Indigenous Water Management:

Sustainable water conservation strategies in karstic dominated area in Rote Island, NTT Province, Indonesia

By:

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B.E (Hons) ***State University of Brawijaya*****, Indonesia 2000**

M.Sc ***Saxion Hogeschool Ijselland*****, the Netherlands and**

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A thesis submitted in fulfilment of the Requirements for the Degree of

Master of Engineering Science (Research)

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THESIS REPORT

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DEDICATION

TO IKA

my wife, you’re the gentle light who encourages me to step forward for our future in the name of the Lord

TO DIKA AND MARVEL

my sons, you’re extraordinary blessing from the lord who gives blissful joy and hope to me

CERTIFICATE OF AUTHENTICITY

I hereby declare that the work presented in this thesis is my own, except where otherwise noted, and was carried out in the Civil Engineering Department, Monash University (Australia). To the best of my knowledge, this thesis contains no material which has been accepted for the award of any other degree or diploma in any university and contains no material previously published or written by another person, except where due reference is given.

Dua Kudushana S.Y. Klaas

Civil Engineering Department
Monash University
2009

Abstract

The overall objective of the study are to analyse the Mamar in Rote Island, Indonesia including its hydrogeological system, water allocation and distribution, interaction patterns and social benefit for the community in Rote Island and to develop recommendation based on the analysis above towards sustainability of water use. The research present findings from literature review, field investigation, discussion and interview with inhabitants.

A theoretical and analytical foundation of karst system with regard to Rote Island is presented starting with climatological overview of the island and continues with hydrogeological, hydrochemical and water balance analysis in the study area. The study then presents the result of field investigation in seven villages in the island consisting of visual examination on geomorphological characteristics, on site water measurement and social survey in seven villages. The analysis is concluded with a set of recommendation on sustainable water management that incorporates physical karst characteristics in the island, hydroclimatological features and social arrangement in the island.

Climatologically, Rote Island, located between two main continents which are Australia and Asia and two oceans, which are Pacific and Indian Oceans is characterised by a typical monsoonal climate characterised by two distinct seasons (dry and wet) The annual rainfall ranges averagely from 1000 to 1400 mm with rain peaks between December and January and declines substantially on August or September.

The geology of Rote Island which is located in the Banda Arc subduction zone is characterised by two major rock types, which are Bobonaro Formation (61.1 %) that mainly consists of silt, and coralline limestone. Therefore, the island is categorised as karst dominated area with the formation of carbonate rocks that dictate the island. Confirming the dissolution process of karst rock, the hydrochemistry properties of groundwater in the study

area indicate that carbonate and bicarbonate which denote limestone and dolomite dominate the geology of the area.

In this study, the physical characteristics including the hydrological and hydrogeological of the Mamar is discussed, while the social aspects involved in the Mamar including organisational framework, organisational mechanism and working relationship, stakeholder and their role, rule in its institution and the enforcement mechanism are reviewed. Then, the potential trade-offs in Rote Island that may hamper the capability of Mamar spring to supply adequate water for the whole communities in Rote Island are examined before proposing measures as recommendation that can be taken to deal with potential water trade-offs in the island. Water balance analysis in the study area is presented to quantify the respond of karst system to hydroclimatological characteristics of Rote Island. The analysis shows vulnerability of groundwater availability in the study area as any change in land use which influences the infiltration and runoff components may greatly impact the total water budget in the study area. This in turn in the context of hydrologic cycle of karst area affects the groundwater supply to karst springs.

A conceptual model of karst system in Rote Island is then proposed in this study based on findings from literature review, field investigation and visual examination at the island. The model suggests that the type of karst aquifer in Rote Island differs spatially which is determined by geological formation in the pertinent area and timely which is determined by seasonal fluctuation of water table related with water input which is rain that functions as an input for recharge process in the area determines the amount of water discharged at spring. Consequently, this karst system is susceptible as it could respond rapidly to natural and anthropogenic processes.

The indigenous water management called Mamar is studied during the field investigation and presented in this study. Mamar System is defined as a local knowledge and practice of water management in Rotenese society in Rote Island to conserve karstic groundwater spring in order to primarily provide sufficient water for plantation and drinking water for the community living surrounding it. The Mamar System consists of a set of hierarchical order that is developed to conserve the spring and the plantation area surrounding it. Mamar spring that has primary functions, which refer to basic life supporting and economic roles in the community, and secondary functions which comprise of administrative, social and ecological functions, is a significant natural resource in the karstic-dominated island of Rote. The water manager called *Manaholo*, is responsible to administer the spring as well as the plantation area carrying tasks accompanied with a set of regulation. At the end the result of social survey using questionnaires, discussion and interview methods is presented showing the inhabitants' perspectives on existing management of Mamar System over the Mamar spring.

After reviewing the hydroclimatological, hydrogeological and social characteristics of Rote Island, a set of recommendation is proposed in this study. The proposed measures are technical measures, including determination of Protective Karst Area (PKA) and groundwater monitoring at Mamar springs, political measures, including legalisation of protective karst area (PKA) and public awareness campaign for adaptive society on sustainable water management, and socio-economical measures, including strengthening of Mamar System and cultivation of economic plants at diffuse recharge area.

Acknowledgement

Above all, I would like to greatly thank God Almighty in the name of Jesus Christ, my Saviour for all blessings that sustain my life and the purpose driven life that brings me to the completion of this study.

My family in Indonesia to whom I dedicate this study for: Papa Mama Klaas, Bapak Ibu Muhadi, Mba Esa and K'Nuel, dik Firman and dik Mubi, and all people who prayed for me and my family in Kupang and Banyuwangi.

I bestow my sincere gratitude to my supervisor, Dr. Gavin Mudd who diligently, critically and patiently guided me to the finalisation of this thesis.

To those also this page is dedicated are the members of Hawthorn-Oakleigh-Clayton Cell Group: Edy Sebayang, Arlinta Barus, Erik and Diana Simamora and your beloved sons, who persistently support me and my family when we stay in Melbourne for study. Time and frailty can't change the connection among us in the name of the Lord. The profound gratefulness is also presented for the member of CIUC, Caulfield Kappa, Paskaling, Daely, Hetharia families, to name some of them, who exceedingly pray and encourage us when we were pilgrim in this land.

My dazzling colleagues: Kok Yun Lee (Singapore) and Mahmoud Mesbah (Iran) who are keen to share lives and knowledge as friends and member of Monash academia. May our friendship last to wherever and whenever we are.

Table of Content

List of Figures

List of Tables

Chapter 1

INTRODUCTION

1.1. Situation Review

Water issues are considered as the primary problem on Rote Island, in East Nusa Tenggara Province (NTT), Indonesia. Each year society suffers from water-related disaster such as frequent drought. The disaster occurs in the dry-hot period of the year ranging from April until November. Characterised by minimum rainfall, drought crests on August resulting in some major detrimental consequences such as water shortage, harvest failure, and environmental destruction. The regional planning and development of this island are impeded by this condition.

Nevertheless, in some areas in Rote Island people practises local water management rules called “MAMAR”, which in this study called as Mamar System. Mamar System is an indigenous knowledge of managing a spring and the plantation area surrounding it. The mamar plantation generally occurs as a small pocket of forest around natural springs and along permanent streams and rivers or on land irrigated by the spring. The Mamar System, in which the spring physically and its mechanism socially are the essential components, acts as the hub of the community. This indigenous institution perhaps was the embryo of community engagement, which would advance into territory authorisation since traditionally people developed their social relationship around water resources. This unique customary has run for centuries in the way supplying water needs for daily consumption, agriculture, livestock, food, medicine, material for weaving and manufacture of households utensils and others. Regarded as the main source of livelihood, the Mamar develops society’s behaviour towards sustainable water conservation as well as environment-friendly agriculture and livestock practices.

The Mamar spring, which is characterised by physical features of karst landscape that dominates Rote Island, is the centre of the community as it continuously supplies water for the whole society throughout the year. Inhabitants rely upon the water provision of the spring. However, there are some factors that pose threats to the capability of mamar spring to supply adequate water for the whole communities in Rote Island. Those factors, namely increase in population, land use change, global climate change and abandonment of Mamar System as local knowledge, are argued to impact the hydrologic cycle of karst areas by which water recharge capacity to karst aquifer is reduced. The ultimate consequence is water insecurity as water supply from Mamar spring is declined. Therefore, it is important to develop a set of recommendations based on physical karst characteristics of Rote Island and the indigenous Mamar System in order to achieve sustainable water management in this island.

1.2. Research objective

The overall objectives of the research are:

1. To analyse the Mamar including its hydrogeological system, water allocation and distribution, interaction patterns and social benefit for the community in Rote Island.
2. To develop recommendation based on the analysis above towards sustainability of water use.

1.3. Main Research Questions

Having reviewed the current situation, the main research questions for this study are formulated:

1. What are the physical characteristics including the hydrological and hydrogeological of the Mamar?
2. What are the social aspects involved in the Mamar including organisational framework, organisational mechanism and working relationship, stakeholder and their role, rule in its institution and the enforcement mechanism?
3. What potential trade-offs in Rote Island that may hamper the capability of Mamar spring to supply adequate water for the whole communities in Rote Island?
4. What measures as recommendation can be taken to deal with potential water and environment trade-offs in this island?

1.4. Research boundaries

In order to deliver the answers to the main research questions, research boundaries are determined. The research boundaries direct this study into a confined and specific scope based on a realistic timeframe and efforts that can be afforded in this study. The geographical boundary is specifically set for Rote Island. This boundary reflects the local water management in this island including the physical karst characteristics that govern the physical hydrogeology properties and socio-cultural characteristics behind Mamar System. The study then streams to the review of the physical and social aspects of Mamar and identifies possible trade-offs that pose threats opposed to capability of Mamar spring to provide water for the whole community. At the end recommendations towards sustainable water management of Mamar are addressed.

1.5. Research methodology

1.5.1. Data and analysis

Primarily, data was obtained from literature review. This encompasses examining reports, books and journal articles relevant to this research. Furthermore, all data compiled were validated and compared by conducting field investigation in Rote Island. Field investigation aims at looking at and verifying the existing data obtained from literature review. The investigation also intends to gain other data such as social data from social survey and water discharge from direct measurement at Mamar springs. In the social survey, interview with relevant stakeholders were conducted in five villages. Interviews focus on acquiring their apprehension of problem and point of views towards Mamar. In order to quantify their perspective toward the local water management questionnaires were used. In the water discharge measurement, direct measurement method is used to determine flow rate of spring water in six locations.

1.5.2. Personal knowledge

This study was undertaken using a set of data that supports the analysis of Mamar System. A significant data for arguing the analyses and recommendations at the end of this study is essential. However, published data regarding Mamar is very limited. This indigenous water practice has mostly been known orally rather than being documented. Nevertheless, in this study, besides gathering existing literature, the efforts are also focussed to compile data in the form of oral traditions or customary narrated by locals in personal communications during the field investigation. This personal or communal knowledge, which is a legacy inherited for generations, is considered decisive in this study as it, together with physical data available for Rote Island, constructs the overall framework of Mamar analysis.

1.5.3. Research step model

Flowchart of the research is presented in Figure 1 – 1. It shows steps conducted in the study to answer the main research questions. This figure also illustrates the research methodology and how the results of each step are presented in the report.

In general, data were compiled from existing data available for Rote Island and field investigation. Those data that can be categorised as hydroclimatological data that feed hydrologic analyses, hydrogeological data that are used in geology and hydrochemistry analyses, and socio-cultural data which are relevant to social analysis. In the analyses part those data were examined to outline the water balance review on a particular study area, conceptual geological initiation of Mamar springs and Mamar System with regard to social and cultural values in Rote Island. Based on this outline potential trade-offs are concluded before arriving at proposed conservation strategies that is constructed to achieve a sustainable water management of the Mamar in Rote Island.

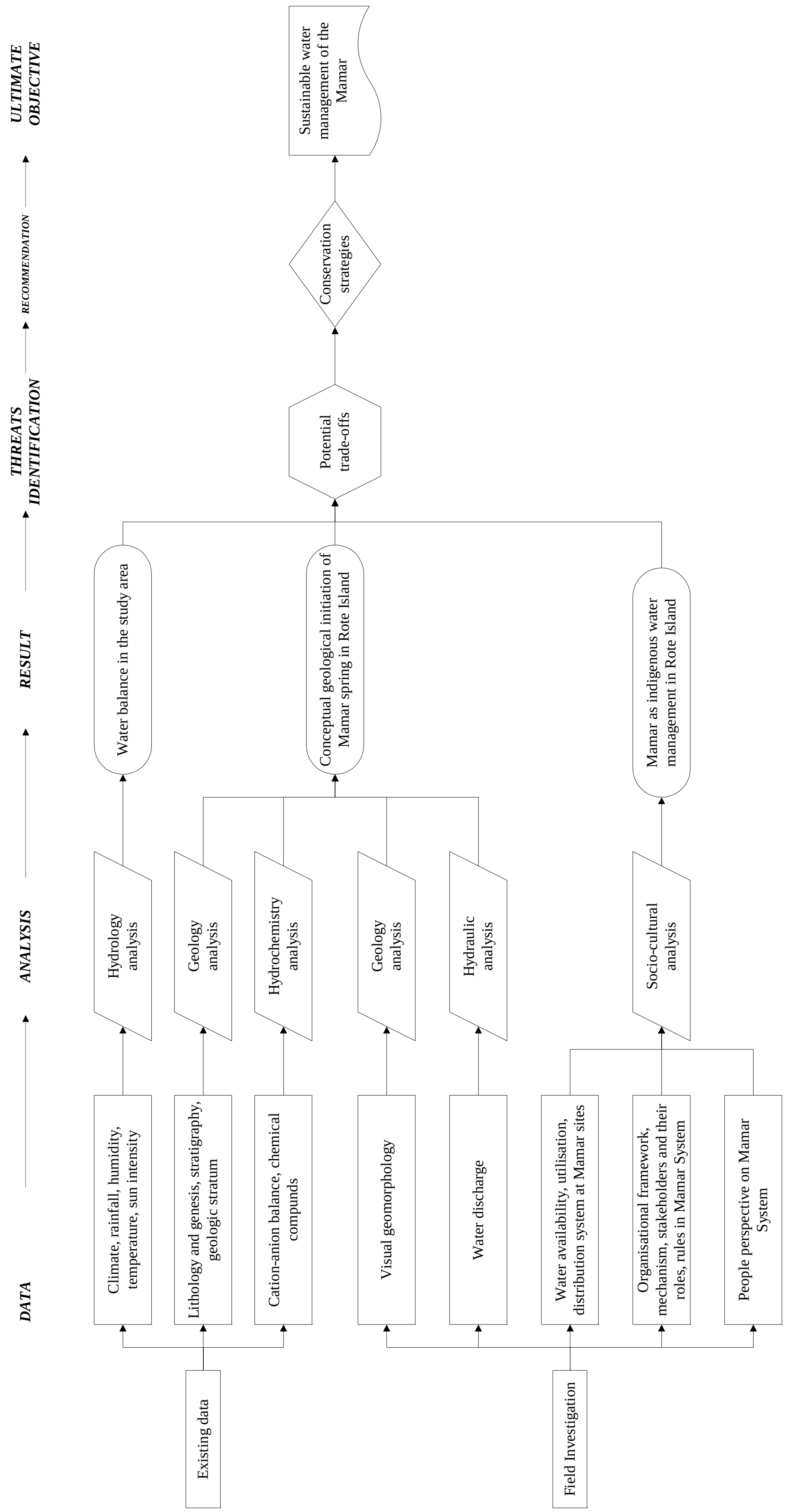


Figure 1 – 1. The research step model

Chapter 2

LITERATURE REVIEW

2.1. Introduction

This chapter firstly presents overview of the study area in section 2.2 including physical situation i.e. geography, topography and social aspects. In section 2.3 – 2.4, literature review is presented as foundation for further analysis. The sections consist of karst theories (Section 2.3) including explanation of its geomorphology, hydrogeology and hydrochemistry. Water balance concept (Section 2.4) is introduced by describing its components which are precipitation, evapotranspiration, surface runoff, infiltration and groundwater storage.

2.2. Description of the area

2.2.1. Geography and topography

Geographically, Rote Island is located between 10^{o}25’ and 11 ^{o}00’ South Latitude and between 121^{o}49’ and 123 ^{o}26’ East Longitude (Figure 2 – 1). Situated in south of Indonesian archipelago, this island lies in a line of outer islands that share a border with Australia to the southeast. There are two seas encircling this island, which are Savu Sea at north and Timor Sea at south.

The total area of this island is approximately 978.5 km^2 with elevation ranges mainly between 0 and 150 m above sea level (68.6%). Topography of this island is dominated with a highly undulated landscape that forms a very complex drainage system. Distribution of slope surface is varied where flatter areas are primarily found in both west and east ranging from 0.20 to

0.35 %. The slopes then substantially change between 11 – 28% towards the middle north of the island.

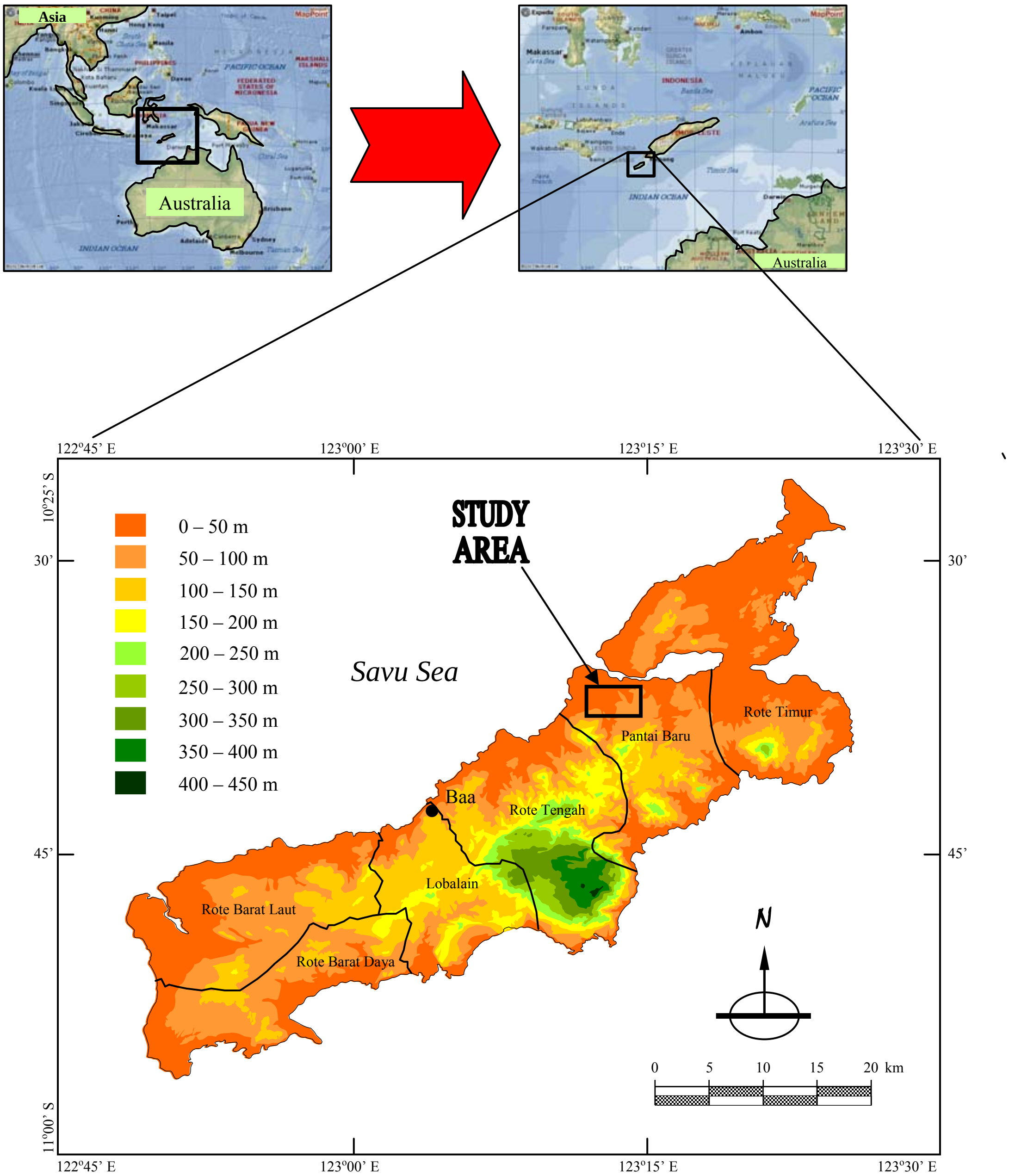


Figure 2 – 1. Study area

2.2.2. Population and socio-economy

Administratively Rote Island consists of six sub-districts (Figure 2 – 1). The total population of this island based on 2004 census were about 110,000 people. In general, from census data (BPS, 2002) collected in 2002 and 2004 population in Rote Island annually tends to increase by approximately 2.33% (Figure 2 – 2). The most notable rise appears in Lobalain Sub-district situated in the middle of the island where the growth reaches 13.56%. Meanwhile other sub-districts rise between 0.63 and 6.55%.

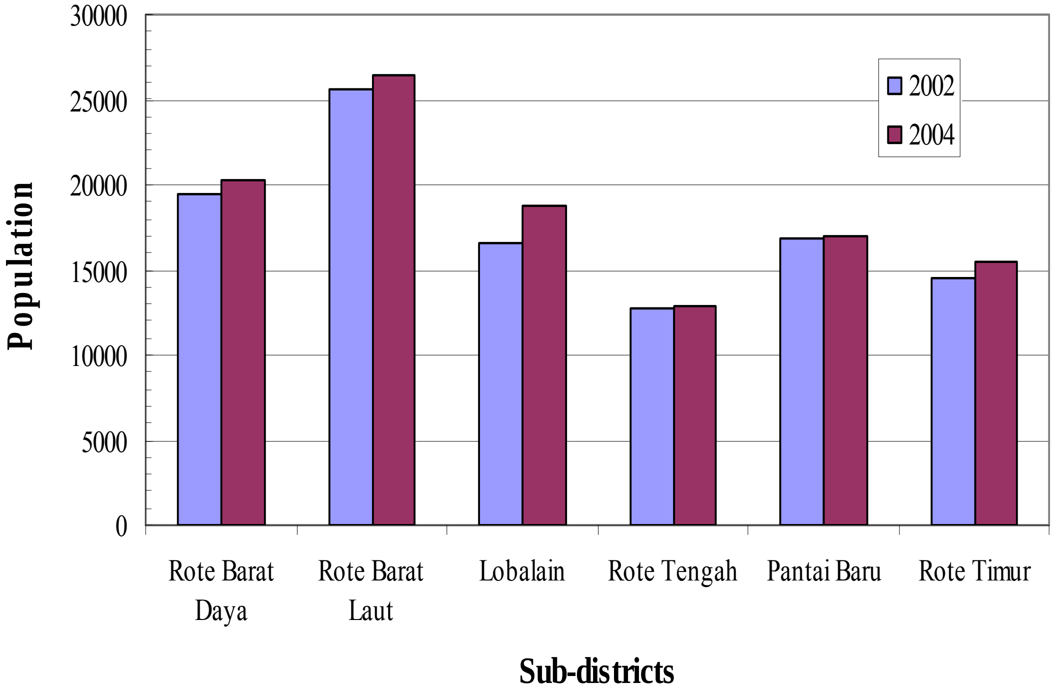


Figure 2 – 2. Population change in Rote Island between 2002 and 2004 (BPS, 2002, 2004)

The major change in demography in Lobalain Sub-district reflects population boom due to migration right after the shift of level of government from sub-district to regency. In the new administrative category, Rote Island has its own local government and legislative body. It also receives more allocation of funds from the central government in Jakarta. Therefore there was a significant demand for both infrastructures and human resources which already drove people to migrate to this island. Nevertheless, the distribution of migration is uneven. Migrants mostly resides in the capital (Baa) which is situated in Lobalain Sub-district in where people may enjoy quantitatively more and better facilities such as telecommunication, education and entertainment.

Most of the people in Rote Island rely on agriculture sector, from which 47% of the economic revenue comes (BPS, 2004) while other sectors such as service and trade play minor role in building the economy of this island. In agriculture sector, people make living from cultivation products such as rice, corn, sweet potato, groundnut, mung bean, shallot and watermelon. Shallot and watermelon are sold in other regencies in the province such as Kupang, TTS, TTU and Belu and become main source of income for the inhabitants. However, agriculture activities tend to be performed as small household-based farming system in which the ultimate objective is to feed domestic needs. Moreover, according to BPS (2004) agricultural activities only utilise 37% of the potential 47,700 Ha farming area in the island in which dry farming terrain dominates (63%). This has become the main economic concern as it is identified that the availability of water and thin top soil that dominates this karstic island are the major factors that impede development in agriculture sector.

2.3. Karst

2.3.1. Karst definition and its distribution

According to Ford & Williams (2007), karst is a form of landscape which consists mainly of soluble carbonate rocks such as limestone, marble and gypsum. This particular terrain is commonly characterised by substantive underground drainage systems, where complex cave systems are found. Karst landscape can be found all over the world, mainly in Mediterranean (Hussain, Al-Khalifah, & Khandaker, 2006; Raeisi & Karami, 1997), East Europe (Bonacci & Magdalenić, 1993; Fendek & Fendekova, 2005), East Asia (Liu, Groves, Yuan, & Meiman, 2004; Sweeting, 1995), North America (Hose & Pisarowicz, 1999; Miller, 1996) and Australia (Eberhard, 2004). Karst landscape occurs not only as a vast zone that dominates in part of these areas but also as a terrain that forms the overall shape of small islands such as those in Pacific (Allred & Allred, 1997; Terry, 2005) and Caribbean regions (Frank et al., 1998; Mylroie & Mylroie, 2007). In Indonesia, karst features are found in Java Island (Haryono & Day, 2004), West Papua (Polak, 2000), Sumba Island (Soenarto, 2004) and Rote Island (Sashidaa, Munasrib, Adachia, & Kamatac, 1999).

Karst plays important role in supporting live all over the world (Beach, Luzzadder-Beach, Dunning, & Cook, 2008; Jong, Cappy, Finckh, & Funk, 2008; Xiao & Weng, 2007). Its significant areas which cover 7-12% of the earth land surface (Drew, 1999) are occupied by people who rely on mainly its water provision. Its distinguished hydrologic characteristic which is storing water in its porous rock layers is essential by which approximately 20-25% of world population relies partly or wholly on water provision from its water (D. C. Ford & Williams, 1989). Apart from water provision function, karst also plays significant role as mineral resources as well as reserve of valuable energy resources such as oil and natural gas (Chen, Pan, Sa, Han, & Guan, 2005; Morozov, 2007). Moreover, the aesthetic value of karst landform such as cave and scenic area attracts people to visit for recreation and academic purposes (Veni, DuChene, & Crawford, 2001).

2.3.2. Karst geomorphology

Karst geomorphology is principally formed by highly soluble rocks. These types of rock that are often simply called carbonate rocks, are basically formed in a process conducted by organic activities. These activities take a long span of time, therefore, carbonate rocks can experience post-depositional modification (D. Ford & Williams, 2007). The formation of carbonate rock is dominated by limestone with a combination of dolomite, calcite and aragonite. The texture of carbonate rocks is very much varied from one place to another.

Limestone, which is the main source of a carbonate rock, is principally formed of calcite ($CaCO_3$). The main source of calcite that builds limestone structure is marine organisms. According to Ford and Williams (2007), limestone is mainly found in shallow tropical to warm moderate aquatic areas, particularly ramps and platforms. Here, limestone is formed by biological activities in marine environment where various animals develop a shell or skeleton. After these animals die their remnants then accumulate as deposits to form limestone. Moreover, limestone's highly soluble characteristic enables groundwater to dissolve or precipitate it and then build a calcite-formed limestone that can be easily seen as stalagmites and stalactites in karst caves.

Practically, there are several methods used to classify carbonate rocks. However, they can be categorised in two main divisions, which are matrix content-based and grain size-based approaches. Folk (1959) suggested a method of discerning limestone rock by recognising its physical appearance of allochems which are remnants of marine organism in rock structure. Moreover, Dunham (1962) and Lucia (1999) recommended carbonate classification based on depositional texture. Meanwhile, Jennings (1987) proposed another method which consists of more practical division of limestone rock by dividing rock based on its main grain size (Table 2 – 1).

This study focuses on outer appearance of rocks and not on matrix level which has to be performed in a laboratory. Therefore, Rote karst limestone is classified using classification developed by Jennings (1987).

Table 2 - 1. Type of limestone based on its main grain size (Jennings, 1987)

No	Type of limestone	Main grain size
1	Calcirudites	> 2 mm
2	Calcarenites	2 – 0.2 mm
3	Calcisiltites	0.2 – 0.02 mm
4	Calcilutites	< 0.02 mm

2.3.3. Karst hydrogeology and water potential

2.3.3.1. Ground water recharge process

In karst system, following a rainfall event water infiltrates soil layers and travels through highly permeable drainage networks. By gravity and capillarity forces water moves through fractures and pores to other points. Water is then stored in areas where highly permeable karstic carbonate soil rests on low permeable rocks, where an aquifer develops. In this process, the water table is therefore maintained by soil characteristics such as pore size and soil permeability. At a point where, controlled by the local geological setting the water table reaches the earth surface a karst spring is created (D. Ford & Williams, 2007). Water transport process in karst system is intricate due to extreme spatial heterogeneity of conduits network in karst system. The irregularity and disordered landform generate complex hydrological characteristics (Jaquet, Siegel, Klubertanz, & Benabderrhamane, 2004). Therefore it is a challenge to recognise a particular type of karst. However, principally karst can be distinguished by its geological setting from where water moves. Source of water that feeds karst drainage system determines karstification process of a particular karst area. In this regard, karst is classified as autogenic, allogenic and mixed of them (D. C. Ford & Williams, 1989).

In autogenic process (Figure 2 – 3), water is governed by internal characteristics of karst while in allogenic process water is originated in other types of rock thus it is controlled by external hydraulic behaviour. Autogenic karst receives water from solely karst rocks because the area is covered only by carbonate rocks. This karst category can be found in vast area of karst mainly in continental landscape. Irregularity of rock surface and high permeability of carbonate rock permit water to infiltrate in a diffusive way.

