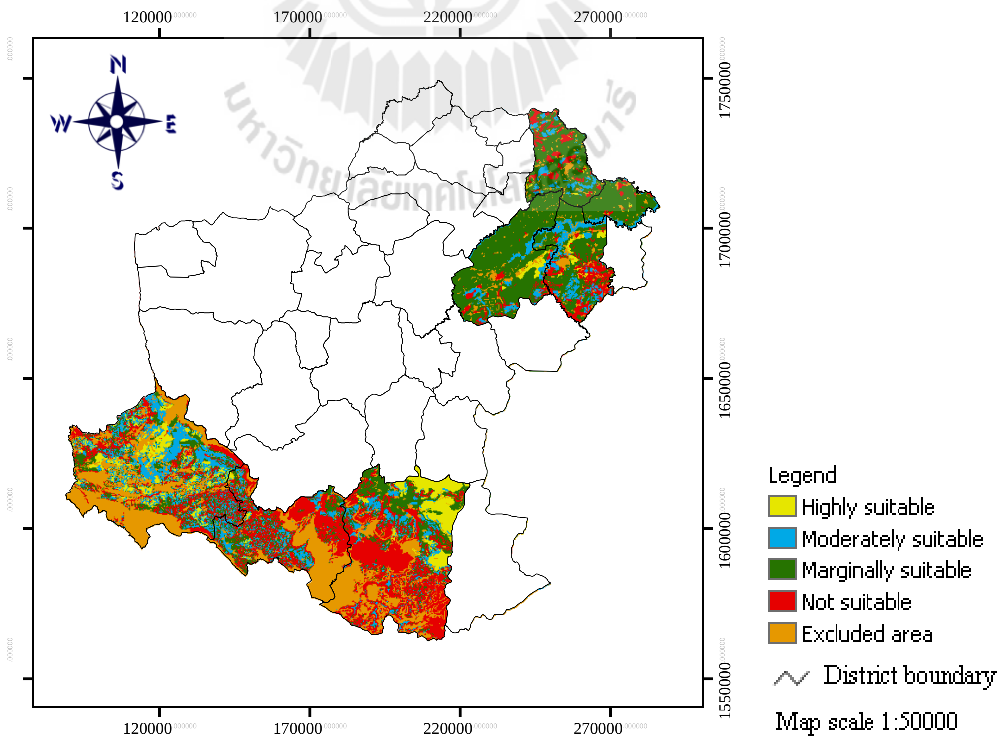


Figure 4.8 Land suitability map for maize cultivation.

A weighted suitability for each crop is suggested as shown Table 4.4. It can be said that in general three crops were moderately suitable to plant in the province with respective scores of 0.7587 (sugarcane), 0.6882 (cassava), and 0.6221 (maize). These scores may be useful for authorities in recommending the suitable choice of crops in general. However the specific land suitability map for each crop should be used whenever possible.

4.2.3 Composite land suitability map

To aid farmers in choosing appropriate crop for their land the composite land suitability map for all three crops was constructed as shown in Figures 4.9 (a) and (b). Simple suggestion is that a particular plot of land should be devoted to crops most suitable for the area (i.e., those in the S1 class) while crops with second-best suitability (S2 class) should have a second priority. It was evident from these composite maps that the most suitable lands (S1) for all three crops concentrate mostly in the southeastern region, over an area of four associated districts (Khon Buri, Soeng Sang, Nong Bunnak, Chok Chai) while the marginally suitable (S3) was found mostly over the lowland close to the main river network, due mostly to its poor drainage capacity (Figure 4.2c) but it is considered highly suitable for rice plantation. And the least fertile land (N) for all crops is mostly clustered over region of rough terrain in vicinity of high mountains in the far south of the province. Apart from these aforementioned zones, most other areas were considered rather suitable (S2) for each crop, especially for sugarcane whose moderately suitable land covers about 44.23% of the total land area under consideration (Figure 4.7). However, it should be noted that the development of land suitability map for each crop presented so far was based principally on long-term average data of the input parameters, especially the climate data, this makes them become virtually static suitability map which might not respond well to the rapid, or gradual, changes in characteristics of some input data, especially rainfall. This deficiency should be adjusted in further work.

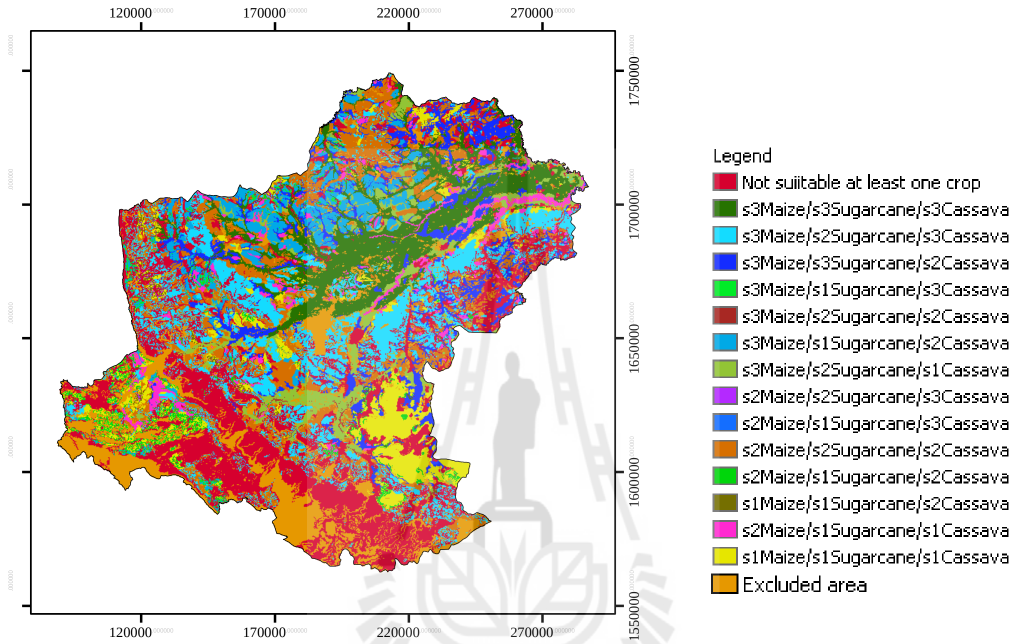


Figure 4.9a Composite suitability areas for cassava, sugarcane, and maize cultivation.

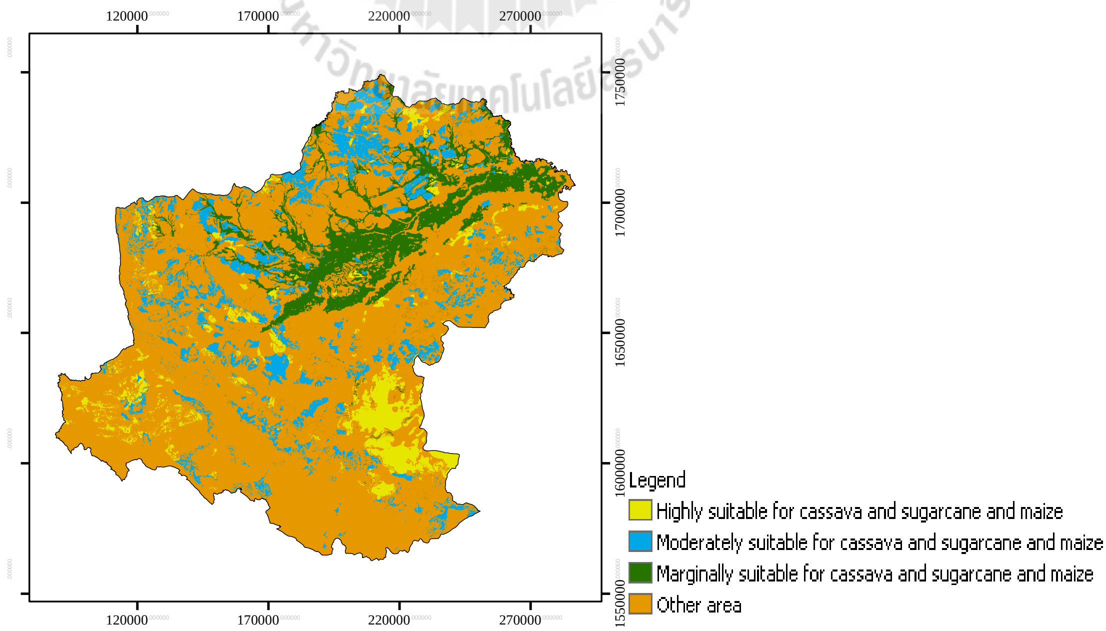


Figure 4.9b Joint three levels of land suitability (S1, S2, S3) for all three crops.

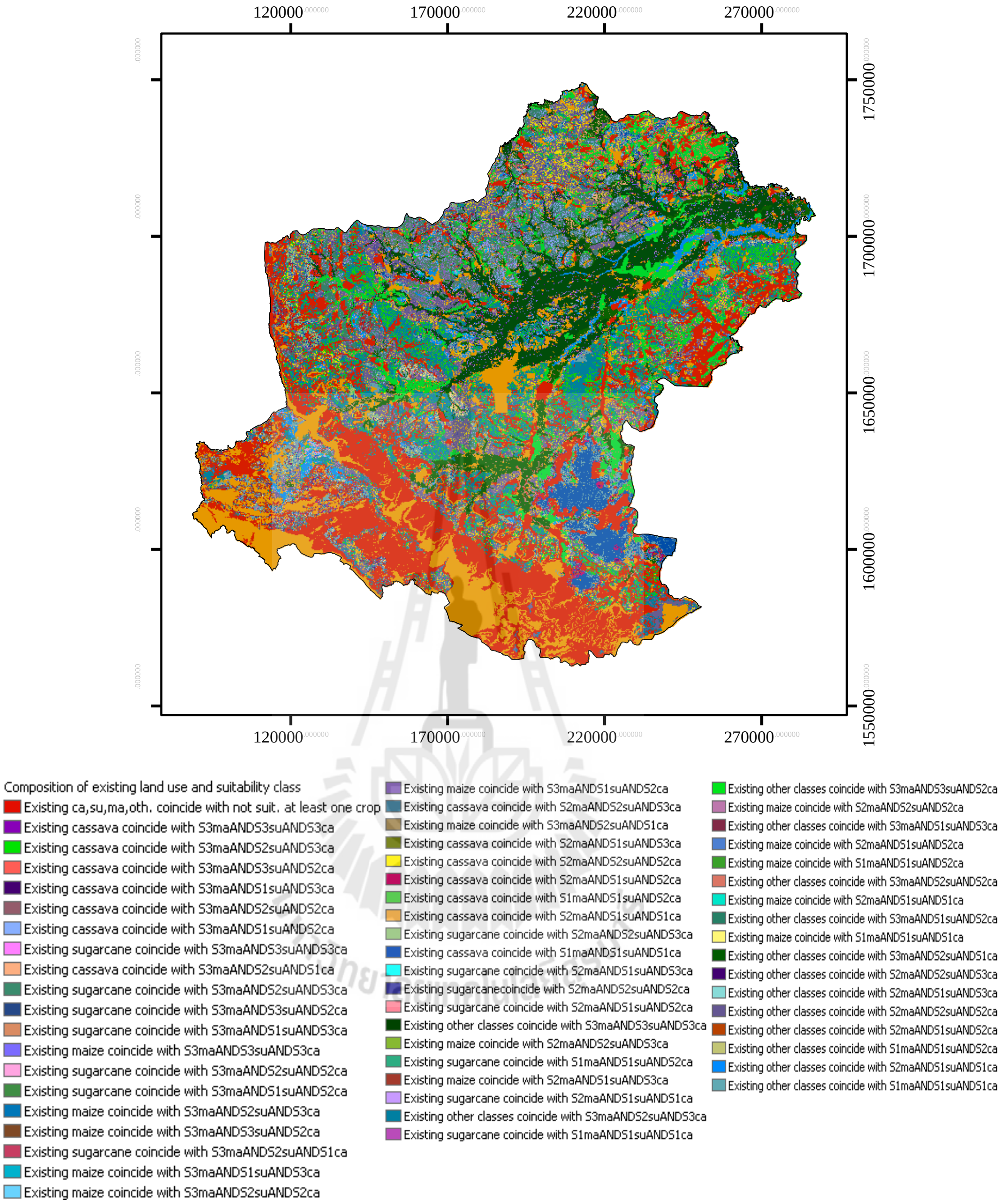


Figure 4.9c Composition of classified crop map in 2006 and land suitability maps.

Comparing the LULC proportion in 2006 listed in Table 4.1 with the most suitable area in Table 4.4, it was found that the most popular crop in that year was cassava (3,606.66 km^2) followed by maize (1,227.97 km^2) and sugarcane (987.99 km^2), while for an amount of highly suitable land (S1), sugarcane was the most favorite (3,540.95 km^2) followed by cassava (2,742.23 km^2) and then maize (1,329.98 km^2). This suggests that sugarcane was the least preferable crop in that year for farmers in the province although more land is suitable for the crop, while cassava was far more popular. As a result, in terms of the land quality, implication for policy maker is that sugarcane should be the publicly promoted with the consideration of economic return and trading regulations allowed.

In addition, the proper use of land for planting each crop in the year 2006 was indicated by overlap area (or coincided area) between existing areas with their suitability classes as demonstrated in Figure 4.9 (c) (composition of classified crop map in 2006 and land suitability map) and Table 4.5a-c. According to Table 4.5a-c, crop selection for each area was found not well match, for example, the total S1 area of 2,742.23 km^2 for cassava, only 741.56 km^2 (or 27.04%) was used for planting it and the majority of 72.96% was used for other activities. The same situation was also evidenced for sugarcane and maize (for the worse) in which only 6.70% (for sugarcane) and 5.11% (for maize) were used for planting them that year, respectively, while about 28.63% of the total S1 area for sugarcane and 47.43% for maize were devoted to cassava instead. This means that farmers in the province do not know which crops best suits their land or do not pay much attention to the importance of inherent land quality suitability in making decision on which crop to be grown in each area. The expected net benefit, varied year by year as shown in Table 4.6 for example, as return from their crop production might be more of a concern to them as a crucial source of income for the family. However, sugarcane should be publicly promoted as the net benefit can be increased by increasing the productivity (average yield per rai). The productivity of sugarcane can be increased not only by growing in suitability area (sugarcane had the maximum of most suitable areas) but also by providing supplementary irrigation.

Table 4.5a Crop planting information on the classified S1, S2, S3, and N land suitability maps (cassava).

SUIT class	Area	LULC class							
		CAS	SGC	MAZ	OTH	FOR	U/B	WAT	Total
S1	km^2	741.56	108.74	146.26	1509.10	132.84	82.92	20.68	2742.23
	%	27.04	3.97	5.33	55.03	4.84	3.02	0.75	100.00
S2	km^2	966.26	369.65	466.18	3142.76	359.61	167.07	10.60	5482.25
	%	17.63	6.74	8.50	57.33	6.56	3.05	0.19	100.00
S3	km^2	986.04	340.97	407.09	3867.27	537.55	251.71	15.36	6406.09
	%	15.39	5.32	6.35	60.37	8.39	3.93	0.24	100.00
N	km^2	582.89	88.56	147.20	1000.03	1269.31	46.13	3.53,	3137.81
	%	18.58	2.82	4.69	31.87	40.45	1.47	0.11	100.00
Total	km^2	3276.75	907.91	1166.73	9519.16	2299.31	547.82	50.17	17758.19
	%	18.45	5.11	6.57	53.60	12.95	3.08	0.28	100.00

Table 4.5b Crop planting information on the classified S1, S2, S3, and N land suitability maps (sugarcane).

SUIT class	Area	LULC class							
		CAS	SGC	MAZ	OTH	FOR	U/B	WAT	Total
S1	km^2	1013.77	237.29	332.84	1608.44	242.97	91.00	15.13	3541.54
	%	28.63	6.70	9.40	45.41	6.86	2.57	0.43	100.00
S2	km^2	1611.84	506.72	513.12	3808.97	1181.36	219.99	11.59	7853.72
	%	20.52	6.45	6.53	48.50	15.04	2.80	0.15	100.00
S3	km^2	567.34	152.96	293.72	3811.02	443.34	227.19	22.38	5518.05
	%	10.28	2.77	5.32	69.06	8.03	4.12	0.41	100.00
N	km^2	83.22	10.54	26.53	289.81	425.49	9.24	0.64	845.48
	%	9.84	1.25	3.14	34.28	50.33	1.09	0.08	100.00
Total	km^2	3276.16	907.52	1166.21	9518.23	2293.16	547.42	49.74	17758.19
	%	18.45	5.11	6.57	53.60	12.91	3.08	0.28	100.00

Table 4.5c Crop planting information on the classified S1, S2, S3, and N land suitability maps (maize).

