รายงานวิจัยฉบับสมบูรณ์

โครงการ “ฟุตพริ้นท์น้ำของพืชอาหาร อาหารสัตว์ และพลังงาน เพื่อจัดการทรัพยากรน้ำอย่างมีประสิทธิภาพ”

(Water footprinting of food, feed and fuel for effective water resource management)

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Water footprinting of food, feed and fuel for effective water resource management

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สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย (สกว.)

(ความเห็นในรายงานนี้เป็นของผู้วิจัย สกว. ไม่จำเป็นต้องเห็นด้วยเสมอไป)

บทคัดย่อ

ความต้องการอาหารที่เพิ่มสูงขึ้นเนื่องจากการเพิ่มขึ้นของประชากร และการขยายตัวอย่างรวดเร็วของการผลิตและการใช้พลังงานชีวมวลในช่วงที่ผ่านมา ก่อให้เกิดความกังวลเกี่ยวกับความตึงเครียดด้านน้ำซึ่งจัดเป็นทรัพยากรที่สำคัญอย่างยิ่งสำหรับประเทศไทยซึ่งมีอุตสาหกรรมการเกษตรเป็นพื้นฐาน โดยเป็นแหล่งผลิตอาหารเพื่อการบริโภคทั้งภายในประเทศและส่งออก รวมถึงเป็นแหล่งผลิตวัตถุดิบเพื่อใช้สำหรับการผลิตอาหารสัตว์ และเชื้อเพลิง (เชื้อเพลิงชีวภาพ) การศึกษานี้จึงได้ประยุกต์ใช้แนวคิดของวอเตอร์ฟุตพริ้นท์ (Water footprint: WF) เพื่อประเมินหาปริมาณการใช้น้ำของพืชอาหาร อาหารสัตว์ และเชื้อเพลิงที่สำคัญในประเทศไทย พร้อมกับการประเมินหาตัวชี้วัดความตึงเครียดด้านน้ำ (Water stress index: WSI) ของ 25 ลุ่มน้ำที่สำคัญของไทยเพื่อใช้สำหรับบ่งชี้ถึงโอกาสการเกิดการแย่งชิงทรัพยากรน้ำที่มีอยู่อย่างจำกัดในแต่ละพื้นที่ ซึ่งแผนที่ความตึงเครียดด้านน้ำ (Water stress map) ที่ได้จากการศึกษาบ่งชี้ว่าลุ่มน้ำที่มีค่าตัวชี้วัดความตึงเครียดด้านน้ำสูงที่สุด คือ ลุ่มน้ำมูล ตามด้วยลุ่มน้ำชี เจ้าพระยา และท่าจีน ตามลำดับ ขณะที่ผลการประเมินค่าความต้องการใช้น้ำของพืชเศรษฐกิจที่สำคัญจำนวน 10 ชนิด เช่น ข้าว มันสำปะหลัง อ้อย ปาล์มน้ำมัน และถั่วเหลือง เป็นต้น พบว่าจะมีค่าแตกต่างกันอย่างมากในแต่ละพื้นที่ซึ่งเกิดจากหลายปัจจัยด้วยกัน

การศึกษานี้ยังได้ทำการประเมินถึงโอกาสของการเกิดผลกระทบด้านการตึงเครียดและการแย่งชิงน้ำ (Water deprivation impact) อันเนื่องมาจากนโยบายการผลิตและการใช้เอทานอลของไทย ซึ่งผลการศึกษาพบว่า WF ของเอทานอลมีค่าอยู่ระหว่าง 1,396-3,105 ลิตรต่อลิตรเอทานอล โดยเอทานอลจากมันสำปะหลังมีค่า WF สูงที่สุดตามด้วยเอทานอลจากกากน้ำตาลและอ้อย อย่างไรก็ตาม หากพิจารณาเฉพาะความต้องการใช้น้ำชลประทาน (Blue WF) เอทานอลจากกากน้ำตาลมีค่า Blue WF สูงสุด คือ 699-1,220 ลิตร/ลิตรเอทานอล ขณะที่เอทานอลจากมันสำปะหลังและอ้อยจะมีค่าใกล้เคียงกันคือในช่วง 449-566 และ 450-859 ลิตร/ลิตรเอทานอล ตามลำดับ และเพื่อให้สามารถผลิตวัตถุดิบได้พอเพียงสำหรับเป้าหมายของแผนการพัฒนาพลังงานทดแทนในปี 2021 พบว่า จะมีความต้องการน้ำชลประทานเพิ่มขึ้นอีกประมาณ 1,625 ล้าน ลบ.ม. หรือคิดเป็นร้อยละ 3 ของปริมาณน้ำชลประทานที่ใช้การได้ในปัจจุบัน โดยมีลุ่มน้ำมูลและชี ซึ่งอยู่ในภาคตะวันออกเฉียงเหนือเป็นพื้นที่โอกาสเกิดความตึงเครียดด้านทรัพยากรน้ำสูงอันเนื่องมาจากการส่งเสริมการผลิตเอทานอลของไทย

กล่าวโดยสรุป การประเมินวอเตอร์ฟุตพริ้นท์และตัวชี้วัดความตึงเครียดด้านน้ำ เป็นเครื่องมือที่สำคัญสำหรับการบ่งชี้ถึงพื้นที่ที่มีโอกาสเกิดความตึงเครียดด้านน้ำสูงอันเกิดจากการขยายตัวของกิจกรรมในภาคการเกษตรในอนาคต รวมถึงช่วยในการประเมินหามาตรการสำหรับการวางแผนและจัดการทรัพยากรน้ำเพื่อการผลิตอาหาร อาหารสัตว์ และพลังงานอย่างยั่งยืนในอนาคต โดยโครงการฯ ได้นำเสนอมาตรการต่างๆ ที่จะช่วยส่งเสริมให้เกิดประสิทธิภาพด้านน้ำและการจัดการทรัพยากรน้ำสำหรับการเกษตรของไทย อันจะช่วยบรรเทาปัญหาการเกิดความตึงเครียดหรือการแย่งชิงน้ำสำหรับการผลิตอาหาร อาหารสัตว์ และพลังงานในอนาคต

Abstract

Increasing demand of agriculture with rising population and consequent increased demand of food and more recently, the proliferation of biomass-based energy promises to increase stress on water, an already scarce resource. This is of particular concern to Thailand which has a large agricultural base both for food for local consumption and export as well as for feed and fuel (bio-fuels). The study has applied the water footprint concept to evaluate the consumptive water use for 10 major food, feed, fuel crops in Thailand e.g. rice, cassava, sugarcane, oil palm, soybean and others. In addition, the water stress index (WSI) of 25 major watersheds of Thailand has also been evaluated to indicate the competitive pressure on water resources availability in a specific region. The water stress map classified by WSI criteria set in the study pointed out that the watershed that has the highest WSI is Mun followed by Chi, Chaopraya, and Thachin, respectively. While, there is a large variation of WF results of crops grown in different provinces due to several factors.

As the promotion of bioethanol in Thailand raises concerns on the possibility of increased stress on water, particularly vis-à-vis competition for food, feed and fuel. The study has applied the WF assessment and the WSI developed for 25 major watersheds of Thailand to determine the water deprivation impact potentials from bioethanol production in Thailand as a case study. The results show that the water footprint of bioethanol in Thailand varies between 1,396-3,105 L water/L ethanol with cassava ethanol having the highest WF followed by molasses and sugarcane ethanol. Nevertheless, in terms of blue water consumption, important for water resources management, molasses is the highest at around 699-1,220 L/L ethanol, followed by sugarcane and cassava at 450-859 and 449-566 L/L ethanol, respectively. To satisfy the AEDP's target of bioethanol production in 2021, around 1,625 million m^3 of irrigation water/year will be additionally required. The Mun and Chi watersheds in Northeast Thailand would have a significant increase in irrigation water demand that could potentially lead to pressures on water stress and competition with other users.

In summary, the WF assessment and the WSI index can provide the useful information for identification of the potential areas of water stress due to the expansion of agricultural activities and for determining the measures for improving water resource planning and management for sustainable food, feed, and fuel crops production in the future. Several measures are also recommended in the report to enhance the water efficiency and water resource management for agricultural sector in Thailand and to mitigate the water completion for food, feed, fuel production in the future.

บทสรุปผู้บริหาร

โครงการ “ฟุตพริ้นท์น้ำของพืชอาหาร อาหารสัตว์ และพลังงาน เพื่อจัดการทรัพยากรน้ำอย่างมีประสิทธิภาพ” ดำเนินการโดยบัณฑิตวิทยาลัยร่วมด้านพลังงานและสิ่งแวดล้อม มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี ร่วมกับมหาวิทยาลัยเกษตรศาสตร์ และสถาบันเทคโนโลยีแห่งเอเชีย ภายใต้การสนับสนุนเงินทุนวิจัยจากฝ่ายเกษตร สำนักงานกองทุนสนับสนุนการวิจัย ตามสัญญาเลขที่ RDG5520028 โดยมีวัตถุประสงค์เพื่อศึกษา water footprint ของพืชอาหาร อาหารสัตว์ และพลังงานที่สำคัญของประเทศไทย และเพื่อประเมินสถานการณ์และโอกาสการเกิด water stress โดยผลการศึกษาจะนำไปสู่การจัดข้อเสนอแนะเพื่อการจัดการทรัพยากรน้ำอย่างยั่งยืนในอนาคต โดยมีรายละเอียดขอบเขตการศึกษา และผลการศึกษา โดยสรุปดังนี้

1. ระเบียบวิธีการศึกษาวิจัย

1.1 วอเตอร์ฟุตพริ้นท์ (Water footprint: WF) เป็นเครื่องมือหนึ่งที่นิยมใช้อย่างกว้างขวางในปัจจุบัน เพื่อประเมินปริมาณและประสิทธิภาพการใช้น้ำของผลิตภัณฑ์ โดยนิยมวัดในหน่วยของปริมาณน้ำต่อตันผลิตภัณฑ์ เช่น ลบ.ม./ตันผลิตภัณฑ์ ซึ่งหลักการประเมิน WF ที่นำเสนอโดย Hoekstra (2003) เป็นการประเมิน WF ของผลิตภัณฑ์โดยพิจารณาถึงปริมาณการใช้น้ำตลอดสายโซ่การผลิตผลิตภัณฑ์นั้นๆ ซึ่งปริมาณการใช้น้ำดังกล่าวจะถูกแยกออกเป็น 3 ประเภท ได้แก่ Green water ซึ่งจะแสดงถึงปริมาณน้ำฝนใช้การในการผลิตผลิตภัณฑ์ Blue water แสดงถึงปริมาณการใช้น้ำชลประทานในการผลิตผลิตภัณฑ์ และ Grey water แสดงถึงปริมาณการใช้น้ำเพื่อเจือจางผลกระทบของน้ำเสียที่เกิดขึ้นจากกระบวนการผลิตเพื่อให้เป็นไปมาตรฐานที่กำหนด ซึ่งในการศึกษานี้จะมุ่งเน้นที่การประเมินหาปริมาณการใช้น้ำ (Consumptive use) ทั้งในส่วนของ Green water และ Blue water ของพืชอาหาร อาหารสัตว์ และพลังงานที่สำคัญของประเทศไทยจำแนกตามรายจังหวัดและปฏิทินการปลูกพืช เพื่อให้สามารถประเมินได้ถึงความต้องการใช้น้ำของพืชโดยรวม และความต้องการใช้น้ำชลประทานในแต่ละพื้นที่การเพาะปลูกพืชเศรษฐกิจสำคัญ ในขณะที่ Grey water จะไม่ถูกพิจารณาในการวิจัยนี้เนื่องจากมีวิธีประเมินผลกระทบด้านน้ำเสียที่เหมาะสมกว่าในปัจจุบัน เช่น การประเมินผลกระทบด้าน Eutrophication หรือ Ecotoxicity เป็นต้น

1.2 ตัวชี้วัดความตึงเครียดด้านน้ำ (Water stress index: WSI) เป็นเครื่องมือหนึ่งที่นิยมใช้เพื่อประเมินระดับความตึงเครียดด้านน้ำในละพื้นที่ ซึ่งในการศึกษานี้ได้อ้างอิงหลักการประเมิน WSI ของ Pfister et al. (2010) เป็นหลักการประเมินหาค่า WSI เพื่อใช้สำหรับเป็นพื้นฐานในการวิเคราะห์เพื่อคำนวณหาผลกระทบขั้นกลางและขั้นปลายอันเกิดจากการใช้น้ำ (water use impacts) ตามหลักการของการประเมินวัฏจักรชีวิต (Life cycle assessment: LCA) ต่อไป โดยการศึกษานี้ได้ทำการประเมินหาค่า WSI ในระดับลุ่มน้ำ (Watershed) กล่าวคือ 25 ลุ่มน้ำที่สำคัญของประเทศไทย โดยตัวชี้วัดดังกล่าวนี้ถูกคำนวณจากสัดส่วนของปริมาณความต้องการใช้น้ำต่อปีเทียบกับปริมาณ

ทรัพยากรน้ำที่มีอยู่ในแต่ละลุ่มน้ำ ประกอบกับปัจจัยด้านการแปรปรวนของปริมาณน้ำฝนในแต่ละพื้นที่ โดยผลการประเมินสามารถจำแนกระดับความตึงเครียดด้านน้ำออกเป็น 5 ระดับ ดัง**ตารางที่ 1**

ตารางที่ 1 การจำแนกระดับความตึงเครียดด้านน้ำ โดยอ้างอิงจากค่า WSI (Pfister et al., 2009)

ระดับความตึงเครียดด้านน้ำ	ค่าตัวชี้วัด WSI
รุนแรงมาก (Extreme)	> 0.9
รุนแรง (Severe)	< 0.9
ตึงเครียด (Stress)	0.5
ปานกลาง (Moderate)	0.1 – < 0.5
ต่ำ (Low)	< 0.1

2. สรุปผลการศึกษา

2.1 ความต้องการใช้น้ำของพืชอาหาร อาหารสัตว์ และพลังงานที่สำคัญของประเทศไทย

ตารางที่ 2 แสดงผลการประเมินเปรียบเทียบค่าความต้องการใช้น้ำของพืชอาหาร อาหารสัตว์ และพลังงานที่สำคัญของไทย โดยพบว่าค่าความต้องการใช้น้ำของพืชมีความแตกต่างกันในแต่ละพื้นที่เพาะปลูก เนื่องจากปัจจัยด้านปริมาณฝน สภาพภูมิอากาศในแต่ละพื้นที่ และที่สำคัญได้แก่ปริมาณผลผลิตต่อไร่ในแต่ละพื้นที่ซึ่งมีความแตกต่างกัน แต่อย่างไรก็ตามปริมาณความต้องการใช้น้ำในตารางที่ 2 นี้เป็นความต้องการใช้น้ำของพืชในทางทฤษฎีซึ่งในทางความเป็นจริงค่าความต้องการใช้น้ำของพืชต่างๆ จะต่ำกว่านี้เนื่องจากส่วนใหญ่การเพาะปลูกพืชหลายประเภทเป็นการปลูกในพื้นที่นอกเขตชลประทาน

ตารางที่ 2 ผลเปรียบเทียบความต้องการใช้น้ำของพืชที่สำคัญของไทย[1]

พืชเศรษฐกิจที่สำคัญ	ค่าเฉลี่ยความต้องการใช้น้ำ (ลบ.ม./ไร่)	ช่วง (ลบ.ม./ไร่)	ค่าเฉลี่ยความต้องการใช้น้ำ (ลบ.ม./ตันผลผลิต)	ช่วง (ลบ.ม./ตันผลผลิต)
ข้าวนาปี	849	780 - 891	1,825	1,333 – 2,401
ข้าวนาปรัง	892	865 - 932	1,495	1,254 – 1,811
ข้าวโพดเลี้ยงสัตว์	609	572 – 666	932	823 – 1,036
มันสำปะหลัง	1,243	1,215 – 1,260	402	395 – 406
อ้อย	1,647	1,614 – 1,682	136	131 – 138
ปาล์มน้ำมัน*	2,184	2,141 – 2,227	1,015* [2,195]	905 – 5,306*

[1] ข้อมูลความต้องการใช้น้ำของพืชในตารางที่ 2 แสดงค่าผลรวมความต้องการใช้น้ำรวมทั้งหมดของพืช

พืชเศรษฐกิจที่สำคัญ	ค่าเฉลี่ยความต้องการใช้น้ำ (ลบ.ม./ไร่)	ช่วง (ลบ.ม./ไร่)	ค่าเฉลี่ยความต้องการใช้น้ำ (ลบ.ม./ตันผลผลิต)	ช่วง (ลบ.ม./ตันผลผลิต)
ถั่วเหลือง	500	451 – 549	1,755	1,581 – 2,011
ถั่วเขียว	275	229 – 367	2,588	2,045 – 3,989
มะพร้าว	2,170	2,096 – 2,227	2,366	2,074 – 2,666
สัปปะรด	2,170	2,099 - 2,227	682	611 - 783
ถั่วลิสง	509	460 - 556	2,121	1,742 – 2,780

หมายเหตุ: *ค่าเฉลี่ยความต้องการใช้น้ำต่อตันผลผลิตปาล์มน้ำมัน 1,105 ลบ.ม./ตันคำนวณมาจากค่าเฉลี่ยไม่นับรวมภาคตะวันภาคตะวันออกเฉียงเหนือและภาคเหนือที่เพิ่งเริ่มปลูกปาล์มน้ำมันในระยะแรกซึ่งยังไม่มีการให้ผลผลิตหรือมีผลผลิตที่ต่ำอยู่ ขณะที่อีกค่าหนึ่งคือ 2,195 ลบ.ม./ตัน เป็นค่าเฉลี่ยนับรวมทุกภาค

2.2 ความต้องการใช้น้ำ Blue water ของพืชอาหาร อาหารสัตว์ และพลังงานที่สำคัญของประเทศไทย

ตารางที่ 3 แสดงผลเปรียบเทียบความต้องการใช้น้ำ Blue water หรือ ความต้องการใช้น้ำชลประทานสำหรับการปลูกพืชแต่ละชนิด ซึ่งจัดเป็นประเด็นที่สำคัญในมุมมองของอุทกวิทยา และเป็นข้อมูลที่จำเป็นสำหรับการบริหารจัดการทรัพยากรน้ำโดยเฉพาะช่วงหน้าแล้ง โดยผลการประเมินชี้ให้เห็นถึงความต้องการใช้น้ำชลประทานต่อตันผลิตภัณฑ์ของพืชแต่ละชนิด ซึ่งมีความแตกต่างกันไปในแต่ละพื้นที่เพาะปลูก โดยพบว่า การปลูกพืชเศรษฐกิจในภาคตะวันออกเฉียงเหนือ เช่น ข้าวนาปรัง ข้าวโพดเลี้ยงสัตว์ และอ้อย มีค่าความต้องการใช้น้ำชลประทานค่อนข้างสูงเมื่อเทียบกับภาคอื่นๆ ซึ่งหมายถึงว่า เมื่อเทียบกับปริมาณน้ำฝนใช้การที่มีอยู่ปัจจุบันยังไม่พอเพียงกับความต้องการใช้น้ำของพืชในทางทฤษฎี จึงมีความจำเป็นอย่างยิ่งที่จะต้องขยายพื้นที่ชลประทานในภาคตะวันออกเฉียงเหนือเพื่อให้เพียงพอกับความต้องการใช้น้ำของพืช รวมถึงเพื่อให้เกิดการพัฒนาประสิทธิภาพด้านการเกษตร โดยเฉพาะอย่างยิ่งการขยายพื้นที่เพาะปลูกพืชพลังงาน เช่น ปาล์มน้ำมันซึ่งมีความต้องการใช้น้ำสูง การขยายพื้นที่เพาะปลูกปาล์มน้ำมันไปในภาคอื่นๆ เช่น ภาคเหนือและภาคตะวันออกเฉียงเหนือจึงมีความจำเป็นที่จะต้องพิจารณาถึงความเหมาะสมด้านปริมาณน้ำฝนและระบบชลประทาน เพราะความต้องการน้ำชลประทานที่สูงย่อมนำไปสู่ต้นทุนการเพาะปลูกพืชที่สูงขึ้นด้วย แต่อย่างไรก็ตามค่าปริมาณการใช้น้ำจริงๆ ของพืชหลายชนิด เช่น อ้อย และมันสำปะหลังจะมีค่าต่ำกว่าค่าความต้องการใช้น้ำชลประทานที่แสดงในตารางที่ 3 เนื่องจากส่วนใหญ่เป็นการปลูกในพื้นที่นอกเขตชลประทาน

ตารางที่ 3 ผลเปรียบเทียบความต้องการใช้น้ำ Blue water ของพืชที่สำคัญของไทย[2]

พืชเศรษฐกิจที่สำคัญ	ค่าเฉลี่ยความต้องการใช้น้ำ blue water (ลบ.ม. blue water/ตันผลิตภัณฑ์)		ช่วง (ลบ.ม. blue water/ตันผลิตภัณฑ์)
	ฤดูแล้ง	ฤดูฝน	
ข้าวนาปี	-	466	284 (N) – 928 (S)
ข้าวนาปรัง	1,107	-	915 (S) – 1,571 (NE)
ข้าวโพดเลี้ยงสัตว์	808	-	672 (N) – 921 (NE)
มันสำปะหลัง	65	10	54 (N) – 98 (C)
อ้อย	23	11	22 (N) – 49 (NE)
ปาล์มน้ำมัน*	331 (846)	61 (59)	199 (S) – 2,114 (N)
ถั่วเหลือง	1,542	-	1,461 (C) – 1,790 (NE)
ถั่วเขียว	1,856	14	89 (S) – 3,804 (NE)
มะพร้าว	819	110	587 (S) – 1,177 (NE)
สัปปะรด	234	32	172 (S) – 326 (C)
ถั่วลิสง	1,367	6	208 (S) – 2,063 (NE)

หมายเหตุ: N: ภาคเหนือ; NE: ภาคตะวันออกเฉียงเหนือ; S: ภาคใต้; C: ภาคกลาง

*ค่าเฉลี่ยความต้องการใช้น้ำ Blue water ต่อตันผลผลิตปาล์มน้ำมัน 331 และ 61 ลบ.ม./ตันคำนวณมาจากค่าเฉลี่ยไม่นับรวมภาคตะวันภาคตะวันออกเฉียงเหนือและภาคเหนือ ขณะที่ค่าในวงเล็บ คือ 846 และ 59 ลบ.ม./ตัน เป็นค่าเฉลี่ยนับรวมทุกภาค

2.3 ผลการประเมินผลิตภาพด้านน้ำ (Water productivity)

ตารางที่ 4 แสดงผลเปรียบเทียบผลิตภาพด้านน้ำของพืชเศรษฐกิจที่สำคัญ โดยอ้างอิงจากราคาสินค้าเกษตรที่เกษตรกรขายได้ปี 2553/2554 และรายได้สุทธิของเกษตรกร (หลังหักต้นทุนการผลิต) จากผลิตภัณฑ์สินค้าเกษตรเทียบต่อปริมาณความต้องการใช้น้ำชลประทาน จากผลการประเมินพบว่าพืชที่ให้ผลิตภาพด้านน้ำสูงมีหลายชนิด เช่น มันสำปะหลัง อ้อย สับปะรด และถั่วเขียว แต่อย่างไรก็ตามค่าผลิตภาพดังกล่าวย่อมแปรเปลี่ยนไปตามปัจจัยหลายด้าน โดยเฉพาะด้านราคาสินค้าเกษตรซึ่งขึ้นกับหลายปัจจัย เช่น สภาพอากาศในแต่ละปี โรคระบาด และความต้องการในตลาด

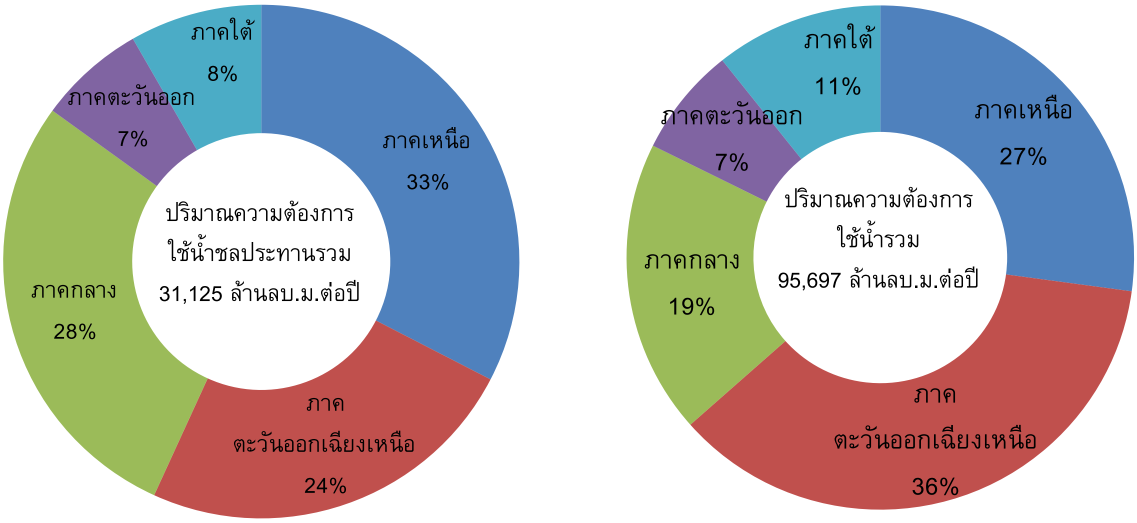
[2] ข้อมูลในตารางที่ 3 แสดงเฉพาะค่าความต้องการใช้น้ำชลประทาน หรือ Blue water ของพืชเท่านั้น จึงมีค่าน้อยกว่าค่าความต้องการใช้น้ำรวมของพืชในตารางที่ 2

ตารางที่ 4 เปรียบเทียบผลิตภาพด้านน้ำของพืชอาหาร อาหารสัตว์ และพลังงานที่สำคัญของไทย

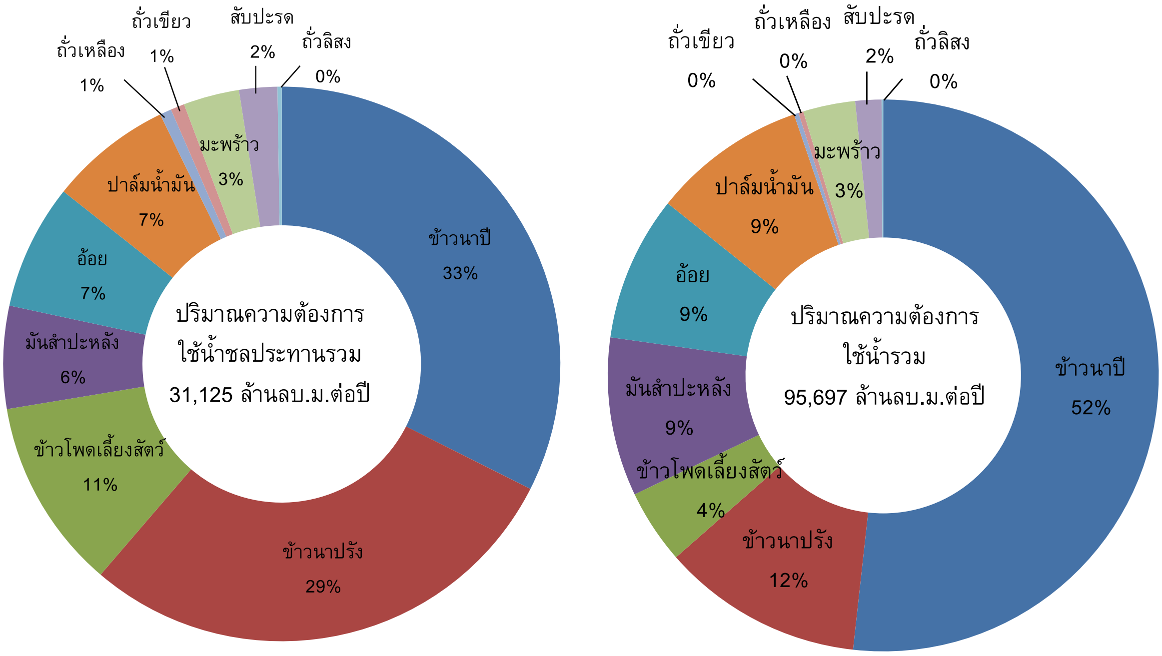
พืชเศรษฐกิจที่สำคัญ	ราคาสินค้าเกษตร/ปริมาณการใช้น้ำชลประทาน (บาท/ลบ.ม. Blue water)	รายได้สุทธิของเกษตรกร/ปริมาณการใช้น้ำชลประทาน (บาท/ลบ.ม. Blue water)
ข้าวนาปี	18	1
ข้าวนาปรัง	8	1
ข้าวโพดเลี้ยงสัตว์	7	3
มันสำปะหลัง	25	3
อ้อย	29	5
ปาล์มน้ำมัน	11	3
ถั่วเหลือง	10	3
ถั่วเขียว	18	8
มะพร้าว	5	3
สับปะรด	21	7
ถั่วลิสง	15	3

2.4 ประมาณการณ์ความต้องการใช้น้ำสำหรับการเกษตรในภาพรวมของประเทศไทย

จากสถิติการเกษตรประจำปี 2553/2554 และค่าความต้องการใช้น้ำของพืชอาหาร อาหารสัตว์ และพลังงานที่สำคัญของไทยจำนวน 10 ชนิด สามารถประเมินปริมาณความต้องการใช้น้ำชลประทานทางการเกษตรเป็นรายภาค และรายผลิตภัณฑ์เกษตรได้ดังรูปที่ 1 และ 2 ตามลำดับ โดยปริมาณความต้องการใช้น้ำรวมทั้งหมดมากที่สุดอยู่ที่ภาคตะวันออกเฉียงเหนือ แต่อย่างไรก็ตามหากพิจารณาเฉพาะความต้องการใช้น้ำชลประทานสำหรับจะอยู่ที่ประมาณ 31,125 ล้านลบ.ม.ต่อปี โดยภาคเหนือ มีความต้องการใช้น้ำชลประทานมากที่สุด ตามมาด้วยภาคกลาง ภาคตะวันออกเฉียงเหนือ ภาคตะวันออก และภาคใต้ตามลำดับ ในขณะที่หากพิจารณาถึงพื้นที่การเกษตรทั้งหมดของประเทศไทยกล่าว (ประมาณ 152 ล้านไร่) จะพบว่าภาคตะวันออกเฉียงเหนือมีพื้นที่การเกษตรมากที่สุดคิดเป็นร้อยละ 43 ของทั้งประเทศตามด้วยภาคเหนือ และภาคกลางซึ่งมีสัดส่วนร้อยละ 22 และ 20 ตามลำดับ แต่อย่างไรก็ตามในความเป็นจริงกว่าร้อยละ 33 ของพื้นที่ชลประทานทั้งหมดจะอยู่ที่ภาคกลางและเป็นพื้นที่สำหรับเพาะปลูกข้าวเป็นส่วนใหญ่ ในขณะที่หากจำแนกตามรายพืชเศรษฐกิจ ข้าวเป็นพืชเศรษฐกิจของไทยที่ต้องการน้ำชลประทานมากทีสุดโดยอยู่ที่ประมาณ 19,068 ล้านลบ.ม.ต่อปี หรือคิดเป็นร้อยละ 62 ของความต้องการใช้น้ำชลประทานทั้งหมดสำหรับการเพาะปลูก ตามด้วยข้าวโพดเลี้ยงสัตว์ ปาล์มน้ำมัน อ้อย มันสำปะหลัง มะพร้าว สับปะรด ถั่วเหลือง ถั่วเขียว และ ถั่วลิสง ตามลำดับ ขณะที่จังหวัดที่มีความต้องการใช้น้ำสำหรับการเพาะปลูกมากที่สุด ได้แก่ จังหวัดนครสวรรค์ พิษณุโลก กำแพงเพชร และเชียงราย ตามลำดับ



รูปที่ 1 ปริมาณความต้องการใช้น้ำรวมและการใช้น้ำชลประทานทางการเกษตรเป็นรายภาค

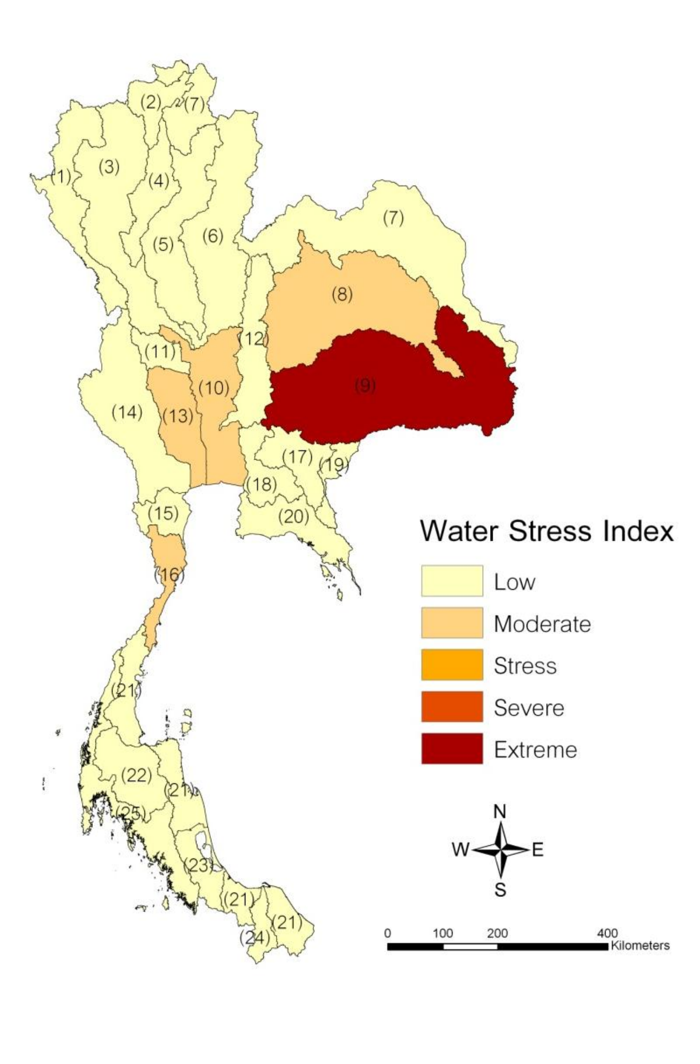


รูปที่ 2 ปริมาณความต้องการใช้น้ำรวมและน้ำชลประทานทางการเกษตรเป็นรายผลิตภัณฑ์เกษตร

2.5 ตัวชี้วัดความตึงเครียดด้านน้ำ (Water stress index: WSI)

รูปที่ 3 แสดงแผนภาพระดับความตึงเครียดด้านน้ำ และค่า WSI ที่ได้จากการศึกษาโดยจำแนกตามลุ่มน้ำที่สำคัญของประเทศไทย โดยผลการประเมินพบว่า ลุ่มน้ำที่มีความตึงเครียดระดับรุนแรงมาก ได้แก่ ลุ่มน้ำมูล โดยรองลงมาได้แก่ ลุ่มน้ำชี ลุ่มน้ำเจ้าพระยา และลุ่มน้ำท่าจีน ตามลำดับ ซึ่งจัดอยู่ในระดับปานกลาง ดังนั้น แผนการบริหารจัดการน้ำอย่างเหมาะสมในอนาคตจึงมีความจำเป็นอย่างมากสำหรับลุ่มน้ำทั้ง 4 ลุ่มน้ำข้างต้น เพื่อป้องกันการเกิดปัญหาความตึงเครียดด้านน้ำและการแย่งชิงน้ำ (Water competition) ในอนาคต โดยเฉพาะอย่างยิ่งเมื่อมีการส่งเสริมให้เกิดการ

ปลูกพืชพลังงานมากขึ้น อย่างไรก็ตามแผนการบริหารจัดการน้ำในลุ่มน้ำตอนล่าง เช่น ลุ่มน้ำเจ้าพระยา จำเป็นต้องจัดให้สัมพันธ์กับลุ่มน้ำตอนบนอื่นๆ



ลุ่มน้ำ	WSI
(1) ลุ่มน้ำสาละวิน	0.017
(2) ลุ่มน้ำกก	0.018
(3) ลุ่มน้ำปิง	0.023
(4) ลุ่มน้ำวัง	0.021
(5) ลุ่มน้ำยม	0.044
(6) ลุ่มน้ำน่าน	0.015
(7) ลุ่มน้ำโขง	0.014
(8) ลุ่มน้ำชี	0.471
(9) ลุ่มน้ำมูล	0.927
(10) ลุ่มน้ำเจ้าพระยา	0.339
(11) ลุ่มน้ำสะแกกรัง	0.031
(12) ลุ่มน้ำป่าสัก	0.050
(13) ลุ่มน้ำท่าจีน	0.287
(14) ลุ่มน้ำแม่กลอง	0.018
(15) ลุ่มน้ำเพชรบุรี	0.022
(16) ลุ่มน้ำชายฝั่งทะเลตะวันตก	0.158
(17) ลุ่มน้ำปราจีนบุรี	0.016
(18) ลุ่มน้ำบางปะกง	0.026
(19) ลุ่มน้ำโตนเลสาป	0.019
(20) ลุ่มน้ำชายฝั่งทะเลตะวันออก	0.015
(21) ลุ่มน้ำภาคใต้ชายฝั่งทะเลตะวันออก	0.067
(22) ลุ่มน้ำตาปี	0.060
(23) ลุ่มน้ำทะเลสาบสงขลา	0.014
(24) ลุ่มน้ำปัตตานี	0.025
(25) ลุ่มน้ำภาคใต้ชายฝั่งทะเลตะวันตก	0.012

รูปที่ 3 แผนภาพระดับความตึงเครียดด้านน้ำ (Water stress map)

2.6 ค่า WF ของเอทานอลและโอกาสเกิดความตึงเครียดด้านน้ำจากนโยบายพลังงาน

จากแผนการส่งเสริมการพัฒนาพลังงานทดแทนของประเทศไทย (AEDP: 2012-2021) ได้มีการกำหนดเป้าหมายการส่งเสริมให้เกิดการผลิตเชื้อเพลิงชีวภาพ ได้แก่ ไบโอเอทานอล ที่ปริมาณ 9 ล้านลิตรต่อวัน โดยใช้วัตถุดิบหลักได้แก่ มันสำปะหลัง อ้อย และกากน้ำตาล โดยมีวัตถุประสงค์เพื่อสร้างความมั่นคงด้านพลังงาน ควบคู่ไปกับการพัฒนาชนบทโดยการสร้างรายได้ที่สูงขึ้นและมั่นคงให้กับเกษตรกร แต่อย่างไรก็ตามความต้องการพืชพลังงานที่มากขึ้นทำให้เกิดความกังวลเรื่องความต้องการใช้น้ำ และความตึงเครียดด้านน้ำที่จะตามมาในอนาคต การศึกษานี้จึงได้ประยุกต์ใช้หลักการประเมิน WF และตัวชี้วัดความตึงเครียดด้านน้ำข้างต้น มาใช้เพื่อประเมินถึงปริมาณความต้องการใช้น้ำที่เพิ่มสูงขึ้น (โดยเฉพาะอย่างยิ่งน้ำชลประทาน) จากเป้าหมายการผลิตไบโอเอทานอลของประเทศ

ข้างต้น และประเมินหาพื้นที่ที่มีโอกาสเกิดความตึงเครียดด้านน้ำสูงเมื่อโรงงานเอทานอลได้ดำเนินการผลิตเอทานอลตามเป้าหมาย โดยอาศัยตัวชี้วัดที่เรียกว่า Water deprivation (หน่วย: ลบ.ม.เทียบเท่า) ซึ่งคำนวณได้จากค่าความตึงเครียดด้านน้ำ (WSI) และค่า Blue WF ของการผลิตเอทา-นอลในแต่ละพื้นที่ที่ตั้งโรงงาน โดยผลการศึกษาสรุปได้ดังนี้

