PROJECT KOH TAO

Tackling water shortage

Additional Master Thesis, October '16

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Abstract (บทคัดย่อของรายงาน)

This report serves to inform the local government of Koh Tao on the status of their current water system and advises on an alternative in order to make sure that future tap water demand can be met in a sustainable and reliable manner.

Koh Tao is an island in the gulf of Thailand with a surface area of approximately 21km^2. The various coral reefs surrounding the island are of great value for the touristic sector. In 2015 roughly 500,000 tourists visited Koh Tao, of whom most came to dive. Being a popular tourist destination puts stress on the local water supply system. As a consequence the price of tap water ranges between 150 and 600 ฿ (Thai Baht) per cubic meter, which equals roughly $4 to $17. The main source of tap water is groundwater (85%) that is pumped to the surface from local aquifers. This system implies a low buffer capacity, especially during the dry season. Other sources are water shipped in from the mainland (5%), rainwater catchment (5%) and small scale desalination (5%).

The local government of Koh Tao, the client, has stated the boundary conditions where the proposed alternative water supply system has to comply with. The most important boundary condition is a minimal impact on the vulnerable coral reefs of Koh Tao because the island derives a large share of its value from this. It is also important that the capacity is such that the future demand can be met, since the touristic sector is expected to grow in the future. It has been estimated that the touristic sector on Koh Tao will grow until 700,000 annual tourists, which will correspond with a tap water demand of 5,400,000m^3/year and a peak demand of 18,000m^3/day during high season.

Currently precipitation is the main source of fresh water on Koh Tao. Rain water can be utilized either by direct catchment or by extracting infiltrated water from the subsurface. The potential of rainwater utilization depends on the presence of water bearing layers and paved surfaces. Optimizing the current method of rainwater utilization demands governmental control. Due to the mismatch between touristic high season and rainy season storage may be required. Optimisation of the current system is not considered the preferred solution.

Reverse osmosis desalination (RO) is a method in which seawater is desalinated under pressure by means of a filter. From the analysis it showed that this method has a very flexible character when it comes to capacity and can be applied on Koh Tao without causing excess environmental impact.

In order to assess what is the preferred solution a multi criteria analysis (MCA) has been conducted. The MCA gave the first indication that a RO plant is the preferred solution. In order to obtain more certainty a risk analysis has been conducted. The conclusion of this analysis is that all identified risks can be mitigated or avoided such that the residual risk is acceptable. The economic feasibility of a RO plant has been investigated as well. From this analysis it showed that a RO plant with a lifetime of 25 years is expected to have a Net Present value (NPV) of a little over 192 million ฿ and internal rate or return (IRR) of 9.34%. From the MCA, in combination with the economic feasibility study and risk analysis it shows that RO desalination is a method which seems very viable on Koh Tao and therefore has been qualified as the preferred solution.

Thai Abstract (บทคัดย่อของรายงาน)

รายงานฉบับนี้จัดทำขึ้นเพื่อรายงานแก่เทศบาลตำบลเกาะเต่ากับสถานะของระบบน้ำของพวกเขาในปัจจุบันและให้คำแนะนำเกี่ยวกับทางเลือกในการสั่งซื้อเพื่อให้แน่ใจว่ามีความต้องการน้ำประปาในอนาคตที่สามารถพบได้ในลักษณะที่ยั่งยืนและเชื่อถือได้

เกาะเต่าเป็นเกาะในอ่าวไทยมีพื้นที่ผิวประมาณ 21 ตารางกิโลเมตร แนวปะการังรอบๆ เกาะมีค่ามากสำหรับภาคการท่องเที่ยว ในปี 2015 จำนวนนักท่องเที่ยวเข้าเยี่ยมชมเกาะเต่าอย่างคร่าวๆ ประมาณ 500,000 คนซึ่งส่วนใหญ่มาเพื่อดำน้ำ เกาะเต่ากลายเป็นจุดหมายปลายทางยอดนิยมของนักท่องเที่ยวส่งผลกระทบให้แก่ระบบน้ำประปาท้องถิ่น เป็นผลให้ราคาของน้ำประปาอยู่ระหว่าง 150 ถึง 600 ฿ ต่อลูกบาศก์เมตรซึ่งเท่ากับประมาณ (บาท)4 ดอลล่า ถึง 17 ดอลล่า แหล่งที่มาของน้ำประปาคือน้ำบาดาล)85%) ที่ถูกสูบขึ้นมายังพื้นผิวจากชั้นหินอุ้มน้ำ ระบบนี้บอกเป็นนัยถึงความจุบัฟเฟอร์ต่ำโดยเฉพาะอย่างยิ่งในช่วงฤดูแล้ง แหล่งอื่น ๆ คือ มีการขนส่งน้ำเข้ามาจากแผ่นดินใหญ่)5%), น้ำฝนที่กักเก็บน้ำ)5%) และการกลั่นน้ำทะเลขนาดเล็ก)5%)

รัฐบาลท้องถิ่นของเกาะเต่า ได้ระบุเงื่อนไขขอบเขตที่ซึ่งนำเสนอระบบน้ำประปาเป็นทางเลือกเพื่อให้สอดคล้องกับลูกค้า เงื่อนไขขอบเขตที่สำคัญที่สุดคือการส่งผลกระทบน้อยที่สุดให้แก่แนวปะการังที่มีค่าของเกาะเต่าเพราะเกาะมีรายได้จากการแบ่งปันทรัพยากรที่ค่านี้ นอกจากนี้ยังมันเป็นสิ่งสำคัญเกี่ยวกับปริมาณสูงสุดที่จะรับนั้นคือความต้องการในอนาคตสามารถพบได้ตั้งแต่ภาคการท่องเที่ยวที่คาดว่าจะเติบโตอีกในอนาคต มีการประเมินว่าภาคการท่องเที่ยวบนเกาะเต่าจะเติบโตจนถึง 700,000 คนต่อปี ซึ่งจะสอดคล้องกับความต้องการน้ำประปาของ 5,400,000 ล้านลูกบาร์คเมตรต่อปี และความต้องการสูงสุดของ 18,000 ล้านลูกบาร์คเมตรต่อปี ต่อวันในช่วงไฮซีซั่น ..

ขณะนี้ปริมาณน้ำฝนเป็นแหล่งที่มาหลักของน้ำจืดบนเกาะเต่า มีเพียงส่วนน้อยของการตกตะกอนน้ำฝนที่ถูกนำมาใช้ประโยชน์จากการเก็บกักน้ำโดยตรง ส่วนใหญ่ที่สุดคือการใช้น้ำบาดาลจากตาน้ำจืดซึ่งส่วนใหญ่เป็นการบรรจุใหม่โดยการตกตะกอนแทรกซึม เพื่อตอบสนองความต้องการน้ำในอนาคตด้วยวิธีการปัจจุบันของการจัดหาสถานที่และอัตราการขุดบ่อที่จะต้องมีการปรับให้เหมาะสม เนื่องจากไม่ตรงกันระหว่างฤดูการท่องเที่ยวสูงและช่วงเวลาที่มีการกักเก็บน้ำฝนมากที่สุดเพื่อน้ำไปใช้เป็นน้ำประปานั้นถือเป็นสิ่งจำเป็น ข้อเสียที่สำคัญของวิธีนี้คืออิทธิพลของภาครัฐต่ำ การใช้ประโยชน์จากน้ำบาดาลคือมีการจัดตั้งเฉพาะแห่ง และการถือครองที่ดินโดยรัฐบาลมีข้อจำกัด ลูกค้าแค่เพียงบอกกล่าวที่ซึ่งพวกเขาเห็นน้ำจืดที่มีอยู่นั้นสำหรับทุกคน และ สำหรับราคาที่สมเหตุ สมผล จึงควรเป็นหน้าที่ของพวกเข้า รัฐบาลควรจะเป็นเจ้าของหรืออย่างน้อยการควบคุมการผลิตน้ำจืดเพื่อให้บรรลุเป้าหมายนี้

การกลั่นน้ำทะเลด้วยการทำออสโมซิส)RO) เป็นวิธีการในการที่นำน้ำทะเลมาทำการแยกเกลือออกที่ซึ่งอยู่ภายใต้ความกดดันโดยวิธีการของตัวกรอง จากการวิเคราะห์แสดงให้เห็นว่าวิธีการนี้มีลักษณะที่มีความยืดหยุ่นมากเมื่อมันมาถึงขีดความสามารถและสามารถนำมาใช้บนเกาะเต่าไม่ก่อให้เกิดผลกระทบต่อสิ่งแวดล้อมเกิน

เพื่อประเมินสิ่งที่เป็นทางออกที่ต้องการวิเคราะห์หลายเกณฑ์ ได้รับการดำเนินการ เอ็มให้ข้อบ่งช (เอ็มา้)แรกที่โรงงาน RO เป็นทางออกที่ต้องการ เพื่อให้ได้ความเชื่อมั่นมากขึ้นการวิเคราะห์ความเสี่ยงได้รับการดำเนินการ บทสรุปของการวิเคราะห์นี้ก็คือความเสี่ยงที่ระบุทั้งหมดสามารถบรรเทาหรือหลีกเลี่ยงดังกล่าวว่ามีความเสี่ยงที่เหลือเป็นที่ยอมรับ ความเป็นไปได้ทางเศรษฐกิจของพืช RO ได้รับการตรวจสอบเช่นกัน จากการวิเคราะห์นี้มันแสดงให้เห็นว่าเป็นพืช RO กับอายุการใช้งาน 25 ปีคาดว่าจะมีมูลค่าปัจจุบันสุทธิ)NPV) ของน้อยกว่า 192,000,000 ฿และอัตราผลตอบแทนภายในหรือการลงทุน)IRR) 9.34% จากเอ็มร่วมกับการศึกษาความเป็นไปได้ทางเศรษฐกิจและการวิเคราะห์ความเสี่ยงมันแสดงให้เห็นว่า RO กรองน้ำทะเลเป็นวิธีการซึ่งดูเหมือนว่าทำงานได้มากบนเกาะเต่าและดังนั้นจึงได้รับการรับรองว่าเป็นทางออกที่ต้องการ

Acknowledgements (การรับทราบ)

We would like to use this opportunity to thank the local government of Koh Tao and specific mayor Mr. Chaiyan Turasakun for his kind invitation to conduct research on Koh Tao. We are thankful for the provided workspace and the access provided to all relevant documents. The warm welcome and the relaxed and positive atmosphere at the office contributed to the joy we had doing Project Koh Tao.

Special thanks go to Watchaya Pitakuksorn (Fon) for her enthusiastic contribution to make this project happen. You have given Project Koh Tao a smile and provided countless insights that allowed our analysis to be more accurate and thorough. You were always open to help and learn, with a joke on the side. We are happy to call you a friend.

The supervision by Dr. Ir. Heijman and Ir. W.M.J. Luxemburg has allowed for a very steep learning curve. Thrust was expressed from the very beginning that we, as two master students in Geo-Engineering, would be able to successively conduct this research. We are very thankful for your guidance and approach towards us and the project.

We would like to thank the Lamminga Fund for their support to Project Koh Tao as their help made this project financially possible.

List of Symbols (รายการของสัญลักษณ์)

\$	American Dollars	USD
฿	Thai Baht	THB
mm	Millimeter	
m	Meter	
m^3	Cubic meter	
L	Liter	
km^2	Square kilometre	
$\Delta\Pi$	Osmotic pressure	
ΔP	Differential pressure	

List of Abbreviations (รายการของคำย่อ)

CAPEX	Capital Expenditures
ERS	Energy Recovery System
Fe	Iron (element)
HP	High Pressure
IRR	Internal Rate of Return
NF	Nano Filtration
NPV	Net Present Value
NPW	Non-Profit Water
NRW	Non Revenue Water
OPEX	Operational Expenditures
PPM	Parts Per Million
RO	Reverse Osmosis
TDS	Total Dissolved Solids

Definitions of Water (ความหมายของน้ำ)

In this report different types of water are distinguished.

Fresh water – Brackish water – Salt/Sea water

- Fresh water contains no or an unnoticeable concentration of sea salt (e.g. rainwater).
- Salt/sea water is water with a high concentration of salt as available in the ocean surrounding Koh Tao.
- Brackish water contains a noticeable concentration of salt which is less than the concentration in salt/sea water.

Drinking water – Tap water – Wastewater

- Drinking water is water of drinking quality, currently supplied on Koh Tao in various bottle sizes.
- Tap water is water from the tap, this type of water is currently equal to (filtered) fresh water.
- Wastewater is consumed tap or drinking water which is collected in a drainage system.

Rain water – Ground water

- Rain water is equal to precipitation
- Groundwater is water available in the subsurface and this water can be either fresh or brackish.

Table of Contents (สารบัญ)

1 Introduction (กถามุข)

Koh Tao is a small island (21km^2) in the Gulf of Thailand and a popular destination for (scuba diving) tourists. The demand for tap water on the island commonly exceeds the local supply capacity. Project Koh Tao was set up to analyse the current water system and tried to find a sustainable solution to produce tap water. Readers not familiar with Koh Tao are advised to consult Appendix A to F in order to get a general understanding of the island. These appendices summarise the desk study on Koh Tao which was made the first weeks of Project Koh Tao to get a throughout understanding of the island. A schematic outline of the island can be seen in Figure 1.

In this report amounts of money are expressed in both American Dollars ($) and Thai Baht (฿). The exchange rate is likely to change over time in the future. An exchange rate of 36฿ = 1$ has been used in this report. There is no fixed translation for the name of the island from Thai to English. In literature both Ko Tao and Koh Tao will be found. In this report the name Koh Tao is consistently used. When looking at the map of Koh Tao (Figure 1) it shows that the island of Koh Nang Yuan is located just west of the main island. When talking about Koh Tao in this report only the main island is meant. Koh Nang Yuan solely has a touristic purpose and is supplied from the main island. Due to its small size it is not considered.

Figure 1: Schematic map of Koh Tao showing the different residential areas, beaches and the road system [1]

1.1 Team of Students and Professors

Project Koh Tao is initiated and conducted by Erik Beutick BSc. and Wik Breure BSc. as an additional master thesis. Both students are studying for a master degree in Civil Engineering at Delft University of Technology.

Delft University of Technology collaborates with a large number of other educational and research institutes within the Netherlands and abroad and has a reputation for high-quality teaching and research. TU Delft has extensive contacts with governments, trade organisations, consultancies, the industry and small and medium-sized companies. Students and supervisors involved in Project Koh Tao are based at TU Delft.

Supervision during the project was provided by Dr. Ir. S.G.B. (Bas) Heijman expert in Water Management and Ir. W.M.J. (Willem) Luxemburg expert in Hydrology. Both supervisors are lecturers and researchers at Delft University of Technology.

1.2 Government of Koh Tao

The government of Koh Tao, represented by the mayor Mr. Chaiyan Turasakun and Surat Thani province representative Watchaya Pitakuksorn, is the customer in this project. Hereinafter often referred to as the 'client' in this report. Great care was taken to make sure that the eventual proposal complies with the boundary conditions defined by the client. Access to previous research reports and data has been given, as well as help with translating important sections from Thai to English. Important headers and the summary have been translated to Thai in order to allow for more convenient reading of the report.

1.3 Partner

Project Koh Tao is supported by Royal HaskoningDHV. Royal HaskoningDHV is an independent, international engineering and project management consultancy company with 135 years of experience. Backed by the expertise and experience of 6,500 colleagues all over the world, their professionals combine global expertise with local knowledge to deliver a multidisciplinary range of consultancy services for the entire living environment from over 150 countries. The water services department of Royal HaskoningDHV provided expertise during the project

2 Problem Definition and Project Target (เป้าหมายของโครงการ)

The island of Koh Tao has a natural source of fresh water. Due to the high amount of tourists (approximately 500.000 in 2015) the demand for fresh water is so high that it exceeds the supply capacity of the groundwater system. In order to mitigate this deficit alternative supply methods have been introduced. Fresh water is transported from the mainland by boat, desalination is applied locally and some households catch rainwater from their roofs. Water is mainly distributed by means of pickup trucks, transporting one to several cubic meters at the time. A pump is used to transport the water from the truck to a storage tank connected to a house or hotel. This method of water supply is very labour and transport intensive. As a consequence, water is very expensive on Koh Tao. In combination with the supply deficit the price of a cubic meter (m^3) of water ranges between 150 and 600 Thai Baht, which equals roughly $4 to $17. Apart from the high costs, this method also implies a very low buffer capacity since the availability of the resources depends strongly on the rainfall amount and frequency.

The quality of the tap water is such that it is used for personal hygiene, cleaning, pools and irrigation. Drinking water is sold in bottles, as tap water is not meant for drinking. Koh Tao, being a popular holiday destination, is in need of a reliable water system that enables residents and companies on the island to live and expand in a sustainable manner. In particular because the stress on the water system is likely to increase in the future due to an increasing annual amount of tourists.

The goal of this study was to assess different alternatives that potentially increased the reliability and capacity of the water system and reduced the costs per unit of volume compared to the current situation. A possible capital investment as a part of the solution has been assessed as well. Besides the targeted capacity, the solution had to comply with the boundary conditions that were implied by the government of Koh Tao. Methods assessed were:

- Utilization of rainwater: As Koh Tao is subjected to rain seasons, an assessment was made looking at the potential of rainwater as sustainable fresh water resource. Direct catchment as well as utilization of groundwater that originates from rainwater has been assessed.
- Seawater as a resource: Seawater may be considered a very abundant resource. Through the process of reverse osmosis seawater can be turned into fresh water.

The alternatives have been compared by means of a multi criteria analysis, in which scores were given for different properties of the method in combination with weighing factors. This resulted in an overall score for every method and allowed for a quantitative comparison between the different alternatives. Properties that have been considered are: capital investment, operational costs, legal applicability, price per unit, lifetime, maintainability, buffer capacity, reliability and environmental impact, quality of produced water and time and space needed to establish the new system.

When one of the solutions has a significant preference over the other, this solution will be considered in a more comprehensive manner. Eventually leading to a proposal which states the most viable solution knowing the approximate costs and benefits.

3 Boundary Conditions (คำนิยามในภาษาอังกฤษ)

The main point of concern when looking at the future of Koh Tao is the state of the coral reefs that surround the island. This also implies the most important boundary condition the eventual solution has to comply with: the environmental impact has to be minimal. During the past years the stress on the coral reefs has increased due to an increased annual tourist arrivals and changed climate conditions. The touristic value of Koh Tao is strongly dependant on the state of the coral reefs, which means that no concessions are acceptable with respect to the environmental situation.

No specific budget has been given. The proposed solution is expected to come with an implementation plan in which the economic feasibility and viability is explained. A solution capable of earning back the initial capital investment is preferred. The local government will not necessary be owner of the water supply system. The system will be controlled by the government though, in order to allow for monitoring and correction if necessary. The government considers it a task to supply Koh Tao with water in exchange for a reasonable price. By controlling the exploitation this can be guaranteed. There is no set future unit price for tap water. A unit price in the range of 60-80 ฿/m^3 (≈ 1.7 – 2.2 \$/m^3) is described by the client as a good to reasonable price. It is mainly important that the price is a significant reduction compared to the current situation.

The local government usually considers terms of 5 years. Due to increased annual tourist arrivals the economic welfare on Koh Tao increased rapidly in a short period of time. As a consequence of the rapid increase and the relative short terms considered the capacity of the islands infrastructural works became insufficient. In Appendix G these acknowledged issues on Koh Tao are further discussed. In order to meet the future demand a robust required capacity estimate is requested and the lifetime to be considered for the proposed water system is 25 years. The infrastructure on Koh Tao is being improved using a step by step approach. For a new water system this means that the water delivered to the customer can develop from tap water to drinking water over time if the required infrastructure is present. Until this situation is realised the supply of tap water is the most important target.

4 Current Water System (ระบบน้ำในขณะนี้)

The current water system of Koh Tao has been analysed in terms of supply and discharge. The current and future demand has been estimated, the capacity of the proposed future solution was based on the estimated future demand.

4.1 Water Supply

Tap water on Koh Tao is mainly used for personal hygiene, cleaning, pools and irrigation. Water is mainly distributed by means of pickup trucks, transporting one to several cubic meters at the time (Figure 2). A pump is used to transport the water from the truck to a storage tank. Before Koh Tao became a popular touristic destination, rainwater was the only source utilized as tap water. This happened by direct catchment or pumping from the subsurface after infiltration. Being such a popular touristic destination nowadays has put strain on the water supply system of the island. As a consequence, tap water supply from the fresh groundwater that is naturally available does not fulfil the demand at all times. Alternative solutions have been introduced; water is brought to Koh Tao by boat daily and on a small scale tap water is produced by desalination techniques. This system brings along high costs per unit, has a low buffer capacity and a low reliability. All residents have a private or shared water tank close to their house or business. Most water tanks are placed up the mountain or are elevated from ground level such that water flows under gravitational force to the tap points. Due to scarcity the price of tap water is very high and ranges from 150 up to 600 ฿ (≈ 4 to 17 $) per cubic meter.

4.1.1 Groundwater as a tap water resource

Cracks in the weathered granite bedrock act as shallow aquifers from which groundwater is pumped to the surface (see Chapter 5). The shape of the island with different slopes and mountain peaks (Figure 33) naturally creates different funnels that causes rainwater to flow towards aquifers located at a lower point. Generally these aquifers are very shallow and allow for a limited pumping rate ranging from 0-5 m^3/hour depending on the size and recharge rate of the well. The latter is directly related to rainfall, meaning that the pumping capacity depends on the meteorological conditions as well. According to the local government there are approximately 25 deep wells and 125 shallow wells, all privately owned [2]. The pumping rate of the different pumps is unknown. Water from the wells is brought to the customer without any further treatment. Water from a well is distributed by means of small water trucks and pickup trucks with a water tank and pump on the back as shown in Figure 2. Some businesses and households are directly supplied from a well by pipe infrastructure and pay neighbours that own the well to make use of their water. The largest share of tap water consumed on Koh Tao is utilized groundwater.

4.1.2 Direct catchment of rainwater

On a small scale individuals collect rainwater from their roof by means of a gutter and store it in a tank. This water is utilized in a single household or small community for washing, the toilet and as tap water.

4.1.3 Supply of tap water from the mainland

The scarcity and price of water on Koh Tao makes it favourable to buy water on the mainland and ship it to the island. This water is delivered at the Mae Hat pier at the main residential area of the island Ban Mae Hat which is located at the west shore (Figure 1). The shortest distance between the mainland (City of Chumpon) and the pier is about 70km. From findings on the island it is known that at least three resorts are supplied by water from the mainland. The production method of the shipped water is unknown.

Figure 2: A pickup truck is charged with tap water at a pumping station

4.1.4 Sea water as resource for tap water

On a small scale seawater is used to produce fresh water. Findings on the island showed that at least nine resorts are supplied by two small scale reverse osmosis (RO) plants. The two plants are privately owned by separate resort owners. The production capacities are roughly $10m^3/h$ and $40m^3/h$. One resort is experimenting with fresh water production by means of distillation. This water does not have drinking quality.

4.1.5 Drinking water

Drinking water is supplied in bottles and jerry can like cylinders that can be used in combination with a small tap. There is a wide selection of brands and the water mainly originates from Thailand. Drinking water and ice is also produced locally from groundwater in a privately owned reversed osmosis plant in combination with UV-treatment. The retail price of drinking water is in the range 500-25,000฿/m^3 (≈ 35-700 \$/m^3) depending on brand, packing and seller.

4.2 Wastewater

Wastewater on Koh Tao is mainly produced by tourist accommodations and households. There is little too no industry on the island and the main agricultural activity is coconut plantations. Wastewater treatment is not yet a common practise on Koh Tao. The majority of households and facilities collect wastewater in septic tanks. Wastewater consists of biological degradable substances and non-biodegradable substances. Most of the biodegradable substances are degraded in the septic tanks. The overflow of the tanks is used for irrigation or dumped directly on land or in the ocean. Because not all solids degrade the tanks have to be emptied from time to time, the thickened sludge from the tanks is dumped or collected with the garbage. Not all residences have septic tanks, some dump their wastewater directly on land or in the ocean by means of an effluent pipe. Others have a system that leaves the water from the shower and sink to infiltrate in the ground, but collects wastewater from the toilet.

4.3 Water Demand

The main water demand on Koh Tao is caused by tourist residential facilities, such as resorts and hostels. A smaller share of the total demand comes from use by locals and agriculture. The tourist demand, demand by locals and rest demand on Koh Tao have been analysed individually. Based on findings on the island and with the help of literature figures have been estimated for the different demands. The argumentation on which the assumptions are based as well as the entire calculation for the total current (2015) and future (2020) water demand can be found in Appendix H.

4.3.1 Current demand

Studies on the water demand in touristic areas in Spain, Vietnam and Tanzania have been used to estimate the water demand of tourists on Koh Tao, the average daily water demand per tourist is estimated at 500 liters. The 10,000 permanent residents are expected to use far less, their current average water demand has been estimated to be 80 liters per day. In the water demand calculation a rest demand factor was obtained equal to 1.3 times the sum of the tourist and local resident demand. In order to account for spillage and leakage another multiplication factor of 1.3 is introduced.

In 2015 approximately 500,000 tourists visited Koh Tao and the average tourist stay in 2015 was 7.9 days [2]. Thereby the calculated current total water demand equals 3,800,000m^3 per year.

A rough estimate, based on interviews with locals on Koh Tao, is that 85% of the current tap water is supplied by groundwater, 5% is shipped from the mainland, 5% is supplied by direct catchment of rainwater and the remaining 5% is supplied by desalination methods.

4.3.2 Future demand

Water demand by tourist is expected to remain fairly constant over time whereas the water demand of permanent residents is expected to grow up to 120 liters per day in 2020. The annual amount of tourists visiting Koh Tao is expected to increase from 500,000 in 2015 to 700,000 in 2020. The amount of local residents is expected to remain more or less constant over this period of time.

For the total future demand calculation the rest demand factor is again equal to 1.3 times the sum of the tourist and local resident demand. Also the spillage and leakage factor is unchanged and equal to 1.3. Conservative assumptions have been made concerning the different water demands and the non-profit water since the capacity of the proposed solution is based on the estimated future demand. 2020 is a relatively near future but most convenient for the client since the development of Koh Tao as a popular island for tourists is subject to a lot of insecurities.

The main purpose of visiting Koh Tao (diving) is not expected to change and thereby the future average tourist stay is expected to be in the order of the average 7.9 days found for 2015. The future total annual water demand is calculated to be 5,400,000m^3. The required peak capacity, during high season in November and December, is 18,000m^3/day.

4.3.3 Relation tap water demand and price

The amount of water suppliers on Koh Tao is limited, which causes the situation to have clear signs of an economical oligopoly. This may be an explanation why the price is inflated. As a consequence, the price for tap water on Koh Tao is not in proportion with the actual scarcity. For example the unit price hardly reduces during monsoon season, when water recharge is abundant. The fact that people are willing to pay the current price also indicates price inelasticity for water. In other words, tap water being an elementary need has caused the current price to have a limited influence on the demand. According to the authors it is likely though that there is a certain upper limit to this inelasticity.

5 Geology and Geo Hydrology (ธรณีวิทยาและภูมิศาสตร์อุทกวิทยา)

Koh Tao effectively is big block of granite. More specifically medium to fine grained biotite muscovite granite [3]. The so called belt where Koh Tao and its neighbouring islands, Koh Samui and Koh Phangan, are located on is characterized by S-type granites that were formed in the Triassic. The entitlement S-type refers to the origin of the granite, in this case meaning that the formation originates from partially melted sedimentary rock that has gone through a weathering process at the surface. Volcanism at the sea bottom has produced an outburst of granitic magma with such a volume that the surface of the sea was reached, producing the island of Koh Tao when it solidified [4]. Due to tectonic activity the rock mass was turned resulting in joints that have an orientation roughly perpendicular to the surface. The surface geology consists of rock outcrops or a shallow layer of sand, effectively the weathering product of the granite as it has eroded over time. When considering the geological process that formed Koh Tao, it is unlikely that deep horizontal layers of other rock or loose material are present.

When looking at the hydraulic properties of solid granite no intergranular flow may be expected. This means that all the flow occurs through the joints in the granite rock. When assessing the hydraulic conductivity of the granite mass as a whole a large variation and anisotropic behaviour is likely to be found. The hydraulic conductivity mainly depends on the joint orientation, distance between joints, and aperture. For fractured granite, a hydraulic conductivity of $8 \cdot 10^{-9}$ to $3 \cdot 10^{-4}$m/s is representative [5].