Meanwhile, allogenic karst system (Figure 2 – 3) is supported merely by non-karst system from where water percolates down to karst stream subsystem. After precipitation runoff process takes place conveying water to lower level places where water inundates and infiltrates in a rate faster than that in autogenic karst system.

The last category that prevails in most of karst area worldwide is the mixed between autogenic and allogenic (Figure 2 – 3). In this system, water comes from both karst and non-karst rocks forming complex percolation systems that feed springs through underground drainage system.

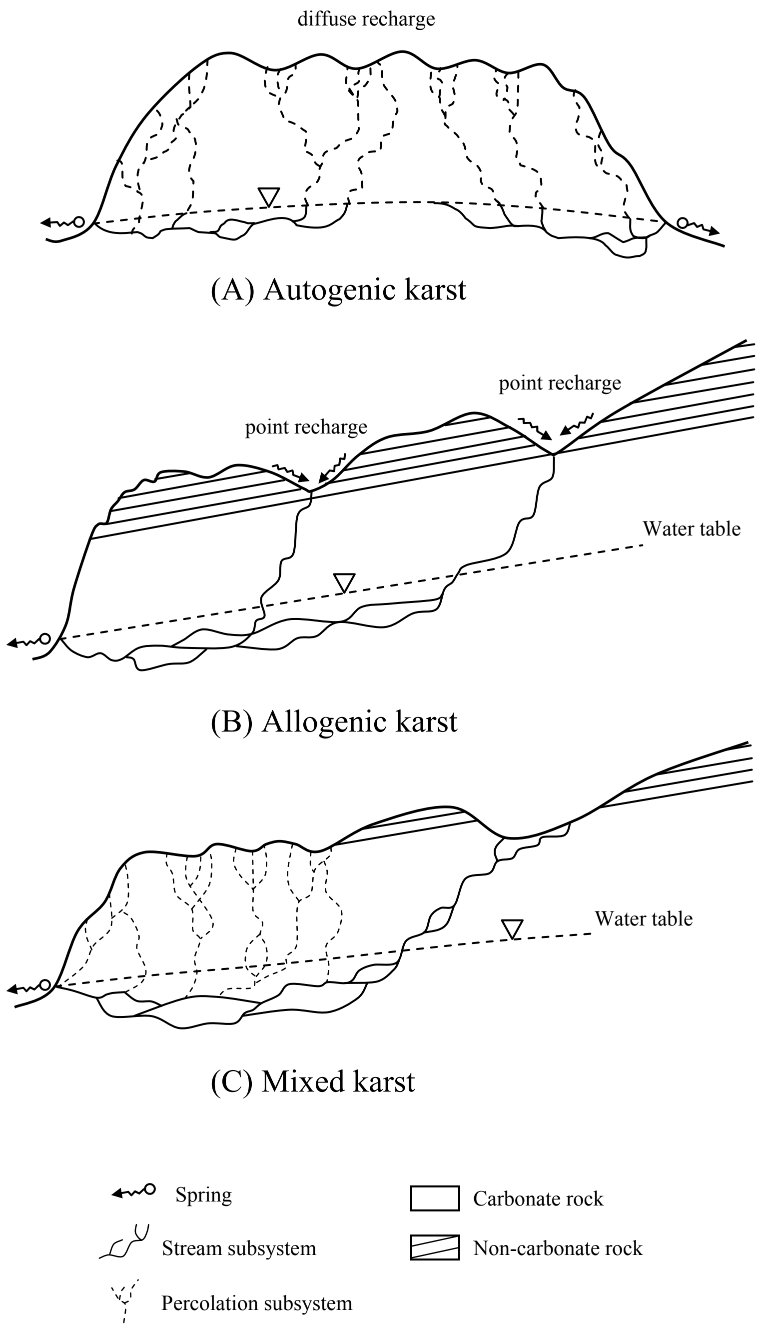


Figure 2 – 3. Types of karst based on inundation characteristics (D. Ford & Williams, 2007).

2.3.3.2. Groundwater flow and aquifer in karst system

Generally, water transport in karst system follows universal flow concept in which it is influenced by gravity and capillarity forces. Once water infiltrates from earth surface, it goes down through layers of soils and rocks. However, since karst is characterised by its complexity of drainage system due to occurrence of secondary porosity such as fissures, channels, conduits (Jaquet et al., 2004), fractures (Maramathas & Boudouvis, 2006) and sinkholes, groundwater travels in an extensive heterogeneity. Nevertheless, it is generally accepted that groundwater flow in karst aquifers is classified as diffuse and conduit flow (Kiraly, 1998; Shuster & White, 1971). Diffuse flow is typified by three distinct hydraulic behaviours, which are low hydraulic conductivity, high storage capacity and laminar flow. Conversely, high hydraulic conductivity, low storage volume and turbulent regime are prevalent in conduit flow (Bauer, Liedl, & Sauter, 2003). These two types of flow occur as a result of different characteristics of aquifer in karst environment in which soluble carbonate rocks develop over time. Therefore, groundwater flow is governed by the nature of karst aquifers. White (1969) considered three different types of karst aquifer based on major hydrologic aspects and associated cave features. In this division, karst aquifers occur as diffusive flow, free flow and confined flow aquifers. Diffuse flow aquifer is mainly characterised by lack of existence of dissolution process-related landforms, such as caves and fractures. If they exist, these solutional cavities are small and weakly integrated and occasionally appear as widened joints or bedding planes (White, 1969). Thus, the karst system is more compact in term of geological layers due to limited occurrence of secondary porosity and hence high primary porosity. Figure 2 – 4 shows that this karst system maintains a well defined water table and it emerges as small springs and seeps when it reaches earth surface (Shuster & White, 1971). Groundwater flow is characterised as laminar flow through a porous media governed by Darcy’s Law in which groundwater flows in a direction of pressure gradient line.

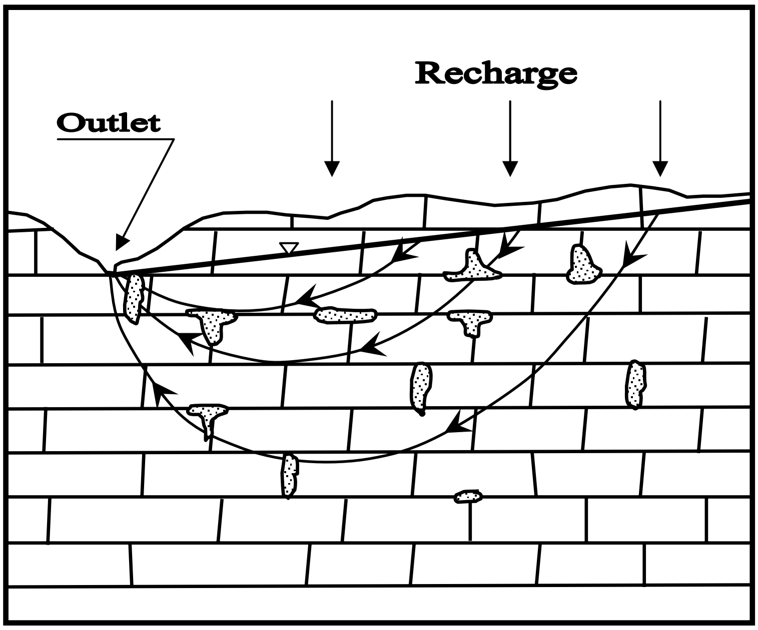


Figure 2 – 4. Diffuse flow aquifer (White, 1969).

In contrast, in conduit flow aquifers secondary porosity are more likely to be found. Caves, fissures and sinkholes dominate karst landscape. High degree of secondary porosity is seen as a much more complex karst system than the diffusive one. As intense dissolution process takes place, the karst system develops widened-fractures networks which consist of small conduits and a major channel in where water from small conduits accumulates (Figure 2 – 5). As a result groundwater in recharge area flows through those irregular small conduits and ends at a defined major conduit. The big conduit which is often found as an underground stream performs as a low hydraulic passage (White, 2003) towards where instead of going to nearest surface outlet, water from surrounding secondary porosity network goes. Therefore in this karst system, the outlet typically occurs as a single large spring (Shuster & White, 1971). The complexity of conduits network which is determined by porosity type, type of recharge (section 2.3.3.1) and hydraulic gradient (Palmer, 2000) combined with irregularity of channel size contributes to turbulent flow regime characteristic of conduit karst aquifers.

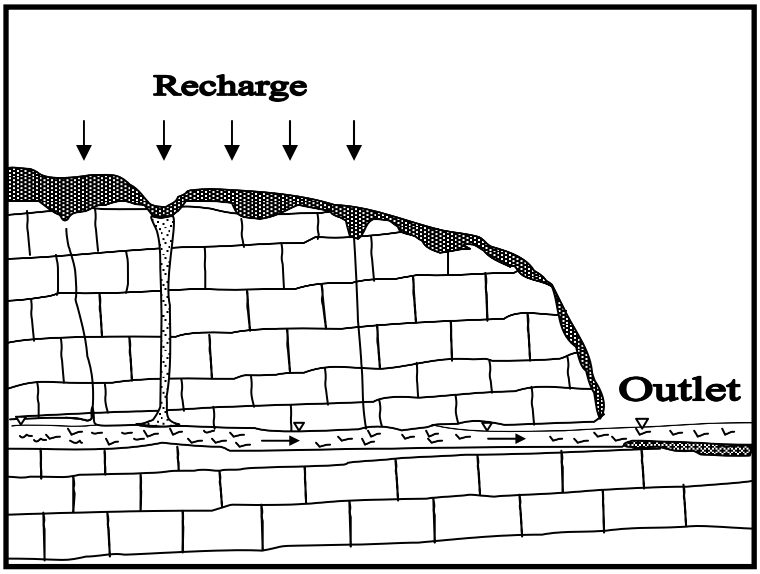


Figure 2 – 5. Conduit aquifer (Shuster & White, 1971).

The third aquifer, which is confined flow, mainly occurs in areas where geological layering of rocks determines to where the groundwater flow goes (White, 1969). This type of aquifer is differentiated as artesian (Figure 2 – 6) and sandwich aquifers (Figure 2 – 7). In artesian aquifers, groundwater is kept flowing under its hydrostatic head. Carbonate formation in which groundwater flow is basically underlain by impervious layer that constrains water to flow underneath it.

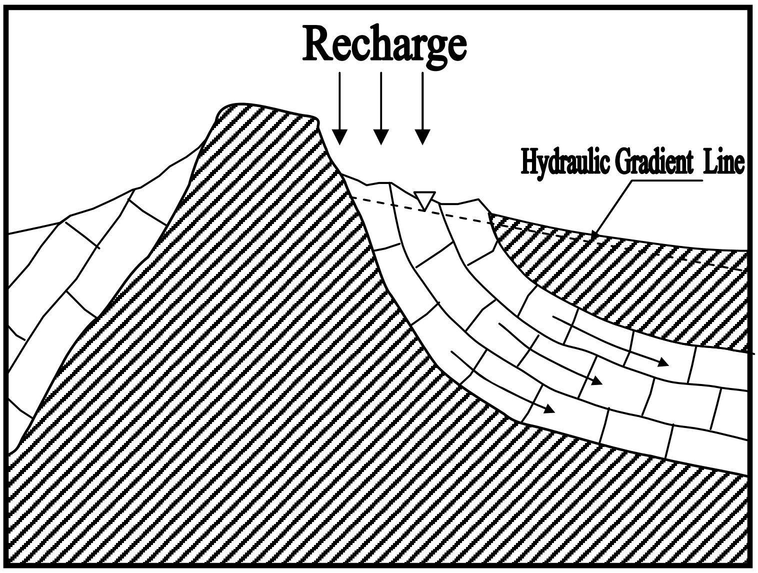


Figure 2 – 6. Confined artesian aquifer (White, 1969).

Meanwhile, sandwich aquifer is characterised by its thin aquifer (< 12 m) compared to the overlying formation. Recharge is considered small in a very dense drainage network which is parallel to diffuse flow pattern. Therefore, groundwater flows in a much smaller and slower compared to that in artesian aquifer.

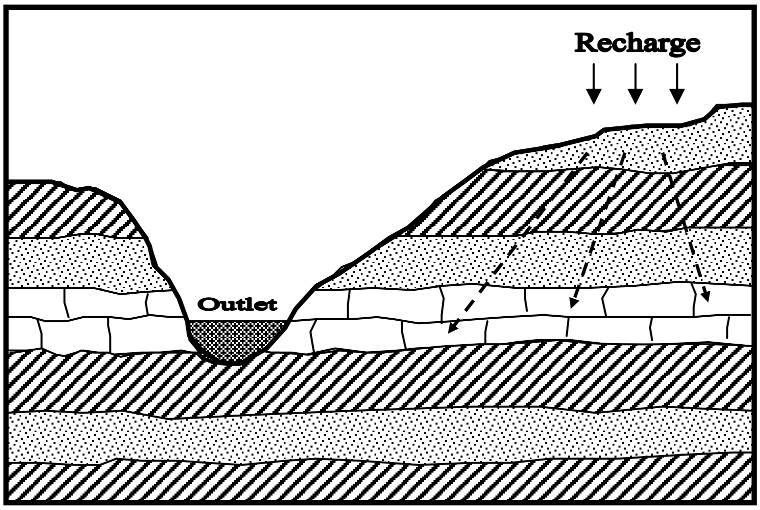


Figure 2 – 7. Confined sandwich aquifer (White, 1969).

The summary of different type of aquifers and their characteristics are presented in Table 2 – 2.

Table 2 – 2. Hydrological classification of carbonate aquifers (White, 1969).

Flow type	Hydrological control	Associated cave type
Diffuse flow	Gross lithology.	Caves rare small, have irregular patterm
	Shaley limestones; crystalline dolomites; high primary porosity	
Free flow	Thick, massive soluble rocks	Integrated conduit cave systems
Perched	Karst system underlain by impervious rocks near or above base level	Cave streams perched, often have free air surface
Open	Soluble rocks extend upwards to surface	Sinkhole inputs; heavy sediment load; short-channel-morphology caves
Capped	Aquifer overlain by impervious rock	Vertical shaft inputs; lateral flow under capping beds; long integrated caves
Confined flow	Structural and stratigraphical controls	
Artesian	Impervious beds which force flow below regional base level	Inclined three-dimensional network of caves
Sandwich	Thin beds of soluble rock between impervious beds	Horizontal two-dimensional network caves

2.3.3.3. Karst spring

In hydrologic cycle, recharge of an area bounded by physical borders such as surface elevation or confined rock is stored as groundwater. Water is then discharged into surface through springs. The potential of groundwater available on karst springs is essential to be determined since this source of water plays vital role in developing the community. Therefore, it is imperative to understand the origin and evolution of springs. Ford and Williams (2007) based on its hydrological and hydraulically characteristics suggested following karst spring categories:

1. Free draining springs
2. Dammed springs
3. Confined springs

These three types of spring are categorised by different attributes as shown in Table 2 – 3 and Figure 2 – 8.

There have been several efforts to estimate hydraulic variables of karst spring in different scale. Dreiss (1989) investigated influence of storm-derived water and seawater intrusion on karst spring using chemistry tracing method (Ca and Mg). This study confirms that spring located near shoreline is apparently subject to change in chemical concentration of water due to two sources of water. When rainfall is at peak supply water to spring through both diffuse and conduit systems from upstream become higher. Therefore hydraulic head of the rain-fed groundwater is high by which it has greater influence on chemical concentration at spring outlet. Meanwhile, when minimal supply from storm occurs spring flow chemistry experiences perturbation from seawater intrusion. A study by Weiss and Gvirtzman (2007) employed MODFLOW to model groundwater recharge of perched karstic aquifers. In their study they found relationship between aquifer recharge rate and measured precipitation. Meanwhile, Reasi and Karami (1997) measured the specific conductance, pH and water temperature of karst spring water to understand the characteristics of karst aquifer.

In this study, the only hydraulic characteristic of karst spring measured was water discharge. The measurement was conducted in several karst spring throughout Rote Island.

Table 2 – 3. Hydrological and hydraulical characteristics of karst springs (D. Ford & Williams, 2007).

Spring type	Hydrological and hydraulical control characteristics
Free draining springs	Rock slope towards and lies above adjacent valley Water flows under gravity force Entirely or dominantly vadose karst system Overlying soil stratum below karst rock determines two types of spring
Hanging	Without impervious layer below karst rock
Contact	Subterranean ponding and isolated phreatic zones due to folded soil stratum
Dammed springs	Intermittent location as response to water table fluctuation Consist of one main low-water spring with other high-water relief springs Different barriers and their location causes three types of spring:
Impounded	Impoundment as major barrier (fault or conformable contact)
Aggraded	Valley aggradation as major barrier, such as glacio-fluvial deposits
Coastal	Denser salt water as major barrier
Confined springs	Karst rock are confined by an overlying impervious formation High hydrostatic pressure Associated with high-water relief Different cause of water exit route causes two types of spring:
Artesian	Water exit route provided by fault planes
Fault guided	Water exit route provided by eroded caprock

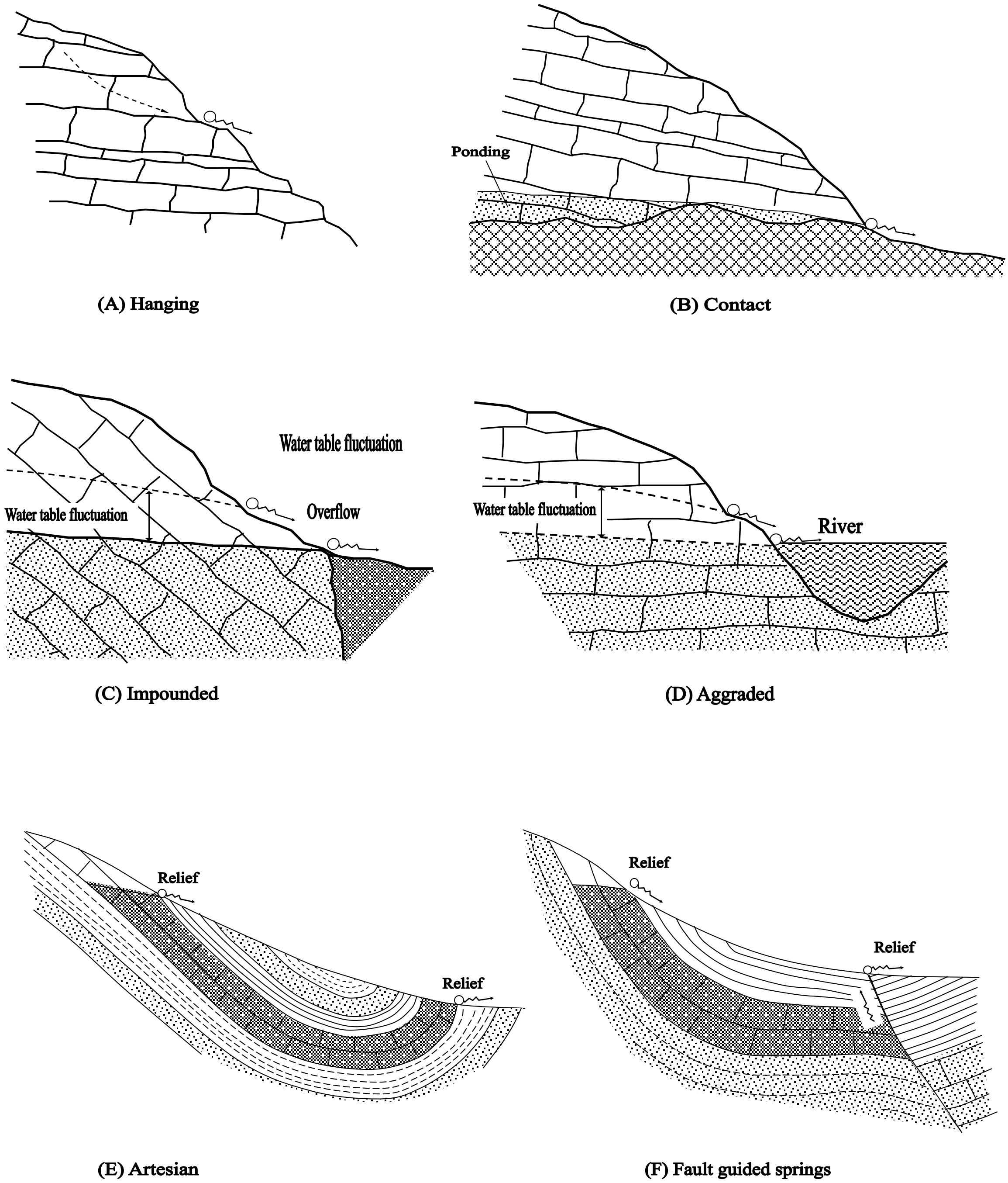


Figure 2 – 8. Types of karst springs (D. Ford & Williams, 2007).

2.3.4. Karst hydrochemistry

Groundwater quantity in karst system is significantly influenced by dissolution process of carbonate rocks, such as limestone, dolomite, marble and gypsum, which are the primary source of karst. This process, often called karstification, is a process in which rock is dissolved by water preceded by physicochemical processes (Bakalowicz, 1975). In karst, the rate of dissolution is high since carbonate rocks themselves are categorised as soluble ones. According to Jakucs (1977) the dissolution of limestone and other carbonate rocks in water is subject to three solvents, which are pure water, carbon dioxide-contained water and other chemical agents, such as soil acids. During dissolution process part of carbonate rock is absorbed in water, while at the same time ions both cations and anions in the particular rock are dissolved by water as solvent. In pure water solubility of limestone is very low therefore carbon dioxide derived from mainly from organic activity and precipitation is the main element in dissolution process (Waltham, Bell, & Culshaw, 2005). Having carbonate dissolution of limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) as examples the chemical reaction in carbon dioxide-contained water is as follow:

$$CaCO_3 + CO_2 + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^- \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \Leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^- \quad \ldots\ldots\ldots\ldots \quad (2)$$

The processes above result in the release of Ca^{2+} and Mg^{2+} ions in water. Other cations that are found in karstic water are sodium (Na^+), potassium (K^+), manganese (Mg^{2+}) and calcium (Ca^{2+}), while the anions are ions of chloride (Cl^-), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}) and nitrate (NO_3^-).

Together with pH and turbidity, cations and anions are important water characteristics. The clarification of ionic pattern of water is the key to recognise types of rocks that form the structure of carbonate rocks. For example, when dissolution occurs in groundwater dolomites, $CaMg(CO_3)_2$ releases Ca^{2+} and Mg^{2+} ions while calcites, $CaCO_3$, discharges Ca^{2+} and HCO_3^- . Therefore, when sample of groundwater containing these ions is taken one can suggest that dolomite is one of the rocks' fractions.

In order to verify the precision of laboratory analyses, charge balance analysis is performed. This analysis is designed to check the result against two types of errors in chemical analyses, which are precision and accuracy. In this analysis, cations and anions of groundwater samples were compared by using following equation (Appelo & Postma, 2005):

$$EB = \frac{\sum cations + \sum anions}{\sum cations - \sum anions} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3)$$

where, *EB* = electrical balance (%); cations = ions of Na^+, K^+, Mg^{2+}, Ca^{2+}, and others (meq/L); anions = ions of Cl^-, HCO_3^-, SO_4^{2-}, NO_3^- , and others (meq/L).

EB represents the divergence of the result towards the real and expected chemical properties of water. On the other hand, inaccuracy can arise from both field sampling and laboratory analyses. However, the deviation should not exceed 5%.

2.4. Water balance

2.4.1. General concept

In general concept of hydrologic cycle, particle of water continuously moves from one place to another in different events. As depicted in Figure 2 – 9, those hydrologic events that generally occur in karst systems are precipitation, evaporation, transpiration and runoff.

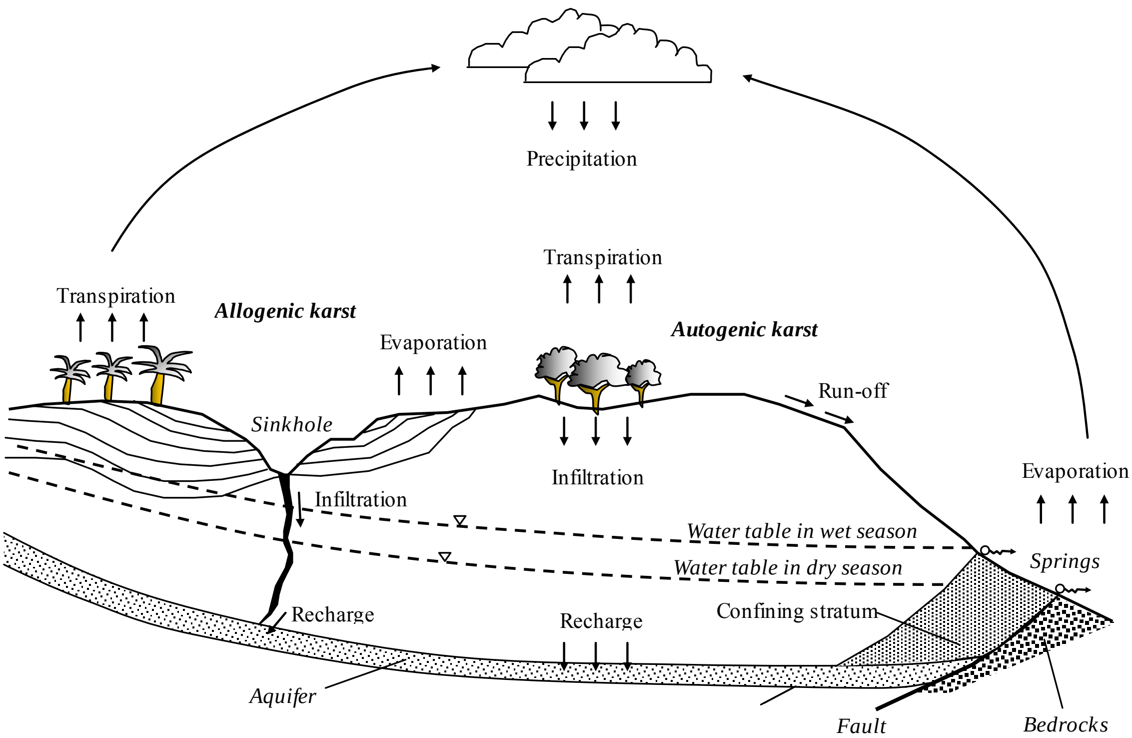


Figure 2 – 9. Concept of hydrologic cycle in karst environment.

Water coming from the earth is precipitated mainly in the form of rain. Part of it is intercepted and evaporates back to the atmosphere while the rest falls on soil and flows on the ground as runoff or infiltrate into the ground through secondary porosity, such as sinkhole or diffusive karst drainage system. Water that infiltrates flows as subsurface water which may feed surface stream or groundwater in which water is stored in karst aquifer and emerges as both gravity and artesian springs at places where groundwater aquifer meets ground surface. Together with surface water, water emerged at springs then evaporates back to the atmosphere. The events above resume with water being precipitated to the earth

An important factor to understand the hydrological characteristics of the groundwater system in the karst area is to model water balance in which all water elements are interrelated in a single equation. The overall system can be simply quantified in a mass balance equation which the different of inputs and output are equivalent to change in water storage in earth (Bras, 1990):

$$\frac{\Delta S}{\Delta T} = I - Q \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where ΔS = change of storage (L); ΔT = time (T^{-1}); I = input ($L\ T^{-1}$), Q = output ($L\ T^{-1}$).

Input is defined as precipitation (P), meanwhile, output are those that release water from the system which are evaporation (E), runoff (q_s), transpiration (T), and infiltration (F). In this model interception is negligible since the savannah-dominated area in Rote Island doesn't allow much water to intercepts when precipitation takes places as rate of interception basically relates to vegetation type and density (Dingman, 2002). Therefore, equation (4) becomes:

$$P = ET + q_s + F + \frac{\Delta S}{\Delta T} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where P = precipitation (LT^{-1}); ET = evapotranspiration (LT^{-1}), q_s = surface runoff (LT^{-1}), F = infiltration (LT^{-1}); $\frac{\Delta S}{\Delta T}$ = change in storage over time (LT^{-1}).

There are several assumptions used in water balance analysis of Rote Island karst. Firstly, the catchment area of study area (Figure 2 – 1) is determined based on surface drainage area in which water flows by gravity force from the highest elevation to the lowest points where the test wells located. The aquifer strata in drainage basin are also assumed to horizontally sit orderly without any leakages or seepages from possible fault or other rock deformation. Therefore, lateral groundwater inflow from an external catchment is considered negligible in this case (Szilagyi, Harvey, & Ayers, 2003). Secondly, the aquifer slope is considered to incline accordingly following surface gradient. Therefore groundwater flowing in karst aquifer goes to the same direction to which surface water flows. Hence, using these assumptions the pertinent drainage area of the study area is drawn using a topographical map supplied by Bappeda (2004).

In Chapter 3, using the water balance equation and several assumptions above water entering and leaving the karst system in a selected site in Rote Island is quantified. The analysis uses a set of data consisting of hydroclimatological and water discharge records apart from existing soil data. Water discharge data available for this analysis is that recorded in 1991 (PU, 1992) taken from an exploration well project in Olafuliha'a Village. This one-time discharge data is then collaborated with climatological data ranging between 1991 and 2005 to generate general representation of the karst behaviour in Rote Island.

2.4.2. Precipitation

Water that is stored as water vapour in atmosphere is released back to earth as precipitation. Precipitation can take place in the form of rain, snow, sleet or hail (Ward & Trimble, 2004). In Rote Island, precipitation only presents as rainfall. Spatial factors that determine the occurrence of rainfall in one place are land-cover situation and geographical location. On the other hand temporal factors such as sea water temperature, air pressure and wind play crucial role in generating and positioning the likely of rainfall. The temporal factors produce variability of rainfall pattern of one place over time. Dingman (2002) stated that the seasonality of these climatological factors attributes to the pattern of precipitation which consequently influences annual water balance.