ตารางที่ 7 แสดงค่า WF ของผลิตภัณฑ์เอทานอลจากมันสำปะหลัง อ้อย และกากน้ำตาล โดยพิจารณาตลอดสายโซ่การผลิต ตั้งแต่การปลูกพืชวัตถุดิบ การแปรรูปวัตถุดิบทางการเกษตร และการผลิตเอทานอลในอุตสาหกรรม โดยผลการศึกษาพบว่าเอทานอลจากมันสำปะหลังมีค่า Total WF สูงที่สุด ตามด้วยเอทานอลจากกากน้ำตาลและอ้อยตามลำดับ แต่หากพิจารณาเฉพาะความต้องการใช้น้ำชลประทาน จะพบว่าการผลิตเอทานอลจากกากน้ำตาลจะมีความต้องการใช้ชลประทานสูงที่สุดเมื่อเทียบกับเอทานอลจากอ้อยและมันสำปะหลัง อย่างไรก็ตามในปัจจุบันพื้นที่ปลูกมันสำปะหลังและอ้อยส่วนใหญ่อยู่นอกเขตชลประทาน ดังนั้นค่าการใช้น้ำชลประทานที่แท้จริงในปัจจุบันของอ้อยและมันสำปะหลังจะมีค่าต่ำกว่าผลที่ได้ในตารางที่ 7

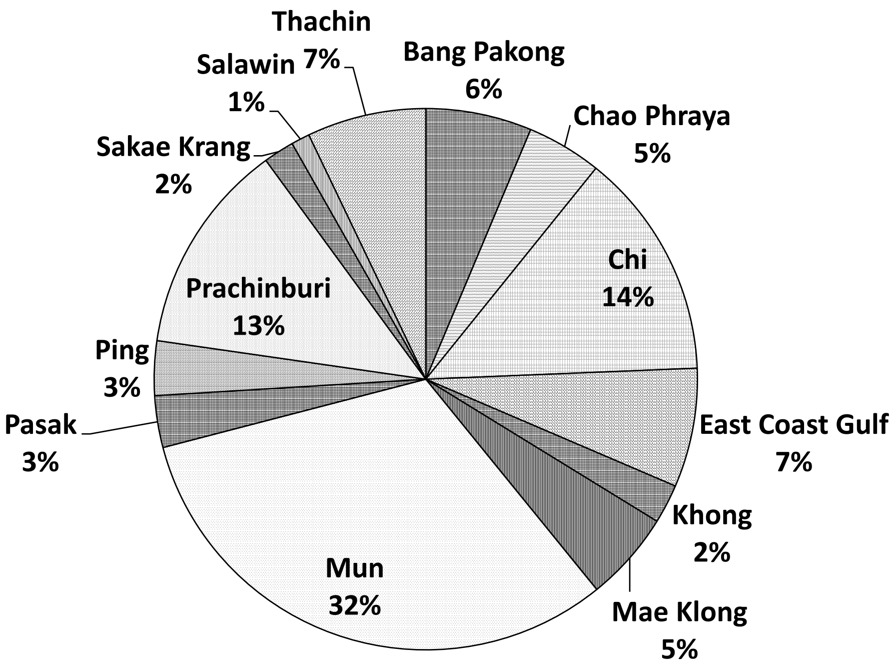
ตารางที่ 7 ค่า WF ของเอทานอลจากมันสำปะหลัง อ้อย และกากน้ำตาลในประเทศไทย

ผลิตภัณฑ์เอทานอล	**ค่า Water footprint (ลิตรน้ำ/ลิตรเอทานอล)**	
	Total WF	**Blue WF**
เอทานอจากมันสำปะหลัง	2,372 – 2,579	499 - 566
เอทานอลจากอ้อย	1,396 – 2,196	490 - 859
เอทานอลจากกากน้ำตาล	1,976 – 3,105	699 – 1,220

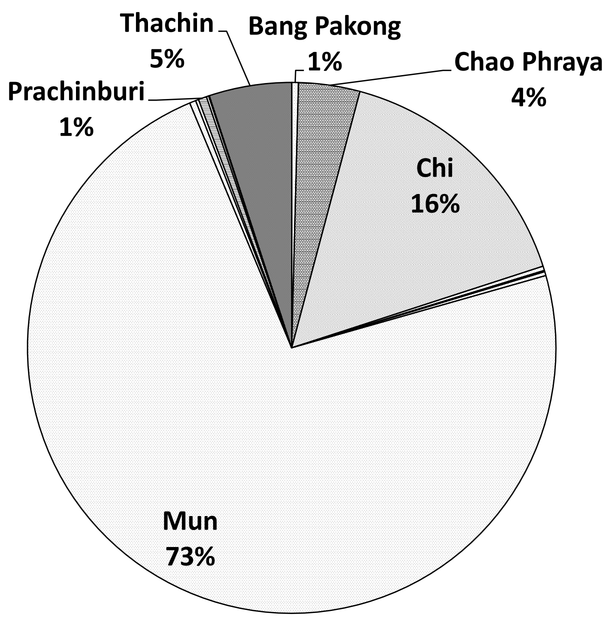
ตารางที่ 8 แสดงปริมาณความต้องการใช้น้ำต่อปีเพื่อการผลิตเอทานอล 9 ล้านลิตรต่อวัน ตามเป้าหมายของรัฐบาลในปี 2564 จำแนกตามประเภทของการผลิตเอทานอล โดยพบว่าจะมีความต้องการใช้น้ำรวมเพิ่มขึ้นทั้งหมดเท่ากับ 8,185 ล้านลบ.ม./ปี โดยเป็นน้ำชลประทานที่ต้องการเพิ่มสูงขึ้นเท่ากับ 1,625 ล้านลบ.ม./ปี หรือเทียบกับเท่ากับร้อยละ 3 ของความจุใช้การ (active storage) ของไทยในปัจจุบัน และหากจำแนกตามพื้นที่ลุ่มน้ำ จะพบว่าลุ่มน้ำที่มีความต้องการใช้น้ำชลประทานเพิ่มสูงขึ้นมากที่สุดได้แก่ ลุ่มน้ำมูล ตามด้วยลุ่มน้ำชี และลุ่มน้ำปราจีนบุรี ตามลำดับ (ดังรูปที่ 4) และหากประเมินถึงโอกาสการเกิดผลกระทบด้าน Water deprivation อันเนื่องมาจากการใช้น้ำที่เพิ่มสูงขึ้น จะพบว่าจะมีโอกาสเกิดมากที่สุดในส่วนของลุ่มน้ำมูล ตามด้วยลุ่มน้ำชี และลุ่มน้ำท่าจีน ตามลำดับ (ดังรูปที่ 5)

ตารางที่ 8 ปริมาณความต้องการใช้ (ล้านลบ.ม.ต่อปี) เพื่อการผลิตเอทานอล 9 ล้านลิตรต่อวันตามเป้าหมายรัฐบาลในปี 2564

โรงงานผลิตเอทานอล	ฤดูแล้ง		ฤดูฝน		รวม	
	Green water	Blue water	Green water	Blue water	Green water	Blue water
เอทานอลจากมันสำปะหลัง	754	933	3,974	25	4,728	958
เอทานอลจากอ้อย	8	17	75	1	83	18
เอทานอลจากกากน้ำตาล	102	295	1,039	159	1,141	454
เอทานอลจากมันสำปะหลังและกากน้ำตาล	74	146	534	49	608	195
รวม	938	1,391	5,622	234	6,560	1,625



รูปที่ 4 สัดส่วนความต้องการใช้น้ำชลประทานเพื่อการผลิตเอทานอลในปี 2564 จำแนกตามลุ่มน้ำ



รูปที่ 5 สัดส่วนความต้องการใช้น้ำที่มีโอกาสก่อให้เกิดผลกระทบด้าน Water deprivation ในปี 2564 จำแนกตามลุ่มน้ำ

3. ข้อเสนอแนะแนวทางสำหรับการจัดการทรัพยากรน้ำอย่างยั่งยืนในอนาคต

จากผลการประเมินสถานการณ์ความตึงเครียดด้านน้ำ และปริมาณความต้องการใช้น้ำที่แท้จริงของพืชอาหาร อาหารสัตว์ และพลังงานของไทยที่ได้จากการศึกษานี้เห็นได้ว่ามีความจำเป็นอย่างยิ่งที่จะต้องมีแผนการบริหารจัดการทรัพยากรน้ำอย่างเหมาะสมในอนาคตเพื่อหลีกเลี่ยงและบรรเทาการเกิดความตึงเครียดด้านน้ำในอนาคตอันเนื่องมาจากความต้องการการใช้น้ำในภาคการเกษตรที่มีแนวโน้มเพิ่มสูงขึ้นอันเนื่องมาจากความต้องการด้านอาหาร อาหารสัตว์ และโดยเฉพาะอย่างยิ่งพลังงานทดแทนที่มีความต้องการเพิ่มสูงขึ้นอย่างมากอันมาจากนโยบายการส่งเสริมของรัฐบาล โดยมีข้อเสนอแนะแนวทางการเพิ่มประสิทธิภาพการใช้น้ำและการจัดการทรัพยากรน้ำสำหรับภาคการเกษตร สรุปได้ดังต่อไปนี้

3.1 การลดปริมาณการใช้น้ำของพืช (Crop evapotranspiration: ET)

การใช้น้ำของพืช (Crop evapotranspiration) ในช่วงการเพาะปลูก จัดเป็นกระบวนการที่มีความต้องการใช้น้ำสูงสุด โดยเห็นได้ว่ากว่าร้อยละ 70 ของปริมาณการใช้น้ำทั้งหมดของประเทศไทยเป็นการใช้น้ำในภาคการเกษตร หรือหากผลิตที่ผลิตภัณฑ์ เช่น เอทานอล เห็นได้ว่าความต้องการใช้น้ำของพืชในช่วงการเพาะปลูกพืชวัตถุดิบ คิดเป็นสัดส่วนถึงร้อย 95 - 98 ของปริมาณความต้องการใช้น้ำทั้งหมด (WF) ของผลิตภัณฑ์เอทานอล ดังนั้นการลดการใช้น้ำของพืชจึงมีความสำคัญอย่างมากต่อการเพิ่มประสิทธิภาพการใช้น้ำในภาคการเกษตร โดยค่าปริมาณการใช้น้ำของพืชขึ้นกับปัจจัยหลายอย่าง เช่น อุณหภูมิ สภาพดิน ปริมาณผลผลิตต่อไร่ ช่วงเวลาการเพาะปลูกและเก็บเกี่ยว

รวมถึงแนวปฏิบัติในช่วงการเพาะปลูกพืช เช่น ค่าปริมาณการใช้น้ำของพืชจะเพิ่มสูงขึ้นเมื่ออุณหภูมิสูงขึ้น เป็นต้น ดังนั้นการลดปริมาณการใช้น้ำของพืชจึงจำเป็นต้องหาแนวทางดังต่อไปนี้

- การประเมินและหาแนวทางในการลดรอบการเพาะปลูกให้สั้นลง หรือหาทางเพิ่มผลผลิตให้สูงขึ้น แต่อย่างไรก็ตามทั้งสองข้อนี้จะต้องมีการประเมินหาความเหมาะสมและความคุ้มค่า เพราการลดรอบการเพาะปลูกและเก็บเกี่ยวให้สั้นลงย่อมส่งผลถึงผลผลิตที่อาจลดลงไปด้วย
- การส่งเสริมการวิจัยและพัฒนาพันธุ์พืชพลังงาน เช่น อ้อยและมันสำปะหลังที่ให้ผลผลิตต่อไร่ที่สูง อันจะมีความสำคัญต่อความยั่งยืนของอุตสาหกรรมการผลิตเอทานอลของไทยในอนาคต โดยลักษณะพันธุ์พืชในอุดมคติในมุมมองของอุทกวิทยา ที่ช่วยลด WF ของพลังงานทดแทนได้ต่ำสุด ก็คือ พันธุ์ที่สามารถทนแล้งได้ ให้ผลผลิตที่สูงแม้จะเพาะปลูกในที่นอกเขตชลประทาน
- การส่งเสริมให้เกิดแนวปฏิบัติที่ดีในเกษตรกรรายย่อย เนื่องจากค่าผลผลิตต่อไร่ของพืช เช่น อ้อยและมันสำปะหลัง ยังมีค่าต่ำมากเมื่อเทียบกับศักยภาพของท่อนพันธุ์ กล่าวคือ ค่าเฉลี่ยผลผลิตของมันสำปะหลังและอ้อยอยู่ที่ปัจจุบันอยู่ที่ 19.3 และ 76.2 ตันต่อเฮกตาร์ตามลำดับ แต่ค่าผลผลิตตามศักยภาพของท่อนพันธุ์ดังกล่าวอยู่ที่ 31-50 ตันมันสำปะหลังต่อเฮกตาร์ และ 94-112 ตันอ้อยต่อเฮกตาร์ โดยแนวปฏิบัติที่ดีที่ควรส่งเสริมควรครอบคลุมตั้งแต่ การปรับปรุงคุณภาพดินด้วยปุ๋ยอินทรีย์ การเตรียมพื้นที่ การวางแผนการเพาะปลูก รวมถึงการบำรุงรักษาและการกำจัดวัชพืช ไปจนถึงการเก็บเกี่ยวผลผลิต

3.2 การพัฒนาระบบชลประทานในพื้นที่ที่มีความเสี่ยงต่อความตึงเครียดด้านน้ำในอนาคต

จากผลการศึกษาพบว่าควรมีการพัฒนาและเพิ่มประสิทธิภาพของระบบชลประทานในพื้นที่เพาะปลูกที่มีความเสี่ยงต่อการเกิดความตึงเครียดด้านน้ำในอนาคตอันเนื่องมาจากนโยบายด้านพลังงานและการขยายตัวของอุตสาหกรรมการผลิตพลังงานทดแทน เช่น พื้นที่ลุ่มน้ำมูล และลุ่มน้ำชี เป็นต้น โดยการพัฒนาและเพิ่มประสิทธิภาพของรูปแบบของกการชลประทานในพื้นที่เพาะปลูกอาจดำเนินการได้หลายวิธี เช่น การให้น้ำทางผิวดิน (Surface Irrigation) การให้น้ำแบบฉีดฝอย (Sprinkler Irrigation) รวมถึงการให้น้ำแบบประหยัด (micro irrigation) และการให้น้ำใต้ผิวดิน (Sub-Surface Irrigation) รวมไปถึงการพัฒนาระบบกักเก็บน้ำขนาดกลางและขนาดใหญ่ในอนาคต

3.3 การส่งเสริมให้เกิดการขยายพื้นที่เพาะปลูกในพื้นที่ที่เหมาะสม

ภาครัฐควรมีมาตรการการส่งเสริมให้เกิดการเพาะปลูกพืชแต่ละชนิดในพื้นที่ที่มีสภาพเหมาะสม ทั้งในด้านสภาพดิน และภูมิอากาศ รวมถึงหลีกเลี่ยงการขยายการเพาะปลูกในพื้นที่ที่มี

ความเสี่ยงต่อการเกิดความตึงเครียดด้านน้ำ แต่มุ่งเน้นไปที่การส่งเสริมให้เกิดผลผลิตต่อไร่ที่มากขึ้นในบริเวณดังกล่าว

3.4 การส่งเสริมให้เกิดการผลิตเอทานอลจากอ้อยมากขึ้น

เนื่องจากผลการประเมินพบว่า เอทานอลจากอ้อย มีค่า WF ที่ต่ำที่สุดโดยเฉพาะอย่างยิ่งปริมาณความต้องการใช้น้ำชลประทานเมื่อเทียบกับเอทานอลจากมันสำปะหลังและกากน้ำตาล แต่อย่างไรก็ตามในปัจจุบัน รวมถึงจากแผนการผลิตเอทานอลในอนาคต พบว่ายังมีสัดส่วนเอทานอลจากอ้อยที่น้อยอยู่เมื่อเทียบกับเอทานอลจากกากน้ำตาลและมันสำปะหลัง อ้อยจึงมีศักยภาพอย่างมากที่ควรส่งเสริมสำหรับการผลิตพลังงานทดแทนเช่นเอทานอลในอนาคตเพื่อลดความต้องการใช้น้ำ แต่อย่างไรก็ตามยังมีข้อจำกัดในการใช้อ้อยเพื่อผลิตเอทานอลหลายด้านที่ต้องได้รับการแก้ไข เช่น พระราชบัญญัติอ้อยและน้ำตาลทรายพ.ศ.2527 ซึ่งไม่เอื้อต่อการส่งเสริมให้เกิดการผลิตเอทานอล รวมถึงปัญหาด้านวัตถุดิบเนื่องจากอ้อยจะมีการผลิตเฉพาะอย่างระหว่างเดือนธันวาคมถึงมีนาคม ขณะที่ความต้องการเอทานอลมีทั้งปี

3.5 เพิ่มประสิทธิภาพการใช้น้ำในกระบวนการแปรรูปวัตถุดิบ และกระบวนการผลิตเอทานอล

แม้ว่าความต้องการใช้น้ำในกระบวนการแปรรูปผลผลิตทางการเกษตร และกระบวนการผลิตเอทานอลจะมีค่าต่ำมากเมื่อเทียบกับความต้องการใช้น้ำของพืชในช่วงการเพาะปลูก แต่อย่างไรก็ตามการใช้น้ำในภาคอุตสาหกรรมจัดเป็นน้ำชลประทานที่มีต้นทุนและมีมูลค่าสูง ดังนั้นการส่งเสริมให้เกิดการใช้น้ำอย่างมีประสิทธิภาพในภาคอุตสาหกรรมการผลิตเอทานอล โดยการนำกลับมาใช้ซ้ำ (reuse) หรือการนำกลับมาใช้ใหม่ (recycle) จึงมีความจำเป็น ยกตัวอย่างเช่นการนำคอนเดนเสทจากกระบวนการกลั่นเอทานอลกลับมาใช้ ซึ่งนอกจากจะช่วยลดการใช้น้ำแล้ว ยังช่วยลดการใช้พลังงานได้อย่างมาก นอกจากนี้ควรมีการพัฒนาจัดทำแนวปฏิบัติที่ดีสำหรับการจัดการน้ำอย่างเหมาะสมในอุตสาหกรรมเกษตรเป็นรายอุตสาหกรรมที่สำคัญ เช่น อุตสาหกรรมน้ำตาล เหมือนในประเทศบราซิล ซึ่งมีการเผยแพร่แนวปฏิบัติที่ดีทั้งในส่วนของการผลิต และการใช้ประโยชน์น้ำเสียจากอุตสาหกรรมการผลิตน้ำตาลและเอทานอลจากอ้อย เช่น การนำไปผลิตปุ๋ย และ ไบโอแก๊ส เป็นต้น นอกจากนี้ภาครัฐควรมีการส่งเสริมให้เกิดการวิจัยและพัฒนาเทคโนโลยีการผลิตและการจัดการของเสียต่าง ๆ ในอุตสาหกรรมเกษตรที่สำคัญมากยิ่งขึ้น

3.6 ส่งเสริมให้เกิดพัฒนาด้านฉลาก WF ของผลิตภัณฑ์เกษตร เพื่อสร้างความตระหนักด้านน้ำในภาคการบริโภค

เพื่อให้เกิดความยั่งยืนด้านการใช้น้ำในอนาคต การสร้างความตระหนักด้านน้ำในภาคการบริโภคจึงมีความจำเป็นอย่างยิ่ง ดังนั้นการส่งเสริมให้เกิดการพัฒนาฉลาก Water footprint จึงเป็น

แนวทางหนึ่งที่จะช่วยให้เกิดความตระหนักทั้งผู้ผลิตและผู้บริโภคในการรับผิดชอบต่อการใช้น้ำเพื่อให้เกิดการใช้น้ำได้อย่างมีประสิทธิภาพและยั่งยืนในอนาคต

4. ข้อเสนอแนะแนวทางการศึกษาวิจัยต่อในอนาคต

4.1 การประเมินเชิงลึกตัวชี้วัดความตึงเครียดด้านน้ำ (WSI) ในลุ่มน้ำที่สำคัญที่ประเมินได้จากการศึกษานี้ เช่น ลุ่มน้ำมูล ชี เจ้าพระยา และท่าจีน เพื่อให้ทราบถึงความต้องการใช้น้ำในภาคต่างๆ รวมถึงทราบถึงศักยภาพด้านทรัพยากรน้ำผิวดิน น้ำใต้ดิน และระบบชลประทานที่มีอยู่ปัจจุบัน และเพื่อให้ได้ค่า WSI ที่มีความแม่นยำมากขึ้น และทราบถึงปัญหา สาเหตุ และโอกาสของการเกิดด้านความตึงเครียดด้านน้ำในพื้นที่ศึกษาที่แท้จริง อันจะนำไปสู่การหามาตรการที่เหมาะสมในการปฏิบัติต่อไป ซึ่งการประเมินดังกล่าวนี้ยังถือเป็นการทวนสอบผลการศึกษาที่ได้กับสถานการณ์ในพื้นที่จริงว่ามีความสัมพันธ์เป็นอย่างไร

4.2 การพัฒนาวิธีการคำนวณตัวชี้วัดด้านความตึงเครียดด้าน (WSI) โดยการปรับปรุงค่าความน่าเชื่อถือของตัวแปรอื่นๆ ในการคำนวณ เช่น ระดับความสามารถในการควบคุมและบริหารจัดการทรัพยากรน้ำที่มีอยู่ในแต่ละลุ่มน้ำ เนื่องจากในความเป็นจริงแต่ละลุ่มน้ำจะมีความสามารถในการบริหารจัดการทรัพยากรน้ำได้ต่างกัน เช่น บางแห่งอาจมีเขื่อนหรืออ่างเก็บน้ำขนาดใหญ่ แต่บางแห่งอาจไม่มี เป็นต้น

4.3 การศึกษาเพื่อหาวิธีการประเมินมูลค่าทางเศรษฐศาสตร์หรือผลกระทบภายนอก (externalities) ของการใช้ทรัพยากรน้ำ โดยตัวอย่างเช่น วิธีการประเมินมูลค่าทางเศรษฐศาสตร์ เช่น Residual Imputation method สามารถนำมาประยุกต์ใช้เพื่อประเมินหามูลค่าทางเศรษฐศาสตร์ของการใช้น้ำชลประทานสำหรับการปลูกพืชชนิดต่างๆ ภาจใต้ภาวะข้อจำกัดด้านพื้นที่ชลประทานที่แตกต่างกัน ซึ่งผลที่ได้จะมีประโยชน์อย่างมากสำหรับการเป็นข้อมูลเพื่อสนับสนุนการประเมินความคุ้มค่าของการลงทุนพัฒนาระบบชลประทานในอนาคต

4.4 การประเมินประสิทธิภาพด้านน้ำ Water footprint และ Water productivity ของพืชเศรษฐกิจที่สำคัญ เช่น ข้าว โดยพิจารณาถึงความแตกต่างระหว่างพันธุ์ วิธีการเพาะปลูก รวมถึงการสูญเสียน้ำในระบบชลประทานปัจจุบัน อันจะนำไปสู่การกำหนดมาตรการการส่งเสริมการเพาะปลูกและการปรับปรุงระบบชลประทานได้อย่างเหมาะสมสำหรับการเกษตรในอนาคต

Executive Summary

The project entitled "Water footprinting of food, feed and fuel for effective water resource management" has been performed by the Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology (KMUTT) in collaboration with Kasetsart University (KU) and the Asian Institute of Technology (AIT) and supported financially by the Agricultural Division (Division 2) of the Thailand Research Fund (TRF) according to the contract no. RDG5520028. The aim of the study is to assess the water footprint of key agricultural food, feed, and fuel crops and to evaluate the situation and potential to affect the water stress in different regions of Thailand. According to the results, recommendations for water resource management are identified and proposed. The scope and results of the study are concluded as follows:

1. Research methodology

1.1 Water footprint (WF) is one of the techniques that is widely used today for assessing the amount and efficiency of freshwater use for producing a product and its supply chain. The WF of a product is generally expressed in water volume per unit of product e.g. m^3/ton. The concept of WF was initially introduced by Hoekstra (2003). The WF assessment method divides the water use along the entire the production chain of product into three components; green water (in other words, the total effective rainfall), blue water (or the total irrigation water), and grey water (the fresh water required to assimilate the pollutants generated during crop cultivation to reach the accepted water quality standard). The WF assessment concept was used in the study to assess the total crop water use and irrigation water required by each cultivated area. The assessment emphasizes on the amount of consumptive water used, including both green and blue water, by major food, feed, and fuel crops in Thailand classified by provinces and cropping calendars. Grey water is not considered in the study as impacts of wastewater can be evaluated in the terms of eutrophication and eco-toxicity.

1.2 Water stress index (WSI) is one of the indices widely used to explain the water vulnerability in terms of stress of each area. To assess the WSI at watershed level, the modified water stress indicator developed by Pfister et al. (2009) is applied as the characterization factor for water consumption in Life Cycle Impact Assessment (LCIA), and all the 25 watersheds of Thailand are included in this study. WSI is derived from the ratio of annual total water withdrawals to hydrological availability of a watershed including variation related to monthly and annual rainfall. The levels of water stress can be classified into five categories as shown in **Table 1**.

Table 1 Water stress classification (Pfister et al., 2009)

Category/Condition	WSI
Extreme	> 0.9
Severe	< 0.9
Stress	0.5
Moderate	0.1 – < 0.5
Low	< 0.1

2 Summary results

2.1 Crop water requirement of major food, feed and fuel crops in Thailand

Table 2 shows the comparison of water requirement of major food, feed, and fuel crops in Thailand. The details of the results indicate that the water requirement of each crop is different in different cultivated areas due to many factors e.g. the differences of rainfall, weather, and especially crop productivity. However, the crop water requirement results shown in **Table 2** are the theoretical values of consumptive water use for crops; in actual practice the results might be lower as there are various crops cultivated in non-irrigated areas.

Table 2 Water requirement of major food, feed, and fuel crops in Thailand[1]

Staple crops	Average water requirement (m^3/rai)	Range (m^3/rai)	Average water requirement (m^3/ton)	Range (m^3/ton)
Major rice	849	780 - 891	1,825	1,333 – 2,401
Second rice	892	865 - 932	1,495	1,254 – 1,811
Maize	609	572 – 666	932	823 – 1,036
Cassava	1,243	1,215 – 1,260	402	395 – 406
Sugarcane	1,647	1,614 – 1,682	136	131 – 138

[1] Water requriement Table 2 refers to the total consumptive water use

Staple crops	Average water requirement (m^3/rai)	Range (m^3/rai)	Average water requirement (m^3/ton)	Range (m^3/ton)
Oil palm*	2,184	2,141 – 2,227	1,015* [2,195]	905 – 5,306*
Soybean	500	451 – 549	1,755	1,581 – 2,011
Mungbean	275	229 – 367	2,588	2,045 – 3,989
Coconut	2,170	2,096 – 2,227	2,366	2,074 – 2,666
Pineapple	2,170	2,099 - 2,227	682	611 - 783
Peanut	509	460 - 556	2,121	1,742 – 2,780

Remark: *The average water requirement of oil palm i.e. 1,105 m^3/ton of fresh fruit bunches (FFB) was calculated based on assumption that the North and the North-East were not taken into account because oil palm plantations in those two regions are in the initial stages which has low / no yield. Meanwhile, the water requirement of about 2,195 m^3/ton of FFB is the average of the country. The maximum water requirement of about 5,306 m^3/ton of FFB was derived for the Northern region.

2.2 Blue water requirement of major food, feed and fuel crops in Thailand

Table 3 shows the comparison of “blue water requirement” or “irrigation water requirement” per ton of crop and the ranges from the different cultivation areas. This “irrigation water requirement” information is important for the viewpoint of hydrology and it is necessary for water resource management especially the irrigation water required during the dry season. The results show that plantation of crops such as second rice, maize and sugarcane in the North-Eastern region require higher amounts of irrigation water as compared to other regions. This implies that the existing effective rainfall is not sufficient for the theoretical crop water requirement. Consequently for sufficient crop water requirement, it is necessary to expand the irrigation area in the North-East. Especially, for the case of expansion of energy crops plantation like such as oil palm which requires high water use to the North and the North-East, appropriate areas that have enough rainfall or/and irrigation need to be considered. Nevertheless, the high irrigation water requirement will also increase production cost of oil palm plantation for which the economic feasibility should be investigated. However the actual WF of crops e.g. sugarcane and cassava should be lower than the results shown in Table 3 because they are mainly cultivated in non-irrigation areas.

Table 3 Blue water requirement of major food, feed, and fuel crops in Thailand[2]

Staple crops	Average blue water requirement (m^3 of blue water/ton)		Range (m^3 of blue water/ton)
	Dry season	Wet season	
Major rice	-	466	284 (N) – 928 (S)
Second rice	1,107	-	915 (S) – 1,571 (NE)
Maize	808	-	672 (N) – 921 (NE)
Cassava	65	10	54 (N) – 98 (C)
Sugarcane	23	11	22 (N) – 49 (NE)
Oil palm*	331 (846)	61 (59)	199 (S) – 2,114 (N)
Soybean	1,542	-	1,461 (C) – 1,790 (NE)
Mungbean	1,856	14	89 (S) – 3,804 (NE)
Coconut	819	110	587 (S) – 1,177 (NE)
Pineapple	234	32	172 (S) – 326 (C)
Peanut	1,367	6	208 (S) – 2,063 (NE)

Remarks: N: Northern region; NE: Northeastern region; S: Southern region; C: Central region

*Regarding oil palm, the North and the North-East were not taken into account for the values of 331 and 61 m^3/ton of FFB while the values of 846 and 59 m^3/ton of FFB were the average of all regions.

2.3 Water productivity

Table 4 shows the comparison of water productivity of major food, feed, and fuel crops. The water productivity refers to agricultural product prices (year 2010/2011) and net income of farmers related to the ratio of agricultural products and irrigation water requirement. The results reveal that water productivities of many crops such as cassava, sugarcane, pineapple, and mungbean are high. However the water productivity is influenced by several factors particularly the agricultural product price depending on weather, epidemics, market demand, etc.

Table 4 Water productivity of major food, feed, and fuel crops in Thailand

[2] Blue water footprint in Table 3 is referred to the irrigation water requirements which will be lower than the total water footprint values shown in Table 2

Staple crops	Agricultural product prices/Irrigation water use (THB/m^3 Blue water)	Net income of farmers/Irrigation water use (THB/m^3 Blue water)
Major rice	18	1
Second rice	8	1
Maize	7	3
Cassava	25	3
Sugarcane	29	5
Oil palm*	11	3
Soybean	10	3
Mungbean	18	8
Coconut	5	3
Pineapple	21	7
Peanut	15	3

2.4 Water requirement of agricultural sector in Thailand

Considering the agricultural statistics during year 2010/2011 and the water requirement of major food, feed, and fuel crops in Thailand, the irrigation water requirements classified by region and product can be assessed as presented in **Figures 1 and 2**, respectively. The total of irrigation water requirements for cultivation is approximately 31,125 million m^3/year and the North has the highest share followed by the Central, the North-East, the East, and the South. While, based on the total agricultural areas of Thailand (about 152 M.rai), the North-East region shares about 43%, followed by the North and Central which share about 22% and 20%, respectively. Nonetheless 33% of existing irrigation areas are in the Central region which is most suitable for rice cultivation. In case of staple crop categories, rice has the highest irrigation water requirement at 19,068 million m^3/year followed by maize, oil palm, sugarcane, cassava, coconut, pineapple, soybean, mungbean, and peanut, respectively. Considering by provinces, the highest water required for cultivation is found in Nakhonsawan, Phitsanulok, Kamphaengphet, and Chiang Rai.

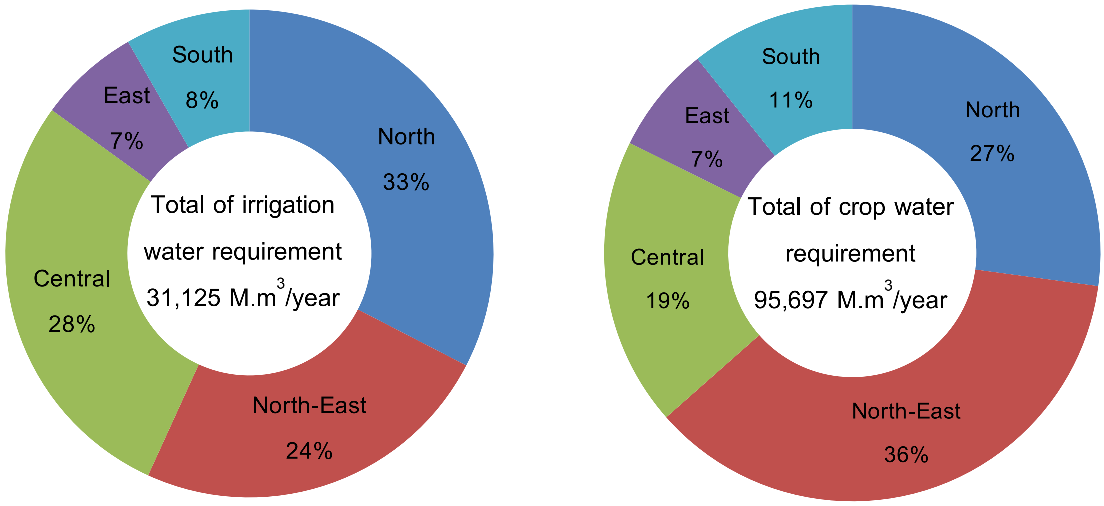


Figure 1 Water and Irrigation water requirements for agriculture classified by regions

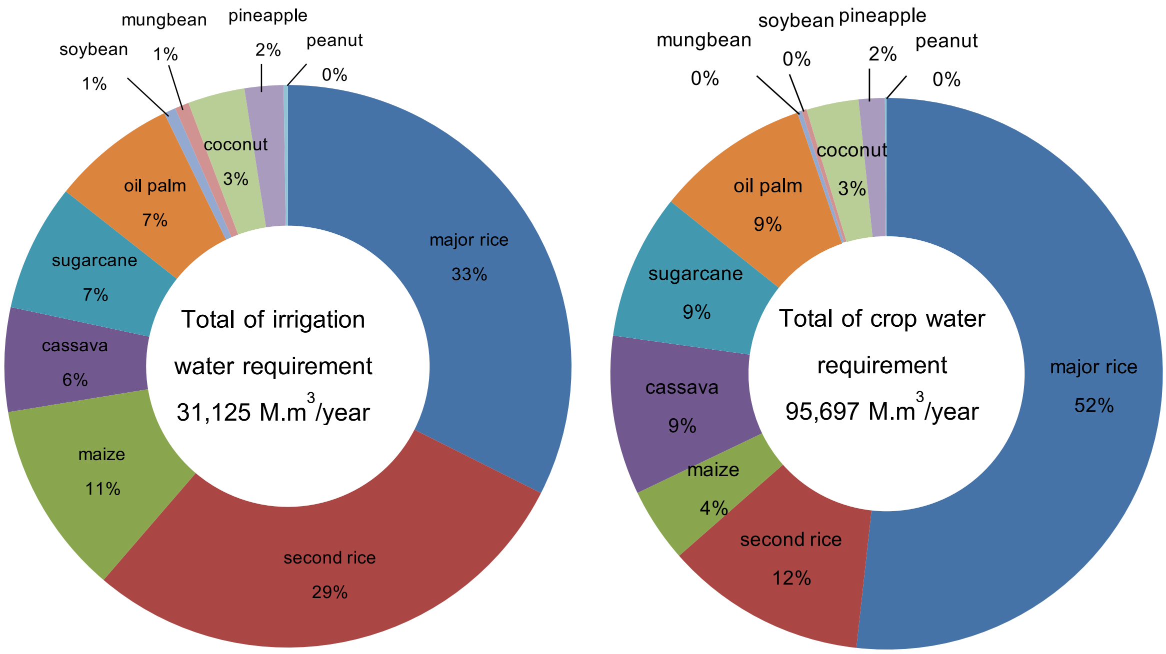
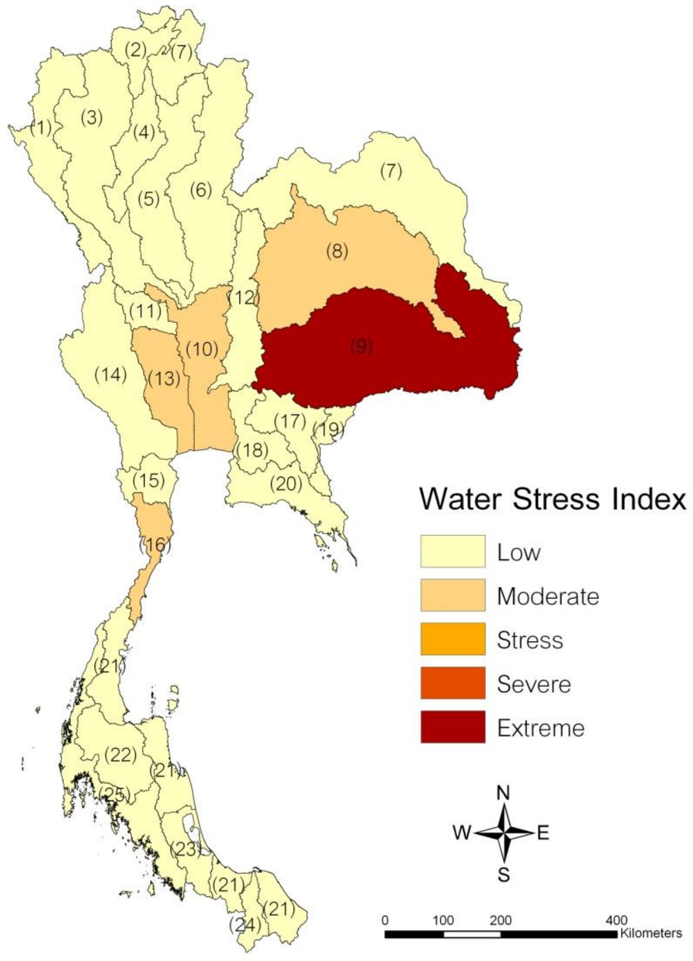


Figure 2 Water and Irrigation water requirement for agriculture classified by products

2.5 Water stress index (WSI)

Figure 3 shows levels of water stressed areas illustrated with a map and values of WSI classified by 25 watersheds of Thailand. The results reveal that the most significant area is Mun watershed followed by the moderate areas including Chi, Chao Phraya, and Thachin watersheds. Therefore to prevent water competition and stress in those four watersheds, appropriate plan for water resource management is very much required especially when cultivation of energy crops is highly promoted. Furthermore, the plan of water resource management for lower-watershed e.g. Chao Phraya should be correlated with the plan of the upper watershed.



Watersheds	WSI
(1) Salawin	0.017
(2) Kok	0.018
(3) Ping	0.023
(4) Wang	0.021
(5) Yom	0.044
(6) Nan	0.015
(7) Khong	0.014
(8) Chi	0.471
(9) Mun	0.927
(10) Chao Phraya	0.339
(11) Sakae Krang	0.031
(12) Pasak	0.050
(13) Thachin	0.287
(14) Mae Klong	0.018
(15) Petchaburi	0.022
(16) West Coast Gulf	0.158
(17) Prachin Buri	0.016
(18) Bang Pakong	0.026
(19) Thole Sap	0.019
(20) East-Coast Gulf	0.015
(21) Peninsula-East coast	0.067
(22) Tapi	0.060
(23) Thale sap Songkhla	0.014
(24) Pattani	0.025
(25) Peninsula-West coast	0.012

Figure 3 Map of water stressed areas of Thailand classified by 25 watersheds

2.6 Water footprint of ethanol production and the potential to affect the water stress resulting from the energy policy

According to the Alternative Energy Development Plan (AEDP: 2012-2021), 9 million liter/day by 2021 is set as the target of bioethanol; cassava, sugarcane, and molasses are the major feedstocks. The purpose of this plan is to build up energy security together with rural development via increasing income of farmers; however, the proliferation of bioethanol production promises to increase stress on water and pressure on water resources resulting from increasing demand for energy crops. The study therefore aims to assess the sustainability implications of the bioethanol policy mandate in Thailand on water. Water requirements for cassava, molasses, and sugarcane based ethanol production in various provinces where bioethanol plants are located are evaluated using the WF concept. Also, the environmental impacts of freshwater use (especially irrigation water) for bioethanol production are assessed in terms of the water deprivation potential (unit: m^3eq) using the WSI developed specifically for the 25 main watersheds in Thailand.

Table 7 shows the WF of bioethanol from the three major feedstocks in Thailand. The bioethanol production systems namely feedstock cultivation, feedstock processing and ethanol conversion are taken into account. The results show that ethanol from cassava has the highest WF followed by molasses and sugarcane ethanol. However, in terms of the irrigation water requirement, molasses ethanol production is the highest while the actual WF of cassava ethanol and sugarcane ethanol is less than the obtained results in Table 7 as most of sugarcane and cassava cultivated in non-irrigated areas.