Whether fractured granite is capable of serving as an aquifer hosting fresh water depends on the joint orientation. Vertical joints have to be present in order to allow infiltrating rainwater to flow into the granite rock. If the vertical joints are connected to a horizontal joint system deeper into the aquifer the storage capacity will be increased [6]. According to the local government, joints in the granite tend to serve as the main aquifer from which groundwater is pumped to the surface [2]. This means that a reasonable space volume is present in these joints and fractures.

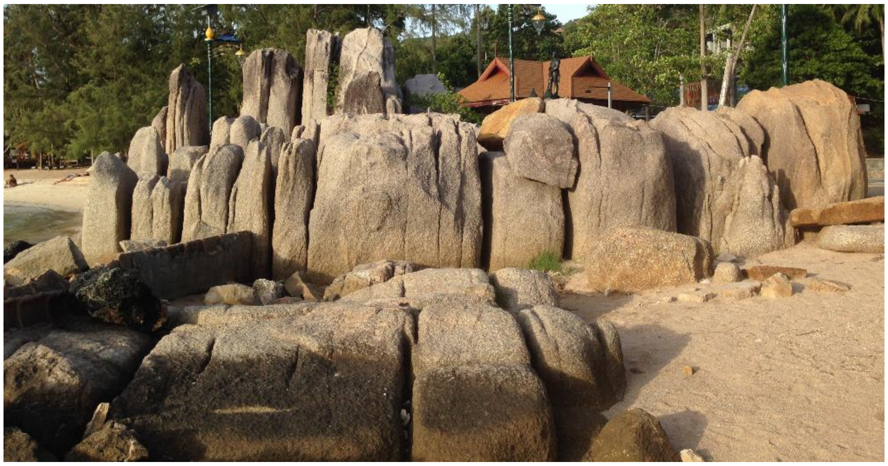

Figure 3: Outcrops at Sairee Beach, west Koh Tao

The state of a rock mass can be assessed by looking at outcrops, with the assumption that the orientation of joints and fractures that can be seen at the surface are representative for the state of the entire rock mass. From visual assessment of the rock mass on Koh Tao it can be concluded that the granite outcrops show joints with an orientation perpendicular to the surface. This confirms the theory that the upper meters of the granite rock on Koh Tao have the ability to form an aquifer. Jointed rock on Koh Tao is shown in Figure 3.

6 Hazards Related to the Freshwater Lens (อันตรายที่เกี่ยวข้องกับเลนส์น้ำจืด)

The freshwater lens on Koh Tao is currently exploited as the main tap water resource. From extraction and interaction with this water hazards can be identified, and will be discussed in this chapter.

6.1 Polluted Wastewater

As described in chapter 4.3 very little or no wastewater treatment occurs on Koh Tao. Wastewater dumped on land infiltrates in the subsurface, if this wastewater contains hazardous substances (chemicals and/or pathogens) it may pollute the freshwater lens.

Treatment by means of a septic tank is also no guarantee for pollution free disposal. When too much non-biodegradable substances are disposed in the sewer system the performance of the septic tanks will be small. In most public restrooms there is a warning not to put any papers, napkins or tampons in the toilet. The performance of septic tanks also decreases when cleaning products are used to clean the bathroom. Such products destroy the environment in the septic tank.

In septic tanks most of the suspended particles are captured but wastewater contains more than only suspended solids. The dissolved nutrients in the outflow of the tanks commonly cause problems, the danger of dissolved nutrients depends on the type and concentration. When dumped in the ocean it can affect the sensitive coral reefs by growth of bacteria and algae and when dumped on land the danger of leakage to the freshwater lens and thereby pollution of the groundwater is present. No quantitative measurements on the quality of wastewater has been conducted in this research.

6.2 Pollution from Waste

When rainwater infiltrates at the surface towards the freshwater lens it might dissolve matter from the medium it is travelling through, forming a so called leachate. Depending on the medium the infiltrating water travels through, the leachate can be either harmless or induce an environmental risk. On Koh Tao a junkyard is present on top of a hill and is exposed to the surrounding environment. This allows rainfall to travel through the waste as it infiltrates or runs off. Visual assessment of this site shows that waste with different origins is present, ranging from organic and plastics to waste oil filters. Leachate from this waste, may contain increased concentrations of harmful substances, and may have a modified pH.

6.3 Salt Water Intrusion

In general small islands are characterized by a lens shaped aquifer containing fresh water. This lens occurs because of the difference in density between fresh and saline water, effectively causing the fresh water to float on top of the saline water. The aquifer is charged with fresh water through rainfall that infiltrates into the ground. In the case of Koh Tao, water trapped in the aquifer can be in touch with saline water that finds a way through fractures in the granite bedrock. Pumping water out of the freshwater lens may cause a seawater intrusion with an increased salinity of fresh groundwater as a consequence. This mainly happens if the pumping rate is higher than the recharging rate, as shown at the right hand side of Figure 4 Figure 4 [6].

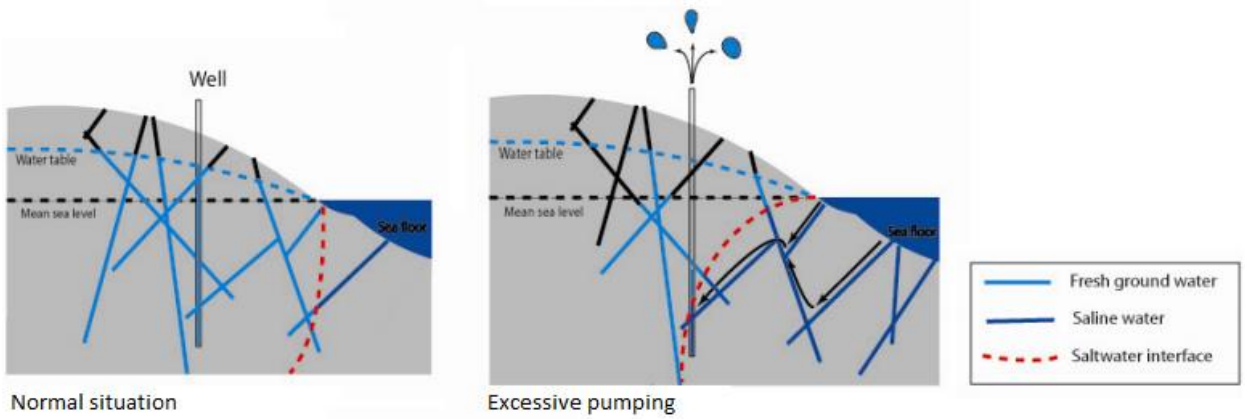

Figure 4: Pumping groundwater from a fractured granite aquifer. Right side showing salt water intrusion due to excessive pumping [6]

No exact data is available on the amount of water that is extracted from the freshwater lens on Koh Tao. Exploitation of groundwater resources is a private business and the government does not own wells. A shallow well with a maximum depth of 3 meters does not have to be declared with the local government. Deeper wells have to be declared, meaning that the government is aware of the amount of deep wells present on the island. Nevertheless, they never mapped their location and extraction rate. In a study conducted by the government it is estimated that approximately 125 shallow and 25 deep wells are present on the island [2].

This makes it hard to assess whether the extraction from the freshwater lens is larger than the recharge rate. The best way to assess whether saltwater intrusion is occurring is by asking well owners that have experience with the salinity of the fresh water they are pumping to the surface.

From an interview with the owner of 5 deep wells at the pier of Mae Haad (Figure 5, landmark 1), it showed that during the dry season a total amount of $10m^3$/day could be extracted and during the wet season a total of $15m^3$/day. The pumping sequence is such that pumping occurs for 2 hours, followed by a pause that takes at least 2 hours. This is repeated 3 times a day, meaning a total of 6 hours of pumping per day. No measuring devices are applied in order to assess whether the salinity increased. Towards the end of the dry season it happens that the water starts to taste slightly salty, when showering or washing with water from the well. This is a clear indication that the water is turning brackish as the result of the inflow of salty water. When the rain season starts in October the recharge rate is such that the increased salinity of the groundwater is reversed.

Figure 5: Locations of wells at Mae Head (1) and at Green Fresh Drinking Water (2)

The company Green Fresh Drinking Water, shown in Figure 5 as landmark 2, produces drinking water from groundwater by means of a reverse osmosis process in combination with UV treatment. From an interview with the owner of this company it became clear that an increased salinity is not a problem that has to be dealt with. The quality of the groundwater that is utilized at Green Fresh Drinking Water is tested at a lab in Bangkok twice a year. From the fact that no increased salinity of the groundwater has been measured, it can be derived that probably a Nano Filtration (NF) filter was used at the RO plant. This low pressure filter has a higher porosity causing a lower Total Dissolved Solids (TDS) rejection rate but allows for the rejection of hardness, metals (Fe) and organic matters [7].

Comparing the location of wells 1 and 2 displayed in Figure 5, it shows that well 1 is located much closer to the shore line. This means that this well is likely to become brackish first if saltwater intrusion occurs.

7 Considered Solutions (การแก้ปัญหาการพิจารณา)

In this chapter two potential solutions are analysed. Analysed methods are; Rainwater utilization by means of direct catchment and groundwater extraction and desalination by means of reverse osmosis. Both methods are already applied at Koh Tao. Supply by means of a pipeline or boat connection between the mainland and Koh Tao as a future solution were rejected in an early stage by the major of Koh Tao. Complicated legal works and expected high costs in combination with the wish to be self-sufficient were reasons not to consider these methods.

7.1 Rainwater Utilization: Direct Catchment

Figure 6 schematizes the general process to utilize rainwater. This figure gives a clear insight in the process from precipitation to fresh water availability. In the coloured boxes on the right side the intermediate stages and losses are given. This chapter only focusses on the process from precipitation to fresh water by means of direct catchment, in the next chapter all remaining steps and stages will be discussed.

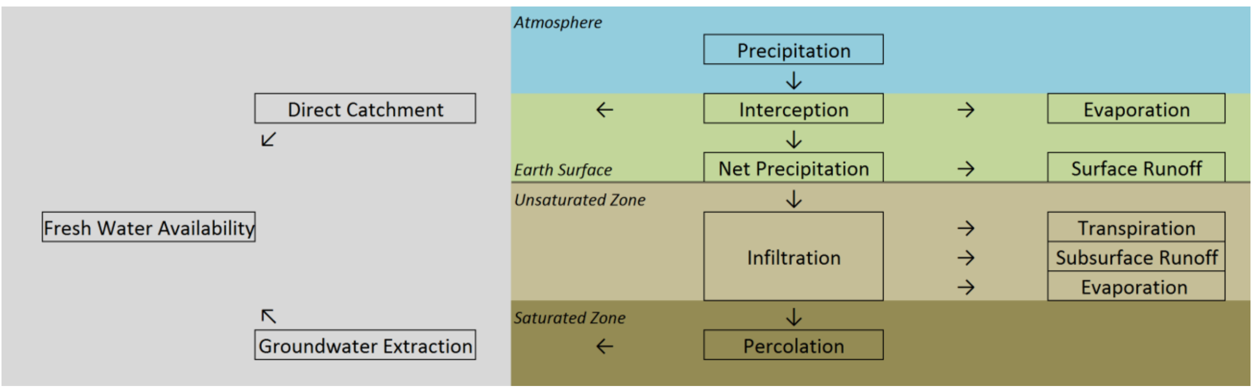

Figure 6: Flowchart to determine the precipitation availability as resource for fresh water

In Appendix I the annual precipitation on Koh Tao is analysed for the period 1968 to 2015. The data is considered normally distributed and an annual mean precipitation on Koh Tao of 1933.8mm has been calculate and the standard deviation equals 319.1mm.

7.1.1 Current share of direct catchment

Direct catchment is basically collecting water from paved surfaces and is already part of the current water system. Direct catchment is locally organised, the water is stored in the main water tank of an accommodation and used in the same way as the tap water supplied by any other method. Another way of dealing with collected rainwater is separate storage and use for a specific purpose such as irrigation.

Concerning the amount of households and tourist accommodations a rough estimate can be given of the current annual volume of precipitation utilized as tap water by direct catchment. From visual inspection on the island it is estimated that direct catchment occurs from about one third of the total roof area on Koh Tao. In 2015 there were 4335 households on the island and 606 businesses [2]. For households an average roof surface area of $30m^2$ seems appropriate. For businesses, which vary from resorts to small shops, an average roof surface area of $300m^2$ is approximated. Concerning that multiple functions can be located under one roof, the total roof area is approximated to be roughly $300{,}000m^2$. With an average precipitation of 1.9m, this means that currently an annual approximated amount of 190,000m^3 fresh water is collected. This is about 5% of the current demand.

7.1.2 Applicability of direct catchment

Water catchment is in theory possible form all paved surfaces, but roofs are the most suitable. This is because, unlike water from paved streets, there are hardly any suspended solids in this water and it is less likely to be polluted. With the growing population and tourist arrivals on Koh Tao the total roof surface is expected to grow as well. Under the assumption that construction of new facilities is tourism driven a rough assumption can be made that growth in total roof area is directly proportional to the growth in annual tourist arrivals. The growth in annual tourist arrivals over the period 2015-2020 is approximated to be 40% (Appendix H). With this assumption, the total roof area in 2020 is calculated to be roughly (300.000 x 1.4 =) 420,000m^2.

7.1.3 Potential of direct catchment

To investigate the potential of direct catchment with the expected roof surface of 2020 the lower limit of 1.4m annual rainfall has been used. This is the lower boundary of the 90% confidence interval and means that the probability of an annual precipitation larger than the lower limit of 1.4m is 95%. The lower limit is preferred over the mean since a robust solution is demanded by the client.

Potentially an amount of about (420,000 x 1.4 ≈) 600,000m^3 fresh water can be collected from the roof surface in 2020. This is about 10% of the expected future demand which is estimated to be 5,400,000 m^3/year. In other words, a significant share of the future demand can be supplied by direct catchment from roofs. The real share will be lower since evaporation loss has not been taken into account yet. More significant, it is not realistic to calculate catchment from all roofs and to assume that the storage capacity is such that all potential roof catchment can be utilized. The high intensity of rain events as indicated in Appendix I cause losses by overflowing gutters and storage tanks. As a rough estimate it can be said that every square meter of roof has the potential to produce 1m^3 tap water per year. In this estimate about 40% moisturising loss, evaporation loss and loss due to overflowing gutters or tanks is considered.

Further increase of the catchment share in the water supply system is possible by collecting water from other paved areas than roofs, or make the system more efficient by equipping more roofs with gutters and increasing storage capacity.

7.1.4 Impact and controllability of direct catchment

Creating a catchment surface that significantly contributes to the future demand would imply creating more paved surface and would have major impact on the setting and landscape of Koh Tao. Also, the annual precipitation distribution consists of a dry period and a monsoon period (see Appendix I). This in combination with the mismatch between touristic high seasons and period with most precipitation (see Appendix H) demands a high storage capacity. The collected water needs treatment to become of drinking quality. Governmental control or regulation on direct catchment is hard since the water is collected from roofs which are mainly privately owned.

7.2 Rainwater Utilization: Groundwater Extraction

Only a part of the precipitation will reach the subsurface and recharge the freshwater lens. The volume of precipitation available as groundwater recharge is reduced by multiple factors as indicated in Figure 6 and Figure 7.

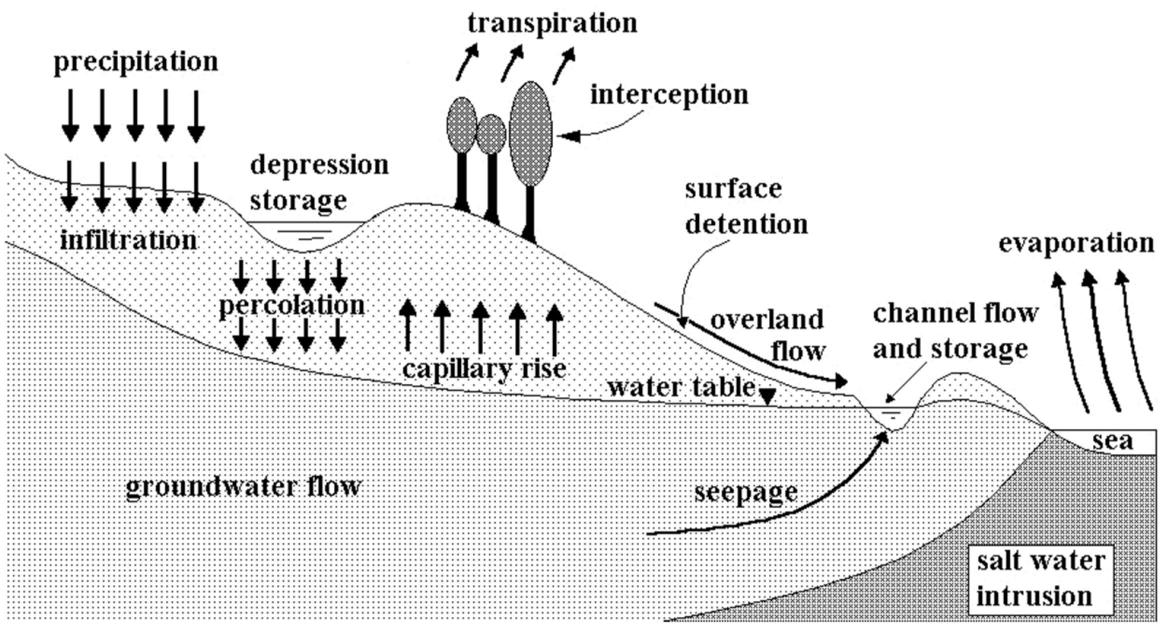

Figure 7: Descriptive representation of the hydrological cycle [8]

At first a part of the precipitation is intercepted by objects on the surface and returns directly to the atmosphere by evaporation. The remaining precipitation, the net precipitation, reaches the earth's surface. A share of this water runs off, this is called surface runoff. The amount of surface runoff depends on the capacity of the subsurface to take up water. Surface runoff is also called overland flow and generally carries soil particles and debris, causing a muddy brown colour. If the surface has a water bearing capacity a part of the net precipitation will infiltrate. Water that infiltrates reaches the soil moisture and will first enter the unsaturated zone. A share of the infiltrated water will percolate to the saturated zone and is called groundwater recharge. The share that is groundwater recharge depends on the soil moisture content. When the water infiltrates it first replenishes the soil moisture deficit in the unsaturated zone before percolating to the saturated zone. The difference between unsaturated and saturated zone is the ability to take up water, the saturated zone is not able to take up any more water. Part of the infiltrated water returns to the atmosphere in the form of transpiration and evaporation form the soil. Transpiration is evaporation of groundwater by vegetation. The combined effect of evaporation from the soil and transpiration is called evapotranspiration. For infiltrated water it is also possible to runoff. This is called fast subsurface flow and occurs in the shallow subsurface of hill slopes. The water flows through preferential pathways, for instance through root channels, horizontal cracks or along contact zones between different soil layers. This rapid sub-surface flow is often called interflow and can be substantial on hillslopes with a shallow layer of weathered rock as present on Koh Tao.

The unsaturated zone can also be supplied from the saturated zone, this process is called capillary rise and occurs when the pore suction in the unsaturated zone is high. This phenomena is not taken into account.

The potential groundwater extraction on Koh Tao can be determined in a water balance. A water balance is an equation that is based on the principle of conservation of mass. This means that within arbitrary boundaries no water can be created or disappear [9]. The boundaries of the system are the borders between land and ocean. A sustainable annual extraction rate is equal to or smaller than the annual recharge rate. If more groundwater is extracted than recharged salt water intrusion might occur. This arbitrary condition has been chosen to represent the maximum annual extraction rate. In formula the balance looks like:

$$Maximal\ extraction = Recharge \tag{1}$$

The recharge depends mainly on the annual precipitation. Other factors are irrigation and (waste) water that is dumped on the surface, this is water that is brought back in the system and is called renewed water. In formula the recharge looks like:

$$Recharge = R_P + R_r \tag{2}$$

With:	R_p	Recharge by precipitation	[m^3]
	R_r	Recharge by renewed water	[m^3]

For precipitation the concerned losses are interception, surface runoff, evapotranspiration and subsurface runoff as indicated in Figure 6 and Figure 7. The recharge by precipitation can be calculated by:

$$R_P = (P * (1 - I) * (1 - Q_{sur}) - ET) * (1 - Q_{sub}) * A \tag{3}$$

With:	P	Precipitation	[m]	ET	Evapotranspiration	[m]
	I	Interception	[-]	Q_{sub}	Subsurface runoff	[-]
	Q_{sur}	Surface runoff	[-]	A	Area	[m^2]

The interception and runoff rates as well as the evapotranspiration depend on the type of surface cover. For Koh Tao three main surface cover categories have been distinguished (see Appendix J). The corresponding characteristics are determined in Appendix K, a summary is presented in Table 1.

Since all surface cover categories have different characteristics R_p is split in $R_{p,Rain}$, $R_{P,Set}$ and $R_{P,Coco}$ for respectively rainforest, settlement and coconut plantation area.

$$R_p = R_{p,Rain} + R_{p,Set} + R_{p,Coco} \tag{4}$$

Table 1: Surface category characteristics

Category	Rainforest	Settlement	Coconut plantation
Interception [fraction]	0.15	0.10	0.10
Surface runoff [fraction]	0.15	0.70	0.30
Evapotranspiration [mm]	450	150	400
Subsurface runoff [fraction]	0.20	0.10	0.15

Groundwater is not only recharged by precipitation, tap water infiltrates back to the subsurface when used as irrigation or dumped as wastewater. Before infiltration the renewed water is reduced by runoff and evaporation from the surface. After infiltration the renewed water is reduced by subsurface runoff and evapotranspiration. Investigation on Koh Tao revealed that wastewater is often dumped on surface, either directly or by overflowing septic tanks (See chapter 4.3). Irrigation is also contributes to the recharge by renewed water. Coconut plantations often have a reservoir from which the trees are irrigated during dry spells and vegetation present in resorts is often irrigated by wastewater. Recharge by renewed water will mainly happen in settlement areas. Based on observations on the island and a discussion between the authors a rough estimate has been determined; a quarter of the water demand recharges the freshwater lens and is indicated as renewed water. In formula form this looks as follows:

$$R_r = 0.25 * Demand \tag{5}$$

The total recharge, or maximal sustainable annual groundwater extraction, has been integrated in a model. The input is the total surface area considered and the division of this area over the surface cover categories, the precipitation, the share of renewed water and the share of the total demand supplied by groundwater. The output is the total recharge.

7.2.1 Current share of utilized groundwater

Currently groundwater is expected to supply 85% of the tap water demand. Visual inspections on the island showed that almost all wells are located on the west side of the island in the three biggest watersheds; watershed 13, 19 and 23 as indicated in Figure 33 (Appendix J). These watersheds cover about 7km^2 of the island and it is believed that almost 100% of the total groundwater supply is extracted in this area. The few wells found outside the three big watersheds were mainly small and shallow wells from which it is expected that they are for private use only.

Almost all settlement areas on the island are covered by the three big watersheds. A division in surface cover of these watersheds is approximated to be; rainforest: 20%, settlement area: 50% and coconut plantation: 30%. The results are shown in Table 2.

Table 2: Surface cover of the three biggest watersheds divided in three main categories

Category	**Surface cover[%]**	**Area[m²]**
Rainforest	20	1,400,000
Settlement	50	3,500,000
Coconut plantation	30	2,100,000
Total	100	7,000,000

The recharge of the three big watersheds is calculated by:

$$Recharge = R_{p,Rain} + R_{p,Set} + R_{p,Coco} + R_r \tag{6}$$

Groundwater recharge by renewed water is related to the demand, an estimated 25% of the demand recharges the freshwater lens. Recharge by renewable water is expected to occur primary in the settlement area within the three biggest watersheds.

$$R_r = 0.25 * 3{,}800{,}000 = 950{,}000 m^3 \tag{7}$$

The current annual extracted volume is assumed to be in the order of 3,230,000m^3 (85% of the current demand of 3,800,000 m^3). Since a sustainable extraction is expected when the annual recharge exceeds the annual extraction, the minimal annual precipitation can be calculated with a maximal extraction of 3,230,000m^3.

With a total surface of 7km^2, the surface category division of Table 2 and characteristics of Table 1 (Appendix K) the minimal annual precipitation was calculated by iteration. The results are shown in Table 3, the intermediate stages are rounded to whole numbers.

Table 3: Minimal annual precipitation required to meet a sustainable current groundwater extraction

Category	**Rainforest**	**Settlement**	**Coconut plantation**
Precipitation[mm]	1426.1		
Interception[%]	15	10	10
Net precipitation[mm]	1212	1283	1283
Surface runoff[%]	15	70	30
Infiltration[mm]	1030	385	898
Evapotranspiration[mm]	450	150	400
Subsurface runoff[%]	20	10	15
Percolation[mm]	464	212	424
Surface cover[m²]	1,400,000	3,500,000	2,100,000
Recharge[m³]	650,000	740,398	889,720
Total recharge by precipitation[m³]	2,280,119		
Recharge by renewed water[m³]	950,000		
Total recharge = max extraction[m³]	3,230,000		

A minimum annual precipitation of 1426.1mm is required to meet the current demand in a sustainable manner. Since the precipitation on Koh Tao is described by a normal distribution (Appendix I) the chance of not meeting the current demand can be calculated. The obtained minimal annual precipitation is the lower boundary of the confidence interval. By determination of the corresponding z-value the probability of annual precipitation larger than this lower boundary can be calculated with the table available in Appendix L.

The z-value is determined by:

$$z = \frac{mean - precipitation}{standard\ deviation} \tag{8}$$

From the statistical analysis on provided precipitation data (Appendix I) a mean annual precipitation equal to 1933.8mm and a standard deviation equal to 319.1mm was found. With a minimal precipitation of 1426.1mm the z-value is calculated to be 1.59.

$$z = \frac{1933.8 - 1426.1}{319.1} \approx 1.59 \tag{9}$$

Figure 35 provided in Appendix L shows that the corresponding probability of sufficient recharge equals 94.4%. In other words, the probability of a non-sustainable extraction is 5.6% which is approximately once every 18 years. Although the assessment of the recharge and demand are based on assumptions there is a clear indication that there are already periods where extraction exceeds the recharge. This theory is supported by the salt water intrusion described in Chapter 6.

7.2.2 Applicability of groundwater utilization

Groundwater utilization is relative easy and cheap, the main requirement is a water bearing layer. The complex geotechnical and geohydrological conditions of Koh Tao mentioned in Chapter 5 make it unlikely that a fresh water bearing layers or joints in the granite are present over the full island surface. Thereby the presence of an aquifer is not guaranteed at all locations. A geohydrological survey is required to the map the locations and investigate volumes of the aquifers present on Koh Tao.

It is believed that the groundwater currently utilized is extracted from the three big watersheds on the west side of the island, watershed 13, 19 and 23 as indicated in Figure 33 (Appendix J). When no other locations are found with groundwater available for utilization; the extraction from these watersheds has to be optimized. Optimization would include new wells and controlled extraction.

7.2.3 Potential groundwater extraction

Potential groundwater extraction has to be determined in the prior mentioned geohydrological survey. In 2020 the annual demand is expected to be 5,400,000m^3. If the groundwater share of the total demand remains equal the extracted volume in 2020 will be in the order of 4,590,000m^3 (85% of the future demand of 5,400,000 m^3). Groundwater recharge by renewable water will, equally to the current system, primarily occur in the three biggest watersheds.

$$R_r = 0.25 * 5{,}400{,}000 = 1{,}350{,}000 m^3 \tag{10}$$

The maximal sustainable extraction is again equal to the recharge. When the boundary conditions are equal to the current situation a minimal annual precipitation of 1770.9mm is found by iteration. The results are presented in Table 4 where the intermediate stages are rounded to whole numbers.

Table 4: Minimal annual precipitation required to meet a sustainable future groundwater extraction

Category	**Rainforest**	**Settlement**	**Coconut plantation**
Precipitation[mm]	1770.9		
Interception[%]	15	10	10
Net precipitation[mm]	1505	1594	1594
Surface runoff[%]	15	70	30
Infiltration[mm]	1279	478	1116
Evapotranspiration[mm]	450	150	400
Subsurface runoff[%]	20	10	15
Percolation[mm]	664	295	608
Surface cover[m^2]	1,400,000	3,500,000	2,100,000
Recharge[m^3]	929,012	1,033,651	1,277,466
Total recharge by precipitation[m^3]	3,240,128		
Recharge by renewed water[m^3]	1,350,000		
Total recharge = max extraction[m^3]	4,590,000		

By determination of the z-value the reliability belonging to 1770.9mm annual precipitation can be calculated. The z-value is determined by:

$$z = \frac{1933.8 - 1770.9}{319.1} \approx 0.51 \tag{11}$$

From the table in Appendix L the corresponding probability of sufficient recharge can be determined and equals 69.5%. Thereby the probability of a non-sustainable extraction of 30.5%, which is approximately once every 3 years. In other words, if none of the boundary conditions changes the probability of a non-sustainable extraction is once every three years. If new fresh water bearing layers are found or the extraction from the three watersheds is optimized the probability could be reduced. The probability could also be reduced by an increased recharge due to change in surface cover characteristics or increased renewed water volume.