The study area is situated between Asian and Australian Continents, and between Pacific and Indian Oceans. This spatial factor eventually shapes Indonesian rainfall pattern. Any changes of land and sea temperature may change the season and start the onset of another one. Kaplan et al.(1998) generated climatological model using 135 year sea surface temperature (SST) data to analyse interannual variability of sea surface temperature. This study shows strong correlation between tropical Pacific and Indian Ocean SSTs in shaping rainfall pattern over Indonesia (D'Arrigo & Wilson, 2008). The complexity of spatial and temporal-induced factors that prevail over Indonesian archipelago brings about a variability of rainfall throughout the country (E. Aldrian & Susanto, 2003).

The geographical position of Indonesia, in which influence of SSTs in both Pacific and Indian Oceans as well as climatological variation in its adjacent continents, i.e. Australia and Asia seems to cause an irregular or heterogenous rainfall pattern over this maritime nation. However, there were two studies that attempted to divide the archipelago into different climatic regions. Hamada et al.(2002) grouped Indonesia into four climatic areas based on daily 30-year rainfall data all over Indonesia. Whereas, Aldrian and Susanto (2003) separated Indonesian archipelago into three rainfall regions. In latter study, each region has distinct characteristics, which are generally determined by local and remote response to sea-surface temperature. In this classification, Rote Island falls in region A (Figure 2 – 10), which covers areas from south Sumatera to Timor Island, southern Kalimantan, Sulawesi and part of West Papua. Cumulatively, this climatic region shares about 60% of the total Indonesian archipelago. Figure 2 – 11 shows the region A has one peak which ranges between about 270 and 365 mm/month and one trough on August or September.

The seasonality of rainfall of Indonesia region is strongly influenced by Asian and Australian monsoons. Monsoonal rainfall is principally affected by difference in temperature of land and its adjacent ocean. The influence of monsoonal rainfall pattern was verified to be dominant in East Java which shares the same rainfall area (region A) (Figure 2 – 10 and 2 – 11) as Rote Island in a climatological study by Aldrian and Djamil (2008) who analysed and simulated rainfall data from 40 stations over 50 years. Another study by Nicholls (1995) using meteorological data in Darwin and SSTs in Indian Ocean also confirmed relationship between air pressure in Northern tip of Australia and Indian monsoon rainfall. Meanwhile, studies by Aldrian and Susanto (2003) and Naylor and Battisti (2007) ratified that the monsoonal rainfall pattern in Indonesia are the wet northwest (NW) monsoon from November to March and the dry southeast (SE) monsoon between May and September. The typical first monsoonal pattern also appears over Northern Australia in which wet season takes place (McBride & Nicholls, 1983; N. Nicholls, McBride, & Ormerod, 1982). Therefore, the interaction between ocean-atmosphere system in both Asia and Australia influences the climatological pattern in Indonesia.

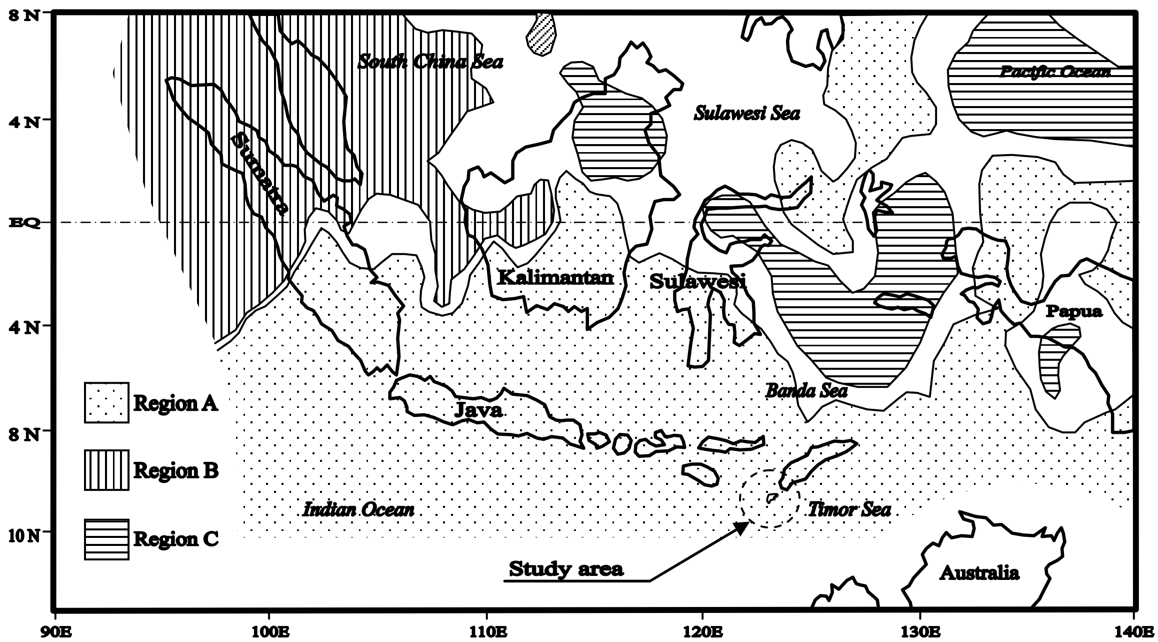


Figure 2 – 10. Situation of Rote Island in the three climate regions, modified after Aldrian and Susanto (2003).

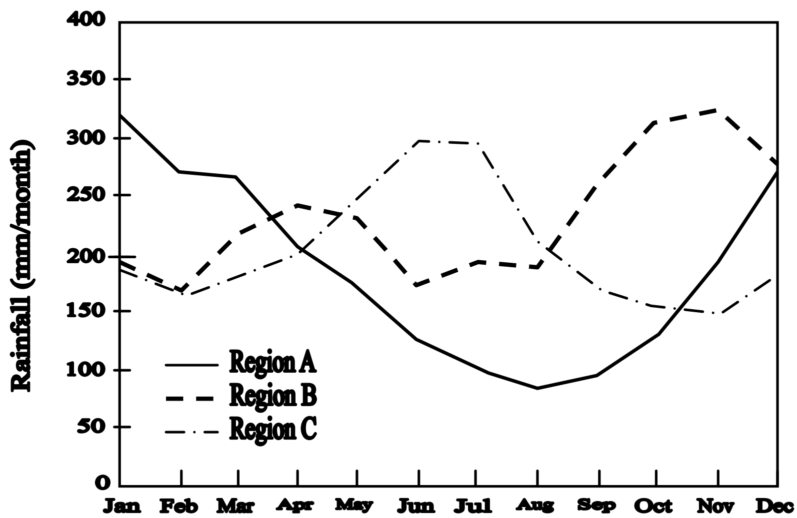


Figure 2 – 11. Rainfall pattern in three climatic regions; modified after Aldrian and Susanto (2003).

With regard to Southern Oscillation Index, which gives rise to the El Niño – La Nina phenomenon, Indonesia also experiences impact of inconsistent climatological alteration in Pacific region. Some studies (Haylock & McBride, 2001; N. Nicholls, 1984) showed that there is a strong relationship between El Niño - Southern Oscillation (ENSO) and stimulation of rainfall generation in Indonesia. It is postulated that the weakening of El Niño in east Pacific is associated with the onset of rainfall which appears to start on November when the sea-surface temperature increases dramatically. On the other hand, the commencement of El Niño directs Indonesian Low, which represents low SSTs to progress eastward in tropical Pacific lowering rainfall intensity and thus causing drought over Indonesia (D'Arrigo & Wilson, 2008). Another study by Hendon (2003) in which monthly rainfall records from 43 stations across Indonesia, including that in Kupang Municipality (a town lies next to Rote Island) were observed and analysed showed strong correlation between Indonesian rainfall and Indo-Pacific SSTs which reflects ENSO deviations in the Pacific basin. Studies above are then supported by Aldrian and Djamil (2008) who addressed Indonesia region, in particular Java Island, that falls into the same rainfall region as Rote Island, on which ENSO signal induces significant impact during the period of September until November.

Mapping of Indonesia's rainfall characteristics, combined with understanding of physical interaction of climatological variables as well as their relationship within monsoonal Asia-Australia and Pacific El-Nino context is important to understand the climate variability in this region. This knowledge is significant to generate a comprehensive prediction of Indonesia climate in the future with a relation to global warming issue. Indication of severe impact of greenhouse warming in Indonesia is reported by Abram et al (2007) whose study was carried out on mid-holocene corals in Mentawai Islands in Sumatra. Using the coral geochemical records from the equatorial eastern Indian Ocean, they outlined ocean-drought interaction of this area over the past 6,500 years in a model. The coral records and model shows a strong connection between the events of ENSO and Asian monsoon and droughts dynamic in Indian Ocean Dipole area. Another climatological data reconstruction between 1782-1992 based on study on tree ring of nine teak trees (*Tectona grandis*) derived from living teak trees growing on Java and Sulawesi Islands, and one coral oxygen isotope series ($\delta^{18}O$) from Lombok Strait (D'Arrigo et al., 2006; D’Arrigo et al., 2006) shows a firm connection between drought events in Indonesia and the tropical Indo-Pacific climate system. These studies suggest that a raise in Asian monsoon intensity as well as intensified global warming may increase droughts in Indonesian archipelago (D'Arrigo & Wilson, 2008). Consequently, as drought intensifies by which lesser rainfall rate occurs, recharge to groundwater to some extent diminishes. Referring to the Intergovernmental Panel on Climate Change report that temperature on earth surface increases steadily (IPCC, 2001), which may exaggerate drought extent and occurrence, this physical response to the climate change by the karst area in Rote Island may have detrimental impact on sustainability of groundwater usage for the whole community.

2.4.3. Evapotranspiration

Quantification of evapotranspiration is critical to determine overall water balance in study area. This natural process plays crucial role in hydrologic cycle as approximately up to 70% of water is restored back to atmosphere after precipitation on land (Baumgartner & Reichel, 1975).

There are numerous methods developed to measure evapotranspiration as well as different terms for evapotranspiration analysis. Some of the terms described here are those from Morton’s (1983) complementary relationship. The first term is Point Potential Evapotranspiration (PPET) or Potential Evapotranspiration (E_{TP}) that is mostly applied in the irrigation sector. Granger (1989) describes PPET as the upper boundary of evapotranspiration when soil surface is saturated. It represents maximum amount of water that can be freely evaporated and transpired at a given point. Meanwhile, Areal Actual Evapotranspiration (AAET) or Areal Evapotranspiration (E_T) characterises the maximum evaporated and transpired water from an area so large that the effects of temperature and humidity of an overpassing air are considered negligible. The relationship of the two terms which is shown in Figure 2 – 12 is that when water available for soil-plant system increases, AAET also increases which results in equal decrease of PPET on the other side (Chiew & Leahy, 2003). As the increase of soil water progresses through PPET and AAET unite and become Areal Potential Evapotranspiration (APET) in which evaporation at the point and its pertinent area greater than 1km^2 are considered equivalent. In this study the evapotranspiration term used in the water balance analysis is the Point Potential Evapotranspiration (PPET).

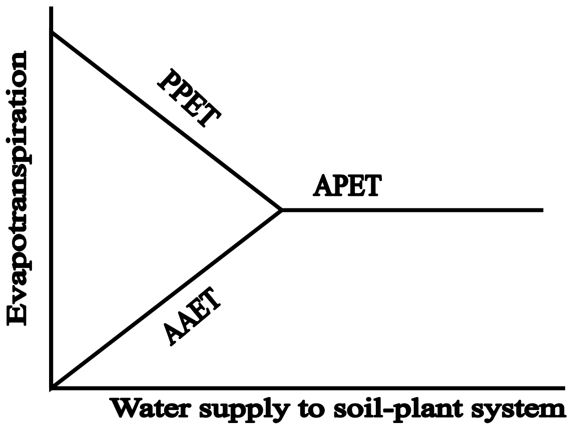


Figure 2 – 12. Concept of complementary relationship among evapotranspiration terms (Chiew & Leahy, 2003).

PPET has been used since 1950s (McVicar et al., 2007) and it has widely been used since as a method to calculate evapotranspiration in diverse discipline. The multi-variety type of method to calculate evapotranspiration directed Doorenbos dan Pruitt (1975) to develop reference evapotranspiration method that is used to calculate evapotranspiration of varied plants by incorporating their plant coefficients. This initial effort led to numbers of methods established to analyse reference evapotranspiration.

Among other methods, Penman-Monteith Combination Method (Monteith, 1965) is the most widely used method in quantifying evapotranspiration (M. E. Jensen, Burman, Allen, & American Society of Civil Engineers. Committee on Irrigation Water Requirements., 1990) and accepted by Food and Agriculture Organisation (FAO) as a standard method (Allen, Pereira, Raes, & Smith, 1998). This method basically uses two main components, which are climatology and plant's physiology factors (Rana & Katerji, 1998). Its strong climate-fed data relationship makes it superior as it can be mostly used everywhere (Droogers & Allen, 2002) and it is successfully used in varied climate condition (Lemeur & Zhang, 1990; Steiner, Howell, & Schneider, 1991; Stöckle, Kjelgaard, & Bellocchi, 2004; Ventura, Spano, Duce, & Snyder, 1999). However, this method requires a wide range of meteorological data which are often not available in many places especially in developing countries.

Another method that is also widely used to quantify evapotranspiration is pan evaporation. This technique uses an open water tank to measure evaporation rate of water in it with a reference to grass. This approach is practicable as a substitute in areas where climate variables are limited (Martínez, Alvarez, González-Real, & Baille, 200). However, since the weather and physical variables in different areas are diverse which result in bias in measuring evaporation rate of a grass surface (Jacobs, Heusinkveld, & Lucassen, 1998) empirical pan coefficients are used (Doorenbos & Pruitt, 1977). Nevertheless, Morton (1983) argued that even with modification using pan coefficients, pan evaporation doesn't reflect the actual evapotranspiration of the area because the availability of water for evapotranspiration which is influenced by nearby variables.

Coping with limited weather data and spatial heterogeneity, another method based solely on temperature data (G. H. Hargreaves & Samani, 1985; G. L. Hargreaves, 1994) was developed to analyse evapotranspiration. This method is also established as an alternative for supposedly incorrect and unreliable weather data measurement (D. T. Jensen, Hargreaves, Temesgen, & Allen, 1997) due to human and mechanical errors. The equation used is as follow:

$$ET_0 = \alpha \cdot 0.408 \cdot R_a \left(T_{avg} + \beta\right)\left(T_{\max} - T_{\min}\right)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where, ET_0 = evapotranspiration potential (mm.day^{-1}); α = constant = 0.0023; β = constant = 17.8; R_a = extraterrestrial solar radiation (MJ.m^{-2}d^{-1}). T_{avg} = average daily temperature (^oC); T_{max} = maximum daily temperature (^oC); T_{min} = minimum daily temperature (^oC). The constant 0.408 is used to convert R_a to evaporation equivalents in mm, while Hargreaves et al. (1985) employed the constants α and β to accommodate measured ET_0.

Nevertheless, high humidity condition may result in overestimation of evapotranspiration as well as underestimation for high windspeed occurrence (Temesgen, Allen, & Jensen, 1999). Therefore, Droogers and Allen (2002) suggested modification of Hargreaves equation by introducing monthly precipitation data as follow:

$$ET_0 = \alpha . R_a \left(T_{avg} + \beta\right)\left(T_{\max} - T_{\min} - \gamma . P\right)^{\rho} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Where, α = constant = 0.00053; β = constant = 17.0; γ = constant = 0.0123; ρ = constant = 0.76; P = precipitation (mm/month).

Droogers and Allen (2002) indicates that this equation is substantially better than Penman-Monteith Method compared to global daily reference evapotranspiration. This method is assumed to be applicable in other parts of the world by modifying the constant, α. In a study in humid area of Western Balkan by Trajkovic (2007) it is confirmed that with empirical adjustment on constant, ρ, the Hargreaves Method can suit with the established reference evapotranspiration data.

Concerning climatological data that feeds in evapotranspiration analysis, there is a significant lack of recorded data available for Rote Island. The only record obtainable is temperature and solar radiation data. Therefore, this equation is used in the analysis of evapotranspiration of Rote Island presented in Chapter 3 (section 3.4.3).

2.4.4. Surface runoff

When water precipitates onto the earth, some is intercepted and goes back to atmosphere through evaporation and transpiration, while some may infiltrate into the ground. The remaining water, which is called excess precipitation moves across the earth's surface and becomes overland flow or runoff. In general, runoff takes place when rainfall rate surpasses infiltration rate of soil. Thus it depends on soil characteristics and local topographic features. Runoff process generally follows gravitational forces to reach discharge points such as stream, lake and sea.

Todini and Bossi (1986) classified runoff model into two main divisions, i.e physical and stochastic. Physical models involve sets of calibration procedure to clarify relationship between precipitation depth and runoff, while stochastic approach suggests hypothetical relationship between predicted runoff and randomised soil and meteorological variables. Physical models, such as Stanford Model (James, 1972), Unit Hydrograph (Sherman, 1932) are built upon conceptual estimation of runoff which is then calibrated with recorded flows at outlets such as rivers and lakes. Meanwhile, Stochastic Models, such as those from Sarino and Serrano (1990), Hromodka and Whitley (1994) and Unny and Karmeshu (1984), mainly incorporate the variability of precipitation distribution and evaporation to model uncertainty in runoff prediction. The effectiveness of physical and stochastic approaches depends significantly on volume of data available for calibration. Moreover, the application of one method that is applicable to a watershed is subject to modification when it is introduced to another one.

The lack of physical data available in the form of record of river discharge in this study becomes a major point, by which it is improbable to either use calibrating-data based or stochastic approaches. Therefore, SCS Method (Viessman & Lewis, 1996) is used to quantify run-off. SCS method incorporates several basic elements which mainly refer to natural land-cover characteristics such as type of soil and infiltration capacity and human-induced factor such as land-use. The SCS method is primarily designed to accommodate high demand in quantifying runoff from ungauged catchment. Ponce and Hawkins (1996) marked several advantages of this curve-based method which mostly value its simplicity and reliability. Therefore this method is widely used in engineering application.

There are several studies (Currens & Graham, 2004; Qannam, 2003; Wu, Jiang, Yuan, & Li, 2007) that employed SCS method to quantify characteristics of karst areas. These study confirmed the effectiveness of SCS method to predict both infiltration and run-off in karst environment. Another rationale to use this method is that there is a limited hydrological and soil data in the study area.

The basic assumption used in this method is that in initial stage of rain event, water is kept in initial retention, V_I (Figure 2 – 13). Water is then separated into retention, V_R and surface discharge, Q_{ef}. The amount of retention drops gradually while surface discharge increases over time following a proportional line.

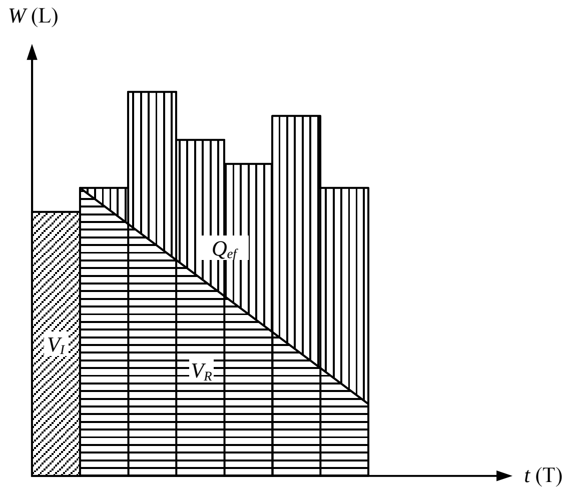


Figure 2 – 13. Concept of runoff process in SCS method (Viessman & Lewis, 1996).

The equation used in this method is as follow (Viessman & Lewis, 1996):

$$q_s = \frac{(P - 0.2 * S)^2}{P + 0.8 * S} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where, q_s = runoff (mm/day); P = rainfall (mm/day), S = maximum watershed storage (mm/day)

And also watershed storage using (Wanielista, Kersten, & Eaglin, 1997),

$$S = \frac{25400}{CN} - 254 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where CN = curve number (dimensionless – see Appendix A).

In SCS method, *CN* refers to hydrologic soil type of the area which is mainly determined by topographic values of the concerning study area. In this regard, U.S. Soil Conservation Service provides guidance, which is shown in Appendix B.

2.4.5. Infiltration

Infiltration is a process in hydrological cycle in which water goes from earth surface through soil layers in a vertical and lateral direction. After precipitation, water penetrates soil with principally two forces, which are gravity and capillarity. Infiltration process mainly depends on soil parameters and water content in soil. Therefore, the rate of infiltration by which water is delivered to aquifer layers is characterised by soil and water variables. Soil type determines permeability by which water moves from one to another point. Generally, the more porous the soil the higher the permeability of soil is, and hence infiltration rate.

It is important to note that not all infiltration feeds the groundwater, thereby becoming recharge. Soil has capacity to retain water that infiltrates it before it reaches the groundwater. The capability of water to infiltrate is determined by permeability and capillarity characteristics of soil which varies largely among soil types (Morel-Seytoux, 1981). In karst system where the landscape is dominantly carbonate, water infiltrates with a higher rate than that in much denser soil types such as clay. Permeability variable in karst environment is very much determined by specific characteristics of its terrain which is influentially marked with secondary porosities such as fissures, channels, conduits, fractures and sinkholes (Jaquet et al., 2004; Maramathas & Boudouvis, 2006).

Most infiltration models, several of which are briefly explained here, are developed using physical models, conceptual models and empirical relations (Chahinian, Moussa, Andrieux, & Voltz, 2005). Green-Ampt Method is a physical model that defines infiltration rate as a function of water movement surround wetting front in soils in which difference between initial and final soil moistures is determined (Govindaraju, Kavvas, Jones, & Rolston, 1996; Wanielista et al., 1997). This method requires a laboratory work using sample of soils taken from the site. A model developed by Diskin and Nazimov (1996) suggests a conceptual approach that employs a transition called ponding that influence the process of infiltration (Chu & Mariño, 2005). This approach mainly depends on variations of rainfall and infiltration intensities, moisture content and moisture storage during storm event. An empirical model by Horton (Horton, 1933) is based on assumption that infiltration rate varies with to time and location (Wanielista et al., 1997). To effectively use this method, one has to perform laboratory tests and field experiments for calibration. Another empirical method which is developed by Soil Conservation Service (USDA, 1971) weighs the correlation between direct runoff and precipitation. This method called SCS does not require a calibration of the parameters and uses a set of defined tables, thus it is primarily suitable to accommodate analysis in watersheds where only precipitation data are available.

Among the theories above, SCS Method is used in this study. The reasoning is that there is a limited hydrological and soil data in the study area which hampers the use of other methods. SCS Method shown in Equation (10) considers infiltration as a function of precipitation and watershed storage, in which the latter element is defined based on soil type, land use and wetness of watershed (Kumar & Jab, 1982):

$$F = \frac{(P - I_a) \cdot S}{(P - I_a + S)} \qquad \text{(10)}$$

where F= infiltration (mm/day); P = precipitation (mm/day); I_a = initial abstraction = $0.2 \cdot S$ (mm/day); S = maximum watershed storage (mm/day).

2.4.6. Change in groundwater storage

Excess infiltration which reaches groundwater is called recharge and is a fundamental factor in groundwater flow. Once recharge process initiates, water is stored in porous media of soil called as groundwater storage. Therefore recharge process determines groundwater storage by which it replenishes quantity of water in groundwater storage. The recharge process taken place in karst environment is conceptually described in Figure 2 – 14.

Recharge process is determined by several factors. According to Nolan et al. (2007) recharge in several places can be different significantly due to heterogeneity of catchments' characteristics such as topography, sediment and climate. In karst area recharge process takes place as diffuse or point-based type or combination of the two (see Section 2.3.3.1). The area, categorised as autogenic and allogenic, where the rain falls determines the subsequent flow type of water through the complex drainage system of karst. Explained in Section 2.3.3.2, parts of water evaporate during infiltration process, while in point recharge water goes directly to groundwater aquifer through secondary porosities such as fissures and sinkholes.

On the other hand, controlled by diffuse recharge other parts of water remain in soil in a condition governed by atmospheric variables, such as humidity and temperature, and soil condition such as type of soil and soil moisture that influences the capacity of soil layers in storing water. Modification of any of these geohydrogeological and climatological variables could result in change in groundwater storage.

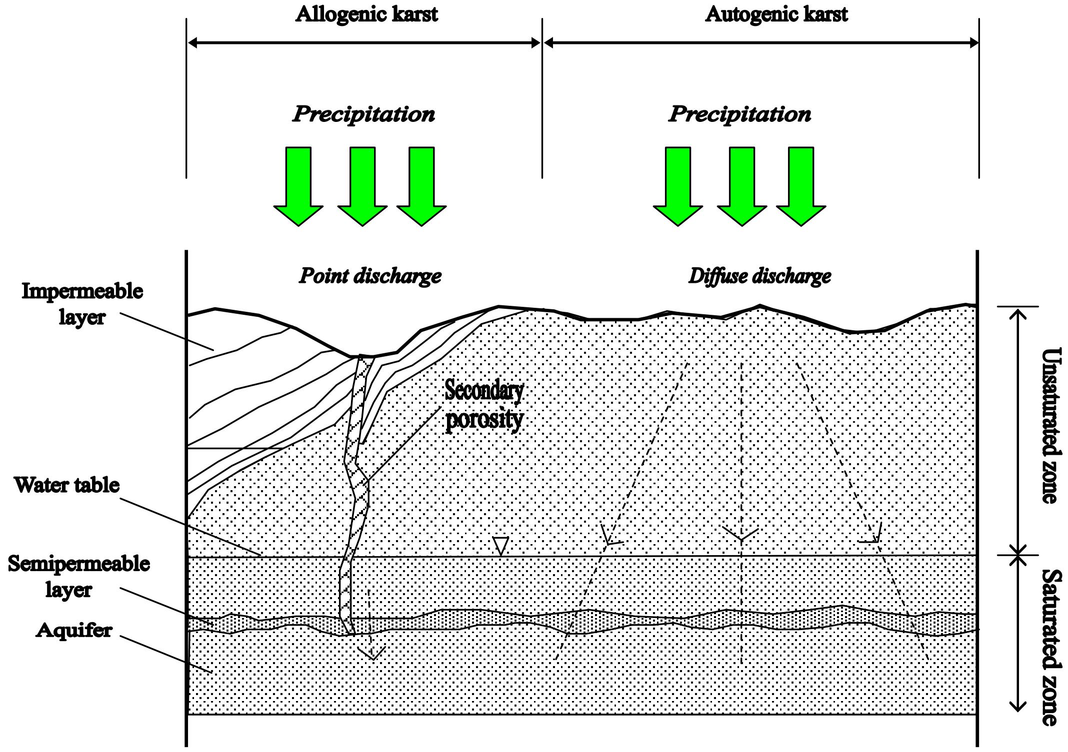


Figure 2 – 14. Conceptual recharge process in karst environment.

2.5. Conclusion

1. Generally, this chapter presents a broad theoretical basis of the area including geographical, topographical, demographical and socio-economical description of Rote Island. The review then continues with general overview of karst system consisting of geomorphology, hydrogeology and water potential and hydrochemistry aspects. The chapter is concluded with review on water balance theories including precipitation, evapotranspiration, surface runoff, infiltration and change in groundwater storage.

2. There is a population increase (2.33%) in Rote Island, a figure which significantly occurs in Lobalain Sub-district due to increased rate of immigration (13.56%). This may have

potential impacts on main sector which is agriculture concerning threats on water availability and land use. The explanation of this correlation is explained in Chapter 5.

3. Hydrogeologically, there are three types of inundation system in karst terrain which are autogenic, allogenic and mixed of autogenic and allogenic. These systems dictate groundwater recharge process in karst area, which consists of two main types of flow: diffuse and conduit flows. Ground water flowing through the aquifer then rises up to surface at places known as karst springs. Determined by its hydrological and hydraulically, karst spring is categorised as free draining, dammed and confined springs. In this study, the dynamic and characteristics of karst hydrogeology in Rote Island, initiating from precipitation, to recharge events and spring discharge, is comprehended by using water balance analysis explained in Chapter 3.

Chapter 3

HYDROGEOLOGICAL SITUATION OF THE MAMAR

3.1. General

In this chapter, the hydrogeological situation of the Mamar in Rote Island is analysed. The analysis starts with presentation of hydrological conditions, including the climate, rainfall, humidity and sun intensity, of Rote Island in Section 3.2. In Section 3.3 the geological setting of the island is explained covering the lithology and genesis of the Island, its stratigraphy and geological stratum. The analysis narrows to the study area whose aspects, i.e. geological setting, groundwater's chemical composition and water balance, are analysed in Section 3.4. The result of the field investigation including visual examination on geomorphology of Rote Island and water measurement at Mamar springs is presented in Section 3.5 as, together with results from previous sections, a supporting tool to draw a hypothetical karst model of Rote Island which is presented in Section 3.6.

3.2. Hydrology

3.2.1. Climate

In general Rote Island has a typical monsoonal climate characterised by two distinct seasons, which are dry and wet season. Peaking in August, the dry season extends from April to November, while the wet season prevails between December and March. In boreal winter, continental wind transports from Asian high-pressure centre to Australian, whereas in the boreal summer the low-pressure centre in Asia and high-pressure centre in Australia generates wind flowing to Asia through this island (Inoue & Welsh, 1993) clarifying its monsoonal nature.

Located between two main continents, which are Australia and Asia, the Indonesian archipelago is greatly affected by the change and variation in temperature, atmospheric pressure and wind trade in both continents. Rote Island, as part of this archipelagic nation, is situated southeast and adjacent to the northern part of Australia continent. The only natural barrier separating the two regions is the Timor Sea approximately 500 km wide. This factor consequently leaves Rote Island being susceptible to any change in climate condition in Australia. Tropical cyclones, which are often accompanied by torrential rain and extreme wind, irregularly occurs in Rote Island between November and April (Nicholls, 1985) as a result of disturbance in wind and pressure in Australia continent (Fandry & Steedman, 1989; W. M. Gray, 1998).