Table 7 WF of cassava, sugarcane and molasses bioethanol production in Thailand

Bioethanol products	Water footprint (L water/L bioethanol)	
	Total WF	Blue WF
Cassava ethanol	2,372 – 2,579	499 - 566
Sugarcane ethanol	1,396 – 2,196	490 - 859
Molasses ethanol	1,976 – 3,105	699 – 1,220

The results in **Table 8** show that to satisfy the AEDP bioethanol target in year 2021, around 8,185 million m^3/year are required with 1,625 million m^3 irrigation water or equivalent to 3% of active water storage of Thailand in year 2012. Considering the 1,625 million m^3 irrigation water by watershed, Mun, Chi and Prachinburi are the three important watersheds that would have the significant increase in irrigation water demand for bioethanol production. (as seen in **Figure 4**). Considering the water deprivation potentials (m^3eq/year), Mun, Chi and Thachin would be the three main watersheds that have high potential to confront the pressures on water stress and competition with other users if the water resources are not properly managed in the future (as **Figure 5**).

Table 8 Estimated water requirements (million m^3/year) to satisfy the AEDP's target of producing 9 M.litre ethanol/day by 2021

Ethanol plants	Dry season		Wet season		Total	
	Green water	Blue water	Green water	Blue water	Green water	Blue water
Cassava ethanol	754	933	3,974	25	4,728	958
Sugarcane ethanol	8	17	75	1	83	18
Molasses ethanol	102	295	1,039	159	1,141	454
Cassava/molasses ethanol	74	146	534	49	608	195
Total	938	1,391	5,622	234	6,560	1,625

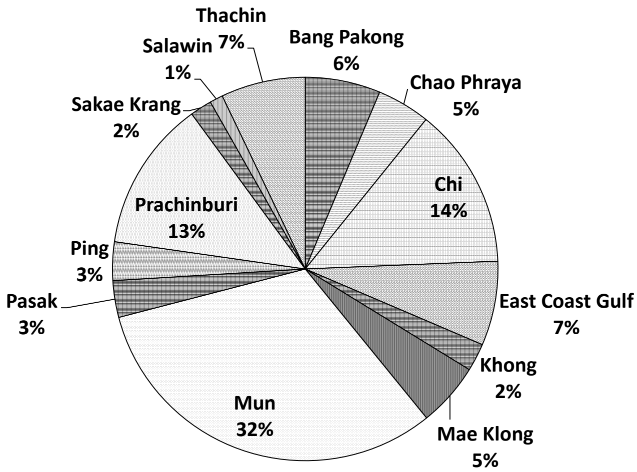


Figure 4 Share of irrigation water requirements for bioethanol production in 2021 classified by watersheds

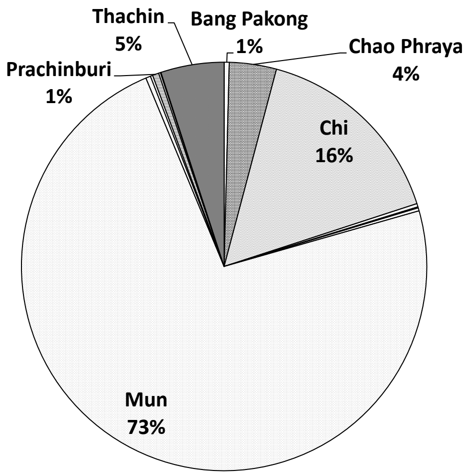


Figure 5 Share of water deprivation potentials from bioethanol production in 2021 classified by watersheds

3. Recommendations for sustainable water resource management in the future

According to the situation of water stress and the crop water requirements of major food, feed, fuel crops in Thailand revealed by the study, there is a necessity for the government to have an appropriate plan for sustainable water resource management to avoid and/or mitigate the water stress arising from the increasing of agricultural water requirement in the future. The increased demands for water are not only for food and feed crops but also for fuel crops according to the energy policy. Therefore, the following measures are recommended to enhance the water efficiency and water resource management for the agricultural sector in Thailand.

3.1 Crop evapotranspiration (ET) reduction

More than 70% of the total water consumption of the country is for the agricultural sector especially during the cultivation stage of crops which is expressed by the "crop evapotranspiration (ET)". For example, in the case of bioethanol, 95-98% of the total water footprint of bioethanol products is from the bioethanol feedstock cultivation. Hence, to reduce the "crop evapotranspiration" or "crop water use" is significant to enhance water efficiency for agricultural sector. There are many factors that can influence the evapotranspiration of crops such as temperature, soil properties, crop yields, crop cycle and agricultural practices; for example, ET generally increases with temperature. Nevertheless, the following measures are recommended to reduce the crop evapotranspiration.

- To assess and identify the methods to shorten the crop cycle or else to improve the crop yields. However, these two methods generally must be traded off with each other as shortening the crop cycle may result in lower biomass accumulation which in turn will decrease the final yield.

- To promote research and development on crops variety improvement especially the varieties that are suited for energy production. For example, the ideal fuel crops in the water supply perspective to minimize the WF of biofuels should be drought-tolerant, high-yield crops grown on little irrigation water or in non-irrigated areas.

It is important to encourage the good agricultural practices (GAP) for farmers, especially small-scale farmers in rural areas. This is because nowadays the average crop yields in the country, such as for cassava and sugarcane are still lower than their genetic potentials. For example, the average cassava and sugarcane yields today are just around 19.3 and 76.2 tons/hectare, respectively. However, based on the existing varieties and their genetic potentials, the yields of cassava and sugarcane could potentially be around 31-50 ton/ha and 94-112 ton/ha, respectively. To achieve the high genetic potential yields, those high yields must be supported with good agricultural practices in farming e.g. improving soil quality by using organic fertilizers and good practices in land preparation, plantation, harvesting and regularly weed control.

3.2 Irrigation development in the high potential water stress areas

The WF and WSI assessment in the project reveal that the development and improvement of irrigation system efficiency should be promoted in the areas that potentially have high water stress due to the expansion of the biofuels industry e.g. Mun and Chi watersheds. The promotion is not only to be the large scale water storage implementation, but the small scale irrigation systems by using local water reservoirs in the plantation areas are also possible e.g. surface irrigation, sprinkler irrigation, micro-irrigation, and sub-surface irrigation and water storage systems. For medium and large scales, it is suggested to increase and enhance the efficiency of irrigation system.

3.3 Promotion for expanding of energy crop cultivation in the suitable areas

Zoning or promoting the new crop plantation areas for supporting the energy policy of the government such as bioethanol and biodiesel policy is necessary to be considered by the policy makers. The suitable areas should be identified and set by taking the factors of water resource availability and water stress into consideration. The promotion should emphasize on crop's productivity improvement instead of expansion of cultivation areas. This is in order to avoid the other consequent impacts not only related to water competition but also land competition for food, feed, and fuel.

3.4 Promotion of sugarcane ethanol in the Thai bioethanol plan

The results show that ethanol derived from sugarcane juice has the lowest total WF and also the irrigation water required as compared to cassava and molasses ethanol. However, the volume of ethanol produced directly from sugarcane juice is lesser than that from cassava and molasses. Therefore sugarcane is found as the crucial feedstock that can increase the security of feedstocks supply for bioethanol production in Thailand. The government should therefore emphasize promotion of ethanol production from sugarcane juice by solving some of the existing constraints such as the Sugar Act of 1984 which does not support ethanol production from sugarcane and the duration of sugarcane supply which is limited to just over the period of December to March.

3.5 Enhancing water use efficiency in feedstock processing and ethanol conversion

Although feedstock processing and ethanol conversion have very low contributions to the WF of bioethanol as compared to the crop evapotranspiration, those industrial processes directly involve blue water use which is recognized as the important element of WF as it is more associated with the environmental impacts as compared to the green water. To reduce water use during industrial processing, the water reuse and recycle program has to be encouraged. For example, the condensate recovery in sugar mills and in ethanol conversion plant e.g. distillation stage can help not only saving water but also energy. Brazil has accelerated the basic guidelines of water management to sugar milling industries along with the new technologies development such as dry cleaning of sugar cane to eliminate sugarcane washing, treatment of vinasse by biodigestion technique to reduce the organic load and recirculating into the process. Moreover, the appropriate treatment and utilization of the high organic wastewater generated from the mills and from the ethanol conversions such as using it as agri-fertilizer can help mitigate impacts on ecosystem due to wastewater release. Therefore, research and development for the feedstock processing technologies and ethanol conversion technologies need to be encouraged.

3.6 Development and promotion of WF label of agricultural products to raise awareness in water consumption

In order to develop sustainable water consumption in the future, raising awareness in water consumption for both producer and consumer sides is necessary. The development and promotion of water footprint label or other forms of reporting could be one of the measures to make both producers and consumers realize their contributions to the water use and water impacts which in turn would lead to the efficient and sustainable use of water resources in the future.

4. Suggestions for future research

4.1 Comprehensive assessment of WSI should be conducted for the critical watersheds in Thailand revealed by the study i.e. Mun, Chi, Chao Phraya, and Thachin watersheds. This is to understand the local availability of the surface and ground water resources and the efficiency of existing irrigation system compared to the water demands in those specific regions. This work can also be a part of a verification process of the WSI results with the actual situation. The information from WSI assessment and the precise WSI values will help policy makers understand the real problems and causes of water stress in the studied region and help to identify the appropriate measures for enhancing water efficiency in practice.

4.2 Improvement of the WSI calculation methodology by considering factors such as the ability to control and manage the water resources in each watershed because different watersheds will have different capability in water resource management. For example, the watersheds that have dams or large water storage should have more ability to manage the water resources and this factor should be readjusted in WSI calculations in the future.

4.3 Development of methodology for assessing the economic value or externalities of water resource uses. The economic valuation method such as residual imputation method (RIM) can be used to evaluate the economic value of irrigation water used for different crops production and irrigated land constraints. The results would be the essential information to support the policy makers in their decisions on the feasibility of investment or implementation of the irrigation system in the future.

4.4 Comprehensive WF assessment for the vital crops e.g. rice by considering the different varieties, cultivation locations, agricultural practices and the water loss from the existing irrigation system. This would help to identify the suitable promotion measures for enhancing water efficiency in the future.

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CHAPTER 1

Introduction

1.1 Rationale

Even though three fourths of the earth's surface is under water, only a very small percentage of that water is actually usable for the many human activities. Freshwater is a scarce resource in many regions of the world. This shortage is further exacerbated by the increase in variability of water distribution due to the impacts of climate change. Freshwater is consumed by many activities such as irrigation for agriculture, bathing, washing, cooling and processing. It is also contaminated by many domestic and industrial activities. However, agriculture is one of the major consumers of water (Scanlon et al., 2007; Gordon et al., 2010). Increasing demand of agriculture with rising population and consequent increased demand of food and more recently, the proliferation of biomass-based energy promises to increase stress on water, an already scarce resource. This is of particular concern to Thailand which has a large agricultural base both for food for local consumption and export as well as for feed and fuel (bio-fuels).

1.2 Objectives and Targets

The overall objective of this project is to assess the water footprint for evaluating the water stress situation in Thailand especially the area where food, feed and fuel are in competition, with the specific objectives and target as follows.

1.2.1 Specific objectives

- Reviewing & testing the existing methodologies of water footprinting in the field
- Evaluating the water footprint of key agricultural products (food, feed and fuel) in Thailand and assessing the water stress situation in different regions of Thailand
- Identifying strategies for water resource management

1.2.2 Expected outputs

- Map of water stress indices for various regions of Thailand & identified critical agricultural activities (food, feed, fuel) in regions of high water stress
- Water footprint values of key agricultural products (food, feed and fuel) in Thailand
- Recommendations of the strategies for reducing water stress through improved water resource management

CHAPTER 2

State of water resources in Thailand

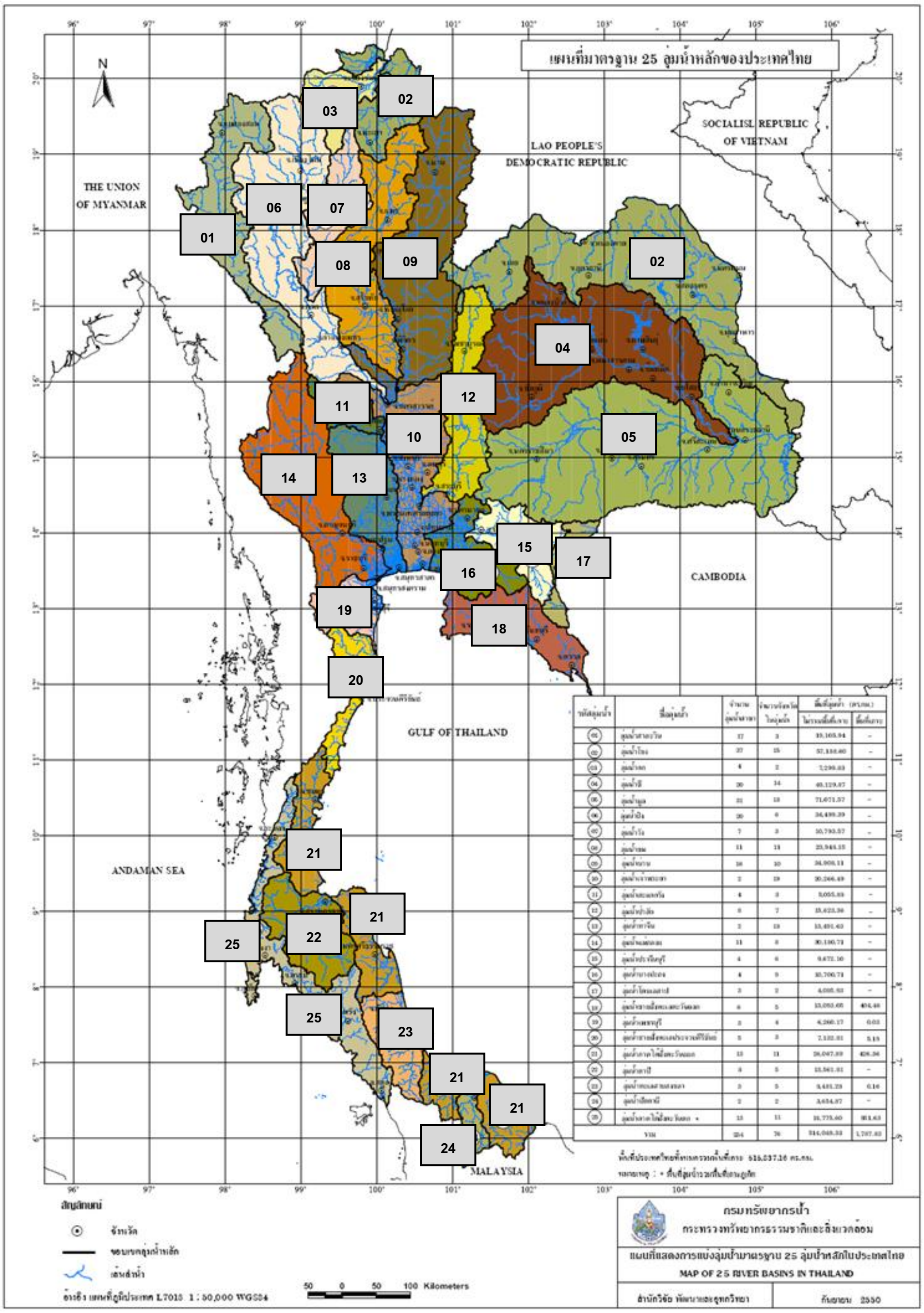
2.1 Surface water resources

Thailand is located in the South Eastern region of Asia at the geographical coordinates of about 15° 0' 0" N latitude and 100° 0' 0" E longitude; the country's climate is therefore mainly tropical i.e. exhibiting hot and humid conditions throughout the year. For hydrological purposes, the office of the national water resources committee has divided Thailand into 25 major river basins (**Figure 2.1**) based on hydrological criteria covering the catchment areas of about 515,837 km^2 (including islands and Phuket). In addition, the 25 watersheds can also be regrouped into 9 basin groups based on the flow of water as shown in **Table 2.1**.

Table 2.1 Major basin groups in Thailand

9 basin groups	Catchment areas (km^2)	25 major basins	Numbers of sub-basins
1. Mekong Sub-basin Group	188,775.80	1. Khong, 2. Kok, 3. Chi 4. Mun, 5. Tonle Sap	95
2. Salawin Sub-basin Group	19,105.94	6. Salawin	17
3. Chao Phraya-Tha Chin Basin Group	158,586.58	7. Ping, 8. Wang, 9. Yom 10. Nan, 11. Sakae Krang 12. Pasak, 13. Chao Phraya 14. Tha Chin	70
4. Mae Klong Basin Group	30,180.71	15. Mae Klong	11
5. Bang Pakong Basin Group	20,372.81	16. Prachinburi 17. Bang Pakong	8
6. East Coast Gulf Basin Group	13,497.51	18. East Coast Gulf	6
7. West Coast Gulf Basin Group	13,398.20	19. Phet Chaburi 20. Prachuapkhiri-Khan Coast*	8
8. South-eastern Basin Group (Gulf of Thailand's side)	52,192.37	21. Peninsula-East coast 22. Tapi, 23. Thale Sap Songkhla, 24. Pattani	26
9. South-western Basin Group (Andaman Sea's Side)	19,727.23	25. Peninsula-West Coast	13
Total	**515,837.15**	**25 major basins**	**254**

Source: Bureau of Research, Development and Hydrology (2009)



Code	Watershed
01	Mae Nam Salawin
02	Mae Nam Khong
03	Mae Nam Kok
04	Mae Nam Chi
05	Mae Nam Mun
06	Mae Nam Ping
07	Mae Nam Wang
08	Mae Nam Yom
09	Mae Nam Nan
10	Mae Nam Chao Phraya
11	Mae Nam Sakae Krang
12	Mae Nam Pasak
13	Mae Nam Tha Chin
14	Mae Nam Mae Klong
15	Mae Nam Prachinburi
16	Mae Nam Bang Pakong
17	Tonle Sap
18	East Coast Gulf
19	Mae Nam Phet Chaburi
20	Prachuapkhiri-Khan Coast
21	Peninsula-East Coast
22	Mae Nam Tapi
23	Thale Sap Songkhla
24	Mae Nam Pattani
25	Peninsula-West Coast

Figure 2.1 Maps of major river basins in Thailand

(Source: Bureau of Research, Development and Hydrology, 2009)

2.2 Rainfall

Thailand's average annual rainfall is around 1,500 mm ranging from 1,200 mm in the north and the central plain to 2100-2300 mm in the western part of the south and the eastern part of the country. However, the rainfall has been varied in each year; in 2011 the country average value was around 1,974 mm which is significantly higher than the normal average rainfall and this led to the severe floods in Thailand. The total volume of water from rainfall in all river basins in Thailand is estimated at 728,027 – 800,000 million m^3, around 70-75 percent of which or around 514,604 million m^3 is lost through evaporation, evapotranspiration and infiltration; the remaining 25-30 percent or around 213,423 million m^3 constitutes the runoff that flows in rivers and streams (**Table 2.2**). About 30-34% of the surface runoff or approximately around 72,560 million m^3 annually will be stored in the reservoirs. However, due to the continual improvement and development of irrigation projects in Thailand, in year 2010, the total capacity of large and medium scale of irrigation project is 73,712 million m^3 covering around 24.17 million rais or 3.7 million hectare of irrigated areas. The total capacity of small-scale water resources development projects all over the country is around 1,753 million m^3 covering the beneficial areas of about 10.12 million rais or 1.6 million hectare (OAE, 2011).

Table 2.2 Thailand's surface water resources in 2011 (Bureau of Research, Development and Hydrology, 2009)

	Range of rainfall[2] (mm)	Average annual rainfall[2] (mm/year)	Average annual rainfall during Apr 2007- Mar 2008[1] (mm/year)	Amount of rainfall[2] (million m^3)	Amount of rainfall during Apr 2007- Mar 2008[1] (million m^3)	Amount of run off[2] (million m^3)	Amount of run off during Apr 2007-Mar 2008[2] (million m^3)
Northern	900-3,100	1,248	7,712.60	156,967	162,749.65	38,567	42,277.76
Salawin	900-3,100	1,354	1748.7	24,257	31333.21	8,376	13,159.95
Kok	1,100-2,200	1,478	1,356.70	11,668	10,711.15	4,177	3,695.35
Ping	900-1,900	1,125	1,050.10	38,118	35,594.19	8,725	7,368.00
Wang	900-1,400	1,099	1,020.30	11,856	11,011.08	1,617	1,651.66
Yom	1,000-1,600	1,159	1,212.40	27,375	28,632.04	3,657	4,581.13
Nan	1,000-1,800	1,273	1,324.40	43,693	45,467.98	12,015	11,821.67
Northeastern	800-2,900	1,329	4,246.40	235,237	248,975.23	61,513	49,573.72
Khong	900-2,900	1,548	1,711.10	88,904	98,258.21	30,769	34,007.17
Chi	900-1,700	1,174	1,285.40	58,083	63,597.74	11,244	7,377.34
Mun	800-2,500	1,266	1,249.90	88,250	87,119.28	19,500	8,189.21
Central	800-2,200	1,145	7,782.10	116,378	113,531.32	24,975	33,106.35
Chao Phraya	800-1,600	1,084	881.30	21,813	17,737.04	1,732	3,192.67
Sakae Krang	1,000-1,500	1,234	1,095.80	6,405	5,688.30	1,125	1,251.43
Pasak	900-1,800	1,213	901.10	19,764	14,679.82	2,897	1,908.38
Thachin	800-1,500	1,041	977.30	14,239	13,370.44	1,364	1,283.56
Mae Klong	900-2,200	1,334	1,522.60	41,131	46,952.42	15,129	20,424.30
Petchaburi	900-1,400	1,064	972.20	5,961	5,447.24	1,385	2,342.31
West Coast Gulf	800-1,600	1,048	1,431.80	7,065	9,656.06	1,343	2,703.70
Eastern	800-4,400	1,649	5,929.70	63,380	59,028.62	23,882	23,366.43
Prachin Buri	1,100-2,600	1,584	1,394.50	16,603	14,614.36	5,164	3,945.88
Bang Pakong	1,100-2,600	1,346	1,019.90	10,738	8,136.76	3,344	2,533.79
Thole Sap	800-3,000	1,516	1,274.60	6,293	5,290.86	2,394	2,013.17
East-Coast Gulf	1,100-4,400	2,151	2,240.70	29,746	30,986.64	12,980	14,873.59

	Range of rainfall[2] (mm)	Average annual rainfall[2] (mm/year)	Average annual rainfall during Apr 2007- Mar 2008[1] (mm/year)	Amount of rainfall[2] (million m^3)	Amount of rainfall during Apr 2007- Mar 2008[1] (million m^3)	Amount of run off[2] (million m^3)	Amount of run off during Apr 2007-Mar 2008[2] (million m^3)
Southern	1,400-4,400	2,121	8,381.50	156,065	123,042.02	64,486	48,761.20
Peninsula-East coast	1,400-3,800	2,052	1,642.40	54,081	43,280.52	22,261	18,610.63
Tapi	1,400-3,900	2,061	1,119.80	25,195	13,688.44	10,530	6,022.91
Thale sap Songkhla	1,500-2,900	1,992	1,509.30	16,923	12,821.50	6,628	3,461.81
Pattani	1,600-2,500	1,939	1,859.20	7,478	7,170.93	2,670	3,155.21
Peninsula-West coast	1,600-4,400	2,559	2,250.80	52,388	46,080.63	22,397	17,510.64
Total		1,499	34,052.30	728,027	707,326.84	213,423	197,085.46

Remarks: [1]Bureau of Research, Development and Hydrology (2009)

[2]Department of Water Resources (2008)

2.3 Ground water resources

Groundwater is a vital source of freshwater in Thailand as it is estimated that 75 percent of domestic water is obtained from groundwater sources (Ti and Facon, 2003). The volume of groundwater stored over the 27 groundwater basins is estimated to be around 1,144,289 million m^3. The groundwater system in Thailand is mainly recharged by rainfall and by seepage from the rivers and the hydrological balance studies estimate that around 13-18 percent of rainfall would infiltrate the soil and about 9% reach the aquifer (Ti and Facon, 2003). The water cycle balance of Thailand developed by the Department of Water Resources showed that the total of natural groundwater recharge is 103,626 million m^3 per year or 9% of the stored groundwater (ONEP, 2010). Recently, the amount of natural groundwater recharge slightly increased to around 104,700 million m^3 per year spreading over groundwater basins. Nevertheless, the performance of rainfall reaching the aquifer is valid only for basins under favourable geologic conditions, such as those basins in the Northern Highlands, the upper Central Plain and along the Gulf Coastal Plain. For the other basins, such as those in the lower Central Plain including Bangkok and on the Khorat Plateau, it is estimated that only 5-6 percent of the rainfall reaches the aquifer.

Even though a huge amount of groundwater available in Thailand for supporting and replacing surface water in the areas where tap water is not enough or is inaccessible, the utilization of groundwater needs to be carefully managed to avoid adverse impacts such as land subsidence, contamination of groundwater from saline water intrusion, and so on. The limitations have been found in several locations especially in Bangkok. Nowadays, the use of groundwater has continuously increased not only in the urban areas but also in the rural areas for agriculture, industries and households; however, the volume of groundwater used nowadays is just only 8,000 million m^3 and still far from the total stored groundwater (DGR, 2012).

2.4 Water demand

Thailand is like other Asian countries where with increasing population and economic growth, fresh water resource management is important for sustaining future economic and social development. The rapid rural development, industrialization and income growth have raised water demand for domestic usage, agriculture and industries drastically. The statistics of water demand in 2009 revealed that the water demand for the whole country was around 76,564 million m^3 which shared by agriculture, ecosystem balance, domestic consumption (households) and industries around 74%, 12%, 8% and 6%, respectively (HAII, 2010). Meanwhile, the available water supply on that time was only 73,563 million m^3 including 55,563 million m^3 of stored water in large and medium reservoirs and 18,000 million m^3 of water downstream of dam and groundwater excluding natural water resources. The volume of water deficit found was around 3,001 million m^3 per year. **Table 2.3** shows the historic data on water requirements and water shortage classified by regions in Thailand. The results show that during 1993-2006, total water demand has increased from 61,507 million m^3 to 87,495 million m^3 per year as well as the volume of water shortage has increased from 4,756 to 12,560 million m^3 per year. The central region which including of Chao Phraya, Sakae Krang, Pasak, Thachin, Mae Klong, Petchaburi, and West Coast Gulf basins is the region of largest water consumption in Thailand. Moreover, the volume of water requirement in 2014 is predicted to be increased to 79,685 million m^3 whereas available water that can be accessed is estimated around 75,563 million m^3 including the additional 2,000 million m^3 of stored water from the large and medium reservoirs that are being constructed. Hence, the shortage is estimated to be around 4,122 million m^3 (DWR, 2008).

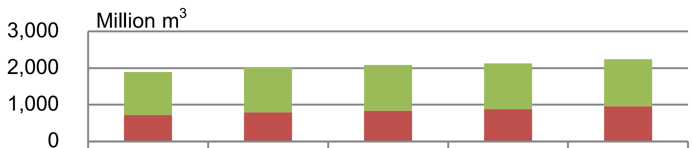
Table 2.3 Water requirement classified by watersheds

Regions and Watersheds	Water requirement*(m^3/year)			Water shortage*(m^3/year)		
	1993	1996	2006	1993	1996	2006
North (Salawin, Kok, Ping, Wang, Yom, Nan)	8,764	10,655	13,065	141	1,408	2,792
North-East (Khong, Chi, Mun)	6,389	8,409	11,814	961	1,003	2,637
Central (Chao Phraya, Sakae Krang, Pasak, Thachin, Mae Klong, Petchaburi, West Coast Gulf)	36,137	45,613	47,336	1,965	2,179	3,089
East (Prachin Buri, Bang Pakong, Thole Sap, East-Coast Gulf)	4,314	4,761	5,935	750	591	756
South (Peninsula-East coast, Tapi, Thale sap Songkhla, Pattani)	5,933	6,282	9,345	939	1,132	3,286

Source: DWR (2008)

Table 2.4 shows the water withdrawal for different basins in Thailand obtained from the Royal Irrigation Department (RID, 2011) and the water demand shared by different sectors (HAII, 2010). The withdrawals are normally classified into six sectors, namely agriculture, domestic, industry, tourism, ecosystem and livestock.

Although the water resources development programme has been implemented and developed continually, the country is still facing serious supply constraints especially during dry season due to several reasons such as lack of enough fresh water storage and good water resource management, low efficiency of water delivery and open channel systems. In addition, variations of water quantity due to locations and seasons also bring about the shortage of water in some watersheds (ONEP, 2010). In 2010, 65% of the total water demand was for agriculture with 45,054 million m^3 of water supplied in irrigated areas and 61,116 million m^3 of water required by non-irrigated areas (RID, 2010). The variations in season and location have the most significant impact to the agricultural sector in Thailand because nowadays the irrigated areas for agriculture are just only 35,200 km^2 requiring water supply around 59,900 million m^3 per year; while, the non-irrigated areas are 174,400 km^2 (RID, 2012a). The water resources for agriculture today are therefore highly reliant on rainfall. For households, tap water is the major water supply source; **Figure 2.2** shows that the amount of tap water provided by Metropolitan Waterworks Authority (MWA) (for Bangkok, Samut Prakan and Nonthaburi) and Provincial Waterworks Authority (PWA) (for the rest of country) has increased continuously.



	2006	2007	2008	2009	2010
MWA	1,173	1,224	1,251	1,250	1,282
PWA	722	795	835	884	960

Figure 2.2 Water distributed by provincial and metropolitan waterworks authorities

Source: PWA (2010) and MWA (2010)

Table 2.4 Water demands of 25 watersheds (RID, 2011)

Watersheds	Water demands (million m^3/year)									Total
	Domestic	Agriculture-Wet Season		Agriculture-Dry Season		Industry	Tourism	Livestock	Ecosystem	
		Irrigated area	Non-Irrigated areas	Irrigated area	Non-Irrigated areas					
Salawin	30.34	26.54	642.75	21.06	127.56	4.11	0.59	3.29	1838	2,694.24
Khong	238.66	0	0	377.17	1,116.21	24.85	-	54.06	3552.9	5,363.85
Kok	160.69	0	0	80.32	81.85	11.41	-	10.16	698.4	1,042.83
Chi*	213.81	4,295.02 (irrigated area) and 15,039.85 (non-irrigated areas)				33	3.91	62.39	1,884.70	21,532.68
Mun*	297.12	4,260.80 (irrigated area) and 33,892.00 (non-irrigated areas)				44.6	6.29	135.76	1,382.60	40,019.17
Ping	70.02	1,158.10	81.35	1,198.21	21.04	36.62		13.17	1,671.90	4,246.41
Wang	160.69	84.72	382.79	50.71	57.28	21.41	-	4.13	173.4	935.13
Yom	60.97	764.59	1,885.61	404.49	249.38	18.16	1.52	12.02	200.63	3,597.37
Nan	166	47.61	239.53	386.45	486.02	31.5	3.28	27.7	1172.4	2,560.49
Chao Phraya	652.2	1,812.68	1,239.55	1,316.92	225.13	896.65	-	18.23	1261.44	7,422.81
Sakae Krang	20.4	105.00	292.40	63.10	43.90	3.2	-	4.1	89.1	621.20
Pasak	86.01	158.14	1,058.71	178.59	298.9	103.26	-	27.73	894.8	2,806.14
Thachin	172.8	1,086.50	1,409.80	680.6	220.8	210.65	-	29.79	228.2	4,039.14
Mae Klong	112.6	134.88	196.9	412.55	150.56	96	-	35.33	1865.6	3,004.42
Prachin Buri	20.7	0	0	169.08	173.53	12.66	-	66.2	117.4	559.56
Bang Pakong	292.27	0	0	364.7	222.5	74.5	-	75.59	238	1,267.56
Thole Sap	23.62	16.86	248.64	26.02	95.96	6.5	-	3.62	262.2	683.43
East-Coast Gulf	117.06	0	0	109.1	279.4	161	-	52.13	1087.8	1,806.49

Watersheds	Water demands (million m³/year)									Total
	Domestic	Agriculture-Wet Season		Agriculture-Dry Season		Industry	Tourism	Livestock	Ecosystem	
		Irrigated area	Non-Irrigated areas	Irrigated area	Non-Irrigated areas					
Petchaburi	42.02	0	0	111.38	136.91	6.1	-	5.95	463.6	765.96
West Coast Gulf	40.27	116.99	753.67	35.10	56.53	989.6	-	5.6	318.2	2,315.95
Peninsula-East coast	265.37	768.82	4,227.14	282.70	388.58	1345.92	-	13.77	4466.7	11,759.00
Tapi	86.95	48.43	2,551.73	25.70	338.56	96.58	-	4.76	3,797.50	6,950.21
Thale sap Songkhla	93.09	0	0	142.31	139.87	73.79	-	6.37	740.9	1,196.33
Pattani	31.58	81.72	291.17	66.70	59.42	9.41	-	1.08	1527.1	2,068.18
Peninsula-West coast	150.51	0	0	44.87	309.74	44.19	11.60	6.54	3807.33	4,374.78

Remarks " 0 " means The amount of effective rainfall is higher than agricultural uses

* Water demands for agriculture in Mun and Chi watersheds cannot be separated into wet and dry seasons

2.5 Water stress problem

Table 2.5 shows the drought-affected regions reported by the Thai Meteorological Department (TMD). Actually, almost the whole country has experienced drought from the past until now resulting from lack or rains and delayed seasonal rains occurring two periods in a year as shown in **Table 2.5**. The first period takes place during the middle of rainy season (June-July) due to delayed seasonal rains. The second period affecting the upper part of the country (North, North-East, Central, and East) starts from the winter season until the summer season (October-May) as a result of continuous decreasing trend in rainfall. However, the significant drought-affected regions are the North-East and the Central and the two major sectors that suffered from the drought situation were the domestic and agricultural sectors (TMD, 2007; DPM, 2007; LDD 2009; 2012). This is because those two regions are not influenced by the southwest monsoon and the drought situation will be worse if no tropical cyclones are passing (TMD, 2007).

Table 2.5 Drought-affected regions in Thailand during 1990-2006

Year	Drought-affected areas	Causes
1990	North	Rain-shortage (Jun-Sep)
1991	Lower part of the North, North-East, Central, and West	Rain-shortage Low level of stored water
1992	North-East, Central, South, and North	Rain-shortage (Mar-Jun) Delayed seasonal rain (Jun-Jul)
1993	North-East, Central, East and South	Drought (Mar-Jun) Delayed seasonal rain (Jun-Jul)
2003	North-East, North, South, Central, East	Rain-shortage (Nov-Jul)
2004	North-East, North, South, Central, East	Rain-shortage (Nov-May)
2005	North-East	Drought
2006	North-East, North	Drought (Nov-May)

Source: Year 1990-1993 (TMD, 2007) and Year 2003-2006 (LDD, 2009)

Recently, the Department of Water Resources (DWR) has also reported that the drought-affected provinces in 2011 were mostly located in the North and North-East i.e. 17 provinces in the North and 20 provinces in the North-East as listed in **Table 2.6** (DWR, 2012).

Table 2.6 Drought-affected provinces in 2011

Region	Drought-affected provinces
North	Mae Hong Son, Chaing Mai, Chaing Rai, Lamphun, Phayao, Nan, Lampang, Phrae, Uttaradit, Sukhothai, Tak, Kamphaengphet, Phitsanulok, Phichit, Uthaithani, Phetchabun, Nakhonsawan
North-East	Udon Thani, Loei, Nong Khai, Bueng Kan, Ubon Ratchathani, Mukdahan, Nongbualumphu, Khon Kaen, Mahasarakham, Sakon Nakhon, Si Sa Ket, Surin, Chaiyaphum, Amnat Charoen, Kalasin, Roi Et, Nakhonratchasima, Nakhon Phanom, Buriram, Yasothon
Region	**Drought-affected provinces**
Central	Saraburi, Samutprakan, Kanchanaburi, Phetchaburi, Prachuapkhirikhan
East	Sakaew, Nakhonnayok, Prachinburi, Chachoengsao, Chonburi, Rayong, Chanthaburi, Trat
South	Trang, Satun, Chumphon

Source: DWR (2012)

According the state of environment in 2010, Thailand was under drought since November 2009 to June 2010 and 25,798 villages were faced with this problem and the number of villages faced with drought tended to increase (ONEP, 2010). Major reasons of water shortage during dry season of some locations are the lack of reservoir, low inflow to reservoir, inefficient use of water as well as delayed seasonal rains particularly in the cultivation period of irrigated and rainfed areas during June to July. Most of low storage watersheds always face water deficit every year; these are Yom, Wang, Khong, Chao Phraya, Thachin, Sakae Krang, Prachin Buri, Bang Pakong and Thale sap Songkhla. Water demand of those watersheds is higher than the volume of water storage especially Chao Phraya and Thachin because of receiving outflow from Ping, Nan, Pasak and Mae Klong. Additionally, the Provincial Waterworks Authority (PWA) had forecasted the shortage for raw water sources and the results revealed that Kok, Khong, Mun, Chi, Salawin, Chao Phraya, Nan, Pasak, Ping, Sakae Krang, Thachin, Wang, Yom tended to confront the water shortage for tap water production due to increasing of water requirements for agriculture and other activities as can be seen in **Table 2.7** (PWA, 2009).

Table 2.7 Forecasted water demand for the major river basins

Watersheds	Sub-watersheds	Raw water requirement (million m^3)	Percent share of total run off	Raw water requirement (million m^3)	
				2019	2029
Salawin	17	10.29	0.12	15.75	20.63
Kok	4	9.02	0.22	13.48	17.43
Ping	20	64.07	0.76	87.85	116.18
Wang	7	13.46	0.83	15.94	19.43
Yom	17	16.21	0.44	18.83	22.64
Nan	16	20.72	0.17	25.68	31.85
Khong	37	74.62	0.24	104.16	129.46
Chi	20	120.38	1.07	182.85	238.44
Mun	31	120.38	1.07	182.85	238.44
Chao Phraya	2	218.69	12.62	345.65	487.45
Sakae Krang	4	1.81	0.16	2.32	2.97
Pasak	8	22.8	0.78	31.21	41.25
Thachin	2	134.53	9.86	230.32	334.98

Source: PWA (2009)

The scarcity of fresh water resources is expected to continue to grow and the reason is not only about the quantity of water resource but also the quality. Therefore, an appropriate water management plan and balance of water utilization among various sectors such as agriculture, industries (both upstream and downstream industries), service sectors and also household in the future are necessary. Also, proper wastewater control and management need to be further encouraged to avoid the contamination to natural water bodies which in turn will deteriorate the water quality.

CHAPTER 3

Food, feed and fuel production in Thailand

3.1 Land utilization in Thailand

The total land area of around 51.136 million hectares of Thailand can be classified into three main categories i.e. agricultural land, forest land and other land (land for non-agricultural purposes) comprising around 41%, 33% and 26%, respectively. Agricultural land means the total area of every piece of land held by farmers for agriculture. Forest land means the area under forest as defined by the Royal Forest Department. The other land means the residual area after reduction of forest and agricultural areas from the total areas of the country including degraded forest areas, municipal areas, non-farmer residence, business and industrial areas, roads, railways, water ways, reservoirs, public areas and other non-agricultural areas (OAE, 2010a). For agricultural land which is a limited and essential natural resource for producing food, feed, fiber and currently must also include fuel, the statistics (as shown in **Table 3.1**) reveal that it has increased slightly as has also the forest land. However, there was a slight decrease in the total area of non-agricultural land as well due to several national plans and acts in Thailand to protect and promote reforestation and the Land Reform for Agriculture Act which are the main laws to allocate land in non-agricultural group to farmers for cultivation.