SUIT class	Area	LULC class							
		CAS	SGC	MAZ	OTH	FOR	U/B	WAT	Total
S1	km^2	630.84	54.01	67.93	459.33	84.56	32.13	1.12	1329.98
	%	47.43	4.06	5.11	34.54	6.36	2.42	0.08	100.00
S2	km^2	648.69	230.05	236.52	1726.96	297.39	115.45	15.66	3270.82
	%	19.83	7.03	7.23	52.80	9.09	3.53	0.48	100.00
S3	km^2	1351.25	485.36	652.58	5752.37	592.15	328.78	28.48	9191.09
	%	14.70	5.28	7.10	62.59	6.44	3.58	0.31	100.00
N	km^2	645.75	138.38	209.25	1579.68	1320.93	72.44	5.16	3971.68
	%	16.26	3.48	5.27	39.77	33.26	1.82	0.13	100.00
Total	km^2	3276.53	907.81	1166.27	9518.34	2295.03	548.80	50.42	17758.19
	%	18.45	5.11	6.57	53.59	12.92	3.09	0.28	100.00

Table 4.6 Net benefit of crop production (cassava, sugarcane, maize) in 2010-2012.

Year	Crop	Average yield (kg/rai)	Cost (baht/ton)	Price (baht/ton)	Net benefit (baht/ton)	Net benefit (baht/rai)
2010	Cassava	2,972	1,616	1,840	224	665.73 (3)
	Sugarcane	10,905	861	965	171	1,864.76 (1)
	Maize	650	5,549	8,130	2,581	1,677.65 (2)
2011	Cassava	3,088	1,682	2,680	998	3081.82 (1)
	Sugarcane	12,192	908	945	245	2987.04 (2)
	Maize	677	5,692	7,630	1,678	1136.01 (3)
2012	Cassava	3,419	1,798	2,090	292	998.348 (3)
	Sugarcane	12,280	954	900	243	2984.04 (1)
	Maize	674	8,354	9,410	3,056	2059.744 (2)

Note: Maize can be grown two times per year (Figure 3.5).

Source: Office of Agricultural Economics (2013).

4.3 Water management for selected farmland

As described in Chapter 3, work in this part focuses principally on the conceptual design of a farm pond to supply water to all concerned crops planted in the selected area. The achieved results are as follows.

4.3.1 Crop water requirement (CWR)

Total amount of water requirement (CWR) for the entire growing season of each crop was determined from monthly ET_{crop} during its growing season as illustrated in Table 4.7 and Figure 4.10. This requirement is principally fulfilled by two water sources as presented in Eq. 3.15, i.e., rainfall (in terms an effective rainfall) and supplementary water. In terms of the ET_{crop}, it was found that both cassava and sugarcane need water the most during the monsoon months of the province (May-

October) which covers the middle and peak growing stages of both crops regarding crop calendar shown earlier in Table 3.5. While peak demand for water of maize was evident in two periods in accordance with its two planting seasons per year, i.e., June-July and December-January. Sugarcane and maize were found having comparable total need water each year at 936.6 mm and 934.8 mm respectively, while cassava requires considerably less, at 767.6 mm.

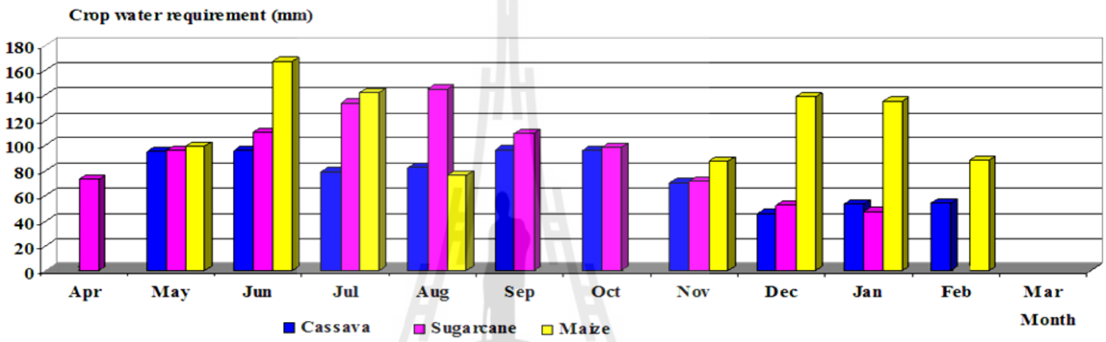


Figure 4.10 Monthly distribution of the water requirement (ET_{crop}) for each crop.

Note: Maize has two planting seasons in one year.

Table 4.7 Monthly ET_{crop}, effective rainfall and net IWR

Crop	Monthly ET_{crop} (mm) (average 30 years for climate data)												Total (mm)
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
Cassava	0.0	94.9	95.9	78.9	82.0	96.4	96.1	70.3	46.0	53.0	54.1	0	767.6
Sugar-cane	73.3	96.3	110.2	133.2	144.7	109.5	98.4	71.4	52.2	47.4	0	0	936.6
Maize	0	99.2	167.2	142.2	76.0	0	0	87.8	138.9	135.4	88.1	0	934.8
Total	73.3	290.4	373.3	354.3	302.7	205.9	194.5	229.5	237.1	235.8	142.2	0	2639.0
Monthly effective rainfall in 2001/2002													
Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Total (mm)
Rainfall (mm)	1.2	68.5	30.1	24.6	59.9	68.9	49.2	0	0	0	0	42.8	345.2
Monthly net irrigation water requirement (net IWR) in 2001/2002 (mm)													
Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Total (mm)
Cassava	0	26.5	65.8	54.3	22.1	27.5	46.9	70.3	46.0	53.0	54.1	0	466.5
Sugar-cane	72.1	27.9	80.1	108.6	84.8	40.6	49.2	71.4	52.2	47.4	0	0	634.3

Maize	0	30.7	137.1	117.6	16.1	0	0	87.8	138.9	135.4	88.1	0	751.7
Total	72.1	85.1	283.0	280.5	123.0	68.1	96.1	229.5	237.1	235.8	142.2	0	1852.5

4.3.2 Optimum pond capacity

Following the procedure in section 3.4.2, a representative area was systematically selected. The results are presented in Figures 4.11 and 4.12. This area is located in the western part of Mueang Distict, with total area of 176,756.0 m^2 (17.676 ha or 110.47 rai) with sufficient stream network and actual crops planted.

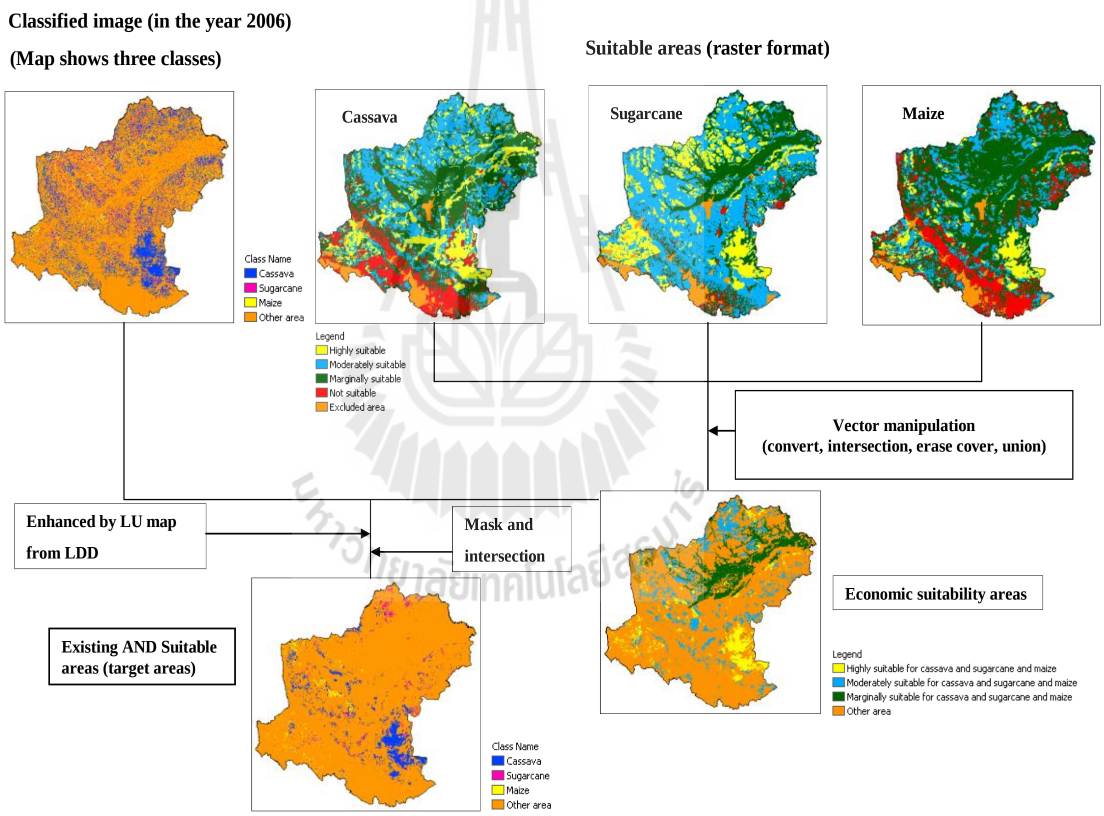


Figure 4.11 Representative area selection process.

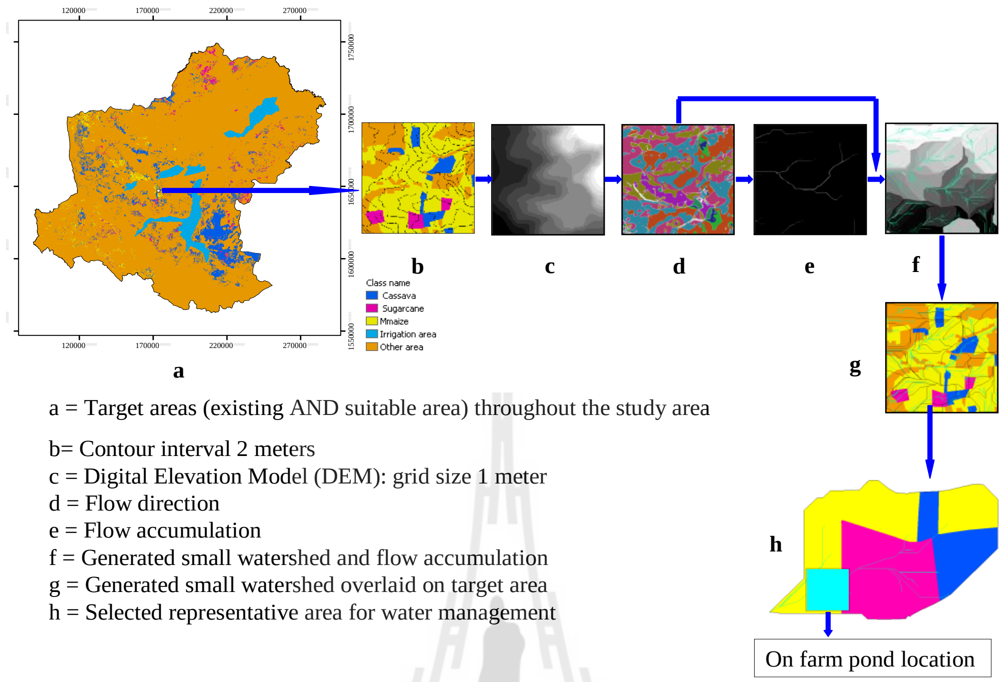


Figure 4.12 Selection process and detail of the representative area.

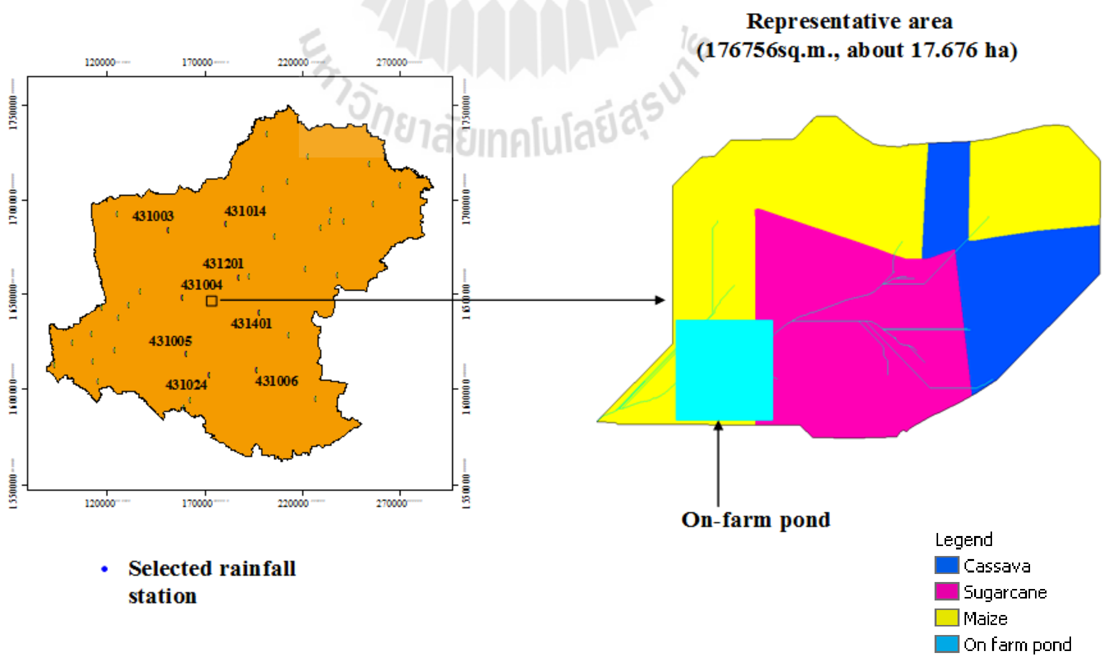


Figure 4.13 Location of the selected rainfall stations.

Table 4.8 ID and name of the applied rainfall stations.

Station ID	Station name
431201	Nakhon Ratchasima Meteorological Station
431401	Chokchai Meteorological Station
431003	Dan Khun Thot Rain Station
431004	Sung Noen Rain Station
431005	Pak Thong Chai Rain Station
431006	Khon Buri Rain Station
431014	Non Thai Rain Station
431024	Forestry Control Unit No.3 NMA, Pak Thong Chai District

The proposed square-shape pond was located at the downstream end of the watershed (representative area) to harvest runoff originated upstream (Figure 4.13 and Figure 4.16). The water stored in the pond shall be used to irrigate all three crops grown in the area in 2006,i.e., cassava = 30,444.30 m^2 (19.03 rai),
sugarcane = 57,706.61 m^2 (36.07 rai), and maize = 74,205.09 m^2 (46.38 rai). The initial size of the pond was taken as 120*120 m^2. Eight rainfall stations in the vicinity of the area were selected (as shown in Figure 4.13 and Table 4.8). The average annual rainfall of these stations during 1977-2006 were reported in Figure 4.14. Double mass curves of cumulative data were presented in Figure 4.15a-h. The slopes of these curves are the same which means that rainfall data from these stations are consistent.