On the other hand, climatological influence from Asia from which monsoonal Asia variations generate also greatly shapes the climate of Rote Island (E. Aldrian & Susanto, 2003; D'Arrigo & Wilson, 2008; Kaplan et al., 1998). Other studies over an extensive range of rainfall data in Indonesia (Edvin Aldrian & Djamil, 2008; McBride & Nicholls, 1983; Naylor & Battisti, 2007; Nicholls, 1995; Nicholls, McBride, & Ormerod, 1982) confirmed strong relationship of ocean-atmosphere system between Asia and Australia that is associated with rainfall pattern in Indonesia. This implies that the seasonal changes in sea surface temperature (SST) that take place in both Indian and Pacific Oceans contribute to the generation of rainfall in Indonesia.

In addition, the climate over Indonesia archipelago and thus Rote Island are significantly affected by Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) modes. The spatial-climatological correlation between Indian and Pacific Oceans is to some degree associated with ENSO phenomenon with which the aperiodic oscillation of Indian Ocean

Dipole (IOD) interacts. As a climate phenomenon, the IOD originates in the tropical parts of the Indian Ocean. The occurrence of IOD is indicated with a fall of SST in the southern part of the Indian Ocean whilst it increases in the western part of the Indian Ocean. Meanwhile at the same time, ENSO commences directing Indonesian Low, which represents low pressure system due to warm sea surface in western Pacific to progress eastward lowering rainfall intensity and thus causing drought over Indonesia (D'Arrigo & Wilson, 2008). Therefore the relationship between ENSO and IOD is described as a condition which IOD accentuates the ENSO influence over the Indonesian region which causes decline of moisture that amplify the dryness (Ashok, Guan, Saji, & Yamagata, 2004). While on the other hand, the weakening of ENSO in the eastern part of Pacific Ocean is associated with the onset of rainfall in Indonesia region, in where warm and moist air is created due to increase in SST in the southern part of Indian Ocean (Edvin Aldrian & Djamil, 2008; D'Arrigo & Wilson, 2008; Haylock & McBride, 2001; Hendon, 2003; Nicholls, 1984).

3.2.2. Rainfall

Rainfall data of six rainfall-gauging stations as well as other climatological data, such as temperature, humidity and sun intensity, were provided by Bureau of Climatology and Geophysical in Kupang (BMG, 2007). Those stations are Lekunik, Papela, Olafuliha’a, Dale Holu, Busa Langga and Batu Tua (Figure 3 – 1).

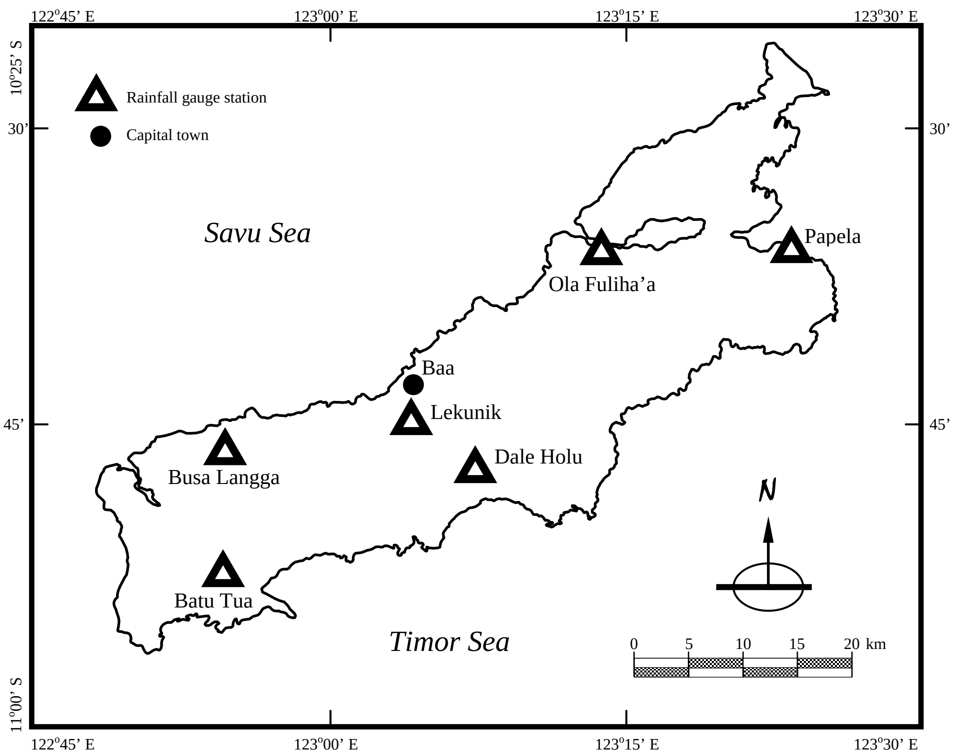


Figure 3 – 1. Distribution of rainfall gauge stations in Rote Island

Since the island is generally flat, by which nearly 80% of the area lies between 20 and 30 m above sea level, these stations are considered to stand on the same elevation above sea level. The average monthly rainfall data recorded in those six gauging stations are given in Figure 3 – 2.

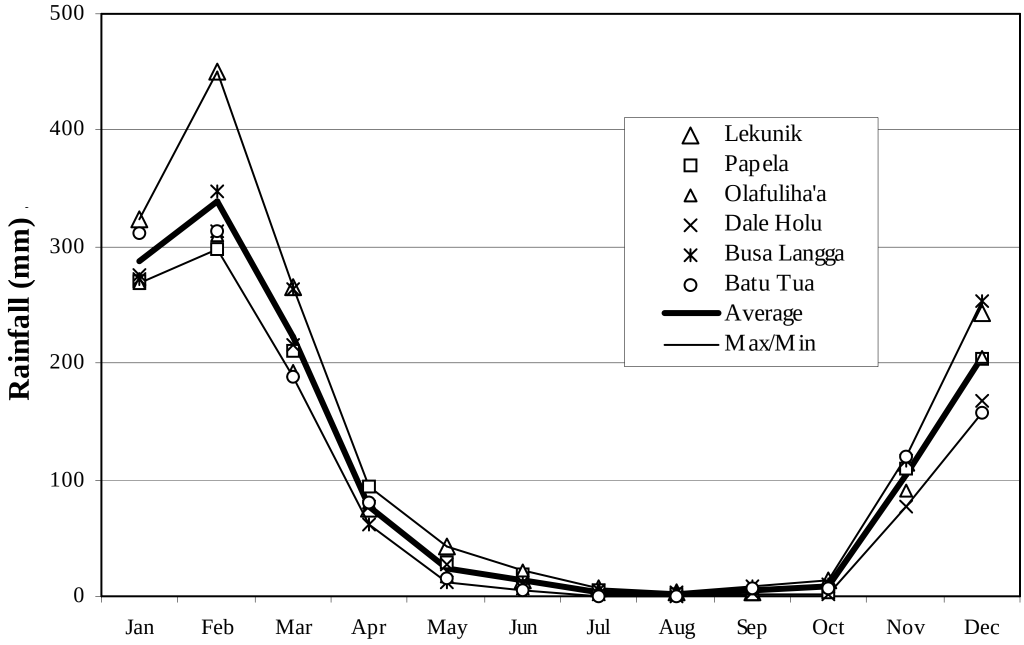


Figure 3 – 2. The average monthly rainfall distribution at six stations in Rote Island

In general, almost all rainfall occurs during the wet season, which prevails between December and March. During these months, quantity of rain rises from approximately 200 mm in December to less than 350 mm in February (Figure 3 – 3). The rainfall intensity then abruptly decreases on subsequent months and reaches its lowest point in August with only 2 mm/month. The dry season then ends in October or the middle of November followed by sharp rise of rainfall in late November or December to commence the wet season.

Climatologically, Rote Island is situated in rainfall region A (Figure 3 – 3) which constitutes areas from south Sumatera to Timor Island, southern Kalimantan, Sulawesi and part of West Papua. This region together with other two regions is a rainfall region which was developed by Aldrian and Susanto (2003) whose category indicates that the region has one peak between

December and January and one trough on August or September. The typical rainfall pattern in both Region A and in Rote Island is shown in Figure 3 – 3.

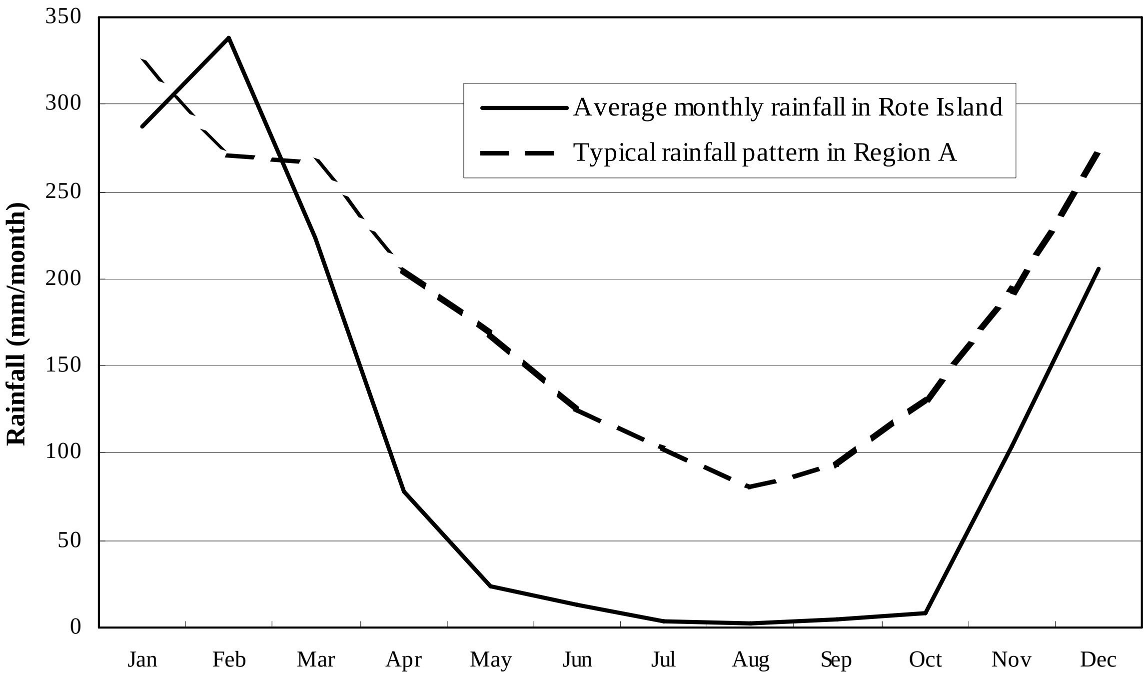


Figure 3 – 3. The average monthly rainfall of Rote Island compared to rainfall pattern of Region A.

There are considerable variations of annual rainfall in Rote Island. The maximum rainfall data was 2400 mm in 1995, whereas the minimum one was 567 mm in 2003. However, the annual rainfall ranges averagely between 1000 and 1400 mm (Figure 3 – 4).

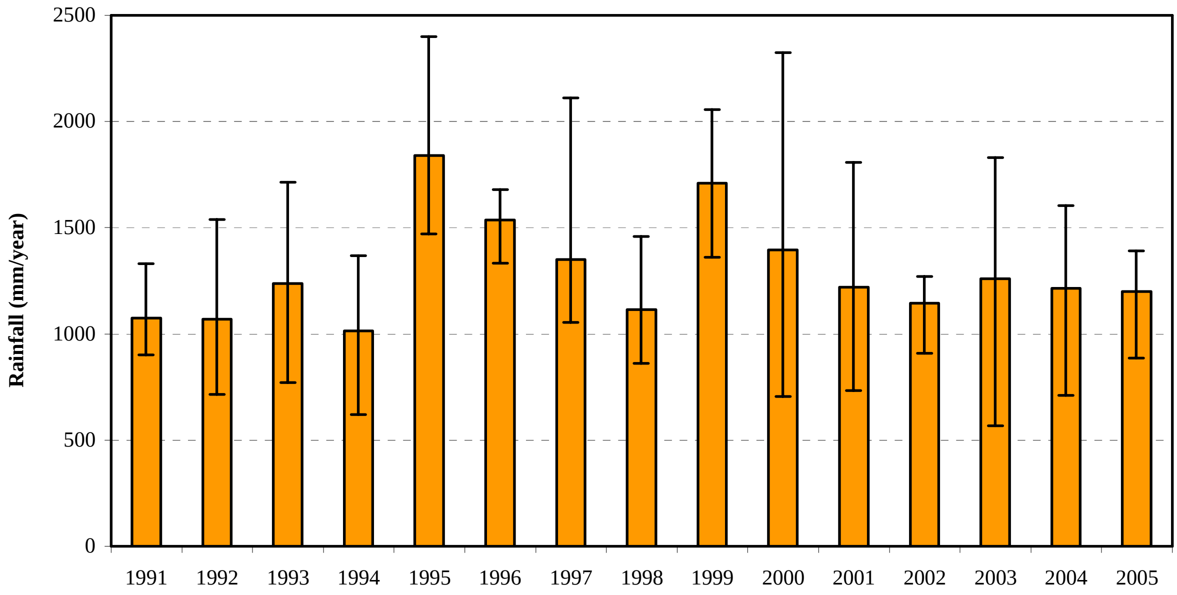


Figure 3 – 4. The average annual rainfall distribution in Rote Island between 1991 and 2005

The fluctuation of daily rainfall over a period from 1991 to 2005 is presented in Figure 3 – 5.

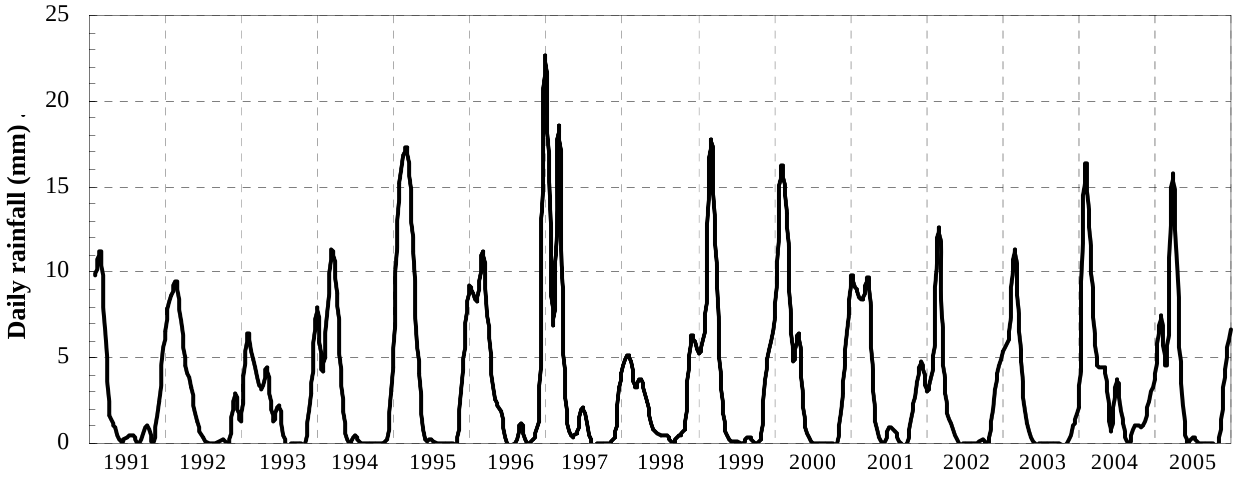


Figure 3 – 5. The daily rainfall in Rote Island over a period from 1991 to 2005

Using the average annual rainfall distribution at the six rainfall gauge stations in this island an isohyetal contour map is drawn in Figure 3 – 6. Isohyetal Method is widely favoured to quantify areal mean rainfall because it suits the requirement for Thiessen Method (D. M. Gray, 1973) and gives more precise result (Patra, 2001). Thiessen Method is characterised by construction of a series of triangles or polygons that connect nearby rainfall stations (Ball & Luk, 1998; Sen, 1998; Teegavarapu & Chandramouli, 2005). Rainfall data in each station was spatially plotted on the map and by using interpolation lines were drawn by connecting points that have similar precipitation quantity.

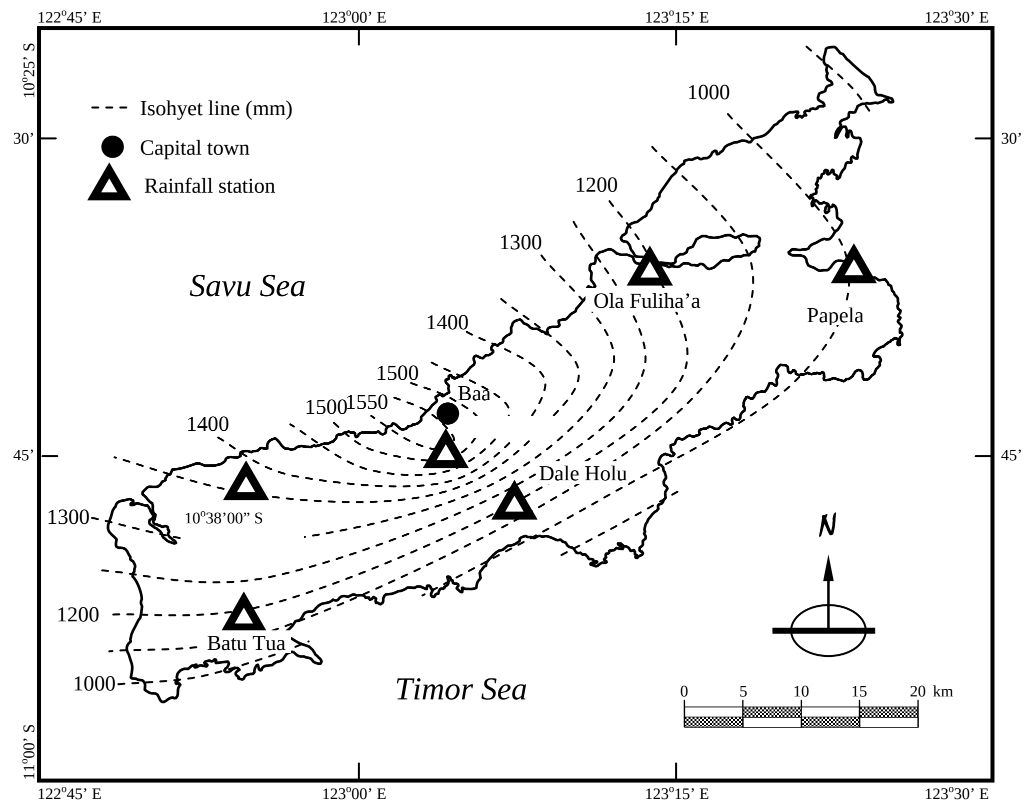


Figure 3 – 6. Isohyetal contour map of average annual rainfall in Rote Island

In Figure 3 – 6, it is shown that the highest annual rainfall value occurs in the area adjacent to the capital of the island. It than gradually drops following diverging lines to southeast part of the island. The rainfall contour shows that the north coast of the island experiences more rain than that on south coast. Therefore, this rainfall pattern suggests that Savu Sea contributes more stimulus to the development of rain in this Island that that of Timor Sea. However, since the size of this island is relatively small and it is considered flat the variation of rainfall distribution is considered negligible.

3.2.3. Humidity

The record on humidity condition in this island shows a range between 76 and 92%. As can be seen in Figure 3 – 7, the humidity increases during wet months (December – February) and subsequently drops in dry season. The driest condition occurs on November marked with 76% humidity. Rote Island maintains it's reasonably humid condition throughout the year.

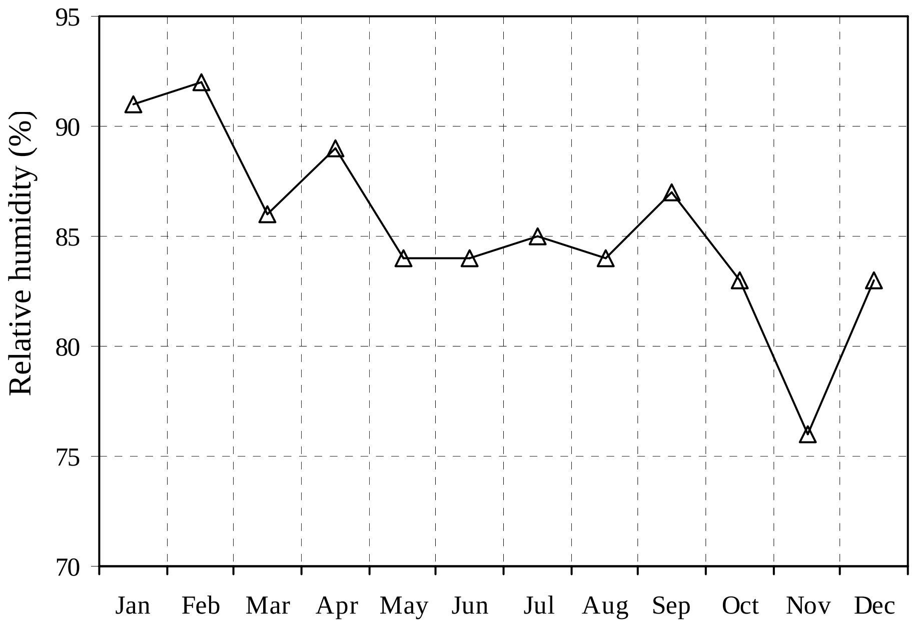


Figure 3 – 7. Average monthly relative humidity

3.2.4. Temperature

The temperature in Rote Island which is derived from 2002 and 2003 (BPS, 2004) is shown in Figure 3 – 8. It generally ranges between 25 and 34 ^{o}C.

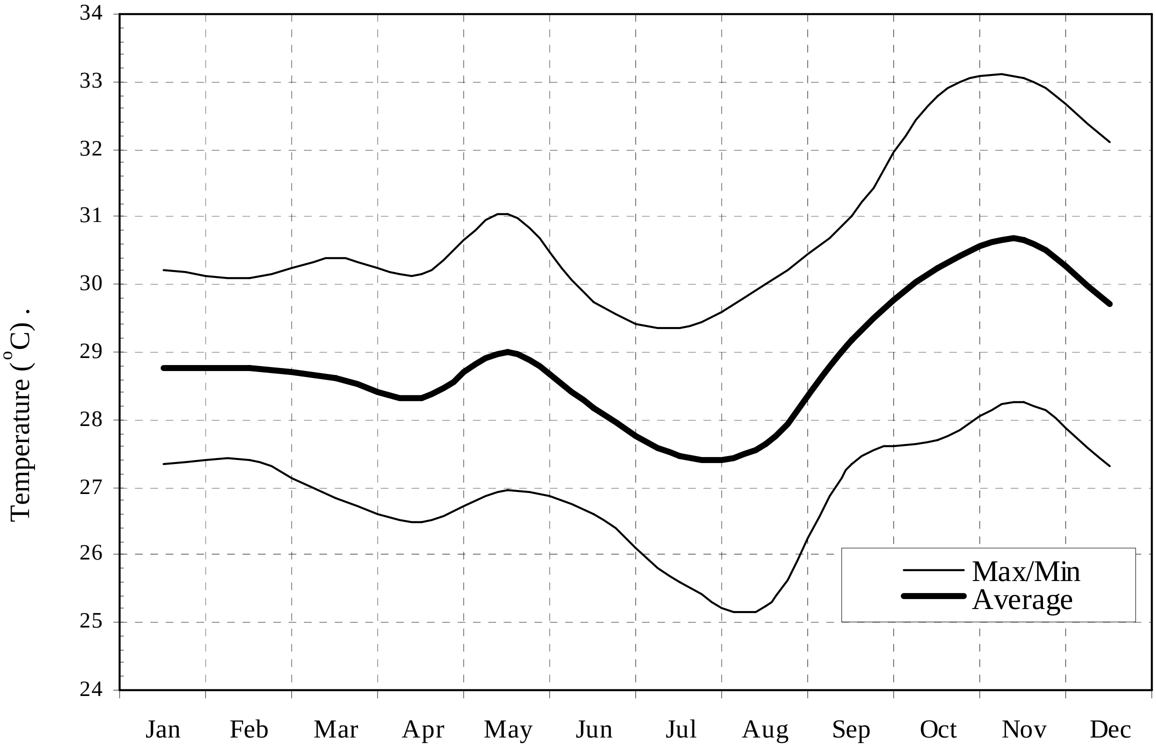


Figure 3 – 8. Temperature in Rote Island

3.2.5. Sun intensity

In general, mean daily sunshine in Rote island ranges between 5.5 and 11.2 hours (Figure 3 – 9). This typical monsoonal season characteristic plainly divides the two seasons prevailing in this island. The highest sun intensity occurs in dry season when it peaks at 11.2 hours in October. It then declines rapidly in wet season to 5.5 hours and sharply increases to 7.8 hours in March to commence the long dry season.

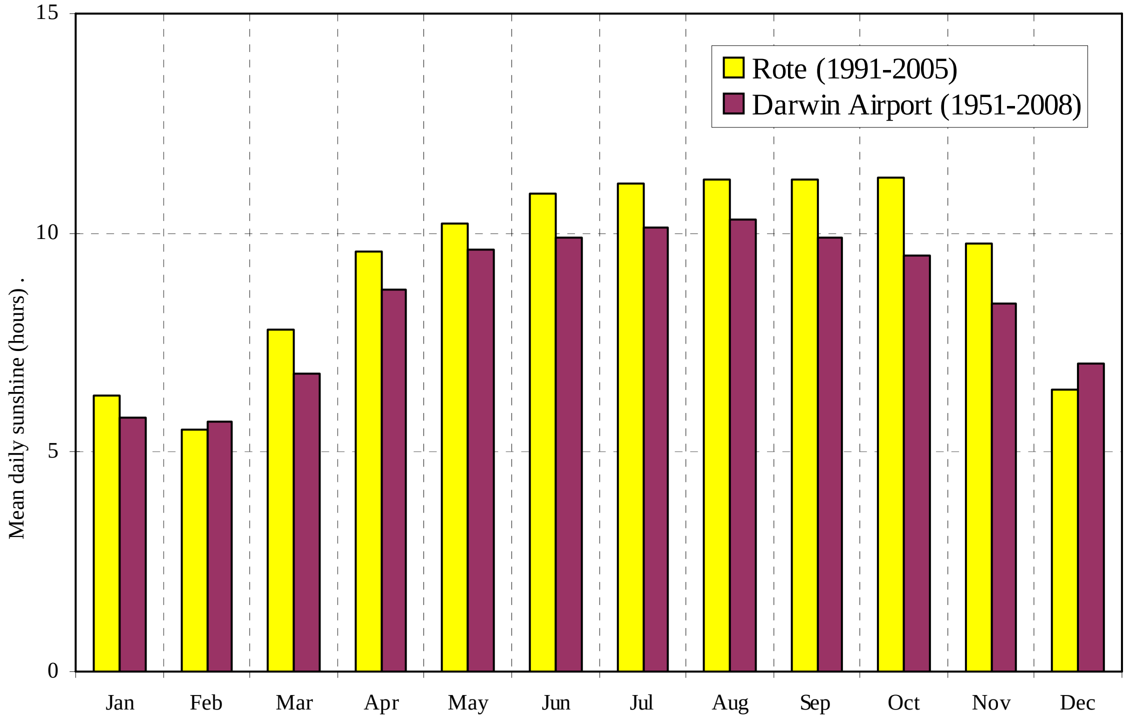


Figure 3 – 9. Mean daily sunshine in Rote Island compared to Darwin data

In comparison with another site in the adjacent region, i.e. Darwin (ABM, 2008) Figure 3 – 9 shows that the two places share the same trend.

3.3. Geology of Rote Island

3.3.1. Lithology and genesis

Geographically, Indonesia archipelago lies between two major continents (Australia and Asia) and two oceans (Pacific and Indian). This geographical position suggests that the geology of Indonesia is a shared characteristic of these continents and oceans. Hamilton (1978) and

Rangin, Jolivet, & Pubellier (1990) in Martini et al (2004) indicated that Indonesia was positioned in a convergent zone surrounded by three main plates: the continental Asian Plate, the oceanic Pacific Plate and the oceanic Indian Plate. The movements of these plates led to the formation of Banda Arc.

Rote Island is geologically positioned in the Banda Arc subduction zone (Figure 3 – 10). This approximately 2300 km arc lines extends from Seram Island, curls south west and ends at Sumba Island. Due to the collision of three major plates the geological setting of this island is extremely complex (Sashida, Munasri, Adachi, & Kamata, 1999) as different type of rocks and sediments from these three plates heterogeneously shaped it.

The Banda Arc is typically different compared with its neighbourhood islands of Indonesia. Mainly characterised by imbricated metamorphic, ophiolitic and sedimentary sequences (Martini et al., 2004), this arc consists of raised atoll islands with no or less sign of volcanic activity. Meanwhile, other islands located west of this arc, such as Flores, Sumbawa and Bali, are identified as neogene volcanic islands which are often described as the “belt of fire” since volcanic active mountains are numerously found.

Geological data in Rote Island was first recorded by Wichmann during the Dutch exploration in 1888-1889 (Rothpletz, 1891). He reported some early findings of geological exploration in Rote Island and Timor Island, which is located approximately 15 km northeast of it. During this investigation, he found some fauna species in rock strata from Mesozoic and Paleozoic age. Other works that confirm the early indication of Mesozoic period of samples found in Rote Island are those of Brouwer (1922), Riedel (1952), Riedel (1953) from which the last two studies focused on using Radiolaria as time-indicators. Apart from these Mesozoic conclusion there is a dissimilar argument of Tan Sin Hok (1927) regarding the recognition of those samples, which are now mostly kept in Instituut voor Mijnbouwkunde, Delft –

Netherlands. He assumed that specimens collected near Bebalain area which is situated in Lobalain Sub-district as of “young Tertiary Age”. However, following a re-examination study it is confirmed that they dated to Cretaceous (Mesozoic) to Pliocene (Tertiary) (Jafar, 1975). The most recent exploration by Sashida *et al* (Sashida et al., 1999) on radiolarian faunas in Rote Island identified samples dating to Middle and Late Triassic, Middle Jurassic and Early Cretaceous.