Table 3.1 Classification of land areas in Thailand (OAE, 2010a)

	Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Forest	M.ha	17.01	16.10	17.01	17.01	16.76	16.76	16.76	15.86	17.16	17.16
	%	33%	31%	33%	33%	33%	33%	33%	31%	33%	33%
Agricultural Land	M.ha	20.99	20.97	20.94	20.91	20.88	20.84	20.85	20.86	21.08	21.05
	%	41%	41%	41%	41%	41%	41%	41%	41%	41%	41%
Other land*	M.ha	13.31	14.24	13.36	13.39	13.68	13.71	13.71	14.59	13.07	13.10
	%	26%	28%	26%	26%	27%	27%	27%	28%	25%	26%

Remark *Non-agricultural

3.2 Situation of food crops production

Thailand is known as an agro-industrial based country; agricultural sector development is therefore essential to the Thai economy and society. In 2011, the agricultural sector contributed about 9% of GDP (BOT, 2011) and accounted for 38% of total employment in Thailand. Furthermore, Thailand is also known as the one of the world's leading country in agricultural commodities exports. In 2010, Thailand ranked as the 6th largest rice (paddy) producer and the world's largest rice exporter (OAE, 2010a). Moreover, Thailand is also the world's largest cassava producer and exporter contributing about 70% of the world market share and ranked as the world's second leading sugar exporter after Brazil which is the outstanding sugarcane producer. The major proportion of agricultural land use classified by main activities in Thailand is for rice cultivation contributing around 50% of the total agricultural land, followed by cultivation of field crops, fruit and standing timber, vegetable and ornamental plants and pasture land which are 21%, 21%, 0.9% and 0.8%, respectively (based on year 2009). The remaining areas are idle land which means the areas left unused for more than 5 years, residential areas and other lands in agricultural areas which mean the areas in the farms allocated for non-production purposes such as roads, paths, ditches, ponds, wells, etc. (OAE, 2010a).

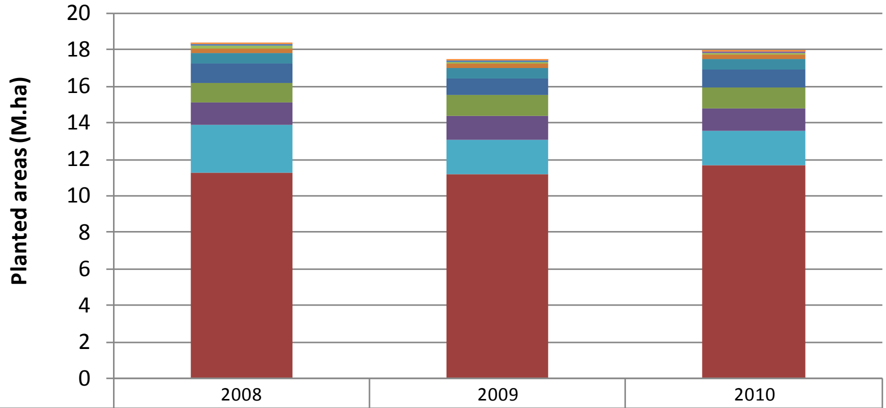
A variety of food crops, oil crops, fruit trees, vegetables, perennial trees, and ornamental plants are grown and sold as commodities in Thailand nowadays; the top ten crops ranked by harvested areas, production amount, and net economic value are summarized as **Table 3.2**. The ranking shows that rice is playing as the most important crop in terms of planted areas and the net production value followed by para rubber, cassava, maize, industrial sugarcane and oil palm respectively. Planted areas of major crops in Thailand are shown in **Figure 3.1**.

Table 3.2 Top ten crops/plants in Thailand ranked by harvested areas, production quantities and net production values

Ranking	Area Harvested	Production	Net Production Value
1	Rice	Sugar cane	Rice
2	Natural rubber	Rice	Natural rubber
3	Cassava	Cassava	Cassava
4	Maize	Oil palm fruit	Sugar cane
5	Sugar cane	Maize	Mango, Mangosteen, Guava
6	Oil palm	Natural rubber	Palm oil
7	Mango, Mangosteen, Guava	Mango, Mangosteen, Guava	Pineapple

Ranking	Area Harvested	Production	Net Production Value
8	Coconut	Pineapple	Banana
9	Fruit	Banana	Fruit
10	Vegetables	Coconut	Vegetables

Source: FAOSTAT 2010



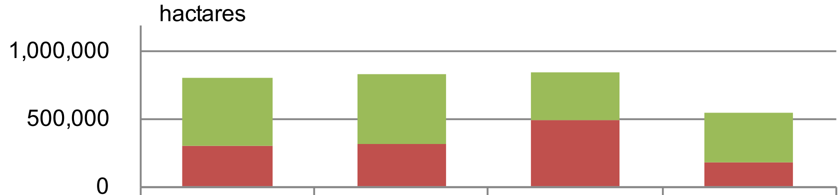
	2008	2009	2010
Pineapple	0.10	0.09	0.10
Cotton	0.0015	0.0015	0.0015
Groundnuts	0.03	0.03	0.03
Sorghum	0.03	0.03	0.03
Soybeans	0.12	0.12	0.11
Coconuts	0.25	0.24	0.23
Oil palm	0.58	0.51	0.58
Sugarcane	1.05	0.96	1.01
Maize	1.07	1.14	1.14
Cassava	1.24	1.33	1.21
Para rubber	2.67	1.86	1.93
Rice	11.24	11.18	11.64

Figure 3.1 Crops production and planted areas (Data source: DEDE, 2008-2010)

3.3 Situation of animal feed production

The livestock sector consists of various industries including dairy, beef, poultry and swine. In Thailand, even though the livestock sector is only a relatively small part of the overall agricultural sector, the sector is growing and there is an increasing demand for animal feed continuously which in turn leads to concerns about land and water competition for food, feed and fuel production. In general, Thailand has a surplus in energy feeds but a deficit in protein feeds. This is indicated from the shortage of hay and pasture for feeding dairy cattle in the dry season (FAO, 2002). The climate of Thailand is suitable for tropical pasture crops production, especially in the north and the northeast part of Thailand. Most of the forage crops (both grass and legume family crops) are recommended for plantation in the rainy season from May to September. **Figure 3.2** shows the grassland and pasture lands in

Thailand during 2008 – 2011; the areas of grass plantation and the total have been gradually increasing year by year until 2010, but there seems to be an unexplainable sudden decrease in 2011. (Bureau of Animal Nutrition Development, 2009).



	2008	2009	2010	2011
Pasture lands (ha)	507,682	507,682	348,413	369,218
Grass plantation (ha)	303,531	320,675	494,720	184,401

Figure 3.2 Forage crops plantations and pasture lands during 2008-2011

(Data source: Bureau of Animal Nutrition Development, 2011)

Apart from the grass and legumes which are considered as animal feeds for cattle, there are still the other agricultural products and agro-industrial by-products that are also used as feed and/or as raw materials for the feed mill industry. For example, pineapple waste silage from food canning industries and rice straw are essential to feed the ruminants. Broken rice and maize so far have been used as the base ingredients of feed for the poultry industry. Also, there is an increasing use of cassava chips and sorghum to substitute maize and use of soybean and fishmeal as protein supplements. The major raw materials (both crops and agro-industrial by-products) required for the feed mill industry in Thailand nowadays are as follows: corn, soybean, cassava chips, dehulled soybean, fine rice bran, coarse rice bran, wheat bran, wheat flour, wheat gluten, fish meal, etc. For example, in 2009, the broiler and swine industry in Thailand required around 0.7 M.ton of broken rice, 3.19 M.ton of corn, 1.12 M.ton of fine rice bran, 2.21 M.ton of dehulled soybean and 0.17 M.ton of fish meal and the demands for all those feedstocks were expected to increase to 0.72, 3.26, 1.15, 2.26 and 0.18 M.tons, respectively in 2010 (OAE 2010b). Management plan for balancing use of land and water resources for future food, feed and biofuels production is therefore necessary to the policy decision's makers. Additionally, water scarcity is also another problem for the livestock sector as the livestock industry had experienced the shortage of water for animals to drink, for cleaning of animals and their pens and for cooling pigs in the summer. One of the reasons is the inefficient use of water as farmers generally do not pay for the surface water. Hence there is no incentive for them to use it efficiently.

3.4 Situation of biofuels production

The rising price of fossil energy in the world market is leading the country to face political, economic and social challenges because Thailand relies highly on imported energy especially crude oil for driving economic growth. To counter the energy crisis and to achieve sustainable development, the government has proposed alternative energy as a national agenda since 2004. Various alternative energy policies have been expedited and promoted in parallel by the Ministry of Energy (MOE) and one of the recognized policies is the promotion of production and use of biofuels/bioenergy from crops and biomass in the country. Biofuels have been promoted as alternative fuels for Thai society especially for transportation for several years in order to reduce dependency on oil import along with mitigation of greenhouse gas emissions and to spur the rural development. Nowadays, first generation biofuels such as bio-ethanol derived from sugarcane and cassava, and biodiesel derived from palm oil play an important role as fuels for transport to substitute gasoline and diesel, respectively. This can be seen from the production volumes of bio-ethanol which increased from 0.37 million litres/day in 2006 to 1.3 million litres/day in 2011; while, the production of biodiesel increased from 0.33 million litres/day in 2007 to 1.62 million litres/day in 2011. In addition, the increased production of biofuels is inclined to continue as per the recent 10 years alternative energy development plan: AEDP 2012-2021. The ambitious goals of bio-ethanol and biodiesel production have been set at 9 and 5.97 milliion litres/day by 2021, respectively (as shown in **Figure 3.3**). To satisfy this new AEDP, agrofuel crops production need to be expanded both in terms of cultivation areas and productivity (DEDE, 2012a; EPPO, 2010; Sarochawikasit, 2009).

Although a variety of crops grown in Thailand can be used for fuels production such as sugarcane, cassava, sweet sorghum, maize, etc., presently, only sugarcane, cassava and oil palm are the major feedstocks being promoted for the commercial ethanol and biodiesel production. **Table 3.3** shows the harvested areas of cassava, sugarcane and oil palm classified by region in Thailand. The Northeastern region is the main region for growing cassava in Thailand contributing 53% of the total planted areas of cassava in 2009. Sugarcane is widely planted in the Northeastern, Central and Northern regions of Thailand; with the Northeastern region having the biggest share at 38%. This implies that the ethanol development policy in Thailand would have the most effect on land and water resources in rural areas of the Northeastern region as cassava and sugarcane are widely grown in this region. Also, the new cassava and sugarcane ethanol plants are generally located in the Northeastern and Central regions as well.

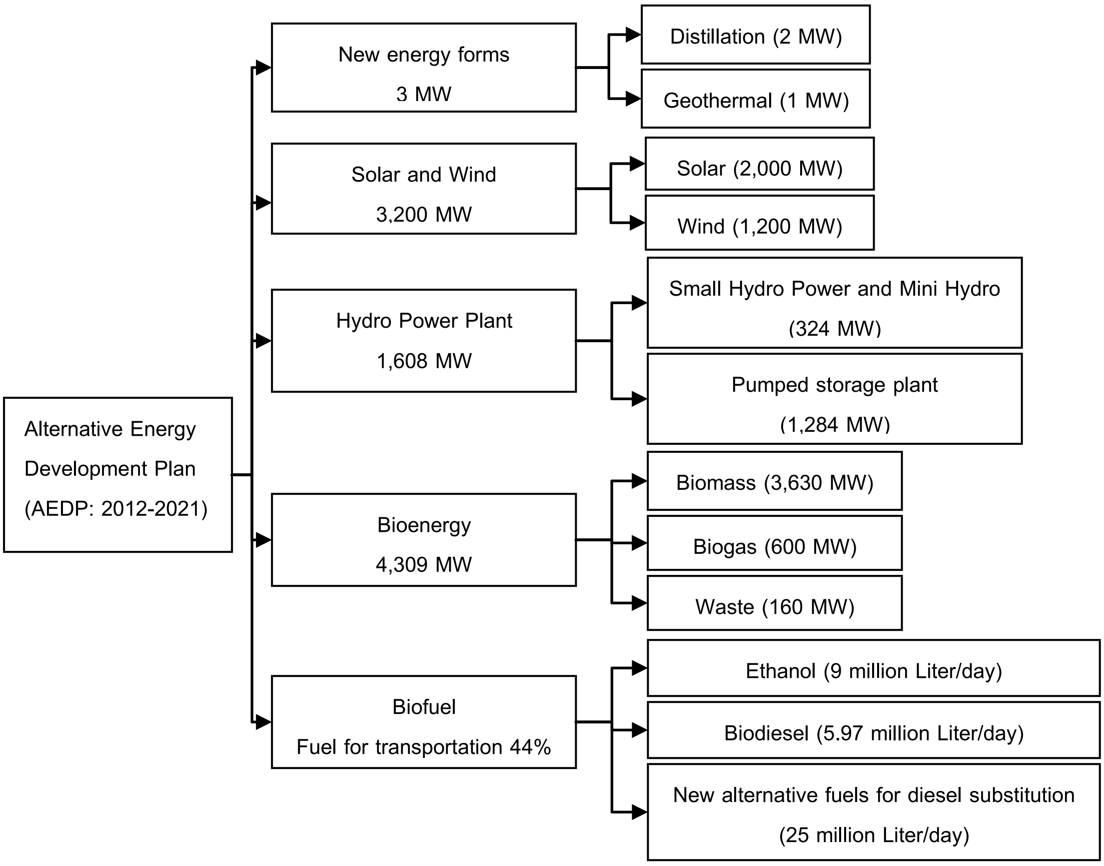


Figure 3.3 Alternative Energy Development Plan: AEDP 2012-2021 (DEDE, 2012a)

Contrary to ethanol, promotion of biodiesel in Thailand will have the most influence to the rural areas in the Southern region of Thailand as oil palm, the major feedstock for biodiesel production, is mainly cultivated in the south. Nevertheless, due to the increased demands for CPO, the government is promoting oil palm cultivation to the other regions e.g. Northern and Northeastern region as shown in **Table 3.3**.

Table 3.3 Planted areas of major biofuel feedstock crops in Thailand

Regions	Cassava				Sugarcane				Oil palm			
	2008	2009	2010	2011	2008	2009	2010	2011	2008	2009	2010	2011
Northern	185	234	229	227	288	285	296	331	1	1	3	3
Northeastern	679	722	653	629	403	339	363	513	7	7	12	13
Central	376	417	345	328	363	340	350	415	61	66	71	74
South	-	-	-	-	-	-	-	-	519	547	566	571
Whole country	1,240	1,373	1,227	1,184	1,054	964	1,010	1,259	588	622	652	662

Remark: unit = 1,000 hectare

Source: OAE (2011)

CHAPTER 4

Review on water footprint and water stress assessment methods

4.1 Water footprint definition

The concept of “water footprint” was introduced by Hoekstra (2003) and its framework was subsequently elaborated. The water footprint is an indicator of freshwater use by accounting for both direct and indirect water use of a consumer or producer. The water footprint of a product is therefore generally expressed in water volume per unit of product e.g. m^3/ton of product or sometimes it is alternatively called as “virtual water content”. Nowadays, water footprint assessment has become one of the widely used techniques for assessing water use efficiency in producing a product (Hoekstra and Chapagain, 2008; Hoekstra et al., 2011). The key advantage of water footprint assessment is that it is relatively easy to communicate to people (both technical and non-technical) to understand the virtual water consumed for a product or process which in turn would bring about the identification of measures for improving the sustainability, efficiency and equitability of water use.

The water footprint of a product divides the water use over the entire production chain of the product into three components i.e. green water, blue water and grey water as shown in **Figure 4.1**. The green water refers to the volume of rainwater consumed during the production process of product. This is particularly important for agricultural and forestry products, where it refers to the total rainwater evapotranspiration plus the water incorporated into the harvested crops and wood. Blue water refers to the volume of surface and groundwater consumed (evaporated and incorporated) into the production of a product or service. Grey water refers to the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality to comply with the defined water quality standards. This concept of dilution water requirement has been recognized from earlier studies (Postel et al., 1996; Chapagain et al., 2006). The aggregate volume of those three water components as shown in Equation (1) is then so called the “water footprint of products” or alternatively called as “freshwater appropriation” (Mekonnen and Hoekstra, 2011).

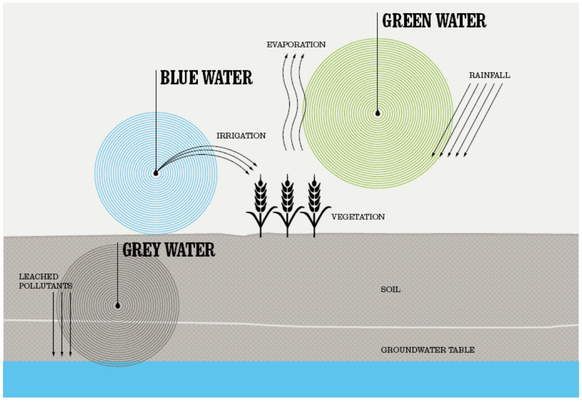


Figure 4.1 Blue, green and grey water in water footprint (WWF-UK and SABMiller, 2009)

4.2 Water Stress Index definition

Over the past decades, several indices have been developed to quantitatively evaluate the vulnerability of the water resources of a basin. One of the indices widely used to explain the water vulnerability is the water stress or water scarcity indicator. There are different levels of measuring water stress or water scarcity such as country/region level or basin level. For country/region level, the scarcity of water resources is generally expressed in terms of annual per capita water resources availability of a country. One of the most widely used indicator of water stress for this case is the "Falkenmark indicator" (Brown and Matlock, 2011; Babel and Wahid, 2009). This indicator is defined as the fraction of the total annual runoff available for human use. Based on the water available per capita, the water conditions in an area are categorized into four levels i.e. no stress, stress, scarcity, and absolute scarcity (Falkenmark, 1989). However, the limitations of using the national annual average value is that it tends to obscure the important scarcity information at smaller scales and it omits some important factors when comparing among countries such as lifestyle, climate, culture, etc. (Rijsberman, 2006). Therefore it is still difficult to characterize water stress as there are many equally important facets to water use, supply and scarcity. For example, water resource of a basin will be used for many purposes e.g. human requirement, agriculture, industry, ecosystem, transportation, etc. Therefore, selecting the criteria to justify the stress can be varied depend on the facts of water use, supply and scarcity in each basin/region and also people's perspective and prioritization. Nevertheless, at basin level, the water stress can be estimated from the ratio of total water withdrawals to the total water resources available in a river basin. This indicator is alternatively called as "Withdrawal-to-Availability (WTA)" index, the most commonly used indicator for hydrological water stress indication of a basin.

4.3 Studies on water footprint and water stress assessment

In Thailand, the research on water footprint assessment and impacts assessment on water usage is still in the initial stage and most water footprint studies are in progress and mainly focused on agricultural products such as sugarcane, rubber, oil palm, cassava, microalgae, maize and rice in some specific locations of Thailand by using the common water footprint approach (Nilsalab et al., 2012; Kaechan and Gheewala, 2013). There has not yet a comprehensive study that looks at the overview of the whole country picture of water footprint for growing crops for food, feed and fuels production and the studies that integrate the assessment of water footprint or life cycle assessment of water use and its environmental and socio-economic impacts together with the water stress index in order to see the potential of water scarcity from crops and crops derived production in each river basin; the main objective of this project is to address this gap.

Example of a complete study is the water footprint of cassava based ethanol in Thailand of Pongpinyopap & Mungcharoen (2011), the results show that the volume of green water use is higher than the blue water use because of efficient use of rainfall. Moreover, cultivated area will reduce due to the increasing of yields. Another study of cassava based ethanol has also been done by Kongboon & Sampattagul (2012) and the results show that the water use of cassava is higher than sugarcane because of the lower yields of cassava compared to sugarcane. In addition, increased ethanol production is leading to the increased water demand. Sukumalchart and colleagues (2011) assessed the monthly water footprint of maize cultivated in 40 provinces of Thailand and the results show that maize cultivation relies highly on green water or rainfall and this is the key factor influencing the total water footprint of maize. However, if focuses only on the estimation of green water footprint of crops, it is found that there are various studies on assessment of crop water consumptions using the CROPWAT model (Pongpinyopap & Mungcharoen, 2012). The results show that there are variations of water consumed for crops depending on many factors; water in soil is found to be a factor needs further investigation. Regarding watershed level, Khlong Phlo, a sub-basin of Khlong Prasea basin, is selected as a case study of sugarcane, oil palm, and cassava plantation for biofuels production conducted by Babel et al, (2011). The purpose of this study is to assess water use and potential impact of land use change resulting from the expansion of those three feedstock and the result shows that the highest water footprint is oil palm and the lowest impact on water resource is produced by cassava. Besides, increasing irrigation with fertilizer to the feedstock affects the level of water stress. In addition, the SWAT model is used for scenario analysis of land use change and the result shows that orchard areas are suggested for changing to the biofuel feedstock in terms of water balance and water quality.

There have not been studies using water stress so far in Thailand. The previous studies generally assessed the potential water stress or water shortage by using the estimated balance of water demand and supply in each region especially water demand and supply for agricultural sector. For example, the Water Resource Engineering Department of Mahanakorn University of Technology (2007) has compared the water shortage in 25 watersheds and the results revealed that Ping, Khong, Chi, Mun, Nan, Peninsular-west coast, and Kok are the critical watersheds that have experienced and will continue to face the situation of water crisis. The Consultative Group on International Agriculture Research (CGIAR) has reported that Thailand is expected to be in a water crisis situation by 2015 (Fernquest, 2009). In addition, based on the assessment of water resources after accounting for the risks from the climate variability to the various of spatial and temporal rainfall data in Thailand, the sub-watersheds in the north-eastern part of Thailand face both flooding and drought in June and July (Chitradon et al., 2009).

Regarding some studies in other countries, 12 crops from various countries for bioenergy production were selected for water footprint study (Gerbens-Leenes et al, 2009a, b). 80% of global crop production is used as criteria for selecting crop types. the green and blue water are evaluated; grey water is not considered. To obtain the green water, crop water requirement is evaluated via crop evapotranspiration throughout the crop growing season. This data was estimated via CROPWAT model derived from FAO method in addition to weather parameters such as temperature, humidity, wind speed, etc. which are required as data input for calculation based on each cropped areas by country. To obtain the blue water, irrigation requirement is calculated by subtracting effective precipitation from the crop water requirement. Accordingly, the water footprint of crops accounted only in cultivation phase can be determined by dividing the total water (green and blue) with crop yields. Moreover for assessing water footprint of bioenergy, considering some parts of the crops used for bioenergy production is more efficient than considering all parts. Comparing the results show that the water footprint of bioethanol and biodiesel are higher than that of bioelectricity because some parts of the crop were used for biofuel production while all parts of the crop were used for bioelectricity generation.

Chapter 5

Research Framework and Methodology

5.1 Research framework

The study aims to introduce and combine the water footprint and water stress assessment as the tools for effective water resource management for future food, feed and fuel production in Thailand. The research framework as shown in **Figure 5.1** is divided into five major phases i.e. (1) assessment of water requirement of crops/agricultural products, (2) assessment of water stress indicator of each region and basin, (3) integrated assessment of water footprint and water stress indicator, (4) policy scenarios and sensitivity analyses, and (5) formulation of recommendations for effective water resource management for future food, feed and fuel production.

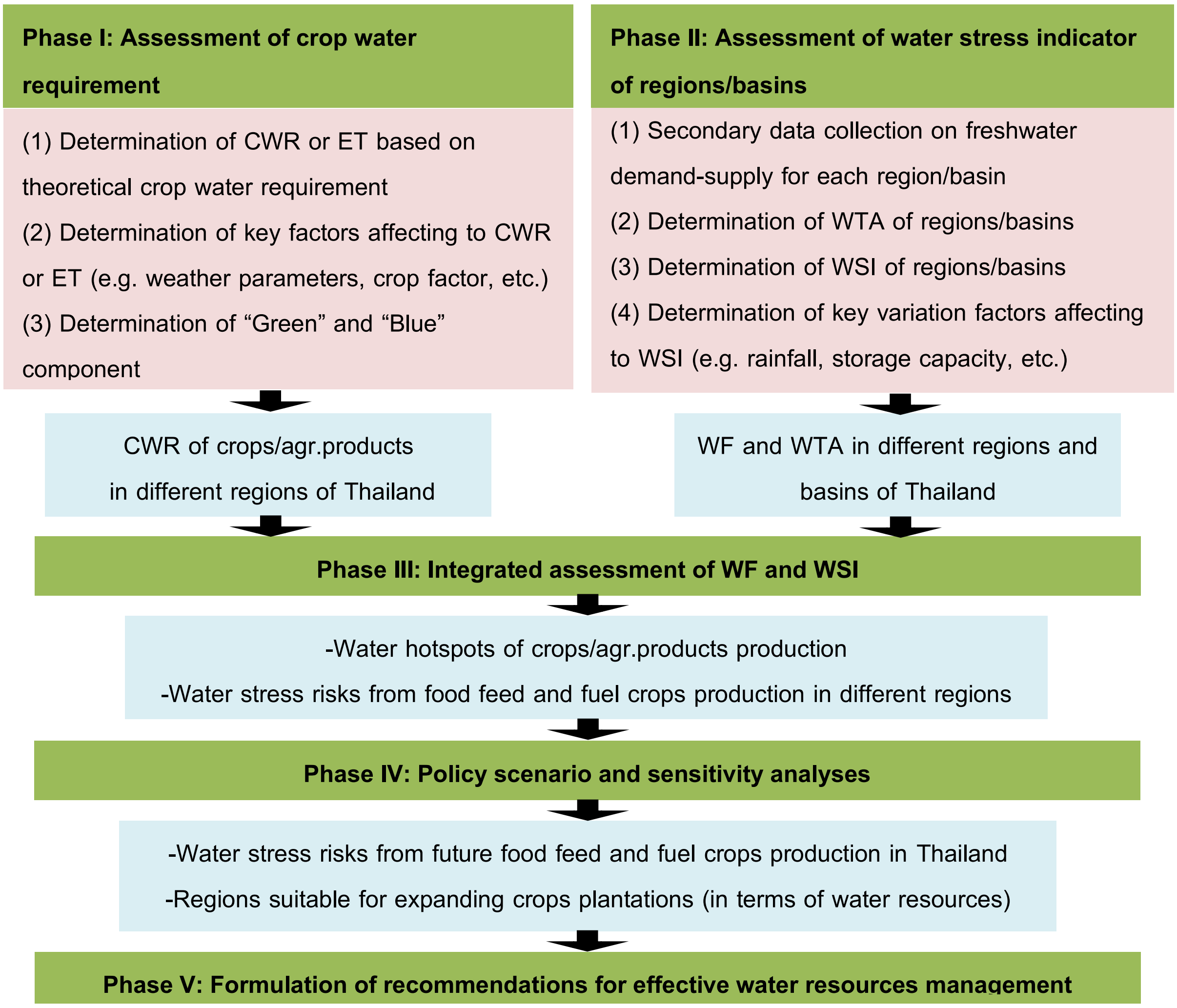


Figure 5.1 Research framework

5.2 Methodology

5.2.1 Water footprint calculation for crops

The general formula for determining the total water footprint of the process (WF_{proc}) of growing crops or tree (both annual and perennial crops) guided in the framework of Hoekstra et al. (2011) is shown as **Equation (1)**.

$$WF_{crop} = WF_{crop,green} + WF_{crop,blue} + WF_{crop,grey} \qquad \text{[Unit: } m^3\text{/ton]} \qquad \textbf{(1)}$$

Where $WF_{crop,green}$ refers to the green water used for growing a crop (in other words, it implies to the total rainwater evaporated from the field during the growing period) [m^3/ha]; $WF_{crop,blue}$ refers to the blue water use (or the total irrigation water evaporated from the field during the growing period) [m^3/ha]; $WF_{crop,grey}$ refers to the fresh water required to assimilate the pollutants generated during crop cultivation to reach the accepted water quality standard [m^3/ha]. The water footprint of crops [in m^3/kg], thus, can be examined by looking each component; green, blue and grey.

In this study, only green and blue components are taken into account. The grey water is not taken into consideration because its meaning is not related to an impact of water use, but water pollution.

To determine WF_{green} and WF_{blue} of crops or the related agricultural products as shown in **Equation (1)**, the "Crop Water Use (CWU)" or generally known as "Crop evapotranspiration (ET)" must be firstly calculated. Evapotranspiration process is the combination of two separate processes whereby water is lost on the one hand from soil surface by evaporation and on the other hand from the crop by transpiration (Allen et al., 1998). The evapotranspiration rate is normally expressed in millimetres (mm) per unit of time to show the amount of water lost from cropped surface in units of water depth. The time unit can be an hour, day, month or even an entire growing period or year (Allen et al., 1998).

The evapotranspiration rate from a field can be either directly measured or estimated by using the model based on empirical formulas. Nevertheless, as measuring evapotranspiration is costly and complicated; hence, using a modelling approach is currently quite common (Hoekstra et al., 2011; Chapagain & Orr, 2009; Pfister et al., 2011). Several models have been developed for estimating the evapotranspiration of crop growing, but the widely recognized models today are the EPIC model (Williams, 1995), the CROPWAT model

(FAO, 2010a) and the AQUACROP model (FAO, 2010b). However, the results of crop evapotranspiration can be varied by many factors such as weather parameters, crop factors, management and environmental conditions, therefore the reliability of results depends on the data input for those parameters in the models e.g. the specific spatial data, meteorological/climate data, cropped areas, soil maps, irrigation maps, agrochemicals use, water quality, crop yields, etc. (Land and Water Development Division, 2012; Tungsombun, 2006).

In the study, the crop evapotranspiration (ET) will be calculated from the crop coefficient (Kc) and the reference crop evapotranspiration (ET_o) as shown in **Equation (2)**. The accumulation of daily evapotranspiration calculated from **Equation (2)** over the growing period of crop will result in the total crop evapotranspiration or total crop water use as shown in **Equation (3)**.

$$ET_{crop} = K_C \times ET_0 \qquad \text{[Unit: mm/day]} \qquad \textbf{(2)}$$

$$WF_{crop,green\ or\ blue} = 10 \times \sum_{d=1}^{lgp} ET_{crop,green\ or\ blue} \qquad \text{[Unit: m}^3\text{/ha]} \qquad \textbf{(3)}$$

Where ET_{crop} represents crop evapotranspiration [mm/day]; K_C represents crop coefficient [dimensionless]; and ET_0 represents the reference crop evapotranspiration [mm/day]. **Equation (3)** shows the general formula to calculate WF_{green} and WF_{blue} of crops, ET_{crop} obtained from **Equation (2)** must be classified into the green water evapotranspiration ($ET_{crop,green}$) and blue water evapotranspiration ($ET_{crop,blue}$) by using the source of water supply for growing crops. The factor 10 is used to convert water depths in millimetres into water volumes per land surface in m^3/ha. The summation will be done over the period from the day of planting (day 1) to the day of harvest (*lgp* stands for length of growing period in days).

5.2.2 Water Stress Index (WSI) methodology

The water stress of a basin can commonly be estimated from the ratio of total water withdrawals to hydrological availability of a basin. This indicator is alternatively called as "Withdrawal-to-Availability (WTA)" index. The general equation is expressed as follows:

$$WTA_i = \sum_j WU_{ij} / WA_i \qquad \textbf{(5)}$$

where WTA_i represents to the withdrawal to availability ratio for each watershed *i*; WU_{ij} represents to the water withdrawal from watershed/basin *i* by each sector *j* (or commonly referred as the sum of estimated water use for industrial, agricultural, and domestic sectors); WA_i represents to the water availability of the watershed/basin. As the water withdrawal is the gross quantity of water extracted from any source, either permanently or temporarily, for a given use, it can be either diverted to a distribution network or used directly. The critical ratios that are generally used to identify the moderate and severe water stress are 20% and 40%, respectively (Alcamo et al., 2000).

To assess the water stress index (WSI) of a basin, the modified water stress indicator developed by Pfister et al. (2009) and Ridoutt & Pfister (2010) are referred i.e. the WTA will be initially calculated for each watershed/basin *i*. However, the factor regarding seasonal variations to the flows and availability of water will be applied as the weighting factor. The weighted WTA is then will be expressed as WTA* and the WSI is calculated as **Equation (6)**:

$$WSI = \frac{1}{1+e^{-6.4WTA^*(\frac{1}{0.01}-1)}} \quad \textbf{(6)}$$

Equation (7) shows the simple formula to determine the WTA* i.e. the WTA as shown in **Equation (5)** will be adjusted by the variation factor (VF) which is introduced to account for seasonal variations in water availability. SRF refers to strongly regulated flows (e.g. dams, reservoirs, etc.). **Equation (8)** shows the formula to calculate the VF by using the standard deviations of monthly average (S^*_{month}) and annual rainfall (S^*_{year}). The levels of water stress can be classified into five categories from low to extreme as shown in **Table 5.1**.

$$WTA^* = \begin{cases} \sqrt{VF} \times WTA \;\; for\ SRF \\ VF \times WTA \;\; for\ non-SRF \end{cases} \quad \textbf{(7)}$$

$$VF = e^{\sqrt{\ln(S^*_{month})^2 + \ln(S^*_{year})^2}} \quad \textbf{(8)}$$

Table 5.1 Levels of water stress classified by Pfister et al. (2009)

WSI	Category/Condition
> 0.9	Extreme
< 0.9	Severe
0.5	Stress
0.1 – < 0.5	Moderate
< 0.1	Low

The advantage of using the water stress index proposed by Pfister et al. (2009) is that it can be used as the characterization factor for water consumption in Life Cycle Impact Assessment (LCIA). However, the water stress assessment methodology as mentioned above is just the proposed methodology that will be tested along with the others and may even be adjusted to suit the conditions of Thailand in case the field results indicate such a need.

The step-by-step procedure to calculate the water stress index can be summarized as follows:

1. Determining the ratio of total water withdrawals to hydrological availability of a basin or called as "Withdrawal-to-Availability (WTA)" by using **Equation (5)**

2. Determining the "WTA*" or namely "weighted WTA" for a basin by using **Equations (7)** and **(8)**. The weighting factor is applied to the WTA which was initially calculated for each watershed/basin *i* from step 1. This is to account for variations in monthly or annual flows. As per **Equation (7)**, the WTA will be adjusted by the variation factor (VF) which can be derived from the standard deviations of monthly average (S^*_{month}) and annual rainfall(S^*_{year}) as shown in **Equation (8)**. Then, the variation of rainfall will be accounted in the WTA as well as the factors regarding the strongly regulated flow (SRF) and non-strongly regulated flow (non-SRF) of the basins/water storages. As **Equation (7)**, the water storage as dam or large and medium reservoirs is supposed to be the SRF in this study and the adjusted WTA ratio is categorized into SRF if water is delivered from the water storage; otherwise, the adjusted WTA ratio is classified as non-SRF. The results obtained will range from 0 to 1, which is essential to serve as a characterization factor for the suggested midpoint impact category "water deprivation" in life cycle impact assessment (LCIA). The minimal water stress is 0.01 as per the calibration of **Equation (5)**.

3. Verifying the methodology used and the WSI results by cross-checking the water stress situation recorded by the Royal Irrigation Department (RID). Nevertheless, the water stress indicator as proposed above needs to be tested along with the others and may even be adjusted to suit the conditions of Thailand in case the field results indicate such a need.

5.3 Scope of the study

5.3.1 Scope of the water footprint (WF) assessment

5.3.1.1 Scope of the crops for food, feed and fuel

According to the Thai agricultural statistics (FAOSTAT, 2010), there are 6 staple crops (based on economic values and planted areas) selected for performing WF assessment in the study i.e. (1) Rice; (2) Cassava; (3) Sugarcane; (4) Maize; (5) Soybean; and (6) Oil palm.

5.3.1.2 Scope of the WF assessment scenarios

The definitions of WF proposed by Hoekstra (2003) are applied in this study. Additionally in the practice, the results of crop water footprint must be varied by many factors such as such as geographical condition of planted areas (irrigated and non-irrigated), seasonal factor (wet season and dry season). Therefore, the specific assessment of WF of those staple crops for different conditions needs to be performed in Thailand. **Table 5.2** shows the scope of WF assessment in the project.

Table 5.2 Scope of WF assessment

Season	Irrigated area	Non-irrigated areas
Wet season	WF of staple crops grown in the different regions i.e. North, North-East, Central, East, and South of Thailand	
Dry season		

5.3.1.3 Definitions of the geographical condition and seasonal condition

- "Irrigated agricultural area" is termed as agricultural areas provided with irrigation supplies under Royal Irrigation Department (RID) through irrigation system and/or irrigation projects (large and medium scales) and other local administration via people's irrigation projects and/or additional irrigation projects (OAE, 2011);
- *"Non-irrigated agricultural area"* is defined as agricultural areas not provided with irrigation supplies or outside of irrigated areas (OAE, 2011);
- *"Wet season"* is defined as the period between 1st of May to 31st of October

- *"Dry season"* is defined as the period between 1st of November to 30th of April;
- Crop year refers to the period of time for crop production typically starting on 1st of May and finishing on 30th of April.

5.3.1.4 Data sources and assumptions used

To perform the water footprint assessment of staple crops, the data required and data sources are described in **Table 5.3**.

Table 5.3 Data requirements and sources for WF calculation

WF calculation parameters	Data requirement	Data source
Crop water use (CWU)	Crop year (length of growing period)	OAE
	Cultivated area	OAE and LDD
	Crop productivity	OAE
Crop evapotranspiration (ET)	Crop coefficient (K_C)	RID
	Reference crop evapotranspiration (ET_0) calculated from the Penman-Monteith equation	RID
Green water	Effective rainfall	RID
Blue water (Irrigation water)	Crop Irrigation requirement	RID
	Irrigation efficiency	RID
	Irrigation schedule	RID

Accordingly, the assessment of water footprint will be separated into the cases where crops are planted in the irrigated and non-irrigated areas; therefore, water supply sources and amount of water required for the crops must be different and need to be considered. **Figure 5.2** shows the different inventory data required for the case that crops are cultivated in irrigated and non-irrigated areas. For the irrigated agricultural areas, more information such as irrigation efficiency is required in the assessment. While, the major water source for the non-irrigated agricultural areas is the effective rainfall.

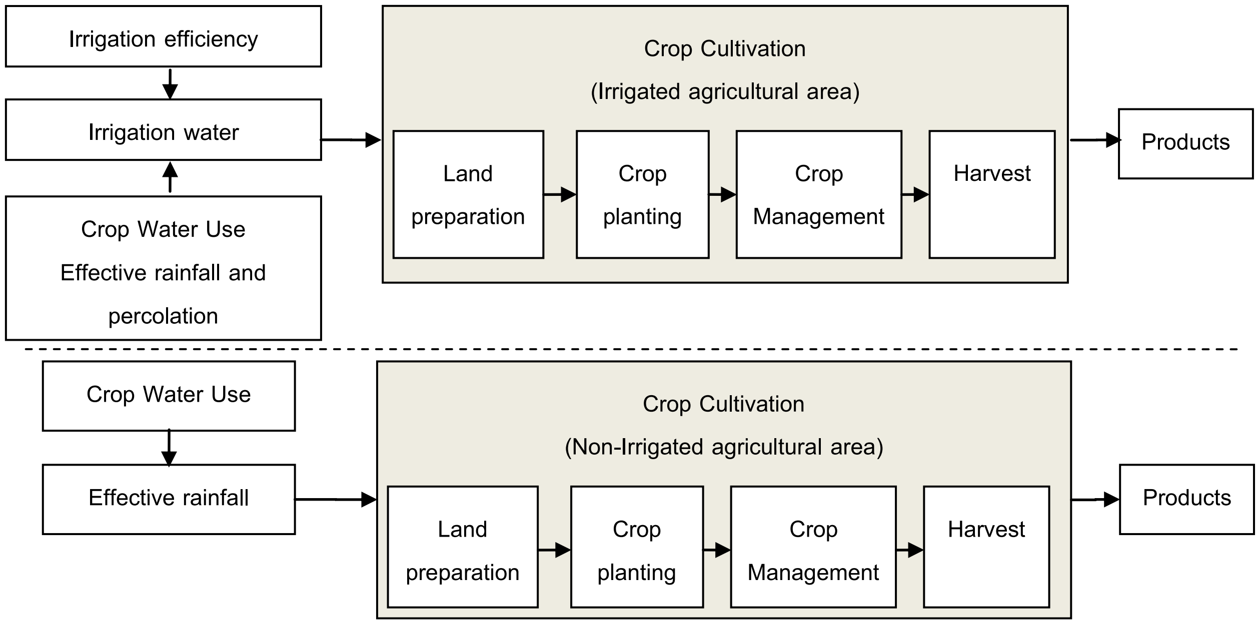


Figure 5.2 Schematic of water footprint inventory data

5.3.2 Scope of the water stress index calculation

The office of the national water resources committee has divided Thailand into 25 major river basins based on hydrological criteria covering the catchment areas of 515,837.16 km^2 (including islands and Phuket). Therefore, the study aims to develop and determine the water stress indicator based on those 25 basins as listed in **Table 5.4** by using the available secondary data of water availability and consumptive uses combined with the variation factors e.g. rainfall and ability to regulate the water supply.