7.2.4 Impact and controllability of groundwater utilization

In the current situation actual groundwater extraction is related to the demand. It is likely that well owners try to extract water as long as there is demand for tap water. In other words, it is likely that well owners pump until there is no more recharge or until the recharge is of insufficient quality (salt). Governmental control on the extraction is necessary to make sure no permanent damage is done to the freshwater lens. Implementation of governmental control is difficult since the wells are privately owned and their existence is often unregistered.

When new government owned or controlled wells are installed a unit price can be set and the quality can be controlled. It is expected that installation of new wells will have significant impact on the remaining rainforest area on Koh Tao. Land acquisition for new wells may also be an issue since land ownership is poorly listed.

In theory the subsurface is an important storage medium, water can be stored in the saturated and unsaturated zone. If managed correctly groundwater has the potential of being a reliable resource. An extraction rate exceeding the recharge rate is in principle no problem as long as the exceedance is for a short period of time. The mismatch in tourist arrival peaks and precipitation peaks as determined in Appendix H indicate regular exceedance. Storage is expected necessary to deal with the mismatch and guarantee sufficient water supply during the dry season. When the subsurface provides insufficient storage capacity, on surface storage facilities may be constructed and filled during monsoon season when recharge is excessive.

Groundwater as a resource for drinking water is possible and already occurs on Koh Tao (see Chapter 4). Treatment in a central plant demands infrastructure since the wells are diffusely located on the island. Threats to groundwater as a resource of drinking water are pollution due to leakage and the prior mentioned salt water intrusion (See Chapter 6).

7.3 Reverse Osmosis Desalination

In order to produce drinking water from sea water the process of reverse osmosis (RO) desalination can be applied. With this method sea water passes through a membrane under pressure, rejecting dissolved solids (i.e. salt) from the solution producing desalinated water. For a more detailed description of the inner workings of the separation process it is recommended to consult Appendix M.

7.3.1 Current share of RO

Currently there are two privately owned RO installations on the island. It is believed that at least nine resorts are supplied by these installations. The production capacities of the installations were declared $10m^3/h$ and $40m^3/h$. Roughly 5% of the current demand is expected to be supplied by means of RO.

7.3.2 Applicability of RO

RO can be applied on sea water with a TDS content up to 45,000 ppm and produces a desalinated solution with a characteristic residual content of 500 ppm [10] (see Appendix M). The Gulf of Thailand has a typical TDS value of approximately 32,000 ppm [11]. This was verified and confirmed by on site measurements using a PCE-CM 41 pen type conductivity meter. From this measurements a TDS value of approximately 36,000 ppm was found (Appendix N), which is within the range that allows for the application of RO desalination.

7.3.3 Technical requirements

The process of desalinating water by means of RO happens in several steps. Figure 8 shows a flowchart which schematically shows the different steps required.

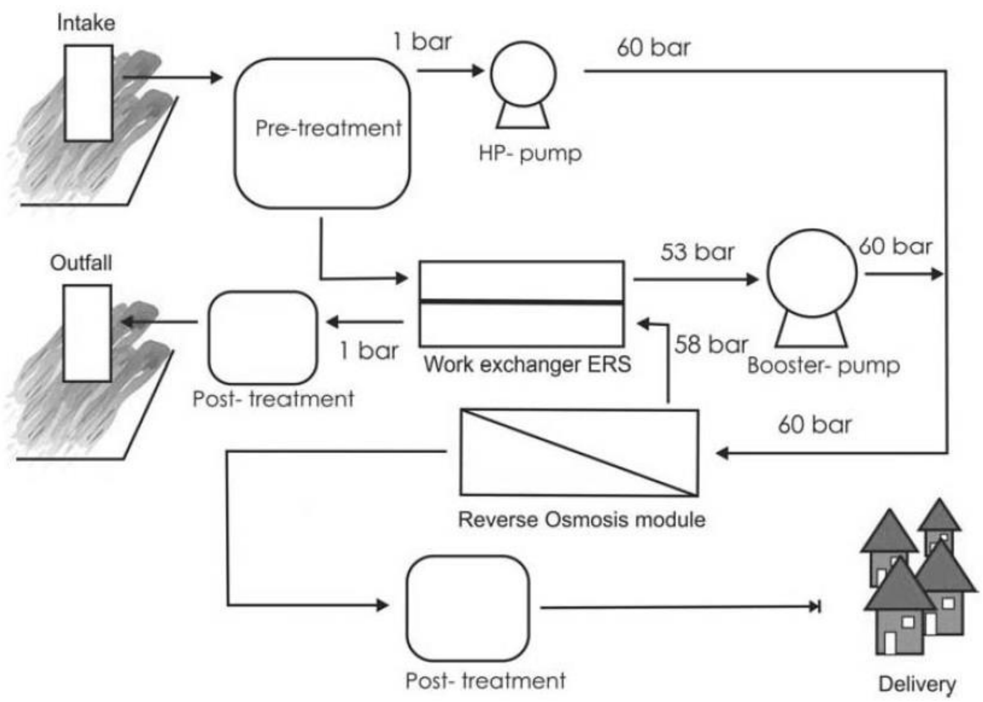

Figure 8: Schematic flow chart of reverse osmosis process [10]

The process starts by extracting water from the ocean by means of intakes that are located on the shoreline (beach wells) or at the sea bottom in the open ocean. To protect the reverse osmosis membrane from becoming blocked by solids and colloid particles that can be present in the seawater, the water is filtered before passing through the membranes as a part of the pre-treatment step. In order to reduce scaling and fooling anti scalant and foolant substances are added to the feed (see Appendix M). Hereafter the feed is pressurized by means of a high pressure pump and led to the reverse osmosis module. The required pressure for a successful reverse osmosis process depends on the salinity of the feed and targeted TDS rejection rate and recovery rate (see Appendix M). In the example of Figure 8 a pressure of 60 bar is required. In the reverse osmosis module the purified water is extracted from the feed by means of cylindrically shaped layered reverse osmosis filters, producing water with a high salt content (brine) as a waste product. A representative recovery rate for a RO process is 40%, meaning that from every liter that enters the intake 40% is turned into permeate and 60% into waste brine [10]. Despite being a waste product, the brine flow still contains energy in the form of remaining pressure. Therefore the brine is led to the work exchanger energy recovery system (ERS). Here, the remaining energy is fed to an equal volume of incoming seawater (feed). This system causes RO desalination to be much more energy efficient. The depressurized brine is treated in the post treatment module before discharge in the ocean. The part of the feed that has been pressurized by means of the ERS goes through a booster pump that makes sure that the feed has the same pressure as the part of the feed that is pressurized by means of the high pressure pump. Permeate that leaves the RO module is treated in a post-treatment module to make sure that the water meets the tap or drinking water requirements before being delivered to the customer. As stated in the boundary conditions the initial target is to supply tap water which is not of drinking quality.

Later, if the right infrastructure is present drinking water can be produced. Water with both qualities can be produced using a RO installation in combination with the appropriate post treatment step.

7.3.4 Space requirements

A typical large scale RO desalination plant has an approximate ground space requirement of 128m^2. A typical setup, as well as the individual components are displayed in Figure 9 [10].

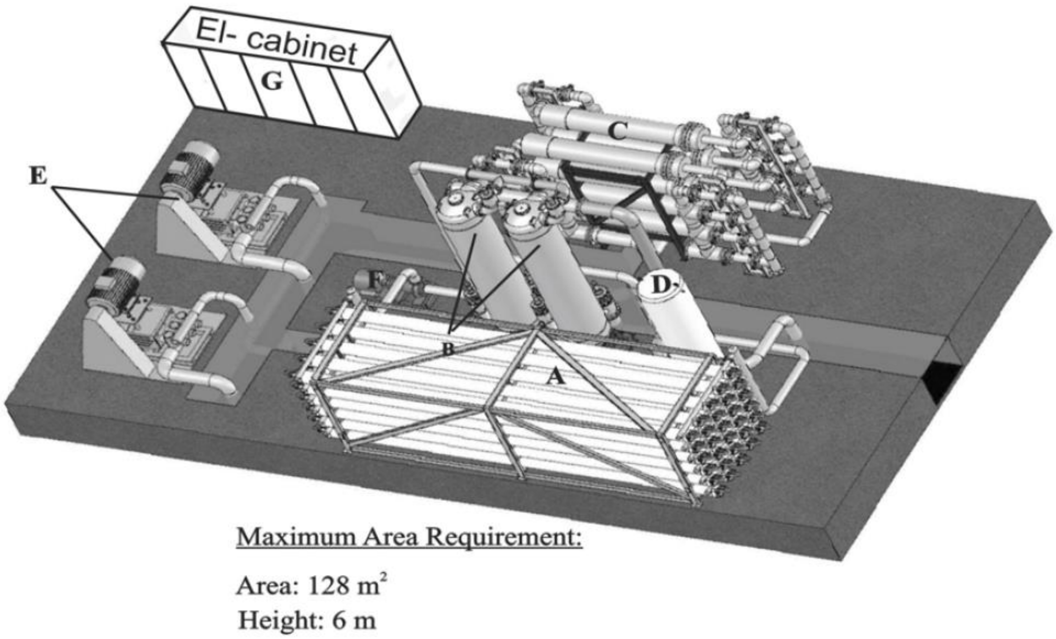

Figure 9: Typical layout of a RO plant. A: pressure vessel, membranes and manifolds; B: pressure recuperator towers; C: bag filters; D: seawater feeding tank; E: high pressure pumps; F: booster pump; G: electro-cabinet [10]

7.3.5 Maintenance

The performance of the RO membrane is heavily influenced by its condition. This is mainly the result of membrane deterioration and concentration polarization in combination with scaling and fooling (see Appendix M). Periodic inspection and maintenance are required to make sure that the targeted fresh water output of the plant is met. Till what extend maintenance and replacement of the membrane is needed depends on how successive the pre-treatment has been, as this part of the process is responsible for neutralizing and absorbing particles that can cause scaling and fooling. A very rough estimate is that a membrane has to be replaced every 5 years [7]. The easiest way to clean the membrane is by a process called backwashing. In this case the process is shut off and the water flow is reversed, as the process of osmosis occurs. This causes particles that stick on the membrane to be removed when the flow of water passes. During downtime the membranes can be cleaned physically as well using cleaning chemicals (Appendix M) [10].

7.3.6 Required capacity

It has been estimated that the peak water demand amounts approximately 18,000m^3/day (see Appendix H). In order to find the required capacity of the RO plant the availability has to be included into the calculation. This parameter, a coefficient between 0 and 1 without a unit, accounts for planned downtime like maintenance and unplanned downtime such as breakdowns. An arbitrary value of 0.9 has been assumed to represent an RO plant availability of 90%. In formula form this looks as follows:

$$Required\ Capacity\ RO\ Plant\ = \frac{Peak\ Demand}{Availability\ Coefficient} = \frac{18{,}000}{0.9} = 20{,}000\ m^3/day \qquad (12)$$

From this it follows that the required plant capacity equals 20,000m^3/day. An important note here is that this is not equal to the actual amount the plant will produce as the production can be adjusted to be lower than the peak capacity if necessary. The RO module is a series of filters, which can be expanded relatively easily in the future if the capacity turns out to be too low at some point in time in the future. This makes the capacity of a RO plant robust and relatively flexible.

The required capacity has been calculated using the peak demand, which implies that there are no other sources on Koh Tao producing water. Even though this is not true the approach using the peak demand is used anyway because a robust system is requested in the boundary conditions.

7.3.7 Environmental impact

The process of reverse osmosis interacts with the surrounding environment at the raw sea water intake and in the form of brine disposal. In order to minimize the impact of the waste brine on the environment three parameters are considered essential: The amount of brine produced and disposed, the location of the outlet, and the diffusion rate. The latter is a function of the naturally occurring sea water flow and the installation of a diffuser at the outlet [12].

For the plant on Koh Tao, an average permeate production of 15.000m^3/day and a recovery rate of 40% has been assumed. In order to produce this amount of permeate a daily amount of 22.500m^3 of brine is disposed into the sea. The seawater contains approximately 3.2% salt, which means that the brine contains 5.3% salt when assuming a rejection rate of 100%.

In order to assess the impact from brine disposal on the reefs of Koh Tao a comparative study has been conducted. The brine production of these plants compared to Koh Tao are given in Table 5.

Table 5: Brine disposal quantities Koh Tao and reference RO installations in Spain

Plant	**Brine production, m^3/day**
Koh Tao (expected)	22,500
Alicante, Spain [13]	75,000
Blanes, Spain [14]	33,000
Canary Islands, Spain [12]	17,000

From this table it shows that the RO plants in Spain have a brine disposal rate in the same order of magnitude or higher than the future plant on Koh Tao.

The brine coming from the plant is disposed into the sea and is expected to have a slightly increased temperature, increased salinity, lower concentration of dissolved oxygen, and contains anti-scalants, coagulants, biocides, cleaning chemicals and heavy metals. A reduced pH may be expected as well, but can easily be neutralized by means of a neutralizing substance such as calcium carbonate. The expected impact of these factors is explained in Appendix M. The comparative study shows that the ambient concentrations and values are likely to be found at a very short distance from the outlet [12]. Knowing that the dilution rate is likely to be high a proper location of the brine outlet, at sufficient distance from the vulnerable reefs, is likely to lead to no or only a marginal impact from brine disposal.

8 Multi Criteria Analysis (การวิเคราะห์การตัดสินใจหลายเกณฑ์)

In order to find the most favourable solution, a so called multi criteria analysis is conducted. The main advantage of a multi criteria analysis is that it allows for a quantitative comparison of the different considered solutions. As a baseline measurement the current system was assessed as a part of the multi criteria analysis. This allows for an appreciation of the considered solutions with respect to the current system.

8.1 Weighing Factors

In a multi criteria analysis marks between 1 and 5 are given for different aspects of the solution, the so called scores. The meaning of the scores is stated in Table 6. In total 12 aspects will be assessed: water price, political and legal feasibility, capital cost, operational cost, time, space, maintainability, reliability, capacity, sustainability, durability and quality.

Table 6: Scores given in a multi criteria analysis

	- -	-	+ -	+	+ +
Meaning	Terrible	Bad	Reasonable	Good	Outstanding
Score	1	2	3	4	5

The scores given to the different aspects have an uneven contribution to the appreciation of the considered solution as a whole. In order to account for this, weighing factors are introduced. The different aspects as well as the given weighing factor are explained underneath. A weighing factor is given as a number between 1, implying low importance, and 5 which gives the aspect the highest possible importance. The total score is the sum of the individual aspect scores multiplied by their corresponding weighing factors.

8.1.1 Water price

As mentioned earlier the water price on Koh Tao ranges from 150 to 600฿ per cubic meter, which equals roughly 4 to 17$. The boundary conditions state that a significant reduction of the water price is an important feature of the future water system. The client thinks that fresh water availability for everyone on the island is a duty for the local government. 60 to 80฿ has been given to be a preferred future price range. Water is a primary human need and must be available for a reasonable price so that everyone is able to buy tap water. For this reason the price of the water has the maximal weighing factor.

Weighing factor: 5

8.1.2 Political and legal feasibility

Here it is assessed how easily the proposed solution can be realised from a legal and political point of view. The main question here is whether the land that is needed for realisation is accessible or can be acquired by the local government. The feasibility of a solution also depends on the support of locals and higher authorities. If there is no or limited political support it is likely for the project to be rejected in an early stage. For this reason a relatively high weighing factor has been assigned to the political and legal feasibility aspect.

Weighing factor: 4

8.1.3 Capital costs (CAPEX)

Capital costs are the costs that need to be made in order to construct a system that will eventually produce water. An example would be the construction of a reverse osmosis plant, basin or wells. The capital investment is likely to be the largest sum of money required to initiate the establishment, and will be spent before production of water begins. The weighing factor of the capital costs is moderate because the costs of a solution do not indicate the sustainability or lifespan of a solution. The client stated that the price per unit and environmental impact of a solution are the most important factors. It is expected that the client is willing to pay for a design that is more expensive but also more sustainable, robust and reliable than its alternatives.

Weighing factor: 3

8.1.4 Operational costs (OPEX)

Operational costs equal the costs that have to be made in order to produce one unit of water. Often, economy of scale applies to this parameter. This means that the operational cost per unit goes down when larger quantities are produced per unit of time. In the case of producing tap water on Koh Tao, the operational cost can be explained as the price to produce 1 cubic meter. This cost includes: energy consumption, maintenance, labour and for instance chemicals added during the treatment process. The weighing factor is moderate for the same reason as stated under capital costs. It is believed that the client is willing to choose for a design with slightly higher operational costs if that solution is more sustainable. Also because higher operational costs can be partly or completely passed on to the consumers, as long as the price stays within the preferred range.

Weighing factor: 3

8.1.5 Time

This aspect takes into account the time required in order to establish the solution. As an example, the time needed to construct a reservoir, treatment plant, or implement a certain regulation. The weighing factor of the time aspect is relative low because the current system still works. The need for a sustainable solution is present but not urgent enough to choose the quickest solution, there is time to investigate and choose a solution that scores high on other aspects.

Weighing factor: 2

8.1.6 Space

The space aspect consist of the required physical space in order to implement the proposed solution. This is for instance the space needed in order to construct a basin. Aspects that are not visible are considered also, such as piping that will be constructed and covered afterwards. The spatial demand has a low weighing factor. If a limited amount of space is needed to implement a certain water system this can relatively easily be arranged. Only if very large surface areas are required, the space demand may be an issue and is therefore included in this MCA.

Weighing factor: 1

8.1.7 Maintainability

This aspect takes into account how easy it is to maintain the proposed solution and keep it operational. How sensitive is the construction? How often is planned downtime and breakdown maintenance required? If so, how easily can a general problem be solved? Is expert knowledge required in order to stay operational? The maintainability has a moderate weighing factor because the client asked for a robust solution. A design which is likely to be in need of a lot of maintenance is considered non-robust.

Weighing factor: 3

8.1.8 Reliability

The reliability is mainly about the probability that the proposed capacity equals the output in reality. As an example: When considering collecting rainwater, how certain is it that the amount of rainfall meets the demand requirements. Like the maintainability the robustness of a solution is an appreciated aspect by the client. Also the client thinks it is their duty to supply Koh Tao with fresh water. Therefore the weighing factor of the reliability is relatively high.

Weighing factor: 4

8.1.9 Capacity

How well is the proposed solution capable of meeting the water demand? In order to imply a buffer the capacity of the system needs to be larger than the water demand. This difference implies how robust the solution is to expected and unexpected changes and uncertainties. The fact that a relatively high weighing factor has been given follows from the boundary conditions, in which the client states that they consider it their responsibility to supply everybody on the island with water in exchange for a reasonable price. In order to do so, it is important that the required capacity is met.

Weighing factor: 4

8.1.10 Sustainability

The proposed solution will interact with the surrounding environment and imply a certain impact. The presence of sensitive coral surrounding Koh Tao gives the island its main value for tourists. A solution that negatively impacts Koh Tao's vulnerable environment should be avoided, or thorough mitigation should be proposed. The high importance of a sustainable solution was expressed by the client in the boundary values. Therefore the highest possible weighing factor has been given here.

Weighing factor: 5

8.1.11 Durability

What is the lifetime of the solution? When are the costs due to the required maintenance frequency too high? Is the breakdown interval likely to become smaller or larger as a system ages? In other words, how many years can the system be used before replacement is needed. A moderate weighing factor is given here because durability has a high importance, but on the other hand problems with the system such as breakdowns are expected to be solved easily.

Weighing factor: 3

8.1.12 Quality

What is the quality of the produced water? Does the alternative allow for a constant quality or are fluctuations expected? Sufficient tap water on Koh Tao is the first goal set by the client, with the possibility to later produce drinking water if the infrastructure developed properly. The initially targeted quality, not being drinking water quality, gives this weighing factor a moderate value.

Weighing factor: 3

8.2 Results

The possible solutions as well as the current system have been rated by means of the MCA as explained above in chapter 8.1. Rainwater utilization comprises a combination of direct catchment and groundwater extraction. The results are displayed in Table 7 underneath. RO has been rated the highest with a total score that is 83% of the potentially achievable amount of points. A more elaborate view on the outcome can be found in chapter 8.3 in which the outcome of the MCA is discussed.

Table 7: Results Multi Criteria Analysis

	Weighing Factor	*Maximum Score*	Current System	Rainwater Utilization	RO Desalination
Water price	*5*	*5*	1	5	5
Political / Legal	*4*	*5*	5	2	4
OPEX	*3*	*5*	5	4	3
CAPEX	*3*	*5*	5	4	4
Time	*2*	*5*	5	2	3
Maintainability	*3*	*5*	5	4	4
Space	*1*	*5*	5	1	4
Reliability	*4*	*5*	1	2	5
Capacity	*4*	*5*	1	3	5
Sustainability	*5*	*5*	2	4	3
Durability	*3*	*5*	1	5	4
Quality	*3*	*5*	1	3	5
Total score		*200*	109	138	166
% optimal		*100%*	55%	69%	83%

8.3 Discussion MCA

When looking at the MCA the current situation shows some strong points when it comes to political feasibility, OPEX, CAPEX, time, maintainability and space. This is mainly due to the fact that this system is already applies to the island. The low scores on all other factors clearly shows the weak points of the current system. The water price is absurdly high and the system has a low capacity and reliability. The sustainability and durability is low due to the increasing risk of a saltwater intrusion, especially with an increasing water demand in the future, and no quality control is conducted. The freshwater lens also faces the risks of pollution. The water quality varies over time and does not allow for drinking.

The method of rainwater utilization as tap water is relative easy when the required quality is not of a drinking water standard. Expansion of the current system is easy for direct catchment but more complicated for groundwater extraction. Therefore the time factor is relatively low. Utilization of precipitation by direct catchment is more efficient than groundwater utilization since less reduction of original precipitation takes place (Figure 6**Error! Reference source not found.**). However, it is less feasible due to the enormous catchment area required. Regulation of rainwater utilization is considered not possible and regulation of groundwater extraction is considered complicated since it will affect the profit of business owners. Due to large variation in monthly rainfall throughout the year the reliability is low. As a result, an unacceptable probability exists that the amount of rainfall is insufficient during a certain period.

From the MCA it shows that the application of RO on Koh Tao does have some major advantages. These are: A selling price for water within the preferred range, relatively low space requirements, a very high reliability because seawater may be considered a resource that will not deplete and the design has a robust capacity. From Chapter 7, it shows that brine has a potential environmental impact but this can be avoided if the method is implemented properly. No significant downsides have been identified in the analysis and MCA.

9 Recommendation based on MCA (ข้อเสนอแนะ)

From the MCA and subsequent discussion it follows that the application of RO desalination on Koh Tao is the preferred solution for a sustainable future water supply. RO desalination is relatively easy to implement in a short period of time. The production capacity has the ability to grow with the demand and the unit price and quality can be controlled. Further, with a small additional step, it is possible to produce drinking water.

It is expected that rainwater will still be utilized when a RO installation is implemented. Rainwater utilization is a relative cheap method to meet part of the non-potable water demand. The volume of utilized rainwater is likely to reduce since the current unit price is not competitive with the unit price of water produced by RO. The unit price of extracted groundwater is expected to reduce to a price in the range of water available from RO. This is not considered a problem. The main target, bringing down the unit price of water, is still fulfilled. Shipping in water from the mainland should not be necessary anymore after full implementation of a RO plant.

In order to support the recommendation an economic and risk analysis on a water system that is based on RO technology are conducted in Chapter 10 and 11. This will eventually lead to the conclusion, which can be found in Chapter 12

10 Costs and Economic Feasibility RO (ค่าใช้จ่ายและความเป็นไปได้ทางเศรษฐกิจ)

In order to assess the economic viability and feasibility of a RO plant a discounted cash flow analysis has been conducted. From this analysis the net present value (NPV), the value of the project expressed using the present value of money, has been estimated. The used input parameters are stated in Table 8. Because a RO plant is constructed out of a series of filter elements and pumps the capital costs, costs for membrane replacement and maintenance are extrapolated linearly from a consulted literature source [7]. An indication for the price of labour was obtained at the local government.

Table 8: Input parameters discounted cash flow analysis

RO plant parameters	*amount*	*unit*
exchange rate	36	THB/USD
Peak capacity	20.000	m3/day
Average capacity	15.000	m3/day
Yearly capacity	5.475.000	m3/year
Capital cost	1000	USD/m3-day
plant cost CAPEX	20.000.000	USD
Depreciation/payback period	25	years
Interest	6	%
transport	0,3	USD/m3
Transport	-1.642.500	USD/year
Energy cost	*6*	*THB/kWh*
Energy consumption	*3,5*	*kWh/m3*
Energy consumption cost	0,583	USD/m3
Membrane replacement	0,03	USD/m3
Chemicals	0,023	USD/m3
Maintenance/spare parts	0,031	USD/m3
Hire technician/plant worker	*15.000*	*THB/month*
Amount of workers	2	-
Labour	0,0556	USD/m3
variable OPEX	0,7229	USD/m3
Selling price water (USD)	2,00	USD/m3
Selling price water (THB)	72	THB/m3
Tax	20	%
Non Revenue Water	30	%
discount rate i	6	%

The costs mentioned in Table 8 are explained in Appendix O. In order to assess the power costs the expected consumption in combination with the local electricity price was used. In literature, the energy consumption of a large scale RO plant using an energy recovery system (ERS) is given to be in the range of 2.5 to 3.5 kWh/m^3 [7]. A future plant on Koh Tao with a capacity of 20,000m^3/day could be described as a relatively small big scale RO operation, as capacities between 20,000 and 300,000m^3/day are described as big scale operations in most literature. Because energy efficiency is likely to be a little bit lower in small operations an energy consumption of 3.5 kWh/m^3 has been assumed. The selling price of water is set at

72฿/m^3 which equals approximately 2$/m^2. This comes from the boundary conditions, in which is stated that a price in the range of 60-80 ฿ would be favorable. There are a lot of uncertainties when assessing how much the costs will be to transport water from the plant to the consumer. Also because the way of transport is likely to change during the lifetime of the system from delivery by trucks in the beginning to possibly a pipeline infrastructure in the future. In order to account for transportation an arbitrary constant cost of 0.3 dollar/m^3 is assumed by the authors. These costs per cubic meter are likely to be low when water is distributed by means of trucks, but relatively high if pipeline infrastructure is present.

The cash flow is multiplied with a discount factor F [-], which accounts for inflation and risk future transactions will be exposed to. This rate is calculated from the discount rate i [%] and includes the time t in years:

$$F = (1 + i)^{-t} \tag{13}$$

To estimate the appropriate discount rate for a project is a rather arbitrary exercise. According to consulted literature, a discount rate of 4% should be used as this is representative for projects in the hydrological sector in Europe [15]. Some input parameters come from reference studies with probably slightly different circumstances, which implies an uncertainty when using these parameters in this financial model. In order to account for this uncertainty, a slightly increased discount rate i of 6% is used. The capital investment of 20,000,000$ (720,000,000 ฿) is expected to be available in this calculation. The money can for instance come from the central government in the form of tax revenues. This assumption has a strong influence on the discounted cash flow analysis in the sense that no interest has to be paid on a loan that should be taken otherwise. Development of the cash flow per year and corresponding NPV can be found in Appendix P. From this analysis Figure 10 was obtained.