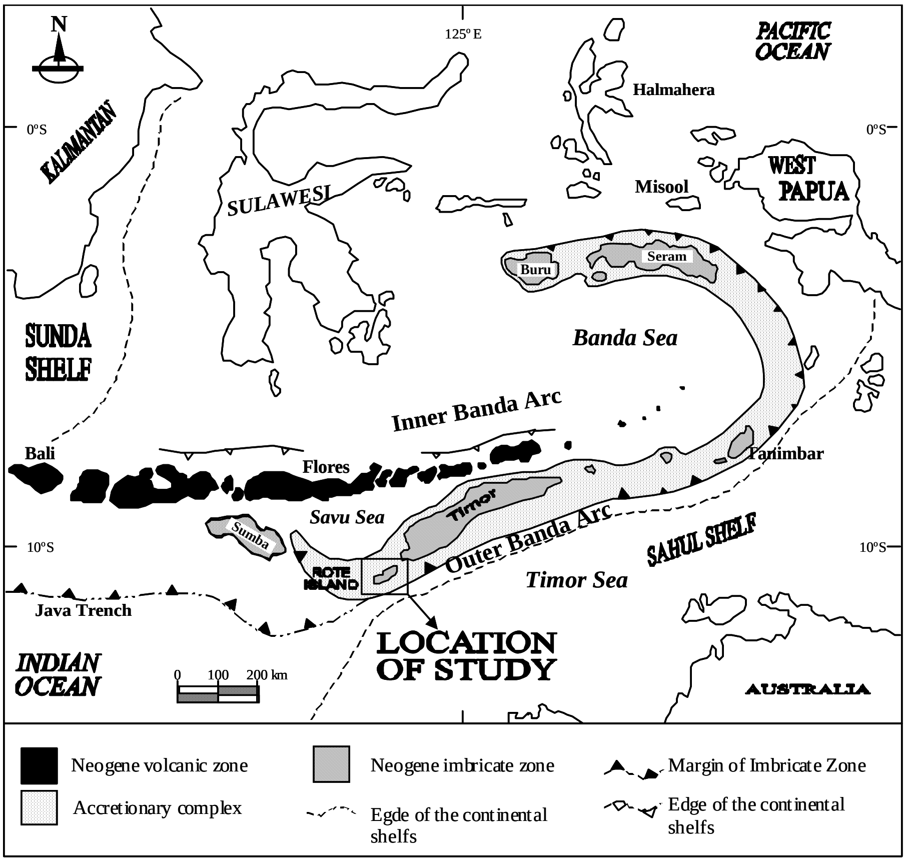


Figure 3 – 10. Map of study area with regard to Banda Arc, modified after Karig et al. (1987), and Martini et al. (2004; 2000).

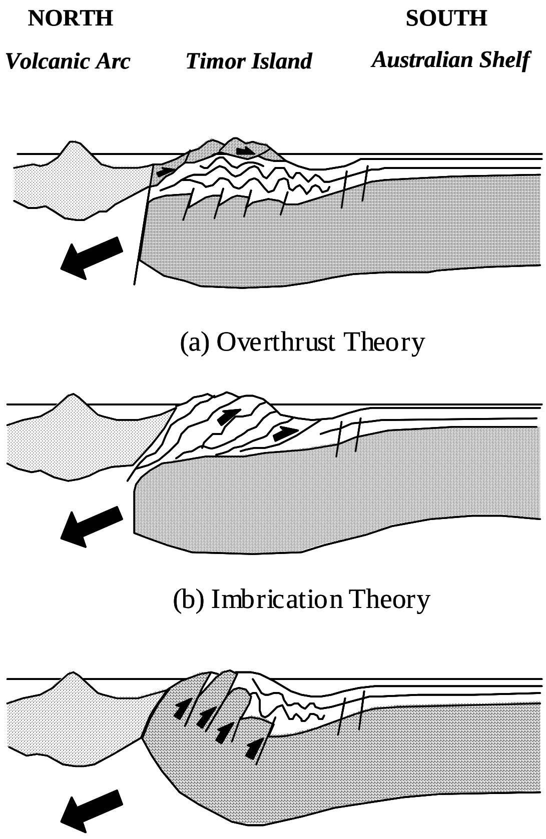
These findings directed some researchers to draw the genesis of Rote Island as described in ESDD report (2003) after modifying Harris et al. (2000). The first theory is Overthrust Theory (Figure 3 – 11) of Audley-Charles (1968) on whereby it was suggested that Timor is the outer edge of the Australian Plate that collided against the Asian Plate in the Middle-Late Miocene Age. This argument implies that part of rocks and sediments found in Timor should be similar with those in Australia. From this perspective, in Timor Island Australian strata overlie Asian strata hence upper rock formations must consist of identical Australian fragments. In the other hand, Hamilton (1979) proposed the second theory called Imbrication Theory (Figure 3 – 11) that rather than overthrusting Asian plate, at Timor Island Australian plate actually experienced underthrust beneath the Asian one. Therefore the accretion of this island is a result of rocks rising from underneath which is different from those from both plates. Conversely, Rebound Theory (Figure 3 – 11) was proposed by Chamalaun & Grady (1978) on which they argued that when they collided, the Australian plate and Asia volcanic arc were spatially at the same level therefore there was no overthrust nor underthrust movement occurred. However, Timor Island is considered as an uplifted Australian margin that rebounds during the collision with Asian plate.

To give a theoretical background of the genesis of the Rote Island, previous studies that investigated remnants of fauna that were found on rocks in Timor and Rote Islands are presented. The first investigation by Rothpletz (1891) concluded that species found in Timor Island had not been located in Australia. His argument was based on Wichmann’s work in 1888-1989 that discovered fossils of fauna species of Monotis and Halobia of Triassic (Mesozoic) period, such as *Halobia wichmannii*, *Monotis salinaria*, *Halobia lomeli*, *lineata*, *charlyana* (*mediterranea* Gemallaro), *norica* and *Daonella cassiana* which are similar with those discovered in Armenia and Russia. In addition Wichmann also found European-likely fossils of Paleozoic and Jurrasic (Mesozoic) ages in volcano mud. This fascinating fact led him to suggest that Timor Island and perhaps Rote Island once were sections of Permian sea enveloping an area of northern part of East India (Himalaya), Europe and this was continued during Jurassic period by the emergence of Liassic and Oölitic marine remnants in Rote Island, such as *Arietites geometricus*, *Harpoceras* cf. *Eserii*, and *Belemnites gerardii*. The second study was conducted by Sashida et al. (Sashida et al., 1999). Using Triassic radiolarian fauna of Rote Island that are indistinguishable with those from European, Japan, Phillippines and Russian Far East, but not Australia, they inferred that this island was part of the warm water current system of Tethyan ocean during Triassic to Middle Jurassic. The two studies support the Imbrication Theory proposed by Hamilton (1978) that Timor Island was formed as a result of underthrusting of Australian continent beneath Euroasia plates.

3.3.2. Stratigraphy of Rote Island

Stratigraphy of an area determines the outline and geological pattern of it. Geological situation in karst terrain is used to understand the hydrogeological characteristics of the karst system in the area.

Generally, the geology of Rote Island is dominated by coralline limestone formation. The formation which is mainly formed by Triassic marine creatures spread all over the island with the majority appearing in the West, Southwest, North and Northeast. Meanwhile, the Bobonaro complex, whose main characteristics are the occurrences of clays and tectonic rocks, cover mostly the middle part of Rote Island. Patches of the Bobonaro Complex are found on the western and eastern areas. Other formations, which include the Noele and Aitutu Formations, insignificantly scatter around the island, while alluvium mostly found in coastal ridges.



(a) Overthrust Theory

(b) Imbrication Theory

(c) Rebound Theory

Figure 3 – 11. Theoretical concept on the genesis of Timor Island, after Harris et al (2000)

According to Rosidi *et al*. (1981) Rote Island has a distinctive stratigraphy ranging from Triassic to Pleistocene ages. A geological situation of this island is presented in Figure 3 – 12 in which the study area is shown in the inserted square.

In Figure 3 – 11, there are four main geological formations in Rote Island. The following parts describe individual formations and their detail (Rosidi et al., 1981):

1. Aitutu Formation (Ra)

This Formation mainly consists of two layers. The upper part is dominated by greyish calcilutite. The lower part is made up of combination of interspersed thin layers of reddish, brownish and greyish silt, marl and limestone. A presence of Halobia sp fossil in this formation indicates a Triassic age. This Formation makes up 0.4 % of the island's area.

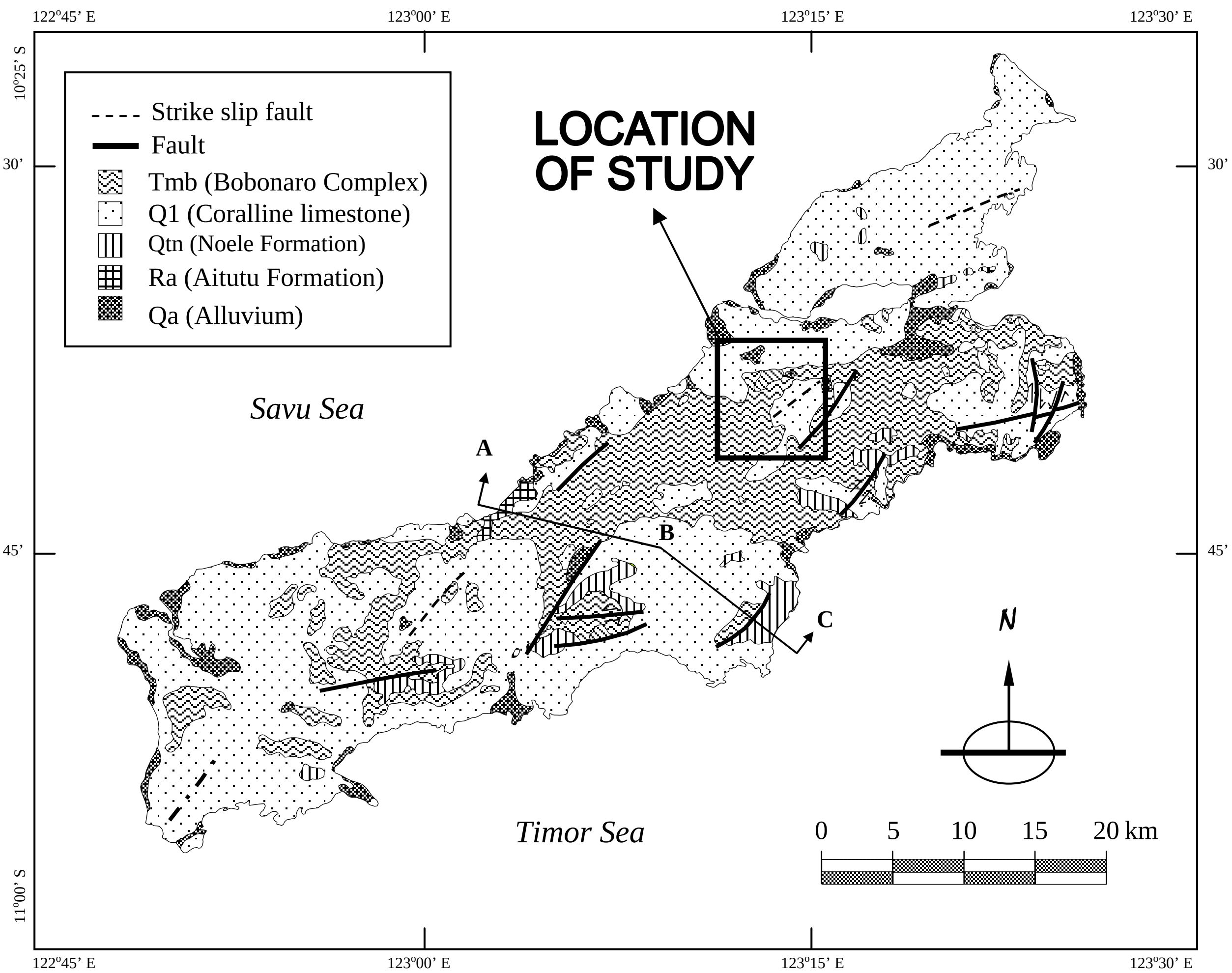


Figure 3 – 12. Geological distribution of Rote Island, after Rosidi et al (1981)

2. Bobonaro Formation (Bobonaro complex) (Tmb)

The Bobonaro Formation, which covers 29.2 % of the island, is composed of two distinct parts, which are scaly clay and mix of tectonic rocks. The deposit of clay is characterised by its dark reddish, greenish and red brownish, bluish grey and purplish colours and is physically soft. The environment is suggested as marine as denoted by Foraminifera plankton fossil. Thus the formation is dated between Middle Miocene and Pliocene ages. The tectonic rock layer comprises of different size rocks of metasandstone, limestone mica, limestone crinoide, chert, pillow lava, and silt limestone. These rocks are suggested to experience an extensive weathering process and became scaly clay. The thickness of this complex is difficult to be determined since it maintains tectonic contact with older formations.

3. Noele Formation (Qtn)

This Formation is identified as being formed during Pliocene – Pleistocene ages. The Formation is recognised by the presence of the interspersion of sandy marl and sandy limestone. Foraminifera are abundantly found in greyish white marl and infrequently discovered in silty marl. The sandy layers made of convoluted and medium to coarse-grained materials range between 10 and 190 cm in thickness. Conglomerate, which is occasionally exposed in this Formation, originated from detrital metamorphic rocks and older rocks. The Formation that covers about 3.9 % of Rote Island is unconformable with upper-layer formation.

4. Quaternary coralline limestone (Q1)

With an extensive 61.1% coverage of the surface, this Formation is considered as the main geological cover of Rote Island. The limestone is characterised with its white and yellow or occasionally red colours. Coralline limestone mainly occurs in this island with a minor emergence of marly limestone of the Pleistocene age.

5. Alluvial deposit (Qannam)

The deposit found along coastal line and on floodplain of rivers is a mixture of sand, gravel, and pebble forming approximately 5.4 % of the island. These sediments and rocks are mainly formed of physical weathering and flushed downstream by surface runoff.

3.3.3. Geological stratum of Rote Island

The explanation of actual geological stratum of Rote Island is problematical since data available from different locations is absent. The only two data, which are in the following section (Section 3.4) used to argue the type of karst that governs recharge process in this island (Section 3.6), are the cross-sectional layout taken from Figure 3 – 12 and presented in Figure 3 – 13 (Rosidi et al., 1981) and bores data taken in Olafuliha'a Village which is presented in Section 3.4.1.

Figure 3 – 13, which is the cross-sectional layout of line A-B-C of an area located at the middle of Rote Island (presented in Figure 3 – 12), shows that two major rock types, which are Bobonaro Complex and coralline limestone, cover the surface area nearby the cross section. Bobonaro Complex mainly consists of silt which in limestone environment can act as

aquitard. On the other side, permeable layers of limestone which largely covers the island could performs as an aquifer that stores water and releases it through springs.

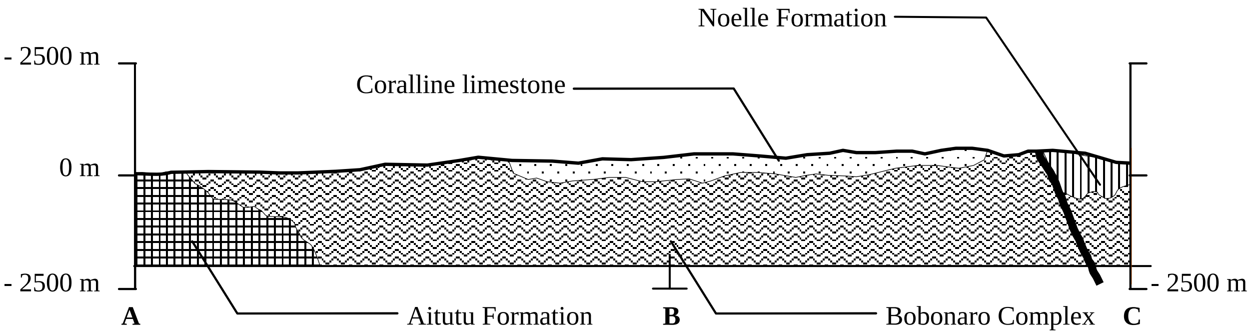


Figure 3 – 13. The geologic cross section of Rote Island (Rosidi et al., 1981)

3.4. Study area

The area in where the study obtains data for the water balance analysis in Section 3.4.3 is in Olafuliha'a Village (Figure 3 – 14). The location geologically dominated by Bobonaro Complex, coralline limestone, alluvium and Noele Formation is characterised by is undulated terrain and located about 20 km northeast of Baa and around 2 km from shoreline. Data is taken from a report of a geological survey conducted by CV. Citra Utama which was designed to evaluate groundwater potential in the area for drinking water purpose (PAT, 1992). In the survey, geological layers, soil and rock samples and groundwater samples were taken and analysed from five bores (TW.01 to TW.05) scattered within a 2-km diameter circle.

3.4.1. Geological setting

In PAT report (1992) the cross-sections of the five bores in the study area were drawn and in this study are compiled into one diagram and presented in Figure 3 – 15. The geological stratum at the bores shows a significant thickness of limestone in soil strata that ranges approximately between 20 and 80 m. In this geological profile, limestone stratums are separated by thin layers of lower permeability soils such as clay and silt that ranges from 2 to 9 m. The measured height of the water table is also noted in Figure 3 – 15 and a cross-section is given Figure 3 – 16.

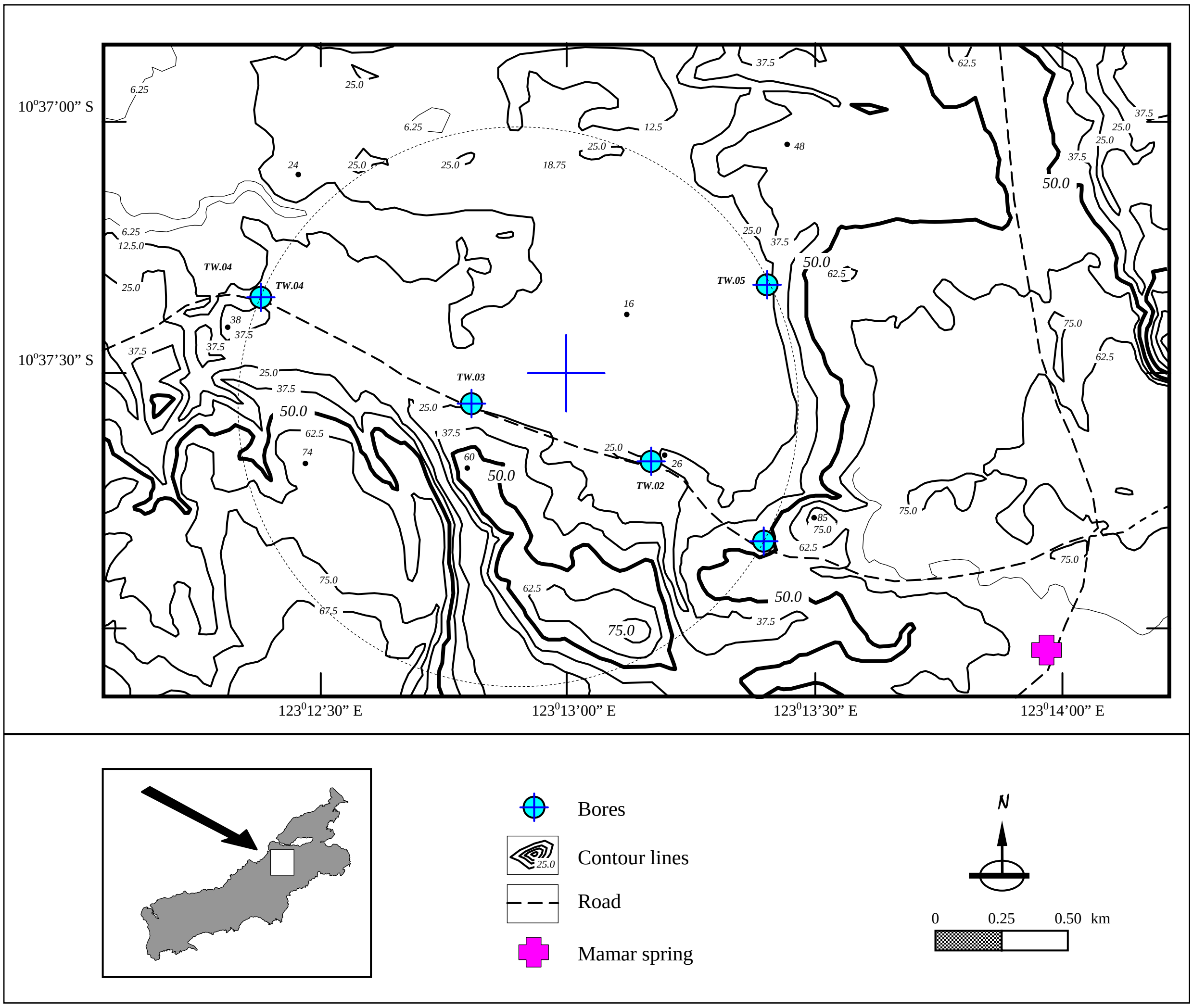


Figure 3 – 14. Location of bores investigation in the study area

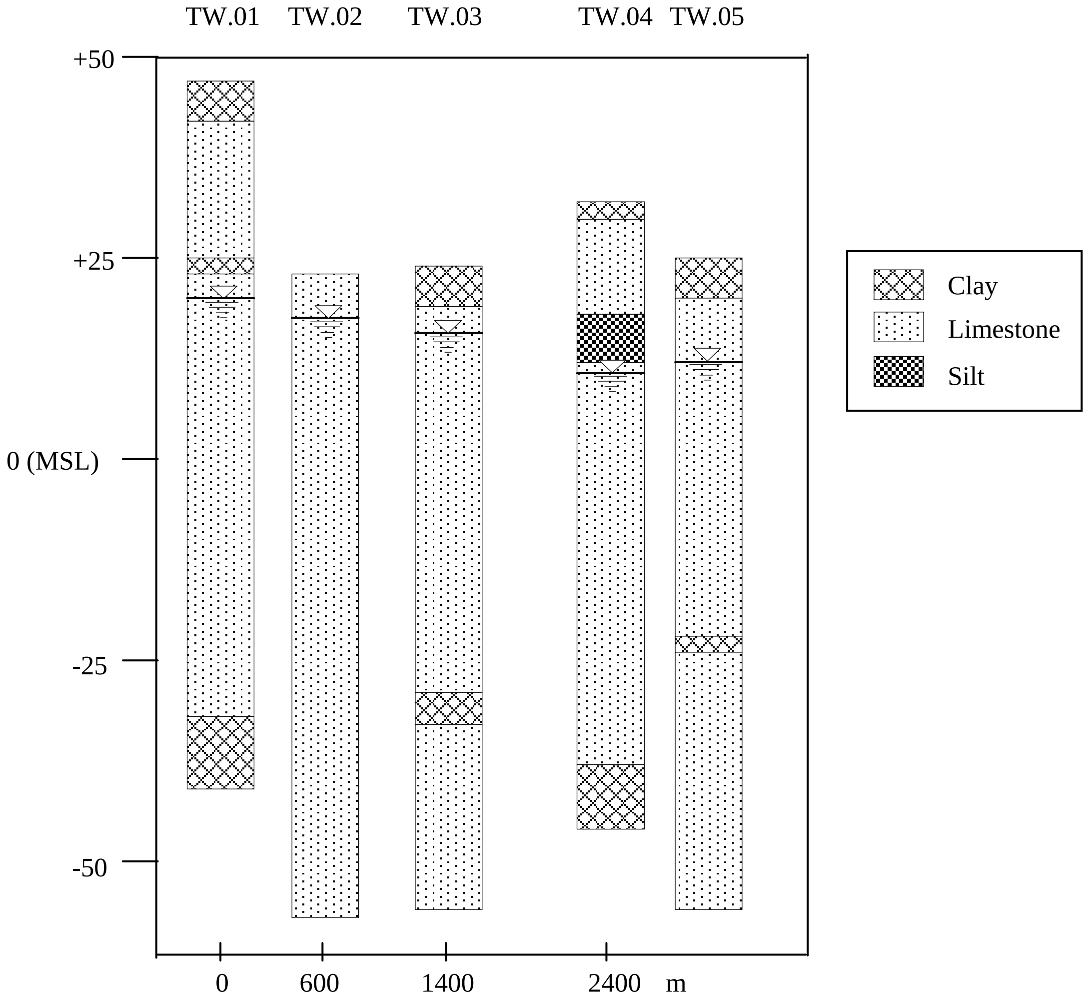


Figure 3 – 15. Soil layer on bores investigation in the study area (Olafuliha'a Village)

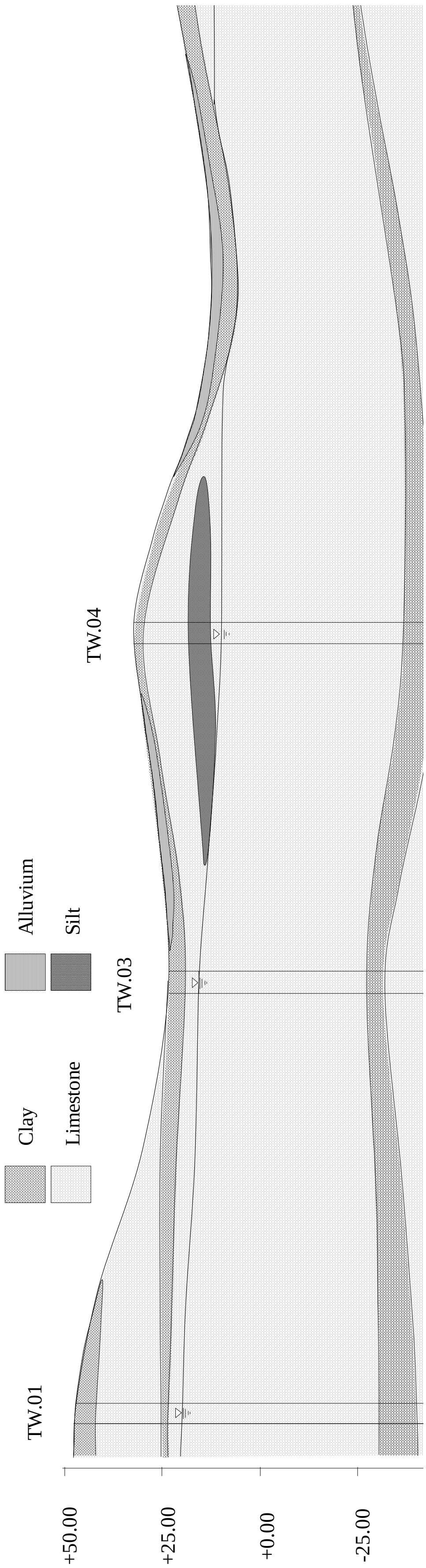


Figure 3 –16. Cross-sectional layout of stratigraphy and groundwater position at bores in Olafuliha’a Village

3.4.2. Chemical composition of groundwater at bores

The hydrochemistry properties of groundwater taken in the study area were determined by laboratory analyses (PAT, 1992). In several water samples, which were taken from the same bores on which geological profile was figured, the electrical conductivity and cation-anion concentrations were measured and analysed in the laboratory in Kupang.

In general the carbonate (CO_3) and bicarbonate (HCO_3) components counting for about 60% dictate the hydrochemistry profile of groundwater at the bores (Figure 3 – 17). The indication of strong limestone ($CaCO_3$) proportion is established by around 14% Ca. Another dominant carbonate rock in karst environment, which is dolomite, lightly occurs in Rote Island karst indicated by the proportion of Mg in each bore that is approximately 6%. A substantial amount of Cl and NO_3 (13%) contribute to the overall figure. Meanwhile, other water components such as Na, K, SO_4, and SiO_2, add minor quantity of solutes to the karst groundwater.

In order to verify the precision of laboratory analyses, charge balance analysis was performed. This analysis is designed to check the result against two types of errors in chemical analyses, which are precision and accuracy. The overall result of charge balance analysis, which complies with the requirement by which ideally the electrical balance (Ghebreyesus) should be less than 5x (Postma & Postma, 2005), is presented in Table 3 – 1. Meanwhile the detailed analysis and result is shown in Appendix D.