Table 5.4 Major watersheds in Thailand classified by regions

Region	Watershed
North	Salawin, Kok, Ping, Wang, Yom and Nan
North-East	Khong, Chi and Mun
Central	Chao Phraya, Sakae Krang, Pasak, Thachin, Mae Klong, Petchaburi and West Coast Gulf
East	Prachin Buri, Bang Pakong, Thole Sap and East-Coast Gulf
South	Peninsula East Coast, Tapi, Thale Songkhla, Pattani and Peninsula West Coast

To obtain the adjusted WTA ratio, flow of water for crop cultivation is classified as SRF for irrigated agricultural areas and non-SRF for non-irrigated agricultural areas. In addition, average rainfall data by month and year are required for estimating the variation factor (VF). Consequently, the water stress index (WSI) derived from the adjusted WTA ratio is determined according to **Equation (5)** and data requirements as presented in **Table 5.5**.

Table 5.5 Data requirements and sources for WSI calculation

WSI calculation parameters	Data requirement	Data source
Water withdrawals	- Consumptive use for agriculture (based on calculated ET) - Consumptive use for other purposes i.e. industry, ecosystem, transportation, household	RID and/or Calculation RID
Water resource availability	- Rainfall and runoff data - Rainwater infiltration (which is accounted for as the renewable groundwater resource) - Factors regarding the ability to regulate water flow of the water basin	RID and DWR
Variation factor (VF)	- Rainfall data (by month and year)	RID

5.4 Interpretation and verification of the results

The WFP assessment aims to identify the water "hot spots" or critical agricultural activities for food, feed and fuel crops production in Thailand. The obtained results will be used for further investigation on the measures to improve the water efficiency and/or water productivity in agricultural sector of Thailand. The level of water stress for various regions of Thailand and the critical agricultural activities in regions of high water stress can be determined by WSI assessment and WSI indices. Therefore, the results from combining the WFP of food, feed and fuel crops and the WSI for each region will be useful information for water resource planning and management for future food, feed, and fuel crops production and also for recommendations on the strategies for reducing water stress through improved water resource management. The verification of the assessment results will be performed by comparing and correlating with the water resource statistics of the Royal Irrigation Department and/or Department of Water Resources[*]. Consequently the advantages and disadvantages of the proposed water stress assessment methodology will also be discussed and adjusted to suit the conditions of Thailand.

[*] The verification of the assessment results is elaborated in Section 7.3 of Chapter 7

CHAPTER 6

Water footprint assessment

In this chapter, data collection and assumptions used for assessing water footprint (WF) and results of WF for major crops in Thailand are presented as follows:

6.1 Determination of consumptive water use of major crops in Thailand

The study assesses the “consumptive water use” or “crop water requirement” from evapotranspiration of major food, feed, and fuel crops grown in different time periods and in different regions of Thailand. Key assumptions used in the calculations are as follows:

- The results obtained from the assessment are the theoretical value of consumptive water use for crops and the water loss from the water distribution system to the crop fields has not been accounted for;

- The general formula used in the calculation of crop water requirement is Crop coefficient (K_C) of Penman Monteith x ET_0 of Penman Monteith;

- The water requirement for paddy field preparation is not considered for major rice;

- The obtained water requirement for second rice includes the water consumption for field preparation at the rate about 200 mm (320 m^3/rai);

- The actual crop calendars in each region of Thailand as shown in **Figures 6.1-6.5** are referred in the calculations;

- Water requirements of fruits/standing timber are calculated based on K_C = 1**.**

6.1.1 Cropping calendar

The consumptive water use of major crops in the different regions of Thailand are calculated based on the actual crop plantation calendar in each region as shown in **Figures 6.1 – 6.5**, the dry season runs from November through April (shaded in the figures).

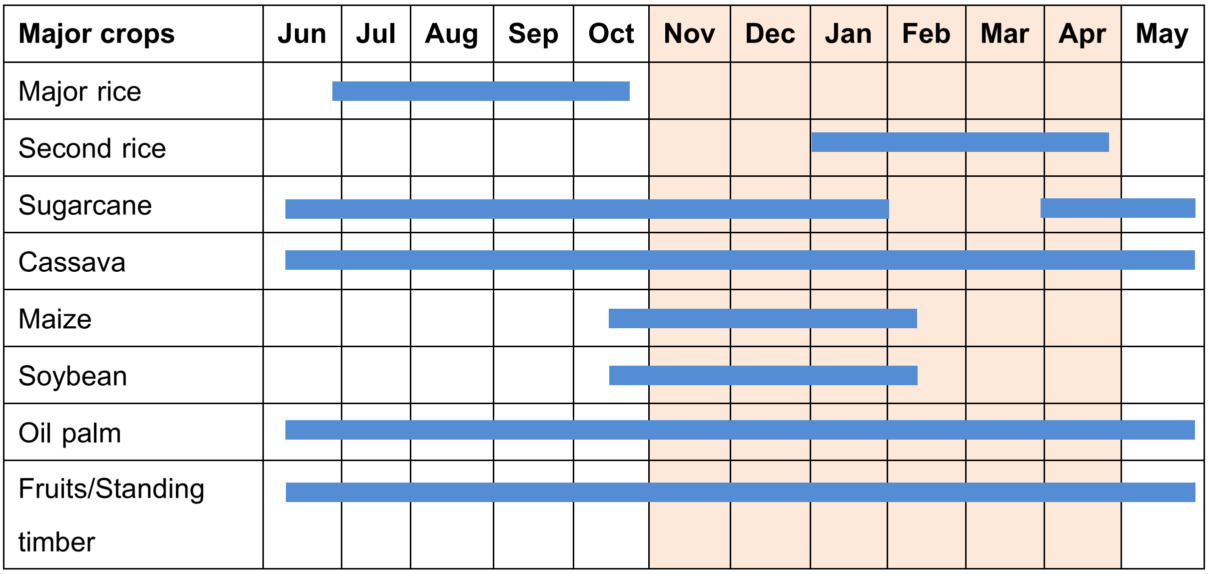


Figure 6.1 Cropping calendar for the Northern Region

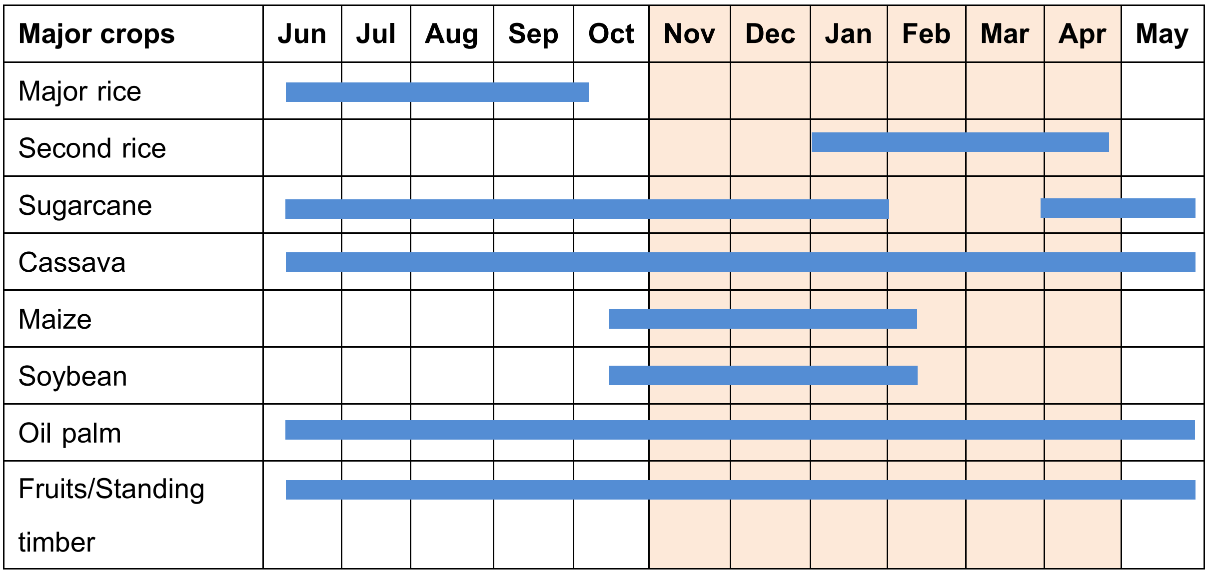


Figure 6.2 Cropping calendar for the North-Eastern Region

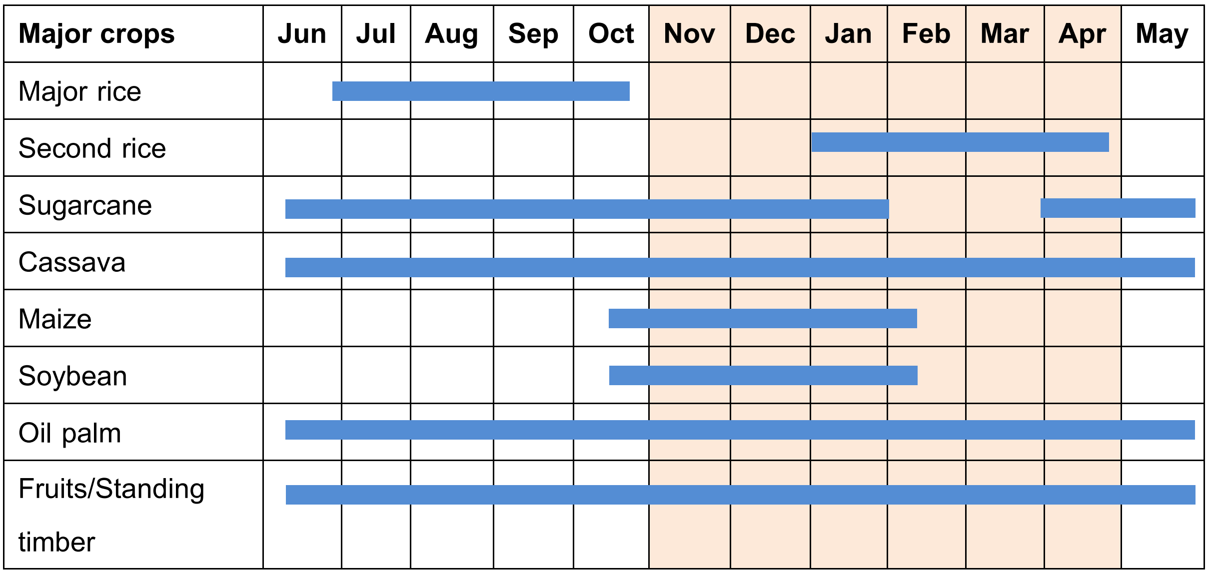


Figure 6.3 Cropping calendar for the Central Region

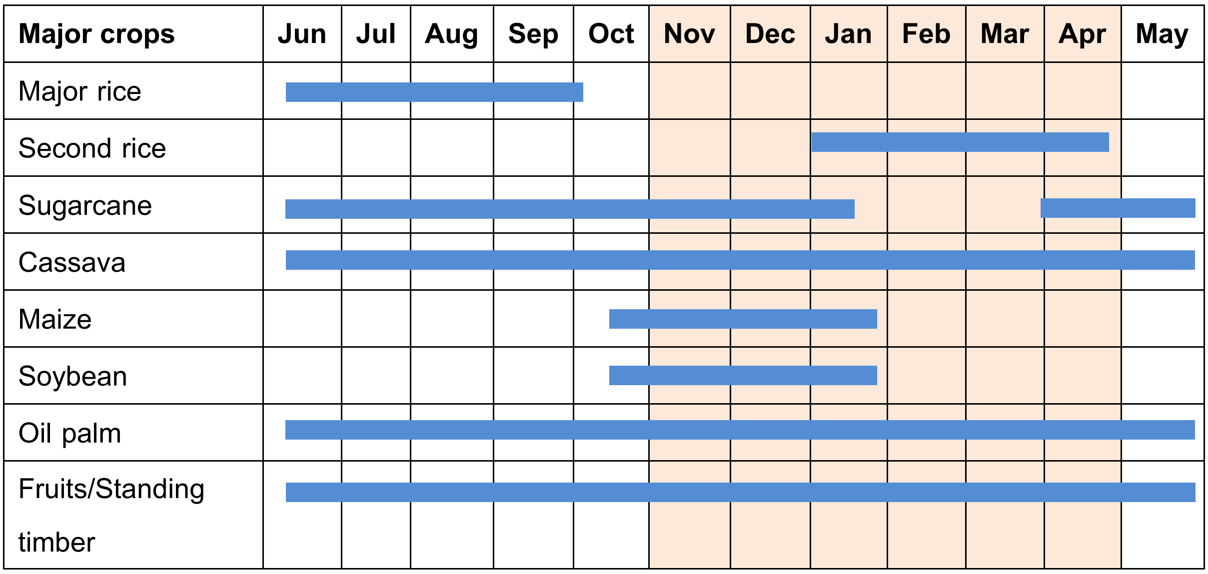


Figure 6.4 Cropping calendar for the Eastern Region

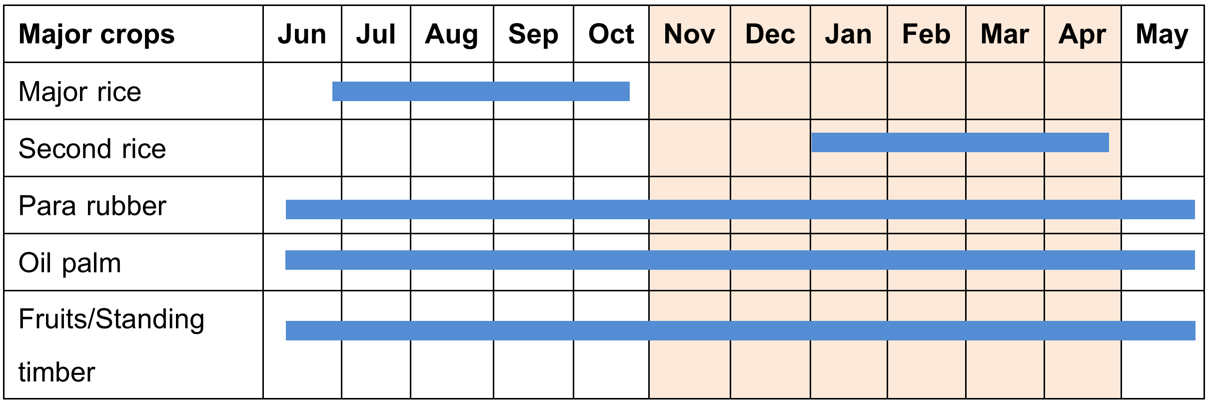


Figure 6.5 Cropping calendar for the Southern Region

6.1.2 Crop coefficient (K_c)

To estimate the evapotranspiration, **Table 6.1** shows the crop coefficient or K_c of Penman-Monteith in Thailand studied by IWM (2011) and other relevant literature (IWM 2008; Kwanyuen et al., 2010; HAII, 2010).

Table 6.1 K_c of various crops in Thailand

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg.
Rice (Gor Kor): Direct Sowing	0.8	1.05	1.25	1.4	1.5	1.55	1.6	1.63	1.68	1.6	1.5	1.36	1.08	0.65			**1.33**
Rice (Gor Kor): Transplanting	1.03	1.07	1.12	1.29	1.38	1.45	1.5	1.48	1.42	1.34	1.23	0.94	0.86	-	-	-	**1.24**
Rice (Khao Dawk Mali 105)	0.66	0.79	0.97	1.18	1.35	1.51	1.61	1.64	1.62	1.6	1.55	1.46	1.28	1.08	-	-	**1.31**
Rice (Basmati)	1.22	1.3	1.36	1.45	1.47	1.49	1.49	1.48	1.46	1.44	1.36	1.23	1.11	0.93	-	-	**1.34**
Wheat	0.5	0.52	0.61	0.76	1.11	1.26	1.33	1.38	1.37	1.32	1.14	0.83	0.62	0.46	0.39	-	**0.91**
Maize	0.63	0.72	0.86	1.13	1.35	1.52	1.61	1.63	1.58	1.5	1.38	1.15	0.9	0.67	-	-	**1.19**
Sweet corn	0.65	0.68	0.84	0.99	1.16	1.22	1.21	1.15	0.96	0.72	0.61		-	-	-	-	**0.93**
Sorghum	0.54	0.57	0.68	0.84	1.05	1.21	1.23	1.26	1.25	1.2	1.12	0.94	0.78	0.69	0.65	0.62	**0.91**
Soybean	0.64	0.69	0.81	1.01	1.23	1.32	1.35	1.34	1.27	1.09	0.85	0.74	0.74	0.72	-	-	**0.99**
Peanut	0.6	0.72	0.85	0.94	1.17	1.24	1.28	1.36	1.04	0.99	0.91	0.77	0.6	0.5	0.45	-	**0.89**
Mungbean	0.58	0.87	1.18	1.4	1.28	1.19	0.66	0.44	0.34				-	-	-	-	**0.88**
Sesame	0.59	0.7	0.85	1.11	1.23	1.28	1.24	1.21	1.13	0.98	0.71	0.55	-	-	-	-	**0.97**
Tobacco	0.45	0.57	0.69	0.88	1.01	1.36	1.61	1.48	1.44	1.3	1.21	1	-	-	-	-	**1.08**
Sunflower	0.68	0.73	0.75	0.78	0.81	0.85	0.9	0.95	0.97	1.06	1.1	1.03	0.92	0.8	0.72	-	**0.87**
Watermelon	1.02	1.14	1.6	1.9	2.1	1.9	1.73	1.44	1.03	0.75	0.65	0.52	-	-	-	-	**1.32**
Tomato	0.73	0.82	0.91	1.01	1.12	1.21	1.3	1.36	1.41	1.41	1.37	1.31	1.22	1.08	0.92	-	**1.15**
Onion	0.75	0.76	0.8	0.88	1.01	1.12	1.21	1.32	1.38	1.41	1.4	1.37	1.33	1.29	1.22	-	**1.15**
Shallot	0.72	0.82	0.94	1.05	1.14	1.2	1.2	1.15	1.08	0.92	0.77	0.67	-	-	-	-	**0.97**
Bitter gourd	0.88	1.09	1.23	1.35	1.43	1.48	1.47	1.46	1.41	1.36	1.29	-	-	-	-	-	**1.31**
Cauliflower	1.01	1.36	1.43	1.47	1.49	1.19	1.17	-	-	-	-	-	-	-	-	-	**1.30**
Chinese kale	0.54	0.6	0.68	0.72	0.78	0.83	0.73	0.67	-	-	-	-	-	-	-	-	**0.69**
Zinnia	0.35	0.58	0.77	0.93	1.07	1.18	1.27	1.33	1.38	-	-	-	-	-	-	-	**0.98**

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg.
Cotton	0.88	1.19	1.34	1.15	0.85	0.62											1.01
Sugarcane	0.65	0.86	1.13	1.35	1.56	1.29	1.20	0.93	0.63	0.52							1.01
castor bean	0.76	0.86	1.01	1.02	1.01	0.89	0.70	0.47									0.84
Taro	1.00	1.23	2.14	2.27	1.66	1.50											1.63
Asparagus	0.68	1.10	1.42	1.48	1.29	1.08	0.83	0.66	0.55	0.61	0.76	0.74					0.93
Curcuma (Siam Tulip)	0.35	0.61	0.65	0.62	1.14	0.67	0.52	0.74									0.66
Rose	0.89	0.95	1.46	1.49	1.16	1.33	2.07	1.79	2.17	2.25	1.73	1.90					1.60
Ruzi grass	0.88	1.23	1.03	0.98	0.77	1.09	0.58	1.24	0.85	1.24	0.57	1.05					0.96
Dwarf Napier	1.12	0.76	1.77	2.11	1.81	1.90	1.95	2.28	2.25	1.98	1.37	1.25					1.71
Hedge Lucern	0.65	1.41	1.53	0.75	0.54	0.68	0.92	1.12	1.28								0.99
Vetiver grass	0.91	0.79	0.87	0.83	1.03	1.37	1.37	1.53	1.33	1.24	1.26	1.34					1.16
Cultivated banana	0.76	1.10	1.45	1.64	2.30	2.11	2.38	2.29	3.28	3.19	3.39	3.39	1.63				2.22
Banana	1.94	1.74	1.78	1.96	2.07	2.18	2.18	1.88	1.86	2.21	2.02	2.22					2.00
Young Lemon tree (1-3 yrs)	1.10	1.38	1.44	1.50	1.29	1.08	1.30	1.40	1.18	1.19	1.06	1.02					1.25
Lemon tree (3-5 yrs)	1.17	1.47	1.51	1.59	1.35	1.14	1.33	1.42	1.21	1.28	1.16	1.11					1.31
Mango tree	2.10	2.46	2.53	2.28	2.29	2.50	1.90	1.69	1.61	1.27	1.24	1.19					1.92
Pomelo	1.74	1.62	1.45	1.12	1.02	1.13	1.97	2.44	2.36	1.97	1.96	1.90					1.72
Jackfruit tree	0.84	0.65	1.27	1.29	1.01	1.29	1.59	1.73	1.77	1.38	1.58	1.83					1.35
Cattail	0.91	0.80	0.88	1.01	1.27	1.48	1.53	1.49	1.54	1.73	1.75	1.70					1.34
Jasmine	1.35	1.49	1.08	1.84	1.46	0.90	1.74	2.18	2.32	2.19	2.56	2.35					1.79
Cassava	0.28	0.29	0.32	0.34	0.50	0.72	0.99	1.13	1.01	0.79	0.58	0.42					0.61

Source: IWM (2008)

6.1.3 Reference crop evapotranspiration (ET_0)

Table 6.2 shows the updated reference crop evapotranspiration (ET_0) by FAO Penman-Monteith method for the different provinces and regions in Thailand are referred from IWM (2011).

Table 6.2 Reference crop evapotranspiration (ET_0) by FAO Penman-Monteith (Unit: mm/day)

Province	ET_0 (mm./day)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Mae Hong Son (MHS)	2.86	3.71	4.65	5.17	4.41	3.26	2.88	3.02	3.09	3.21	2.98	2.76	3.5
Chiang Rai (CHR)	2.81	3.46	4.33	4.91	4.24	3.93	3.47	3.33	3.58	3.41	3.16	2.64	3.6
Phayao (PYO)	2.83	3.53	4.45	4.91	4.40	3.69	3.58	3.38	3.40	3.23	2.92	2.58	3.6
Chiang Mai (CHM)	3.15	4.05	5.05	5.38	4.26	3.91	3.34	3.35	3.33	3.45	3.24	2.90	3.8
Lampang (LPANG)	3.16	3.84	4.78	4.99	4.20	3.93	3.61	3.47	3.43	3.45	3.34	3.00	3.8
Lamphun (LPOON)	2.94	3.79	4.73	5.46	4.56	3.78	3.68	3.47	3.47	3.35	3.06	2.74	3.8
Phrae (PHR)	2.98	3.70	4.48	4.91	4.57	3.73	3.59	3.44	3.50	3.41	3.17	2.68	3.7
Nan (NAN)	2.95	3.60	4.52	4.76	4.27	3.86	3.51	3.17	3.57	3.63	3.19	2.77	3.6
Uttaradit (UTD)	3.25	3.88	4.77	4.91	4.43	3.59	3.50	3.40	3.52	3.59	3.48	2.99	3.8
Tak (TAK)	3.40	3.99	4.91	5.43	4.38	3.41	3.23	3.12	3.03	3.24	3.27	3.03	3.7
Phitsanulok (PSN)	3.27	4.01	4.99	5.32	4.71	3.78	3.65	3.51	3.27	3.55	3.42	3.19	3.9
Phetchabun (PCB)	3.26	3.98	4.62	4.81	4.09	3.66	3.58	3.10	3.21	3.60	3.57	3.26	3.7
Kamphaengphet (KPP)	3.26	3.91	4.35	5.01	4.45	3.92	3.50	3.41	3.55	3.48	3.34	3.11	3.8
Sukhothai (SKT)	3.20	3.76	4.57	5.34	4.20	4.13	3.74	3.61	3.58	3.55	3.48	3.13	3.9
Phichit (PCHIT)	3.28	3.89	4.35	4.60	4.05	3.98	3.50	3.40	3.19	3.47	3.58	3.24	3.7
Nong Khai (NK)	3.11	3.78	4.62	4.62	4.03	3.56	3.51	3.41	3.51	3.63	3.31	3.04	3.7
Loei (LOEI)	3.24	4.01	4.77	4.91	4.32	3.98	3.77	3.47	3.70	3.53	3.33	3.02	3.8
Udonthani (UDT)	3.32	4.07	4.85	5.21	4.56	4.08	3.71	3.55	3.61	3.73	3.70	3.22	4.0
Sakon Nakhon (SKN)	3.29	3.92	4.68	5.01	4.38	4.13	3.72	3.57	3.92	3.84	3.51	3.17	3.9
Nakhon Phanom (NKP)	3.43	3.95	4.39	4.73	4.12	3.86	3.62	3.33	3.66	3.59	3.60	3.21	3.8
Khon Kaen (KK)	3.43	4.00	4.79	4.87	4.46	4.10	3.88	3.52	3.55	3.69	3.66	3.41	3.9

Province	ET_0 (mm./day)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Mukdahan (MDH)	3.65	4.18	5.00	5.15	4.11	3.64	3.56	3.43	3.57	3.80	3.95	3.53	4.0
Mahasarakham (MHK)	3.57	4.19	4.71	5.22	4.62	4.22	3.84	3.64	3.62	3.76	3.83	3.58	4.1
Kalasin (KAL)	4.15	4.89	5.40	5.45	4.80	4.32	4.22	3.65	3.71	4.06	4.30	4.10	4.4
Chaiyaphum (CYP)	3.60	4.20	5.00	5.12	4.47	4.13	3.77	3.61	3.60	3.78	3.89	3.51	4.1
Rio-Et (ROIE)	3.77	4.29	4.79	5.04	4.41	4.26	4.03	3.77	3.61	3.71	3.89	3.71	4.1
Ubon Ratchathani (UBT)	3.82	4.11	4.58	4.58	4.05	3.80	3.72	3.29	3.33	3.53	3.94	3.82	3.9
Sisaket (SSK)	3.40	3.92	4.56	4.75	4.42	4.43	4.19	3.71	3.85	3.62	3.79	3.45	4.0
Nakhonratchasima (NSM)	3.85	4.29	4.69	4.73	4.16	4.22	3.99	3.85	3.35	3.51	3.84	3.78	4.0
Surin (SRN)	3.61	4.18	4.66	4.81	4.20	4.04	3.73	3.53	3.58	3.67	3.80	3.62	4.0
Buriram (BRR)	3.90	4.49	5.04	5.22	4.56	4.33	4.04	3.61	3.62	3.81	4.02	3.78	4.2
Nakhon Sawan (NKS)	3.83	4.61	5.47	5.50	4.51	4.06	3.91	3.60	3.45	3.56	3.69	3.59	4.1
Chainat (CHN)	3.30	3.68	4.34	4.56	4.31	4.27	3.84	3.47	3.42	3.26	3.31	3.21	3.7
Ayutthaya (AYT)	3.95	4.20	4.58	4.58	4.02	4.10	3.73	3.68	3.36	3.46	3.92	3.94	4.0
Pathumthani (PTT)	3.54	3.85	4.44	4.64	4.05	4.15	3.62	3.59	3.26	2.90	3.83	3.54	3.8
Ratchaburi (RATCH)	4.04	4.61	5.27	5.15	4.00	3.96	3.57	3.63	3.44	3.39	3.86	4.01	4.1
Suphanburi (SPB)	3.46	4.12	4.79	4.94	4.13	3.95	3.71	3.42	3.35	3.50	3.53	3.46	3.9
Lopburi (LB)	3.90	4.61	5.13	5.06	4.17	3.75	3.66	3.31	3.26	3.65	3.86	3.88	4.0
Kanchanaburi (KCB)	3.52	4.22	4.76	5.22	4.00	3.52	3.22	3.21	3.03	3.25	3.41	3.42	3.7
Bangkok (BKK)	4.06	4.51	5.11	5.09	4.53	4.44	4.35	4.12	3.76	3.69	4.23	4.10	4.3
Samutprakan (SPK)	1.14	2.03	3.25	3.75	3.74	3.96	3.74	3.36	2.60	1.79	1.46	0.99	2.7
Phetchaburi (PETCH)	3.59	4.23	4.87	4.89	4.22	3.74	3.66	3.17	3.38	3.08	3.39	3.49	3.8
Prachuapkhirikhan (PCK)	3.84	4.31	4.64	4.83	4.19	3.98	3.70	3.54	3.48	3.42	3.66	3.88	4.0
Nakhonpathom (NKP)	3.70	4.35	5.15	5.12	4.02	4.00	3.63	3.16	3.44	3.69	3.92	3.66	4.0
Chachoengsao (CCS)	3.85	3.83	4.19	4.31	3.86	3.52	3.46	3.46	3.26	3.33	3.47	3.51	3.7
Prachinburi (PRC)	3.81	4.06	4.32	4.65	3.98	3.50	3.44	3.15	3.25	3.58	4.02	4.01	3.8
Sakaew (SKE)	3.93	4.41	4.83	4.79	4.04	3.97	3.72	3.50	3.30	3.53	3.77	3.71	4.0
Chonburi (CHON)	4.18	4.44	4.81	5.00	4.39	4.26	4.22	4.02	3.67	3.52	4.21	4.39	4.3

Province	ET_0 (mm./day)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Rayong (RAY)	3.66	3.98	4.32	4.54	4.08	3.97	3.75	3.74	3.42	3.43	3.71	3.69	3.9
Chanthaburi (CHAN)	3.83	3.72	4.03	4.28	3.43	3.11	3.10	2.84	2.95	3.33	3.81	3.91	3.5
Trat (TRAT)	3.80	3.83	4.17	4.28	3.89	3.35	3.32	2.87	3.22	3.35	3.68	3.84	3.6
Chumphon (CHP)	3.40	3.86	4.34	4.33	3.82	3.83	3.59	3.68	3.53	3.37	3.24	3.36	3.7
Ranong (RAN)	3.84	4.21	4.29	4.27	3.76	3.34	3.27	3.30	3.20	3.31	3.41	3.52	3.6
Suratthani (SUR)	3.53	4.12	4.38	4.32	3.80	3.63	3.55	3.62	3.51	3.21	3.11	3.19	3.7
Nakhon Si Thammarat (NST)	3.32	3.77	4.10	4.15	3.69	3.65	3.53	3.64	3.53	3.18	2.99	2.94	3.5
Phatthalung (PTL)	3.65	4.09	4.13	4.20	3.74	3.68	3.51	3.62	3.54	3.31	3.30	3.28	3.7
Phuket (PHU)	4.19	4.50	4.53	4.27	3.79	3.77	3.76	3.83	3.51	3.35	3.34	3.73	3.9
Krabi (KB)	4.08	4.73	4.42	4.21	3.73	3.58	3.54	3.63	3.57	3.07	3.27	3.50	3.8
Trang (TRA)	4.21	4.86	4.67	4.30	3.71	3.60	3.24	3.35	3.26	3.12	3.27	3.64	3.8
Songkhla (SKL)	3.74	4.21	4.34	4.24	3.72	3.67	3.69	3.76	3.57	3.34	2.99	3.16	3.7
Satun (SAT)	4.43	4.60	4.40	4.18	3.64	3.52	3.53	3.65	3.28	3.14	3.32	3.80	3.8
Pattani (PTN)	3.36	3.95	3.91	3.95	3.49	3.39	3.42	3.52	3.48	3.25	2.95	2.85	3.5
Yala (YALA)	3.53	4.20	4.25	4.31	3.77	3.66	3.66	3.80	3.75	3.59	2.94	3.10	3.7
Narathiwat (NRTW)	3.32	3.82	4.07	4.19	3.75	3.63	3.61	3.72	3.40	3.25	2.94	2.92	3.6

Source: IWM (2011)

6.2 Crop water use and Irrigated water requirement for major food, feed, and fuel crops in Thailand (Yr 2010/2011)

This section shows the evapotranspiration (ET) or water requirement of the selected crops calculated from the equation: $ET_{crop} = K_C \times ET_0$. The actual cropping calendar of each region of Thailand was referred in the calculation. Rain water use for growing crops was assumed to be the amount of effective rainfall in each region and the deficit between crop water requirement (ET) and the effective rainfall was assumed to be the amount of irrigated water requirement for growing that crop. The assessment results for ten major food, feed, and fuel crops in Thailand are shown in **Tables 6.3 – 6.13**.

Table 6.3 Crop water use and Irrigated water requirements for major rice

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	-	-	-	-	-	138	240	273	71	-	-	-	-	722
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	-	106	47	-	-	-	-	-	153
North-Eastern	Effective rain water use (m^3/rai)	-	-	-	-	-	126	239	257	69	-	-	-	-	690
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	4	102	42	-	-	-	-	-	148
Central	Effective rain water use (m^3/rai)	-	-	-	-	-	-	121	170	198	60	-	-	-	549
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	-	0	142	89	-	-	-	-	231
East	Effective rain water use (m^3/rai)	-	-	-	-	-	126	228	249	83	-	-	-	-	686
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	-	110	65	-	-	-	-	-	175
South	Effective rain water use (m^3/rai)	-	-	-	-	-	131	128	200	72	-	-	-	-	531
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	3	220	138	-	-	-	-	-	360

Table 6.4 Crop water use and Irrigated water requirements for second rice

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	128	-	-	-	-	-	-	-	-	-	131	-
	Irrigated water requirement (m^3/rai)	247	318	173	-	-	-	-	-	-	-	-	-	738	-
North-Eastern	Effective rain water use (m^3/rai)	-	16	33	-	-	-	-	-	-	-	-	-	49	-
	Irrigated water requirement (m^3/rai)	285	306	262	-	-	-	-	-	-	-	-	-	853	-
Central	Effective rain water use (m^3/rai)	-	25	113	67	-	-	-	-	-	-	-	-	205	-
	Irrigated water requirement (m^3/rai)	119	315	212	15	-	-	-	-	-	-	-	-	660	-
East	Effective rain water use (m^3/rai)	-	69	129	107	-	-	-	-	-	-	-	-	305	-
	Irrigated water requirement (m^3/rai)	128	287	211	1	-	-	-	-	-	-	-	-	627	-
South	Effective rain water use (m^3/rai)	-	-	151	132	86	74	-	-	-	-	-	-	283	159
	Irrigated water requirement (m^3/rai)	-	-	-	245	206	-	-	-	-	-	-	-	245	206

Table 6.5 Crop water use and Irrigated water requirements for maize

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	-	-	-	-	-	-	-	69	30	-	33	69
	Irrigated water requirement (m^3/rai)	37	-	-	-	-	-	-	-	-	-	211	206	453	-
North-Eastern	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	68	5	-	5	68
	Irrigated water requirement (m^3/rai)	48	-	-	-	-	-	-	-	-	-	269	267	584	-
Central	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	64	-	3	3	64
	Irrigated water requirement (m^3/rai)	44	-	-	-	-	-	-	-	-	-	253	232	529	-

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
East	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	69	15	6	21	69
	Irrigated water requirement (m^3/rai)	49	-	-	-	-	-	-	-	-	-	265	262	576	-
South	Effective rain water use (m^3/rai)	47	-	-	-	-	-	-	-	-	66	208	199	455	66
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	-	-	-	-	-	23	28	51	-

Table 6.6 Crop water use and Irrigated water requirements for cassava

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	75	84	109	130	172	188	164	134	30	-	192	897
	Irrigated water requirement (m^3/rai)	31	50	-	-	-	-	-	-	-	-	64	22	167	-
North-Eastern	Effective rain water use (m^3/rai)	-	15	30	66	97	118	165	172	158	121	5	-	115	831
	Irrigated water requirement (m^3/rai)	41	36	38	6	-	2	4	-	-	11	102	28	252	17
Central	Effective rain water use (m^3/rai)	-	17	67	65	101	117	156	151	144	123	-	2	151	793
	Irrigated water requirement (m^3/rai)	38	36	7	14	-	17	21	37	14	2	99	23	216	90
East	Effective rain water use (m^3/rai)	-	48	67	74	98	127	164	185	160	135	15	4	208	869
	Irrigated water requirement (m^3/rai)	42	5	2	-	-	-	11	3	-	-	95	25	168	15
South	Effective rain water use (m^3/rai)	40	32	68	66	51	123	114	189	166	128	86	24	316	772
	Irrigated water requirement (m^3/rai)	-	22	-	3	42	1	58	13	2	-	5	-	30	116

Table 6.7 Crop water use and Irrigated water requirements for sugarcane

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	-	-	-	101	187	205	231	259	209	173	30	-	131	1,264
	Irrigated water requirement (m^3/rai)	-	-	-	59	-	-	3	1	-	31	116	78	253	34
North-Eastern	Effective rain water use (m^3/rai)	-	-	-	95	164	161	211	228	201	161	5	-	100	1,127
	Irrigated water requirement (m^3/rai)	-	-	-	42	3	28	18	10	-	40	161	101	304	99
Central	Effective rain water use (m^3/rai)	-	-	-	84	152	137	168	166	174	168	-	3	87	965
	Irrigated water requirement (m^3/rai)	29	-	-	41	16	74	65	86	27	16	154	82	306	284
East	Effective rain water use (m^3/rai)	-	-	-	117	150	184	194	229	200	197	15	6	138	1,155
	Irrigated water requirement (m^3/rai)	32	-	-	1	13	15	37	23	3	1	155	91	279	93
South	Effective rain water use (m^3/rai)	31	-	-	100	68	149	119	195	194	188	132	78	340	912
	Irrigated water requirement (m^3/rai)	-	-	-	10	86	47	108	76	21	-	9	5	24	338

Table 6.8 Crop water use and Irrigated water requirements for oil palm

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	128	101	201	181	174	167	162	168	30	-	262	1,053
	Irrigated water requirement (m^3/rai)	153	173	107	147	16	-	-	-	-	1	127	147	854	17
North-Eastern	Effective rain water use (m^3/rai)	-	16	33	98	184	149	166	153	156	142	5	-	152	950
	Irrigated water requirement (m^3/rai)	190	159	178	113	11	18	4	-	-	26	174	191	1,005	58
Central	Effective rain water use (m^3/rai)	-	25	113	88	168	133	157	143	143	151	-	3	228	895
	Irrigated water requirement (m^3/rai)	174	156	120	144	34	54	22	23	13	7	165	165	923	154

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
East	Effective rain water use (m^3/rai)	-	69	126	183	166	168	166	167	158	170	15	6	399	995
	Irrigated water requirement (m^3/rai)	192	112	91	35	30	8	12	-	-	-	168	186	783	50
South	Effective rain water use (m^3/rai)	167	34	211	132	75	145	115	176	165	162	141	146	832	838
	Irrigated water requirement (m^3/rai)	19	153	-	70	110	28	59	3	2	-	11	16	269	202

Table 6.9 Crop water use and Irrigated water requirements for soybean

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	-	-	-	-	-	-	-	55	30	-	33	55
	Irrigated water requirement (m^3/rai)	35	-	-	-	-	-	-	-	-	-	142	185	363	-
North-Eastern	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	54	5	-	5	54
	Irrigated water requirement (m^3/rai)	47	-	-	-	-	-	-	-	-	-	190	241	478	-
Central	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	34	-	3	3	34
	Irrigated water requirement (m^3/rai)	64	-	-	-	-	-	-	-	-	-	180	209	453	-
East	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	37	15	6	21	37
	Irrigated water requirement (m^3/rai)	71	-	-	-	-	-	-	-	-	-	185	236	491	-
South	Effective rain water use (m^3/rai)	67	-	-	-	-	-	-	-	-	35	153	182	402	35
	Irrigated water requirement (m^3/rai)	1	-	-	-	-	-	-	-	-	-	13	23	37	-

Table 6.10 Crop water use and Irrigated water requirements for mungbean

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	0	-	-	-	-	-	-	-	-	-	30	-	31	-
	Irrigated water requirement (m^3/rai)	3	-	-	-	-	-	-	-	-	-	129	131	263	-
North-Eastern	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	12	5	-	5	12
	Irrigated water requirement (m^3/rai)	4	-	-	-	-	-	-	-	-	-	176	170	350	-
Central	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	52	-	3	3	52
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	-	-	-	-	-	147	40	187	-
East	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	56	15	6	21	56
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	-	-	-	-	8	125	36	160	8
South	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	53	126	40	166	53
	Irrigated water requirement (m^3/rai)	-	-	-	-	-	-	-	-	-	-	9	1	10	-

Table 6.11 Crop water use and Irrigated water requirements for coconut

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	128	101	201	181	173	167	162	169	30	-	262	1,053
	Irrigated water requirement (m^3/rai)	153	173	106	145	16	-	-	-	-	1	127	147	852	17
North-Eastern	Effective rain water use (m^3/rai)	-	16	28	94	172	139	156	144	149	134	6	-	144	889
	Irrigated water requirement (m^3/rai)	190	159	178	113	11	18	4	-	-	26	174	191	1,005	58
Central	Effective rain water use (m^3/rai)	-	25	113	88	168	133	157	143	143	151	-	3	228	895
	Irrigated water requirement (m^3/rai)	174	156	120	144	34	54	22	23	13	7	165	165	923	154

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
East	Effective rain water use (m^3/rai)	-	69	126	183	166	168	166	167	158	170	15	6	399	995
	Irrigated water requirement (m^3/rai)	192	112	91	35	30	8	12	-	-	-	168	186	783	50
South	Effective rain water use (m^3/rai)	167	34	211	132	75	145	115	176	165	162	141	146	832	838
	Irrigated water requirement (m^3/rai)	19	153	-	70	110	28	59	3	2	-	11	16	269	202

Table 6.12 Crop water use and Irrigated water requirements for pineapple

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	128	101	201	181	173	167	162	169	30	-	262	1,053
	Irrigated water requirement (m^3/rai)	153	173	106	145	16	-	-	-	-	1	127	147	852	17
North-Eastern	Effective rain water use (m^3/rai)	7	19	39	97	172	140	156	144	147	132	12	7	144	892
	Irrigated water requirement (m^3/rai)	190	159	178	113	11	18	4	-	-	26	174	191	1,005	58
Central	Effective rain water use (m^3/rai)	-	25	113	88	168	133	157	143	143	151	-	3	228	895
	Irrigated water requirement (m^3/rai)	174	156	120	144	34	54	22	23	13	7	165	165	923	154
East	Effective rain water use (m^3/rai)	-	69	126	183	166	168	166	167	158	170	15	6	399	995
	Irrigated water requirement (m^3/rai)	192	112	91	35	30	8	12	-	-	-	168	186	783	50
South	Effective rain water use (m^3/rai)	167	34	211	132	75	145	115	176	165	162	141	146	832	838
	Irrigated water requirement (m^3/rai)	19	153	-	70	110	28	59	3	2	-	11	16	269	202

Table 6.13 Crop water use and Irrigated water requirements for peanut

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dry season	Wet season
North	Effective rain water use (m^3/rai)	3	-	-	-	-	-	-	-	-	54	30	-	33	54
	Irrigated water requirement (m^3/rai)	46	-	-	-	-	-	-	-	-	-	142	185	373	-
North-Eastern	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	54	5	-	5	54
	Irrigated water requirement (m^3/rai)	59	-	-	-	-	-	-	-	-	-	190	241	491	-
Central	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	46	17	22	44	46
	Irrigated water requirement (m^3/rai)	54	-	-	-	-	-	-	-	-	8	163	190	402	8
East	Effective rain water use (m^3/rai)	-	-	-	-	-	-	-	-	-	54	15	6	21	54
	Irrigated water requirement (m^3/rai)	60	-	-	-	-	-	-	-	-	-	185	236	481	-
South	Effective rain water use (m^3/rai)	58	-	-	-	-	-	-	-	-	52	153	182	393	52
	Irrigated water requirement (m^3/rai)	0	-	-	-	-	-	-	-	-	-	13	23	36	-

6.3 Direct water footprint of major crops in Thailand (Yr 2010/2011)

Figure 6.6 shows the comparison of direct water footprint of major food, feed and fuel crops in Thailand i.e. major rice, second rice, maize, cassava, sugarcane, oil palm and soybean grown in different regions of Thailand. The results show that the direct water footprint of major rice is 1,913 litre per kg rice and the lowest water efficiency of rice cultivation is shown in the North-eastern region of Thailand. According to **Figure 6.6**, per ton of fresh fruit bunches (FFB), oil palm plantation in the North and Northeastern region of Thailand seems to have a very high water footprint index as compared to oil palm grown in the South or the Central region. This is because oil palm plantation areas in those two regions are the new plantations promoted by the government. Therefore, the FFB yields are still lower than other regions. However, it is expected that when all the palm trees are mature to harvest, the water footprint efficiency of oil palm in those two regions will increase.