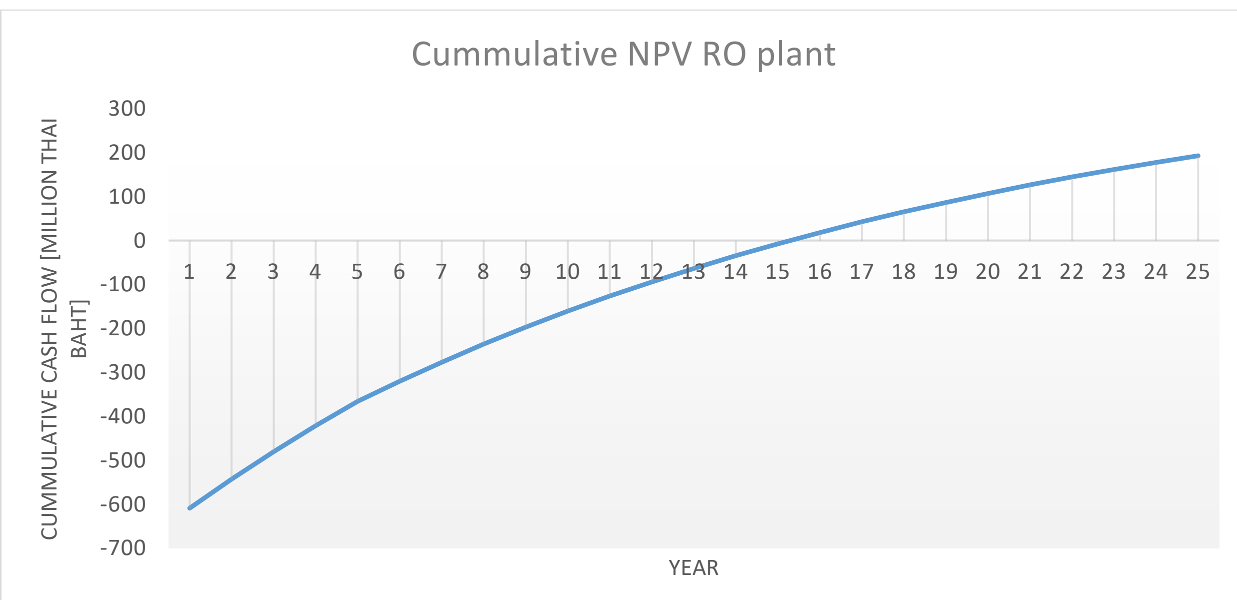

Figure 10: Development cumulative net present value for a RO plant op Koh Tao

This image shows that the NPV, with the given input parameters, amounts approximately 192 million ฿ which equals approximately 5,400,000$. The so called internal rate or return (IRR) can be derived from this analysis as well. This is expressed as the discount rate that results in a NPV of 0. The IRR is a measure that expresses how much uncertainty and risk a project can bear. Here, an IRR of 9.34% has been found (Appendix P).

The NPV and IRR strongly depend on three parameters, being the capital investment, price of energy and selling price of water. The sensitivity is expressed as:

$$Sensitivity = \frac{\Delta\ NPV\ (\%)}{\Delta parameter\ x\ (\%)}\ [-] \tag{14}$$

In this formula x represents the parameter for which the sensitivity will be obtained. A sensitivity of -6.6 is found for the electricity price, meaning that if the energy price increases by 1% the NPV decreases by 6.6%. This means that the NPV is sensitive to fluctuations in the price of energy. The sensitivity for the CAPEX has been found at -3.27, in the same range as the sensitivity for the electricity price. On the other hand, an even higher sensitivity is found for the selling price of water. Here, an increase of 1% in the water price will result in a NPV increase of 15.8%. From this it can be concluded that an increased price for energy or excess CAPEX costs can have a significant impact on the economic feasibility of a RO installation. On the other hand, this can easily be passed on to the customer with a slight price increase. Chapter 4.3.3, *Relation tap water demand and price*, explains that the water demand is unlikely to change with a changing price within certain margins.

The cost image obtained is the result of an analysis in which the write off time equals the lifetime of the plant. This is an assumption that follows the consulted literature [7]. In reality, this cash flow analysis should be subjected to an analysis in which the tax shield is optimized. Such an optimization process may result in a slightly increased NPV as the write off may be deducted from the taxable income.

When considering the lifetime of the plant and expressing the CAPEX in terms of OPEX, using the stated input parameters in Table 8. The price to produce water is of water is 0.87$/m^3 (see Table 9). The lifetime of the plant is estimated to be 25 years, producing 5,475,000 m^3/year according to the model. This equals a contribution of 0.15$ (5.4 ฿) to the cost per cubic meter coming from the capital investment.

Table 9: Price to produce 1 cubic meter of water by means of RO on Koh Tao

	Price to produce: $/m3	Price to produce: ฿/m3	% of price/m3 (rounded)
Capital investment	0.15	5.4	16%
Electric power	0.58	22.88	69%
Membrane replacement	0.03	1.08	3%
Chemicals	0.023	0.828	2%
Maintenance	0.031	1.116	3%
Labor	0.056	2.016	6%
Total cost	**0.87**	**33.32**	**100%**

11 Risk Analysis RO installation (การวิเคราะห์ความเสี่ยง)

In order to identify and properly mitigate the risks a RO plant on Koh Tao implies a risk analysis has been conducted. In this analysis the probability that a certain event occurs and the corresponding severity are the most important parameters, as the risk is represented by the product of the two. In order to assess the probability that a certain event occurs the following scale, ranging from A to E, is used [15]:

A. Very Unlikely (0-10%)

B. Unlikely (10-33%)

C. About as likely as not (33-66%)

D. Likely (66-90%)

E. Very likely (90-100%)

The severity is based on the cost consequence or loss of social welfare if a certain event occurs. The scale applied here ranges from I to V with an increasing severity. A description of the different classes can be seen in Table 10 [15].

Table 10: Severity rating and explanation

Rating	**Meaning**
I	*No effect:* No relevant effect on welfare or cause of excess costs. Also if remedial actions are not taken
II	*Minor effect:* Minor loss of welfare, minimal effects on the project in the long. Remedial or corrective actions are needed
III	*Moderate:* Social welfare loss, project suffers financial damage in the long and medium-long run. Remedial actions are required to correct the problem.
IV	*Critical:* High social welfare loss and excess costs. Loss of primary function of the project. Remedial actions are not enough to avoid severe damage.
V	*Catastrophic:* Project failure with total loss of the function of the project. Large cost and or social consequences.

Estimating the probability and severity is a rather arbitrary exercise. Nevertheless an effort has been made to come up with a proper appreciation of the different risks by means of a comprehensive discussion between the authors. If the probability and severity have been estimated the corresponding risk is determined using the scheme displayed in Table 11 [15].

Table 11: Estimated risk as it follows from the severity/probability analysis

Severity/Probability	I	II	III	IV	V
A	Low	Low	Low	Low	Moderate
B	Low	Low	Moderate	Moderate	High
C	Low	Moderate	Moderate	High	High
D	Low	Moderate	High	Very High	Very High
E	Moderate	High	Very High	Very High	Very High

From the characteristics of an identified risk the proper way to treat this risk has to be found. Here the options are: Acceptance of the risk, prevention of the risk, mitigation, risk avoidance or a combination of these methods. As a guideline the scheme displayed in Table 12 has been used [15].

Table 12: Preferred risk treatment method

Severity/ Probability	I	II	III	IV	V
A	Accept, Prevention or Mitigation		Mitigation		
B					
C					
D	Prevention		Avoid or Prevention and Mitigation		
E					

In this table, different risk treatment methods are proposed based on the different levels of probability and severity. These methods are explained underneath:

Avoiding Risks
A risk with a high probability and a high consequence score is best to be avoided.

Preventing Risk
Risks with a high probability but a low consequence score are risks that can be accepted if the probability is reduced. The probability can be reduced by conducting more investigation and increasing safety in the design.

Mitigating Risk
Risks with a low probability but with a very high consequence score are best to allocate or manage properly. An insurance company may take this risks for the right prize for instance. Risks in a different category can also be allocated to a third party but this is less likely.

Accepting Risk
Risks with a relative low probability and a low consequence score are acceptable risks. When the undesired event appears the repair works and corresponding costs will be limited. Monitoring and fall back scenarios can reduce the consequences of a risk.

After assessing the risk and finding the preferred treatment methodology a residual risk remains. If this risk is still moderate, high or very high it is wise to avoid the risk or adjust the proposed risk treatment method. The risk analysis for constructing a RO plant on Koh Tao is shown in Table 13.

Table 13: Risk analysis RO plant Koh Tao [15]

Risk description	Probability	Severity	Risk level	Risk prevention/ mitigation	Residual risk
Administrative Risks					
Problems with land purchase and acquisition	A	I	Low	Accept risk	Low
Unclear communication between stakeholders	D	II	Moderate	Prevention: communication format, communication manager (project manager)	Low
Delays due to administrative procedures	B	II	Low	Mitigate: if necessary, consult legal support	Low
No approval from higher authority	A	V	Moderate	Mitigate: Early involvement and conduct extensive feasibility study	Low
Risks During Construction Phase					
Investment cost higher than planned	C	III	Moderate	Mitigate: Clear and transparent cost management, risk included in budget.	Low
Delays due to contractors (incapable, bankruptcy, etc.)	C	II	Moderate	Mitigation: Time management and clear communication with contractors	Low
Environmental and Social Risks					
Public opposition and loss of reputation	B	IV	Moderate	Mitigate: Clear project communication, show good intentions and transparency.	Low
Impacts on environment (coral)	B	V	High	Mitigate: Proper location of brine outlet, suitable post treatment	Low
Operational Risks					
Operational costs higher than expected (mainly electricity)	C	III	Moderate	Mitigate: private energy generation unit for RO plant	Low
Water demand not as forecasted	B	IV	Moderate	Mitigate: Flexibility of RO operation. Lower production, slightly higher price.	Low
Excess Unscheduled Downtime	B	III	Moderate	Mitigate: unexpected downtime included in capacity calculation	Low
Excess Non-Revenue Water (NRW)	C	IV	High	Mitigation: Monitoring of losses, frequent inspection of pipe system	Low

11.1 Critical Risks and Mitigation

The highest risks that were found in the risk analysis are discussed individually and in detail in this chapter.

Impact on environment: From the analysis on the environmental impact of the brine that is disposed into the sea it can be concluded that the impact is likely to be small because the volume of brine is relatively small. The study has compared different plants with a higher brine disposal rate and shows positive results on the state of the coral located in the vicinity of the outlet. Nevertheless, in order to minimize the environmental impact of brine an optimal location of the brine outlet and the use of a proper diffuser is crucial. A high diffusion rate is obtained by placing the outlet in a position where the flow rate is high and relatively little coral is present.

Operational costs higher than expected: The critical operational cost parameter is the price of energy, as this has shown to represent 69% of the total costs. Besides that, the energy supply on Koh Tao is known to be an issue as the capacity of the government owned power plant is such that a non-optimal reliability is obtained. Therefore, a private power supply, which only supplies the RO plant is recommended. This can be done by means of generator units using fossil fuel as a source or a sustainable alternative such as solar or wind energy.

Investment costs higher than expected: Unexpected costs may increase the eventual capital investment needed to construct the RO plant. A conservative discount rate of 6% has been used in the discounted cash flow in order to account for unexpected events that imply an additional risk for the project. As stated earlier, a slightly increased water selling price may be a very strong tool to compensate for unexpected costs.

Public opposition: Public opposition may put the project in a bad light, causing the so called social license to operate to be at risk. Therefore frequent, transparent and fair communication towards the community is essential. Here it is important to emphasize that mitigation measures have been taken to minimize the environmental impact and that the water problem, where the community itself suffers from, on the island will be solved if they collaborate.

Water demand lower than expected: A RO plant has a very robust output in the sense that the output can be lowered easily by running the installation less frequently. If it is not running very little costs are made either (electricity, chemicals, etc.). In order to mitigate the loss of income a method may be to increase the water price by a small amount. This is a very effective method as the sensitivity analysis showed that the economic feasibility of a RO plant heavily depends on the selling price of water.

Excess Non Revenue Water: Non revenue water is the result of leakages from the pipe infrastructure and people stealing water from the system. The leakage can be measured at night, when the demand is low. Frequent inspection and monitoring of the system and pipe infrastructure is recommended. Stealing water should be considered a crime and if people are caught doing so they should be punished. A certain low arbitrary NRW percentage should be allowed though, as minor leakages may always be expected.

From this analysis it shows that all identified risks the construction and operation of a RO plant on Koh Tao can be reduced to an acceptable level if the right measures are taken.

12 Conclusion (ข้อสรุป)

The recommendation that followed from the multi criteria analysis stated that RO desalination is the preferred solution. From the economic feasibility study in Chapter 10, it follows that there are strong indications that the construction and exploitation of a RO plant on Koh Tao is economically feasible. The identified risks, as stated in Chapter 11, can be dealt with properly according to the risk analysis. The economic feasibility study and risk analysis confirmed the preliminary recommendation based on the MCA; Tap water supply by means of RO is the preferred solution for a sustainable water system on Koh Tao.

13 Recommendations for future research (คำแนะนำ)

This feasibility study concludes that RO is the most promising solution when establishing a sustainable water system on Koh Tao. For a successful implementation of this method further more detailed research is recommended. First of all, monitoring of the current demand is advised in order to optimize the capacity of RO desalination.

In order to successfully introduce supply of desalinated seawater into the current system a gradual implementation is required. The current infrastructure does not allow for a sudden change in fresh water source. Together with the construction of a RO plant, the infrastructure that enables convenient distribution needs to be developed as well. Implementation of new infrastructure is likely to lag behind on the RO plant in the beginning. Therefore intermediate modes of supply have to be available during construction of infrastructure functions such as pipelines, pumps and connections. A possible solution here is to construct two central water distribution points, one at Mae Haad and one at Sairee (Figure 1), from where desalinated seawater can be bought. This requires buyers to bring the water to their own residence, in a sense infrastructure is the missing part of the system. Revenues from sales of desalinated water can again be invested in further developing the infrastructure. Water with drinking quality can be produced in theory, but a proper infrastructure system is needed so that the water still has drinking water quality when delivered to the user. This can be done by means of a step wise approach, in which the system moves from being a tap water system to being both a tap and drinking water system. A detailed design of such a system would be a subject for a more detailed study or implementation plan.

There are strong indications that implementations of RO is feasible on Koh Tao without causing harm to the coral reefs and sea life. Finding the optimal location of the brine outlet is a matter of optimisation. Such an analysis is recommended when planning on constructing a RO plant. The critical parameters here are finding a position with sufficient flow in combination with the absence of a reef, which is likely to be found further away from the island. Therefore the costs are also an important parameter to consider, as a longer discharge pipe is more expensive.

RO desalination requires energy which is currently produced by generators. The government of Koh Tao owns a windmill that could contribute in the energy supply. The possibility to use renewable energy sources such as solar energy should be considered as well. Another structure already present on Koh Tao that could be included in the new system is a reservoir. Uphill of Tanot bay (Figure 1; Ao Tanot) a reservoir is constructed at a rather strange location. The reservoir is located at more than 200m LAT altitude. The reservoir is not owned by the local government, construction of the reservoir was initiated by a higher authority. The elevated location allows for natural flow which could replace energy added by pumps when distributing water from the reservoir to households and resorts.

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Appendix A: Geography (ภูมิศาสตร์)

Koh Tao is an island that belongs to the Surat Thani province, located in the south east of Thailand (Figure 11). Koh Tao is the most northern and, with a surface area of about 21km^2, smallest island of the three main touristic islands in the gulf of Thailand. The neighbouring island, Koh Pha Ngan is about 46km to the south east. The shortest distance to the main land is approximately 70km. Koh Tao is Thai for Turtle Island. Some say it is named like this because the shape of the island looks like a turtle when seen from Koh Pha Ngan, others state that it is due to the turtles that used to breed on the beaches of Koh Tao. The closest city on the mainland is Chumpon, from where several boats depart daily. It is also possible to reach Koh Tao by boat from Surat Thani, located about 115km south of Koh Tao. Slow boats from both cities supply the island with the required goods [2].

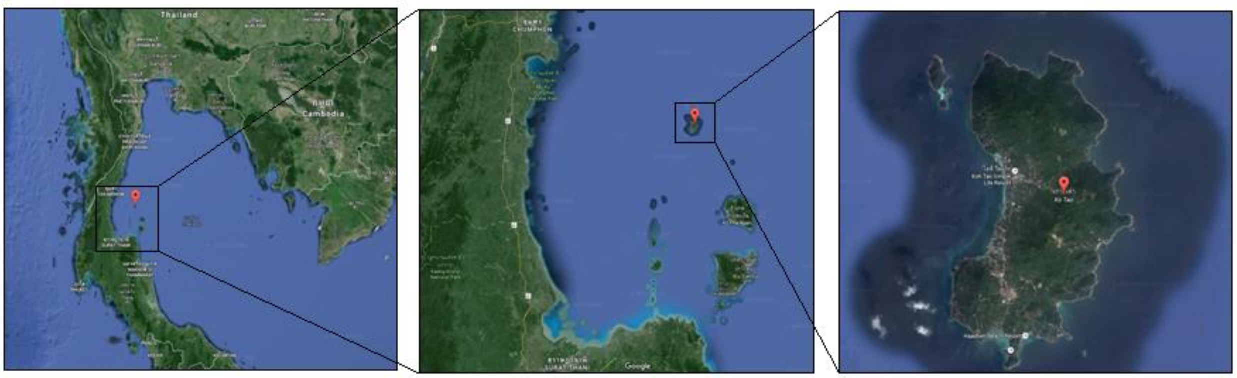


Figure 11: Location of Koh Tao, Left: South Thailand, middle: Surat Thani Province, right: Koh Tao, https//maps.google.com

Koh Tao is a mountainous island, about 70% of the surface area is mountain and 30% is flat (gently sloped) area. The flat area is on the west side of the island where most of the beaches and residential areas are located. The east coast consists mainly of steep cliffs. The highest point of the island is 374m above sea level. A height map of the island as well as a landscape impression can be seen in Figure 12 and Figure 13 respectively. Koh Tao consists of 11 bays between 10 cape peninsulas. In total the island has 28.6km of coastline of which 8km is surrounded by coral. The island is approximately 7.6km long and 3.4km wide.

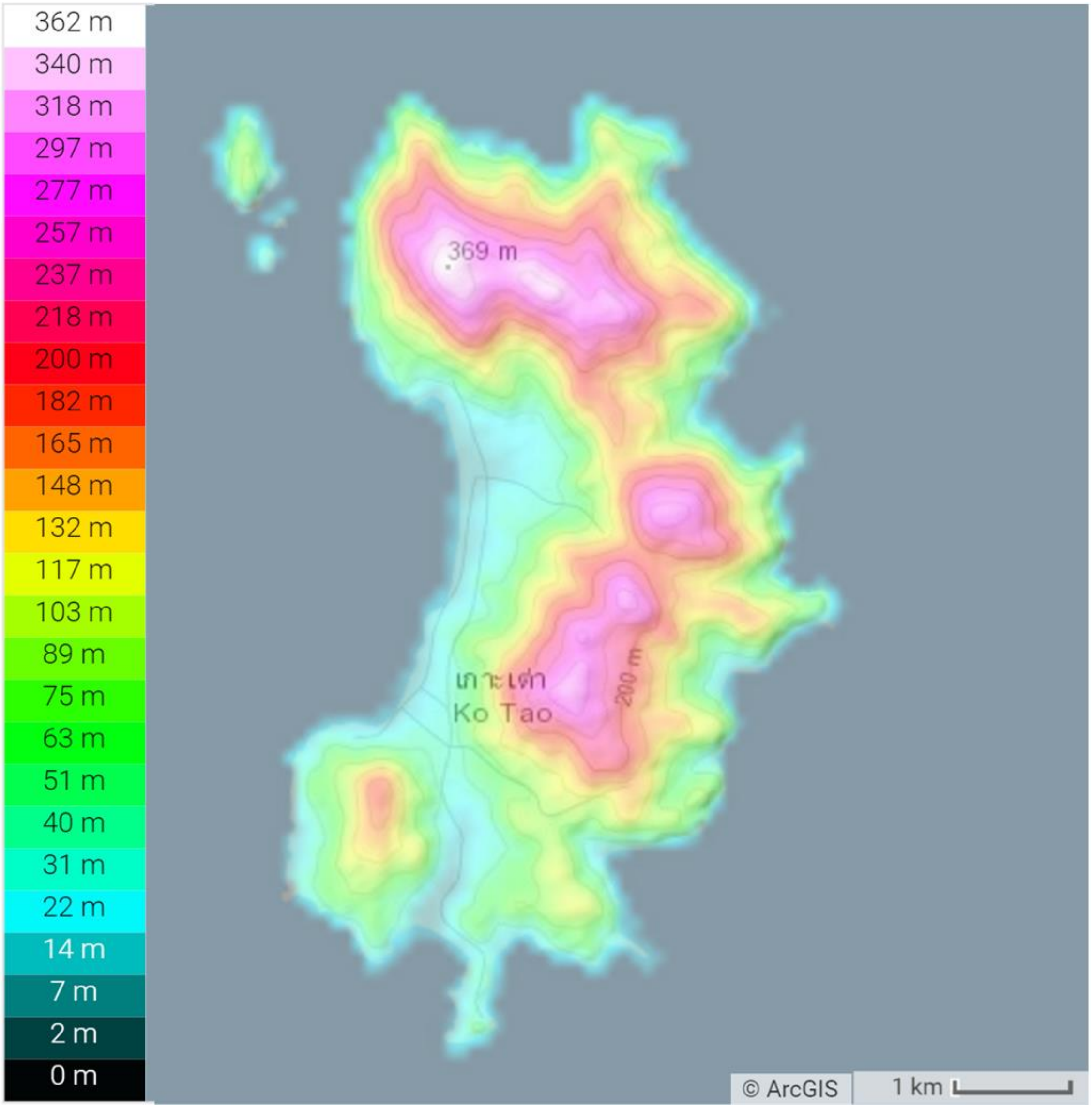


Figure 12: Height map of Koh Tao, http://nl-nl.topographic-map.com/places/Thailand-8114313/, ArcGIS

Figure 13: Landscape impression Koh Tao taken from the very southern point of the island, https//maps.google.com

Appendix B: History (ประวัติศาสตร์)

From old maps and descriptions it shows that Koh Tao was known early on by European cartographers and mariners [16] [17] [18] [19]. A map made by John Thornton in the 17th century shows three islands aligned from north to south located at the east coast of Malay Peninsula. The most northern and smallest island is marked as Pulo Bardia [18], which was the European name for Koh Tao until the 1900s. In 1852 Frederick Arthur Neale published the book 'Narrative of a residence at the capital of the Kingdom of Siam' in which he described Pulo Bardia. The author states that there was a well-developed village on the west side of the island. The farm yards were well stocked with animals such as pigs, poultry and goats. There was plenty of food available and the island harboured a beautiful collection of flowers, birds, butterflies and moths [19]. Compared to modern standards the islands were poorly placed on the maps and some historians doubt if the island described by Frederick Arthur Neale actually was Koh Tao. The information provided by the government of Koh Tao does not mention any inhabitants before 1933 [2].

On June 18, 1899 His majesty the King Chulalongkorn (Rama V 1868-1910) visited Koh Tao and left his monogram on a big boulder which is still visible today [2]. From 1933, Koh Tao was used as a political prison. After a royal pardon in 1947 the former prisoners were brought to the main land and Koh Tao was left abandoned. Although the island was still under royal patronage people from the neighbouring island Koh Pha Ngan headed to Koh Tao not long after the prisoners left and started living there. This is the first generation of the present day community [2].

Recent History

In the 80s the first overseas tourists visited Koh Tao. From that moment onwards the island started developing fast. Prior to this period only a few families housed on the island and lived from fishing or coconut plantations. Better and faster boat connections were put in service resulting in more and more tourists. From the 90s onwards Koh Tao is a well-known scuba diving location. The development continued, paved roads were constructed and wooden huts were replaced by concrete buildings. After the December 2004 tsunami destroying parts of the south western coast of Thailand even more tourists started visiting Koh Tao as it stayed unharmed. Nowadays there are more than 190 tourist accommodations and more than 40 diving schools on the island [2].

Appendix C: Demography (ประชากรศาสตร์)

The people that currently live on Koh Tao have a wide range of backgrounds. Since the 90s Koh Tao is a well-known diving spot and attracts people from all over the world. Over the years, some visitors have decided to stay permanently. The registered population of Koh Tao was 2207 in September 2015 from which 1231 man and 976 woman. Very few people were actually born on the island and most permanent residents are not registered. The local government of Koh Tao estimated the total amount of permanent residents to be approximately 10,000. A population growth of 7.07% is expected over 2016 and the total registered population is expected to be 4300 by 2023 [2]. The core business of Koh Tao is tourism. In 2015 approximately 500,000 tourists visited the island. Tourism attracts guest labor, as in September 2014 there were 4030 registered foreigner workers: 4017 of them were from Myanmar (Burma), 6 from Laos and 7 from Cambodia. The majority of immigrant workers is Burmese due to their good communications skills in English as Burma used to be a British colony [20].

There are three main residential areas located in the west of Koh Tao: Sairee (Ban Sai Ri), Ban Mae Had and Chalok Ban Kao. The big amount of unregistered people living on Koh Tao is evident in the 4335 registered households.

Appendix D: Economy (เศรษฐกิจ)

Coconut plantation and fishing used to be the traditional sources of income on Koh Tao. When tourism turned out to be more profitable a shift took place and tourism became the main source of income. The main reason for tourists to visit Koh Tao are the numerous dive spots surrounding the island. This makes the marine flora and fauna surrounding the island the driving force behind the islands touristic sector. The amount of different touristic businesses on Koh Tao are shown in Table 14 [2].

Table 14: Touristic businesses on Koh Tao (2015)

Type of business	**Amount**
Accommodation: hotel /guest house/apartment rentals.	191
Diving academy	43
financial institution	5
Business travel / Internet	22
Mini Mart 24 hours.	7
Ice cream stand	3
Law Office	1
Restaurants / Pubs / Bars	138
Drugstore (pharmacy)	6
Shops / Services	74
Thai traditional massage	20
Motorised vehicle rental and repair shops	80
Boat operators	10
Fishing trip operators	6

Thai people on Koh Tao have a relatively good income compared to the rest of Thailand. The median income amounts 1 million Thai Baht (28,000$) per household per year. Here it important to note that this number is based on the income of registered households. In September 2015 only 2207 people were registered on Koh Tao, whereas the total amount of permanent residents has been estimated to be approximately 10,000.

Appendix E: Ecology (นิเวศวิทยา)

Before Koh Tao was inhabited the island was covered with tropical rainforests, rock outcrops and sandy bays near the coast. After the royal pardon in 1947 people from the neighbouring Koh Pha Ngan moved to Koh Tao (see Appendix B: History). They started cutting the rainforest to make space for coconut plantations. About 25 years ago Koh Tao started to attract tourism which had recognizable impact on the eco-system.

According to the local government of Koh Tao 64.5% of the surface area of the island is classified as forest, 32.8% as touristic area and 2.7% as utilities in 2015 [21]. A GIS-based assessment in 2005 on the threats of the natural environment on Koh Tao classified 50.6% of the surface area as forest, 36.6% coconut plantations, 6.0% residential area and 6.8% rock outcrops. This assessment showed that almost half of the rainforests has been lost in recent decades. In the northeast of the island most forest got preserved in comparison with the south and western part of the island. In 1975 a surface area of 62ha of the approximated total 1,900ha was altered by humans. In the year 2005 this area had increased to 814ha [21].

From the period 2001 to 2005, the rainforest area on Koh Tao decreased from 1,266 to 967ha. In other words, a reduction of 23%. If this trend continues there will be no forest left by 2075. Approximately 15ha of rainforest is transformed into roads and tourist accommodations each year [21].

Due to Koh Tao's relatively isolated location the biodiversity has been quite constant over the years. In total 63 different species of wild animals have been found on the island. 30 of the 63 animals are bird species, 20 of 63 are reptiles, 7 types of mammals and 3 types of amphibians were found. Typical animals that can be found on the island are birds, squirrels, lizards, geckos, grasshoppers, gadflies and mosquitoes.

Koh Tao hosts 31 species of trees. The forest areas on the island can be divided in evergreen forest with small trees on the top of the mountains, mixed forest on the lower parts and (abandoned) coconut plantations. Areas with swamp-like conditions can be found at the lower altitudes.

Ecology Surrounding Koh Tao

Koh Tao is surrounded by 8km of coral reefs [2]. Coral reefs are diverse underwater ecosystems constructed of micro-organisms and held together by calcium carbonate. The formation of coral is a slow and fragile process. The right combination of water characteristics, light and biodiversity allows coral to grow. Less than 1% of the ocean floor worldwide is occupied by coral reefs but it is believed that these reefs provide a home for as much as 25% of all marine species. Scientists believe more than 1 million species live in coral reefs, with lots of them still unknown. Certain is that the reefs house more than four thousand species of fish alone. Only tropical rainforests can compete with the concentration of biodiversity found in coral reefs, and rainforests occupy twenty times more surface on earth than coral reefs do [22]. The reef forms a natural barrier for Koh Tao and protects the island from tidal waves. The waves erode the coral by approximately one tonne per hectare reef per year. The eroded coral forms the beaches of Koh Tao [2]. Like the rainforest on Koh Tao the reefs surrounding the island also reduced in size over the last decades. A relationship can be seen between the amount of human interaction (divers) and rate of deterioration of the coral. The western part of the island is most altered by humans, this is also the location of the most stressed reefs [21].