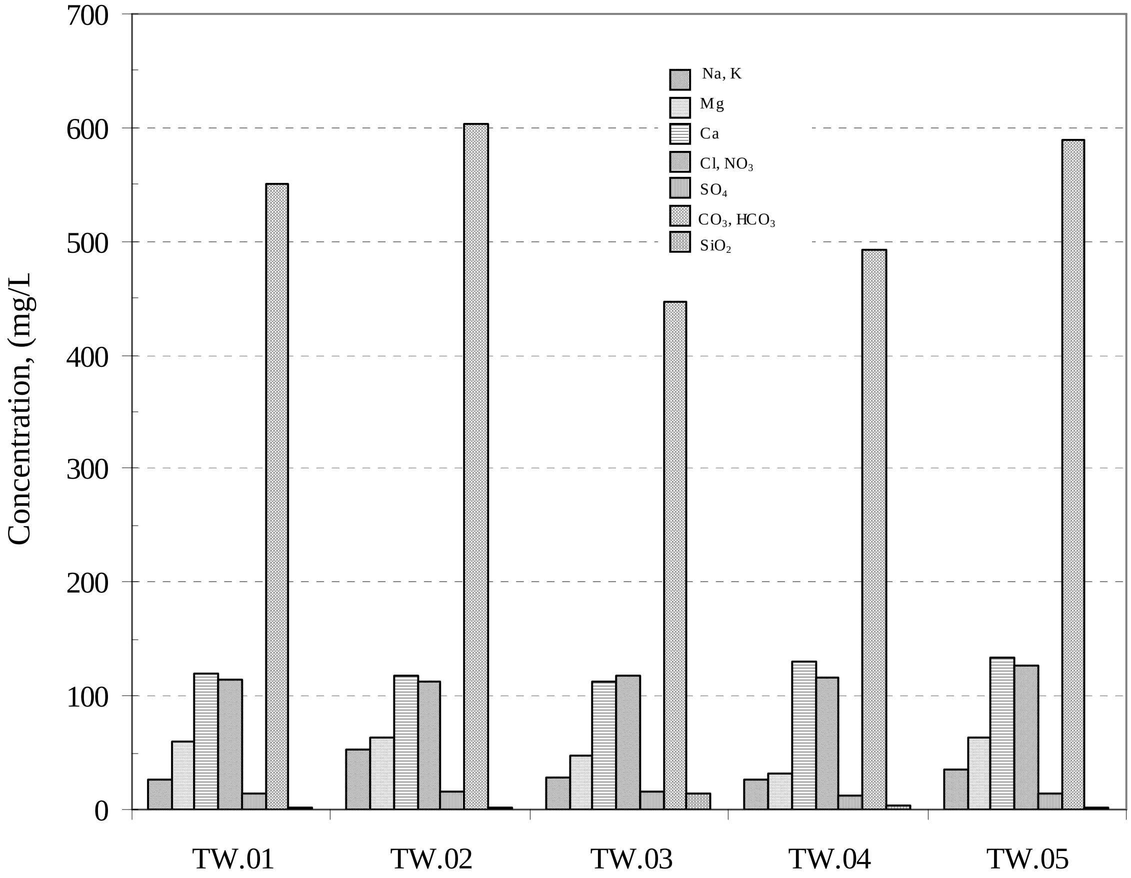


Figure 3 – 17. Chemistry of groundwater from bores TW.01-TW.05

Table 3 – 1. Result of charge balance analysis

Bore	Cations (meq/L)	Anions (meq/L)	E.B
TW.01	11.92	-11.50	1.80%
TW.02	13.12	-12.41	2.78%
TW.03	10.71	-9.93	3.76%
TW.04	10.20	-10.57	-1.81%
TW.05	13.34	-12.54	3.11%

3.4.3. Water balance

Water balance is analysed in the catchment area (Figure 3 – 18) of five bores in Olafuliha'a Village. In this analysis, monthly rainfall data from 1991 to 2005 is used, while evapotranspiration is calculated using Hargreaves Method (Droogers & Allen, 2002).

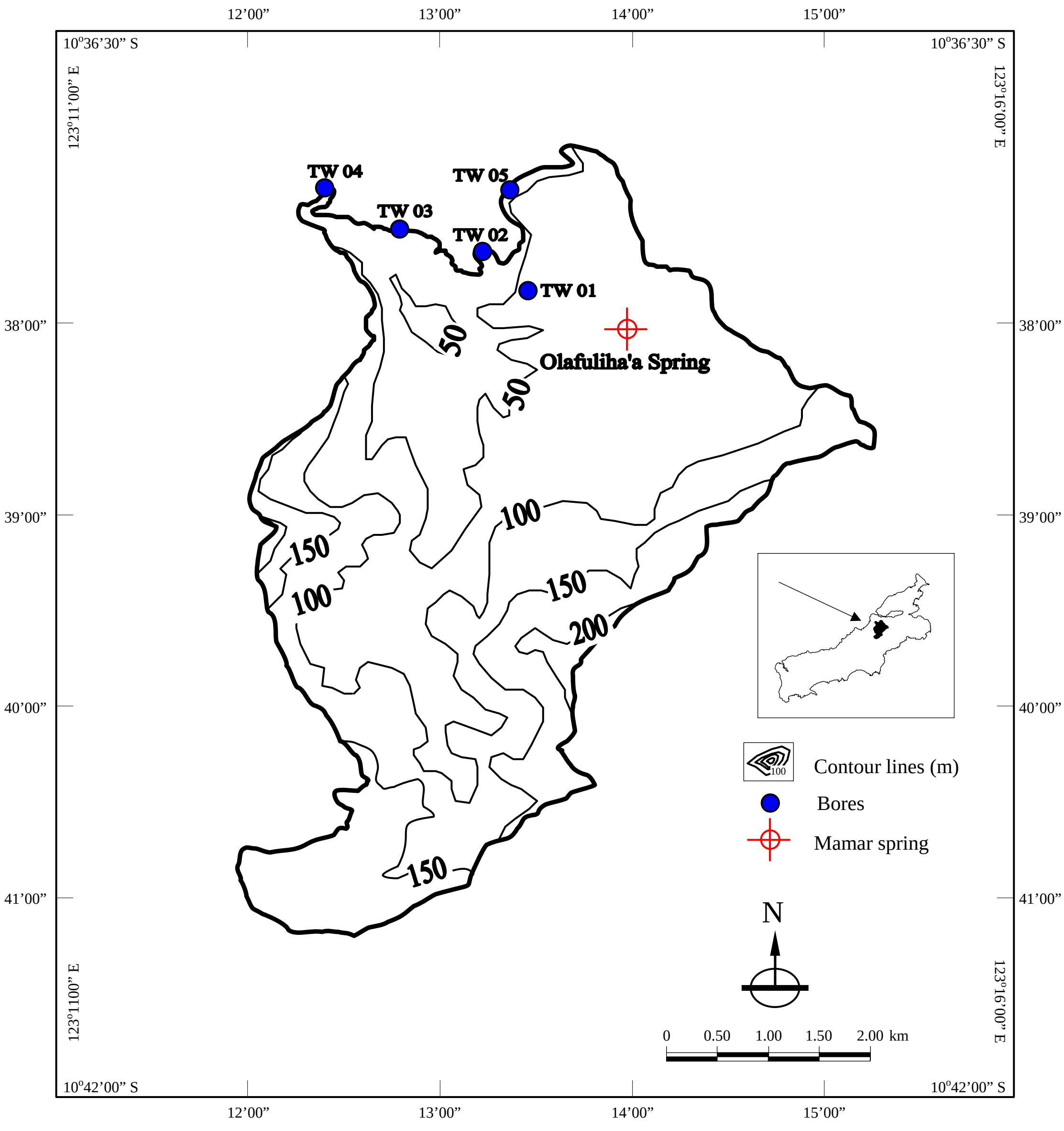


Figure 3 – 18. The catchment area of five bores in Olafuliha'a Village

3.4.3.1. Evapotranspiration analysis

In the evapotranspiration analysis of the study area, the Hargreaves Method (Droogers & Allen, 2002)is used. The rationale of using this method is the simplicity of the method which requires mainly temperature, solar radiation and precipitation data. The analysis is presented in Annex C and the result of the analysis is presented in Figure 3 – 19.

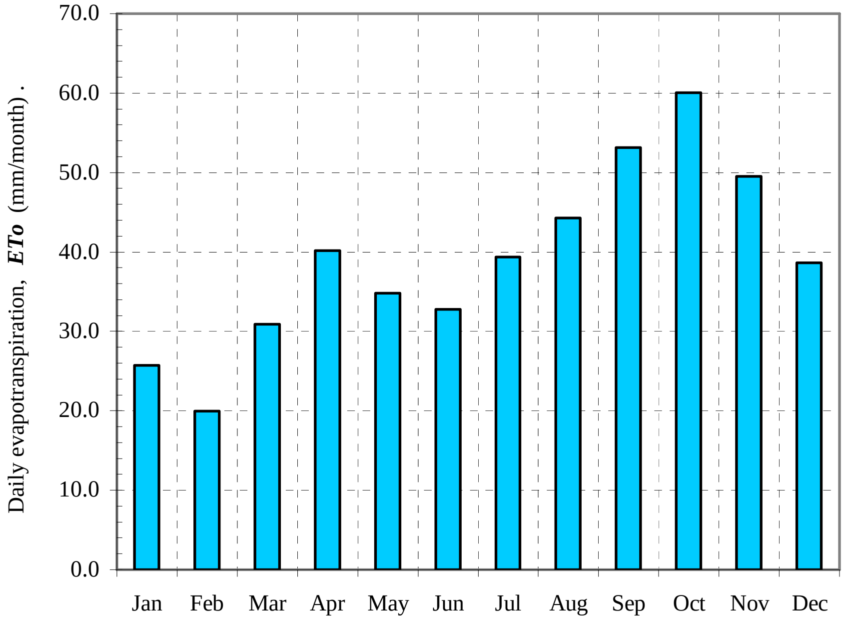


Figure 3 – 19. Calculated monthly evapotranspiration in the catchment of the bores in Olafuliha'a Village

3.4.3.2. Surface run-off analysis

The method used in the surface run-off analysis is Soil Conservation Service (SCS) Method (Viessman & Lewis, 1996). This method is used due to its simplicity and reliability (Ponce & Hawkins, 1996) and there is no direct measurement of run-off in Rote Island.

The analysis begins with identifying physical characteristic of the surface which is land-use. Land use data is derived from Spatial Map of Rote Island provided by Bappeda (2004). Figure

3 – 20 shows that in the catchment that counts for about 4.5 km^2, bush dominates the catchment (53.8%), while forest makes up the second most coverage (16.8%). Meanwhile, plantations, farms and short grass range from 8.5 to 10.8 % of the total basin.

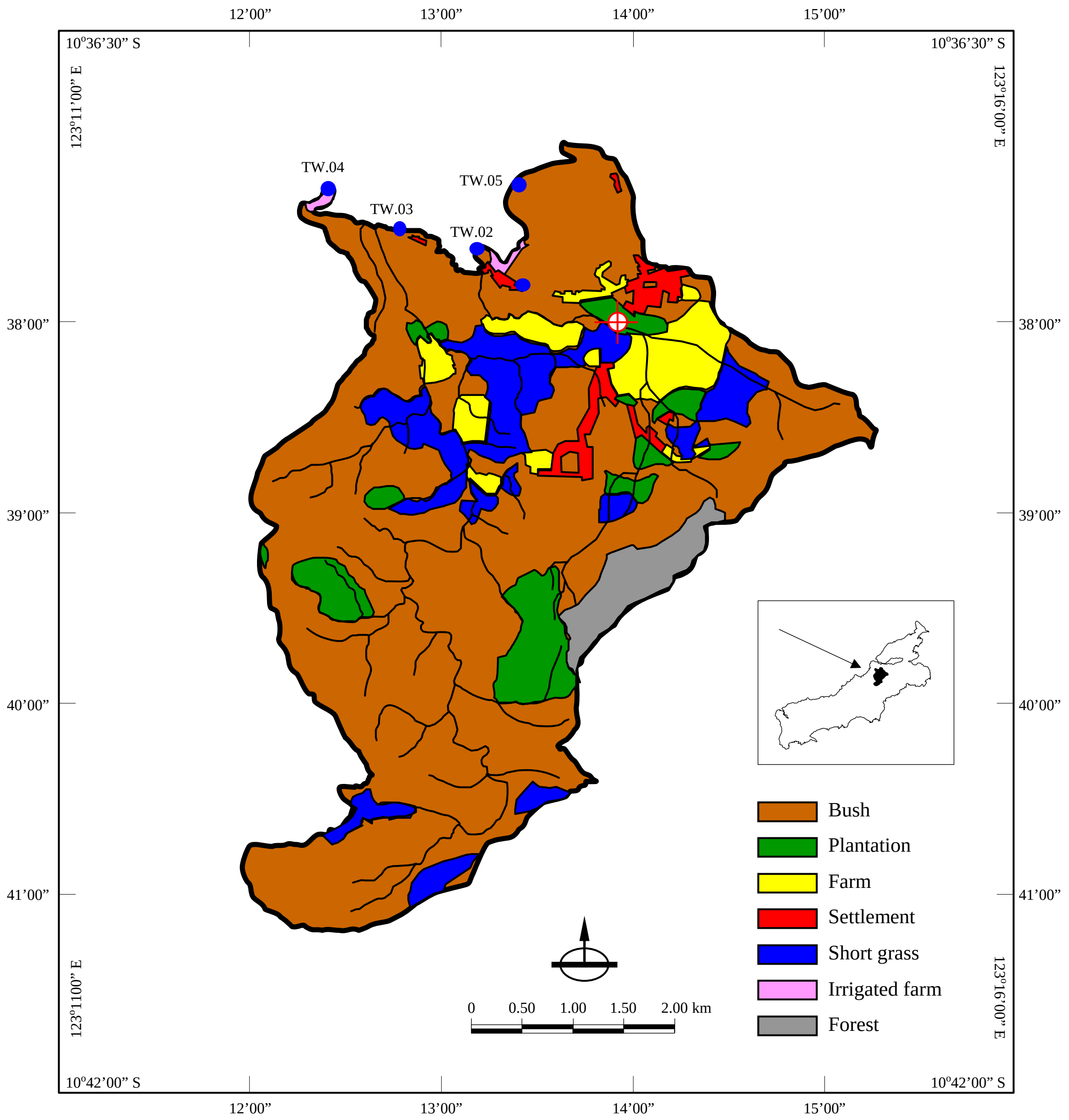


Figure 3 – 20. The distribution of land use in the catchment area

For given rainfall data between 1991 and 2005, the surface runoff analysis in the catchment of the bores is presented in Annex D and the average estimated surface runoff is presented in Figure 3 – 21.

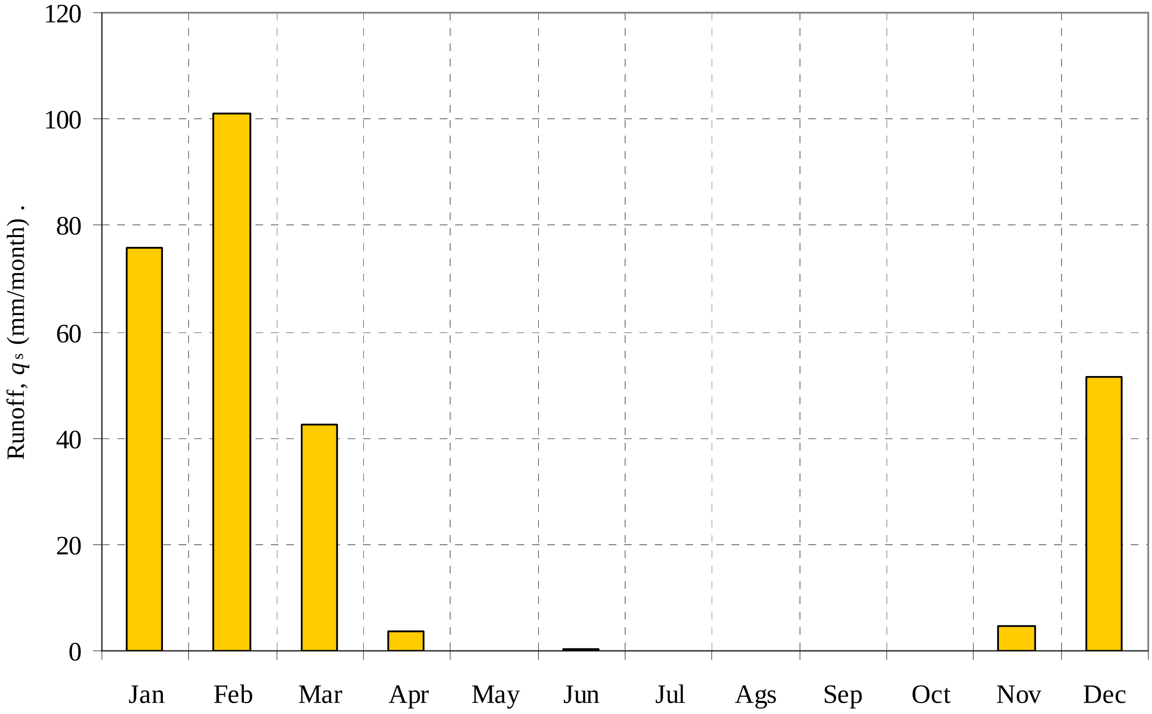


Figure 3 – 21. Estimated runoff in the catchment of the bores in Olafuliha'a Village

3.4.3.3. Infiltration analysis

This study also employs SCS Method (Kumar & Jab, 1982) to analyse infiltration in the study area. The result of the analysis is presented in Figure 3 – 22.

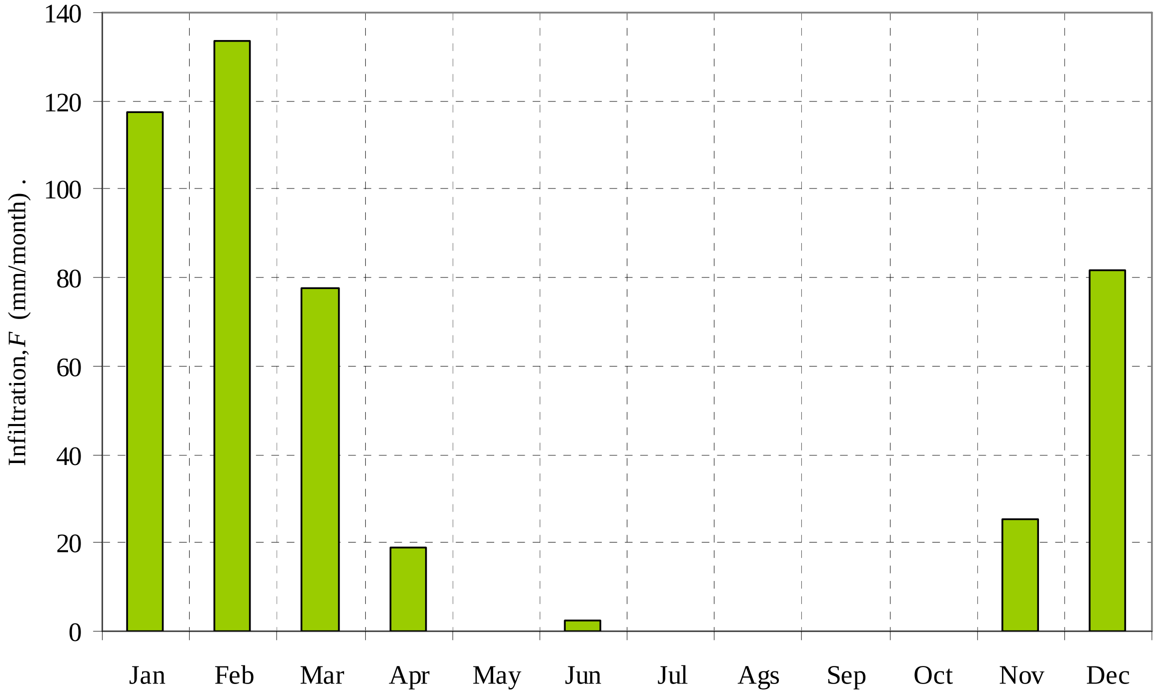


Figure 3 – 22. Average estimated infiltration the catchment of the bores in Olafuliha'a Village

3.4.3.4. Water balance analysis

After analysing rainfall, evapotranspiration, surface run-off and infiltration, the water balance of the study area is quantified. The detailed analysis is presented in Appendix E and the result is shown in Figure 3 – 23.

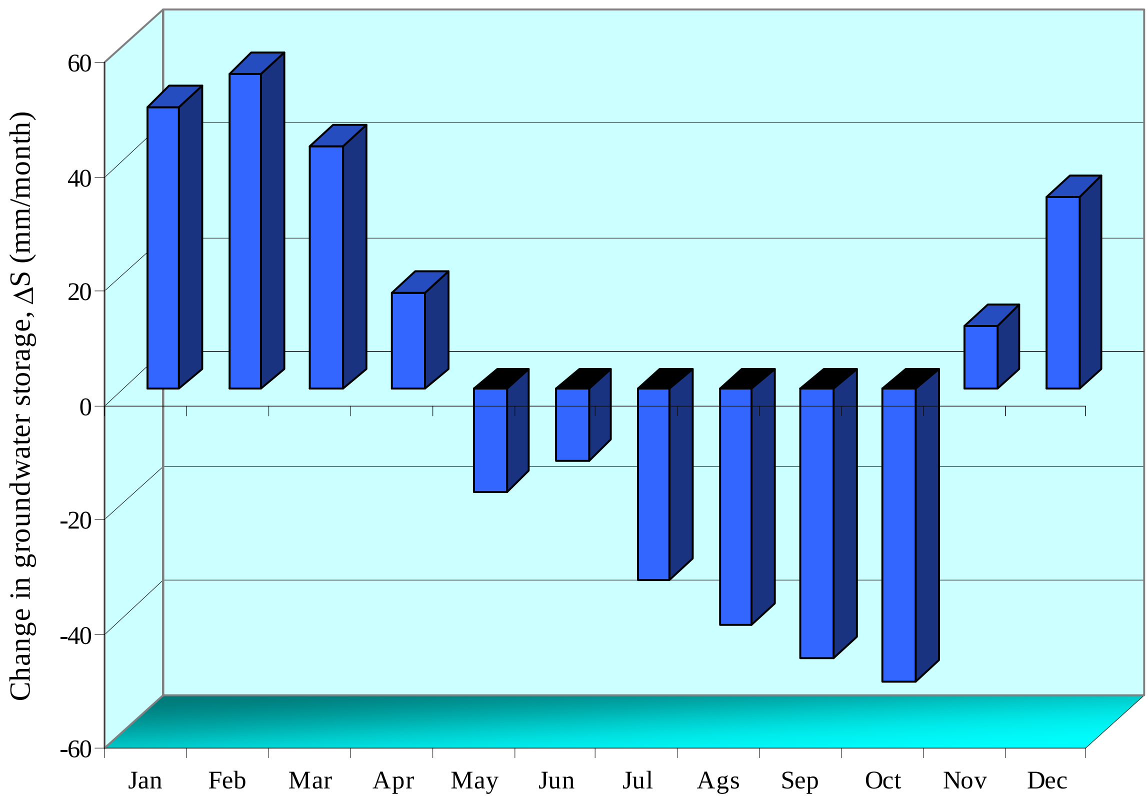


Figure 3 – 23. The average water balance of study area

Figure 3 – 23 shows that throughout the year groundwater storage in the study area experiences a significant fluctuation between 55.2 and -51 mm/month. The negative signs which occur during dry period most notably in October suggest a deficit in water budget. Meanwhile, recharge to groundwater aquifer takes places during rainy months starting from November to April.

The overall balance of the monthly groundwater change is 5.8 mm/month which illustrates the vulnerability of groundwater availability in the study area. Therefore any change in land use which influences the infiltration and runoff components may greatly impact the total water budget in the study area which in turn in the context of hydrologic cycle of karst area affects the groundwater supply to springs.

3.5. Field investigation

In order to verify data found in literature and hydrogeology analysis of the study area in previous sections, which are Section 3.3 and Section 3.4 respectively, a field investigation in several locations in Rote Island was taken place between October and November 2006. The survey which was conducted in eight villages (Figure 3 – 14) consists of visual examination on geomorphological characteristics, on site water measurement and social survey which is then explained in Chapter 4.

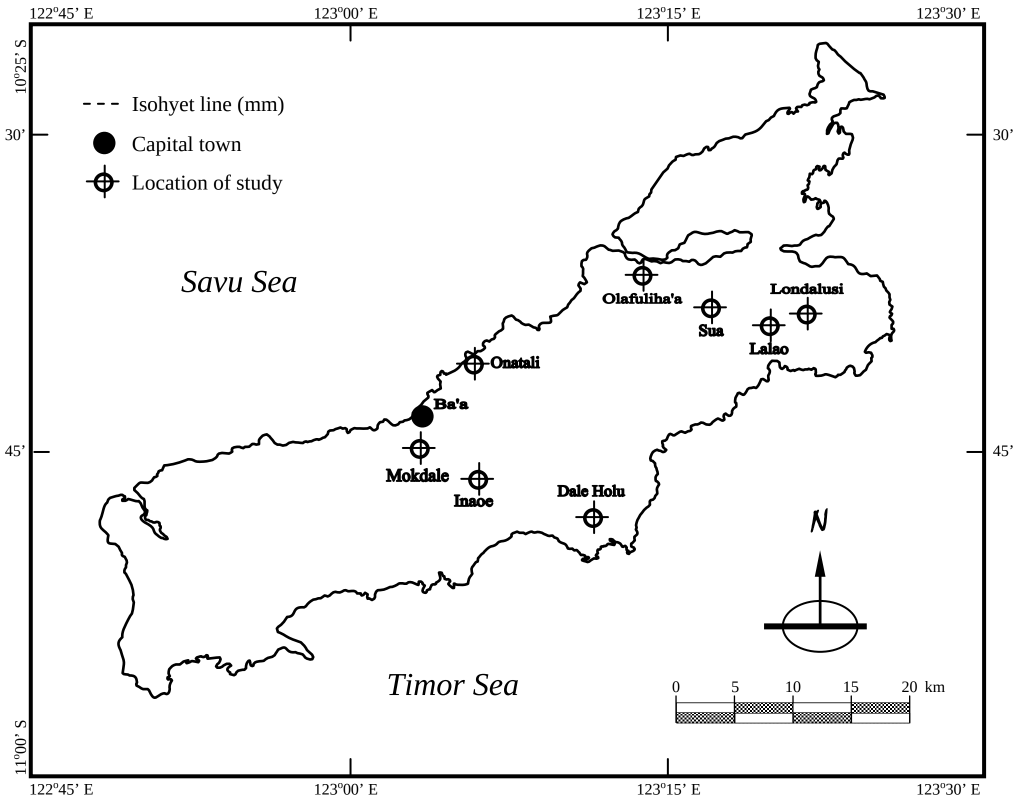


Figure 3 – 24. Locations of field investigation

3.5.1. Visual examination on geomorphology

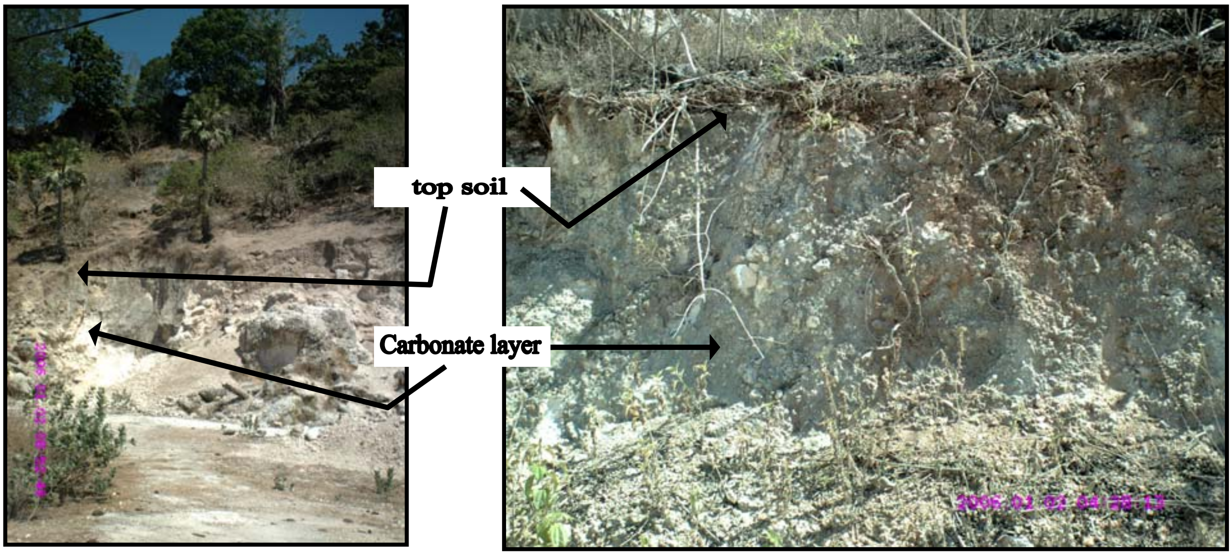
In the field investigation, it can be seen that morphologically the surface profile of Rote Island is dominated with an undulated landscape. Figure 3 – 25 and 3 – 26 that illustrate the common landscape type in this island, shows that the island is generally dry characterised with small number of trees and shrubs.

Figure 3 – 25. Surface landscape in Lalao Village

Figure 3 – 26. Surface landscape in Onatali Village

Findings from precious sections show that there is correlation between the dry condition that occurs especially in dry season that last for about 8 months (April – November) and climatological factors. Low annual precipitation that ranges averagely between 1000 and 1400 mm (Section 3.2.2), humidity that varies from 75 to 90% (Section 3.2.3), temperature which ranges between 25 and 34 ^{o}C (Section 3.2.4), and sun intensity that is reflected with mean daily sunshine which is between 5.5 and 11.2 hours (Section 3.2.5) are argued to significantly influence the availability of water in Rote Island. Water balance analysis in Section 3.4.3 suggests that humid condition and high temperature due to high sun intensity increase evapotranspiration and thus reduces water stored in soil layers.

With regard to geological setting, it is found that in the field investigation in Termanu and Mokdale Villages extensive carbonate layers covers the area with a very thin top soils rest on top of it (Figure 3 – 27).



(A) Karst formation in Termanu Village

(B) Karst formation in Mokdale Village

Figure 3 – 27. Carbonate layers that dominates the areas in Termanu and Mokdale Villages

The locations where field survey was conducted are dominated by karst landscape that is highly soluble rocks such as limestone and dolomite. Figure 3 – 28 shows limestone and dolomite samples found during visual examination in Mokdale Village. The result of geological survey in Olafuliha’a Village (PAT, 1992) in previous section (3.4.1) using bores data shows formation of these typical carbonate rocks in soil strata. The occurrence of these rocks is also confirmed in hydrochemistry analysis in previous section (3.4.2) on water samples taken from the bores.

(A) Limestone

(B) Limestone (two below) and dolomite (above)

Figure 3 – 28. Sample of limestone (A) and dolomite (B) rocks collected from Mokdale Village

In Lalao Village, a sample of carbonate rock is examined (Figure 3 – 29). The physical appearance of the rock shows that the carbonate rock is substantially dissolved by water which left irregular holes all over the rock. Groundwater in karst system is significantly influenced by the dissolution process of carbonate rocks. In this process rock is dissolved by water followed by physicochemical processes. The finding complies with the characteristic of tropical karst suggested by Jakucs (1977) who indicated that up to 75% of carbonate rock is dissolved in karstification process.

Figure 3 – 29. Sample of carbonate rock that had undergone dissolution process

Like other examples of karst terrain, there are caves derived by carbonate dissolution found at some places in Rote Island. In the adjacent island, which is Sumba Island the karst landscape is especially featured by underground river through caves in which conduit aquifer characteristics prevail (Soenarto, 2004). However, although in several places such as in Nioen and Mokdale Villages (Figure 3 – 30 shows) there are carbonate caves that are internally interconnected, in Rote Island there is no indication of groundwater flowing in those caves. It is argued that that the water table is very low so that groundwater cannot feed into the cave network.