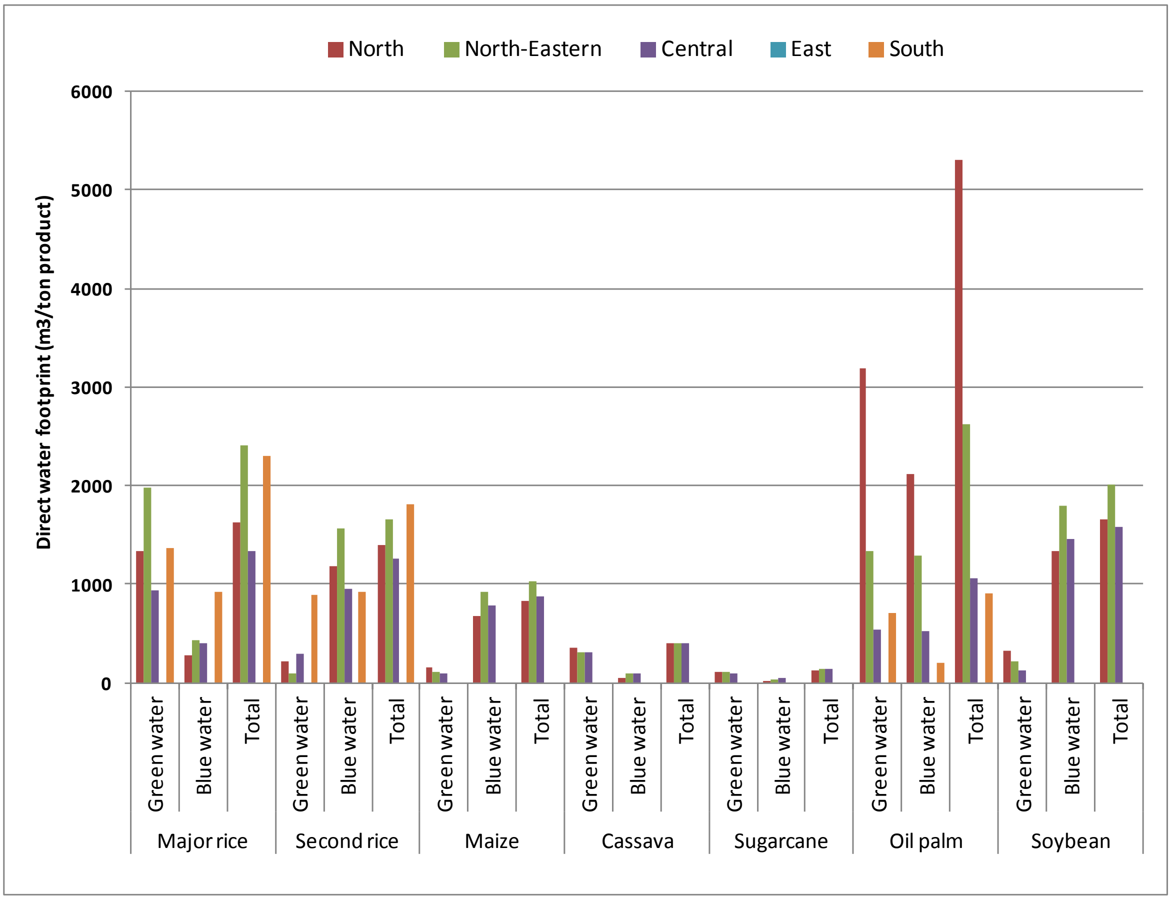


Figure 6.6 Direct water footprints of staple crops in Thailand classified by regions

6.4 Estimated total water requirement for crops by regions (Year 2010/2011)

Figures 6.7 – 6.11 show the estimations of the total water requirements for crops plantation in each region based on the Thailand agricultural statistics (crop plantation areas) during year 2009/2010 and year 2010/2011 (OAE, 2011). However, it must be noted that the results obtained from the calculation do not yet include the distribution loss and water loss from irrigation systems.

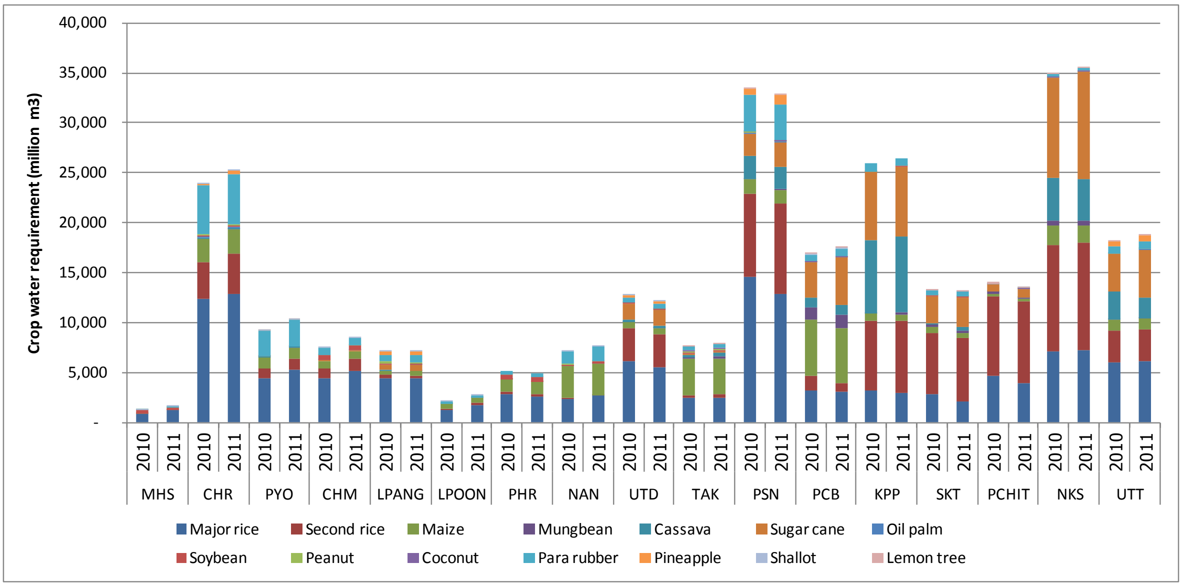


Figure 6.7 Crop water requirements in the Northern region (Year 2010/2011)

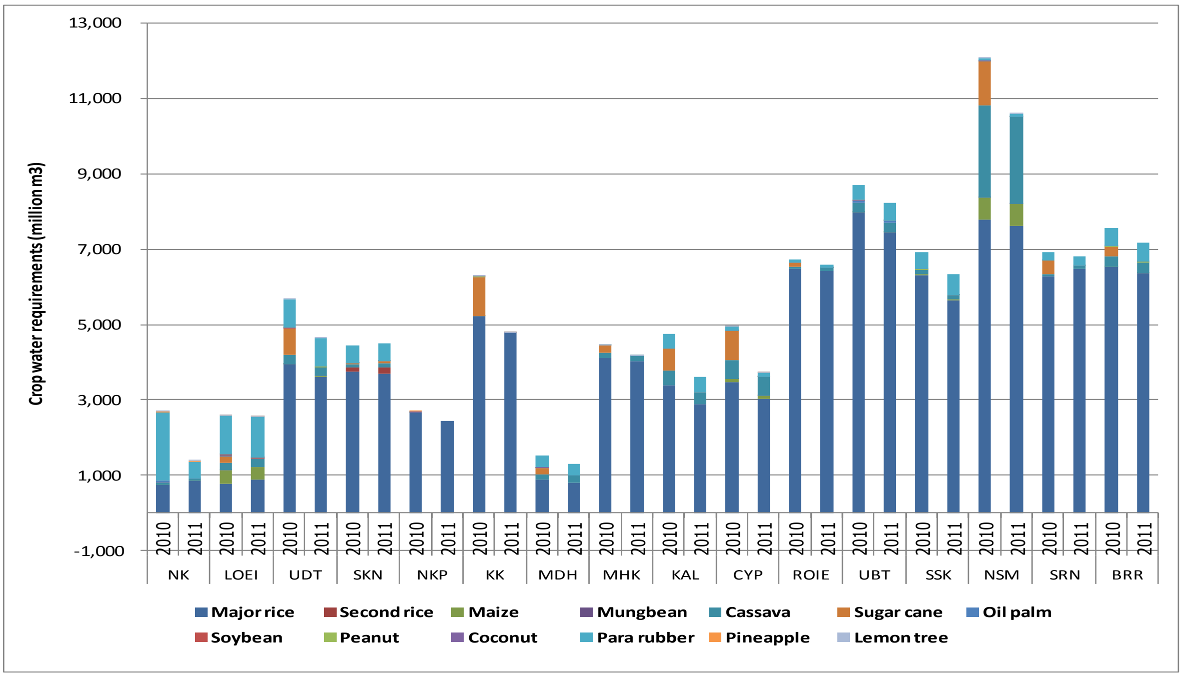


Figure 6.8 Crop water requirements in the North-Eastern region (Year 2010/2011)

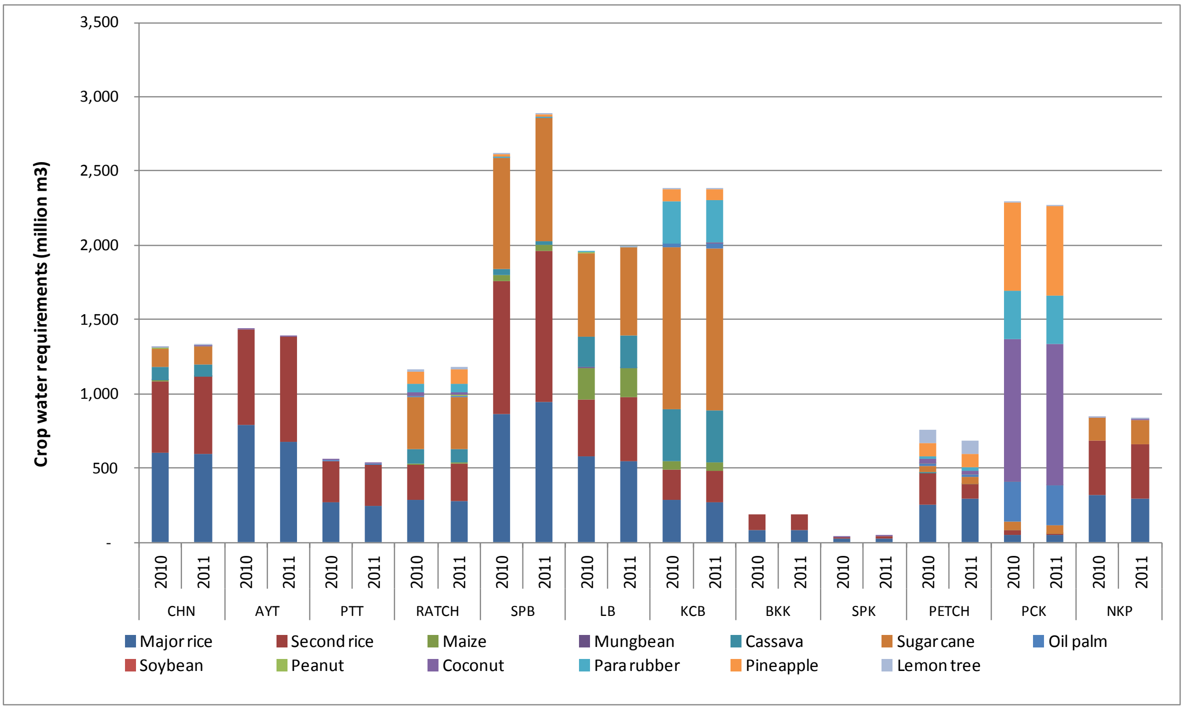


Figure 6.9 Crop water requirements in the Central region (Year 2010/2011)

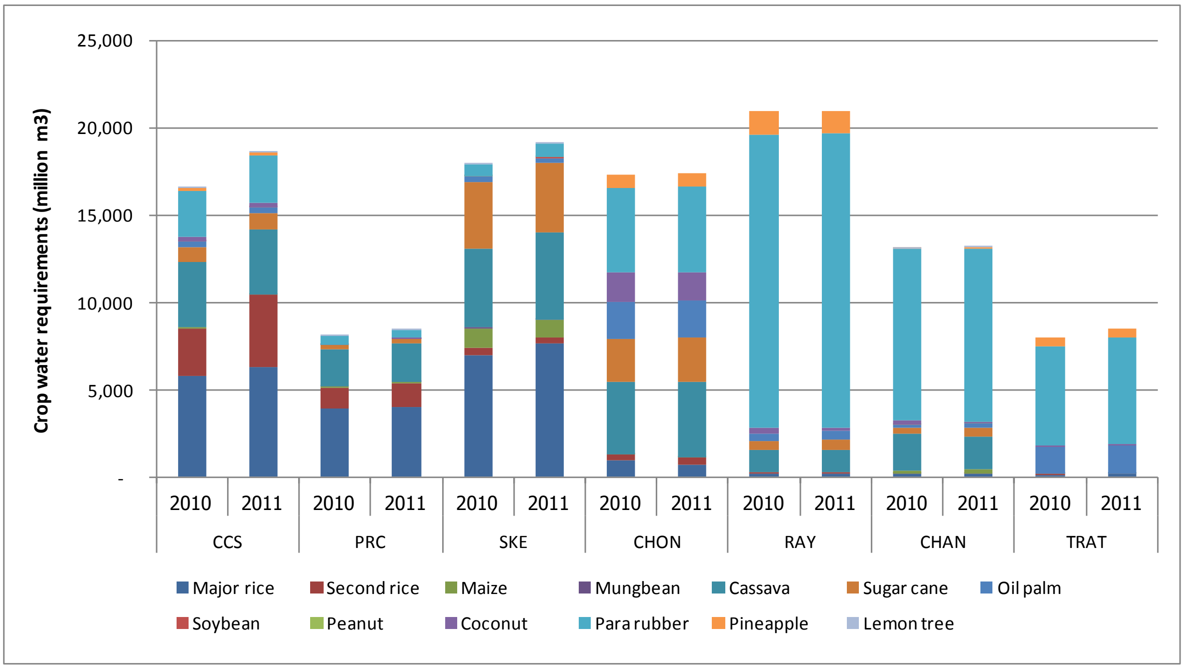


Figure 6.10 Crop water requirements in the Eastern region (Year 2010/2011)

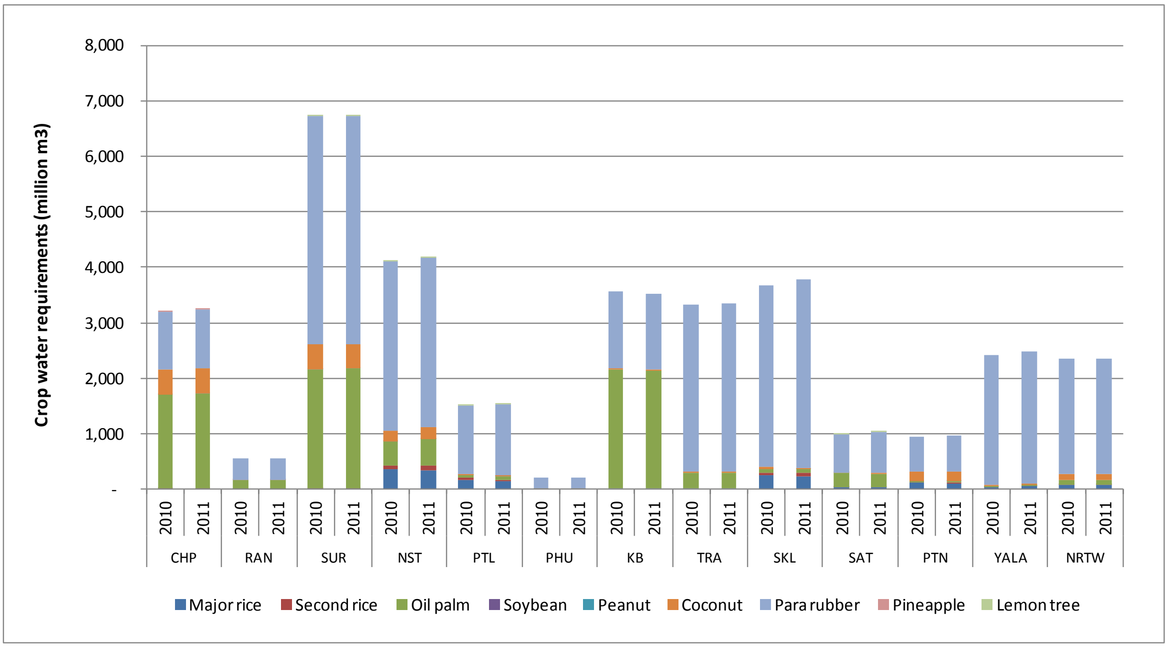


Figure 6.11 Crop water requirements in the Southern region (Year 2010/2011)

Chapter 7

Water stress index assessment

In this chapter, data collection and assumptions used for assessing water stress index (WSI) and results of WSI for the major river basins in Thailand are detailed as follows:

7.1 Data collection for assessing water stress index

To assess the water stress index (WSI) of a basin's geographic location, the hydrological information regarding the water supply, storage and water withdrawals need to be determined. In the study, the "top-down approach" has been used for assessing the WSI indices for all the major watersheds of Thailand. With this approach, the assessment is conducted based on the available data regarding the water resources and water demands for the main sectors referred from several governmental departments e.g. RID and HAII combined with the theoretical calculations. In this data collection phase, the hydrological data regarding rainfall and runoff and the secondary data regarding water withdrawal or water demand for various purposes are collected in order to determine the "Withdrawal-to-Availability (WTA)" index following **Equation (5)**.

7.1.1 Estimation of water withdrawal

To determine the withdrawal-to-availability (WTA), **Table 7.1** shows the estimated water withdrawal for different basins in Thailand obtained from the Royal Irrigation Department (RID, 2011). The withdrawals are classified into four sectors i.e. agriculture, domestic, industry, and livestock**.** The total water withdrawal for a basin is the sum of estimated water uses for those four sectors. Methodologies e.g. water intensity and assumptions used for assessing the water demands for different sectors in **Table 7.1** are referred from the work manual of RID (2011) and are summarized in Sections 3.1.1 – 3.1.4.

Table 7.1 Water demands of 25 watersheds (RID, 2011)

Watersheds	Water demands (million m^3/year)				Total
	Domestic	Agriculture	Industry*	Livestock	
Salawin	30.34	817.91	4.70	3.29	856.24
Kok	160.69	162.17	11.41	10.16	344.43
Ping	70.02	2,458.70	32.62	13.17	2,574.51
Wang	160.69	575.50	21.41	4.13	761.73

Watersheds	Water demands (million m^3/year)				Total
	Domestic	Agriculture	Industry*	Livestock	
Yom	60.97	3,304.07	19.68	12.02	3,396.74
Nan	166.00	1,159.61	34.78	27.70	1,388.09
Khong	238.66	1,493.38	24.85	54.06	1,810.95
Chi	213.81	19,334.87	36.91	62.39	19,647.98
Mun	297.12	38,152.80	50.89	135.76	38,636.57
Chao Phraya	652.20	4,594.29	896.65	18.23	6,161.37
Sakae Krang	20.40	504.40	3.20	4.10	532.10
Pasak	86.01	1,694.34	103.26	27.73	1,911.34
Thachin	172.80	3,397.70	210.65	29.79	3,810.94
Mae Klong	112.60	894.89	96.00	35.33	1,138.82
Petchaburi	42.02	248.29	6.10	5.95	302.36
West Coast Gulf	40.27	962.28	989.60	5.60	1,997.75
Prachin Buri	20.69	342.61	12.66	66.20	442.16
Bang Pakong	292.27	587.20	74.50	75.59	1,029.56
Thole Sap	23.62	387.49	6.50	3.62	421.23
East-Coast Gulf	117.06	388.50	161.00	52.13	718.69
Peninsula-East coast	265.37	5,667.24	1,345.92	13.77	7,292.30
Tapi	86.95	2,964.42	96.58	4.76	3,152.71
Thale sap Songkhla	93.09	282.18	73.79	6.37	455.43
Pattani	31.58	499.01	9.41	1.08	541.08
Peninsula-West coast	150.51	354.61	55.79	6.54	567.45

Remark *including tourism

7.1.1.1 Water demand for industrial sector

Water demand for industry is assessed based on types of industries and their areas. **Table 7.2** shows the 10 major industrial sectors classified by the Department of Industrial Works (DIW). Tourism is accounted as one of the industrial sectors in this assessment and the water intensity of tourism sector will be assessed based on the number of tourists and excursionists.

Table 7.2 Water requirement of industrial sectors (RID, 2011)

Categories	Water consumption (m^3/rai/day)
Accessory	6
Chemical	8
Food	12
Metal	5
Other (General industry)	7
Outside	4
Categories	**Water consumption (m^3/rai/day)**
Paper	4
Textile	5
Non-metal	8
Wood	3
Categories	**Water consumption (liter/person/day)**
Tourist	350
Excursionist	30

7.1.1.2 Water demand for agricultural sector

Water demand for agriculture is assessed based on water required by crops and cultivated areas relating to effective rainfall, water loss via conveyance, and irrigation efficiency as can be expressed in the Equation below.

$$\text{Water demand for agriculture } \left(\mathrm{m^3}/_{\mathrm{rai}}\right) = \frac{[\text{crop water requirement}] - [\text{effective rainfall}] + [\text{water loss}] \times 100}{[\text{irrigation efficiency}]}$$

7.1.1.3 Water demand for livestock sector

Water demand for livestock is estimated from No_{live} x WU_{live}; where, No_{live} is the number of each livestock type and WU_{live} is water use unit per head of each livestock type. **Table 7.3** shows the water use per head of each livestock referred from RID (2011).

Table 7.3 Daily water use per head of livestock

Livestock	Water use (litre/animal/day)
Cow	80
Pig	20
Goat/Sheep	15
Poultry	0.5

7.1.1.4 Water demand for domestic use

Water demand for domestic use is assessed based on the population living in a community. **Table 7.4** shows the estimated water requirements of households based on the standard practice for investigation of basic minimum needs classified by four types of communities.

Table 7.4 Water requirement of households (RID, 2011)

Communities	Water consumption (litre/person/day)
City municipality	250
Town municipality	200
Commune municipality	120
Out of municipality	50

7.1.2 Estimation of water resource availability

Thailand's average annual rainfall is around 1,500-1,700 mm ranging from 1,200 mm in the North and the Central plains to 2,100-2,300 mm in the Western part of the South and the Eastern part of the country. According to the rainfall statistics by provinces during 2002-2011, the average annual rainfall of about 1,710 mm was calculated and the total volume of water from rainfall was around 728,000-800,000 million m^3. **Table 7.5** shows the numbers of large and medium reservoirs in each water basin and their storages and in the **Appendix I** installed cover all basins. The stored water in those reservoirs will become the water supply source for irrigation and waterworks. The numbers of reservoirs are referred to the irrigated water projects under Royal Irrigation Department and other governmental agencies and classified into large, medium, and small scale projects, electrical water pump project, and detention storage project (known as "Kaem Ling Project"). Hence, based on the stored water in reservoirs and the average annual rainfall data, the total water availability can be roughly estimated and the results are shown in **Table 7.6**.

Table 7.5 Numbers of large and medium reservoirs classified by 25 watersheds

Watersheds	Large and Medium Projects			Total Projects			
	No. of projects	Stored water (M. m^3)	Irrigated areas (rai)	No. of projects	Stored water (M. m^3)	Irrigated areas (rai)	Command areas (rai)
Salawin	16	13.8	41,260	343	24.70	93,506	114,262
Kok	8	73	276,200	213	96.88	331,470	262,675
Ping	57	14,122.5	2,137,041	1,172	697.60	2,002,071	1,277,528

Watersheds	Large and Medium Projects			Total Projects			
	No. of projects	Stored water (M. m^3)	Irrigated areas (rai)	No. of projects	Stored water (M. m^3)	Irrigated areas (rai)	Command areas (rai)
Wang	11	350.7	299,067	348	454.22	429,462	207,469
Yom	36	306.3	752,440	675	449.99	958,657	766,732
Nan	66	10,354.4	1,127,814	976	916.50	1,687,078	535,246
Khong	135	1,309.9	1,034,035	2,471	1,718.68	1,790,896	1,373,239
Chi	96	4,462.6	1,474,056	2,228	2,279.81	2,782,529	730,153
Mun	164	4,141.8	1,600,305	2,798	2,546.04	2,089,709	1,528,688
Chao Phraya	39	37.7	6,118,666	380	62.66	6,228,463	998,683
Sakae Krang	7	230.0	279,148	141	231.71	312,548	161,810
Pasak	25	1,124.4	510,970	418	1,144.53	520,034	432,792
Thachin	16	294.5	2,441,126	414	322.65	2,503,776	610,055
Mae Klong	28	26,728.1	1,461,500	371	287.75	1,607,041	319,723
Petchaburi	13	714.4	360,530	155	750.13	383,100	92,780
West Coast Gulf	21	599.5	307,620	350	650.35	340,494	307,603
Prachin Buri	25	141.8	527,215	310	152.76	661,487	162,865
Bang Pakong	19	607.7	1,323,190	284	622.70	1,350,320	206,056
Thole Sap	3	137.0	97,900	151	139.66	99,850	68,670
East-Coast Gulf	42	781.7	508,800	375	807.59	640,470	241,590
Peninsula-East coast	31	95.8	1,345,844	1,083	169.28	1,491,074	639,450
Tapi	21	5,800.2	61,615	146	161.42	107,465	89,630
Thale sap Songkhla	19	52.4	620,190	213	52.56	691,175	219,316
Pattani	4	1,404.0	241,850	201	1.94	250,990	58,574
Peninsula-West coast	21	32.8	150,110	566	57.37	249,627	211,052

Table 7.6 Estimated water availability classified by each basin

Watersheds	Water availability (million m^3/year)		
	Stored water	Surface water (Rainfall)	Total
Salawin	25	25,303	25,327
Kok	97	9,982	10,079
Ping	698	45,765	46,463
Wang	454	13,993	14,447
Yom	450	32,204	32,654
Nan	917	46,285	47,201

Watersheds	Water availability (million m^3/year)		
	Stored water	Surface water (Rainfall)	Total
Khong	1,719	88,356	90,075
Chi	2,280	68,549	70,829
Mun	2,546	96,929	99,475
Chao Phraya	63	25,037	25,100
Sakae Krang	232	6,619	6,851
Pasak	1,145	18,281	19,425
Thachin	323	16,130	16,453
Mae Klong	288	34,890	35,178
Petchaburi	750	6,381	7,132
West Coast Gulf	650	9,367	10,017
Prachin Buri	153	16,449	16,601
Bang Pakong	623	16,837	17,459
Thole Sap	140	11,104	11,244
East-Coast Gulf	808	29,558	30,365
Peninsula-East coast	169	58,684	58,853
Tapi	161	26,823	26,984
Thale sap Songkhla	53	17,909	17,962
Pattani	2	8,709	8,711
Peninsula-West coast	57	56,200	56,258

7.1.3 Estimation of Variation factor (VF)

The variations in monthly or annually rainfall in each regions of Thailand have been accounted for in the assessment as the variation factor (VF) for calculating the weighted WTA as shown in **Equation (8)**. Based on the **s**tandard deviation of monthly average (S^*_{month}) and annual rainfall (S^*_{year}) derived from the rainfall data during years 2002-2011 (as shown in **Appendix II**), the variation factors for each basin in the case of strongly regulated flow (SRF) and non-strongly regulated flow (non-SRF) can be estimated. The water storage as dam or large and medium reservoirs is supposed to be the SRF case in the study and the adjusted WTA ratio is categorized into SRF if water is delivered from the water storages; otherwise, the adjusted WTA ratio is classified as non-SRF. Regarding the classification, the variation factor and the adjusted WTA are calculated based on the SRF case as shown in **Table 7.7.**

Table 7.7 Estimated VF and the adjusted WTA (WTA^*) based on the SRF case

Watersheds	WTA	VF	WTA*
Salawin	0.03	2.7	0.09
Kok	0.03	3.0	0.09
Ping	0.05	2.4	0.13
Wang	0.05	2.3	0.12
Yom	0.10	2.3	0.24
Nan	0.03	2.3	0.07
Khong	0.02	2.6	0.05
Chi	0.28	2.5	0.70
Mun	0.39	2.9	1.11
Chao Phraya	0.25	2.5	0.61
Sakae Krang	0.08	2.3	0.18
Pasak	0.10	2.6	0.26
Thachin	0.23	2.5	0.58
Mae Klong	0.03	2.7	0.09
Petchaburi	0.04	2.9	0.12
West Coast Gulf	0.20	2.3	0.46
Prachin Buri	0.03	2.9	0.08
Bang Pakong	0.06	2.6	0.15
Thole Sap	0.04	2.7	0.10
East-Coast Gulf	0.02	2.7	0.06
Peninsula-East coast	0.13	2.4	0.31
Tapi	0.12	2.3	0.29
Thale sap Songkhla	0.02	2.1	0.05
Pattani	0.07	2.1	0.14
Peninsula-West coast	0.01	2.7	0.03

7.2 Calculations of water stress index (WSI)

To calculate the water stress index for each river basin, a general formula for calculating the water stress index (WSI) of a basin of Pfister et al. (2009) as shown in **Equation (5)** is then applied. **Table 7.8 and Figure 7.1** show the results obtained from the calculations based on the average annual water withdrawals and the water availability as shown in **Table 7.1** and **Table 7.6**, respectively combined with the variation factors shown in **Table 7.7**. The results show that "Mun" basin has the highest WSI value i.e. about 0.92 followed by the "Chi", "Chaopraya", and "Thachin" basins, respectively. Only WSI values from the case of SRF are considered because the assessment is the macro level and in Thailand there are many large, medium, and small reservoirs as shown in **Table 7.5.**

Table 7.8 Water stress index based on average annual rainfall

Map index	Watersheds	WSI
(1)	Salawin	0.017
(2)	Kok	0.018
(3)	Ping	0.023
(4)	Wang	0.021
(5)	Yom	0.044
(6)	Nan	0.015
(7)	Khong	0.014
(8)	Chi	0.471
(9)	Mun	0.927
(10)	Chao Phraya	0.339
(11)	Sakae Krang	0.031
(12)	Pasak	0.050
(13)	Thachin	0.287
(14)	Mae Klong	0.018
(15)	Petchaburi	0.022
(16)	West Coast Gulf	0.158
(17)	Prachin Buri	0.016
(18)	Bang Pakong	0.026
(19)	Thole Sap	0.019
(20)	East-Coast Gulf	0.015
(21)	Peninsula-East coast	0.067
(22)	Tapi	0.060
(23)	Thale sap Songkhla	0.014
(24)	Pattani	0.025
(25)	Peninsula-West coast	0.012

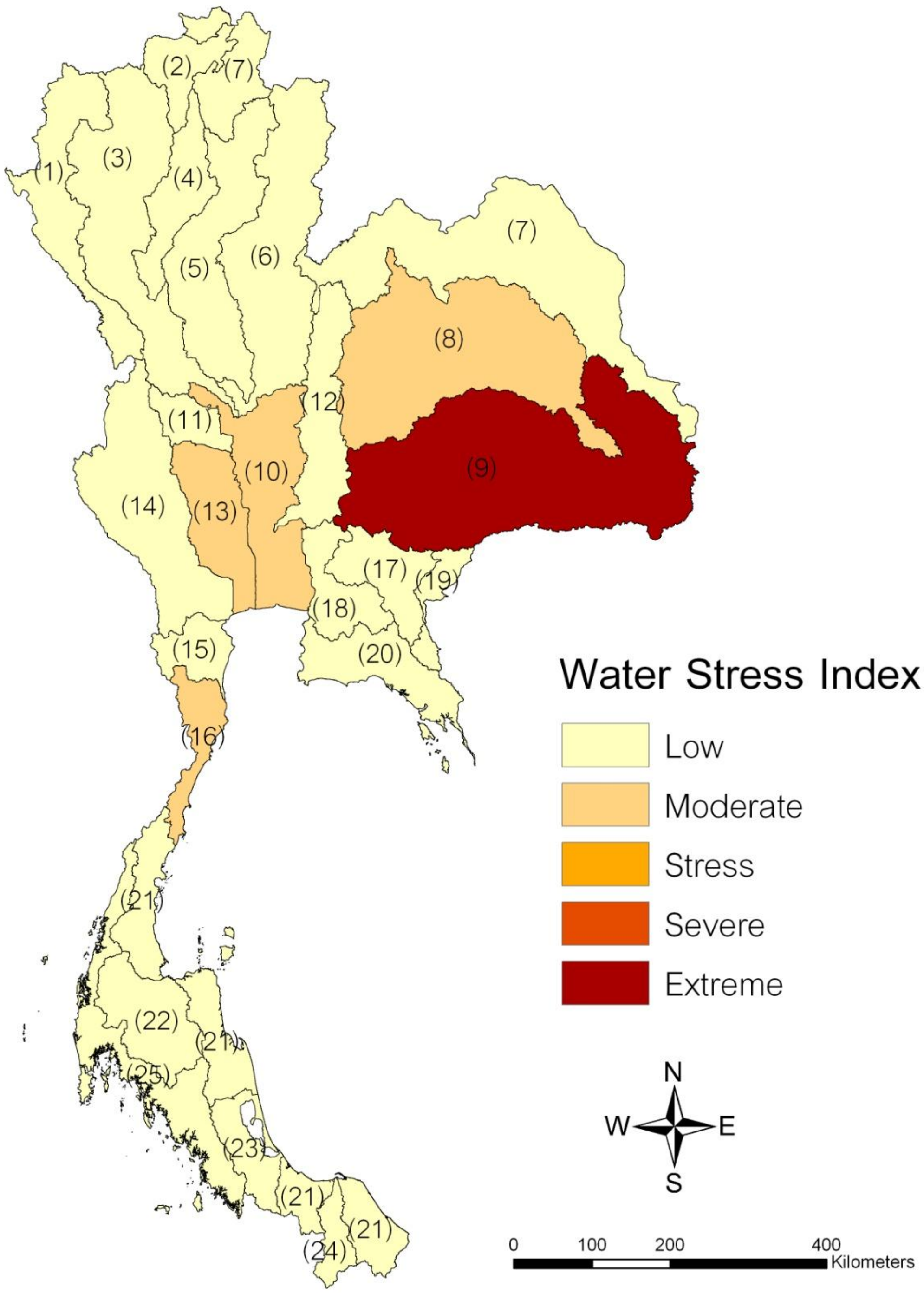


Figure 7.1 Map of water stressed areas of Thailand classified by 25 watersheds

The results obtained from the WSI assessment and also the water requirements for agriculture indicate that "Mun", "Chi", "Chaopraya" and "Thachin" are the important basins that need further investigation, especially the Mun basin which has the highest water demand for agriculture. The appropriate plan for land and water-use in the provinces associated with those basins are necessary for the sustainable food, feed, and fuel crop production in the future. Therefore, in the next chapter, the results obtained from the Water Footprint assessment of major food, feed, and fuel crops in each region of Thailand will be combined with the WSI results in order to identify the appropriate recommendations for future land and water use for food, feed and fuel production in Thailand.

7.3 Verification of the WSI results with the actual situation

To verify whether the WSI results obtained from the assessment are consistent with the actual situation in Thailand, the study results are compared with the annual report regarding the potential drought areas reported by the Land Development Department (LDD) (**Table 7.9**). The comparison reveals that the areas were identified as potentially facing extreme and severe stress level are mainly the same i.e. several provinces in the Northeastern region and some provinces in the Central region. However, there are some deviations found for the case of Northern region where some provinces are reported as the drought areas but these are not revealed by the WSI values obtained in the study. This is because the study is based on the watershed level basis which is larger than the provincial level. Nevertheless, the provinces that were pointed out as the potential water stress areas from both the LDD report and the WSI are as follows: Nakhon Phanom, Nakhonratchasima, Mukdahan, Khon Kaen, Buriram, Prachinburi, Sakaew, Lopburi and Ratchaburi.