The threats to the coral reef surrounding Koh Tao can be divided in human threats and natural threats. The main threats are change in water characteristics like temperature, cloudiness, nutrient level and acidity.

Diving and snorkelling

An approximated 90% of the 500,000 tourists visiting Koh Tao in 2015 went snorkelling and 60% also went scuba diving. More than 40 dive schools are located on the island and day-trippers coming from the neighbouring islands also visit the reefs of Koh Tao. This enormous reef recreation industry causes stress to the reefs, as divers and snorkelers cause physical damage. In the case of snorkelers damage is caused in the shallow waters by walking on the coral. Coral at greater depth is damaged by (inexperienced) divers who struggle with their buoyancy and touch the coral. The majority of human damage is caused by the snorkelers [21].

Boat traffic

Most divers are brought to the reef by boat, damage by boats is mainly physical damage by collision between a boat and the reef or by falling anchors. Also emissions from the boats negatively affect the coral.

Wastewater disposal

Wastewater is dumped in the ocean without treatment. Nutrients and suspended solids in the wastewater affect the reef. With the increasing amount of tourists the amount of wastewater increases as well. Human induced sediment runoff is combined with the wastewater flow and affects the cloudiness of the water. Settlements and roads function as highways for runoff water and sediment during monsoon season [21].

Erosion-related sedimentation

Deforestation causes erosion by wind and water, the erosion material affects the cloudiness and sediments on the reefs which causes the coral to die.

Regional disturbance

Regional disturbances are pollution by oil drilling and overfishing in the Gulf of Thailand. The loss of fish and complete species harms the reefs, coral reefs have a complex relation with the fish that live within them, and they depend on each other. The reefs provide a habitat and security for the fish while herbivorous fish eat the abundant algae found in reef environments which allow the corals to develop. The fishing method also determines the rate of influence [22].

Natural threads

The main natural threat is climate change, increased occurrence of droughts, higher intensity storms and typhoons, sea level rise and coastal erosion have a negative effect on the living conditions of the coral [21]. Due to change in climate the water surface temperature rises, the increased temperature causes coral bleaching. For example, the ocean surface temperature measured over the year 2010 was one of the warmest ever recorded in South East Asia. This caused bleaching of 98% of the reef corals around Koh Tao [21]. Coral bleaching is the phenomena of coral polyps expelling the zooxanthellae (unicellular algae) that live within them when the water temperature is above average. Without zooxanthellae the reefs lose their characteristic colour, all that remains to the visible eye is the white calcium exoskeleton of the coral polyps. The coral polyps need the symbiotic zooxanthellae to survive and will die if it does not take up another alga within a short period of time [22].

Recent events with natural cause that affected the coral of Koh Tao are Hurricane Gay (1989) and Thermal Bleaching events (1998 and 2010). Recovery from natural threats is currently not possible due to the high intensity of human pollution and damage [21].

Relation Ecology and Economy

There is a strong relation between the ecological and economical value of Koh Tao. When asked in a survey, most tourists listed 'natural beauty' as their top reason for coming to Koh Tao [20]. If nothing is done Koh Tao will loose its coral reefs due to the threats described and thus its main economic value. The threats to the reef are, in turn, threats to the local tourism industry and related economies (i.e. hotels, tour groups, restaurants, bars, etc). To sustain and develop the social, economic and environmental welfare it is necessary to also sustain the coral reefs [20].

Measures on Environmental Impact of Tourism

In 2005 local Thai community leaders, businesses, and the large international community of Koh Tao dive operators started the Save Koh Tao Group with a clear mission of addressing local environmental and social problems through the activities of the three branches of the group: Education, Land Conservation, and Marine Conservation [20].

There are also several local conservation initiatives by diving schools such as educational dive courses and coral farms, their goal is to monitor protect and restore the reefs.

Appendix F: Meteorology and Climate (อุตุนิยมวิทยาเงื่อนไขและสภาพภูมิอากาศ)

Koh Tao has a so called tropical monsoon climate [23]. The weather conditions of the island can be divided in three seasons: rainy or southwest monsoon season, winter or northeast monsoon season and summer or pre-monsoon season. The southwest monsoon comes from the Indian Ocean and brings warm and moist air to Thailand. As a consequence excessive rainfall occurs. Typhoons coming from the intertropical convergence zone may reach Koh Tao as well during this period to cause an increased amount of rain. The northeast monsoon brings cold and dry air from China. In the southern part of Thailand this causes mild weather and rain along the east coast, where Koh Tao is located. The periods in which the different seasons occur are:

- Rainy or southwest monsoon season: Starts in May and lasts until the beginning of December with November usually being the month with most rainfall and highest humidity. This is also the longest season, as it lasts seven months.
- Winter or northeast monsoon season: From December until February and is the coldest period of the year. This is the shortest season, lasting three months.
- Summer or pre-monsoon season: This period lasts for four months from February until the beginning of May. It is the dry season with April being the hottest month of the year.

The presence of the sea in the south of Thailand causes milder temperatures compared to the rest of the country. The average temperature throughout the year is 27.9 degrees Celsius. April is the hottest month with an average maximum temperature of 28.9 degrees Celsius, while January and December are the coolest months usually showing an average temperature of 22.2 degrees Celsius. Precipitation is covered in detail in Appendix I.

Appendix G: Acknowledged Issues (ปัญหาที่ทราบ)

In a report published by the local government of Koh Tao, it is acknowledged that the island has problems with wastewater treatment, rainwater, energy supply and infrastructure [2]. These problems are discussed in the next sub chapters. Some of the acknowledged issues were already shortly described in Appendix E covering the ecology.

Wastewater

Most of the wastewater on Koh Tao is produced by tourist accommodations such as resorts and hotels. When located close to the shoreline the most common way of dealing with wastewater is dumping it into the sea by means of an effluent pipe. Very little or no wastewater treatment occurs, which can be derived from a strong smell close to the effluent pipe which suggests the presence of organic matter. Also, the wastewater has a greyish colour and contains suspended black matter (Figure 14).

Figure 14: wastewater flowing into the sea at Sairee Beach

This 'dumping' of wastewater affects marine life around the island in a negative way, which implies an environmental risk. Several reasons are given why wastewater is not managed at the moment:

- Resorts and hotels that produce the wastewater refuse to cooperate.
- Construction of a wastewater treatment plant requires space which is not available and will disturb the touristic area.
- The government does not have sufficient funds to finance a solution.

Rainwater

During monsoon season the different towns experience the consequences of excessive rainfall in the form of reduced mobility. During heavy rain events the roads function as a highway to the ocean for the water. According to statements from local residents in Sairee, days when the water is 'up to your knee' are not exceptional during monsoon season. It is recognised that drainage is one of the factors that has significantly improved over the last decade as the government has invested in a drainage system that transports rainwater to the sea. The current philosophy when dealing with rainwater is transporting it to the ocean without any intention to store it and utilize this water for other purposes. To direct the water some naturally formed trenches have been adapted with a concrete lining and function as drainage canals to guide the water to the ocean. And newly constructed roads have concrete trenches on the side to guide the water. Images of old and new roads as well as a drainage channel are displayed in Figure 15, Figure 16 and Figure 17.

Figure 15: Runoff from a road without trenches

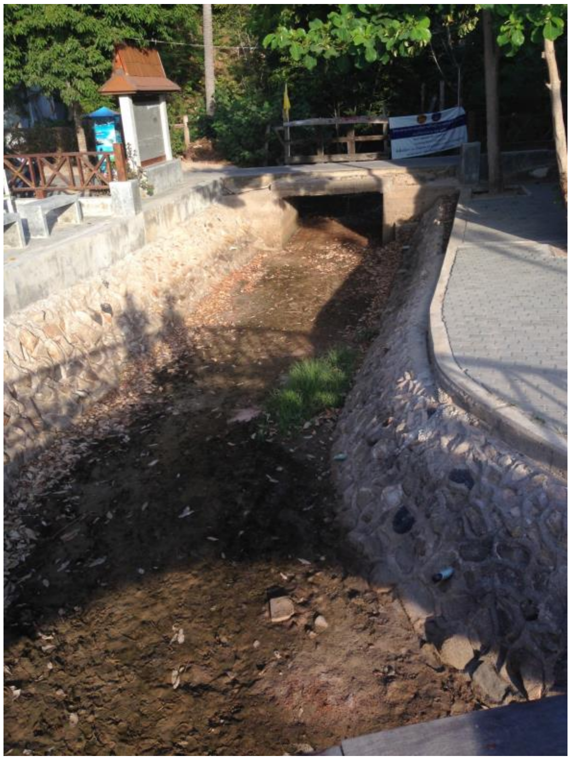


Figure 16: New road with trench (Left) - Figure 17: Drainage canal (Right)

Energy Supply

The public power supply on Koh Tao is arranged through a government owned power plant, and ran by the Provincial Electricity Authority (PAE). Electricity is produced by means of diesel generators and distributed with elevated wires attached to pillars. Energy produced by this plant is sold to customers for a price of around 8฿ (0.22$) per kWh. In contrast with a decade ago, the public system now supplies energy 24 hours a day. The total capacity amounts 7000kW and affords a maximum load of 4500 to 5000kW. Currently the following diesel generators are in available:

- 7 Diesel generators with a production capacity of 1200kW

- 3 Diesel generators with a production capacity of 1250kW

- 2 Diesel generators with a production capacity of 2500kW

According to data from 2014, the energy generated by the government owned power plant supplies 2711 households on Koh Tao. During warm days, the power supply shuts off rather frequently. During a shutoff the system stays down for a period of time that ranges from several minutes up to around one hour. According to people that live on Koh Tao, breakdowns are very common on warm days because of the high energy demand used to power air conditioning systems. This is a clear sign that emphasises the limited capacity of the current power system with respect to peak demand.

Figure 18: Generators and diesel tanks at the government owned power plant

Some private parties own a diesel power generator to supply their own business or household, or sell electricity to others. The capacity of these privately owned plants is not known. Interviewing permanent residents on Koh Tao raises the image that some households have the possibility to use both private and public power. A switch at home that can be flipped to change power supplier in case one of the power systems shuts off. The biggest private power supplier on Koh Tao is called Namsang. The energy they produce costs 35฿ per kWh, almost 1$.

Roads

Koh Tao has a road system that consists of both paved and unpaved roads. In total 5 paved roads are present with a total length of 15km. 7 unpaved roads have a total length of 11km [2]. From observation on site it can be said that the quality of the roads is questionable. Cracks and bumps are present, as well as sudden changes in surface from paved to unpaved. The roads may have a very steep angle from time to time, which makes it unable to reach certain places with motorised vehicles that do not have enough power. Road construction can be seen just north of Sairee Beach, improving the accessibility of this part of the island and traffic safety. The majority of the road users are driving on a scooter. Almost all cars and taxis are four wheel drive vehicles, which is a prerequisite to be able to drive around the island in a convenient and safe manner. The location of both the paved (solid line) and unpaved (dotted line) roads on Koh Tao can be seen in Figure 1.

Appendix H: Water Demand (ความต้องการน้ำ)

The main water demand on Koh Tao is caused by tourist residential facilities, such as resorts and hostels. A smaller share of the total demand comes from use by locals and agriculture. In order to estimate the volume of water that is needed on Koh Tao daily, a good estimation can be made when adding up all the groundwater volumes extracted from the various groundwater pumping stations on the island, plus water that is shipped from the mainland, directly captured rainwater and water from desalination methods. Unfortunately, as the pumps are operated privately, the extracted quantities are unknown. And no record of the other quantities are available.

A good but less accurate estimation can be made when approximating the amount of persons on the island and their water consumption. In the Netherlands, a rule of thumb is used stating that 125L of fresh water per person per day is consumed. The use of water in Thailand is likely to differ from the Netherlands due to different climatic conditions and degree of economical welfare. A difference between local residents and tourists is expected due to different activities on the island. Hotel and resort owners were interviewed to find an appropriate demand per tourist. Sadly no resort owner could provide a valuable number. Most owners have a reservoir in the form of water tanks and want to make sure that the level is sufficiently high, without monitoring the flows.

In this report water demand is the direct water demand. So water that is bought and not water that is consumed higher up in the chain to produce food or fuel for instance. Water demand can be subdivided in direct use (taking showers, flushing toilets, use of tap, etc.), and indirect use (irrigation, swimming pools, cleaning, washing, restaurant purposes, etc.). There is evidence that direct water use is fairly stable across income categories, seasonal variations, socio-economic groups and accommodation types [24].

Tourist Demand

People generally consume more water on holiday than back home. The water demand of a tourist strongly depends on its activities and type of accommodation. The literature suggests global water consumption rates in a range between 84 and 2000L per tourist per day [25]. Resorts consume much more water per visitor than budget hostels. This is mainly because of the green areas in need of irrigation resorts have. A study on resource use in the Vietnamese tourist industry showed that direct water use in the guestrooms always dominates the total consumption in hotels. In resorts the indirect water use, use for garden and swimming pool dominates the total consumption. The major water consumers in hotels ordered from high to low consumption are guestrooms, kitchen, laundry and outdoor activities. For resorts the order is outdoor activity, kitchen, guestroom, laundry [26]. The same results were found in a comparable research for Zanzibar, Tanzania. Hotels with extensive gardens used most water for (continuous) irrigation (50%). While guesthouses used only 15% of their total demand on irrigation. The major proportion of water in Tanzanian guesthouses is spent for direct use (55%) while in resorts the share of direct used water was only 20%. In absolute sense the proportions were comparable, 136L/person/day for guest houses and 186L/person/day for resorts [27]. Unlike Zanzibar Island there are no golf courses present on Koh Tao.

The indirect use comes from facilities as spas, swimming pool, leisure and sports facilities and gardens. These facilities are responsible for a large share of the daily consumption.

- **Gardens** need irrigation, how much depends on the type of plants and the periods of drought.
- **Swimming pools** need water for renewal, to compensate for evaporation and water taken out by users. In luxurious hotels towels are often provided for users of the swimming pool which causes laundry*.
- **Spas** use a lot of tap water and produce large amounts of laundry*.
- **Sports facilities** have a high water demand due to the amount of cleaning needed and the laundry produced by users.

*The water demand for laundry strongly depends on the size and textile quality of the towels used. [25]

The demand per tourist per day depends partly on the occupation rate. All tourist accommodations have a fixed water use independent of the occupancy rate. The higher the occupation rate, the lower the share of this fixed use per tourist. Fixed water use is for cleaning, irrigation and the swimming pool for instance [25]. The fixed water use differs over the year, volumes used for irrigation depend on the season. It is assumed that garden irrigation substantially increases during a dry period. The dry period is also the period with the most tourists so it has been assumed that the fixed water use per person levels out over the seasons.

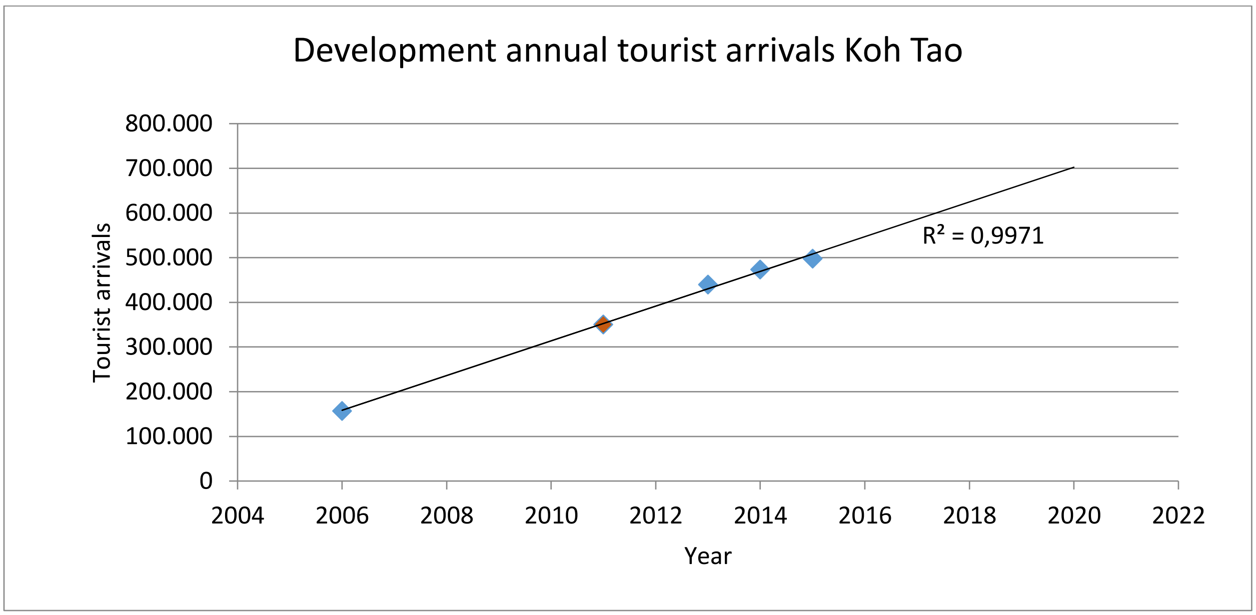


Figure 19: Extrapolated tourist arrivals from known years (Christian calendar)

Figure 19 expresses the known annual tourist arrivals. Only four years of exact data were available. A fifth data point, represented by the red, is found by taking the average of a range of tourist arrivals given for 2011. From linear extrapolation of the known data points a total amount of 700,000 tourists may be expected in 2020. From observations on the island it can be said that the island is capable of growing in the future. On the other hand, an amount of 700,000 tourists is likely to be towards the maximum amount of tourists the island can host. Therefore the amount of 700,000 tourists will be used as the maximum amount of tourists that will be in need of water annually on Koh Tao.

An average tourist visit on the island is 7.9 days [2]. With the development of the island the main purpose for tourism (diving) does not change. Therefore it is expected that the average length of a tourist stay will be about the same in the future. The primary accommodation type on Koh Tao is resort type accommodations. Assumed is that 80% of all tourist stay in a resort type accommodation. Due to the mountainous geography most resorts consist of small huts on a slope, have large green areas and one or more swimming pools. The minority of tourist accommodations are hotels and hostels, located in the villages. The hotels and hostels are low rise buildings; no tourist accommodations with more than four floors are present on the island. Dense high rise tourist areas tend to use comparatively less water than disperse, low tourist density residential resorts [28]. The main tourist activity on Koh Tao is diving, as there are over 40 diving schools on the island. Most of them have one or more swimming pools to train divers.

The research on Zanzibar showed that water use exponentially grows with increasing resort size. As possible explanation is given that bigger resorts use more water for larger pools, and have more extensive irrigated gardens—the two major water consuming factors in the reference study on Zanzibar [27].

There is a global growth in tourism and a trend towards higher-standard accommodation [25]. A research in 2002 predicted an average growth of tourism in Thailand by 6.9% per year till at least 2020. This is confirmed by the image obtained in Figure 19, where an annual growth with the same order of magnitude is displayed.

On Zanzibar the daily average water demand of tourists that stayed in basic accommodation is 248L. The average of tourists that stayed in luxurious accommodation was 931L per day. The total weighted average demand is 685L/person/day for Zanzibar [27]. In Mallorca tourists in basic accommodations use an average of 152L/person/day and tourists that stayed in luxurious accommodations used 502L/person/day [29]. In Thailand the water demand is between 913 and 3423L/day/room occupied [25]. The average amount of tourists per room is unknown. With the assumption that this is assumed to be close to 2, the water demand per tourist per day is most likely somewhere between 457 and 1712L.

A considerable share of these volumes can be staff related. Between 30 and 250L per day. As described earlier in this chapter, more luxurious accommodations have a tendency to consume more water due to spas, multiple swimming pools and a lot of green area [25]. Taking into account the main accommodation type and tourist activity, while bearing in mind the water consumption numbers stated in the consulted literature, in combination with findings on the island, an average daily consumption of 500L per tourist seems a reasonable estimate.

Demand Locals

Water use by residents is far lower than water use by tourists. On Zanzibar the weighted average daily water demand of tourists (685L) was more than 14 times the weighted average water demand of local residents (48L). Higher water consumption by tourist than locals have also been reported for Lanzarote, Spain, where water use by tourists is 4 times the use of local residents. Tourists have a ‘pleasure’ approach to the shower or bath and generally use more water than they would do back home [25].

Together with the economy of the island the demand on fresh water by locals increased rapidly over the last decade. Figures for the island are not known but for the whole of Thailand the water demand per person increased almost 2.5 times between 2012 and 2015 from 48 to 119L/person/day.

Because water is relatively expensive on Koh Tao most residents try to save as much water as possible. The 119L per person per day found for Thailand as a whole is assumed to be overrated for the present day consumption of locals on Koh Tao. The common welfare increased but the majority of residents still have a primitive living. Flushing the toilet, for instance, is done by means of a cup scooping water from a water container in the bathroom. As a comparison in the Netherlands about 5 liters of water is used every time when flushing the toilet, which is a lot more. Other activities that require water, such as laundry and the dishes, is partially done manually on Koh Tao. This requires less water than when a washing machine is used. The current approximated water demand of a local resident is based on interviews with local residents. The current water usage of a local resident is approximated at 80L/day. The average water use of locals is expected to increase with an increasing economic degree of welfare. Also when a sustainable solution is found for the water system of Koh Tao the price per unit is expected to decrease which may cause an increase in water use. Looking at the water consumption of locals in the near-future a daily average of 120L is assumed to be representative.

The registered population of Koh Tao was 2,207 in September 2015. A population growth of 7.07% is expected over 2016 and the total registered population is expected to be 4,300 by 2023 [2]. In September 2014 there were 4,030 registered foreigner workers living on the island. Concerning the local government representatives very few people are actually registered and the total amount of residents on the island is expected to be about 10,000 people.

Rest Demand

Besides tourist demand and demand of local residents there is a small demand from agriculture. Most coconut plantations on the island are replaced by resorts but there are still some left. The coconut trees need irrigation during dry season. Irrigation is done by water from reservoirs filled during rainy season. It is unlikely that tap water is used for irrigation due to the high price per unit. The water stored for agriculture is water that could also be used for households and tourists so agriculture does compete with the other consumers.

There are other water demanding activities that are not taken into account. These are activities such as construction work and dust suppression. Most industry present is timber work which has a small water demand. For the construction of roads and accommodations concrete is needed, concrete demands fresh water. This rest demand contributes to a larger total demand than estimated initially. Very little about the rest demand quantity is known due to the absence of any form of data. In order to include this amount in the total demand a conservative multiplication factor of 1.3 is introduced. This factor is the result of a simple reasoning process in which the order of magnitude has been guessed. Also, spillage during pumping and transportation as well as leakage from the infrastructure and people stealing water from the system is not included when making the first estimate. In order to account for spillage and leakage another conservative multiplication factor of 1.3 is introduced. This factor may vary in practise also depending on how well the water system is exploited and managed.

Total Demand

The total demand on water resources is calculated as the water demand by tourists and residents multiplied by the introduced multiplication factors.

Tourists per year (future)	$N_{tourists,\ future}$	700,000	people
Tourists per year (current)	$N_{tourists,\ current}$	500,000	people
Tourists per month	$N_{tourists,month}$	*variable*	people
Average tourist stay	$t_{tourist}$	7.9	days
Average water demand tourist	$V_{water,t}$	0.50	m^3 per tourist per day
Permanent residents	$N_{permanent}$	10,000	people
Current average water usage locals	$V_{water,cl}$	0.08	m^3 per person per day
Future average water usage locals	$V_{water,fl}$	0.12	m^3 per person per day
Days per year	d	365	days
Rest demand factor	F_r	1.3	[-]
Spillage and leakage factor	$F_{s,l}$	1.3	[-]

$$\left(N_{tourist} * V_{water,t} * t_{tourist} + N_{permanent} * V_{water,nl} * d\right) * F_r * F_{s,l} = yearly\ demand \tag{15}$$

With $_{nl}$ indicating the current or future demand of the local residents.

Approximated current demand (2015):

$$(500{,}000 * 0.50 * 7.9 + 10{,}000 * 0.08 * 365) * \ 1.3 * 1.3 \approx 3{,}800{,}000\, {m^3}/{year} \tag{16}$$

Approximated future demand (2020):

$$(700{,}000 * 0.50 * 7.9 + 10{,}000 * 0.12 * 365) * \ 1.3 * 1.3 \approx 5{,}400{,}000\, {m^3}/{year} \tag{17}$$

The demand for water is not constant throughout the year, due to high and low touristic season. In order to estimate the monthly demand the deviation of tourists visiting Koh Tao throughout the year has to be included. The formula looks as follows:

$$\left(N_{tourist,month} * V_{water,t} * t_{tourist} + N_{permanent} * V_{water,l} * \frac{d}{12}\right) * F_r * F_{s,l} = monthly\ demand \tag{18}$$

With:

$$N_{tourist,month} = \%_{total\ tourists,month} * N_{tourist} \tag{19}$$

The percentages of the total amount of tourists as well as the corresponding water demand are shown in Table 15. It is assumed that the share of tourists that arrives every month stays constant in the future.

Table 15: Water demand based on 700,000 tourists annually, demand of approximately 18,000m^3/day is critical.

month	Tourists per month	Tourists	Monthly water demand	days per month	Daily water demand	rounded daily water demand
January	7.6%	53,476	418,662	31	13,505	14,000
February	8.7%	60,914	468,317	28	16,726	17,000
March	8.4%	58,877	454,718	31	14,668	15,000
April	8.4%	58,885	454,770	30	15,159	15,000
May	7.7%	53,726	420,332	31	13,559	14,000
June	6.6%	45,984	368,654	30	12,288	12,000
July	9.1%	64,049	489,242	31	15,782	16,000
August	10.6%	74,366	558,113	31	18,004	**18,000**
September	8.0%	56,342	437,797	30	14,593	15,000
October	7.3%	50,911	401,541	31	12,953	13,000
November	6.7%	46,883	374,654	30	12,488	12,000
December	10.8%	75,588	566,270	31	18,267	**18,000**

Tourist arrivals are not evenly distributed over the year. No multiannual data was available, the data provided were the boat arrivals per month [2] and the monthly precipitation as determined in Appendix I. In Figure 20 the boat arrivals per month as a percentage of the total annual arrivals per boat are plotted on the primary axes. On the secondary axes the monthly precipitation is plotted as a percentage of the total. The recharge of resources by precipitation is the highest during the period with least arrivals also the demand is high during the period with least precipitation. Storage is needed to overcome this mismatch.

The figure shows 2 clear peaks and 2 clear dips in the monthly arrivals. The dips can be found in June and in November. The dip in November can easily be described by the fact that this is monsoon season. During this month 24% of the total annual precipitation fell. There is no clear explanation for the dip in June. The peaks in August and December are due to the global tourist season in these periods. Assumed is that 2015 is representative for a longer period of time. However, tourist arrivals are expected to be not only season dependant but also weather dependant. Most tourists seek for good weather and favourable water cloudiness to do a dive course or just relax on the beach. Weather conditions on other location in Thailand or Asia can also influence the tourist arrivals on Koh Tao. If conditions on comparable locations are worse than on Koh Tao tourists will alter their travel plans and visit Koh Tao.

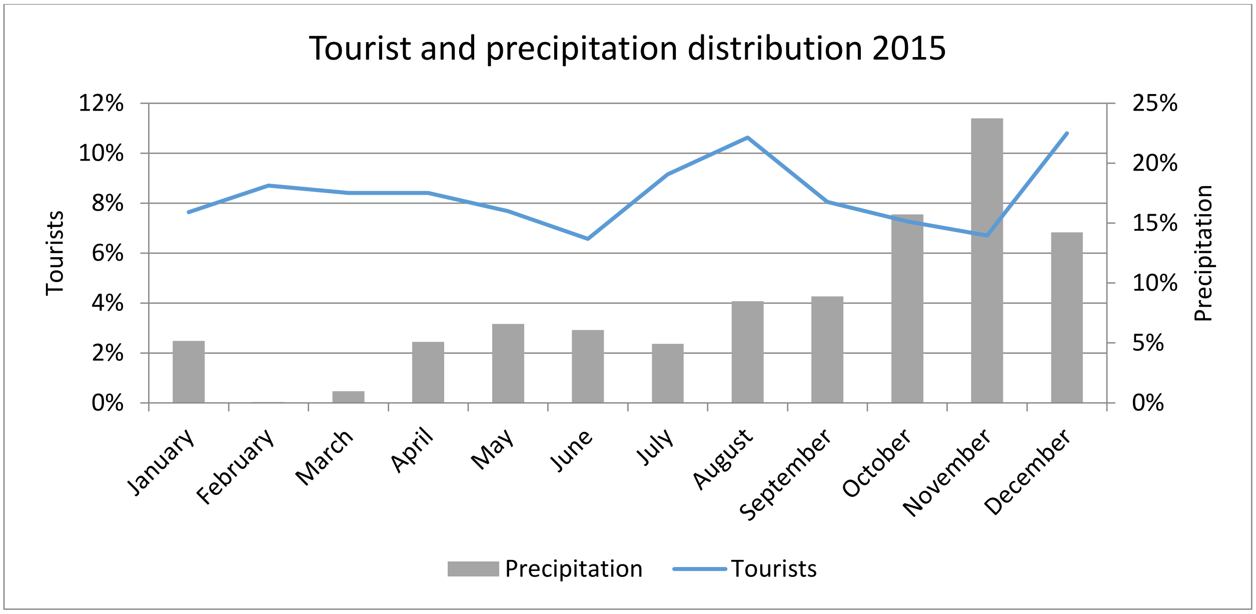


Figure 20: Illustration of mismatch between precipitation peak and tourist peaks

Appendix I: Precipitation (การเร่งรัด)

Koh Tao does not host a weather station. In the vicinity of Koh Tao both Koh Samui and Chumpon are cities that host a weather station from where comprehensive rainfall data is available. For the years 1968 until 2015 rainfall data has been recorded, this equals 48 years of data [30]. Before using this data an assessment has been made to see whether a trend is present as this can have influence on the analysis. Plots of precipitation data as a function of the year, are shown in Figure 21 and Figure 22. From the plots and obtained R^2 value it can be stated that no trend can be distinguished.