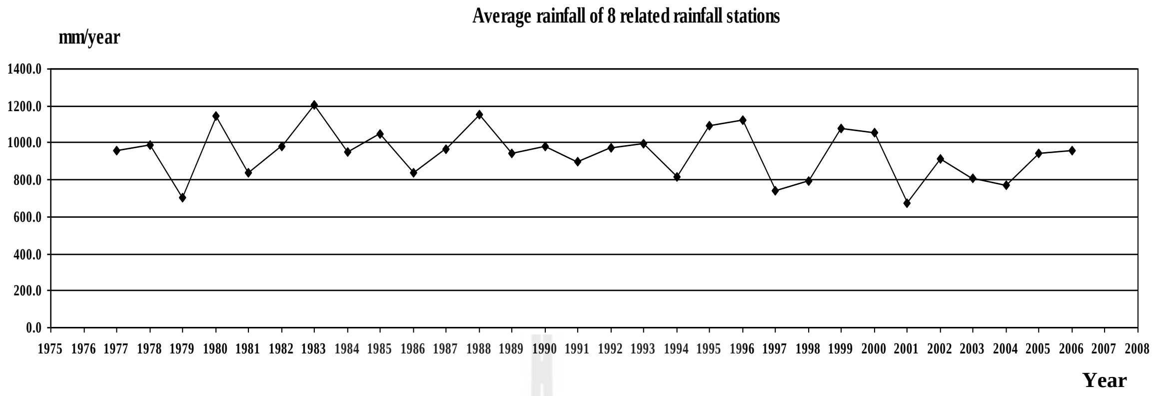
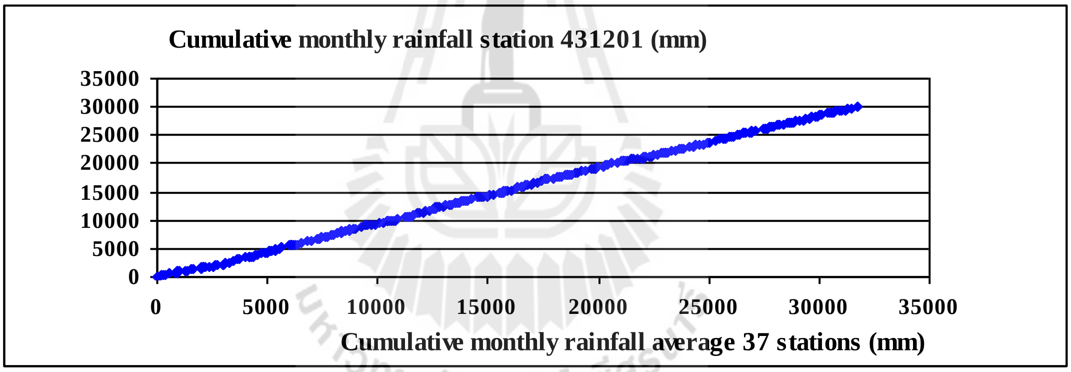
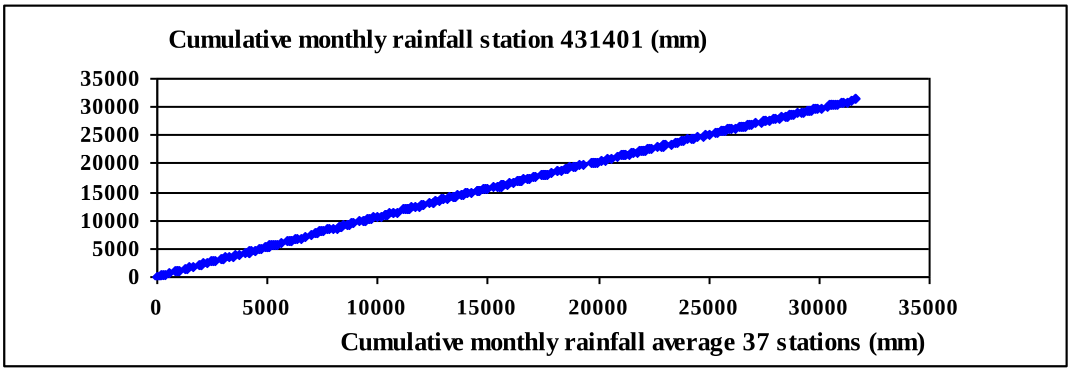


Figure 4.14 Variation of the average annual rainfall data of the representative area during 1977-2006 period and the driest year (2001) was chosen for further analysis.

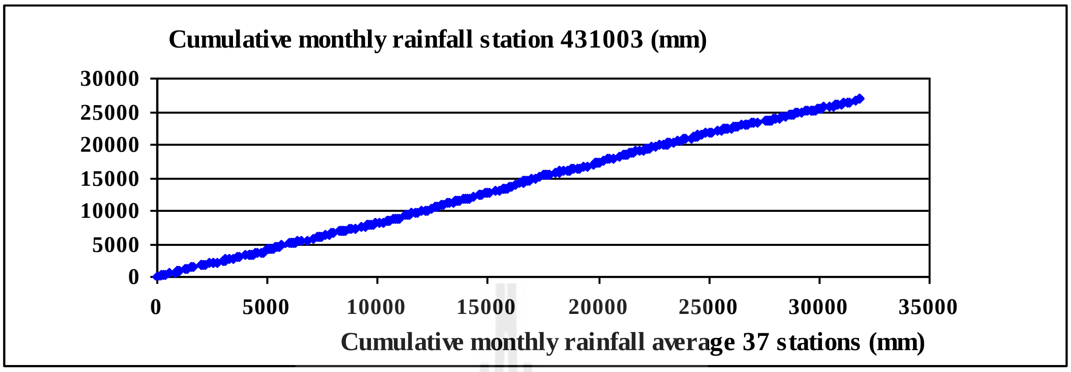


(a) Station 431201 (Nakhon Ratchasima Meteorological Station)

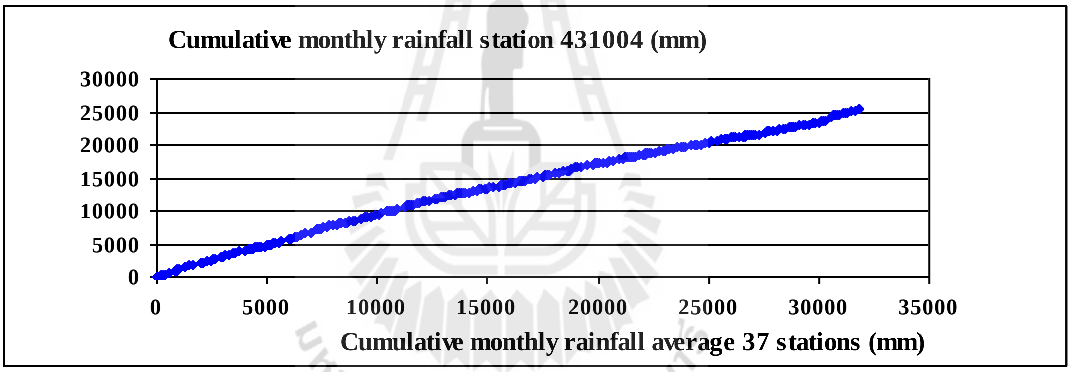


(b) Station 431401 (Chokchai Meteorological Station)

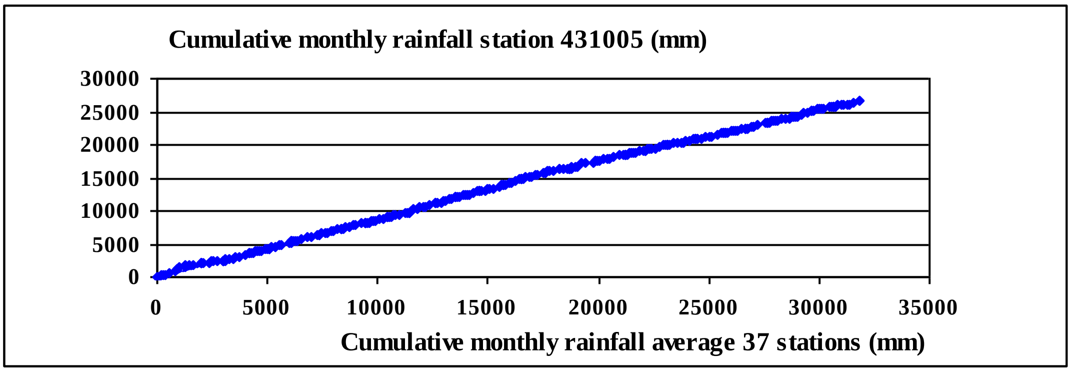
Figure 4.15 Consistency test of the historical monthly rainfall data (1977-2006).



(c) Station 431003 (Dan Khun Thot Rain Station)

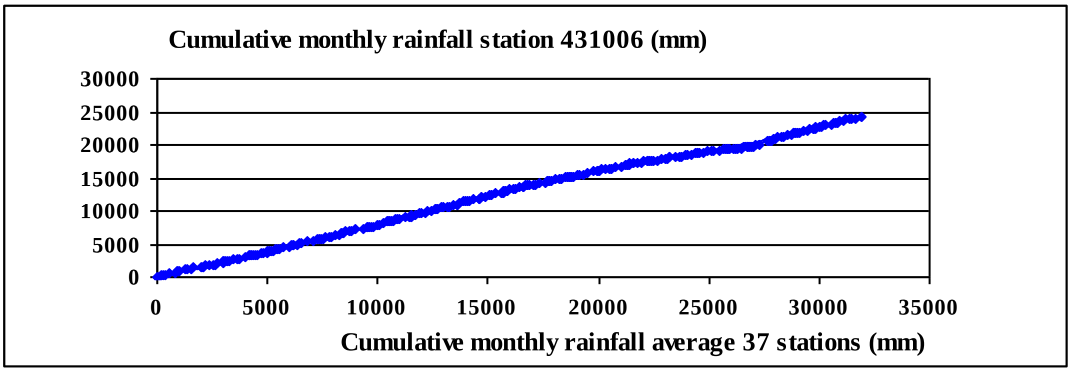


(d) Station 431004 (Sung Noen Rain Station)

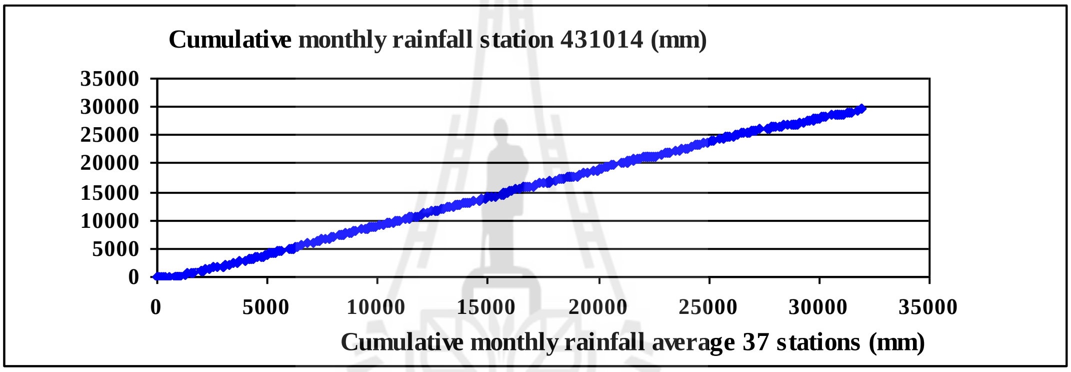


(e) Station 431005 (Pak Thong Chai Rain Station)

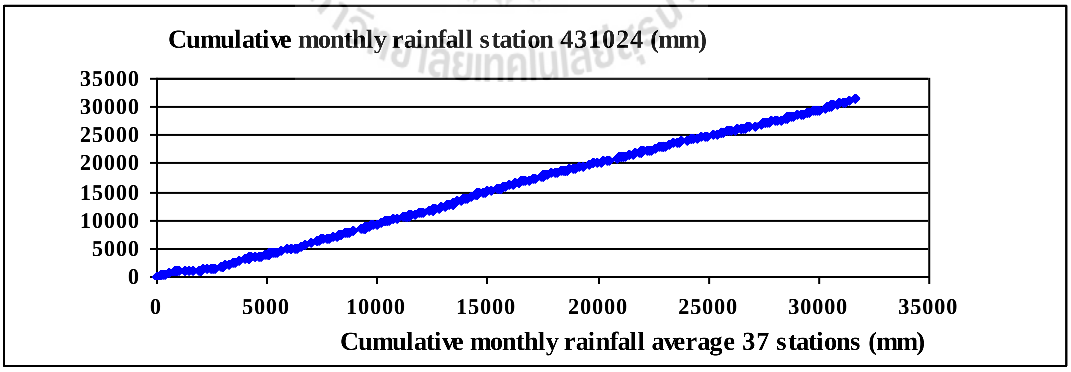
Figure 4.15 (Continued).



(f) Station 431006 (Khon Buri Rain Station)



(g) Station 431014 (Non Thai Rain Station)



(h) Station 431024 (Forestry Control Unit No.3 NMA, Pak Thong Chai District)

Figure 4.15 (Continued).

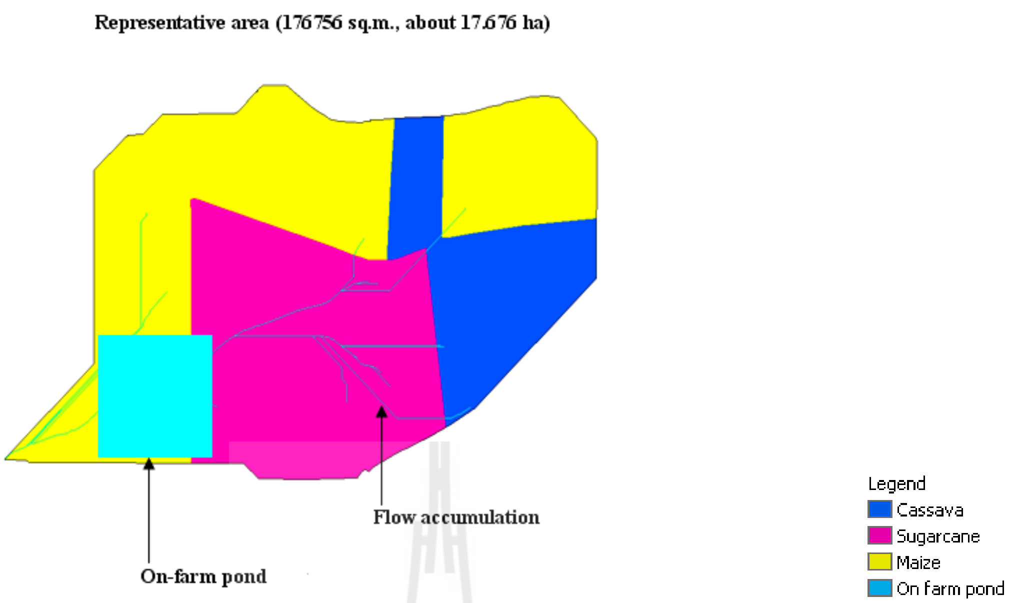


Figure 4.16 Details of LULC and location of the proposed farm pond.

Areal rainfall was calculated using Eq. 3.9 and, then, surface runoff, direct rainfall, and evaporation for the pond were calculated using Eq. 3.10, 3.15, and 3.18 respectively.

For the full irrigation scenario the total net irrigation requirement for all three crops were calculated from Eq. 3.19. Setting the initial pond storage as zero, successive monthly pond storage was calculated using Eq. 3.14. The results were reported in Table 4.9. A maximum storage deficit of 56,094.6 m^3 was obtained which was then used as the optimum capacity of the proposed farm pond to support full need for water (on monthly basis) of all the relevant crops.

For the 120m*120m cross-section this capacity requires a depth of 3.91m. To limit the maximum depth at 3 m. the cross-section must be increased to 137m*137m (10.62% of total representative area) (Figure 4.17). At this stage, optimum volume of the assumed pond was determined based on the water balance analysis for the pond in 2001 (the driest year) at full irrigation rate (or at the full demand of all studied crops each month) as reported in Tables 4.7 and 4.9. In this case, if starting with an empty pond in January, the accumulated water deficit seen in December (or annual year shortage) was appeared to stand at 56,094.6 m^3 which was then used as an optimal capacity of the proposed farm pond to support full need for water (on monthly basis) of all the relevant crops in that year. And as 2001 was the worst-case scenario of rainfall occurrence during 1977-2006, this identified capacity should also be applicable for serving total crop's water demand in other years with more rain for the area also.

As described in Table 4.7, total effective rainfall in 2001 was just 345.2 mm with four months of no effective rainfall at all and only 1.2 mm was available in April. This situation makes the need for irrigation water more severe, i.e. 751.7 mm for maize, 634.3 mm for sugarcane, and 466.5 mm for cassava. Irrigation supply were needed the most during most of November to February due to the seriously lack of effective rainfall (0 mm) while demand for water are still rather high (especially for maize). Similarly, demand for water was also found highest during the months of June and July due to the notable drop in total amount of the effective rainfall on those months (typical characteristics of rainfall data in the area as shown in Table 4.14). Only in March that no shortage appeared due to no crops in the field.

It should be noted that, surface area of the pond proposed in this case (about 10.62% of the total area) is still rather low compared to one suggested in the New Theory of Agriculture addressed in Chapter I (about 30%). This is because the latter number was introduced to enable the pond to provide sufficient water to all activities, especially rice cultivation and household use, not only for economic crop planting like one assumed in this study. However, if the amount of total water demanded (for all activities) for each month is known, similar process can be carried out to identify the appropriate volume and size of pond as demonstrated in this work.

Table 4.9 Pond water balance analysis in 2001 (driest year during 1977-2006).

Month	Direct rainfall (m^3)	Direct runoff (m^3)	Evaporation (m^3)	SI (m^3)	Accumulated pond storage (m^3)
January	11.7	0.0	1,359.3	14,393.4	-15,741.0
February	34.4	0.0	1,452.8	8,185.1	-25,344.6
March	1,201.5	7,235.3	1,812.4	0.0	-18,720.2
April	268.6	228.4	1,799.3	4,162.4	-24,184.9
May	1,664.3	11,805.7	1,684.3	4,692.7	-17,091.9
June	962.1	5,025.8	1,581.6	16,797.3	-29,482.8
July	829.3	3,872.8	1,612.4	16,649.9	-43,043.1
August	1,510.4	10,253.6	1,493.7	6,757.8	-39,530.5
September	1,671.8	11,882.6	1,215.6	3,181.6	-30,373.3
October	1,317.8	8,353.6	1,268.7	42,65.0	-26,235.6
November	214.6	82.9	1,306.4	12,776.0	-40,020.5
December	8.8	0.0	1,359.3	14,723.6	-56,094.6

Note: 1. SI = Maximum supplemental irrigation (100% of total IWR_n)

2. Total IWR_n = IWR_n (cassava) + IWR_n (sugarcane) + IWR_n (maize)

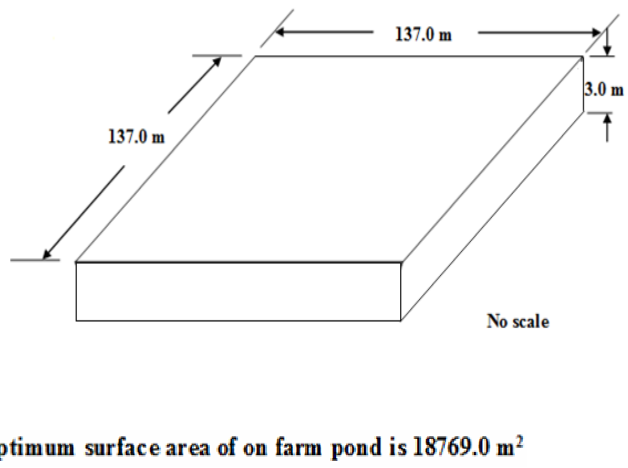


Figure 4.17 The optimum pond structure with maximum capacity of 56,307 m^3.