Table 7.9 Comparison of the WSI results with the actual situation

Description	Land Development Department (LDD)	This study
Report or indicator relevant to the expression of the water stress situation	Annual report on the areas that potentially face the drought situation in Thailand	Water stress index
Classification of the water stress level	Areas the potentially face the drought situation are classified into 5 levels i.e. Areas that have no drought potential (e.g. forest), Drought potential level 1 (Low drought), Level 2 (Moderate drought), Level 3 (Severe drought) and Level 4 (Extreme drought)	Water stress is classified into 5 levels i.e. Low stress, Moderate stress, Stress, Severe stress and Extreme stress
Results regarding areas that potentially confront to the severe and extreme water stress	Around 49% of the total severe and extreme drought areas are in the North-Eastern region followed by the Northern (29%), Eastern (10%), Central (7%) and Southern (5%)	Mun, Chi, Chaopraya and Thachin basins

Chapter 8

Application of water footprint and water stress index for water resources management

This chapter shows the application of water footprint and water stress index for assessing the sustainability implications of the bioethanol policy mandate in Thailand on water. Water requirements for cassava, molasses, and sugarcane based ethanol production in various provinces where bioethanol plants are located are evaluated using the water footprint (WF) concept and expressed in terms of sources i.e. green and blue water. Also, the environmental impacts of freshwater use for bioethanol production in life cycle assessment (LCA) are assessed in terms of the water deprivation potential using the Water Stress Index (WSI) developed specifically for the 25 main watersheds in Thailand. The integration of both WF and water stress index approaches is expected to help policy makers especially the Royal Irrigation Department (RID) of Thailand to understand the impacts of bioethanol production on water use and stress and support them to develop measures to minimize water use and to manage the water resources effectively.

8.1 Bioethanol production in Thailand

The Thai government has promoted the use of alternative energy as a national agenda since 2004 especially bioethanol derived from the local feedstocks such as molasses, cassava, and sugarcane. The promotion of government has spurred bioethanol production in Thailand from 0.3 M.litre/day in 2006 to 1.3 M.litre/day in 2011 (DEDE, 2012b). This growth is inclined to continue as per the ambitious goal of the recent “Alternative Energy Development Plan: AEDP 2012-2021” which set to produce 9 M.litre ethanol/day by 2021. However, the proliferation of bioethanol production promises to increase stress on water and pressure on water resources beyond the natural restoration capacity as agriculture currently consumes 73% of active freshwater storage in the country (RID, 2012b). This is of particular concern because Thailand has a large agricultural base both for food for local consumption and export as well as for feed and fuel.

As of December 2012, there are 19 ethanol plants in operation with total production capacity of 3.07 M.litre/day. These consist of 13 molasses ethanol (MoE) plants (with a total capacity of 2 M.litre/day), 5 cassava ethanol (CE) plants (0.78 M.litre/day) and a sugarcane ethanol (SCE) plant (0.2 M.litre/day). The number of ethanol plants in operation is likely to increase in the coming years as nowadays several new plants are under construction, especially cassava ethanol plants (Preechajarn and Prasertsri, 2012). Meanwhile, 48 ethanol plants are registered with the government with a total production capacity of about 12.5 M.litre/day consisting of 15 MoE plants, 1 SCE plant, 24 CE plants, and 8 multi-feedstocks ethanol (MoE/CE) plants as summarized in **Table 8.1**. Those 48 plants are located/will be located nationwide especially in the North and the Northeastern regions of Thailand where the sugarcane and cassava are widely grown. **Figure 8.1** shows the locations of the 48 ethanol plants in Thailand classified by provinces and watersheds. Around 26 provinces and 11 watersheds are directly related to the ethanol production in Thailand.

Table 8.1 Ethanol plants in Thailand

Ethanol plants classified by feedstock	Licensed plants		Plants in operation	
	Number of plants	Capacity (M.litre/day)	Number of plants	Capacity (M.litre/day)
Molasses	15	2.685	5	0.78
Sugarcane juice	1	0.2	1	0.2
Molasses/cassava	8	1.22	8	1.22
Cassava	24	8.39	5	0.78
Total	**48**	**12.495**	**19**	**3.07**

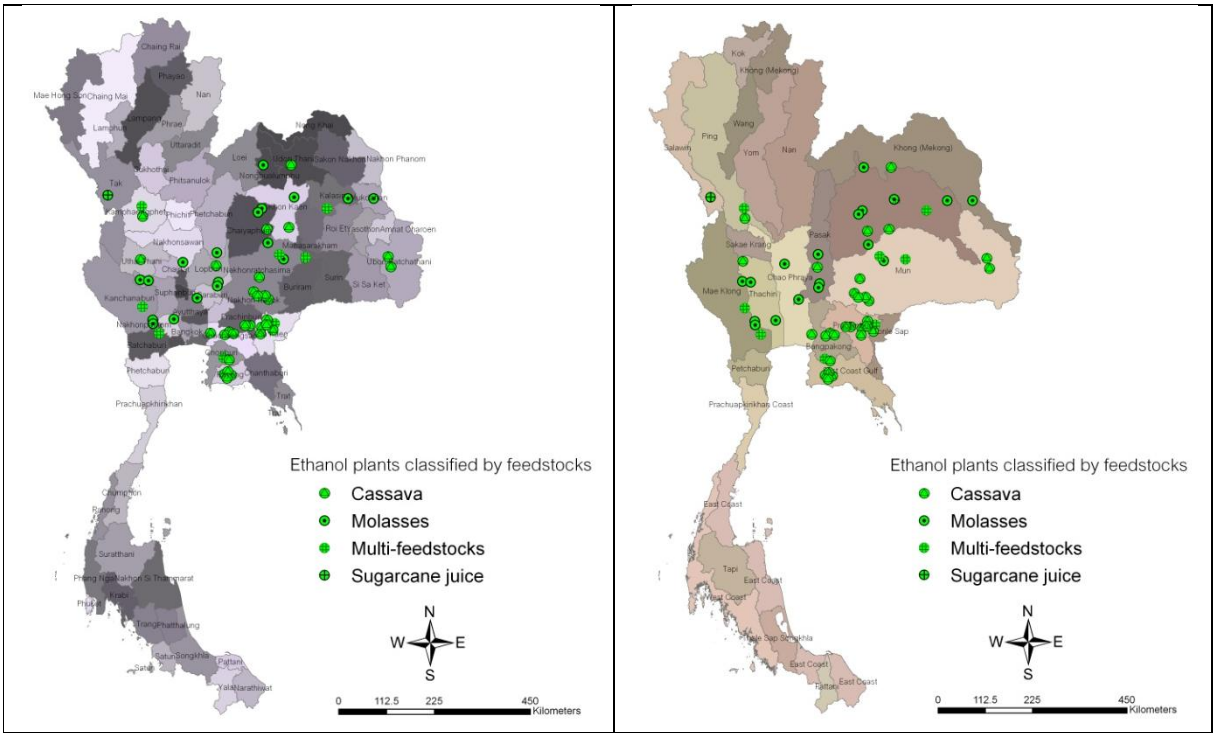


Figure 8.1 Locations of ethanol plants in Thailand classified by provinces and watersheds

8.2 Methodology

In the study, the water footprint concept is used to determine and compare the water requirements for three major bioethanol products in Thailand i.e. ethanol from molasses, cassava and sugarcane. **Figure 8.2** shows the simplified bioethanol production systems which can be divided into three main stages i.e. (1) feedstocks cultivation, (2) feedstocks processing and (3) ethanol conversion. The unit of comparison for the water footprint assessment is a litre of bioethanol (99.5% purity).

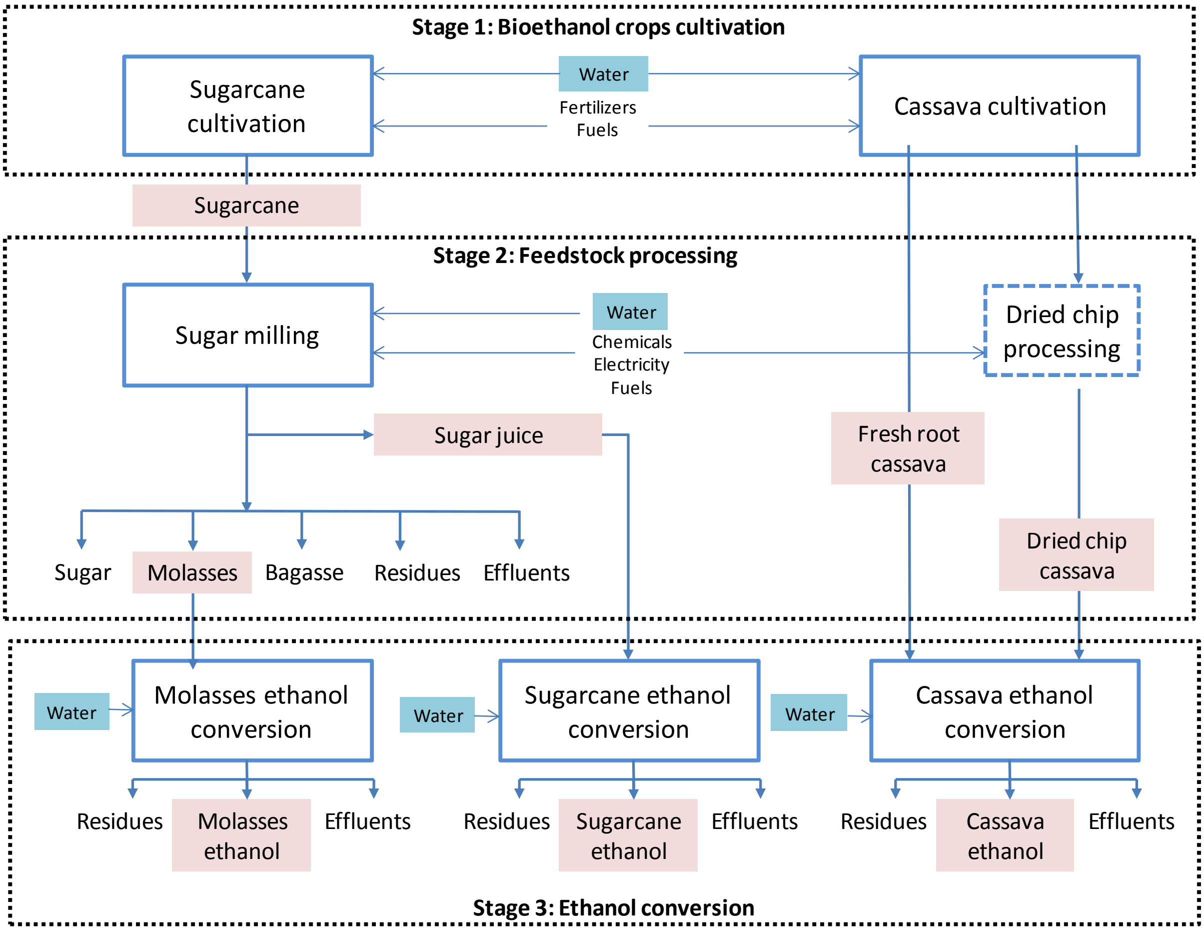


Figure 8.2 Bioethanol production systems in Thailand

8.2.1 Water requirements for bioethanol crops cultivation

In the study, the “consumptive water use” or “crop water requirement” over the period of sugarcane and cassava cultivation in 26 provinces of Thailand where ethanol plants are located is quantified. The general formula is as follows: $ET_{crop} = K_C \times ET_0$ [Unit: mm/day]; where ET_{crop} = crop evapotranspiration i.e. the amount of water evapotranspired by the crops in a specific climate regime and adequate soil water is maintained by rainfall and/or irrigation (Allen et al., 1998); K_C = Crop coefficient of Penman-Monteith; and ET_o = the reference crop evapotranspiration of Penman

Monteith (Allen et al., 1998). The data used for calculation are mainly referred from the national data obtained from the relevant government agencies such as the Office of Agricultural Economics (OAE) (OAE, 2012), the Land Development Department (LDD) and especially the Royal Irrigation Department (RID). As the planting period generally differs from region to region, the sugarcane and cassava calendars of the OAE are referred to in the assessment.

8.2.2 Water requirements for feedstock processing

Sugar milling involves crushing cane to extract sugarcane juice. This juice is clarified to remove any impurities and concentrated into syrup by boiling off excess water, seeded with raw sugar crystals in a vacuum pan and boiled until sugar crystals have formed and grown (Silalertruksa and Gheewala, 2009). The crystals are separated from the syrup by centrifugal process before more crystals are grown in the syrup. Therefore, a variety of products and wastes will be generated in the mills i.e. sugar is the main product; molasses, the syrup remaining after the sugar has passed through the centrifuge for the last time in a mill or refinery, is a by-product as well as bagasse which is generated after sugarcane crushing and it is used to produce steam and electricity to supply for the mills and the surplus electricity is sold to the general grid-mix. The other residues such as filter cake and wastewater effluents from the mills are considered as waste in the study because generally they done not have an economic value and are hence, not traded.

To share the water use from sugarcane cultivation and sugar milling between the sugar (main product) and the by-products i.e. molasses and bagasse, the energy-based allocation techniques is applied in the study. In the mills, a ton of sugarcane processed will generate 109, 45, and 287 kg of sugar, molasses, and bagasse, respectively. However, only the surplus bagasse after internal use in the mills (for own energy requirements) i.e. about 131 kilogram per ton sugarcane, is considered in the allocation calculation. Based on the average energy content of sugar, molasses and bagasse of about 16.33, 11.43 and 7.53 MJ/kg respectively (Silalertruksa and Gheewala, 2009), the allocation factors for sugar, molasses and the surplus bagasse are 0.54, 0.16 and 0.30, respectively. Thus, the factor 0.16 is used for determining the water use for molasses production. Based on all processes including sugarcane washing, extraction, juice treatment, juice concentration by condenser and evaporation (excluding ethanol production), the water use is estimated to be around 1.23 m^3 per ton of processed cane (Macedo, 2005; Gerbens-Leenes and Hoekstra, 2009). The water use in sugar mills for molasses is estimated to be around 4.37 m^3/ton molasses.

The water use in the industrial processes i.e. feedstock processing and ethanol conversion are considered to contribute to the blue WF. Effluents generated in this process contribute to water pollution. As cassava ethanol is mainly produced from fresh cassava root and also the dried chip processing step does not require water; therefore, the process of converting fresh cassava to dried chips form is not accounted for in the study.

8.2.3 Water requirements for bioethanol conversion

8.2.3.1 Molasses ethanol

Molasses ethanol production consists of yeast preparation, fermentation, distillation and dehydration. The study refers production data of molasses ethanol conversion from literature (Silalertruksa and Gheewala, 2009; KAPI, 2007). To produce a litre of molasses ethanol, around 4.6 kilogram of molasses is required or equivalent to around 61 L of molasses ethanol/ton of sugarcane. The water used at the ethanol conversion stage is about 8.6 L/L of molasses ethanol. It is classified as “blue water” and the two main water-intensive processes are the fermentation and the supporting process as steam generation.

8.2.3.2 Sugarcane ethanol

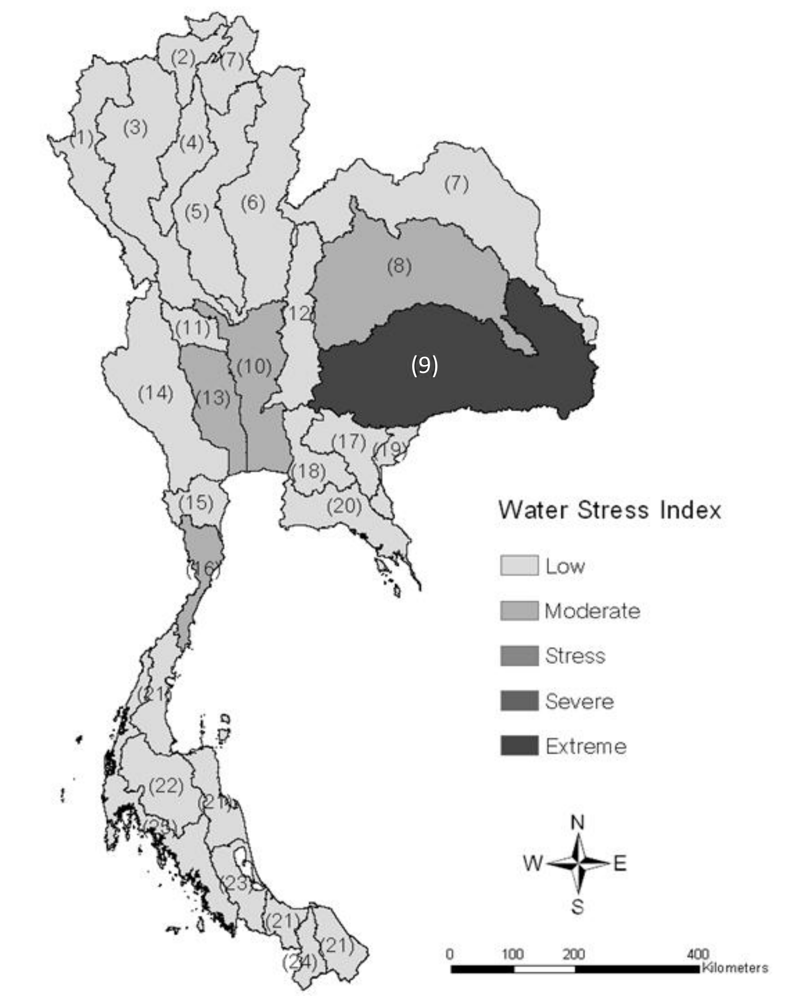
To produce sugarcane ethanol, sugarcane juice which is extracted from sugarcane crushing process will be directly used to produce ethanol without the production of sugar. Bagasse is used to produce steam and electricity. Based on the surplus electricity about 126 kWh would be obtained for the production of 1,000 litre sugarcane ethanol (Silalertruksa and Gheewala, 2011), the allocation factor can be derived for sugarcane ethanol. The blue water required at this stage is estimated to be about 14.3 L/L sugarcane ethanol Blue water required at this stage is about 14.3 L/L sugarcane ethanol and it is mainly for steam production. Spent wash is sent to aerobic ponds with biogas recovery system. To produce a litre of sugarcane ethanol, around 11.6 kilogram of sugarcane is required or equivalent to around 86 L of sugarcane ethanol/ton of sugarcane.

8.2.3.3 Cassava ethanol

The cassava ethanol plant consists of five main processes i.e. (1) cassava preparation including cleaning and milling; (2) liquefaction, (3) fermentation, (4) distillation and (5) molecular sieve dehydration. In this industrial stage, water is used for mixing and liquefaction and for industrial boilers for steam production. Thus, the water used in this stage is mainly classified as “blue water”. About 6.2 kilogram cassava root is required to produce a litre ethanol or equivalent to around 161 L cassava ethanol/ton of cassava root. Blue water use for cassava ethanol production is referred from the literature i.e. around 11.1 L/L cassava ethanol (Silalertruksa and Gheewala, 2009; KAPI, 2007)

8.3 Water stress index (WSI) and characterization factors

Figure 8.3 shows the map of areas of relative water stress and the WSI classified by 25 watersheds of Thailand. The WSI for each watershed is used as the characterization factor for calculating the “water deprivation” impact. The water deprivation impact potential can be calculated from the multiplication of blue water with the water stress index (WSI) in the specific location: *Water deprivation = Blue water x WSI*. This water deprivation potential, so called the “RED (Relevant for Environmental Deficiency) water”, is measured in m^3 water equivalents (m^3eq) and represents a surrogate indicator for the amount of water deficiency to downstream human users and ecosystems (Pfister et al., 2009).



Watersheds	WSI
(1) Salawin	0.017
(2) Kok	0.018
(3) Ping	0.023
(4) Wang	0.021
(5) Yom	0.044
(6) Nan	0.015
(7) Khong	0.014
(8) Chi	0.471
(9) Mun	0.927
(10) Chao Phraya	0.339
(11) Sakae Krang	0.031
(12) Pasak	0.050
(13) Thachin	0.287
(14) Mae Klong	0.018
(15) Petchaburi	0.022
(16) West Coast Gulf	0.158
(17) Prachin Buri	0.016
(18) Bang Pakong	0.026
(19) Thole Sap	0.019
(20) East-Coast Gulf	0.015
(21) Peninsula-East coast	0.067
(22) Tapi	0.060
(23) Thale sap Songkhla	0.014
(24) Pattani	0.025
(25) Peninsula-West coast	0.012

Figure 8.3 Map of water stress indices of Thailand classified according to the 25 watersheds

8.4 Results and Discussion

8.4.1 Water footprint of bioethanol production in Thailand

8.4.1.1 Comparative WF of the bioethanol feedstocks

Figure 8.4 shows the comparison of water footprint per ton of bioethanol feedstock in Thailand including cassava, sugarcane and molasses. Based on the 26 studied provinces, the total WF for cassava, sugarcane and molasses range between 381 – 456, 119 – 188 and 428 – 673 m^3/t, respectively. The large variation of WF results among the provinces is due to the factors such as geographic and climatic variables in each province, cultivation calendar, and the variation in yields.

For irrigation water requirement which is expressed by blue WF, the results show that although both cassava and sugarcane in Thailand are mainly rainfed crops, rain water contributes only about 80% and 71% of the total crop water requirement. The irrigation water required to produce a ton of cassava, sugarcane, and molasses ranges between 47 - 160, 21 - 77, and 79 – 278 m^3, respectively.

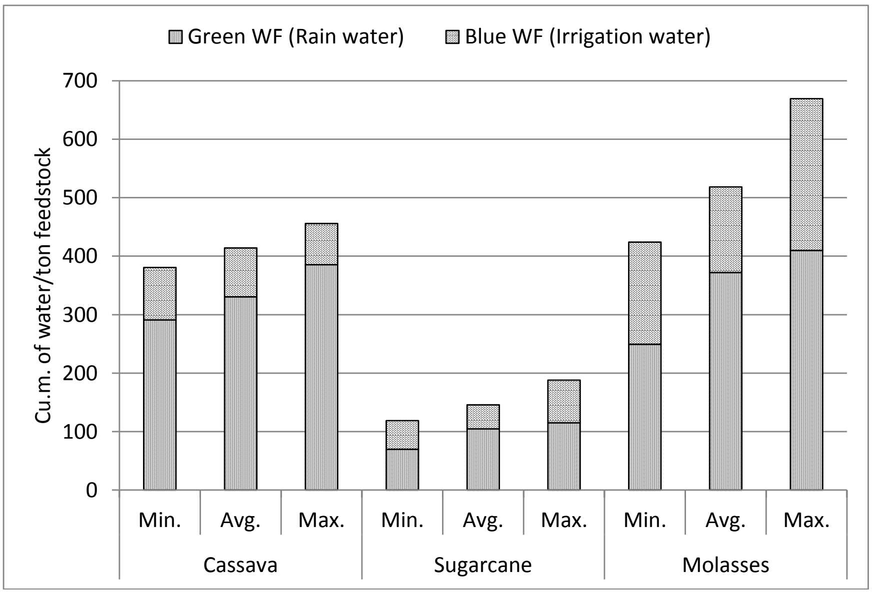


Figure 8.4 WF of major bioethanol feedstocks in Thailand

8.4.1.2 Comparative WF of bioethanol

The water footprint of bioethanol in Thailand varies between 1,396 – 3,105 L/L ethanol as shown in **Table 8.2**. Based on the average WF values, cassava ethanol uses the highest amount of water followed by molasses ethanol and sugarcane ethanol, respectively. Nevertheless, there is the wide range in the results due to the variation in geographic and climatic conditions and also the variation in yields of feedstocks. For example, the WF of cassava ethanol can vary between 2,374 – 2,841 L/L ethanol; while, the ranges of WF of sugarcane and molasses ethanol are 1,396 – 2,196 and 1,976 – 3,105 litre, respectively. The lowest WF for cassava ethanol is in Kalasin province; meanwhile, that for sugarcane ethanol is in Suphanburi. On the contrary, the highest WF for cassava ethanol is in Sa Kaeo province; meanwhile, that for sugarcane ethanol is in Chonburi. However, in terms of the blue water use, cassava uses much less than molasses but nearly the same as sugarcane for bioethanol production. Producing molasses ethanol requires the highest amount of blue water i.e. around 699 – 1,220 L of blue water/L ethanol; meanwhile cassava ethanol and sugarcane ethanol consume around 449 - 566 and 450 - 859 L of blue water/L ethanol, respectively.

Table 8.2 WF of cassava, sugarcane and molasses bioethanol production in Thailand

		Water footprint (L water/L bioethanol)		
		Green WF	**Blue WF**	**Total WF**
Cassava ethanol	Min.	1,806	566	2,372
	Avg.	2,051	528	2,579
	Max.	2,389	449	2,838
Sugarcane ethanol	Min.	814	582	1,396
	Avg.	1,218	490	1,708
	Max.	1,337	859	2,196
Molasses ethanol	Min.	1,147	829	1,976
	Avg.	1,711	699	2,410
	Max.	1,885	1,220	3,105

The contributions of blue water consumed in the various life cycle stages of molasses, sugarcane and cassava ethanol production are shown in **Figure 8.5**. The agricultural stage i.e. feedstock cultivation is the major contributor to the blue water consumption by sharing around 97-98% of the total blue water use. While, the industrial stages such as sugar milling and ethanol conversions contribute just about 2-3% of the total blue water consumption. At the sugar milling stage which is the origin of molasses feedstock, sugarcane washing and sugarcane juice evaporation in a multiple-effect evaporator before further concentrating to become sugar and molasses, are the two major freshwater intensive processes. While in case of sugarcane ethanol production, the ethanol plant is supposed to be attached to the sugar mill and the total blue water consumed since sugarcane washing until distillation of ethanol is estimated to be about 14.3 litre/litre ethanol. For ethanol conversion stage, conversion of cassava to ethanol will require much amount of blue water as compared to conversions of molasses and sugarcane to ethanol. For cassava ethanol, blue water consumption is relatively high in the mixing and liquefaction processes to convert starch to sugar before fermentation and distillation of ethanol.

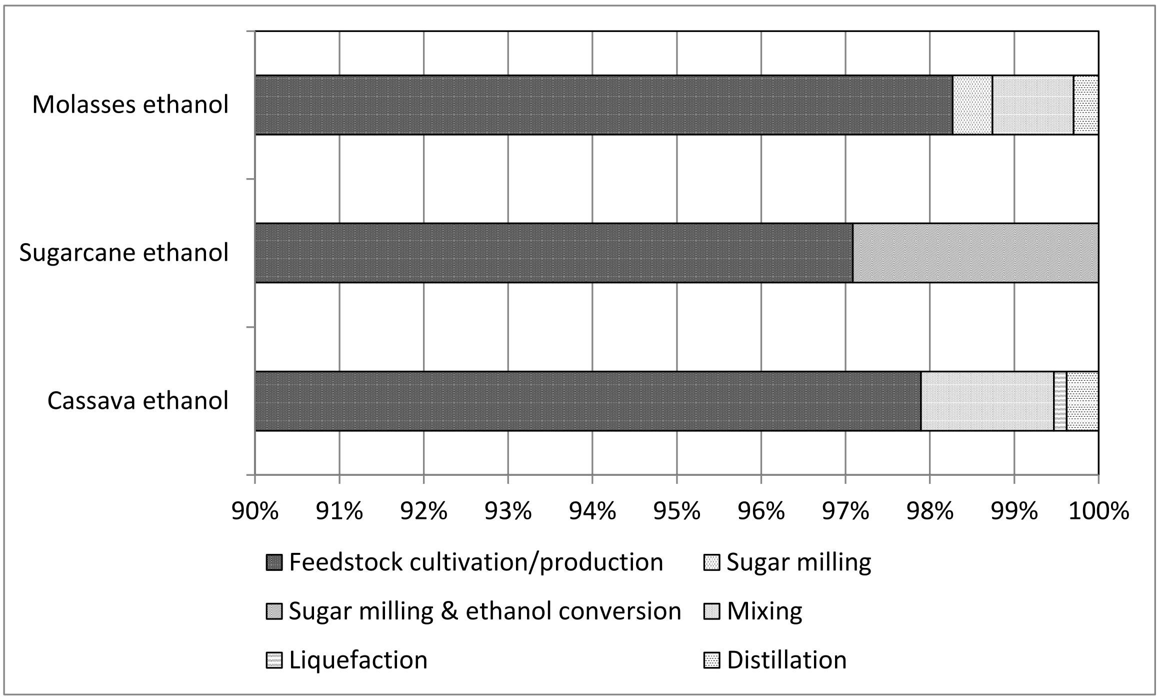


Figure 8.5 Blue water use classified by various processes in the life cycle of bioethanol production

8.4.2 Water deprivation impact potentials from bioethanol production in Thailand

Table 8.3 shows the water deprivation potentials from consumptive water use to produce a litre of bioethanol in the different provinces and watersheds where the ethanol plants are located. The results reveal that the water deprivation indicator can help to screen and prioritize the areas that could potentially face water competition which cannot be revealed just by the WF values. For example, cassava ethanol produced from the watersheds e.g. Mun, Chi and Chaophraya will result in the water deprivation impact greater than that produced in the other watersheds. Therefore, the policy makers should have the measures to support the increased water use for bioethanol production in those regions in the future.

Table 8.3 Water deprivation potentials of bioethanol production in Thailand

Related watersheds	Provinces	Water deprivation impact potentials (m^3 eq./L ethanol)		
		Cassava ethanol	Sugarcane ethanol	Molasses ethanol
Mun	Nakhonratchasima, Buriram, Ubon Ratchathani	442-548		1,806

Related watersheds	Provinces	Water deprivation impact potentials (m^3 eq./L ethanol)		
		Cassava ethanol	Sugarcane ethanol	Molasses ethanol
Chi	Kalasin, Khon Kaen, Chaiyaphum, Nongbualumphu	267-320		2,051
Chao Phraya	Nakhonsawan, Lopburi, Ayutthaya	266		2,389
Thachin	Nakhonpathom, Suphanburi			814
Bang Pakong	Chachoengsao	8		1,218
East Coast Gulf	Chonburi, Rayong	5-8		1,337
Khong	Mukdahan, Udon Thani	6		1,147
Mae Klong	Kanchanaburi, Ratchaburi	7-18		1,711
Pasak	Phetchabun, Saraburi			1,885
Ping	Kamphaengphet	8		1,806
Prachinburi	Prachinburi, Sa Kaeo	6-7		2,051
Sakae Krang	Uthai Thani	18		2,389
Salawin	Tak		6	814

Nevertheless, it must be noted that the consumptive water use for bioethanol feedstocks shown in **Tables 8.2** and **8.3** are the theoretical water consumption which will result in the overestimation for the cultivations that are subject to deficit irrigation (Pfister et al., 2009). This is especially for the cassava and sugarcane in Thailand which are predominantly rainfed crops. However, to estimate the irrigation water consumed by field crops like sugarcane and cassava in reality is difficult as it depends on not only whether the plantation areas are located in the irrigation areas, but also depends on how much the irrigation water available in each year depending on the climatic variables. Anyway, for the rough estimation of irrigation water actually used by sugarcane and cassava, the study refers to the water resources management plan for agricultural plantation in irrigated areas during dry season of year 2011/2012 (RID, 2012b), the report shows that there are around 0.22 M.ha of total field crops planted areas that will be able to receive the irrigation water from RID and around 0.16 M.ha is the sugarcane planted areas. This irrigated sugarcane plantation areas will account for only 13% of the total sugarcane planted areas in Thailand which is about 1.24 M.ha. Based on the average yields of sugarcane which is around 72 ton/ha, the actual blue water footprint of sugarcane in Thailand would be only 5 m^3/ton sugarcane which is quite different from the theoretical blue water value of 41 m^3/ton sugarcane shown in **Figure 8.4**. This brings about a drastic reduction in blue WF per litre of sugarcane ethanol from 490 to 72 L water/L sugarcane ethanol. Nevertheless, the calculation above is based on the official irrigated areas reported by RID; but in reality, some farmers outside the official irrigated areas also use water supplied from other sources for their plantations and also some farmers may use deficit irrigation for which the field survey for the critical watersheds needs to be conducted in the future. However at present, there are no official irrigated areas of cassava plantation in Thailand (Damen, 2010).

8.4.3 Implications of the bioethanol policy mandate on water use and stress

The study assesses the potential impacts on water use and water stress with respect to the policy mandate of bioethanol production in Thailand. Two scenarios are developed including:

Scenario 1: Policy mandate scenario—the scenario assumes that the AEDP's target of producing 9 M.litre ethanol/day by 2021 will be satisfied by the 48 licensed ethanol plants. The scenario assumes that only molasses, cassava and sugarcane juice are the feedstocks. All 48 ethanol plants licensed by the government can start operation in accordance with the proposed schedule and the ratios of feedstocks used for the 8 multi-feedstocks bioethanol plants are assumed on a 50/50 basis by sharing between the molasses and cassava. To satisfy the target of 9 M.litre ethanol/day, the ethanol plants are assumed to operate at 72% of their production capacities;

Scenario 2: Full production capacity scenario—the scenario assumes that all 48 plants will be operated at the full production capacity i.e. 12.495 M.litre ethanol/day. Thus, production of 4,560 M.litre ethanol/year would be the mandated bioethanol target of this scenario. The future changes in yields of cassava and sugarcane per hectare are neglected in the assessment as there are many factors e.g. climatic conditions, agricultural practices, future varieties development affecting the crop yields.

The results show that, to satisfy the AEDP bioethanol target in year 2021, around 8,185 million m^3/year are required with 6,560 million m^3 rain water (80%) and 1,625 million m^3 irrigation water as shown in **Table 8.4**. In addition, if the ethanol plants were fully operated as per the Scenario 2, the demand of irrigation water to fulfill the ethanol production would be increased to 2,256 million m^3 in 2021. The blue water requirements for Scenarios 1 and 2 are equivalent to about 3% and 4% of the active water storage of Thailand in year 2012 which is around 55,268 million m^3. About 60% of the total blue water requirements i.e. 958 million m^3 would be for cassava ethanol production.

Table 8.4 Estimated water requirements for future bioethanol production in Thailand

		Water requirements (Million m^3/year)					
		Dry season		**Wet season**		**Total**	
		Green water	**Blue water**	**Green water**	**Blue water**	**Green water**	**Blue water**
Scenario 1: Policy mandate scenario	Cassava ethanol plants	754	933	3,974	25	4,728	958
	Sugarcane ethanol plants	8	17	75	1	83	18
	Molasses ethanol plants	102	295	1,039	159	1,141	454
	Multi-feedstocks plants	74	146	534	49	608	195
	Total	**938**	**1,391**	**5,622**	**234**	**6,560**	**1,625**
Scenario 2: Full production capacity scenario	Cassava ethanol plants	1,047	1,296	5,520	34	6,567	1,331
	Sugarcane ethanol plants	11	23	104	2	115	25
	Molasses ethanol plants	141	410	1,444	220	1,585	630
	Multi-feedstocks plants	103	203	741	68	844	270
	Total	**1,303**	**1,932**	**7,809**	**324**	**9,112**	**2,256**

Figure 8.6 shows the classification of 1,625 million m^3 blue water required in 2021 to satisfy the AEDP's target of bioethanol production by the different watersheds. Mun, Chi and Prachinburi are the three important watersheds that would have the significant increase in irrigation water demand for bioethanol production. Considering the water deprivation potentials (m^3 eq/year), Mun, and Chi would be the two main watersheds that have high potential to confront the pressures on water stress and competition with other users if the water resources are not properly managed in the future (as **Figure 8.7**). Importantly, both watersheds are in the Northeastern region of Thailand which has the largest crops plantation areas in Thailand. By province, there are three provinces that potentially have the high impact on water use due to the ethanol policy mandate i.e. Nakhonratchasima, Ubon Ratchathani and Chaiyaphum, as they would have several new ethanol plants established there and from the hydrological perspective, those three provinces are under the Mun and Chi watersheds.

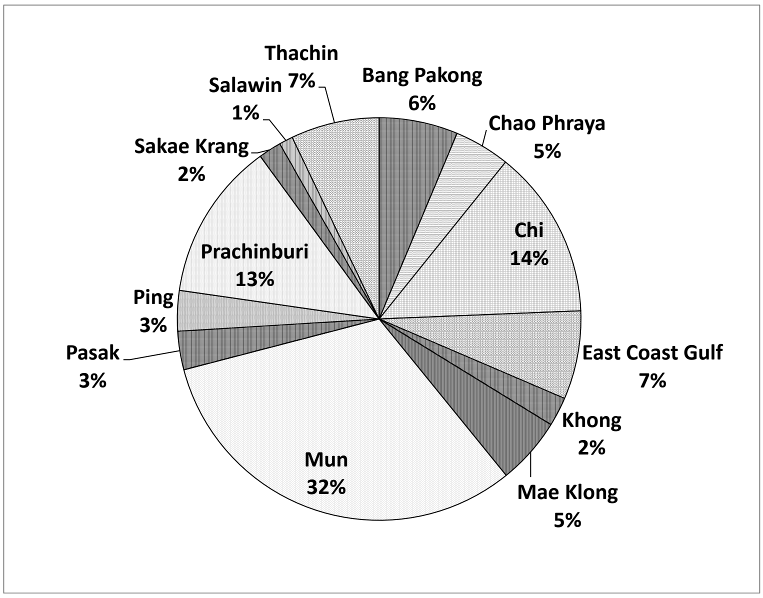


Figure 8.6 Share of blue water requirements for bioethanol production in 2021 classified by watersheds

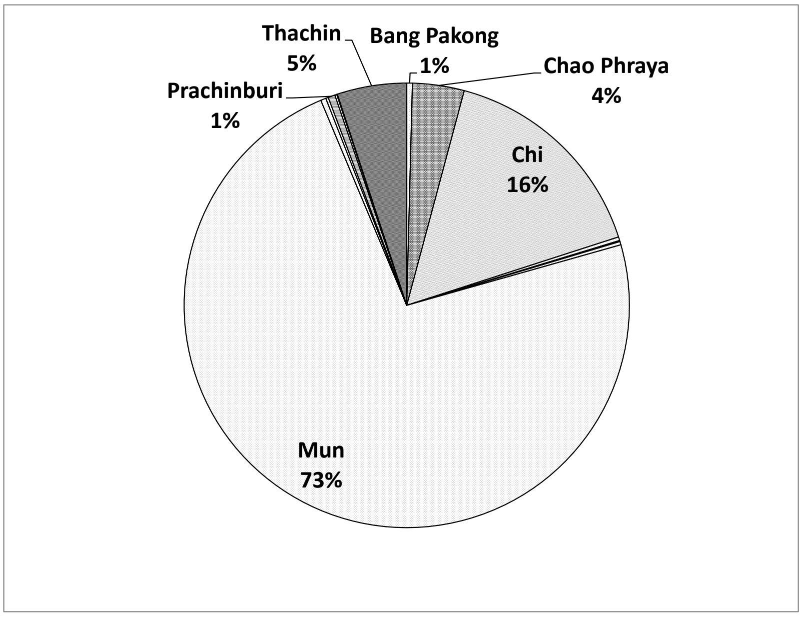


Figure 8.7 Share of water deprivation potentials from bioethanol production in 2021 classified by watersheds

8.5 Recommendations to enhance water efficiency of bioethanol production in Thailand

For the sustainability of large scale bioethanol production in Thailand due to the policy mandate, it is necessary to enhance water resource management and efficiency across the entire life cycle of bioethanol production to avoid the pressure on water competition. Several measures are recommended as follows:

8.5.1 Crop evapotranspiration (ET) reduction

Crop evapotranspiration (ET) during the bioethanol feedstock cultivation stage contributes more than 99% of the total WF of bioethanol or around 95-98% of the total blue water footprint of bioethanol. Therefore, in the water supply perspective, the ideal fuel crops to minimize the water footprint of biofuels should be drought-tolerant, high-yield crops grown on little irrigation water (Domiguez-Faus et al., 2009). There are many factors that able to influence the evapotranspiration of crops e.g. temperature, crop yields, crop cycle and agricultural practices. For example, ET generally increases with the temperature. To reduce the crop evapotranspiration, shortening of the crop cycle or else improving crop yields are the possible methods. However, those two methods generally must be traded off with each other as shortening the crop cycle may result in lower biomass accumulation which in turn will decrease the final yield. Therefore, the development of more efficient crop varieties is important to the sustainability of large scale bioethanol production in the future.