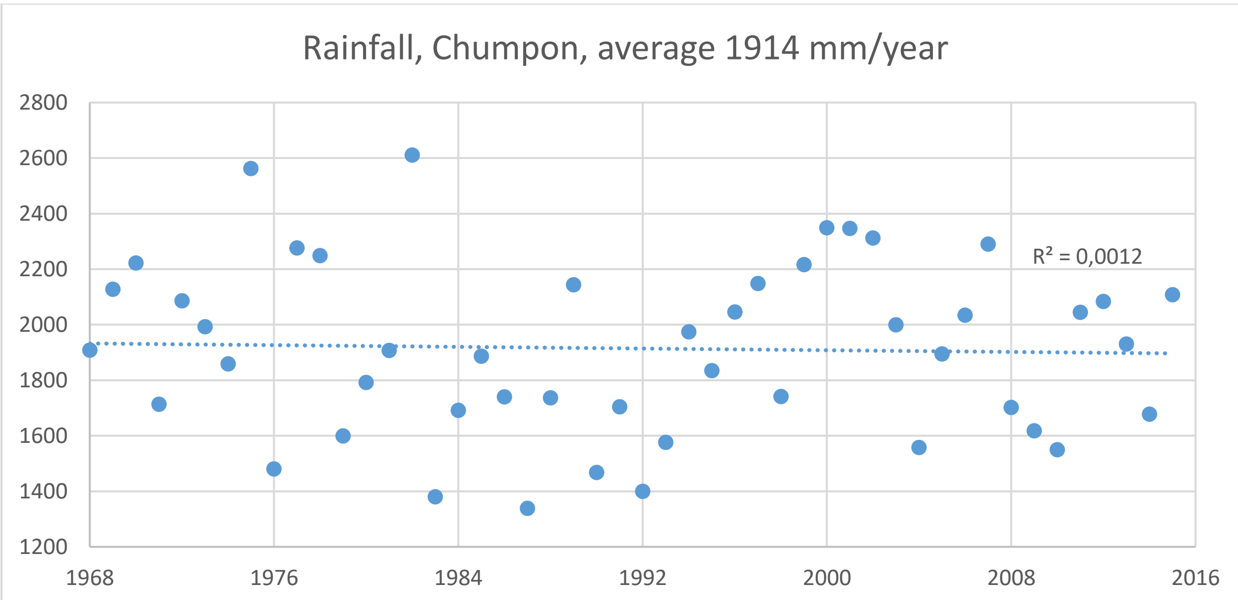


Figure 21: Annual rainfall Chumpon

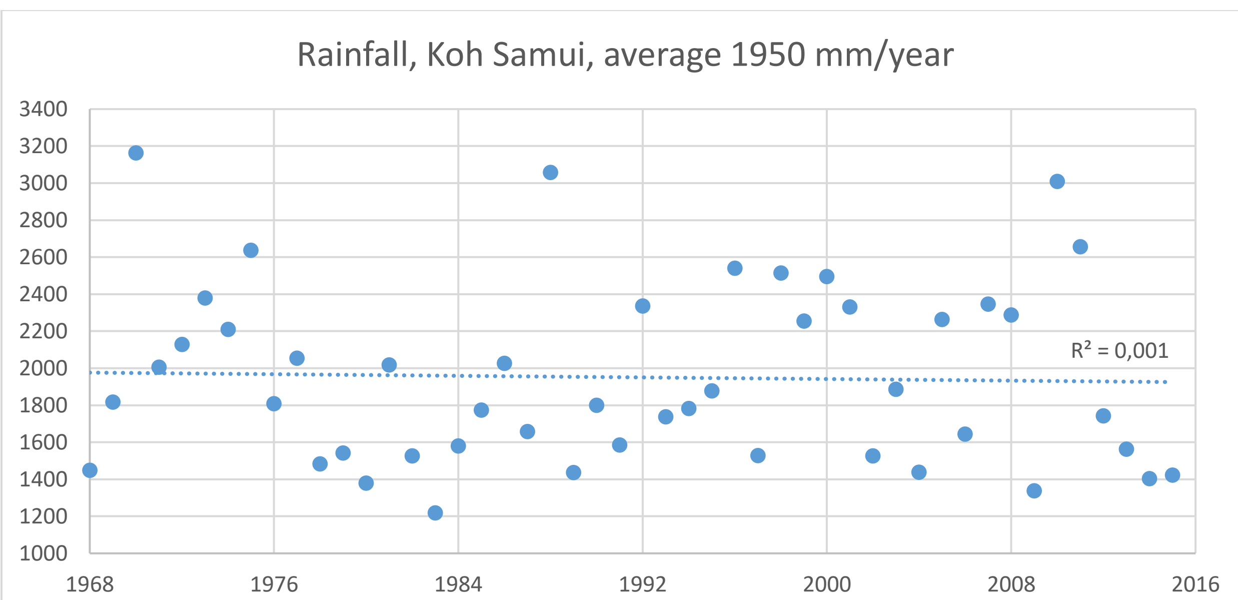


Figure 22: Annual rainfall Koh Samui

Data Interpolation

In order to estimate the rainfall on Koh Tao, supplied data of Chumpon and Koh Samui have been used in combination with an interpolation method. The exact location of the two weather stations are:

Chumpon: 10° 29' 55.5" N, 99° 11' 18.5" E

Koh Samui: 9° 28' 0.0" N, 100° 3' 0.0" E

The location information of the weather stations at Chumpon and on Koh Samui is used to calculate the distance to Koh Tao, which is 84 and 74km respectively (Figure 23). This information is important when implementing an interpolation method.

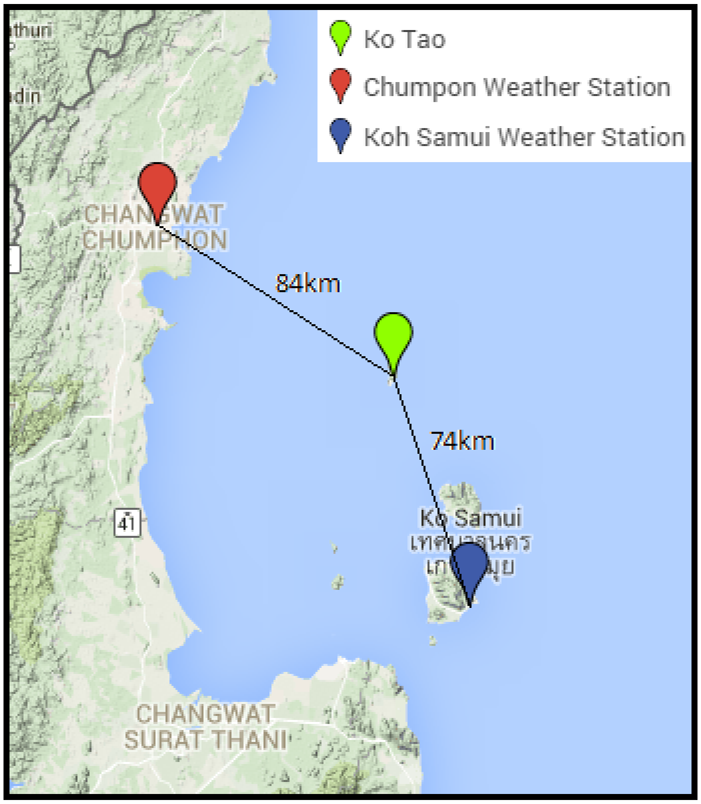


Figure 23: Geographical orientation of weather stations at Chumpon and on Koh Samui with respect to Koh Tao

It can be argued that the distance between both weather stations and Koh Tao have the same order of magnitude. Data from both stations is valuable, and an interpolation method that includes the difference in distance proportional to the weighing factor seems appropriate. Therefore the inverse distance interpolation method has been applied, as shown underneath [9].

$$P = \frac{\sum \frac{P_i}{d_i^n}}{\sum \frac{1}{d_i^n}}, with: n = 1 \tag{20}$$

The power n has been chosen to be one, which causes the formula to imply linear interpolation. The weighing factor given to a rainfall data point from either of the weather stations is directly proportional to its distance to Koh Tao.

Rainfall Data Interpretation and Trend

The interpolation process used to estimate the annual rainfall on Koh Tao has generated data as plotted in Figure 24. Before using this data an assessment has been made to see whether a trend is present as this can have an influence on the normality of the distribution. From the plots and obtained R^2 value it can be stated that no clear trend can be distinguished. This is an indication that the measured years can be used as an estimate for future years without modification.

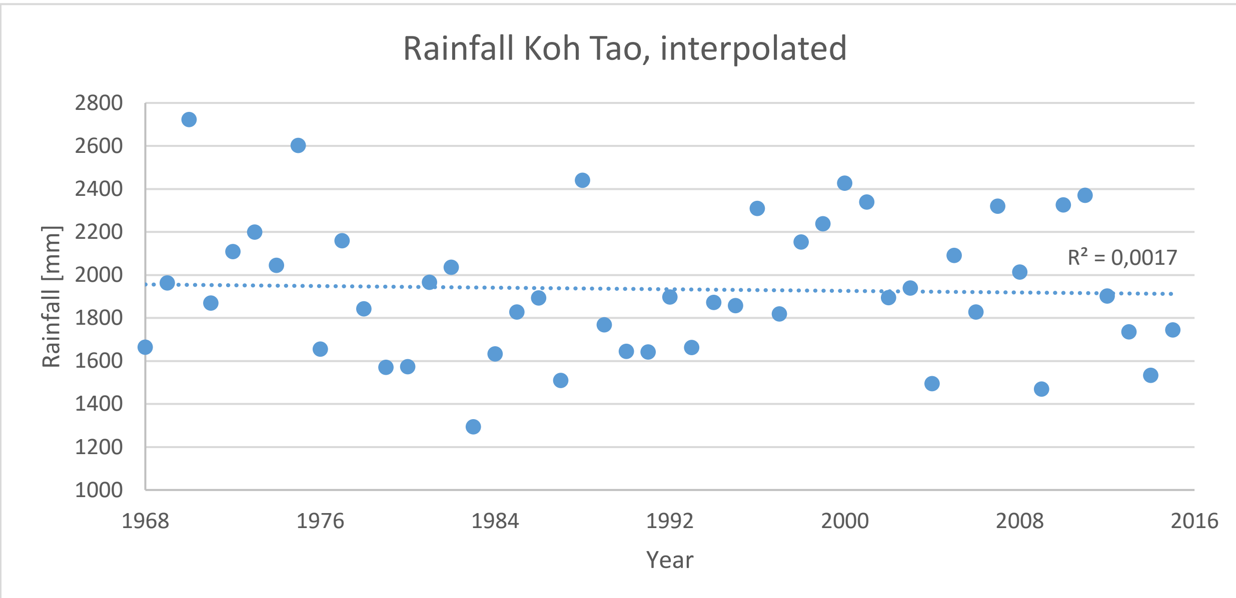


Figure 24: Obtained rainfall data for Koh Tao after interpolation

Rainfall Frequency and Distribution

When analysing the interpolated data the following set of descriptive statistics is found.

Table 16: descriptive statistics for interpolated rainfall data Koh Tao

Mean (μ)	1933.82
Median	1893.045
Standard Deviation (σ)	319.0891
Sample Variance	101817.9
Kurtosis	-0.29502
Skewness	0.398142
Range	1428.305
Minimum	1293.373
Maximum	2721.678
Count	48

An easy normality test for Koh Tao's interpolated rainfall data is conducted by plotting a histogram and visually assessing whether the obtained image looks like a normal curve. The obtained histogram with the frequency of Koh Tao's interpolated rainfall data, using a bucket width of 200mm, is shown in Figure 25. When looking at this histogram the shape of a normal distribution can be clearly identified. On the other hand, it can be argued that the distribution is very slightly positively skewed.

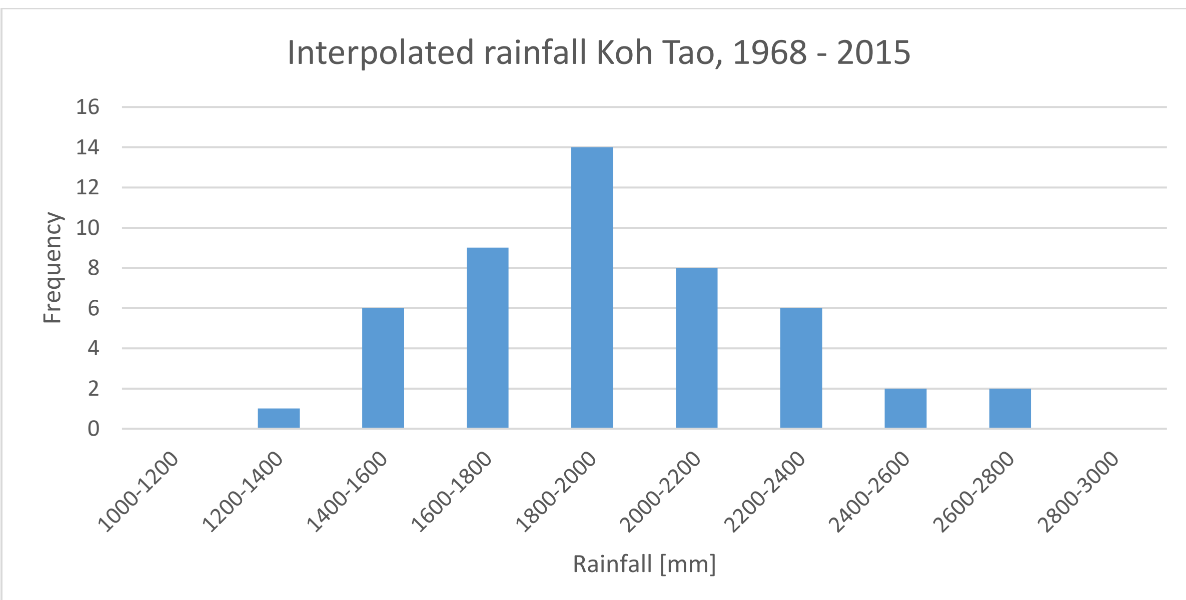


Figure 25: Histogram showing the frequency of the interpolated Rainfall data for Koh Tao

Annual rainfall data is the sum of all rainfall events per year, and therefore the result of a large number of independent events. This is a typical situation where a normal distribution is likely to be obtained. From experience it shows that 80% of the weather stations with long time records receive normally distributed data [31]. Annual rainfall data from 48 years has been used to construct Figure 25. It can be argued that this is a reasonably small dataset. As a consequence it is highly improbable that a good normal distribution will be obtained. Concerning the shape of the histogram and knowing that annual rainfall (a random hydrological event usually characterized by normally distributed data) is described, it has been assumed that the obtained data is normally distributed. As a consequence, the mean annual rainfall equals the expected value [μ].

The assumption that the annual rainfall quantities on Koh Tao can be described by means of a normal distribution allows to determine the rainfall quantity that is exceeded 95% of the years. This can be done by calculating the low bound of the 90% confidence interval, leaving 5% of probability on the low end of the distribution. The z-value is 1.645 (Appendix L), meaning that the lower boundary of the 90% confidence interval is found at a distance of 1.645 times the standard deviation from the mean. Using the descriptive statistics from Table 16, it follows that there is a probability of 95% that the annual rainfall will be larger than 1409mm.

Monthly Rainfall and Days with Rain

The prior calculated annual rainfall is the sum of the monthly precipitations as were provided in the datasets [30]. For both weather stations the average monthly precipitation has been calculated for the provided 48 years of data. Figure 26 shows the results for Chumpon and Koh Samui as well as the interpolated intensity for Koh Tao. During the dry period (February-April) the monthly precipitation recorded at both weather stations match. During pre-monsoon season the monthly precipitation in Chumpon is larger than the monthly precipitation on Koh Samui. The opposite is visible during monsoon season. During monsoon season the largest monthly preciptation is found on Koh Samui. The differences during the wed period may be explained by the different geographical location. Despite the difference in precipitation a comparable relation can be derived for both locations. Therefore interpolation is assumed appropriate to determine representative precipitation figures for Koh Tao.

During the year Koh Tao experiences a relative dry period between January and April, with 100mm or less precipitation per month. From May to September the precipitation is relatively constant and about 150mm per month. During monsoon season the monthly rainfall increases with a peak in November where on average 400mm precipitation is found.

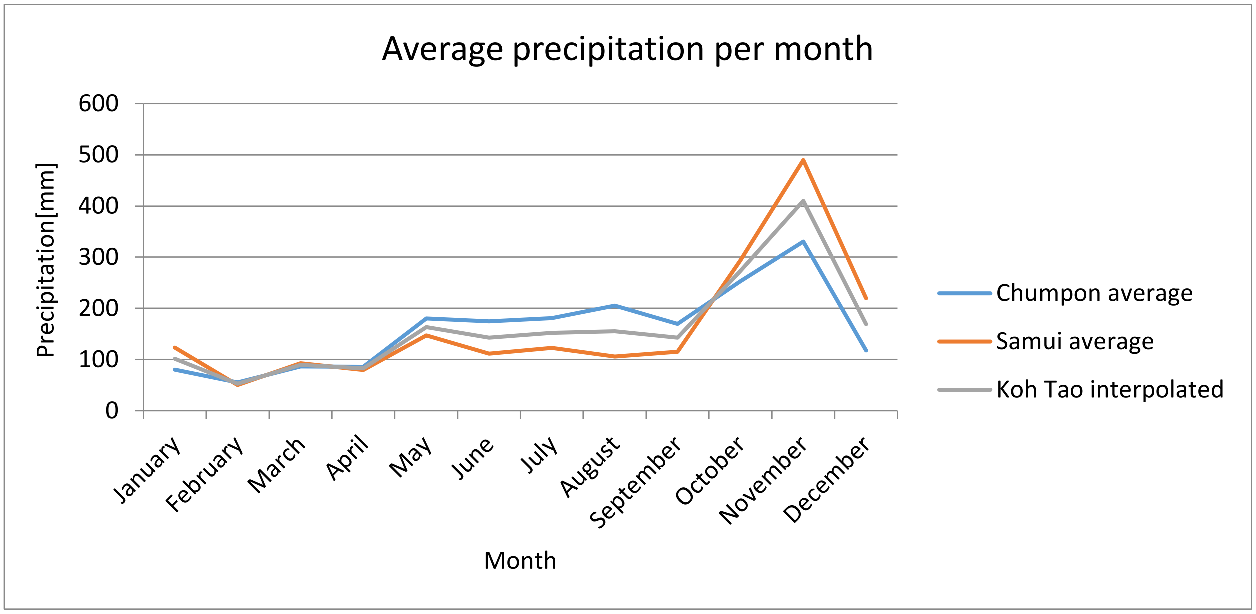


Figure 26: Average precipitation for Chumpon and Koh Samui including interpolated precipitation representing Koh Tao

The dataset also provided the amount of days per month a rain event occurred for the 48 years recorded. Figure 27 shows the average amounts of days with rain for Koh Samui, Chumpon and an interpolated value representing Koh Tao. The same pattern is found as in Figure 26, during the dry season the figures match, during pre-monsoon season the figures for Chumpon exceed the figures of Koh Samui and during monsoon this relation is opposite. Again interpolation is assumed appropriate to determine representative figures for Koh Tao.

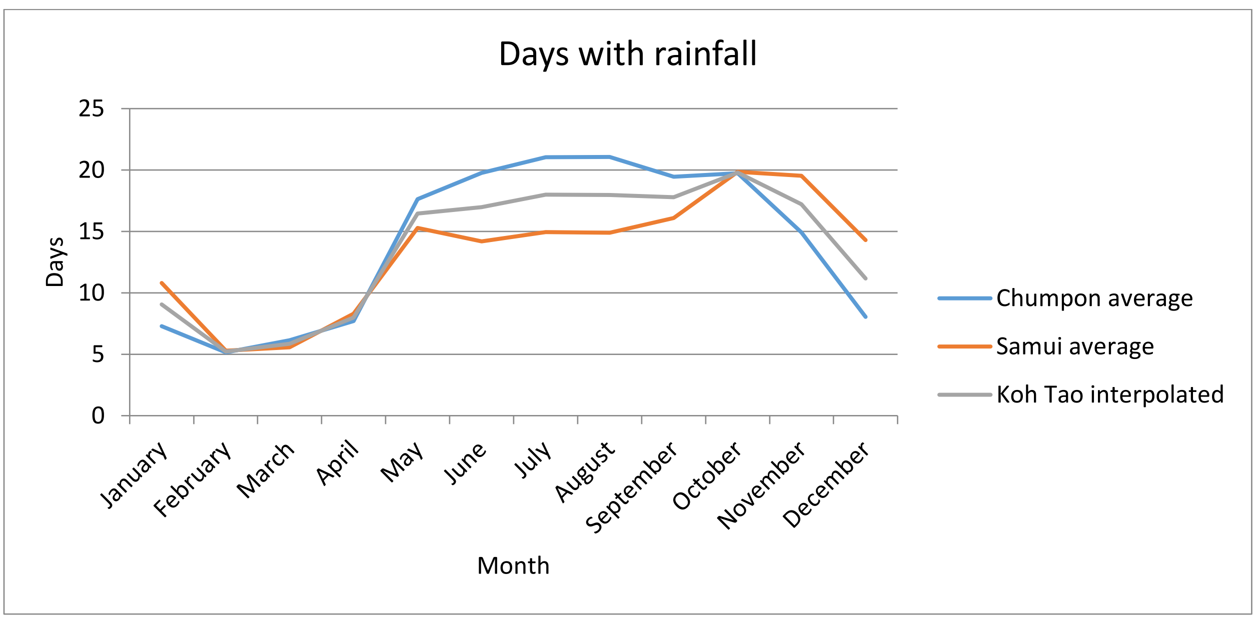


Figure 27: Average amount of days with a rain event for Chumpon and Koh Samui including interpolated data representing Koh Tao

The amount of rainy days per month is the highest during monsoon season and the lowest between January and April. When comparing Figure 26 and Figure 27 it can be said that during monsoon season the amount of rainy days increases only very slightly while the amount of precipitation increases significant over the same period. This indicates higher intensity rain events or longer lasting rain events.

Intensity and Frequency of Rain Events

The average precipitation on a rainy day can be calculated by dividing the total precipitation in one month by the days with rain events in that same month as presented in Figure 28. With exception of the monsoon season a relative constant rainfall of about 10mm is found for the precipitation per rainy day. During monsoon season the rainfall increases up to an average of 24mm per rainy day in November.

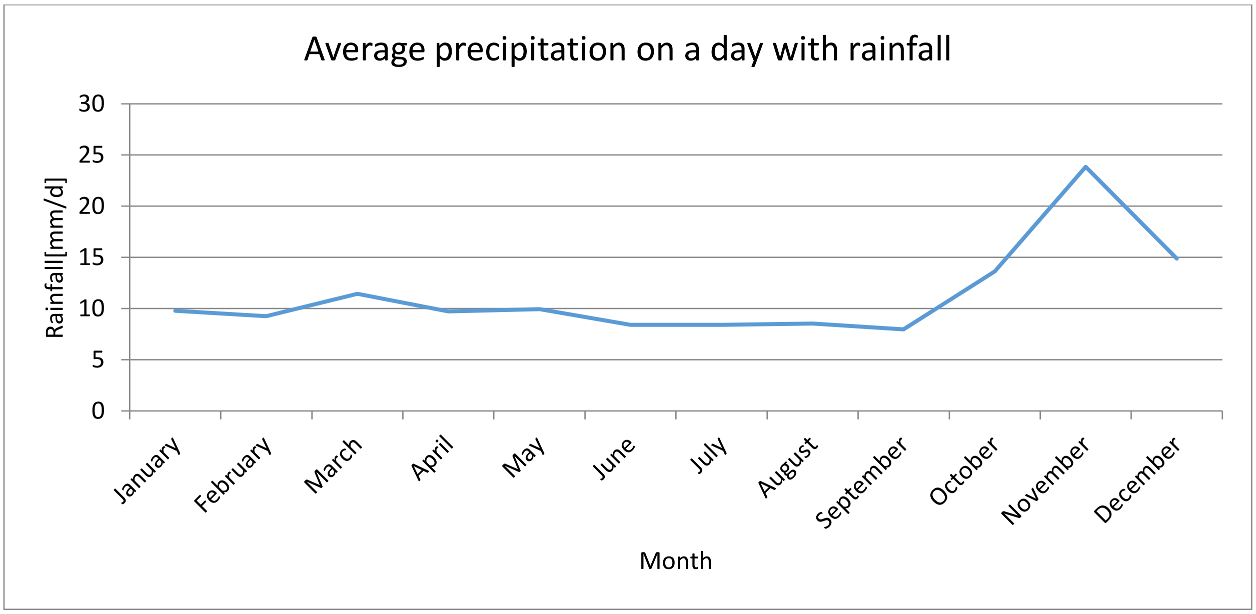


Figure 28: Average precipitation on a day with rainfall presented per month

Figure 29 shows the frequency distribution of the average precipitation on a day with rainfall. Where on the x-axes the interpolated average precipitation on a day with rainfall is divided in ranges of 2mm and on the y-axes the frequency of occurrence is expressed as a percentage of the total amount of rainy days in the dataset. The average precipitation on a day with rainfall ranges between 1 and 58mm. On average an amount of rain between 6 and 8mm falls over 20% of the days with rainfall.

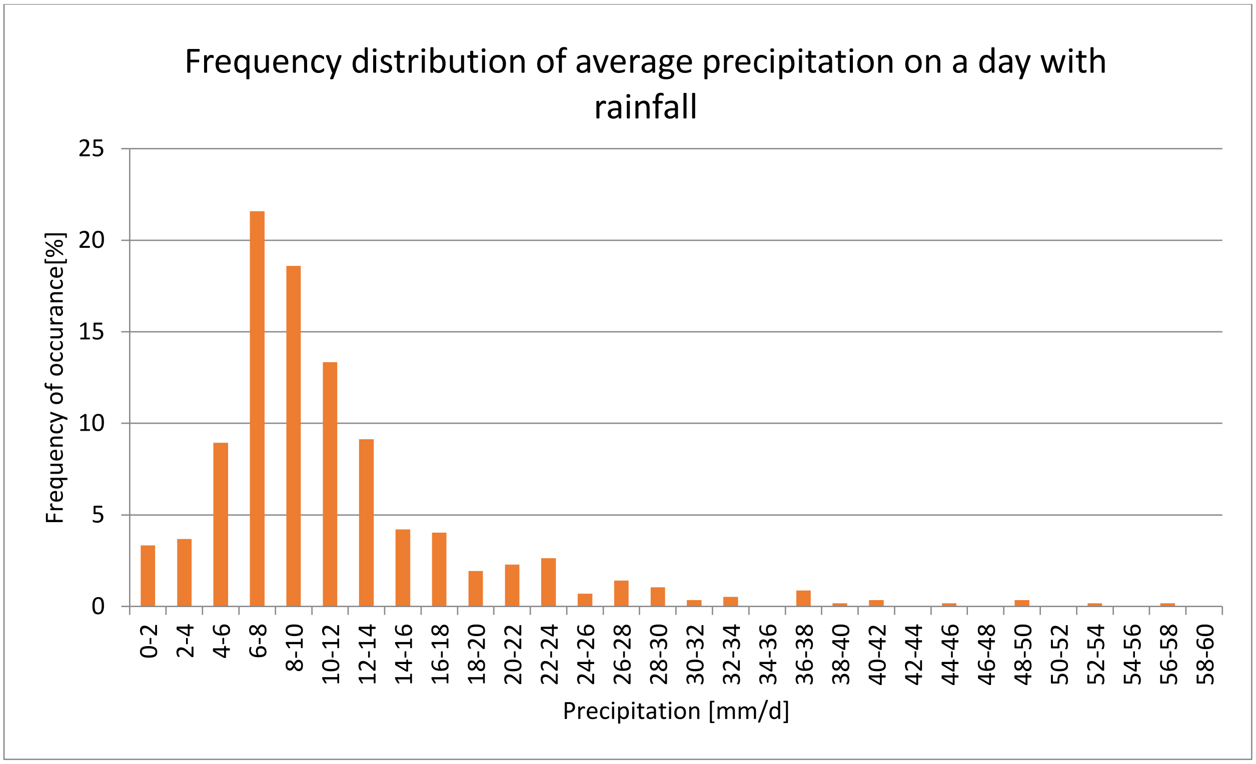


Figure 29: Average precipitation on a day with rainfall

For the analysis on rainwater utilization it is more useful to know what extremes might occur on Koh Tao. Extremes of interest are the intensities of high rain events as well as the length of dry spells. This information could partly be derived from the provided datasets [30] since the biggest precipitation found on a rainy day was given for each month of the 48 recorded years. From the prior mentioned recorded days with rainfall in a month information on dry spells can be derived. Determination of these figures for Koh Tao is again by interpolation between the two provided weather stations.