4.3.3 Determination of pond probability of failure

The optimum pond capacity seen in the previous section ensures sufficiency of the supply water to meet maximum requirement in the target area during period 1977-2006 as it was proposed as a viable solution for the worst-case scenario (i.e., driest year). However, to learn more on its capability as being a sustainable water resource for the use in crop plantations in the area in longer time period, its probability of failure was assessed under three assumed irrigation rates of interest: 100%, 75%, and 50% of the total IWR_n based on the synthetic 100 equally likely series of 50-year data over the representative area. Here, Monte Carlo simulation was applied to simulate end-of-month storage for the pond under 100 equally likely series of 50-year data. Each equally likely series of synthetic rainfall over an area were used to calculate direct runoff (Eq.3.10), direct rainfall (Eq.3.15) and, then, calculate water balance condition for the pond (Eq.3.14) to obtain end-of-month storage.

The Monte Carlo simulation run beginning at the 10^{th} month of the first year (i.e., October), which was assumed to have a 100% water storage in the pond (i.e., pond is in full capacity of 56,094.6 m^3). And run the simulation till the end month of the series. Repeat the simulation run for each of the 100 equally likely series. This completes the run for one irrigation rate.

Vary the irrigation rate (75%, and 50% of the total IWR_n) and repeated the Monte Carlo simulation run process. The describtive statistics of Monte Carlo simulation results are reported in Tables 4.10 (for case SI = 100%), 4.11 (for case SI = 75%), and 4.12 (for case SI = 50%)**,** respectively.

The pond's probability of failure (PF) for each specific scenario was identified using Eq. 3.20 and ultimate results are as reported in Table 4.13. It was found that value of the probability of failure (PF) was noticeably reduced with lower amount of required supplementary irrigation rate (SI) from 54% (for SI = 100%) to 6% (for SI =75%) and 0% (for SI =50%). This means water shortage should not occure for the third scenario, whereas, chances for this situation to occure in first and second scenarios are about 54% and 6%, respectively. For further work, finding rate of the SI value that first makes PF = 0 is recommended.

Table 4.10 Descriptive statistics of the simulated pond storage data in each 50-year time period (case SI = 100 %).

Period No.	Accumulated pond storage (m^3) ($*10^3$)				Period No.	Accumulated pond storage (m^3) ($*10^3$)				Period No.	Accumulated pond storage (m^3) ($*10^3$)			
	Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.
1	531.9	-73.0	173.9	188.3	18	658.1	25.4	339.2	214.0	35	677.6	-72.1	243.8	196.2
2	631.0	8.3	391.1	166.6	19	591.0	-44.1	199.0	188.6	36	552.6	-6.3	219.7	162.6
3	675.9	42.2	402.6	135.1	20	665.6	-0.5	381.7	178.8	37	631.9	-38.9	251.2	188.3
4	622.0	-41.4	270.7	184.4	21	626.5	-3.9	260.4	158.8	38	666.8	-18.5	256.8	197.8
5	638.0	-22.1	213.0	139.2	22	566.0	-39.7	240.3	177.6	39	560.5	-8.6	332.3	165.3
6	582.7	2.4	259.8	128.0	23	623.9	-40.5	309.9	161.9	40	662.4	6.7	377.8	139.9
7	652.0	-2.4	371.6	185.9	24	542.5	-24.1	175.6	155.2	41	544.3	16.3	251.2	147.3
8	603.5	-84.7	188.7	180.1	25	576.5	8.8	236.2	135.3	42	625.3	27.1	365.5	148.9
9	515.8	5.3	242.7	115.3	26	607.3	-32.8	297.8	192.4	43	578.6	-46.2	242.6	148.2
10	664.8	46.3	352.5	149.0	27	643.0	8.0	352.7	180.8	44	716.3	-62.8	384.1	214.5
11	636.0	-21.0	377.6	189.2	28	610.6	-16.8	320.8	159.2	45	667.5	-12.4	388.4	197.1
12	472.6	-37.8	208.4	137.4	29	578.0	7.2	267.5	156.5	46	635.0	-49.1	256.1	207.1
13	624.7	-24.4	296.5	168.7	30	660.3	-38.2	295.1	208.6	47	544.0	3.0	236.0	136.2
14	532.0	-51.3	219.3	140.0	31	605.3	-9.9	397.2	135.5	48	602.7	7.8	263.5	136.9
15	531.3	16.7	268.2	109.8	32	610.8	13.5	284.4	144.3	49	584.9	35.7	389.2	131.5
16	602.8	24.3	298.1	171.2	33	795.2	14.5	470.2	202.1	50	674.7	-10.7	235.4	164.2
17	590.4	-13.2	326.8	151.1	34	685.0	-26.9	237.1	182.1	51	567.0	-4.1	275.9	102.6

Table 4.10 (Continued).

Period No.	Accumulated pond storage (m^3) ($*10^3$)				Period No.	Accumulated pond storage (m^3) ($*10^3$)				Period No.	Accumulated pond storage (m^3) ($*10^3$)			
	Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.
52	569.9	-11.6	276.1	159.8	69	634.1	-65.1	235.8	193.5	86	610.7	-0.7	272.4	123.5
53	633.9	13.4	337.9	141.2	70	593.1	19.5	341.0	167.1	87	668.4	0.1	407.3	171.6
54	709.7	-0.7	263.8	179.8	71	653.2	-16.7	295.8	143.3	88	633.1	9.6	376.1	159.6
55	582.0	32.2	342.4	116.8	72	562.3	9.5	307.2	134.6	89	604.1	-68.5	207.3	192.3
56	610.7	10.6	298.1	170.5	73	577.5	-15.4	191.5	127.2	90	520.1	11.7	306.9	112.9
57	729.2	-6.5	348.9	168.8	74	660.0	21.2	354.1	182.5	91	601.0	-8.0	305.5	183.3
58	550.4	0.7	274.9	132.0	75	681.4	-10.3	436.3	155.3	92	598.7	-6.6	316.3	143.6
59	648.2	-133.6	157.6	194.9	76	573.9	-23.7	239.8	137.4	93	497.4	-5.1	203.5	162.2
60	466.0	33.8	239.4	118.5	77	669.4	-22.4	249.1	159.1	94	591.5	-21.8	252.2	169.9
61	587.4	25.9	384.6	152.2	78	509.7	31.6	281.3	86.0	95	663.6	69.3	428.2	108.1
62	580.6	18.0	313.2	176.9	79	677.8	90.4	432.8	173.1	96	497.6	16.5	287.4	128.5
63	662.5	-7.2	273.2	162.5	80	579.9	3.7	299.5	165.1	97	583.9	29.3	254.5	154.4
64	613.1	52.4	377.6	124.6	81	717.9	-20.4	344.0	209.3	98	519.4	12.4	204.0	119.5
65	626.8	34.5	433.4	106.1	82	655.2	-104.1	323.4	188.7	99	560.9	37.4	332.4	122.3
66	538.0	-63.2	182.9	162.9	83	567.8	5.2	319.3	143.1	100	674.0	10.7	332.0	165.6
67	605.7	-60.0	276.8	227.3	84	744.9	12.9	422.4	203.5					
68	451.0	-74.8	144.2	142.4	85	555.7	9.6	278.8	88.9					

Table 4.11 Descriptive statistics of the simulated pond storage data in each 50-year time period (case SI = 75 %).

Period No.	Accumulated pond storage (m^3) (*10^3)				Period No.	Accumulated pond storage (m^3) (*10^3)				Period No.	Accumulated pond storage (m^3) (*10^3)			
	Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.
1	1569.5	25.8	706.2	484.5	18	1636.9	40.6	863.0	505.2	35	1699.5	-9.5	767.4	491.2
2	1653.0	34.8	908.0	453.9	19	1603.0	37.4	726.5	479.3	36	1574.7	18.8	748.0	459.7
3	1690.5	53.7	917.0	430.1	20	1540.8	13.5	896.2	465.9	37	1665.0	1.3	780.6	484.0
4	1643.3	32.6	796.8	479.8	21	1665.5	31.9	788.3	456.9	38	1624.7	12.4	782.3	488.9
5	1674.1	13.6	737.5	424.6	22	1587.7	7.1	769.6	474.1	39	1551.7	18.1	852.4	458.0
6	1618.6	15.6	784.0	427.2	23	1650.1	28.8	830.3	458.5	40	1664.6	28.7	895.4	433.0
7	1628.3	21.9	890.4	479.3	24	1568.8	28.1	708.4	448.1	41	1562.5	37.3	776.0	441.0
8	1623.3	-14.2	713.7	474.7	25	1593.8	21.7	764.3	426.0	42	1604.5	39.3	887.9	444.7
9	1548.1	18.4	768.7	406.3	26	1642.9	40.4	817.1	484.9	43	1613.1	12.7	767.8	447.3
10	1664.3	56.0	872.6	445.6	27	1664.3	32.4	871.8	476.3	44	1627.2	54.1	902.1	502.5
11	1673.6	3.4	903.9	483.8	28	1647.3	19.6	839.9	452.0	45	1638.9	13.9	906.5	490.3
12	1503.3	-1.0	738.9	435.4	29	1619.0	19.0	793.0	451.8	46	1668.6	8.3	778.4	500.7
13	1662.6	27.0	819.5	462.3	30	1680.9	8.2	820.1	501.8	47	1581.5	33.6	756.3	433.1
14	1568.6	12.7	749.2	441.8	31	1623.5	32.0	917.0	425.0	48	1643.5	20.7	787.2	426.4
15	1559.3	28.7	792.8	394.5	32	1637.1	27.9	811.9	438.4	49	1582.8	47.9	908.1	424.3
16	1627.6	54.7	826.5	466.8	33	1647.8	26.8	986.3	489.6	50	1712.2	17.2	757.4	448.7

17	1636.3	20.9	853.4	449.8	34	1706.1	20.9	765.0	471.6	51	1595.0	16.3	802.8	397.5

Table 4.11 (Continued).

Period No.	Accumulated on farm pond storage (m^3) (*10^3)				Period No.	Accumulated on farm pond storage (m^3) (*10^3)				Period No.	Accumulated on farm pond storage (m^3) (*10^3)			
	Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.
52	1607.1	29.7	799.9	458.0	69	1665.1	22.6	768.4	488.3	86	1652.6	31.6	798.0	422.5
53	1619.1	37.6	857.4	437.1	70	1615.0	32.9	859.8	461.2	87	1643.8	21.2	925.5	467.9
54	1724.0	21.0	786.2	471.7	71	1656.6	30.4	815.5	437.4	88	1574.5	22.9	894.0	452.8
55	1623.2	42.4	864.8	413.6	72	1609.8	22.1	831.2	428.2	89	1643.2	-15.8	737.7	485.7
56	1638.0	23.2	828.0	467.0	73	1618.3	7.1	723.3	416.2	90	1558.3	24.2	828.6	395.8
57	1766.7	8.1	869.6	462.8	74	1696.3	32.5	875.0	478.0	91	1626.5	32.7	828.3	478.6
58	1578.8	26.7	801.9	429.2	75	1708.6	11.6	952.2	446.5	92	1619.0	8.1	837.9	442.3
59	1686.4	-21.6	692.2	488.8	76	1617.8	26.4	765.7	433.8	93	1529.9	31.4	731.9	454.2
60	1491.3	45.0	768.2	414.9	77	1711.1	12.8	782.0	457.3	94	1618.1	15.9	783.6	469.4
61	1631.4	38.8	901.7	445.7	78	1557.9	43.8	803.8	368.0	95	1672.3	78.3	943.2	402.1
62	1587.3	30.2	834.2	472.9	79	1719.5	90.4	954.9	469.4	96	1506.6	53.0	812.5	420.3
63	1687.4	34.6	797.7	454.1	80	1548.1	30.1	819.8	462.0	97	1624.7	41.5	777.7	449.5
64	1643.2	62.0	895.5	419.6	81	1660.5	31.8	860.0	501.6	98	1572.9	69.1	736.5	405.0
65	1669.8	45.6	951.1	381.4	82	1696.2	2.3	845.1	483.7	99	1567.7	48.1	851.5	420.2
66	1580.3	25.8	713.9	457.1	83	1568.1	22.7	842.4	425.1	100	1681.3	22.7	849.9	464.8
67	1567.8	-0.3	799.6	515.7	84	1713.2	25.5	937.7	496.7					

68	1498.9	18.5	676.7	433.6	85	1603.6	22.4	808.5	380.1

Table 4.12 Descriptive statistics of the simulated pond storage data in each 50-year time period (case SI = 50 %)**.**

Period No.	Accumulated on farm pond storage (m^3) ($*10^3$)				Period No.	Accumulated on farm pond storage (m^3) ($*10^3$)				Period No.	Accumulated on farm pond storage (m^3) ($*10^3$)			
	Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.
1	2622.4	49.2	1238.6	786.2	18	2681.7	52.5	1386.7	802.6	35	2735.7	28.7	1290.9	788.4
2	2675.0	46.9	1424.8	753.8	19	2643.6	49.2	1254.0	777.2	36	2621.1	32.4	1276.3	760.7
3	2705.1	64.5	1431.4	731.8	20	2558.2	27.5	1410.8	763.0	37	2708.5	39.9	1309.9	782.6
4	2678.1	44.8	1322.8	778.5	21	2704.5	44.1	1316.1	758.8	38	2671.5	25.8	1307.9	786.6
5	2713.3	33.7	1262.1	726.2	22	2632.9	21.2	1298.8	774.4	39	2600.3	31.7	1372.5	757.5
6	2664.7	28.8	1308.2	732.6	23	2690.7	42.5	1350.6	757.8	40	2706.2	44.0	1413.1	734.8
7	2647.2	45.0	1409.2	777.9	24	2608.6	42.3	1241.3	748.3	41	2607.7	49.7	1300.9	741.1
8	2661.1	26.9	1238.7	772.9	25	2641.1	34.6	1292.5	728.2	42	2648.6	51.5	1410.3	744.9
9	2594.4	31.5	1294.7	709.1	26	2678.5	51.4	1336.4	781.7	43	2655.8	35.6	1292.9	749.6
10	2702.6	63.4	1392.8	746.4	27	2699.8	51.1	1390.9	776.5	44	2667.3	65.6	1420.1	797.0
11	2720.7	27.7	1430.1	784.9	28	2684.0	44.1	1359.0	751.5	45	2679.5	27.4	1424.6	789.7
12	2538.0	22.2	1269.5	737.2	29	2660.1	30.7	1318.5	750.8	46	2702.1	31.7	1300.8	796.5
13	2700.5	49.5	1342.4	763.5	30	2706.8	46.0	1345.2	799.3	47	2622.3	45.4	1276.5	732.8
14	2619.7	26.0	1279.1	746.5	31	2658.8	47.7	1436.8	724.1	48	2684.4	33.7	1311.0	726.2
15	2587.4	40.8	1317.5	698.3	32	2679.3	40.1	1339.4	739.0	49	2621.0	60.0	1427.0	726.4
16	2672.5	65.6	1354.9	765.5	33	2696.1	39.1	1502.4	787.5	50	2749.8	30.3	1279.5	745.7

17	2682.3	33.8	1380.1	752.0	34	2727.1	33.7	1292.8	770.1	51	2641.5	36.6	1329.7	701.2

Table 4.12 (Continued)

Period No.	Accumulated on farm pond storage (m^3) ($*10^3$)				Period No.	Accumulated on farm pond storage (m^3) ($*10^3$)				Period No.	Accumulated on farm pond storage (m^3) ($*10^3$)			
	Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.		Max.	Min.	Mean	S.D.
52	2656.0	42.6	1323.8	759.3	69	2717.4	35.2	1301.0	787.5	86	2694.5	44.4	1323.7	726.2
53	2649.3	49.8	1377.0	737.7	70	2637.7	45.1	1378.6	761.1	87	2676.3	34.4	1443.7	768.5
54	2747.8	38.9	1308.7	768.3	71	2689.6	42.6	1335.2	736.0	88	2607.4	36.2	1411.8	752.5
55	2664.5	52.6	1387.3	716.3	72	2657.3	34.7	1355.2	733.0	89	2682.3	22.2	1268.2	782.4
56	2687.6	35.7	1357.9	768.0	73	2659.2	25.0	1255.1	717.7	90	2604.3	36.7	1350.3	698.2
57	2806.3	22.8	1390.4	763.8	74	2737.1	43.8	1395.8	777.9	91	2652.6	51.0	1351.2	779.0
58	2624.3	41.7	1328.9	731.3	75	2746.5	31.3	1468.1	746.1	92	2657.6	22.5	1359.5	745.6
59	2724.6	24.4	1226.9	787.3	76	2661.8	38.8	1291.7	736.2	93	2575.9	44.1	1260.2	753.9
60	2541.9	56.1	1297.0	716.7	77	2752.8	36.1	1315.0	759.8	94	2663.7	35.6	1315.0	771.0
61	2675.3	51.7	1418.8	745.9	78	2606.1	55.9	1326.4	673.3	95	2710.2	87.4	1458.1	706.0
62	2640.6	42.4	1355.2	772.9	79	2761.2	90.4	1476.9	770.9	96	2556.6	68.8	1337.6	720.4
63	2724.5	46.8	1322.3	754.3	80	2593.1	41.8	1340.1	762.3	97	2665.5	53.7	1300.9	749.1
64	2685.7	67.9	1413.4	721.2	81	2647.2	44.3	1376.1	797.1	98	2626.3	69.5	1269.0	706.5
65	2447.6	32.2	1335.4	772.2	82	2737.2	43.4	1366.7	783.0	99	2614.3	51.5	1370.7	723.9
66	2622.5	38.3	1244.9	756.7	83	2602.6	35.5	1365.6	725.1	100	2705.7	34.7	1367.8	766.5
67	2615.1	21.5	1322.3	810.4	84	2745.6	38.0	1452.9	793.7					

68	2546.8	39.9	1209.2	732.8	85	2651.5	35.3	1338.3	687.0

Table 4.13 Pond's probability of failure obtained from Monte Carlo simulation.