For Thailand, the country average yields of cassava and sugarcane in 2011 were 19.3 and 76.2 tons/ha, respectively (OAE, 2012). The lowest yields are found in the Northeastern region of Thailand which has the large cultivation areas associated with the Mun and Chi watersheds i.e. around 19.2 tons cassava/ha and 74.4 tons sugarcane/ha (OAE, 2012). However, there is a continual development of high yield varieties; the varieties of cassava such as Rayong 5, Rayong 9, Rayong 72 and Kasetsart 50 and the sugarcane varieties such as K 84-200, K 90-54 and U thong 3 are being recommended to Thai farmers which potentially yield about 31-50 ton/ha for cassava and 94-112 ton/ha for sugarcane. Nevertheless, to achieve the high genetic potential yields, those high yields must be supported with good agricultural practices in farming e.g. improving soil quality by using organic fertilizers and good practices in land preparation, plantation, harvesting and regular weed control. In addition, more efficient irrigation systems are also required in the high potential water stress regions. The study revealed that the Mun and Chi are the two watersheds that the government agencies should attach significance.

8.5.2 Promotion of sugarcane ethanol into the Thai bioethanol system

As the results show that ethanol derived from sugarcane juice has the lowest total WF and also the blue water footprint required as compared to cassava and molasses ethanol, the substitution of cassava ethanol and molasses ethanol by sugarcane juice ethanol can help reduce the blue water requirements by around 38 and 192 litre of blue water/litre ethanol, respectively. In addition, sugarcane is found as the crucial feedstock that can increase the security of feedstocks supply for bioethanol production in Thailand and its performance in GHG emissions is better than cassava and molasses ethanol. Nevertheless, based on the registered ethanol plants, there is only one ethanol plant using sugarcane juice as feedstock in operation in Thailand (0.2 M.liter per day ethanol production capacity). The government should therefore emphasize promotion of sugarcane juice ethanol production by solving some of the existing constraints such as the Sugar Act of 1984 which does not support ethanol production from sugarcane, and the duration of sugarcane supply which is limited to just over the period of December to March.

8.5.3 Enhancing water use efficiency in feedstock processing and ethanol conversion

Although feedstock processing and ethanol conversion have very low contributions to the WF of bioethanol as compared to the crop evapotranspiration, those industrial processes directly involve blue water use which is recognized as the important element of WF as it is more associated with the environmental impacts as compared to the green water. To reduce the WF during industrial stages, the water reuse and recycling program has to be encouraged. For example, the condensate recovery in sugar mills and in ethanol conversion plant e.g. distillation stage can help not only saving the water use but also help saving energy. Brazil has accelerated the basic guidelines of water management to sugar milling industries along with the new technologies development such as dry cleaning of sugarcane to eliminate sugarcane washing, treatment of vinasse by biodigestion technique to reduce the organic load and recirculating into the process (Macedo, 2005; Macedo et al., 2008). Moreover, the appropriate treatment and utilization of the high organic wastewater generated from the mills and from the ethanol conversion such as using it as agri-fertilizer can help mitigate impacts on ecosystem due to wastewater release. Therefore, research and development for the feedstock processing technologies and ethanol conversion technologies need to be encouraged.

Chapter 9

Recommendations and Conclusion

9.1 Recommendations for sustainable water resources management

One of the targets set in the 11th National Economic and Social Development Plan (NESDP) is to build the security of food and energy by the development of agricultural sector and enhancing the competency and income stability of farmers to produce enough and high quality food along with the development of alternative energy produced from crops. However, according to the situation of water stress and the crop water requirements of major food, feed, fuel crops in Thailand revealed by the study, there is a necessity for the government to have an appropriate plan for sustainable water resource management to avoid and/or mitigate the water stress arising from the increase of agricultural water requirement in the future. The increased demands for water are not only for food and feed crops but also for fuel crops according to the energy policy. Therefore, the following measures are recommended to enhance the water efficiency and water resource management for the agricultural sector in Thailand

9.1.1 Crop evapotranspiration (ET) reduction

More than 70% of the total water consumption of the country is for agricultural sector especially during the cultivation stage of crops which expressed by the "crop evapotranspiration (ET)". For example, in the case of bioethanol, 95-98% of the total water footprint of bioethanol products is come from the bioethanol feedstock cultivation. Hence, to reduce the "crop evapotranspiration" or "crop water use" is significant to enhance water efficiency for agricultural sector. Even though there are many factors that can influence the evapotranspiration of crops e.g. temperature, soil properties, crop yields, crop cycle and agricultural practices e.g. ET generally increases with the temperature. Nevertheless, the following measures are recommended to reduce the crop evapotranspiration.

- To assess and identify the methods to shorten the crop cycle or else to improve the crop yields. However, those two methods generally must be traded off with each other as shortening the crop cycle may result in lower biomass accumulation which in turn will decrease the final yields.
- To promote the research and development on improvement of crop varieties especially those suitable for energy production. For example, the ideal fuel crops in the water supply perspective to minimize the WF of biofuels should be drought-tolerant, high-yield crops grown on little irrigation water or non-irrigation areas.

To encourage the good agricultural practices (GAP) for farmers especially small scale farmers in rural areas. This is because nowadays the average crop yields for cassava and sugarcane are still lower than their genetic potentials. For example, the average cassava and sugarcane yields today are just around 19.3 and 76.2 tons/hectare, respectively. However, based on the existing varieties and their genetic potentials, the yields of cassava and sugarcane could potentially be around 31-50 ton/ha and 94-112 ton/ha, respectively. To achieve the high genetic potential yields, those high yields must be supported with good agricultural practices in farming e.g. improving soil quality by using organic fertilizers and good practices in land preparation, plantation, harvesting and regularly weed control.

9.1.2 Irrigation development in the high potential water stress areas

The WF and WSI assessment in the project reveal that the development and improvement of irrigation system should be promoted in the areas that potentially have high water stress due to the expansion of biofuels industry e.g. Mun and Chi watersheds. The promotion is not only to be the large scale water storage implementation, but the small scale irrigation systems by using local water reservoirs in the plantation areas are also possible e.g. surface irrigation, sprinkler irrigation, micro-irrigation, and sub-surface irrigation and water storage system. Medium and large scales are suggested to increase and enhance the efficiency of irrigation system in such areas.

9.1.3 Promoting expansion of energy crop cultivation in the suitable areas

Zoning or promoting the new crop plantation areas for supporting the energy policy of the government such as bioethanol and biodiesel policy is necessary to be considered by the policy makers. The suitable areas should be identified and set by taking water resource availability and water stress in consideration. The promotion should emphasize crop productivity improvement instead of expansion of cultivation areas. This is in order to avoid the other consequent impacts; not only water competition but also land competition for food, feed and fuel.

9.1.4 Promotion to sugarcane ethanol in the Thai bioethanol system

The results show that ethanol derived from sugarcane juice has the lowest total WF and also the irrigation water required as compared to cassava and molasses ethanol. Therefore sugarcane is found as the crucial feedstock that can increase the security of feedstocks supply for bioethanol production in Thailand. The government therefore should emphasize promotion of sugarcane juice ethanol production by solving some of the existing constraints such as the Sugar Act of 1984 which does not support ethanol production from sugarcane and the duration of sugarcane supply which is limited to just over the period of December to March.

9.1.5 Enhancing water use efficiency in feedstock processing and ethanol conversion

Although, feedstock processing and ethanol conversion have very low contributions to the WF of bioethanol as compared to the crop evapotranspiration, those industrial processes directly involve blue water use which is recognized as the important element of WF as it is more associated with the environmental impacts as compared to the green water. To reduce the WF during industrial stages, the water reuse and recycling program has to be encouraged. For example, the condensate recovery in sugar mills and in ethanol conversion plant e.g. distillation stage can help not only saving the water use but also help saving energy. Brazil has accelerated the basic guidelines of water management to sugar milling industries along with the new technologies development such as dry cleaning of sugar cane to eliminate sugarcane washing, treatment of vinasse by biodigestion technique to reduce the organic load and recirculating into the process. Moreover, the appropriate treatment and utilization of the high organic wastewater generated from the mills and from the ethanol conversions such as using it as agri-fertilizer can help mitigate impacts on ecosystem due to wastewater release. Therefore, research and development for the feedstock processing technologies and ethanol conversion technologies need to be encouraged.

9.1.6 Development and promotion of WF label of agricultural products to raise awareness in water consumption

In order to develop sustainable water consumption in the future, raising awareness on water consumption for both producer and consumer sides is necessary. The development and promotion of water footprint label could be one of the measures to make both producers and consumers realize their contribution to water use and water impacts which in turn would lead to the efficient and sustainable use of water resources in the future.

9.2 Recommendations for future research

1) Comprehensive assessment of WSI for the critical watersheds in Thailand revealed by the study i.e. Mun, Chi, Chao Phraya, and Thachin watersheds. This is to understand the local availability of the surface and ground water resources and the efficiency of the existing irrigation systems compared to the water demands in those specific regions. This work can be a part of a verification process of the WSI results with the actual situation. The information from WSI assessment and the precise WSI will help policy makers understand the real problems and causes of water stress in the studied regions and help to identify the appropriate measures for enhancing water efficiency in practice.

2) Improvement of the WSI calculation methodology by focusing in more details on the factors e.g. the ability to control and manage the water resources in each watershed because different watersheds will have different capability in water resource management. For example, the watersheds that have dam or large water storage should have more ability to manage the water resources and this factor should be included in WSI calculation in the future. In addition, the methodology for assessing the economic value or externalities of water resource should be further developed. The economic valuation method such as residual imputation method (RIM) can be used to evaluate the economic value of irrigation water used for different crops production under different constraints for irrigated land. The results would be the essential information to support the policy makers in their decisions on the feasibility of investment or implementation of the irrigation system in the future.
3) Comprehensive WF assessment for the vital crops e.g. rice, cassava and sugarcane by considering the different varieties, cultivation locations, agricultural practices and the existing irrigation systems and the water loss. This would help to identify the suitable promotion measures for enhancing water efficiency in the future.

9.3 Conclusion

The project entitled "Water footprinting of food, feed and fuel for effective water resource management" has been conducted to assess the water requirement of key agricultural food, feed, and fuel crops and to evaluate the situation and a potential to affect the water stress in different regions of Thailand. The water requirement of 10 major food, feed, and fuel crops in Thailand including rice (major and second rice), maize, cassava, sugarcane, oil palm, soybean, mungbean, coconut, pineapple, and peanut have been evaluated based on provinces and cropping calendars. The average water requirement for those crops ranges from 402 – 2,588 m^3/ton of crop product. However, based on the irrigation water requirement (or expressed by "blue water requirement" in the study) which is important from the viewpoint of water resources management, the results show that per ton of crop products, mungbean has the highest value i.e. 1,870 m^3/ton, followed by soybean (1,542 m^3/ton), peanut (1,373 m^3/ton), second rice (1,107 m^3/ton), coconut (929 m^3/ton), oil palm (907 m^3/ton), maize (808 m^3/ton), major rice (466 m^3/ton), pineapple (266 m^3/ton), cassava (75 m^3/ton) and sugarcane (34 m^3/ton). In addition, growing crops such as second rice, maize, oil palm and sugarcane in the North-Eastern region will require the highest amount of irrigation water as compared to the other regions. This implies that the existing effective rainfall is not sufficient for theoretical crop water requirement and the irrigation system is necessary. Nevertheless, there is a large variation of water required results among the provinces due to the factors such as geographic and climatic variables in each province, cultivation calendar, and the variation in yields details of which are shown in the report. In terms of water productivity measured by the ratio of net income of farmers from selling crop products and the irrigation water requirements, the results show that Mungbean yields the highest water productivity i.e. 8 THB/m^3 of irrigation water required followed by pineapple (7 THB/m^3 of irrigation water), sugarcane (7 THB/m^3), and cassava and maize (3 THB/m^3), respectively. However, it must be noted that the water productivity can be influenced by several factors particularly the agricultural product price depending on weather, epidemic, market demand, etc. Therefore, the results can also change year-by-year.

As the availability and quality of freshwater resources are unevenly distributed and varied by the hydrological processes in each region, a litre of water used in the already stressed areas is therefore likely to cause more damage than a litre consumed in more water-rich areas. Hence, comparing the water footprint of biofuels individually will not be able to reveal the real burdens of water use if local levels of water stress are not taken in to account. To reveal the competitive pressure on water resources availability in a specific region, the study has evaluated the water stress index (WSI) of 25 major watersheds of Thailand in order to use it as the characterization to determine the water deprivation potential i.e. the amount of water deficient to downstream human users and ecosystems. The levels of water stress are designated into 5 levels including extreme, severe, stress, moderate and low. The water stress map classified by WSI criteria is obtained as shown in the report and the results point out the watershed having the highest WSI is Mun followed by Chi, Chao Phraya, and Thachin, respectively.

The study also applied the WF assessment and the WSI of 25 major watersheds of Thailand to determine the water deprivation impact potentials from bioethanol production in Thailand as a case study for supporting policy makers regarding the promotion of bioethanol. The results revealed the possibility of increased stress on water, particularly vis-à-vis competition for food, feed and fuel. The results show that the water footprint of bioethanol in Thailand varies between 1,396-3,105 L water/L ethanol with cassava ethanol having the highest WF followed by molasses and sugarcane ethanol. Nevertheless, in terms of blue water consumption, important for water resources management, molasses is the highest at around 699-1,220 L/L ethanol, followed by cassava and sugarcane at 449-566 and 450-859 L/L ethanol, respectively. To satisfy the AEDP's target of bioethanol production in 2021, around 1,625 million m^3 of irrigation water/year will be additionally required. The Mun and Chi watersheds in Northeast Thailand would have a significant increase in irrigation water demand that could potentially lead to pressures on water stress and competition with other uses.

In summary, the combination of WF assessment of food, feed, and fuel crops and the WSI information for each watershed is necessary and can provide useful information for identification of the potential areas of water stress due to the expansion of agricultural activities and for determining the measures for improving water resource planning and management for sustainable food, feed, and fuel crops production in the future. Several measures are also recommended in the report to enhance the water efficiency and water resource management for agricultural sector in Thailand and to mitigate the water completion for food, feed and fuel production in the future.

References

Alcamo, J., Henrichs, T., Rosch, T. (2000). World water in 2025: global modeling and scenario analysis. In: Rijsberman, F.R. (Ed.), .World Water Scenarios Analyses. World Water Council, Marseille, France.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). Crop evapotranspiration: guidelines for computing crop water requirements. FAO Drainage and Irrigation Paper 56. Food and Agriculture Organization, Rome.

Babel M.S., Wahid, S.M. (2009) Freshwater under threat: South East Asia Vulnerability assessment of freshwater resources to environmental change. UNEP and AIT, Nariobi, Kenya.

Babel, M.S., Shrestha, B., Perret, S.R. (2011) Hydrological impact of biofuel production: A case study of Khlong Phlo Watershed in Thailand. Agricultural Water Management, 101, 8-26. doi:10.1016/j.agwat.2011.08.019

BOT. (2011). Thai economy: Thailand at a Glance. Bank of Thailand. Retrieved from http://www.bot.or.th/English/EconomicConditions/Thai/genecon/Pages/Thailand_Glance.aspx [cited 2012 Jun 22]

Brown, A., Matlock, M.D. (2011). A Review of Water Scarcity Indices and Methodologies [White paper]. Retrieved from The Sustainability Consortium: http://www.sustainabilityconsortium.org/wp-content/themes/sustainability/assets/pdf /whitepapers/2011_Brown_Matlock_Water-Availability-Assessment-Indices-and-Methodologies-Lit-Review.pdf

Bureau of Animal Nutrition Development (2009). Statistic of grass planting/forage crops and pasture lands [in Thai]. Retrieved from Department of Livestock Development: http://www.dld.go.th/nutrition/Service_knowlage/data_stat/data_grass.htm

Bureau of Animal Nutrition Development. (2011). Information and statistical data of Bureau of Animal Nutrition Development [in Thai] Retrieved from Department of Livestock Development: http://www.dld.go.th/nutrition/stat.htm

Bureau of Research, Development and Hydrology. (2009). Standard map of watershed and sub-watershed classification in Thailand referenced Topography map 1:50,000, Map series L7018, WGS84, UTM Zone 47N [in Thai]. Department of Water Resources.

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G., Gautam, R. (2006). The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries, *Ecol. Econ*., 60(1), 186–203.

Chapagain, A.K., Orr, S. (2009). An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes. *Journal of Environmental Management*, 90, 1219-1228. doi:10.1016/j.jenvman.2008.06.006

Chitradon, R., Boonya-aroonnet, S., Thanapakpawin, P. (2009). Risk Management of Water Resources in Thailand in the Face of Climate Change. Special Edition *on Global Imbalance Stream of Crises*. pp 64-73

Damen, B., 2010. BEFS Thailand: Key results and policy recommendations for future bioenergy development. Food and Agriculture Organization of the United Nations, Rome.

DEDE. (2008-2010). Planted area for production of solid biomass energy by province in 2008-2010. In Thailand Alternative Energy Situation 2008-2010. Retrieved from Department of Alternative Energy Development and Efficiency (DEDE): http://www.dede.go.th/dede/images/stories/6may54_circular/bio_53_24nov_54.pdf

DEDE. (2012a). Alternative Energy Development Plan: AEDP 2012-2021 [in Thai]. Retrieved from Department of Alternative Energy Development and Efficiency: http://www.dede.go.th/dede/images/stories/aedp25.pdf

DEDE. (2012b). Monthly ethanol production: 2007-2012 [in Thai]. Retrieved from Department of Alternative Energy Development and Efficiency: http://www.dede.go.th/dede/images/stories/bioethanol/12.ethanol_product.pdf [accessed April 15, 2013]

DGR. (2012). Groundwater and Agriculture security [in Thai]. Proceeding of Groundwater and Agricultural security, Bangkok, March 30.

Dominguez-Faus, R., Powers, S.E., Burken, J.G., Alvarez, P.J., 2009. The water footprint of biofuels: a drink or drive issue? Environ. Sci. Technol. 43, 3005–3010.

DPM. (2007). Analysis of drought-affected areas in the North-East. Retrieved from Department of Disaster Prevention and Mitigation: http://www.disaster.go.th/dpm/datarisk/drought_face/Drought_NE.pdf

DWR. (2008). Chapter 2: Situation and Development of Water Resources. Strategic plan of Department of Water Resources. Retrieved from http://oldweb.dwr.go.th/content/files/.../0005133_1.doc

DWR. (2012). Drought management plan 2012. Retrieved from Department of Water Resources: http://www.dwr.go.th/contents/files/statuswater/statuswater_th-25042012-141637-225256.pdf

EPPO. (2010). EPPO Annual Report 2009. Retrieved from Energy Policy and Planning Office: http://www.eppo.go.th/doc/index.html#policy

Falkenmark. (1989). The massive water scarcity threatening Africa-why isn't it being addressed. *Ambio* 18(2), 112-118

FAO. (2002). The Livestock Industries of Thailand. Food and Agriculture Organization of the United Nations, Bangkok.

FAO. (2010a). CROPWAT 8.0 model. Retrieved from Food and Agriculture Organization of The United Nations: http://www.fao.org/nr/water/infores_databases_cropwat.html

FAO. (2010b). AQUACROP 3.1. Retrieved from Food and Agriculture Organization of The United Nations: http://www.fao.org/nr/water/aquacrop.html

FAOSTAT. (2010). Crop Production Retrieved from Food and Agriculture Organization of The United Nations: http://faostat.fao.org/site/567/default.aspx#ancor

Fernquest, J. (2009). Water shortage for Thailand by 2015. *Bangkok Post*, November 05. Retrieved from http://www.readbangkokpost.com/easybusinessnews/agriculture/water_shortage_for_thailand_by.php

Gerbens-Leenes, W., Hoekstra, A.Y. Van Der Meer, TH.H. (2009a). The water footprint of bioenergy. PNAS, 106 (25), 10219-10223

Gerbens-Leenes, W., Hoekstra, A.Y., Van Der Meer, TH.H. (2009b). The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. Ecological Economics, 68, 1052-1060.

Gerbens-Leenes, P.W., Hoekstra, A.Y. (2009). The water footprint of sweeteners and bio-ethanol from sugar cane, sugar beet and maize, Value of Water Research Report Series No. 38. UNESCO-IHE. Delft, The Netherlands.

Gordon, L.J., Max Finlayson, C., Falkenmark, M. (2010). Managing water in agriculture for food production and other ecosystem services, Agr. Water Manage., 97:512–519

HAII. (2010). Concepts of the study and assessment on water requirement [in Thai]. Retrieved from Hydro and Agro Informatics Institute: http://www.haii.or.th/wiki/index.php/)

Hoekstra, A.Y. (2003). Virtual water: An introduction. In Virtual water trade, Proceedings of the International Expert Meeting on Virtual Water Trade, Value of Water Research Report Series No.12, IHE Delft, the Netherlands, 12-13 December 2002.

Hoekstra, A. Y., Chapagain, A. K. (2008). Globalization of water: Sharing the planet's freshwater resources, Blackwell Publishing, Oxford, UK.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M. (2011). The Water Footprint Assessment Manual: Setting the Global Standard. Water Footprint Network, Earthscan, UK

IWM (2008). Crop coeeficient (Kc) of Penman-Monteith. Irrigation Water Management Division, Royal Irrigation Department Bangkok.

IWM (2011). The study on reference crop evapotanspiration by Penman-Montheith method of the Irrigation Water Management Division. Retrieved from Royal Irrigation Department: http://water.rid.go.th/hwm/cropwater/iwmd/index_th.htm

Kaenchan, P.. Gheewala, S.H. (2013). A review of the water footprint of biofuel crop production in Thailand. Journal of Sustainable Energy and Environment 4, 45-52.

KAPI, 2007. Recycling and Increasing Value of Waste from Ethanol Production: Final report. Department of Alternative Energy Development and Efficiency, Ministry of Energy, Bangkok.

Kwanyuen, B., Numkhang, P., Phuthongsook, W., Tonwiboonsak, S., (2010). The study of cassava's crop coefficient (Kc). The 11st TSAE conference: Innovation in Agricultural Engineering for Sufficiency Economy and Empowered Communities. 6-7 May 2010, Nakorn Pathom.

Kongboon, R., Sampattagul, S. (2012). Investigating the Water Footprint in Bio-ethanol Crops Production in the Northern of Thailand. Proceeding of the 3rd International Conference on Green and Sustainable Innovation, Thailand, 24-26 May 2012

Land and Water Development Division. (2012). Software: CropWat. Retrieved from FAOWater Development and Management Unit: http://www.fao.org/nr/water/infores_databases_cropwat.html

LDD (2009). Drought risk areas. Retrieved from Land Development Department: http://irw101.ldd.go.th/irw101.ldd/data/data_dro.html

LDD (2012). Forecasting drought for agricultural areas in 2013. Retrieved from Land Development Department: http://irw101.ldd.go.th/lib/images/dro_56th_a4.pdf

Macedo, I.C., Seabra, J.E.A., Silva, J.E.A.R., 2008. Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005-2006 averages and a prediction for 2020, Biomass Bioenergy, 32, 582-595.

Mekonnen M.M., Hoekstra A.Y. (2011). The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577-1600.

MWA. (2010). Annual Report 2010. Retrieved from Metropolitan Waterworks Authority: http://www.mwa.co.th/download/annual_report/annual53/annaul/frame34.html

Nilsalab, P., Gheewala, S.H., Mungkung, R. (2012). Water Assessment of Agrofuels Feedstock Cultivation: Methodology Approaches. Environment and Natural Resources Journal 10, 11-20.

OAE. (2010a). Agricultural Economics Data 2010 [in Thai]. Office of Agricultural Economics

OAE. (2010b). Increasing of raw materials for feed estimated by OAE [in Thai]. Newsletter of Office of Agricultural Economics 27/2010. Retrieve from http://www.oae.go.th/ewt_news.php?nid=7849&filename=index

OAE. (2011). Agricultural Statistics of Thailand 2011 [in Thai]. Office of Agricultural Economics

OAE. (2012). Agricultural statistics of Thailand 2011. Office of Agricultural Economics. Bangkok.

ONEP. (2010). Chapter 2 Water and Coastal Environmental Quality. State of Environment in 2010. Office of Natural Resources and Environmental Policy and Planning

Pfister, S., Koehler, A., Hellweg, S. (2009). Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environmental Science&Technology*, 43 (11), 4098-4104

Pfister, S., Bayer, P., Koehler, A., Hellweg, S. (2011). Projected water consumption in future global agriculture. Scenarios and related impacts. Science of the Total Environment 409, 4206-4216

Pongpinyopap, S., Mungcharoen, T. (2011). Water Footprint of Bioethanol Production from Cassava in Thailand [In Thai]. Kasetsart Engineering Journal, 75, 41-52

Pongpinyopap, S., Mungcharoen, T. (2012). Comparative Study of Green Water Footprint Estimation Methods for Thailand Condition. Proceeding of the 3rd International Conference on Green and Sustainable Innovation, Thailand, 24-26 May 2012

Postel, S. L., Daily, G. C., Ehrlich, P. R. (1996). Human appropriation of renewable freshwater, *Science*, 271(5250), 785–788

Preechajarn, S., Prasertsri, P., 2012. Thailand Biofuels Annual 2012. Global Agricultural Information Network Report. Bangkok.

PWA. (2009). Raw water requirement for water supply business-Chao Phraya, Chi, Khong, Kok, Mun, Nan, Pasak, Ping, Sakaekrang, Salawin, Thachin, Wang and Yom Watersheds. Water Resources Development Division, Water Resource Department, Provincial Waterworks Authority, September

PWA. (2010). Annual Report 2010. Retrieved from Provincial Waterworks Authority: http://www.pwa.co.th/report/AnnualReport2010.pdf

RID. (2010). Summary Report of Development Plan of Irrigation at Watershed System. Retrieved from Royal Irrigation Depart: http://kromchol.rid.go.th/ffd/2011/opm1/RID_Report.pdf

RID. (2011). Work Manual No.8/16: Assessing water consumption by sectors [in Thai]. Retrieved from http://ridceo.rid.go.th/buriram/download/manual-08.pdf [cited 2012 October 17]

RID. (2012a). Water Grid Project [in Thai]. Retrieved from Royal Irrigation Department: http://water.rid.go.th/itcwater/pmoc/watergrid/

RID. (2012b). Water resource planning for dry season 2011/2012. Bangkok.

Ridoutt, B.G., Pfister, S. (2010). A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environmental Change*, 20, 113-120

Rijsberman, F.R. (2006). Water scarcity: Fact or fiction?. *Agricultural Water Management*, 80, 5-22

Sarochawikasit, R. (2009). Alternative Energy Development Plan (2008-2033) [PowerPoint slides], Medium-and Long-term Investment Plan and the Role of the Private Sector. Climate Financing: Clean Technology Fund (CTF) and the Role of the Private Sector Workshop. 13-15 July, Thailand

Scanlon, B.R., Jolly, I., Sophocleous, M., Zhang, L. (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water Resour. Res. 43, W03437.

Silalertruksa, T., Gheewala, S.H., 2009. Environmental sustainability assessment of bio-ethanol production in Thailand, Energy 34, 1933-1946.

Silalertruksa, T., Gheewala, S.H., 2011. Long-term bio-ethanol system and its implications on GHG emissions: A case study of Thailand. Environ. Sci. Technol. 45, 4920-4928.

Sukumalchart, T., Pornprommin, A., & Lipiwattanakarn, S. (2011). Monthly Water Footprint of Maize in Major Cultivated Areas of Thailand. Proceeding of the 1st EIT International Conference on Water Resources Engineering Title “Water Resources Management under Risk of Natural Hazard and Data Uncertainty”, Phetchaburi, Thailand, 18-19 August 2011

Ti, L.H., Facon, T. (2003). From vision to action: A synthesis of experiences in Southeast Asia. The FAO-ESCAP Pilot project on National water visions., Bangkok.

TMD (2007). Drought. In TMD (Eds.), *Meteorological Book* . Retrieved from Thai Meteorological Department: http://www.tmd.go.th/info/info.php?FileID=71

Tungsombun, T. (2006). Crop Evapotranspiration [in Thai]. Supporting document for improvement of water management system for irrigated agriculture. Irrigation Water Management Research Group, Irrigation Water Management Division, Office of Hydrology and Water Management Royal Irrigation Department, Retrieved from Knowledge Management Center of Office of Regional Irrigation 2 http://kmcenter.rid.go.th/kmc02/_data/docs/water-in-p.pdf

Water Resources Engineering Department. (2007). Strategy on water resources development in Thailand. *Civil Engineering Magazine,* 19(2). Retrieved from Mahanakorn University of Technology: http://www.water.civil.mut.ac.th/idea_3.php

Williams, J. R. (1995). ‘The EPIC model’. In V. P. Singh (ed) *Computer Models of Watershed Hydrology*, Water Resources Publisher, CO, 909–1000

WWF-UK and SABMiller. (2009). Water Footprinting: Identifying & Addressing water risks in the value chain [online] England, SABMiller. Retrieved from http://www.sabmiller.com/index.asp?pageid=111&category=susdevelopment&year=2009

Appendix

Appendix I: Numbers of reservoirs classified by river basins (Source: RID, 2012a)

NORTHERN REGION	Salawin	Kok		Ping		Wang		Yom		Nan		Khong		Chi		Mun	
	RID	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others
Large scale																	
No. of project	-	1	-	3	1	2	-	3	-	4	1	4	1	7	2	9	1
Stored water ($M.m^3$)	-	-	-	528.8	13,462	282	-	-	-	769	631,883	633	401,895	1,661.5	2,452	1,269.38	928,285
Irrigated areas (rai)	-	166.000	-	423,000	2,900	167,000	-	480,540	-	9,510	-	165.48	-	1,130,496	-	1,966	-
Medium scale																	
No. of project	16	4	3	42	11	8	1	32	1	51	10	129	1	82	5	149	5
Stored water ($M.m^3$)	13.83	73	-	130.87	0.86	66.23	2.5	305.89	0.38	75.38	421,781	511.46	620,140	348.65	0.4	906.15	0.25
Irrigated areas (rai)	41,260	100,200	10,000	1,118,541	592,600	132,067	-	271,900	-	-	74,150	-	12,000	337,760	5,800	662,520	9,500
Small scale																	
No. of project	304	196	-	934	-	258	-	496	-	591	-	1,867	-	1,521	-	2,322	-
Stored water ($M.m^3$)	10.87	23.88	-	28.29	-	105.99	-	75.98	-	48.62	-	436.36	-	252.04	-	333.34	-
Irrigated areas (rai)	30,870	47,530	-	173,827	-	28,796	-	81,677	-	76,143	-	100,170	-	17,970	-	15,539	-
Command areas (rai)	114,262	262,675	-	1,200,723	-	182,593	-	610,405	-	461,596	-	1,327,435	-	641,228	-	1,203,898	-
Electrical water pump project																	
No. of project	23	12		189		80		125		315		427	-	599	-	286	-
Stored water ($M.m^3$)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Irrigated areas (rai)	21,376	17740		286,703		101,599		121,540		557,271		667,891	-	1,296,303	-	483,365	-
Command areas (rai)	-	-	-	70,440	-	24,876	-	80,208	-	6,400	-	25,574	-	60,775	-	153,540	-

NORTHERN REGION	Salawin	Kok		Ping		Wang		Yom		Nan		Khong		Chi		Mun	
	RID	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others
Detention storage project																	
No. of project	-	-		4		-		19		15							
Stored water (M. m^3)	-	-		9.64		-		68.12		23.5							
Irrigated areas (rai)	-	-		-		-		3,000		-							
Command areas (rai)	-	-		6,365		-		76,119		67,250							

CENTRAL REGION	Chao Phraya		Sakae Krang		Pasak		Thachin	Mae Klong		Petchaburi	West Coast Gulf
	RID	Others	RID	Others	RID	Others	RID	RID	Others	RID	RID
Large scale											
No. of project	22	-	1	9	2	-	9	7	2	1	1
Stored water (M. m^3)	-	-	160	240	960	-	240	-	26,605	710	445
Irrigated areas (rai)	5,955,245	-	143,500	2,328,550	310,800	-	2,328,550	1,343,600	-	336,000	220,000
Medium scale											
No. of project	10	7	5	7	19	4	7	18	1	12	20
Stored water (M. m^3)	15.01	22.7	70	54.48	151.05	13.32	54.48	123.11	-	4.39	154.49
Irrigated areas (rai)	135,821	27,600	128,148	112,576	189,520	10,650	112,576	116,400	1,500	24,530	87,620
Small scale											
No. of project	308	-	119	384	389	-	384	279	-	134	328
Stored water (M. m^3)	9.44	-	1.71	26.28	4.65	-	26.28	164.64	-	35.74	50.86
Irrigated areas (rai)	19,918	-	2,500	28,000	11,882	-	28,000	31,611	-	15,970	31,874
Command areas (rai)	529,533	-	161,810	598,055	417,960	-	598,055	296,323	-	92,280	307,603

CENTRAL REGION	Chao Phraya		Sakae Krang		Pasak		Thachin	Mae Klong		Petchaburi	West Coast Gulf
	RID	Others	RID	Others	RID	Others	RID	RID	Others	RID	RID
Electrical water pump project											
No. of project	30	-	16	11	3	-	11	67	-	8	1
Stored water (M. m^3)	-	-	-	-	-	-	-	-	-	-	-
Irrigated areas (rai)	73,379	-	38,400	31,150	1,832	-	31,150	115,430	-	6,600	1,000
Command areas (rai)	2,000	-	-	-	1,832	-	-	23,400	-	500	-
Detention storage project											
No. of project	10	-	-	3	5	-	3	-	-	-	-
Stored water (M. m^3)	38.21	-	-	1.89	28.83	-	1.89	-	-	-	-
Irrigated areas (rai)	44,100	-	-	3,500	6,000	-	3,500	-	-	-	-
Command areas (rai)	467,150	-	-	12,000	13,000	-	12,000	-	-	-	-

EASTERN REGION	Prachin Buri		Bang Pakong	Thole Sap	East Coast Gulf	
	RID	Others	RID	RID	RID	Others
Large scale						
No. of project	1	-	4	-	3	-
Stored water (M. m^3)	-	-	549	-	522	-
Irrigated areas (rai)	326,000	-	1,214,040	-	213,500	-
Medium scale						
No. of project	23	1	15	3	34	5
Stored water (M. m^3)	139.37	2.4	58.7	137.01	256.5	3.18
Irrigated areas (rai)	201,215	-	109,150	97,900	282,300	13,000

EASTERN REGION	Prachin Buri		Bang Pakong	Thole Sap	East Coast Gulf	
	RID	Others	RID	RID	RID	Others
Small scale						
No. of project	220	-	260	148	280	-
Stored water (M. m^3)	13.39	-	15	2.65	20.66	-
Irrigated areas (rai)	19,819	-	10,180	1,950	23,090	-
Command areas (rai)	158,865	-	206,056	68,670	196,690	-
Electrical water pump project						
No. of project	66	-	5	-	52	-
Stored water (M. m^3)	-	-	-	-	-	-
Irrigated areas (rai)	114,453	-	16,950	-	121,580	-
Command areas (rai)	4,000	-		-	7,150	-
Detention storage project						
No. of project	-	-	-	-	6	-
Stored water (M. m^3)	-	-	-	-	8.43	-
Irrigated areas (rai)	-	-	-	-	-	-
Command areas (rai)	-	-	-	-	37750	-

SOUTHERN REGION	Peninsula-East coast		Tapi		Thale sap Songkhla		Pattani		Peninsula-West coast	
	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others
Large scale										
No. of project	6	-	-	1	2	-	1	1	-	-
Stored water (million m^3)	80	-	-	5,639	-	-	-	1,404	-	-
Irrigated areas (rai)	884,744	-	-	-	190,000	-	241,850	-	-	-
Medium scale										

SOUTHERN REGION	Peninsula-East coast		Tapi		Thale sap Songkhla		Pattani		Peninsula-West coast	
	RID	Others	RID	Others	RID	Others	RID	Others	RID	Others
No. of project	24	1	20	-	14	3	2	-	20	1
Stored water (million m^3)	15.8	-	161.18	-	52	0.42	-	-	32.8	-
Irrigated areas (rai)	445,100	16,000	61,615	-	425,190	5,000	-	-	148,710	1,400
Small scale										
No. of project	1,008	-	105	-	173	-	195	-	520	-
Stored water (million m^3)	69.38	-	0.06	-	0.56	-	0.54	-	24.07	-
Irrigated areas (rai)	99,138	-	15,712	-	31,220	-	8,340	-	51,317	-
Command areas (rai)	621,150	-	88,430	-	216,616	-	55,974	-	210,552	-
Electrical water pump project										
No. of project	42	-	20	-	24	-	1	-	25	-
Stored water (million m^3)	-	-	-	-	-	-	-	-	-	-
Irrigated areas (rai)	60,592	-	30,138	-	44,765	-	800	-	49,600	-
Command areas (rai)	14,800	-	-	-	2,700	-	-	-	-	-
Detention storage project										
No. of project	3	-	1	-	-	-	RID	Others	RID	Others
Stored water (million m^3)	4.1	-	0.18	-	-	-				
Irrigated areas (rai)	1,500	-	-	-	-	-	1	1	-	-
Command areas (rai)	3,500	-	1,200	-	-	-	-	1,404	-	-

Appendix II: Standard deviation of rainfall classified by provinces (unit: mm/month) based on the calculation in the project

NORTH	(S*month)	(S*year)
Mae Hong Son	0.95	0.13
Chaing Rai	0.98	0.10
Phayao	0.95	0.17
Chaing Mai	1.00	0.16
Lampang	0.99	0.19
Lamphun	1.12	0.25
Phrae	1.02	0.16
Nan	1.01	0.17
Uttaradit	1.11	0.28
Tak	0.94	0.16
Phitsanulok	1.00	0.16
Phetchabun	0.91	0.16
Kamphaengphet	0.96	0.16
Sukhothai	1.01	0.24
Phichit	1.11	0.22
Nakhonsawan	0.96	0.18

EAST	(S*month)	(S*year)
Chachoengsao	0.83	0.19
Prachinburi	0.93	0.10
Sakaew	0.84	0.15
Chonburi	0.81	0.09
Rayong	0.85	0.16
Chanthaburi	0.93	0.12
Trat	1.04	0.18

NORTH-EAST	(S*month)	(S*year)
Nong Khai	1.09	0.21
Loei	1.00	0.16
Udon Thani	1.06	0.13
Nongbualumphu	1.12	0.49
Sakon Nakhon	0.98	0.15
Nakhon Phanom	1.14	0.15
Khon Kaen	0.97	0.17
Mukdahan	1.13	0.16
Mahasarakham	1.03	0.17
Kalasin	1.07	0.10
Chaiyaphum	1.05	0.25
Roi Et	1.03	0.08
Ubon Ratchathani	1.07	0.14
Si Sa Ket	1.09	0.15
Nakhonratchasima	0.89	0.12
Surin	1.00	0.09
Buriram	0.93	0.10
Amnat Charoen	1.11	0.20
Yasothon	1.10	0.15

CENTRAL	(S*month)	(S*year)
Chainat	1.15	0.25
Ayutthaya	1.04	0.15
Pathumthani	0.95	0.22
Ratchaburi	1.04	0.12
Suphanburi	0.99	0.16
Lopburi	0.97	0.10
Kanchanaburi	0.83	0.12
Bangkok	0.85	0.18
Samutprakan	0.96	0.20
Phetchaburi	1.13	0.12
Prachuapkhirikhan	1.07	0.22
Nakhonpathom	1.04	0.16
Ang Thong	1.05	0.13
Sing Buri	1.06	0.15
Samut Sakhon	0.92	0.09
Samut Songkhram	1.09	0.28
Nakhon Nayok	1.04	0.17
Nonthaburi	0.85	0.16
Saraburi	0.91	0.18
Uthai Thani	0.89	0.20

SOUTH	(S*month)	(S*year)
Chumphon	0.75	0.09
Ranong	0.92	0.11
Suratthani	0.91	0.20
Nakhon Si Thammarat	0.88	0.21
Phatthalung	1.10	0.28
Phuket	0.52	0.12
Krabi	0.66	0.10
Trang	0.71	0.13
Songkhla	0.88	0.19
Satun	0.81	0.12
Pattani	0.84	0.24
Yala	0.83	0.22
Narathiwat	1.03	0.25
Phang Nga	0.88	0.37