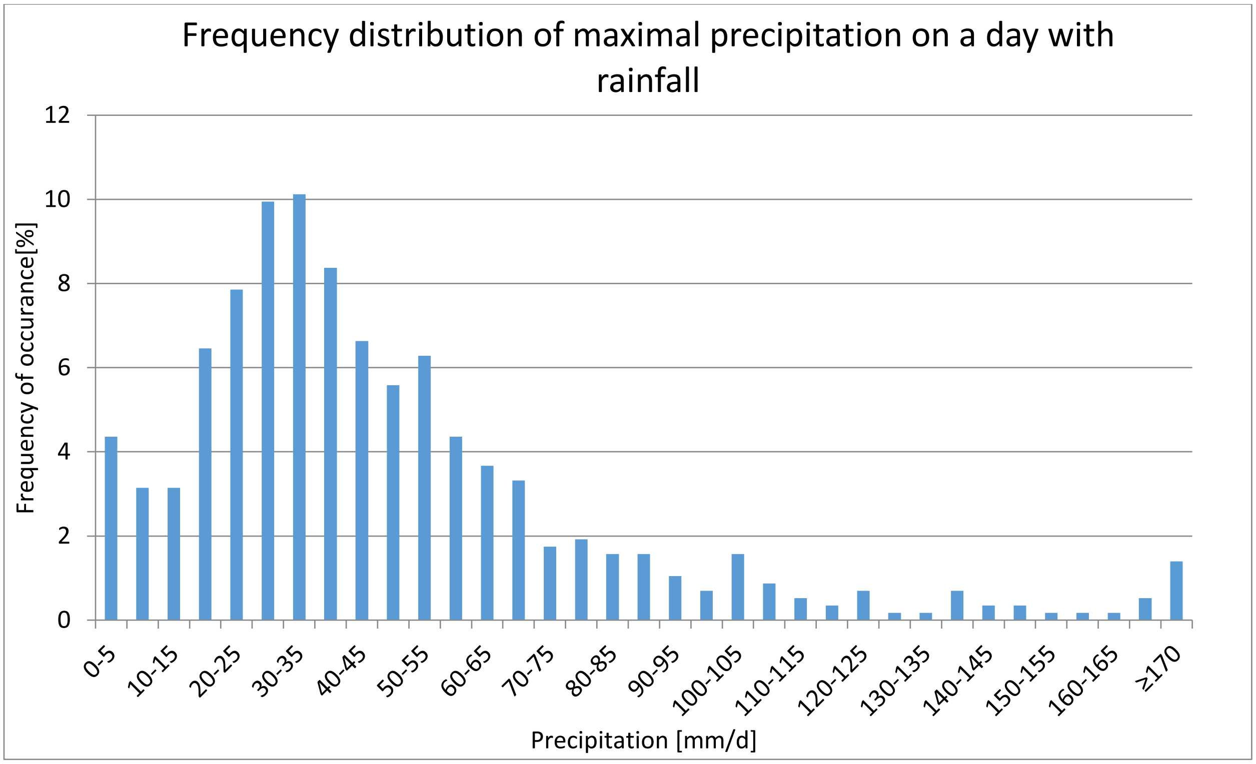


Figure 30: Maximal precipitation found in one day during a month with rainfall

Figure 30 shows the frequency distribution of the maximal precipitation found in one day during a month with rainfall. This time the bin size is 5mm and the frequency is displayed as a percentage of the total amount of months in the datasets. The maximal precipitation found on a day with rainfall ranges between 1 and 405mm. The top of this range is exceptional. In 48 years of record only 8 days with more than 170mm have been found. Days with rainfall over 170mm mean that over 8.8% of the annual precipitation fell on one day. The possibility of occurrence is roughly once every 2190 year.

Dry spells can be found in the datasets by the fact that months were recorded where no days with rainfall occurred. In the 48 years analysed no rainfall was found in February 2014 and 2015 and in December 1970. Only three days with rainfall were recorded from February 1983 to April 1983, one rain event each month. From Figure 26 and Figure 27 it can be found that dry spells are most likely in February.

Appendix J: Surface Area Cover and Watersheds (ฝาครอบพื้นที่ผิวและแหล่งต้นน้ำ)

The ability of rainwater to infiltrate in the subsurface and recharge the freshwater lens strongly depends on the surface cover. Different types of surface cover have different characteristics for interception, runoff, transpiration, evaporation and eventually groundwater recharge. Koh Tao is a mountainous island as described in appendix A. The surface area of the island consists of forest, agricultural land, rock outcrops, villages, beaches, roads and so on. The surface area of Koh Tao can roughly be divided in three main categories; rainforest, settlement and coconut plantation. The categories are shortly explained below and a photographical illustration is given in Figure 31.

Rainforest: This category has a high density of vegetation and is fairly untouched by humans. The vegetation consists mainly of trees. The north and south tip of Koh Tao have the highest rainforest cover and this surface cover category is mainly found on steep slopes.

Settlement: This category contains all buildings, paved roads and facilities for tourists and residents on the island. The main settlements are situated on the shallow sloping west side of the island. Also in this category are areas covered with rock outcrops or a very shallow layer of weathering products. These areas have characteristics comparable with the settlement areas and therefore contribute to the category settlement.

Coconut plantation: The main agricultural activity on the island comes from coconut plantations, coconut trees grow in a grid of about ten meters and the surface between the trees is covered with a grass type vegetation. Nearly all coconut plantations are located on hill slopes.

Figure 31: Surface cover categories, Rainforest – Settlement – Coconut plantation

Determination of the share of Koh Tao currently covered by the cover types is based on documents provided by the local government [2], a division of groundcover in a study from 2010 [21] and site investigation on Koh Tao. Table 17 summarizes the main categories and the share of surface area they cover. Koh Tao consists of a large island that is surrounded by several small islands and rock outcrops. Utilization of fresh water, if present at all, on the smaller islands is expected to be unfeasible. The main island covers an area of about 18.5km^2 [2] [21].

Table 17: Total surface cover divided in three main categories

Category	**Surface cover[%]**	**Area[m²]**
Rainforest	50	9,250,000
Settlement	20	3,700,000
Coconut plantation	30	5,550,000
Total	100	18,500,000

To find the part of precipitation that potentially recharges a certain area the island is divided in watersheds. A watershed is an area that is drained in a certain direction. Physical boundaries, such as mountain ranges supply a convenient natural boundary, as precipitation flows to a different reservoir in theory depending on which side of the mountain it falls down (Figure 32). Here the assumption has been made that no underground connection is present between A and B.

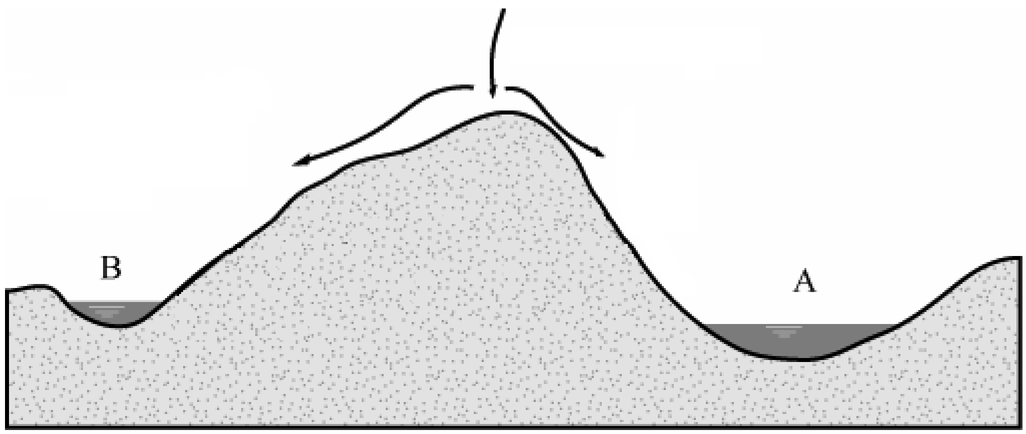


Figure 32: Mountain range dividing watershed A and B

A GIS based assessment on threats to the natural environment of Koh Tao in 2010 divided the island in 27 watersheds as shown in Figure 33. [21] This included Koh Nang Yuan Island (1 to 4), a very small but famous tourist island, located northwest of Koh Tao. The main island of Koh Tao consists of 23 watersheds of various sizes. The west side of the island has more shallow slopes and the watersheds are bigger than on the east side of the island where the slopes are steeper. All watersheds share a boundary with the ocean, the catchment of a watershed flows to this boundary.

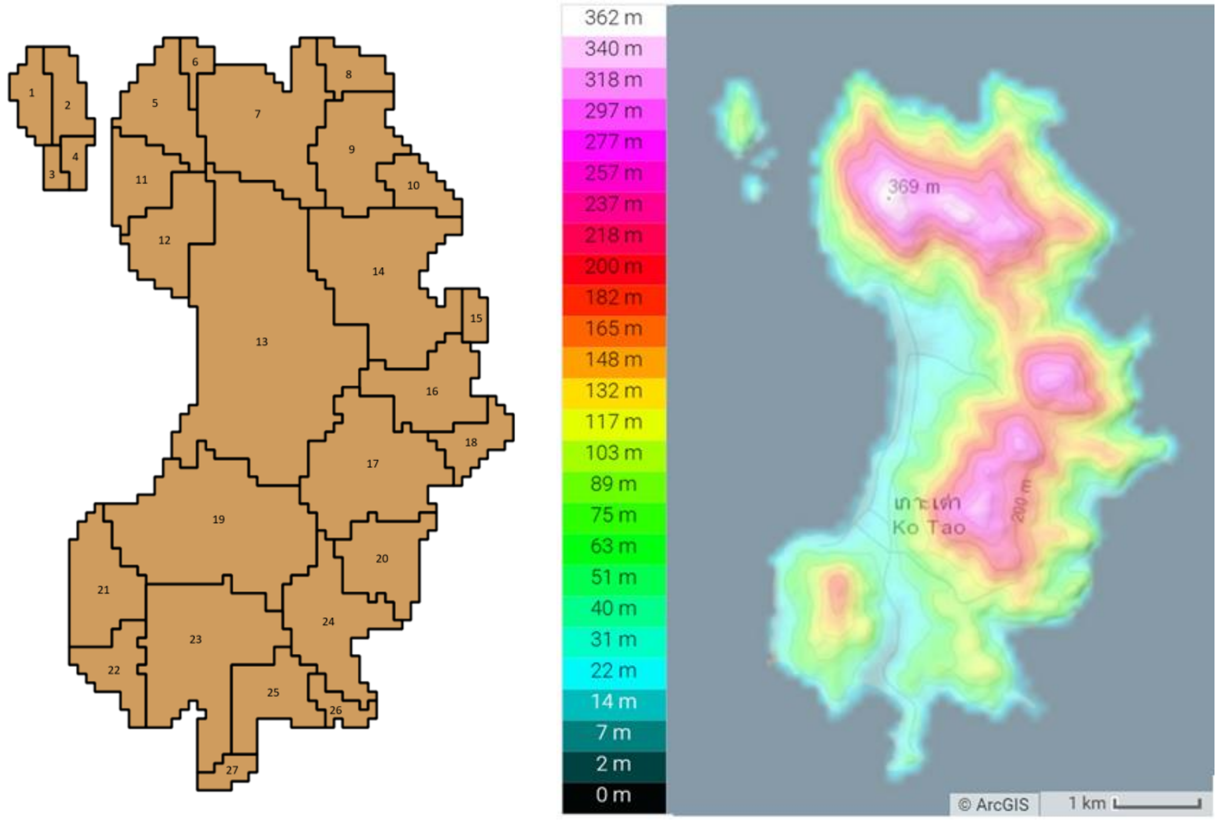


Figure 33: Watersheds on Koh Tao [21] and a height map indicating the physical boundaries

Appendix K: Surface Cover Characteristics (ลักษณะของพื้นผิว)

In this appendix the characteristics of the three main surface cover categories are determined. Determination of the interception, surface runoff, subsurface runoff and evapotranspiration characteristics is arbitrary. If insufficient data was available during this determination process a characteristic is approximated from findings on the island or based on literature with complementary argumentation.

Interception

Precipitation falls on all objects present on earth; vegetation, paved surface, houses, etcetera. Intercepted water is the share of precipitation that is stored temporary on object and is likely to evaporate in a short period of time. Precipitation minus interception is the net precipitation. Interception by tree vegetation is called canopy interception.

The interception-reservoir will be filled at the beginning of a precipitation event. The interception rate of the total annual precipitation strongly depends on the frequency, duration and intensity of the rain events. Depression storage in settlement area depends on the surface type and angle with respect to horizontal.

According to measurements and computations of Horton the interception (I) of unpaved areas depends on the amount of precipitation (P) according to a relation:

$$I = a + b * P^c \tag{21}$$

Where; a, b and c are empirical determined constants and P is the precipitation [32]. With this method the estimated interception is found in Inches. 1 inch is equal to 24.5mm.

Rainforest: The rainforest on Koh Tao is dense untouched evergreen forest area. Canopy interception of trees is equal to rainfall minus through fall of rain and water that reaches the ground by stem flow. The canopy interception percentage of the evergreen rainforest of Koh Tao is expected to be more or less constant throughout the year.

The constants for rainforest are unknown, based on known constants for different types of non-tropical forest a, b and c are approximated to be; a = 0.05, b = 0.18 and c = 1.00 [32]. In the formula the constant a is divided by the precipitation. For precipitation input in mm:

$$I = \left(\frac{0.04 * 24.5}{(P)} + 0.18\right) * 100 \approx 18\% \tag{22}$$

The precipitation has values between roughly 1200 and 2800mm per year. The share of the first term in the equation is negligible and the interception rate will independence of the precipitation be close to 18%.

A study on interception by forests showed that interception is in the order of 13 to 22 percent, depending on the type of forest [33]. In this study evergreen forests are at the lower end of this range. An average interception rate of 15% is considered representative for the rainforest area of Koh Tao.

Settlement: Interception in urban areas is divided in two categories. Part of the precipitation is moisturising loss. And part is stored temporary, this is called depression storage. Moisturising loss is the amount of water adsorbed to roof covers and pavements in such a way, that it cannot runoff any more, only via evaporation this water can be removed. The amount of moisturising loss depends on the type of surface cover. Porous materials tend to adsorb more precipitation than less porous materials. Depression storage is a film of water on objects, this water will evaporate or reach the surface with some delay.

To calculate the volume of moisturising loss an average volume of 0.5mm per rain event is determined [32]. The amount of rain events is unknown but the annual average of days with rain is known. On average 163.5 days with a rain event occur per year. The average amount of rain events per rainy day is also unknown. The moisturising loss is at least 0.5*163.5 days = 0.08m per year. This is between 3 and 6% of the total annual precipitation. Considering evaporation as part of the depression storage and more than one rain event per rainy day the interception in settlement area is approximated at 10%.

Coconut plantation: Compared to the rainforest the coconut plantations have a low canopy interception, the threes are placed in a grid of about 10 meters. Coconut trees also have a low leaf surface compared to the vegetation found in the rainforest. The ground between the coconut trees is mainly covered with short cut grass type vegetation. Due to the large open space and the minimal ground cover the interception rate of a coconut plantation is approximated to be only 10%.

The results per surface cover category are given in Table 18

Table 18: Interception per surface cover category

Category	Rainforest	Settlement	Coconut plantation
Interception rate	0.15	0.10	0.10

Surface Runoff

Part of the net precipitation runs off on the surface. There are two types of surface runoff. The first type is Hortonian overland flow and occurs when the precipitation intensity exceeds the infiltration capacity of the subsurface. The second type is saturation overland flow and occurs when the subsurface is saturated. The first type occurs mainly on paved roads and the later on wetlands at the toe of a slope.

When no records are available to evaluate the relation between long duration rainfall and runoff or rainfall and peak runoff, the Rational Formula is often used to get an indication of peak runoff [32].

$$Q = C * i * A \tag{23}$$

With:

Q	Peak discharge, runoff	$[L^3T^{-1}]$
C	Rational method runoff coefficient	[-]
i	Rainfall intensity	$[LT^{-1}]$
A	Drainage area	$[L^2]$

The peak discharge is a function of the so called runoff coefficient C. This dimensionless parameter has a value between 0 and 1 and represents not only the runoff coefficient for the peak but also for the total volume of runoff. The value of C depends on the soil group as distinguished by the U.S. Soil Conservation Service (SCS) as well as the kind of surface where the rain falls down upon [34].

The soil group qualification is shown in Table 19 and based on the minimum infiltration rate of rainwater, directly related to the hydraulic conductivity, and looks as follows (1 inch = 24.5mm):

Table 19: Soil group description

Soil group	Infiltration rate [inch/hour]	Infiltration rate [mm/hour]	Soil description
A	0.30 – 0.45	7.4 – 11	Deep sand; deep loess; aggregated soils
B	0.15 – 0.30	3.7 – 7.4	Shallow loess; sandy loam
C	0.05 – 0.15	1.2 – 3.7	Clay loams; shallow sandy loam; soils low in organic content; soils usually high in clay
D	0 – 0.05	0 – 1.2	Soils that swell significantly when wet; heavy plastic clays; certain saline soils

The surface of Koh Tao consists of rock outcrops and weathering products from these rocks, such as sand and gravel. Here it has been assumed that the total beach area is negligible. For each surface area type the most suitable soil group has been determined. The group being known, the kind of coverage of the soil and angle of the surface is important to eventually determine the appropriate runoff coefficient. In order to do so, Table 20 can be used [34].

Table 20: Runoff coefficients per soil group (1 acre ≈ 4047m²)

	Soil Group A			Soil Group B			Soil Group C			Soil Group D		
Slope :	< 2%	2-6%	> 6%	< 2%	2-6%	> 6%	< 2%	2-6%	> 6%	< 2%	2-6%	> 6%
Forest	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Meadow	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Pasture	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Farmland	0.14	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Res. 1 acre	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Res. 1/2 acre	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.46
Res. 1/3 acre	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Res. 1/4 acre	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Res. 1/8 acre	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Industrial	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets: ROW	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Parking	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97
Disturbed Area	0.65	0.67	0.69	0.66	0.68	0.70	0.68	0.70	0.72	0.69	0.72	0.75

Rainforest: Most rainforest is located on relatively steep slopes, with a slope angle of more than 6%. The soil type is a combination between soil group A and B, rock outcrops can also be found which do not allow infiltration. The ground surface is covered with all types of dead and living vegetation that hinder runoff. The runoff coefficient for the rainforest area of Koh Tao is approximated at 15%.

Settlement: Settlement area has paved roads that form a highway for runoff water. The surface is best described by soil group D due to its low infiltration rate. The infiltration capacity in the settlements is low since the majority of the area is covered by concrete. The settlements are mainly located on the west side of the island, where a gentler slope is present. With this knowledge, the runoff coefficient for the settlement area of Koh Tao is approximated at 70%.

Coconut plantation: The area between the trees is covered with low density cut grass type vegetation. The plantations are mainly located on hill slopes. The soil group that best describes the surface cover of a coconut plantation is soil group B. The runoff coefficient for the coconut plantation area of Koh Tao is approximated at 30%.

Table 21: Runoff coefficient [32]

Type of drainage area	Runoff coefficient
Sandy soil	0.05-0.20
Heavy soil	0.13-0.35
Business	0.50-0.95
Residential	0.25-0.75
Industrial	0.50-0.90
Streets	0.75-0.95
Roofs	0.75-0.95
Forests	0.10-0.60
Pastures	0.10-0.60
Arable land	0.30-0.80

The results for surface runoff are summarized in Table 22. The results have been verified with the results of Table 21, which gives the runoff coefficient range of different types of surface cover [32].

Table 22: Surface runoff

Category	Rainforest	Settlement	Coconut plantation
Surface runoff factor	0.15	0.70	0.30

Finding an acceptable value of surface runoff factor C is an arbitrary process, in this case the runoff coefficient is derived from literature and observations on the island. Surface runoff strongly depends on the duration and intensity of rain events. Also, the interval period between rain events influences the degree of saturation of the subsurface. Runoff occurs when the infiltration rate of the soil is exceeded [35].

Evapotranspiration

The infiltrated water generally first enters the unsaturated zone. That is the zone where the pore space between the soil particles contains both water and air. Only in this zone roots of plants are located, as they need oxygen to survive. This part of the unsaturated zone is called the root zone. The roots extract water from this zone for plant transpiration. Transpiration is water vapour diffusion via mainly the pores of the leaves. Water in the unsaturated zone also evaporates. The combined effect is called evapotranspiration.

The evaporation of wet vegetation is computed in the same way as open water evaporation only with different albedo and sometimes a different wind function. However, vegetation is not always wet. The potential evaporation is the evapotranspiration of vegetation that is dry at the outside and its full water need is available in the root zone. The real evaporation is lower than the potential evaporation due to water deficit in the root zone. The potential evapotranspiration can be calculated by formula 24.

With E_{ref} being the reference evaporation, in this case the open water evaporation determined by pan evaporation.

$$E_p = k_c E_{ref} \tag{24}$$

With:

E_p	Potential evapotranspiration from vegetation	$[LT^{-1}]$
k_c	Crop factor	[-]
E_{ref}, E_{pan}	Reference evaporation, in this case based on pan evaporation (open water)	$[LT^{-1}]$

Reference evaporation

The reference evaporation is divined as water transpired by a short green crop, completely shading the ground, of uniform height and never short of water. Grass is often chosen as the reference crop, the potential evapotransipration over short grass is commonly similar to the free-water evaporation found with an evaporation pan [36].

Pan evaporation data is available for Chumpon on the mainland and Koh Samui, one of the neighbouring islands. From this data provided by the Thai metrological institute the pan evaporation in the period from 1982 until 2015 has been plotted for both Chumpon and Koh Samui (Figure 34). The obtained figure shows that the evaporation on Koh Samui has been systematically higher compared to Chumpon.

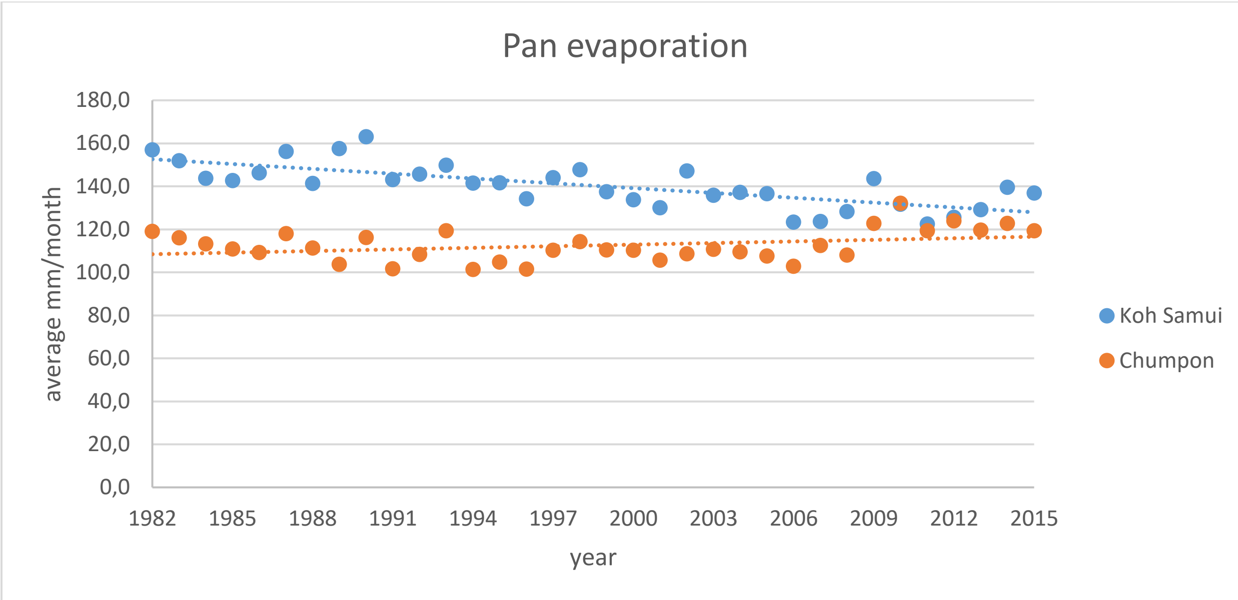


Figure 34: Average monthly pan evaporation at Chumpon and on Koh Samui from 1982 until 2015

Logically the difference can be explained by the surroundings of both locations, as Koh Samui is an island and Chumpon is located on the mainland. Islands are likely to be subjected to higher wind speeds due to the absence of a geography that provides shelter. Wind removes saturated air or air with an increased humidity from the water-air interface and provides drier air that is more capable of absorbing moisture [35]. As an island, the evaporation on Koh Tao is likely to be more like the evaporation measured on Koh Samui. Therefore data from Chumpon has been discarded and the approximated evaporation on Koh Tao is solely based on the data from Koh Samui.

Looking at the Koh Samui pan evaporation data in Figure 34, a downward trend can be distinguished. No clear explanation for this finding can be given by the authors. Therefore a conservative estimation for the expected future evaporation will be made. This is done by refraining extrapolation of this downward trend. Instead, the average value has been chosen to be used as an estimator for the evaporation. The average pan evaporation that is found amounts 140.3mm/month, which equals 1683.4mm/year.

The pan evaporation can differ from the true open water evaporation due to scale effects and heat exchange through the pan. In order to correct for these effects the pan factor is introduced in order to calculate the open water evaporation properly [37]. As a formula this looks as displayed in formula 25:

$$E_{open\ water} = k_{pan} * E_{pan} \tag{25}$$

It is unclear what the pan factor is for the pan that has been used by the Thai metrological department. One thing that can be said is that for most climates the maximum error is 10% [35]. This means that the pan factor ranges between 0.9 and 1.1. The average of this range is a pan factor of 1, implicitly meaning that the open water evaporation equals the pan evaporation.

With the reference evaporation known the potential evapotranspiration for the different type of surface covers can be determined. The potential evapotranspiration per surface cover is determined based on a crop factor based on literature and a surface factor based on findings on Koh Tao [36]. The crop factors found in literature give a value determined under standard conditions. No limitations are placed on crop growth or evaporation from soil water and salinity stress, crop density, pests and diseases, weed infestation or low fertility. The effect of both crop transpiration and soil evaporation are integrated into a single crop coefficient [36].