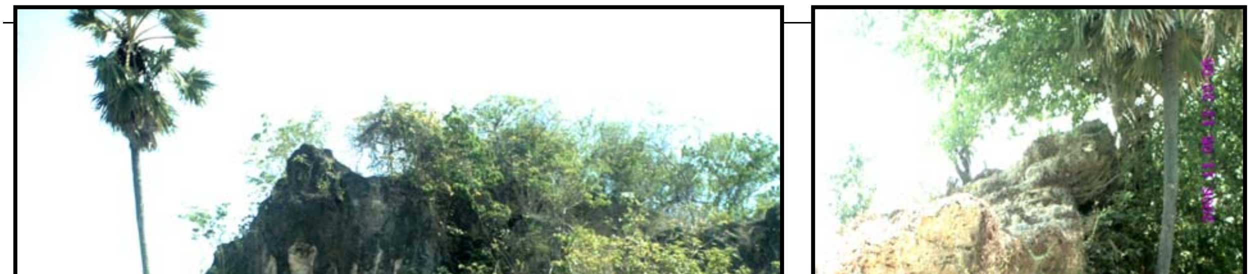


Figure 3 – 30. Carbonate caves in Nioen and Mokdale Villages

3.5.2. Water measurement at Mamar springs

An obvious characteristic of Rote karst is a lack of perennial surface stream due to the wet-dry monsoonal precipitation, high humidity and a significant area of high permeable soil cover such as limestone and dolomite. However, in some areas, where geologically at least two main rock formations meet, natural springs arise and some of them produce a significant amount of water. The areas where these springs occur are drawn superimposing map of geological layer of the island (Figure 3 – 31). The relationship between the springs' initiation and the geological formation in which they occur is discussed afterwards in Section 3.6.

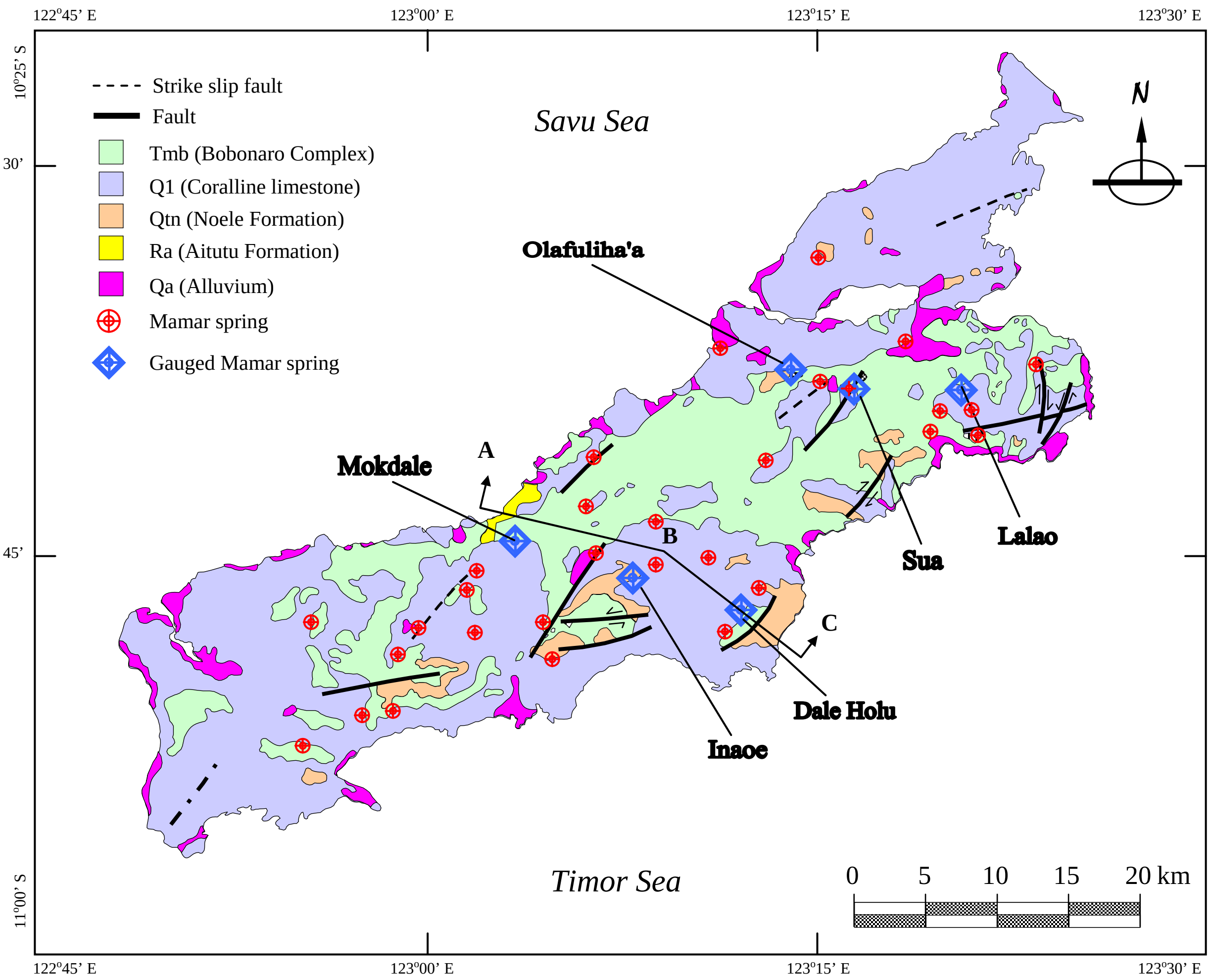


Figure 3 – 31. Location of several Mamar springs in Rote Island

The water measurement was conducted in six Mamar springs located in six villages (Figure 3 – 31) between 31 October and 7 November 2006. In locations where spring water is abundant and there is water channel built at the site (see Figure 4 – 8) water discharge was calculated by measuring flow velocity, time and the area between the points (Wanielista, Kersten, & Eaglin, 1997). Meanwhile, at other sites where groundwater is stored in a cemented box due to limited water discharge (see Figure 4 – 9), flow rate was measured by capturing of a volume of water passing a point of reference which is a pipe coming out from the box using a bucket and time control. The result of water measurement at Mamar springs in Rote Island is presented in and Table 3 – 2, while the detailed result is shown in Appendix F.

Table 3 – 2. Result of water measurement at Mamar springs in Rote Island (October - November 2006)

No	**Name of spring**	**Village**	***Q*** **m³/sec**	***Q*** **L/sec**
1	Dae Loni	Inaoe	0.0001	0.1
2	Dae Mami	Dale Holu	0.0022	2.2
3	Lakamola	Lalao	0.0377	37.7
4	Deoen	Olafuliha'a	0.0040	4.0
5	Odalode	Sua	0.0914	91.4
6	Oemau	Mokdale	0.0825	82.5

3.6. Conceptual geological initiation of Mamar spring in Rote Island

The analysis of main geological formations that cover Rote Island from data available (section 3.3) which is then validated by the field survey (section 3.4) confirms that karst landscape dominates Rote Island. A significant characteristic of Rote Island’s karst is the occurrence of spring called Mamar in several locations. The springs have significant function to provide water for the inhabitants and thus it is important to understand the physical characteristics of the Mamar spring.

In order to understand the initiation of Mamar springs in Rote Island which at the end results in a comprehensive understanding of the karst environment in Rote Island a conceptual model is built based on hydrogeology data available as well as a verification from the field investigation conducted in the area. Although there is a lack of supporting data to sustain the model, this study attempts to present all available data to draw the outline of the conceptual representation of Rote Island's karst model. The outline of the model is constructed by using several arguments as described in subsequent sections.

3.6.1. Relation between geological formation and spring initiation

In Rote Island, karst springs occur in areas where two or three formation meet (Figure 3 – 31). At Olafuliha'a Village, karst spring arises in a point where coralline limestone, Noele, Alluvium and Bobonaro Formations meet. At Lalao, Nioen, Dale Holu, Sua & Mokdale Villages, the spring occurs in a spot where Bobonaro and coralline limestone Formations gather. Another example is the spring in the Inaoe Village in where it occurs at area of collision of coralline limestone and Noele Formations. The types of formation that contribute to the initiation of spring are different. However, it is clear that the collision of these dissimilar formations is one of the key factors that contribute to the occurrence of Mamar springs in Rote Island.

Another significant feature of the springs regarding geological formation is that they occur in areas in where there are at least one impermeable formation and one permeable layer. In all locations of springs, coralline limestone Formation is involved. Limestone layers compared to other Formations is an impermeable, one which can store ample water in its porous layers. It is suggested that when impermeable formation meets the permeable one, it may create fractures at the meeting zone so that groundwater kept in impermeable formation is released through the fractures up to the earth surface and thus emerged as Mamar springs. This suggestion is then used as a foundation for building a hypothesis of the conceptual model of karst springs of Rote Island in section 3.6.3 and 3.6.4.

3.6.2. Relation between theory of Rote Island's genesis and spring initiation

Concerning the genesis of Rote Island, a model called Imbrication Theory (Hamilton, 1978; Harris et al., 2000) in section 3.3.1 in which it is suggested that as Rote Island lies in Banda Arc subduction zone (Martini et al., 2004; Sashida et al., 1999) suggests that the positioning of geological formations in this island is strongly influenced by earth movement which is characterised by sliding of geological layers. At a place where permeable and impermeable layers collide as a result of earth movement, groundwater flows from permeable recharge area guided by its hydraulic head to a point where the permeable layer meets the impermeable one. At this point, fissures or fractures may occur in which ground water comes out to the surface as spring. This suggestion needs to be validated with geological investigation at the spring. However, there is no data at the moment that can be used to verify the suggestion. The only data which is found was during field investigation in Mokdale Village (north of Ba'a) in which there is a vertical bedrock outcrop exposed to earth surface (Figure 3 – 32). It is believed that the outcrop is part of an impermeable formation that is folded forced by tectonic activities and ascends to the surface.

Another significant finding in the analysis is that some of the springs in Rote Island are situated exactly at fault lines as shown in Figure 3 – 31. In this figure, Mamar spring in Mokdale Village and the other two are positioned along the fault line. Other springs such as those in Sua Village and two springs northwest and southwest of Inaoe Village also situated at fault line. This finding reinforces the significant correlation between the initiation of Mamar springs in Rote Island and the genesis theory of this island that in subsequent section (3.6.3 and 3.6.4) function as a basis for suggesting a conceptual model of karst spring's of Rote Island.

Figure 3 – 32. Outcrop in northern part of Ba’a (Mokdale Village)

3.6.3. Conceptualisation of groundwater recharge process in Rote Island

Generally, the groundwater recharge process in karst landscape is categorised into three groups which are allogenic, autogenic and mixed of allogenic and autogenic (Section 2.3.3.1). The distinctive factor is the type of areas in where recharge process takes place.

With regard to ground water recharge process in Rote Island, it is concluded that the karst system is governed by the mixed of autogenic and allogenic karst. In this type of recharge water infiltrates in variety types of land formation. This suggestion is supported by the heterogeneity of karst landforms in Rote Island (Section 3.3.2) that the function as recharge areas. Figure 3 – 12 shows that Mamar springs occur in areas where their recharge process could takes places in different types of rock formation. In impermeable area the point recharge takes place while in permeable area diffuse recharge occurs (Ford & Williams, 2007). Point recharge occurs in impermeable areas where clay dominates such as that in

Bobonaro Complex. Meanwhile, in areas where limestone covers the surface such as that in Noele and Aitutu Formations diffuse recharge dominates the areas conveying water through its porous media to feed water table that goes to outlets i.e. Mamar springs.

3.6.4. Conceptualisation of aquifer characteristics in Rote Island

In general, the groundwater transport in karst system is influenced by the type of aquifer. In section 2.3.3.2), three different types of karst aquifer based on major hydrologic aspects and associated cave features are explained. Those aquifers which are diffusive flow, conduit flow and confined flow aquifers are basically categorised based on hydraulic properties of the flow, occurrence of secondary porosity such as fissures, fractures and caves, and rock formations that typify the spring's occurrence.

Concerning hydraulic properties of the groundwater flow, at all springs where the field investigation took places the flow regime is categorised as laminar flow, characterised by low water velocity and sedimentation at the springs. The dominance of laminar flow suggests that the storage capacity of the aquifer is low. The field investigation took place in dry season (November), thus the water table is assumed to drop due to decrease in water storage in the aquifer. The flow condition may change in wet season where the precipitation averagely increases (Section 3.2.2). However, there is no flow data that can provide a hydrograph throughout the year available at springs.

With regard to the occurrence of secondary porosity, springs in Rote Island, dissimilar to other carbonate springs in surrounding island, which is Sumba Island (Soenarto, 2004), are mainly found as non-cave-fed spring. Cave-fed spring is spring from which water flows from big karstic cave and comes out in a natural open channel. Here, water can be directly diverted for irrigation purpose. In another adjacent island i.e. Timor Island, investigation has also shown that water flows are dictated by a complex underground drainage system called "underground river" (Soenarto, 2002). During field investigation in Rote Island, two caves in Nioen and Mokdale Villages were examined (Figure 3 – 30). Nevertheless, there is no evidence of underground river around the caves neither other locations in Rote Island. It is assumed that that the water table is very low so that groundwater cannot feed into the cave network. Based on data in these areas, it is argued that it is unlikely that conduit aquifer that is characterised by big drainage passage acting as underground stream occurs. For Rote Island, the determination of aquifer based on secondary porosity in this island depends on the locality of the spring with regard to rock formation and time that governs the quantity of water stored in the aquifer.

Pertaining to rock formations that typify the spring's occurrence Rote Island is geologically formed of combination of permeable and impermeable rocks, such as coralline limestone, clay and conglomerates (section 3.3.2.). Furthermore, in section 3.6.1, it is concluded that karst springs occur in areas where two or three formation meet and where there are at least one impermeable formation and one permeable layer (Figure 3 – 31). Based on the geological map (Figure 3 – 31), some of the springs in Rote Island, such as those in Mokdale, Sua and Inaoe Villages are situated exactly at fault lines. It is argued that fractures or fissures formed in the fault zone may create a passage for groundwater to emerge to the surface as springs. Therefore, it is suggested that two types of confined aquifers, which are artesian and sandwich aquifers could occur in Rote Island. But again, the exact type of aquifer varies over sites which is determined by geological formation and times which is determined by seasonal fluctuation of water table related with the input which is rain.

To conclude, the aquifers in Rote Island can be categorised by the hydraulic properties of the flow at springs, occurrence of secondary porosity, and typical rock formations at the springs.

Due to heterogeneity of rock formations and the influence of season which determine water input in recharge process, the type of aquifers spatially and timely varies.

3.6.5. Conceptualisation of spring occurrence in Rote Island

In this part, based on concept of karst aquifers and springs in Rote Island, a conceptualisation of spring occurrence in a selected area is established (Figure 3 – 33). The concept is approached by using the cross-section of rock formations in this island (Figure 3 – 13) and the hydraulic properties of the spring. The location of spring used for the aquifer model is in Dale Holu Village where it is situated exactly at the geologic cross section (Figure 3 – 31).

As concluded in previous section (3.6.4), the type of karst aquifer in Rote Island differs over time. The model in Figure 3 – 33 shows that the seasonal variability of rain as the input for recharge process in the area determines the amount of water discharged at spring. During wet season water table is high enough to give ample water supply at spring, while in dry season it drops and although there is still water at spring the quantity decrease substantially. Other non-natural disturbances such as land use change could potentially deteriorate the condition. Consequently, this karst system is susceptible as it could respond rapidly to natural and anthropogenic processes.

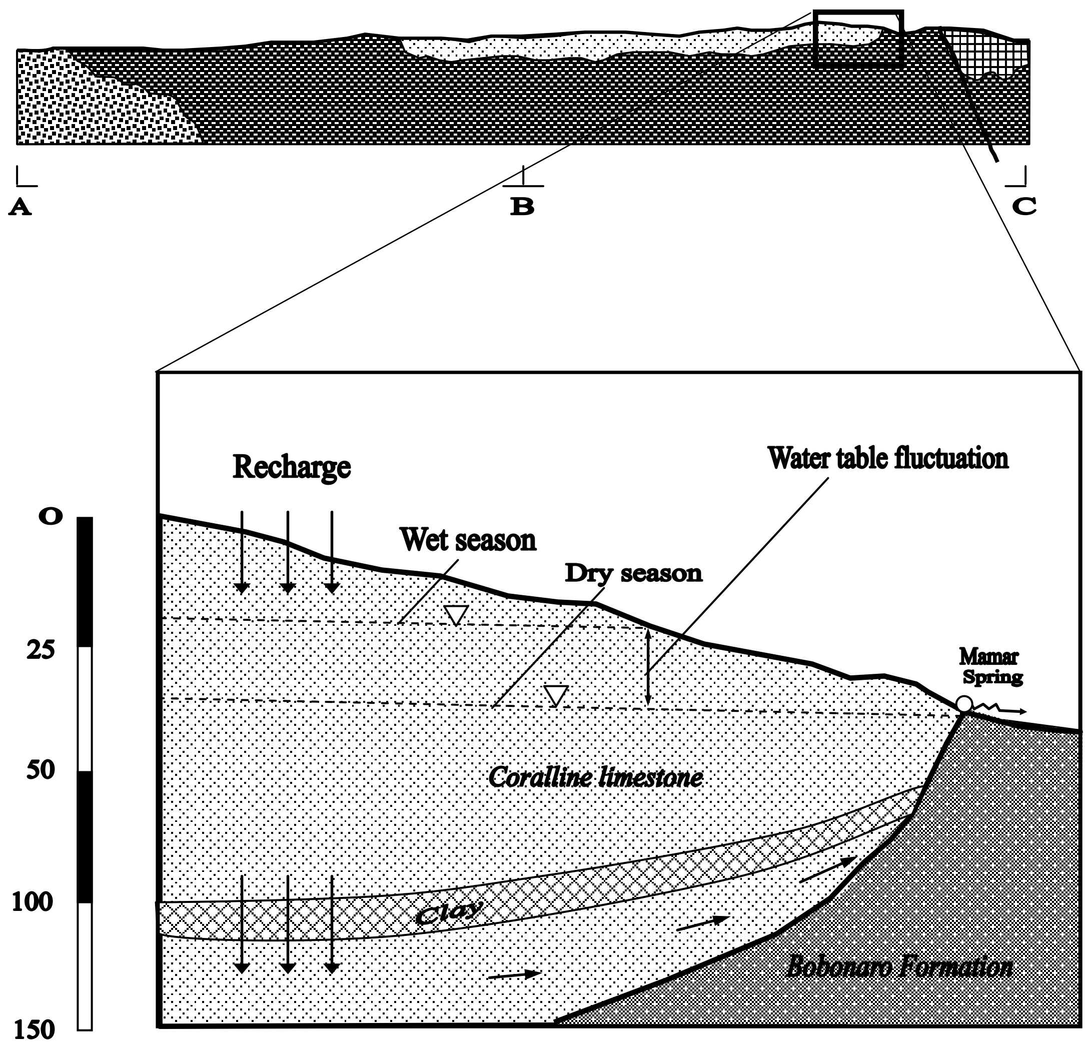


Figure 3 – 33. The detailed figure of cross-sectional soil layer of proposed karst aquifer type in Rote Island

3.7. Conclusion

1. Generally, this chapter provides a theoretical and analytical foundation of karst system with regard to Rote Island. The analysis starts with climatological overview of the island

and continues with hydrogeological, hydrochemical and water balance analysis in the study area. The chapter then presents the result of field investigation in seven villages in the island consisting of visual examination on geomorphological characteristics, on site water measurement and social survey in seven villages.

2. Geographic position of Rote Island influences the generation of rainfall in a way that seasonal changes in sea surface temperature (SST) and atmosphere pressure relate with Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) modes. Thus, the island has a typical monsoonal climate characterised by two distinct seasons, which are dry season (April to November) and wet season (December –March)

3. In wet season, rainfall tops up to about 250 mm in February, while in dry season it decreases abruptly in August with only 2 mm/month. The annual rainfall ranges averagely from 1000 to 1400 mm with the maximum rainfall data was 2400 mm in 1995 and the minimum one was 567 mm in 2003. Rote Island maintains its reasonably humid condition throughout the year (76 and 92%) with the mean daily sunshine in Rote island ranges between 5.5 and 11.2 hours.

4. Water measurement employing direct measure method was conducted as part of field investigation at seven Mamar karst springs located in seven villages.

5. The extraction of overall geological stratum of Rote Island is problematical since data available of different locations is rare. However, in general, the stratigraphy of Rote Island is dominated with karst terrain consisting of coralline limestone formation (61.1%) ranging from Triassic to Pleistocene ages, Bobonaro Formation (29.2 %), alluvial deposit (5.4%), Noele Formation (3.9%) and Aitutu Formation (0.4%). In addition, the geological formation data from study area which is Olafuliha'a Village shows a significant thickness

of limestone in soil strata that ranges approximately between 20 and 80 m, separated by thin layers of lower permeability soils such as clay and silt that ranges from 2 to 9 m.

6. From the visual examination on geomorphology it was found that morphologically the surface profile of Rote Island is dominated with an undulated landscape characterised with small number of trees and shrubs. In Termanu and Mokdale Villages, geologically the areas are dominated by extensive carbonate layers that consist of mostly limestone and dolomite covers the area confirming the hydrochemistry analysis on water samples taken from the five bores. Meanwhile, in Nioen and Mokdale Villages, carbonate caves are inspected without an indication of groundwater flowing in those caves presumably due to a low water table.

7. The hydrochemistry properties of samples from the bores indicate that the carbonate (CO_3) and bicarbonate (HCO_3) components dominate samples' chemistry the counting for about 60%. Ca counts for around 14% indicating limestone ($CaCO_3$) and Mg counts for approximately 6% denoting dolomite ($CaMg(CO_3)_2$). Cl and NO_3 make up about 13% to the overall figure. Na, K, SO_4, and SiO_2 add minor quantity of solutes to the karst groundwater.

8. After analysing hydrogeology data available from five bores and conducting field survey in seven villages in Rote Island, a conceptual model is built based on arguments on the relation between geological formation and spring initiation, the relation between theory of Rote Island's genesis and spring initiation, the conceptualisation of groundwater recharge process, and the conceptualisation of aquifer characteristics in Rote Island. The model suggests that the type of karst aquifer in Rote Island differs spatially which is determined by geological formation in the pertinent area and timely which is determined by seasonal fluctuation of water table related with water input which is rain that functions

as an input for recharge process in the area determines the amount of water discharged at spring. Consequently, this karst system is susceptible as it could respond rapidly to natural and anthropogenic processes.

9. Water balance analysis using Hargreaves Method (evapotranspiration), SCS Method (infiltration and runoff) shows that throughout the year groundwater storage experiences a fluctuation between 55.2 and -51 mm/month. This may illustrates the vulnerability of groundwater availability in the study area. Any change in land use which influences the infiltration and runoff components may greatly impact the total water budget in the study area which in turn in the context of hydrologic cycle of karst area affects the groundwater supply to springs.

10. In general, this chapter highlights the general finding of literature review in Chapter 2 and provides technical approaches to mainly understand the recharge process in karst area of Rote Island which significantly determines the physical behaviour of Mamar spring. The comprehension of physical Mamar springs in this chapter is then complemented with social aspects of the Mamar system in the following chapter (Chapter 4) in order to design appropriate conservation strategies in the framework of sustainable water management in Chapter 5.

Chapter 4

WATER USES AND MANAGEMENT IN MAMAR SYSTEM

4.1. General

In many cultures, groundwater plays a crucial role for building and sustaining those who live around it (Veni et al., 2001). Those cultures had formed local knowledge that corresponds with their belief, customs and traditions. The way they manage groundwater resources reflects these factors and eventually complements with the dynamic of each particular society. Burke & Moench (2000) argued that comprehension of local context that exists in the community is required to understand groundwater role in building the society. It means that attention for optimising groundwater functions needs to specifically address social capacity in community in order to draw a comprehensive picture on how to maintain and conserve groundwater for long-term goals. Therefore efforts to conserve and wisely use water resources require not only knowledge of physical state of a particular system, but also understanding of social aspect of its uses and management.

In Rote Island, water is the centre of community activities as this precious resource that is mainly found as natural spring is spatially limited. However, community developed and maintains a system which is locally acknowledged as Mamar System that regulates and manages most of aspects of water use. Physical analysis of Mamar System in term of hydrogeology and hydrochemistry is reviewed in the previous chapter and in this chapter social aspect of Mamar System is described. In Section 4.2, Mamar System, including the origin of the system, definition and function of Mamar, is explained. Water uses in Mamar springs is presented in Section 4.2 covering the aspects of water availability, utilisation and distribution system. In Section 4.4, the organisational framework and mechanism of Mamar is explained depicting the organisational framework, mechanism and working relationship, stakeholders and their roles and rule as well as enforcement mechanism in Mamar System. At the end (Section 4.5) the perception of inhabitants towards Mamar System is presented

4.2. Mamar System

4.2.1. Origin of Mamar System

Water is the essential key for living in Rote Island. People mainly depend on agricultural activities for their livelihood. Consequently, a continuous supply of water, taken from rivers and springs for irrigating farmland, is mandatory to ensure a good harvest for all inhabitants. However, the perennial characterised river in this island can only be utilised in wet season that last only for about 4 months (section 3.2.2). Its capacity is certainly not ample enough to support irrigation throughout the year. On the other side, other basic needs of water such as domestic and livestock purposes have to be met. Meanwhile the other water source which is spring is consistent to provide water for basic purposes despite its quantity decreases in dry season (Otto, 2006, Roen, 2006). At the end, the only source of water that is dependable is Mamar springs. Its ubiquitous profile in conjunction with time and base flow stands as a gift for people living in this island. Therefore, Mamar springs play an important role and mark a substantial value in the community.

The significance of Mamar spring is considered as vital for the whole community. Consequently, in order to sustain its functions it is important to have a specific order that manage the utilisation of spring water and conservation of the spring. In Rote Island, far before the declaration of independence of Indonesia, a monarchy system ruled. The king or "*manek*" was the supreme individual that reigned using his absolute authority. The extent of a *manek*'s territory mostly stretched to boundaries of a village. The *manek* enjoyed privilege to access all natural resources in his area which including water and fertile land. This right was also given to all supportive instruments in his administration such as "*hulubalang*" or minister and rich people who were mostly imperial families (Klaas, 2006, Bellan, 2006). Therefore, Mamar once was instituted was possessed by this social stratum. They legitimately owned plantation area located surrounding the spring. Meanwhile, other group of people who are ordinary people had only right to access the spring except they can afford to buy the plantations from higher medium class. The acquisition of Mamar plantation was almost impossible but was probable through intermarriage by which a man from lower medium status married a woman from lighter status.

However, the condition has rather changed in republic era of the nation since 1945. The absolute power of *manek* is changed and transferred to national government who administer land tenure of the area including the possession of Mamar spring. Nevertheless, there is little change over the ownership of the Mamar plantation. This area is still owned by those whose ancestor were part of the royal family (Bellan, 2006, Klaas, 2006).

4.2.2. Definition of Mamar System

Quotation of Mamar System is in particular hardly found in any international publication. Until recently, although without a thorough and explicit explanation there are only two reports that cite Mamar. In a report published by International Centre for Research in Agroforestry (ICRAF), Mamar is described as a good example of local fallow management in semi arid region of South East Asia (Burgers et al., 2000) by which it emphasizes the agroforestry system which is a mixture of cultivation of trees, shrubs, crops and livestock. Although the definition contains a reference to water allocation, it does not particularly address the significant characteristics of this system which is the karst groundwater.

In this study, Mamar System is defined as a local knowledge and practice of water management in Rotenese society in Rote Island to conserve karstic groundwater spring in order to primarily provide sufficient water for plantation and drinking water for the community living surrounding it. This definition embraces several main and specific characteristics of the area that uniquely shape the island and society in physical and social context. It is then expanded in more detail in the following sections. Figure 4 – 1 shows a Mamar spring called Oemau in Mokdale Village.

Figure 4 – 1. Mamar spring in Mokdale Village

4.2.3. Function of Mamar spring

In general Mamar spring has two major functions, from which primary function refers to basic life supporting and economic roles in the community. Meanwhile, secondary function comprises of administrative, social and ecological functions. The functions of Mamar springs is presented in Figure 4 – 2.

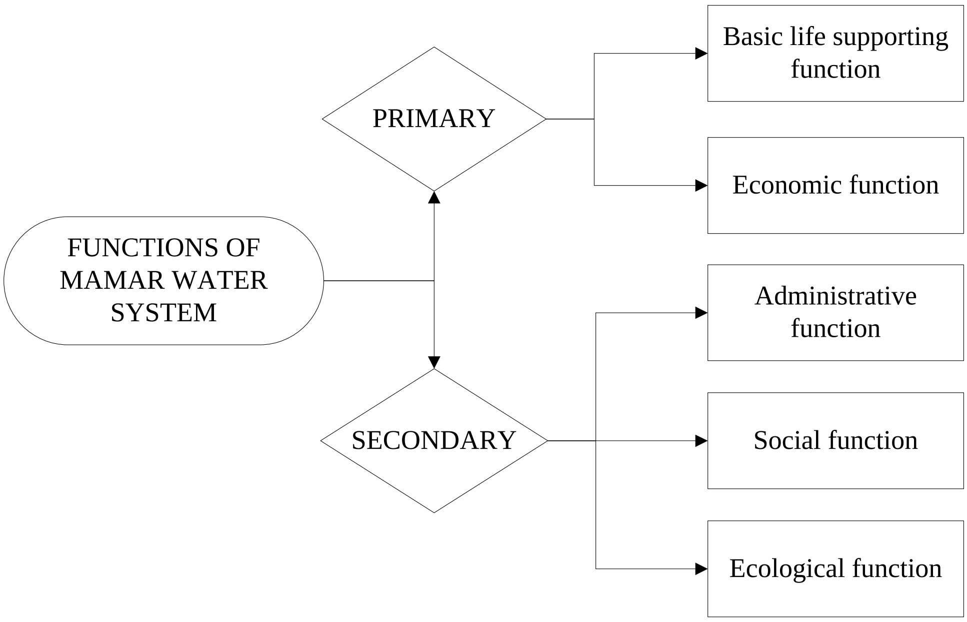


Figure 4 – 2. Function of Mamar spring

4.2.3.1. Primary function

a. Basic life supporting function

Mamar spring is the centre of Rote Island community. Natural water from Mamar spring eventually serves as an indispensable need for the community. People consume water as basic need for life. Water is then used to grow plants in plantation area and irrigate farmland.