Scenario	Number of equally likelyseries resulting in failure	Total number of equally likely series throughout the simulation run	Probability of failure (%)
(1) SI = 100 % total IWR_n	54	100	54
(2) SI = 75 % total IWR_n	6	100	6
(3) SI = 50 % total IWR_n	0	100	0

4.4 Development of proper crop calendar

As stated in Chapter III, knowledge of monthly water need by each considered crop (based on the known monthly ET_{crop}) can be applied, in association with prior knowledge of raining pattern over an area, to prepare proper crop calendar for the area where month with peak demand for water of the crop should be coincide with the month having highest amount of rainfall in that area (FAO, 2011). This FAO guideline was applied in this study where data of the specific monthly crop's water demand was gathered from Table 4.7 and amount of potential rainfall at 80% probability of exceedence for each month was derived using the Weibull formula described in Chapter III. Here, these data were identified from 5,000 values of the synthetic rainfall data for each month generated in Section 4.3.4 (for 5,000 years in total). Similar to natural monthly rainfall pattern, the 80% probability of a synthetic rainfall exceedence for an area had a bimodal distribution pattern with 2 peaks (in May and September respectively). The cropping calendar for cassava, sugarcane, and maize were adjusted accordingly to this knowledge. The month where the maximum crop evapotranspiration (ET_{crop}) occurred was moved to coincide the most with first peak and second peak as appropriate as illustrated in Figure 4.18.

Table 4.14 Monthly rainfall data at 80% exceedence probability in 5000-year dataset.

Areal rainfall data (based on 80% exceedence probability) (mm)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	2.4	16.8	42.0	103.9	62.5	63.3	85.6	158.4	74.9	1.5	0

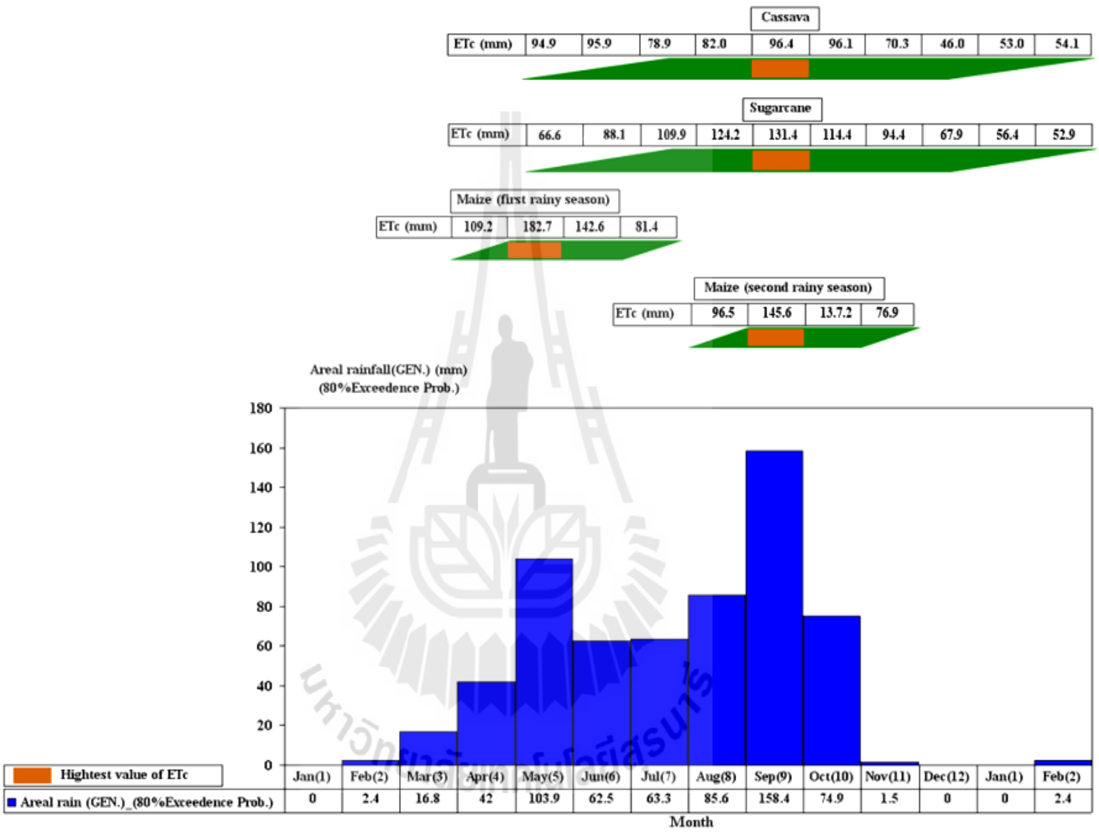


Figure 4.18 The proposed crop calendar for cassava, sugarcane, and maize.

Details of the old and new crop calendars for all studied crops are presented in Table 4.15 and Figure 4.8, in which, that of the cassava remains the same, while that of the sugarcane was shifted forward by a month (begun in May not April) and that of maize shifted backward (started in April and August instead of in May and November as usual). This adjustment was aimed to reduce the burden of supplying large amount of water to fulfill water shortage at each month for each crops. This preferred efficiency can be directly assessed by the comparison of the monthly water deficiency (ΔW) defined in Eq. 3.26 resulted from both old and new calendars and results are reported in Table 4.16. It was found that for sugarcane, the reduction of 27.40 mm (or 4.32%) in total need for water in one season was found, while for maize, that value was 85.90 mm (or 10.90%). These data confirm the prior believe that by adjusting crop calendar appropriately, the use of water might be noticeably more efficient than normal for planting all crops of interest. In addition, the variation of crop calendar to suit the most with its climate demand is also recommended by FAO (2014) as the way to increase crop yield and to make crop fit with the climate distortions that are apparently seen more often in both space and time aspects at present. The relationship of crop yield and water is comprehensively reviewed in FAO paper on crop yield response to water (FAO, 2012).

Table 4.15 Traditional crop calendar in the study area.

Crop	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Cassava (Old)												
Cassava (New)												
Sugarcane (Old)												
Sugarcane (New)												
Maize (Old)												
Maize (New)												

Table 4.16 Monthly water deficiency (ΔW) for two crop calendars (old/new).

Crop	Monthly water deficiency (mm)												Total
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
Cassava (Old)	0.0	26.5	65.8	54.3	22.1	27.5	46.9	70.3	46.0	53.0	54.1	0.0	466.5
Cassava (New)	0.0	26.5	65.8	54.3	22.1	27.5	46.9	70.3	46.0	53.0	54.1	0.0	466.5
Sugarcane (Old)	72.1	27.9	80.1	108.6	84.8	40.6	49.2	71.4	52.2	47.4	0.0	0.0	634.3
Sugarcane (New)	0.0	0.0	58.0	85.3	64.3	62.5	65.2	94.4	67.9	56.4	52.9	0.0	606.9
Maize (Old)	0.0	30.7	137.1	117.6	16.1	0.0	0.0	87.8	138.9	135.4	88.1	0.0	751.7
Maize (New)	108.0	114.3	112.5	56.8	36.6	76.7	88.1	76.7	0.0	0.0	0.0	0.0	669.8

4.5 Effects of supplementary irrigation on crop yield and WUE

In this part, relationship between average crop yield and amount of supplementary water for each interested crop was determined for Nakhon Ratchasima Province based on relevant reports on this issue from field experiments (for each crop) previously conducted in Thailand. First, based on data shown in Table 2.6, the relationships of final crop yield and amount of the given supplementary water (for all listed crop) were drawn and results were reported in Figure 4.19, 4.20, 4.21, and the relationship of respond crops yield and all supplementary irrigation rates were also reported to demonstrate the rate of change in WUE at different supplementary irrigation rate as seen in Figure 4.22. In all assessed experimental cases, the corresponding WUE (SI) was identified from the rate of change in crop yield per unit of the supplementary irrigation water, or the slope value of a relationship graph drawn for crop yield and amount of the supplementary water in each associated experiment depicted in Table 4.17. These obtained values of the WUE (SI) for each crop were then applied to predict crop yield in the chosen area at different rates of the supplementary irrigation, i.e., 25%, 50%, 75%, and 100% of the IWR_n for the crops in 2001 as illustrated in Table 4.18 and Table 4.19.

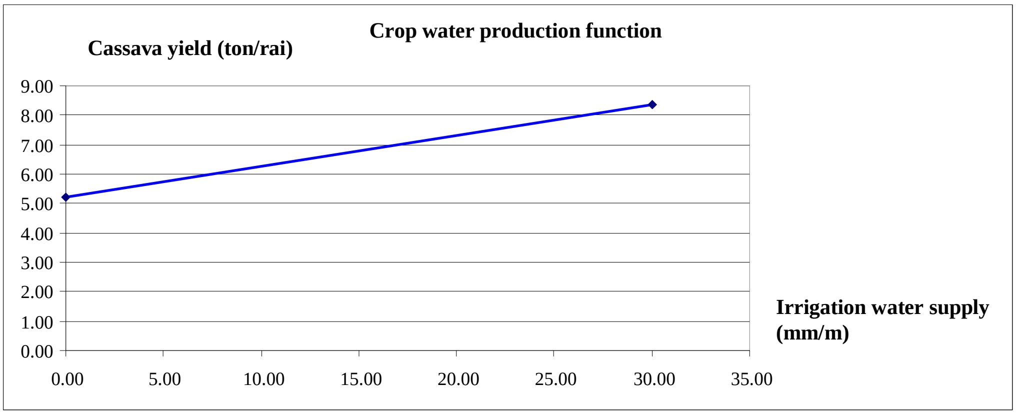
Amount of the eventual crop yield for each value of the considered irrigation rate (for each crop) was estimated based on the following equation:

$$\text{Yield} = \sum_{i=1}^{n} \text{WUE(SI)}_i \cdot \Delta\text{SI}_i \tag{4.1}$$

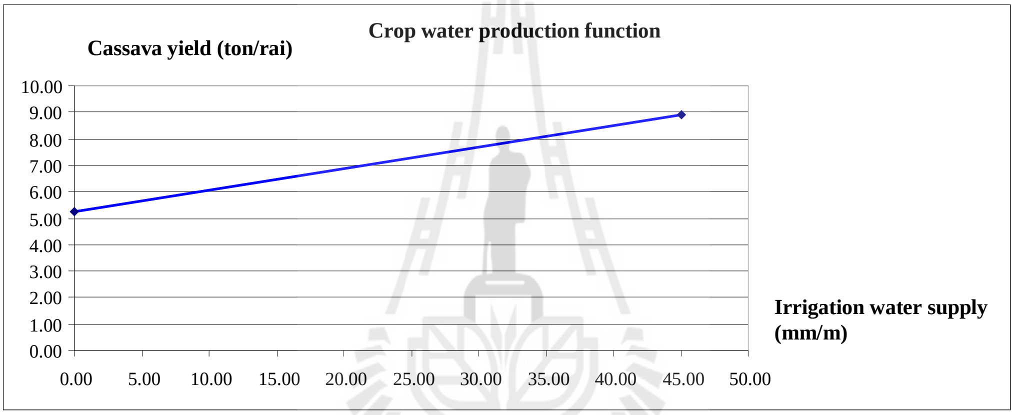
where WUE(SI)_i is the water use efficiency for part i^{th} of the supplementary irrigation, or ΔSI_i, and n is total number of the SI parts in use. For example, the SI at 100% for cassava was found to be 46.65 mm/m in 2001 (from Table 4.7), this data was then separated into 3 parts: 0-30, 30-45, and 45-46.65 mm/m with the associated WUE (SI) of 105.2, 36.7, 12.7 kg/rai, respectively (from Table 4.17). Therefore, the yield was obtained as follows:

Yield = (105.2)x(30) + (36.7)x(15) + (12.7)x(1.64) = 3726.83 kg/rai.

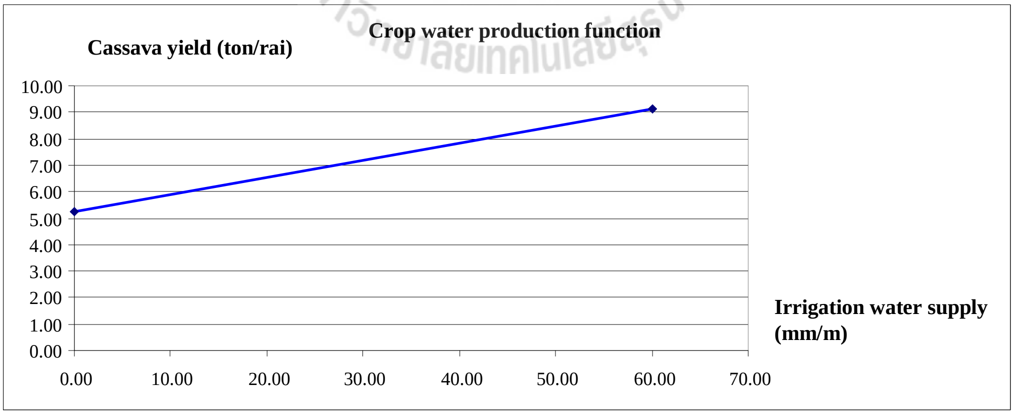
However, the estimated yield reported in Table 4.18 must be altered if land quality is also taken into account and this was examined by multiplying an assigned constant affiliated with each classified land suitability class (i.e., S1, S2, S3, N) to the original yield data in Table 4.18, presumed that the original data were derived for the S1 class for cassava and sugarcane, and S2 class for maize (based on a mutual comparison of crop yield in rainfed condition in the used experimental cases with those found in Nakhon Ratchasima Province). Therefore, the defined suitability factor (C) values in this study are C_{S1} = 1.0, C_{S2} = 0.8, C_{S3} = 0.6, C_N = 0.4 (for cassava and sugarcane) and C_{S1} = 1.25, C_{S2} = 1.0, C_{S3} = 0.75, C_N = 0.5 (for maize). As a result, total yield of each crop in the area in 2001 could be predicted from Eq. 3.27 and amount of crop land known beforehand whose results are shown in Table 4.19.