Rainforest: The rainforest area contains great variety in vegetation. Most trees found in the rainforest area on Koh Tao and on the list of FAO have a crop factor close to 1.0 [36]. Most crops in the FAO list are fruits. The crop factor of rainforest is approximated to be equal to 0.95. The forest area not only consists of vegetation, a small part is covered with rock outcrops. The surface factor derived for the forest area is 0.9. The annual potential evapotranspiration of the forest area is:

$$E_{p,rainforest} = 0.9 * 0.95 * 1683.4 \approx 1440mm \qquad (26)$$

Settlement: In settlement area a limited amount of vegetation is present. Most settlements have a high percentage of paved surface. The water that evaporates from the surface is already treated in the interception. But the surface cover of the settlement area also has a considerable permeability. Water that infiltrates in paved area can hardly evaporate any more. The moisture- and vapour transport through the joints between the elements is very limited because of their limited surface, their height and the type of soil (sand) in the joints between two elements [32]. The vegetation in the settlement area is comparable to the vegetation in the rainforest. Approximately 30% of the settlement area consists of vegetation. The potential evapotranspiration is calculated by:

$$E_{p,settlement} = 0.3 * 0.95 * 1683.4 \approx 480mm \qquad (27)$$

Coconut plantation: The coconut plantations consist of coconut trees and lawn. The crop factor of coconut trees is between 0.95 and 1.0 depending on the growth stage. The crop factor of grass is 1.0 [36]. A surface factor of 0.8 is added since there are roads and rocks present on most coconut farms. The potential evapotranspiration of coconut plantations is:

$$E_{p,coconut\ plantation} = 0.8 * 1.0 * 1683.4 \approx 1345\text{mm} \qquad (28)$$

The actual evapotranspiration depends on the potential evapotranspiration and the availability of water in the unsaturated zone. Also factors such as soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration. The effect of soil water content on evapotranspiration is conditioned primarily by the magnitude of the water deficit and the type of soil. On the other hand, too much water will result in water logging which might damage the root and limit root water uptake by inhibiting respiration [36].

The availability of water in the unsaturated zone depends on the amount of annual rain events, the intensity and the division in time. Koh Tao is a monsoon area which means that the precipitation is strongly divided over the year (Appendix I).

Converting the potential evapotranspiration to a representative annual evpotransporation (E_{adj}) is an arbitrary process. To do so the potential evapotranspiration has been multiplied by a factor α.

$$E_{adj} = \alpha * E_p \tag{29}$$

Factor α takes into account the season dependency of the amount of precipitation events as discussed in Appendix I. It is likely for the root zone to contain insufficient or too much water to reach potential evapotranspiration for significant periods per year. The rain events with the highest intensity occur in the period with the most days with a rain event (monsoon season). Also, transpiration is a process that occurs primarily during daytime for the vegetation present on Koh Tao. A brainstorm session in which the prior mentioned knowledge is taken into consideration resulted in the expectation that on average one-third of the potential evapotranspiration is reached. For this reason the α-factor has been given the arbitrary value of 0.3. The annual representative values per surface category in millimeter are given below and summarized in Table 23:

$$E_{adj,Rainforest} = 0.3 * 1440 \approx 450mm \tag{30}$$

$$E_{adj,Settlement} = 0.3 * 480 \approx 150mm \tag{31}$$

$$E_{adj,Coconut\ plantation} = 0.3 * 1345 \approx 400mm \tag{32}$$

Table 23: Annual evapotranspiration per surface cover category

Category	Rainforest	Settlement	Coconut plantation
Evapotranspiration[mm]	450	150	400

The reduction factor is primarily based on recharge of the root zone. In settlement area the vegetation is often irrigated by wastewater and the coconut plantations on Koh Tao are also irrigated during dry spells but only with stored directly caught precipitation. When the reservoirs are empty no irrigation is likely since the unit price of water is high.

The accuracy of the potential evaporation and the α-factor is low. Thereby the accuracy of total evapotranspiration is low. In practice the crop factor strongly depend on the growth-stage and the condition of the vegetation. Also the annual precipitation characteristics strongly determines the availability of water in the root zone.

Subsurface Runoff

Subsurface runoff is a slow process compared to surface runoff. The top layer on Koh Tao consists mainly of weathering products, which are situated on top of weathered granite (see chapter 5). Subsurface runoff takes place in the layer of weathered materials as well as sandy layers. Water in the pore spaces flows through preferential flow paths. The flow speed is determined by the pore space and the pore space depends on density of the grain lattice. Flow is possible due to a difference in head. On Koh Tao the difference in head is mainly caused by the relief of the (weathered) bedrock and the extraction of groundwater [38].

Water flows through the top layers to the ocean or comes back to the surface by seepage. Water flowing through the subsurface is also still available for evaporation and transpiration. Not all subsurface flow is lost, the flow can partly be utilized as tap water when it recharges a well.

Rainforest: Most of the rainforest area is located on the steep sloping east and north side of the island. The steep slopes will contribute significantly to the subsurface flow. Estimated is that 20% of the infiltrated water flows via the subsurface to the ocean.

Settlement: The settlement area is located mainly on the shallow sloping west side of the island. Infiltrated water has little chance to evaporate as mentioned in the evapotranspiration part of this appendix. The subsurface runoff coefficient of the settlement area is estimated at 10% of the infiltrated water.

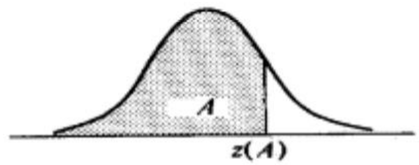
Coconut plantation: Full grown coconut trees have relative shallow roots reaching to a depth of a little over 1m with a diameter of approximately 4m [36]. Plantations are located on slopes varying from shallow to steep. The percentage of infiltrated water lost due to subsurface flow is estimated at 15%.

The results for subsurface runoff are summarized in Table 24.

Table 24: Subsurface runoff rate per surface cover category

Category	Rainforest	Settlement	Coconut plantation
Subsurface runoff rate	0.20	0.10	0.15

Appendix L: Confidence Interval Determination (ช่วงความเชื่อมั่น)



z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998

Figure 35: Confidence interval determination

With the confidence interval the probability of a certain event is calculated. In case of Chapter 7 the probability of a (non-)sustainable extraction rate was calculated. The precipitation on Koh Tao is described by a normal function with a mean of 1933.8mm and a standard deviation of 319.1mm (Appendix I). Calculation of corresponding z-value is possible with the following formula:

$$z = \frac{mean - precipitation}{standard\ deviation} \tag{33}$$

Appendix M: Reverse Osmosis Desalination (ระบบรีเวอร์สออสโมซิส)

Desalination is the process of removing dissolved matter (salt) from sea or brackish water. Two methods can be distinguished, being thermal based and membrane based desalination.

Reverse osmosis (RO) is a method in which a semi permeable membrane is applied. This membrane separates two solutions and only allows water to pass through. In theory, dissolved matter such as salt will not be able to pass through the membrane. If the concentration of salt is different at both sides of the membrane osmosis will occur. Osmosis is the process of water flowing through a semi permeable membrane from the low to the high concentration of dissolved matter. This process is driven by the osmotic pressure (ΔΠ), the difference in concentration implies. Flow will stop if the concentration on both sides is equal, meaning that ΔΠ = 0 Bar. The process of osmosis is shown on the left in Figure 36.

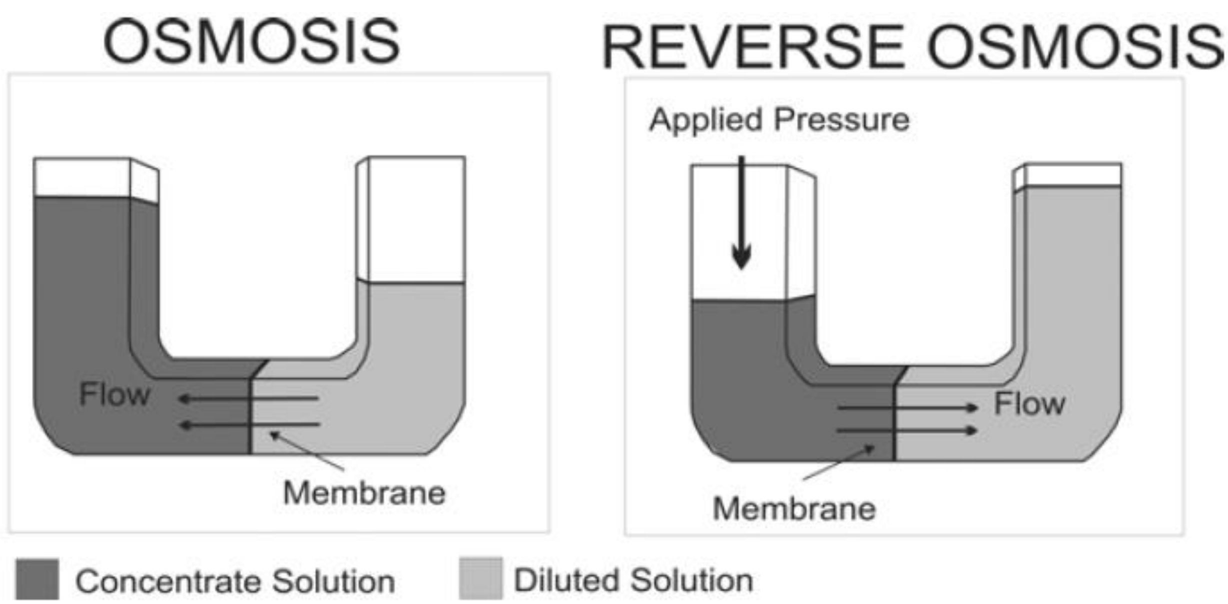


Figure 36: principle of osmosis and reverse osmosis (Flow indicates the water flow) [10]

The diluted solution has a lower salt concentration, causing water to flow to the concentrate solution side lowering the salt concentration there until both concentrations are equal. The process of osmosis will be reversed if a differential pressure ΔP larger than the osmotic (counter) pressure is applied on the concentrated solution. In other words, reverse osmosis (RO) means that water from a solution with a higher salt content flows to a solution with a lower salt content. The osmotic pressure is determined by the difference in salt concentration between both sides of the semi permeable membrane. A higher difference implies a larger osmotic pressure. This explains why a higher pressure has to be applied when reversing the osmotic process on sea water than on brackish water. In practice, pressures vary between 15 bar in brackish water and 60-80 bar in salt water [10]. The typical salt content (TDS) of raw water is 1,000 to 45,000 ppm, with a product water quality of typically less than 500 ppm.

Efficiency of RO process

The percentage of salt that is removed by the semi permeable membrane when water passes through is called rejection. In practice there is a relationship between the applied differential pressure, initial salt content of the feed, and rejection rate. Generally, a higher applied pressure will increase the rejection rate.

The amount of water that passes through the semi permeable membrane per unit of time (permeate flux) is also a function of the applied differential pressure. This is an important parameter when assessing the production capacity of a RO desalination plant. Figure 37 shows the relation between the applied differential pressure, salt content, rejection rate and permeate flux [10].

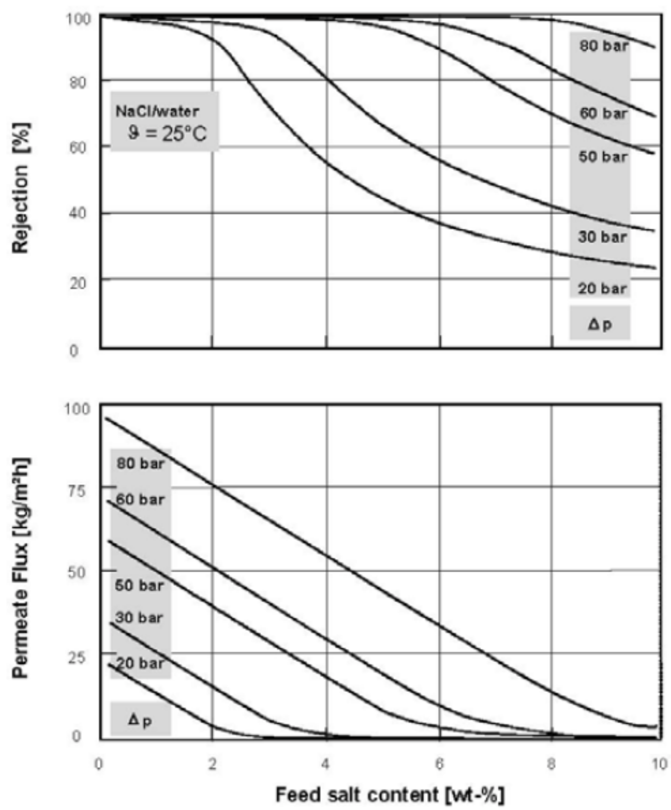


Figure 37: Relation between the salt content, rejection and permeable flux in a RO plant as a function of the applied pressure on the feed [10]

There are factors that may limit the performance of the RO process. These are concentration polarization, membrane deterioration and blocking principles. The latter can be divided into scaling and fooling. The mentioned limiting factors are introduced underneath together with other features of RO desalination.

Concentration polarization

Rejected dissolved matter accumulates and causes a high concentration right in front of the membrane. This phenomena is called concentration polarization and has several negative consequences on the performance of the RO plant [10].

- The salt flux increases, meaning that more salt passes through the membrane. In other words, the rejection decreases.

- The osmotic pressure increases at the membrane. At a constant differential pressure the water flux is decreased.
- Solid particles that accumulate on the membrane may form a cake. This decreases the effective surface of the membrane (see fooling).
- The concentration of dissolved salts can increase up to such an extent that a phase change occurs and solid salt precipitates on the membrane (see scaling).

Membrane deterioration

Pre-treatment of the feed by means of oxidants causes the membrane surface to oxidize. Even trace concentrations of oxidants may initiate significant deterioration of the membrane. Very high and low pH values may contribute to deterioration as well when certain polymeric membranes are used. Therefore the pH value of the feed has to be kept between certain boundaries in order to keep from excessive damage of the membrane surface. This pH range differs depending on the kind of membrane used [10].

Scaling

At the feed side of the membrane super-saturation of inorganic compounds can occur due to concentration polarization. A film of precipitated salt can be formed at the surface of the membrane. As a consequence, mass transport through the membrane is reduced or even inhibited. Typical scaling substances are: $CaCO_3$, $CaSO_4$, $BaSO_4$ and silica. In order to avoid scaling the feed can be treated by means of pH adjustment and adding oxidizing chemicals such as chlorine and ozone [10].

Fooling

In case of fooling a layer is formed at the membrane that consists out of matter that is transported in the form of a suspension or colloid. The layer can also be formed as a result of bio growth, so called bio-fooling. The main consequence of fooling is that it reduces the mass transfer capacity of the membrane. Besides that, an increased pressure loss over the membrane causes a lower rejection rate. Fooling can be mitigated by pre-treating the feed by means of (sand bed) filtration or membrane pre-treatment. Bio-fooling can be reduced by adding chlorine to the feed during pre-treatment. Besides that periodic chemical membrane cleaning has to be conducted. Nevertheless membrane fooling cannot be stopped completely, and has to be tolerated to some extent [10].

Pre-Treatment

Pre-treatment has to be done in order to remove suspended particles by means of a filter and adjust the consistency of the feed by means of chemicals in order to reduce scaling and fooling. To control scaling, oxidants are added to the feed. Besides that, the pH value is adjusted as well. In order to prevent biological fooling, chloride is used. Pre-treatment can also be done by means of a (beach) filtration, or a combination of both [10].

Post-Treatment

The discharge from a RO operation has a high salinity as it contains the salt that was removed by the plant. pH values in the acid range (lower than 7) may be expected as well. The fact that Koh Tao hosts coral that is susceptible to an increased acidity of seawater it is important to make sure that the acidity of discharge does not exceed a value of 8 [10]. In practice this means that an alkalizing substance has to be added to the discharge before being released into the sea. If drinking water is produced, $CaCO_3$ is added in order to ensure that the produced water has a taste people are used to.

Temperature

The temperature of the feed water is not increased during intake with the RO process. Due to friction and flow through the plant the brine is expected to have a temperature which is 1 to 2 degrees centigrade higher with respect to ambient water. From the dilution model applied to the Barrup Peninsula RO plant wastewater would be less than 2 degrees warmer than the ambient water 7 meters from the outlet. At a distance of 110 and few hundred meters from the outfall the temperature had lowered to 0.25 and 0.1 degrees above ambient temperature respectively [12].

Salinity

The salinity of the brine that is produced depends on the recovery rate of the RO plant. A higher recovery rate implies a higher brine salinity as well. In general it can be said that the produced brine has a salinity of approximately twice the salt content with respect to seawater. This increased salt content causes a difference in density between the brine and seawater. If there is too little mixing, the brine might form a layer under the less dense sea water. In order to establish sufficient dilution sufficient flow is required. Another parameter that determines whether an increased salinity is present at a certain distance from the outlet is the amount of brine that is produced per unit of time. When looking at the Canary Island desalination plant, that produces approximately 17,000m^3 brine per day, the salinity is back to sea water salinity only 20 meters from the outlet. A note here is that the brine production of this plant is about 5 times as high as the expected production of a RO desalination plant on Koh Tao. As a consequence, the distance where no noticeable increase in salinity can be seen is likely to be much smaller than the 20 meters stated above [12].

pH

Pre-treatment at the RO plant is de-chlorination of the feed water. This may cause the brine to become slightly acidic. pH values in the acid range (lower than 7) may be expected. The fact that Koh Tao hosts coral that is susceptible to an increased acidity of seawater it is important to make sure that the acidity of discharge does not exceed a value of 8. In practice this means that an alkalizing substance has to be added to the discharge before being released into the sea. Without adding an alkalizing substance, such as $CaCO_3$, the acidity is likely to be back to ambient values within meters from the outlet [12].

Dissolved oxygen

Heating of feed water reduces the percentage of dissolved oxygen in the produced brine. Due to marginal heating of feed water in the RO process a non-significant reduction in dissolved oxygen percentage is expected. In order to reduce the occurrence of corrosion at the membrane and remove residual chlorine NaHSO3, or sodium bisulphite, is added to the feed. A property of this chemical compound is that it is oxygen consuming. As a consequence, the amount of dissolved oxygen in the feed and therefore produced brine is reduced. Rapid dilution is expected to bring the dissolved oxygen back to ambient levels close to the outlet [12].

Added Chemicals

During the RO process chemicals are added to the feed and as a part of the post treatment step. Their application as well as their expected impact is explained below.

Anti-scalants

These are chemicals that are used with the purpose of reduce the occurrence of scaling. If not familiar with the principle of scaling it is recommended to consult subchapter scaling of this appendix. Anti scalants in general have a low potential negative effect on sea life. This is mainly due to the fact that they are applied in very low concentrations, typically 2 ppm, and therefore imply a low environmental risk [12].

Coagulants

Coagulants can be applied during the pre-treatment stage in order to bind suspended matter forming bigger particles that can be removed easier when cleaning the membrane by means of backwashing. The principle of backwashing is explained in subchapter 'maintenance' of the report. When the membrane is cleaned the waste is usually released with the brine through the outlet. Ferric oxide is an often used coagulant that has the property to color the waste brine, which implies a reduced light penetration rate as a consequence. In order to reduce the need for ferric oxide in the pre-treatment stage suspended matter should be taken out of the feed by means of pre filtration [12].

Biocides

Seawater at the intake usually contains living organisms such that can cause fooling when in touch with the filter. A strong oxidant such as chlorine is toxic to sea life and can be used to prevent so called bio-fooling. As a product halogenated organic by-products are formed. These organic compounds have a harmful influence on marine live when released into the sea. In order to prevent this, the chlorine is neutralized by means of sodium metabisulphite before the feed reaches the membrane. As a result the low concentrations of chlorine remain in the waste brine [12].

Cleaning chemicals

Periodic cleaning is required in order to keep the RO plants performance at its targeted level. The kind of cleaning chemical required depends on the kind of membrane that is applied. Membrane cleaning happens during downtime, which allows for separation from waste brine and disposal on land. An alternative is to release the cleaning chemicals together with the brine. When disposal together with brine is applied, neutralization is required as the cleaning chemicals cause a moderate to extreme pH in the acidic range [12].

Heavy metals

The brine discharge coming from a RO desalination operation is likely to contain low concentrations of heavy metals due to the fact that the plant is mainly constructed out of corrosion resistant stainless steel. This also means that there is a direct relationship between the amounts of heavy metals released and the quality of steel applied when constructing the plant. Corrosion might cause increased concentrations of iron, chromium, nickel and molybdenum in waste brine. Heavy metals in the feed water accumulate in the waste brine, causing an increased concentration. A RO desalination plant on Koh Tao will have a size such that sufficient dilution of heavy metals is expected at a short distance from the outlet [12].

Sea Life Interacting with Intake

If an open water intake is used sea life is likely to be sucked in if no other precautions are taken. In general a screen with a 5mm mesh is applied to keep large sea animals from entering the intake. If the flow rate at the intake does not exceed 0.1m/s sea life such as fish or sea turtle hatchings are capable of swimming away. Smaller animals and plankton are likely to end up in the RO installation [12].

Appendix N: Salt Content Sea Water (เกลือทะเลเนื้อหา)

In this appendix the method used to estimate the amount of total dissolved solids (TDS) in Koh Tao's sea water is described, as well as the obtained results.

In order to measure the amount of total dissolved solids (TDS) a PCE-CM 41 pen type conductivity meter is used. This piece of equipment allows for measurements in fluids with a TDS value of maximum 13.200 ppm, at a resolution of 10ppm and an accuracy of ±3%. Seawater has a TDS value higher than the maximum of 13.200 ppm that can be measured. Therefore, a dilution series is made in an attempt to find the TDS by means of linear extrapolation. The aim of this experiment is to find the order of magnitude only, which explains why only one dilution series is made.

Nestlé drinking water, purchasable on Koh Tao in a plastic bottle, is used to dilute seawater. During the first measurement the TDS of this drinking water is measured. After that 100ml of sea water is put into measuring cup and diluted with 200ml of bottled water. The conductivity meter is capable of estimating the TDS content of this solution. Hereafter 100ml of drinking water is added to the solution and the TDS content measured after homogenization by means of a plastic stick. The process of diluting the solution and measuring the TDS content continues with steps of 100ml until a solution with 100ml seawater and 1000ml drinking water is formed.

The measured TDS contents is plotted as a function of the drinking water fraction in the solution, as shown in Figure 38.

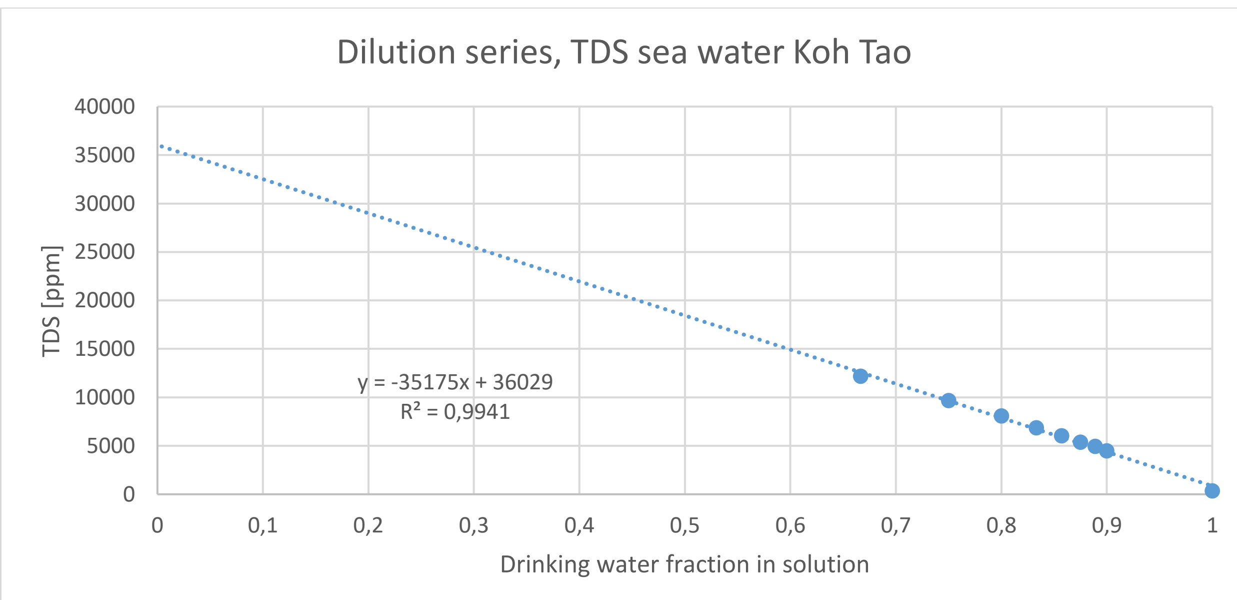


Figure 38: TDS sea water Koh Tao extrapolation of dilution series

A strong linear correlation is found, with a R^2 value of 0.9941. This allows for reliable extrapolation of the results. When looking at the trend line at a drinking water fraction of 0, the theoretical amount of TDS in seawater can be found. From this experiment and complementary analysis a TDS content of 36.029 ppm is derived for sea water around Koh Tao. This measurement was taken in May 2016.

Appendix O: Cost of RO Desalination (ค่าใช้จ่ายของการกลั่นน้ำทะเล)

Over the years the characteristic costs for sea water reverse osmosis have decreased significantly, from around 2$/m^3$ in 1998 to 0.5$/m^3$ in 2004. This change is mainly the result of technological membrane improvements and more competition on the market. Economy of scale applies to industrial processes such as RO, meaning that the price per produced m^3 of water depends on the capacity of the system. The costs and capacity of different RO operations can be seen in Table 25. Generally, this table shows that a higher capacity implies a lower eventual water price [7].

Table 25: Capacity and costs of different reverse osmosis operations [7]

Location	m^3/day	Operative since	\$/m^3
Eilat, Israel	20,000	1997	0.72
Larnaca, Cyprus	56,000	2001	0.83
Tampa, Florida	106,000	2003	0.56
Ashkelon, Israel	272,000	2004	0.54

The price is a sum of different factors. Table 26 shows a representative range of costs. Here, the capital cost is referred to as an operational cost taking into account the interest rate and lifetime of the plant. In this example a RO plant with a daily capacity of 200.000m^3/day is considered [7].

Table 26: Representative range of costs for a RO plant with a capacity of 200,000m^3/day

Product water cost component	$/m3
Capital cost, including land fee (25 years at 6.0% interest)	0.203 – 0.338
Electric power ($0.060/kWh)	0.180 – 0.240
RO membrane replacement (5 years membrane life)	0.025 – 0.035
Chemicals	0.020 – 0.025
Maintenance and spare parts	0.023 – 0.038
Labor	0.03
Total cost	*0.481 – 0.676*

Appendix P: Discounted Cash Flow RO Plant (**การคิดลดกระแสเงินสด**)

The elaborate estimated discounted cash flow for a RO plant looks as shown in Table 27.

Table 27: Discounted cash flow from which NPV of a RO plant on Koh Tao follows

	1	2	3	4	5	6	7	8	9	10	11	12
production m3	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*
Revenue $	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000
transport	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500
OPEX variable	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817
Gross income	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683
Depreciation	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000
Net income before tax	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683
Tax	0	0	0	0	0	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937
Profit after tax	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747
Capex	-20,000,000	0	0	0	0	0	0	0	0	0	0	0
Cash Flow	-17,935,317	2,064,683	2,064,683	2,064,683	2,064,683	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747
Cumulative cash flow	-17,935,317	-15,870,633	-13,805,950	-11,741,267	-9,676,583	-7,864,837	-6,053,090	-4,241,343	-2,429,597	-617,850	1,193,897	3,005,643
discount factor	0.943	0.890	0.840	0.792	0.747	0.705	0.665	0.627	0.592	0.558	0.527	0.497
NPV	-16,920,110	1,837,561	1,733,548	1,635,423	1,542,851	1,277,210	1,204,915	1,136,712	1,072,370	1,011,670	954,406	900,383
Cumulative NPV	-16,920,110	-15,082,549	-13,349,001	-11,713,579	-10,170,727	-8,893,517	-7,688,602	-6,551,890	-5,479,520	-4,467,850	-3,513,445	-2,613,062
Cumulative NPV (Million THB)	-609	-543	-481	-422	-366	-320	-277	-236	-197	-161	-126	-94

13	14	15	16	17	18	19	20	21	22	23	24	25
5,475,000	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*	*5,475,000*
7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000	7,665,000
-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500	-1,642,500
-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817	-3,957,817
2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683	2,064,683
-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000	-800,000
1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683	1,264,683
-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937	-252,937
1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747
0	0	0	0	0	0	0	0	0	0	0	0	0
1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747	1,811,747
4,817,390	6,629,137	8,440,883	10,252,630	12,064,377	13,876,123	15,687,870	17,499,617	19,311,363	21,123,110	22,934,857	24,746,603	26,558,350
0.469	0.442	0.417	0.394	0.371	0.350	0.331	0.312	0.294	0.278	0.262	0.247	0.233
849,418	801,337	755,979	713,187	672,818	634,734	598,806	564,911	532,935	502,769	474,310	447,463	422,134
-1,763,644	-962,307	-206,329	506,859	1,179,677	1,814,411	2,413,217	2,978,128	3,511,063	4,013,832	4,488,143	4,935,605	5,357,740
-63	-35	-7	18	42	65	87	107	126	144	162	178	193