(a) Cassava: Experiment 1 (0-30 mm)



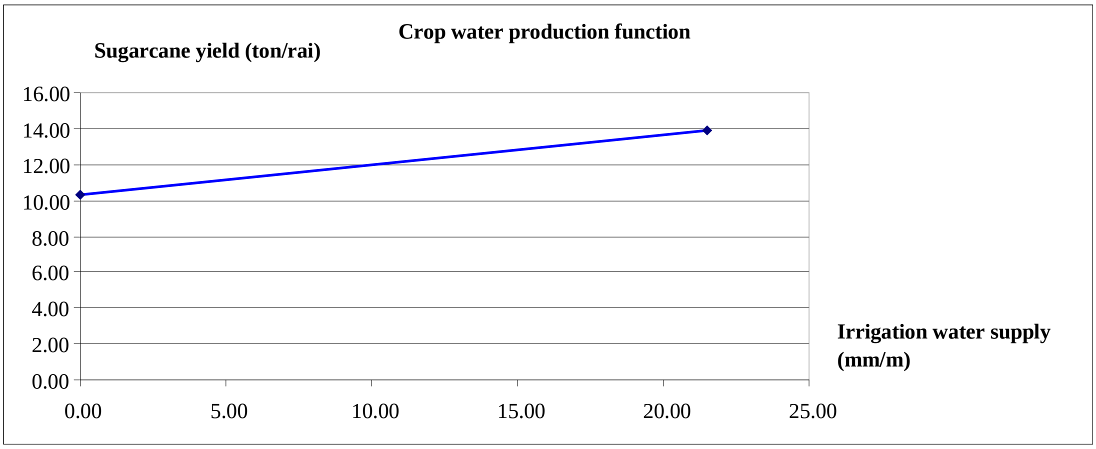
(b) Cassava: Experiment 2 (0-45mm)



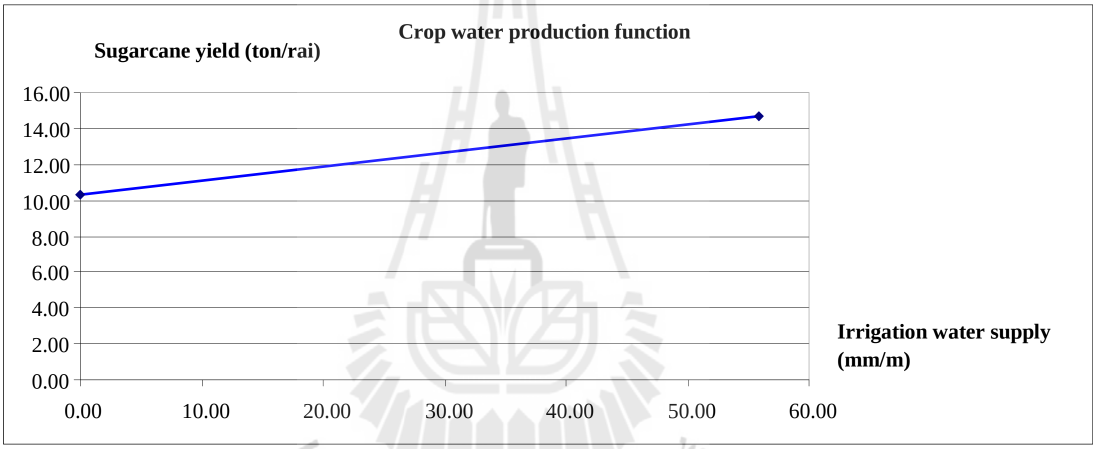
(c) Cassava: Experiment 3 (0-60 mm)

Figure 4.19 Effects of irrigation water on cassava yield (from three experiments).

Note: 1. Yield at origin (rainfed condition) = 5.23 ton/rai



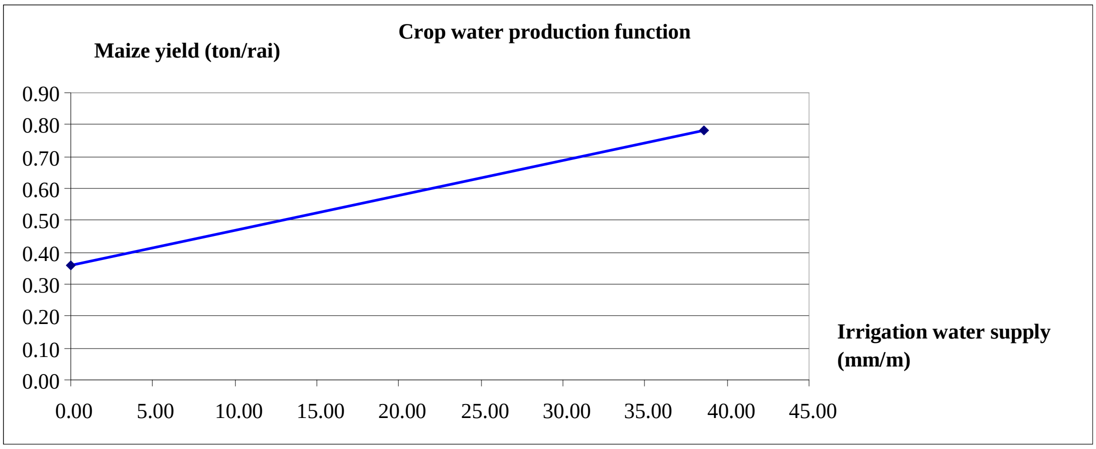
(a) Sugarcane: Experiment 1 (0-21.48 mm)



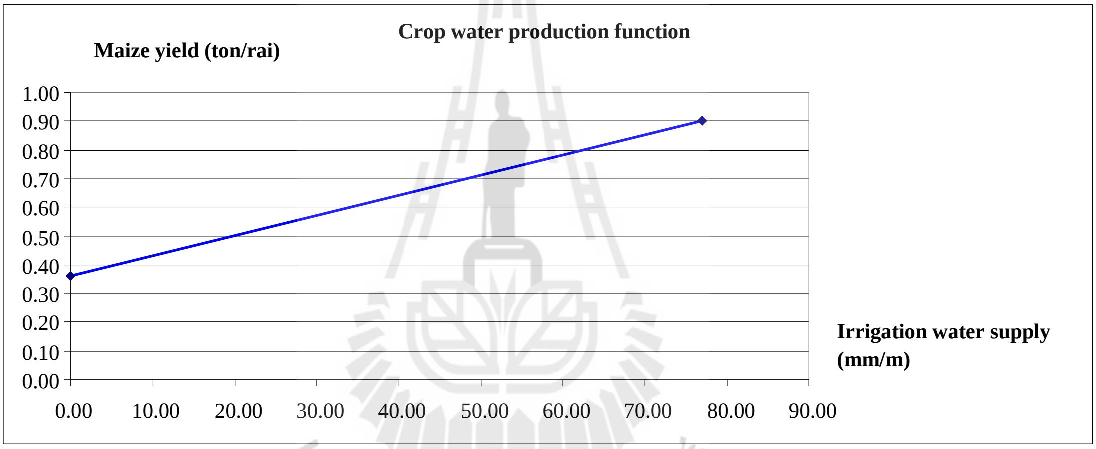
(b) Sugarcane: Experiment 1 (0-55.86 mm)

Figure 4.20 Effects of irrigation water on sugarcane yield (from two experiments).

Note: 1. Yield at origin (rainfed condition) = 10.31ton/rai



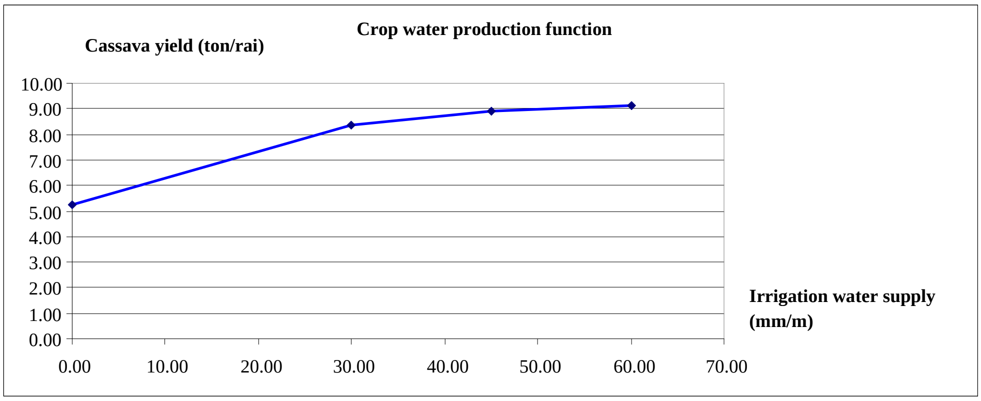
(a) Maize: Experiment 1 (0-38.6 mm)



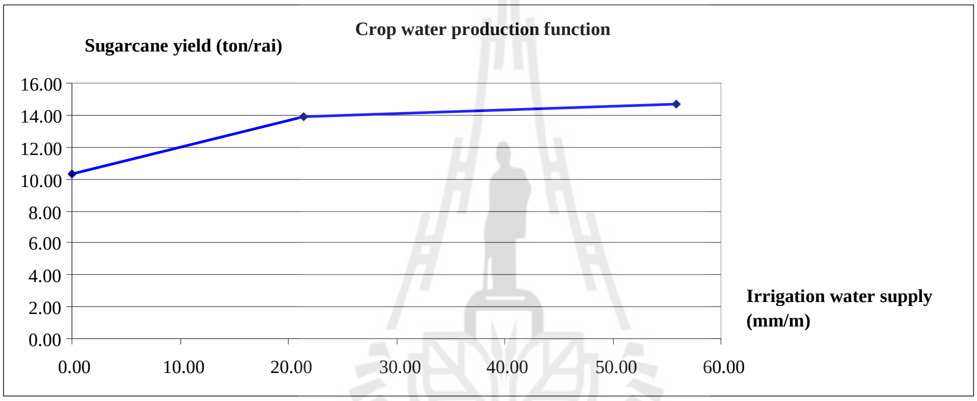
(b) Maize: Experiment 1 (0-77.1 mm)

Figure 4.21 Effects of irrigation water on maize yield (from two experiments).

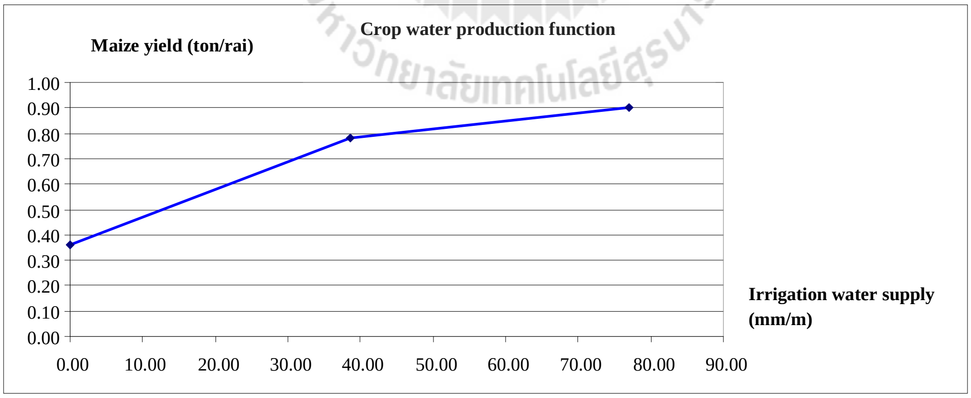
Note: 1. Yield at origin (rainfed condition) = 0.36 ton/rai



(a) Cassava: Integrated experiment 1-3 (0-30, 30-45, 45-60 mm)



(b) Sugarcane: Integrated experiment 1-2 (0-21.48, 21.48-55.86 mm)



(c) Maize: Integrated experiment 1-2 (0-38.6, 38.6-77.1 mm)

Figure 4.22 Integrated effects of irrigation water on three specific crops yields.

Table 4.17 Data of the WUE (SI) for all listed crops (from Figure 4.22).

SI Condition	Cassava		Sugarcane		Maize	
	Range (mm)	WUE (SI) (kg/mm)	Range (mm)	WUE (SI) (kg/mm)	Range (mm)	WUE (SI) (kg/mm)
SI-Case 1	0-30	105.2	0-21.48	167.13	0-38.6	10.8
SI-Case 2	0-45	80.7	0-55.86	78.5	0-77.1	7.3
SI-Case 3	0-60	60.6	-	-	-	-
SI-Case 4.1	0-30	105.2	0-21.48	167.13	0-38.6	10.8
SI-Case 4.2	30-45	36.7	21.48-55.86	22.9	38.6-77.1	3.7
SI-Case 4.3	45-60	12.7	-	-	-	-

Table 4.18 Effects of supplied water on crop yield and WUE. Here (+) means an increase from that of the rain-fed condition (case SI = 0).

% IWR_n	Cassava (S1)					Sugarcane (newly planted) (S1)				
	SI (mm/m)	Yield (kg/rai)	+ (%)	WUE (kg/mm)	+ (%)	SI (mm/m)	Yield (kg/rai)	+ (%)	WUE (kg/mm)	+ (%)
0 (rain-fed)	0	2806.30	0	4.17	0	0	8972.28	0	13.32	0
25	11.66	1226.63	43.71	5.89	41.20	15.86	2650.68	29.54	16.87	26.62
50	23.33	2454.32	87.46	7.55	81.09	31.72	3824.45	42.62	18.16	36.34
75	34.99	3284.08	117.03	8.62	106.64	47.57	4187.41	46.67	18.27	37.16
100	46.65	3726.83	132.80	9.07	117.61	63.43	4550.61	50.72	18.37	37.91

% IWR_n	Maize (S2)				
	SI (mm/m)	Yield (kg/rai)	+ (%)	WUE (kg/mm)	+ (%)
0 (rain-fed)	0	521.69	0	0.77	0
25	23.49	253.69	48.63	1.11	44.16
50	46.98	447.89	85.85	1.36	76.62
75	70.47	534.80	102.51	1.42	84.42
100	93.96	621.71	119.17	1.49	93.51

$$\mathrm{WUE} = \frac{\text{Yield (rainfed + irrigation)}}{\text{Water (rainfall + irrigation)}}$$

Table 4.19 Effects of supplied water and land suitability on crop yield (kg/rai).

% IWR_n	Cassava (kg/rai)				Sugarcane (kg/rai)			
	S1 (1.0)	S2 (0.8)	S3 (0.6)	N (0.4)	S1 (1.0)	S2 (0.8)	S3 (0.6)	N (0.4)
25	4032.93	3226.34	2419.76	1613.17	11622.96	9298.37	6973.78	4649.18
50	5260.62	4208.50	3156.37	2104.25	12796.73	10237.38	7678.04	5118.69
75	6090.38	4872.30	3654.23	2436.15	13159.69	10527.75	7895.81	5263.88
100	6533.13	5226.50	3919.88	2613.25	13522.89	10818.31	8113.73	5409.16

% IWR_n	Maize (kg/rai)			
	S1 (1.25)	S2 (1.0)	S3 (0.75)	N (0.5)
25	969.23	775.38	581.54	387.69
50	1211.98	969.58	727.19	484.79
75	1320.61	1056.49	792.37	528.25
100	1429.25	1143.40	857.55	571.70

From results shown in Tables 4.17, 4.18 and 4.19, it can be primarily concluded that effects of irrigation on predicted crop yield is quite strongly evidenced. For example for cassava, the supply of irrigation water at 25% of the total need (for the entire season) shall increase potential yield of the crop by 43.71% from that found under normal rainfed condition. But if a 100% of needed water is supplied, predicted yield shall dramatically increase by about 132.8% from that of the rainfed crop. Other crops were appeared to have the same trend. Irrigation was also found to notably increase the seasonal WUE for each studied crop also as seen in Table 4.18. Similar effects were reported in several works on different crops. For example, Ko and Piccinni (2009) found that grain yield of corn would increase by about 21.65% if the irrigation rose from 50% ET_{crop} to 100% (in this study for maize it gained about

48.63%). Similarly, Pene and Edi (1999) found that the cane yield was increased by about 60.10% (first ratoon) and 121.25% (second ratoon) if a 100% water requirement was supplied compared to that in the rainfed condition. In this study, the result was about 50.72% (newly planted).

In order to predict the potential increasing of cassava, sugarcane, and maize yield at the whole province under the effect of different supplementary irrigation rate. The composition of classified crop map in 2006 and land suitability map (Figure 4.9 (c)) was used as the case study (or model) to predict the potential increasing yield (comparing to rainfed condition) of the 3 crops. Similar to Table 4.19, the effect of supplied water and land suitability on crop yield in the year 2006 was calculated using WUE data from Table 4.17 and average cassava, sugarcane, and maize yield in the year 2006 and the result was shown in Table 4.20.

Table 4.20 Effects of supplied water and land suitability on crop yield (kg/rai) (2006).

% IWR_n	Cassava (kg/rai)				Sugarcane (kg/rai)			
	S1 (1.0)	S2 (0.8)	S3 (0.6)	N (0.4)	S1 (1.0)	S2 (0.8)	S3 (0.6)	N (0.4)
25	4696.83	3757.46	2818.10	1878.73	11501.29	9201.03	6900.77	4600.52
50	5924.52	4739.62	3554.71	2369.81	12675.06	10140.05	7605.04	5070.02
75	6754.28	5403.42	4052.57	2701.71	13038.02	10430.42	7822.81	5215.21
100	7197.03	5757.62	4318.22	2878.81	13401.22	10720.98	8040.73	5360.49

% IWR_n	Maize (kg/rai)				
	S1 (1.25)	S2 (1.0)	S3 (0.75)	N (0.5)	Average yield (2006)
25	1180.14	944.11	708.083	472.055	Cassava = 3470.20 kg/rai
50	1422.89	1138.31	853.733	569.155	Sugarcane = 8850.61 kg/rai
75	1531.53	1225.22	918.915	612.61	Maize = 690.42 kg/rai
100	1640.16	1312.13	984.098	656.065	

According to Figure 4.9 (c), that indicated the extent of overlap areas (or coincided areas) between planting areas and their suitability classes, and the information in Table 4.20. The potential increasing of cassava, sugarcane, and maize yield under the effect of different supplementary irrigation rate in each suitability class in Nakhon Ratchasima Province can be predict. The results revealed that the maximum increasing of maize yields were received (39.69%) under the supplementary irrigation of 50% IWR_n. While, under full irrigation, the maximum increasing of cassava yields were received (62.15%) followed by the increasing of maize yields (61.02%) and sugarcane yields were the least increasing (23.98%). The more information was reported in Table 4.21 (a)-(c).

Table 4.21a Potential increasing yield of cassava under the effect of supplied water.

Irrigated condition (Overlap area)	Area (rai)	Cassava Yield at each suitability class and at different irrigation rate (kg)			
		25% IWR_n	50% IWR_n	75% IWR_n	100% IWR_n
Existing cassava coincide with s1 cassava	463476.17	2176868779.54	2745873838.69	3130447825.51	3335651899.78
Existing cassava coincide with s2 cassava	603912.50	2269177062.25	2862315763.25	3263192880.75	3477098688.25
Existing cassava coincide with s3 cassava	616275.00	1736724577.50	2190678905.25	2497497576.75	2661211030.50
Total (s1+s2+s3)	1683663.67	6182770419.29	7798868507.19	8891138283.01	9473961618.53
Rainfed condition: Total area = 1683663.67 rai Total yield = 5842649667.63 kg		5.82% Increase	33.48% Increase	52.18% Increase	62.15% Increase

Table 4.21b Potential increasing yield of sugarcane under the effect of supplied water.

Irrigated condition (Overlap area)	Area (rai)	Sugarcane Yield at each suitability class and at different irrigation rate (kg)			
		25% IWR_n	50% IWR_n	75% IWR_n	100% IWR_n
Existing sugarcane coincide with s1 sugarcane	148306.25	1705713190.06	1879790617.13	1933619853.63	1987484683.63
Existing sugarcane coincide with s2 sugarcane	316700.00	2913966201.00	3211353835.00	3303314014.00	3395334366.00
Existing sugarcane coincide with s3 sugarcane	95600.00	659713612.00	727041824.00	747860636.00	768693788.00
Total (s1+s2+s3)	560606.25	5279393003.06	5818186276.13	5984794503.63	6151512837.63
Rainfed condition: Total area = 560606.25 rai Total yield = 4961707282.31 kg		6.40% Increase	17.26% Increase	20.62% Increase	23.98% Increase

Table 4.21c Potential increasing yield of maize under the effect of supplied water.

Irrigated condition (Overlap area)	Area (rai)	Maize Yield at each suitability class and at different irrigation rate (kg)			
		25% IWR_n	50% IWR_n	75% IWR_n	100% IWR_n
Existing maize coincide with s1 maize	42456.25	50104318.88	60410573.56	65023020.56	69635043.00
Existing maize coincide with s2 maize	147825.00	139563060.75	168270675.75	181118146.50	193965617.25
Existing maize coincide with s3 maize	407862.50	288800502.59	348205675.71	374790969.19	401376670.53
Total (s1+s2+s3)	598143.75	478467882.21	576886925.03	620932136.25	664977330.78
Rainfed condition: Total area = 598143.75 rai Total yield = 412970407.87 kg		15.86% Increase	39.69% Increase	50.56% Increase	61.02% Increase

Remark: 1. Not suitable areas were excluded from the prediction.

2. In case of rainfed condition, the average yield in 2006 was used to calculate the total yield of all 3 suitability classes (s1, s2, and s3).

CHAPTER V

CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusions

This chapter summarizes achievement of all works accomplished in this thesis in accordance with the application of geo-informatics incorporated with water balance model and Monte Carlo simulation method to land and water management according to King Bhumibol's New Theory of Land and water management for the production of the three economic crops (cassava, sugarcane, and maize).

The classified LULC map of Nakhon Ratchasima Province was derived from the Landsat-TM imagery taken in November 2006. It was found that out of the 20,699.02 km^2 of the province the three economic crops had occupied 27.77%; with 17.42% cassava, 4.147% sugarcane and 5.93% maize. Large cassava fields were notably seen in the southeastern districts. The overall accuracy of 86.36% and Kappa coefficient of 0.83 were found for data presented in this built LULC map.

Using 6 land quality attributes suggested by the FAO guideline for rain-fed agriculture (FAO, 1983) it was found that the province was moderately suitable for the three crops with sugarcane being more preferable having the highest percentage of land in both high (S1) and moderate (S2) suitability classes (at 19.94% and 44.23%) while only 4.76% was found not suitably. Cassava was the second favorite crop with percentage in S1 and S2 classes of 15.44% and 30.87%. Maize was the least favorable crop here with highly suitable land of just 7.49% while the majority (51.76%) was identified as marginally suitable and 22.33% as not suitable.

A representative area for land and water management study was identified based on four primary criteria: (1) being a small lowland watershed (derived from DEM of 1-m contour map), (2) being a rain-fed agricultural area locating outside existing irrigation zone, (3) having all three concerned crops planted therein, and (4) having high land suitability condition (S1) for all interested crops. The area was in western Mueang District, having a total area of 176,756.0 m^2 (104.39 rai). It was found that a pond of capacity 56,094.6 m^3 was needed to provide supplementary irrigation for production of the three crops in this area.

Monte Carlo simulation revealed that the pond was not able to provide 100% irrigation equal to 54% or not able to provide 75% irrigation equal to 6% but was able to provide 50% irrigation without fail. This means for reliable operation, the pond should be planned for lower than 75% irrigation.

Using the FAO guideline for crop calendar planning a calendar with months of highest demand coinciding with month of peak rainfall (May and September) for sugarcane and maize were found to require less supplementary irrigation than the traditional calendar. For cassava this calendar is the same as the traditional one. This planning resulted in a reduction of total irrigation for sugarcane by 27.40 mm (or 4.32%) while for that of maize by 85.90 mm (or 10.90%).

Using results from field experiments previously conducted in Thailand relationships between average crop yield and amount of supplementary water for each crop were determined. These crop-water production functions showed that crop yield and WUE increase with increasing irrigation and approach a maximum asymptotically. Compared to the rain-fed situation, the yield at 100% irrigation increased by 132.8% for cassava, 50.72% for sugarcane and 119.17% for maize while the WUE increased by 117.61% for cassava, 37.91% for sugarcane, and 93.51% for maize, respectively. In addition, the expected yields for the whole province were estimated at 162.15%, 123.98% and 161.02% for cassava sugarcane and maize under 100% irrigation respectively. With 75% irrigation the provincial expected yields were estimated at 152.18%, 120.62% and 150.56% for cassava sugarcane and maize respectively.

5.2 Recommendations

5.2.1 Recommendations for using the study results

From the results and discussion presented earlier the following recommendations are given:

1) Suitability maps presented here can be distributed to agricultural extension agents to advise farmers and land owners in crop selection in conjunction with other economic considerations as well as promoting proper crop variety. This will help reduce production costs and increase expected yields.

Suitability maps at the sub-district level should be prepared for better coverage and identification of land ownership. However, in some areas of Nakhon Ratchasima Province, there are problems of soil salinity. Therefore, exclusion from the suitability map should be applied for the Level 1 soil salinity areas (very high level of salinity effect, characterized by salt-covered soil surface of more than 50 percent of the area), as well as the Level 2 soil salinity areas (high level of salinity effect, where soil surface salt covers 10-50 percent of the area) before determining the cultivation areas. The Level 1 area covers approximately 111.98 km^2, commonly found in the following districts: KaengSanam Nang, BuaYai, Sida, Prathai, Mueng Yang, Kong, Non Dang, Non Sung, Mueang, ChaloemPhraKiat, Kham Tale So, Non Thai, Dan KhunThot, Kham Sakaesaeng, ad Phra Thong Kham. The Level 2 area includes 186.49 km^2 in the following districts: Chum Phuang, ChaloemPhraKiat, KaengSanam Nang, BuaYai, Bua Lai, Prathai, Mueang Yang, Phimai, Ban Lueam, Khong, Kham Sakaesaeng, Sida, Non Dang, Non Sung, Chakarat, Phra Thong Kham, Non Thai, Dan KhumThot, Kham Thale So, and Muang.

2) There should be cooperation among farmers in the form of cooperatives. The number of farmers of each co-op depends on land ownership in the watershed, about 7-8 should be sufficient, where a small pond can be planned and constructed for cooperative crop production. Once the pond is in place other uses can be introduced such as vegetables production and aquaculture for household and co-op consumption. However, the farmers may not be able to carry out the planning and construction of such a collective pond. Therefore, government agencies, such as the Department of Agricultural Extension, should take initiative to promote the activity.

5.2.2 Recommendations for further study

1) The suitability levels S1, S2, and S3 for each crop should be verified with the observed crop yield.

2) Suitability maps at the sub-district level should be prepared for better coverage and identification of land ownership.

3) Suitability map may be produced in layers to include climate data (i.e. rainfall and temperature) to better reflect topographic and microclimate variation.

4) Further study of this nature should include the economic aspects of crop production and costs of water investment.

5) A pilot study of cooperative pond for economic crop production should be attempted. This could be interdisciplinary in nature involving engineering (planning and construction, water distribution, etc.), economic (costs of inputs, yield, prices, externality, etc.) and social (culture, participation, etc.).

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APPENDICES

APPENDIX A

DESCRIPTION OF NAKHON RATCHASIMA DISTRICT

Table A.1 Districts of Nakhon Ratchasima Province.

NO.	District	Area (km^2)	NO.	District	Area (km^2)
1	Kaeng Sanam Nang	306.79	17	Non Sung	691.61
2	Bua Lai	171.95	18	Phimai	892.41
3	Ban Lueam	218.67	19	Chum Phuang	646.39
4	Bua Yai	504.16	20	Lam Thamenchai	266.42
5	Sida	186.41	21	Pak Chong	1957.09
6	Prathai	532.22	22	Sung Noen	783.21
7	Thepharak	358.91	23	Mueang Nakhon Ratchasima	766.09
8	Dan Khun Thot	1375.39	24	Chaloem Phra Kiat	284.31
9	Phra Thong Kham	343.04	25	Chakkarat	562.06
10	Kham Sakaesaeng	341.42	26	Huai Thalaeng	535.35
11	Khong	648.20	27	Pak Thong Chai	1007.83
12	Non Daeng	168.85	28	Chok Chai	547.50
13	Mueang Yang	262.66	29	Nong Bun Nak	550.59
14	Sikhio	1163.18	30	Wang Nam Khiao	1058.50
15	Kham Thale So	209.52	31	Khon Buri	1868.32
16	Non Thai	549.48	32	Soeng Sang	940.33

APPENDIX B

LAND QUALITIES FOR RAINFED AGRICULTURE

B.1 FAO guideline for land evaluation

Table B.1 Land qualities for rain-fed agriculture.

No.	Land quality	Diagnostic criteria	Unit
1	Radiation regime:	Net shortwave radiation in growing season	mW/m^2
	Total radiation	Mean daily sunshine in growing season	h/day
	Day length	Day length at critical period	hour
		Mean temperature in growing season	
2	Temperature Regime	Mean temperature in coldest month of growing season	^{o}C
		Mean daily maximum of hottest month in growing	^{o}C
		season	^{o}C
3	Moisture availability: Total moisture	Length of growing period	day
		Total rainfall in growing period	mm
		Relative evapotranspiration deficit for growing period	ratio
		Relative crop yield calculated by moisture balance	ratio
		modeling	ratio
	Critical periods	Relative evapotranspiration deficit for critical period	%
	Drought hazar	Probability of significant drought presence of vegetation indicators	
4	Oxygen availability to roots (drainage)	Soil drainage class	Class
		Periods of saturation of root zone (duration and frequency)	Days
		Presence of vegetation indicators	-
5	Nutrient availability	<u>Nutrient levels</u>	
		N	%
		Available P	ppm
		Exchangeable K	meq/100g
		Other:	
		<u>Indicators of availability</u>	
		Reaction	pH
		Ratio Fe_20_3 : clay	ratio

Table B.1 (Continued).

No.	Land quality	Diagnostic criteria	Unit
		Indicators of renewal	
		Weatherable minerals	%
		Total P	meq/100g
		Total K	meq/100g
		Soil parent material	class
		Fertility capability classification	
		Presence of condition modifiers a, h, i, x, k (Appendix E)	presence
		Presence of vegetation indicators	-
6	Nutrient retention capacity	Mean for CEC	meq/100g
		Lower horizons TEB	meq/100g
		Presence of FCC condition modifier	presence
		Texture class, lower horizons	class
7	Rooting conditions	Soil effective depth	cm
		Root penetration class	class
		Stones and gravel	%
		Bulk density	g/cm^3
8	Conditions affecting germination or Establishment	Assessment class	class
		Present erosion	class
9	Air humidity as affecting growth	Mean relative humidity of least humid month in growing season	%
10	Conditions for ripening	Successive dry days	day
		and sunshine hours	hrs
		and/or temperature	^{o}C
11	Flood hazard	Periods of inundation during growing season	day
		Frequency of damaging floods	class
12	Climatic hazards	Occurrence of damaging frosts in growing season	-
		Occurrence of destructive storms in growing season	-
13	Excess of Salts: Salinity	EC of saturation extract (topsoil and lower root zone)	mS/cm
		Total soluble salts	ppm
		Presence of FCC condition modifier s	presence
	Sodicity	ESP	%
		SAR	ratio
		Presence of FCC condition modifier n	presence
14	Soil Toxicities: A 1	A1-saturation	meq/100g
		Reaction	pH
	$CaCO_3$, $CaCO_4$	FCC modifier a	presence
		Depth to carbonate	cm

Table B.1 (Continued).

No.	Land quality	Diagnostic criteria	Unit
	Mn Acid sulphate Other	Depth to gypsum $CaCO_3$ in root zone $CaCO_4$ in root zone	cm % %
15	Pests and Diseases	Pest (known incidence) Disease (known incidence) Climatic indicators Soil indicators	
16	Soil workability	Assessment class Topsoil texture Number of days/yr soil in workable condition	class class days
17	Potential for mechanization	Assessment class Slope	class %
18	Land preparation and clearance requirements	Assessment class Landforms Vegetation class	class class class
19	Conditions for storage and processing	Relative humidity in months following harvest Topsoil texture	% class
20	Conditions affecting timing of production	Day-degrees Date of flowering, harvest	^{o}C x day date
21	Access within the production unit	Terrain class Slope angle exceeded by 33% of slopes	class %
22	Size of potential management units	Minimum size	ha
23	Location : Existing access Potential access	Distance from tarmac/earth road Index of accessibility	km -
24	Erosion hazard	Model to give soil loss (USLE, FAOSDA, SLEMSA, or local) Slope/soil groups Observed erosion	t/ha/yr % class
25	Soil degradation hazard	Dispersion ratio Index of crusting Soil rest period requirement	ratio - %

B.2 Land Use Planning Division

LQ 1 Radiation regime. Solar radiation is essential to the photosynthetic process and also to plant growth. Plant responds linearly to an increase in the radiation up to a certain value, beyond which no further increase occurs. The amount of radiation that is received by plant is controlled by latitude, cloudiness, and slope aspect.

LQ 2 Temperature regime. Plants growth is effected by temperature in three main cases: (i) growth ceases below a critical temperature (varying with the plant but typically about 6.5^{o}C), (ii) rate of the growth varies with the temperature, (iii) very high temperatures have adverse effects to plant growth. So, growth rate then reaches a plateau within the optimum temperature range before falling off at higher temperater.

LQ3 Moisture availability. Crops are affected by moisture availability through the effects of moisture stress on growth, and the possible death of crop through drought. Moisture stress occurs when soil water in the rooting zone fall substantially below the field capacity. Either vegetative growth may suffer or fruiting may be affected, as in oil palm. The severity of the effects of moisture stress varies according to the development stage of the crop. Thus maize is particular sensitive during the flowering (silking) period.

LQ4 Oxygen availability to roots (drainage). Plants need to take in oxygen through their rooting systems, and suffer restricted growth or ultimately death if deprived this oxygen.

LQ5 Nutrient availability. Nutrient availability is the capacity of the soil to supply crops with nutrients. This nutrient supply is shared with oxygen and moisture availability. These three land qualities are the most important ones for rainfed crop production.

LQ6 Nutrient retention. Nutrient retention refers to capacity of the soil to retain added nutrients, as against losses caused by leaching. Plant nutrients are held on soil on exchange sites (cation and anion) which are provided mainly by clay particles, organic matter, clay-humus complex.

LQ7 Rooting conditions. Rooting conditions are controlled by soil effective depth as well as ease of root penetration. Effective depth is the depth to a limiting horizon, e.g., rock. The functions of extracting moisture and nutrients are related to rooting conditions.

LQ11 Flood hazard. Flood hazard refers to the damage by water above the ground surface. Its damage may be caused by standing water and moving water. Standing water (inundation) periods cause damage to crops by depriving them of the oxygen. While moving water can flatten or uproot a crop, or cover it with silt. In addition, damage by salt can come when flooding by sea water.

LQ13 Excess of salts. Salinity or excess of free salts affect crops through inhibiting the uptake of water by osmosis. Moderate salinity levels retard growth and reduce yields, whilst high levels of salinity kill crops and may cause area to barren of plants.

LQ14 Soil toxicities. The crops are affected by toxicities in many ways, for example, calcium carbonate and gypsum can affect plants at high concentration. This situation is most likely to occur in semi-arid regions etc.

LQ16 Soil work ability. Workability, or ease of tillage, depends on several interrelated soil characteristics such as texture, organic matter content. Generally sandy soils are easier to work with than clayey soils, also, moisture content can play an important role over soil work ability.

LQ17 Potential for mechanization. This quality refers to condition of the land which specifically affects mechanized agricultural operation, for examples, slope angle, stoniness or extreme shallowness of the soil, and percent of heavy clays etc.

LQ24 Erosion hazard. The erosion of soil is mainly caused by the surface runoff. When erosion occurs, it can take the nutrient from soil surface which affects crop productivity

APPENDIX C

LAND QUALITY FOR CASSAVA, SUGAR CANE, AND MAIZE

Table C.1 Land qualities for cassava, sugarcane, and maize.

Land quality	Diagnostic criteria	Unit
Temperature regime	- Mean temperature in growing period	^{o}C
Moisture availability	- Ann. rainfall	mm.
Oxygen availability	- Soil drainage	class
Nutrient availability	- N	%
	- P	ppm
	- K	ppm
	- Organic matter	%
	- Nutrient status	class
	- Reaction	pH
Nutrient retention	- C.E.C.	meq/100g
	- B.S.	%
Rooting conditions	- Effective soil depth	cm.
	- Water table depth	cm.
	- Root perpetration	class
Flood hazard	- Frequency	yrs/time
Excess of salt	- EC. of salutation	mmho/cm
Soil toxicities	- Depth of jarosite	cm
Soil workability	- Workability class	class
Potential for mechanization	- Slope	class
	- Rockout crop	class
	- Stoniness	class

Table C.1 (Continued).

Land quality	Diagnostic criteria	Unit
Erosion hazard	- Slope	class
	- Soil loss	ton/rai/yr
Temperature regime	- Mean temperature in growing season	^{o}C
Moisture availability	- Total rainfall in growing season	mm
Nutrient retention capacity	- B.S.	%
	- C.E.C.	meq/100g
Nutrient availability	- N	%
	- P	ppm
	- K	ppm
	- pH	-
Water holding capacity	- Soil texture	-
Rooting conditions	- Root penetration	class
Oxygen availability to roots (drainage)	- Soil drainage class	class
Topography	- Landform	type of landform
	- Slop gradient	%
Temperature regime	- Mean temperature in growing season	^{o}C
Moisture availability	- Average annual rainfall	mm
Water holding capacity	- Soil texture	-
Rooting conditions	- Effective soil depth	cm.
Oxygen availability to roots (drainage)	- Soil drainage class	class
Potential for mechanization	- Slope	%
Nutrient availability	- Soil pH	-
	- Soil fertility	class

APPENDIX D

SUITABILTY CLASSES FOR CASSAVA CULTIVATION AT DISTRIC LEVEL

Table D.1 Suitability classes for cassava cultivation at district level.

District	Area	Suitability class (cassava)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Chaloem Phra Kiat	km^2	54.24	10.91	178.07	11.90	255.12
	%	21.26	4.28	69.80	4.66	100.00
Kaeng Sanam Nang	km^2	33.40	182.58	58.97	3.40	278.35
	%	12.00	65.59	21.18	1.22	100.00
Prathai	km^2	47.94	175.65	262.74	3.24	489.56
	%	9.79	35.88	53.67	0.66	100.00
Bua Yai	km^2	69.36	253.01	130.79	9.20	462.36
	%	15.00	54.72	28.29	1.99	100.00
Bua Lai	km^2	34.31	58.89	55.80	2.79	151.78
	%	17.89	41.13	39.52	1.46	100.00
Sida	km^2	3.66	81.08	84.93	2.63	172.31
	%	2.13	47.06	49.29	1.53	100.00
Ban Lueam	km^2	19.72	129.80	48.17	3.65	201.33
	%	9.79	64.47	23.93	1.81	100.00
Khong	km^2	84.54	362.31	152.23	9.03	608.11
	%	13.90	59.58	25.03	1.49	100.00
Non Daeng	km^2	32.78	32.74	82.24	3.75	151.52
	%	21.64	21.61	54.28	2.47	100.00

Table D.1 (Continued).

District	Area	Suitability class (cassava)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Mueang Yang	km^2	72.20	9.35	160.60	1.60	243.75
	%	29.62	3.83	65.89	0.66	100.00
Phimai	km2	145.05	171.03	485.57	24.96	826.61
	%	17.55	20.69	58.74	3.02	100.00
Kham Sakaesaeng	km2	29.41	224.43	64.18	3.97	321.99
	%	9.13	69.70	19.93	1.23	100.00
Phra Thong Kham	km^2	30.37	193.87	77.74	17.91	319.90
	%	9.49	60.60	24.30	5.60	100.00
Chum Phuang	km^2	114.00	138.83	297.22	33.23	583.28
	%	19.54	23.80	50.96	5.70	100.00
Dan Khun Thot	km^2	93.29	633.74	440.58	133.06	1300.66
	%	7.17	48.72	33.87	10.23	100.00
Lam Thamenchai	km^2	39.71	41.09	148.26	17.85	246.92
	%	16.08	16.64	60.04	7.23	100.00
Non Sung	km^2	72.60	95.45	455.03	1.15	624.23
	%	11.63	15.29	72.89	0.18	100.00
Thepharak	km^2	25.99	168.63	94.27	54.66	343.55
	%	7.57	49.08	27.44	15.91	100.00
Non Thai	km^2	24.89	208.87	262.61	8.87	505.24
	%	4.93	41.34	51.98	1.76	100.00
Huai Thalaeng	km^2	26.60	209.93	218.56	42.63	497.85
	%	5.34	42.17	43.90	8.56	100.00

Table D.1 (Continued).

District	Area	Suitability class (cassava)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Mueang Nakhon Ratchasima	km^2	52.11	77.59	392.71	26.52	548.93
	%	9.49	14.14	71.54	4.83	100.00
Chakkarat	km^2	50.58	148.91	272.19	45.41	517.07
	%	9.78	28.80	52.64	8.78	100.00
Kham Thale So	km^2	38.10	54.35	79.13	1.03	172.60
	%	17.92	34.97	46.63	0.48	100.00
Sikhio	km^2	84.31	304.74	345.98	301.28	1036.31
	%	8.14	29.41	33.39	29.07	100.00
Sung Noen	km^2	104.83	227.37	276.40	109.31	717.92
	%	14.60	31.67	38.50	15.23	100.00
Chok Chai	km^2	133.18	140.95	153.67	74.28	502.06
	%	26.53	28.07	30.61	14.79	100.00
Pak Chong	km^2	291.63	287.08	191.96	488.27	1258.95
	%	23.16	22.80	15.25	38.78	100.00
Nong Bun Nak	km^2	270.91	144.52	26.98	74.59	517.00
	%	52.40	27.95	5.22	14.43	100.00

Table D.2 Suitability classes for sugarcane cultivation at district level.

District	Area	Suitability class (sugarcane)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Pak Thong Chai	km^2	172.18	230.39	252.36	229.03	883.94
	%	19.48	26.06	28.55	25.91	100.00
Khon Buri	km^2	269.33	204.64	273.97	695.84	1443.64
	%	18.48	13.87	18.81	48.86	100.00
Wang Nam Khiao	km^2	49.41	124.69	158.76	455.94	788.79
	%	5.26	15.32	19.87	59.55	100.00
Soeng Sang	km^2	191.62	134.83	203.42	256.64	786.55
	%	24.36	17.14	25.86	32.63	100.00
Chaloem Phra Kiat	km^2	27.95	169.13	53.80	4.25	255.12
	%	10.95	66.29	21.09	1.66	100.00
Kaeng Sanam Nang	km^2	51.67	165.78	60.85	0.04	278.35
	%	18.56	59.56	21.86	0.01	100.00
Prathai	km^2	26.10	76.44	384.93	2.09	489.56
	%	5.33	15.61	78.63	0.43	100.00
Bua Yai	km^2	63.83	195.35	202.20	0.97	462.36
	%	13.81	42.25	43.73	0.21	100.00
Bua Lai	km^2	35.97	30.69	84.93	0.19	151.78
	%	18.75	16.00	65.14	0.10	100.00
Sida	km^2	2.54	47.16	122.43	0.19	172.31
	%	1.47	27.37	71.05	0.11	100.00
Ban Lueam	km^2	38.88	107.20	55.08	0.17	201.33
	%	19.31	53.25	27.36	0.09	100.00
Khong	km^2	164.55	256.12	186.95	0.49	608.11
	%	27.06	42.12	30.74	0.08	100.00
Non Daeng	km^2	28.97	34.05	88.50	0.00	151.52
	%	19.12	22.47	58.41	0.00	100.00

Table D.2 (Continued).

District	Area	Suitability class (sugarcane)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Mueang Yang	km^2	29.17	45.95	164.72	3.91	243.75
	%	11.97	18.85	67.58	1.60	100.00
Phimai	km^2	90.26	237.23	469.65	29.47	826.61
	%	10.92	28.70	56.82	3.57	100.00
Kham Sakaesaeng	km^2	161.08	72.86	87.52	0.53	321.99
	%	50.03	22.63	27.18	0.16	100.00
Phra Thong Kham	km^2	141.54	80.79	96.38	1.18	319.90
	%	44.25	25.26	30.13	0.37	100.00
Chum Phuang	km^2	108.69	232.25	225.23	17.11	583.28
	%	18.63	39.82	38.61	2.93	100.00
Dan Khun Thot	km^2	395.81	632.61	262.24	10.00	1300.66
	%	30.43	48.64	20.16	0.77	100.00
Lam Thamenchai	km^2	31.11	130.53	83.91	1.37	246.92
	%	12.60	52.86	33.98	0.56	100.00
Non Sung	km^2	98.67	86.85	438.71	0.00	624.23
	%	15.81	13.91	70.28	0.00	100.00
Thepharak	km^2	91.26	192.29	52.01	7.99	343.55
	%	26.56	55.97	15.14	2.32	100.00
Non Thai	km^2	124.72	107.67	272.83	0.02	505.24
	%	24.68	21.31	54.00	0.01	100.00
Huai Thalaeng	km^2	24.41	149.77	251.95	71.72	497.85
	%	4.90	30.08	50.61	14.41	100.00
Mueang Nakhon Ratchasima	km^2	48.53	264.81	223.11	12.48	548.93
	%	8.84	48.24	40.64	2.27	100.00

Table D.2 (Continued).

District	Area	Suitability class (sugarcane)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Chakkarat	km^2	35.29	300.51	150.24	31.02	517.07
	%	6.82	58.12	29.06	6.00	100.00
Kham Thale So	km^2	33.72	83.65	55.23	0.00	172.60
	%	15.86	53.46	30.68	0.00	100.00
Sikhio	km^2	120.66	747.34	121.91	46.39	1036.31
	%	11.64	72.12	11.76	4.48	100.00
Sung Noen	km^2	118.51	462.90	124.17	12.34	717.92
	%	16.51	64.48	17.30	1.72	100.00
Chok Chai	km^2	40.66	316.97	112.69	31.75	502.06
	%	8.10	63.13	22.45	6.32	100.00
Pak Chong	km^2	595.88	460.52	124.82	77.74	1258.95
	%	47.33	36.58	9.91	6.17	100.00
Nong Bun Nak	km^2	245.58	93.72	166.92	10.78	517.00
	%	47.50	18.13	32.29	2.08	100.00
Pak Thong Chai	km^2	39.75	640.25	129.71	74.27	883.94
	%	4.50	72.43	14.67	8.40	100.00
Khon Bur	km^2	278.15	583.39	321.34	260.89	1443.64
	%	19.10	40.85	22.18	17.87	100.00
Wang Nam Khiao	km^2	65.33	441.77	167.45	114.25	788.79
	%	7.39	57.66	21.03	13.92	100.00
Soeng Sang	km^2	201.71	397.16	145.63	41.89	786.55
	%	25.64	50.49	18.52	5.33	100.00

Table D.3 Suitability classes for maize cultivation at district level.

District	Area	Suitability class (maize)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Chaloem Phra Kiat	km^2	15.08	13.41	214.30	12.34	255.12
	%	5.91	5.26	84.00	4.84	100.00
Kaeng Sanam Nang	km^2	5.44	140.91	112.32	19.68	278.35
	%	1.95	50.62	40.35	7.07	100.00
Prathai	km^2	4.76	54.77	346.71	83.33	489.56
	%	0.97	11.19	70.82	17.02	100.00
Bua Yai	km^2	21.97	136.59	249.31	54.49	462.36
	%	4.75	29.54	53.92	11.79	100.00
Bua Lai	km^2	35.55	18.16	76.11	21.97	151.78
	%	18.54	9.47	55.33	16.67	100.00
Sida	km^2	1.06	42.61	96.98	31.66	172.31
	%	0.62	24.73	56.28	18.37	100.00
Ban Lueam	km^2	6.10	87.25	89.69	18.29	201.33
	%	3.03	43.33	44.55	9.08	100.00
Khong	km^2	4.17	195.40	372.75	35.80	608.11
	%	0.69	32.14	61.31	5.89	100.02
Non Daeng	km^2	14.96	34.98	94.65	6.93	151.52
	%	9.87	23.08	62.47	4.57	100.00
Mueang Yang	km^2	1.39	28.21	201.00	13.14	243.75
	%	0.57	11.57	82.46	5.39	100.00
Phimai	km^2	27.05	88.01	657.00	54.55	826.61
	%	3.27	10.65	79.48	6.60	100.00
Kham Sakaesaeng	km^2	1.37	37.76	274.09	8.78	321.99
	%	0.42	11.73	85.12	2.73	100.00
Phra Thong Kham	km^2	16.27	67.76	215.70	20.17	319.90
	%	5.08	21.18	67.43	6.31	100.00
Chum Phuang	km^2	23.99	117.01	305.80	136.48	583.28
	%	4.11	20.06	52.43	23.40	100.00

Table D.3 (Continued).

District	Area	Suitability class (maize)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Dan Khun Thot	km^2	26.27	271.46	784.30	218.63	1300.66
	%	2.02	20.87	60.30	16.81	100.00
Lam Thamenchai	km^2	6.35	45.78	120.98	73.81	246.92
	%	2.57	18.54	49.00	29.89	100.00
Non Sung	km^2	6.36	35.22	577.95	4.70	624.23
	%	1.02	5.64	92.59	0.75	100.00
Thepharak	km^2	39.14	60.66	134.14	109.60	343.55
	%	11.39	17.66	39.05	31.90	100.00
Non Thai	km^2	3.41	60.45	414.75	26.63	505.24
	%	0.67	11.96	82.09	5.27	100.00
Huai Thalaeng	km^2	5.83	96.16	234.51	161.36	497.85
	%	1.17	19.31	47.10	32.41	100.00
Mueang Nakhon Ratchasima	km^2	22.05	79.78	418.08	29.02	548.93
	%	4.02	14.53	76.16	5.29	100.00
Chakkarat	km^2	8.15	105.32	306.06	97.54	517.07
	%	1.58	20.37	59.19	18.86	100.00
Kham Thale So	km^2	7.76	58.07	103.32	3.45	172.60
	%	3.65	27.31	67.41	1.62	100.00
Sikhio	km^2	52.95	196.05	408.13	379.18	1036.31
	%	5.11	18.92	39.38	36.59	100.00
Sung Noen	km^2	92.39	134.67	324.23	166.62	717.92
	%	12.87	18.76	45.16	23.21	100.00

Table D.3 (Continued).

District	Area	Suitability class (maize)				Total
		High (S1)	Moderate (S2)	Marginal (S3)	Not suitable (N)	
Chok Chai	km^2	26.63	66.79	324.92	83.73	502.06
	%	5.30	13.30	64.72	16.68	100.00
Pak Chong	km^2	198.07	398.70	325.76	336.42	1258.95
	%	15.73	31.67	25.88	26.72	100.00
Nong Bun Nak	km^2	232.40	50.59	206.22	27.78	517.00
	%	44.95	9.79	39.89	5.37	100.00
Pak Thong Chai	km^2	14.71	171.94	367.61	329.69	883.94
	%	1.66	19.45	41.59	37.30	100.00
Khon Buri	km^2	227.71	159.80	342.22	714.04	1443.64
	%	15.51	10.67	23.67	50.16	100.00
Wang Nam Khiao	km^2	18.70	148.73	228.40	392.96	788.79
	%	1.16	18.53	29.17	51.14	100.00
Soeng Sang	km^2	181.95	88.56	213.65	302.25	786.55
	%	23.13	11.26	27.16	38.43	100.00

CURRICULUM VITAE

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