Moreover, livestock lives in a nourishing ground fed by spring water. Therefore in Rote Island, as water is very limited in term of location, quantity and quality, most of the villages are built around Mamar spring where people can get adjacent access to water as a crucial factor for sustaining their life throughout the year.

b. Economic function

Small river flows intermittently only during wet season that last only for effectively 4 months. The availability of water throughout the year spatially shapes the distribution of commercial plants in this island. The only source of water that can maintain water provision to those plants is Mamar spring. Although it’s quantity drops during dry season Mamar spring demonstrates to be the source of ample water for the plantation. People grow plants that produce a marketable yield. Those long-term plants such as coconut (Figure 4 – 3), betel palm (Figure 4 – 4) and banana play important role as important sources of income of the community. Other types of plants that grow seasonally are rice (*Oryza sativa*) and shallot (*Allium oschaninii*). Shallot and betel from Rote Island have a long and profound history sharing as two very valuable agricultural goods in Kupang marketplace. Meanwhile, coconut in bulk quantity is shipped inter-province to supply domestic coconut oil factory. The lucrative business built around agriculture production significantly becomes the main leading sector that contributes 46.8% of the total regency’s revenue (BPS, 2004).

Figure 4 – 3. Coconut trees in plantation area of Mamar spring in Dale Holu Village.

Figure 4 – 4. Betel palms in plantation area of Mamar spring in Inaoe Village.

4.2.3.2. Secondary function

a. Administrative function

One of the identifiable social features of people living in Rote Island is the intensity of disputes that occur in the community. Fox (2007) noting this phenomenon described Rotinese as a touchy and debatable society. The scope of disputes can range from personal disparity to a wider-linked interest that involves clans or villages. The source of the predicament varies with social relationships and traditions.

In Rote Island, identification of land ownership and land boundaries is one of the most crucial issues. The majority of judicial conflicts root from disagreement among parties regarding property borders. In Mamar System, there is an unambiguous establishment of land's perimeters, a function that is approved by all landowners and directed by *manaholo*. The functions and roles of landowner and *manaholo* are explained in Section 4.4.3. One of *manaholo*'s main tasks is to ensure that administration of Mamar is well performed by following particular guide set up by the committee. Therefore, this small and local practice of administrative function plays important role in creating a communal harmony in the society which in turn helps the village to develop.

b. Social function

People coming and fetching water at Mamar spring use this site as a place of meeting. Figure 4 – 5 illustrates people who use the spring for washing and bathing. Here, the function of Mamar is extended to serve as a place for inhabitants to fulfil not only the domestic purposes but also social need which is gathering. People may prefer this site to congregate, as this place is more humid than other places surround (Bellan, 2006). Therefore, it feels more comfortable for a good communication to take place. Moreover, this is the most known and universal place to assemble that doesn't carry any specific denotation regarding any parties in term of personal or collective dispute or clash in the society. Therefore, all inhabitants can access the spring without their personal view being differentiated.

Figure 4 – 5. People meet and utilise Mamar spring in Olafuliha'a Village.

c. Ecological function

Water is a key for surviving in Rote Island. In this karst-dominated island where water is limited, Mamar spring secures water provision for not only the inhabitants but also other creatures fed by the water. In Mamar site, vegetation that is important to sustain people's livelihood is preserved. Livestock that live surrounding Mamar use it as a nurturing ground. Therefore, continual provision of water by Mamar spring undoubtedly supports conservation of Rote Island's local flora and fauna.

4.3. Water uses in Mamar springs

4.3.1. Water availability analysis in Rote Island

In many cultures, communities were built surrounding water. Great well-known civilisations ranging from ancient Egypt to Inca empire in Andean mountain ranges grew around rivers (Zakrzewski, 2007, Nordt et al., 2004). Some of European tribes such as the Germans in Germany and Austria in present time were highly supported by the European longest river, Rhine while those living in East Europe were fed by Danube River (Mellars, 2006, Bridgland et al., 2006). Water resources and other sources that are supported by them are substantial in developing communities towards civilization.

Water becomes an important part of human life that is distinguished from other necessitates as it becomes as a very basic need for sustaining life. People living in coastal and inland areas benefit from seawater and other surface water bodies, such as rivers and lakes. While in other parts of the world where surface water is limited, people rely on water emerging from earth, such as deep wells and springs.

For those who live in small islands, spring seems to be the only alternative that is available. Small catchment area leads to smaller proportion of water being stored and released as surface water. Prolonged dry season influences islands particularly in tropical zone. Rote Island like other island lying surrounding Equator Line receives some rainfall throughout the year. As described in Section 3.2.2, this island that receives 1000 – 1400 mm rainfall per annum is distinctively characterised by its rainfall profile from which highest rainfall occurs in February, whereas it plunges dramatically in August. Generally, rain season last only for four months, while in other months it scarcely rains in this island. Therefore, availability of surface water is very limited. Intermittent rivers are only filled with water during the rain season. For the rest of the year, they are completely empty because there is no water fed by rain.

The condition of water scarcity in Rote Island especially in dry season drives people to depend solely on springs. Here, water has always been available, although in the dry season its quantity to some extent drops. However, their continuity in supporting the community over time has made it so important for them. These karst aquifer-fed springs, identified using Spatial Map of Rote Island provided by Bappeda (2004), which are distributed across this island (Figure 4 – 6), provide significant amounts of water for the community. As an example, from groundwater analysis in Olafuliha'a Village, water transmissivity ranges between around 1800 and 3900 m^2/day. This source of water plays crucial role in sustaining life by not only providing potable water but also water for irrigation of plantations and rice farms. Therefore, they built their society around these springs.

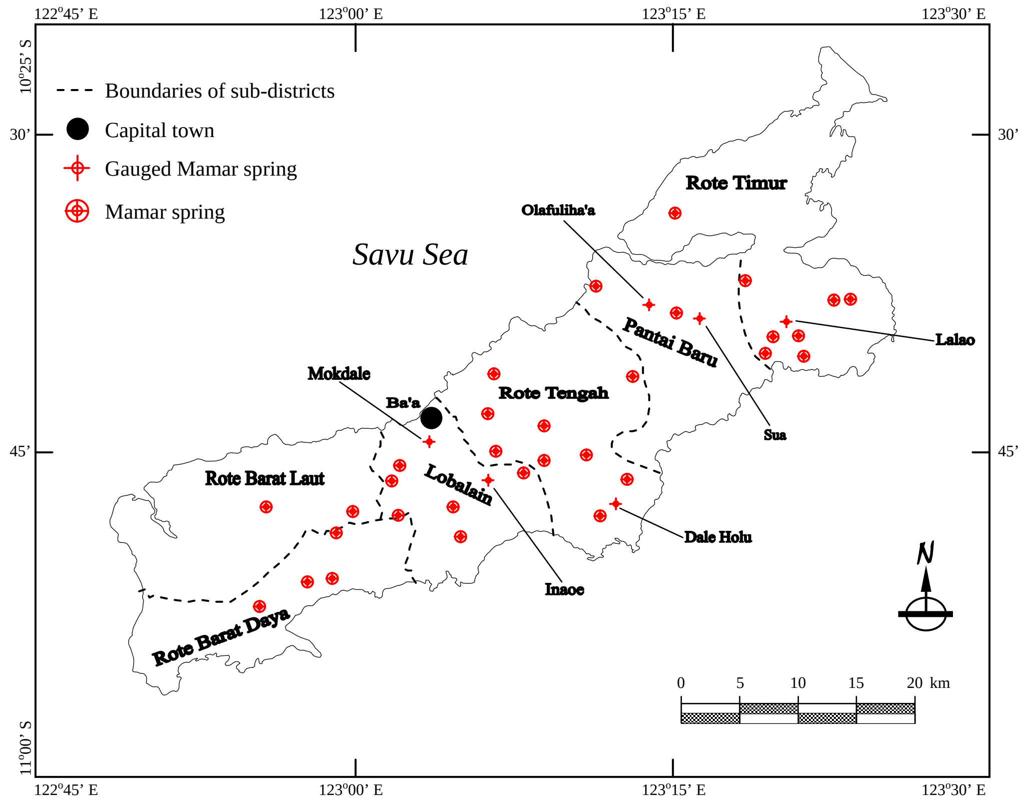


Figure 4 – 6. Spatial distribution of karst spring in Rote Island

In Rote Island, the springs are scattered across the island (Figure 4 – 6). Most of important springs in term of water discharge are found in the north and east part of the island, although there are some significant springs found in the middle part of the island. This figure is closely related with topographical and most importantly geological setting of the island. The relationship between geological pattern and occurrence of karst spring in Rote Island is thoroughly presented in previous chapter (Section 3.6.1). Administratively, karst springs in this island are evenly distributed across the island excluding Rote Barat Laut Sub-district that has only 2 springs. The distribution of springs according to their locality is shown in Table 4 – 1.

Table 4 – 1 Distribution of karst springs in Rote Island

No	Sub-district	Number of spring	Area (km^2)
1	Rote Barat Daya	5	168.9
2	Rote Barat Laut	2	248.5
3	Lobalain	7	145.7
4	Rote Tengah	9	235.9
5	Pantai Baru	4	176.2
6	Rote Timur	9	304.9
		41	1280.1

An extended water data of springs is a crucial part in analysis and formulating the best measures for their conservation and protection. However, data concerning springs' water discharge in Rote Island is very limited and only exists as a one-time record which is not adequate to develop a sufficient picture of overall availability of spring water in this island. Data are only collected to fulfil a temporary purpose such as designing capacity of irrigation channel or water trap. This condition might be caused by limited number of government staff working in this field. Remoteness of springs' location and poor access condition may also hamper measurement and collection of data at field. Most of the inner village roads are lined with bare soil thus during rainfall they become slippery and often cannot be used because of regular inundation at many spots. Therefore it is difficult to reach most locations in rain season.

4.3.2. Water utilisation

Mamar springs have become one of the most important parts of Rotenese communities. The springs provide water that is used as a basic need by all inhabitants. Plants and animals are undoubtedly supported by water provision of Mamar springs. Therefore the communities are built surrounding these springs to secure adjacent access to these critical resources.

Realising their vital function, inhabitants formulated a system that can be used to manage all aspect of this water sources. This system, which is called Mamar, aims at protecting, maintaining and ensuring its availability for all time for all users. These objectives are met by applying technical and social measures. These measures are not meticulously designed but they have done a great proportion in securing its basic function to support the community.

In Rote Island, springs are commonly fortified with cemented wall to prevent it from debris or landslide. However, in some areas the spring is not so well provided with wall for its brink. The wall construction type depends on two main factors. Firstly, technical characteristics of the spring such as water discharge and soil type that occurs in the site determine psychical protection over springs. Quantity of spring water differs from one spring to others. Big springs usually attract more usages, by which they reflect the scale of the community living surrounding the spring. Higher number of users indicates that they can financially afford to build a more sophisticated construction for protecting the springs. Moreover, water that flows and irrigates plantation areas creates a much more economical benefit that enables users, particularly plantation owners, to do so.

Secondly, social value of the springs shapes people’s perspective and initiative towards protecting the springs. Social value applied on Mamar spring includes its role in providing water for basic needs such as potable water. When it can satisfy secondary needs such as plantation and rice farm, spring is highly regarded by the community. In several economically affluent areas such as Baa and Talae Springs water is abundant so people can have enough access to this primary good. On the other hand, other less wealthy regions such as Termanu and Dale Holu, where water is limited, people can only afford to confine water in a cemented tank. In this case, big springs in term of water discharge have an extended value which determines its position in social life of the society. At the end, community give back proportional support for spring protection. Therefore, social factor is closely related with previous factor in a way that the spring’ water quantifiably serves the community. Figure 4 – 7 summarises several factors that affect preferences in choosing the type of spring fortification.

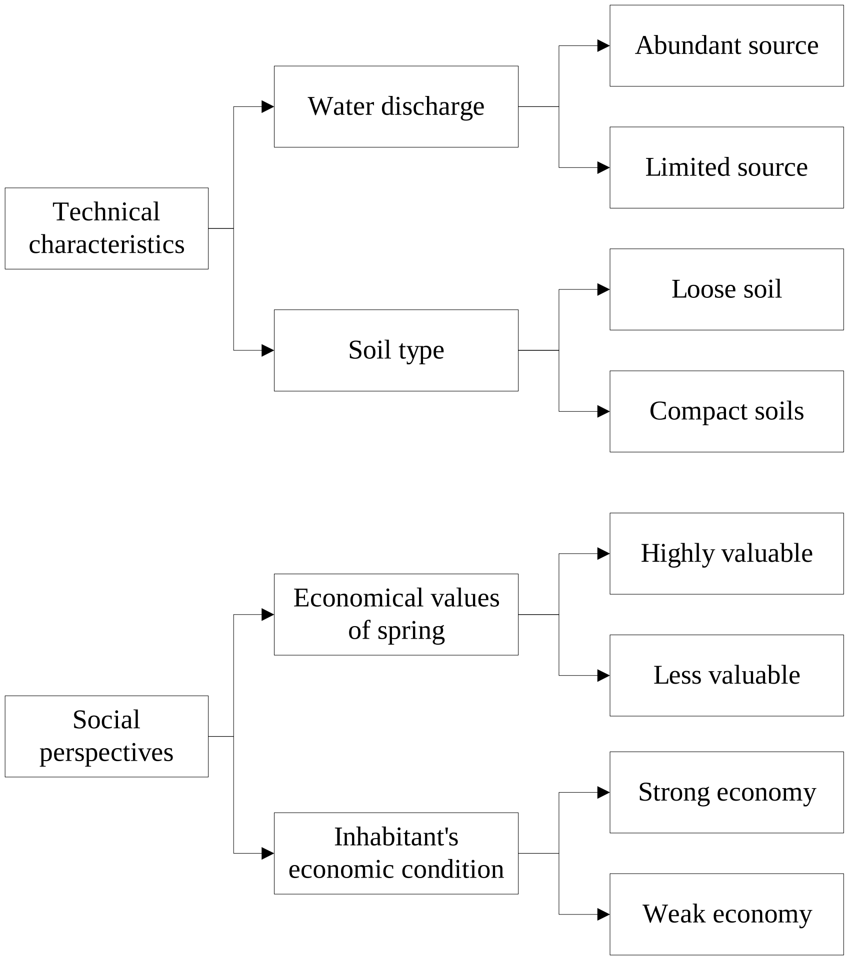


Figure 4 – 7. Factors affecting preference in choosing type of spring fortification

In some areas where a spring's discharge is limited, spring water is tapped through one or two pipes into a cemented tank that functions as small water reservoir. Water flowing in the night is sufficient to fill the tank so that inhabitants can fetch it during the day. In other areas water is abundant so that there is a water pool that is filled with water from the spring. Here, water is separated between drinking water and water for other uses such as bathing, washing and irrigation. Drinking water is collected in a separated area where it comes freshly from the spring. Water then flows to the pool for other public uses described above. These arrangements are shown in Figure 4 – 8 and Figure 4 – 9.

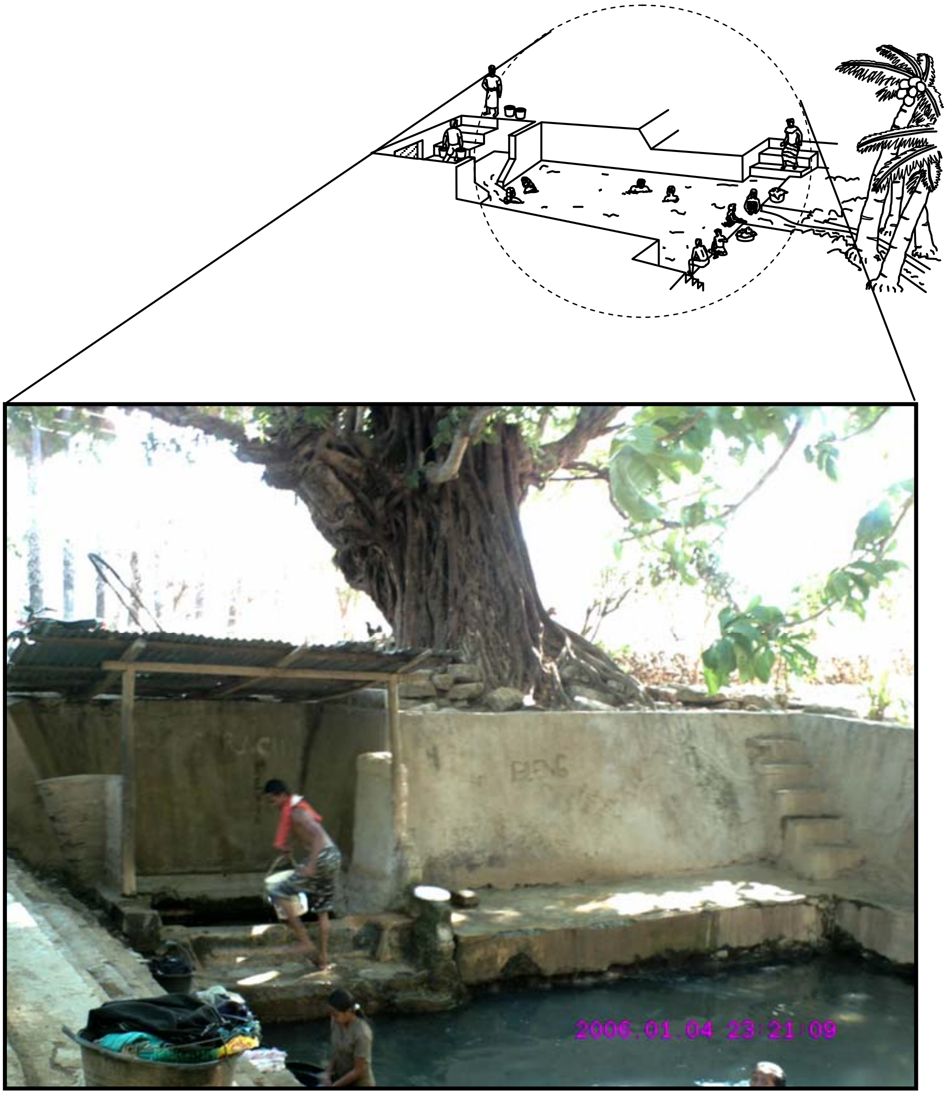


Figure 4 – 8. Water utilisation in Mamar Spring with pool

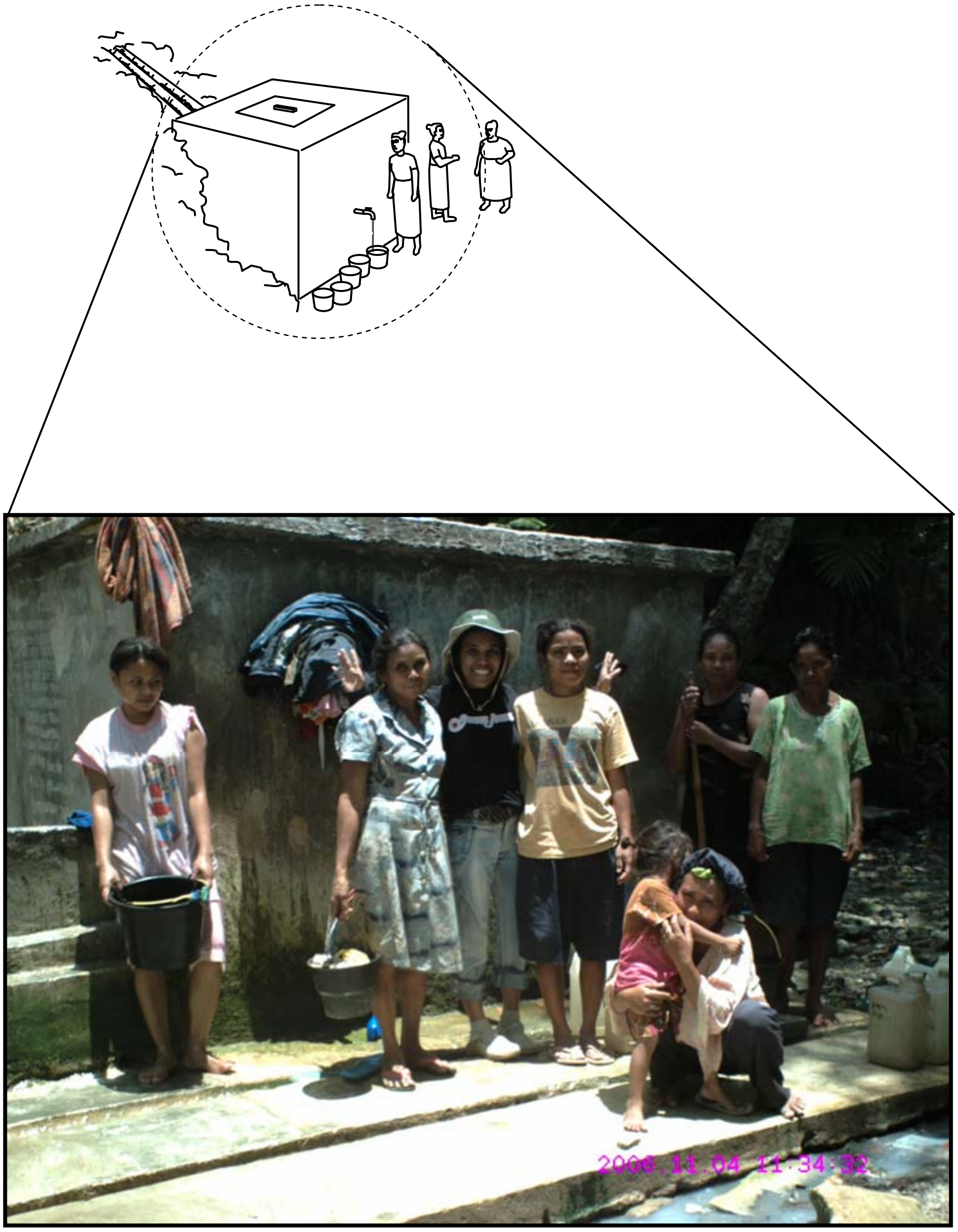


Figure 4 – 9. Water utilisation in Mamar Spring without pool

Water discharged from springs is utilised by all members of community in the village. Inhabitants bringing water buckets come to spring collect water and bring it to their houses. People also come to the spring's pool to take a bath or wash their laundry. Here people of all ages and genders come to use water for themselves or bring it home for household purposes such as potable water, dish washing and toilet or even other purposes such as feeding their livestock and showering plants. Apart from their main livelihood, people also maintain small-scale livestock such as chickens, goats, pigs, bulls and cows. Most houses have chickens while others that have a better financial position may have the rest of the animal category orderly. In their backyard or front yard people often maintain a small-size farm in where they grow short-period plants and fruit such as shallot (*Allium oschaninii*) and watermelon (*Citrullus lanatus*).

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Apart for public use, water from Mamar spring is also used for some special purposes surrounding the spring. While people use it for general purposes upstream, water is used to irrigate local plantations or rice farms downstream. Water flowing from a spring is utilised firstly by all inhabitants for mostly household and private needs before used for irrigation objectives downstream. In spring's vicinity, inhabitants grow varieties of plant, such as coconut (*Cocos nucifera*), betel palm (*Areca catechu*), banana (*Musaceae*), betel (*piper betle*), and mango (*Mangifera*), of which the first two are the most preferred plants because of their social and economical values (Klaas, 2006). In some fertile areas where rice can be cultivated, spring water is used for irrigating rice farm. In this regard, those who possess Mamar land tenure have right to decide water allocation and distribution of water. People also gain extended benefit from a small number of trees that take Mamar site as nurturing ground. Trees such as Kapuk Randu (*Ceiba pentandra*) and Lontar (*Borassus flabellifer*) are the main sources of building construction in the area. Inhabitants use planks from kapuk randu and lontar stems as mainframes. In addition, twigs and leaves of *lontar* which is known as sugar palm are utilised as wall materials of a building In addition to using its leaves as construction materials, people use baskets of plaited leaves to carry water and even use them to build traditional stringed instrument called Sasando. This traditional musical instrument is a prominent tool that has become a well-known representation of the province.

Figure 4 – 10 illustrates different type of water users surround Mamar spring and how they are arranged according to the existing system. Here, water is mainly consumed for domestic purposes by which inhabitants carry water with buckets to their house. There, water is used for household activities including feeding livestock and watering small-scale farm. Meanwhile, water then flows to plantation area in which profitable trees grow. After that water is directed to rice farmland (Figure 4 – 11) which is situated close to the spring. The situation in which the scheme explains is the general view over how water is allocated for various users. The order of water uses follows the rule described above where the main uses

i.e domestic purpose and plantation firstly benefit from spring water. None of the other uses can overlap this privilege such as water is channelled to farmland first rather than to plantation or livestock. This general rule is maintained in the community and any of the infringement may result in penalty over which a *manaholo*, a title for a rural-name of a Mamar manager is responsible for. His function and responsibilities are described in Section 4.3.3.2.

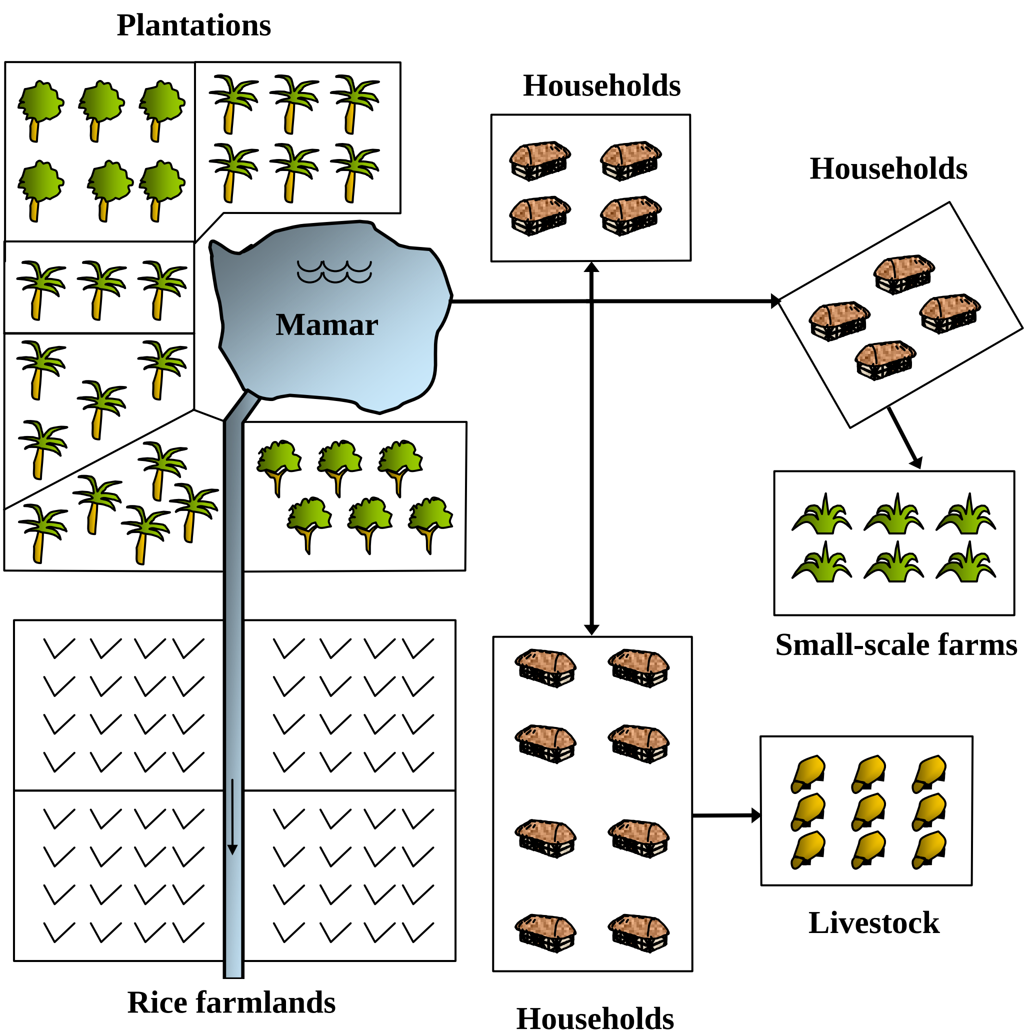

Figure 4 – 10. Scheme of water uses of Mamar Spring

Figure 4 – 11. Rice farmland in Mokdale Village

4.3.3. Water distribution system

Most of the primary springs in Rote Island are well lined with mortar and cement. Walls of the pool and part of spring for potable water are strengthened with reinforced concrete. Generally, there is no pipe system that conveys water directly from a spring to houses. Therefore for consuming and using it, people need to come to the spring. At a Mamar spring in Lalao Village (see Figure 3 – 24), there was a solar powered pump installed to distribute water directly to some houses, nevertheless it does not work anymore due to mechanical malfunction (Lotte, 2006). There is no effort to repair or replace it with other pump. This may be due to lack of financial resources in that village to cover the repair of it and fact that solar powered pump is not a cost-effective option in term of its maintenance. There is limited local knowledge for its repair and most of its hardware need to be shipped from Surabaya in Java Island, which is situated about 2-hour away by jet flight.

Trees and other plants living in Mamar site consume water directly from spring water. Water flows both by surface and sub-surface direction. As water seeps into soil layers, it is distributed throughout the area surrounding a Mamar spring. Therefore, in Mamar site high soil moisture can be discerned from other sites surrounding it.

4.4. Organisational framework and mechanism in Mamar institution

4.4.1. Organisational framework

The establishment of Mamar institution involves a simple organisational arrangement as outlined in Figure 4 – 12. In the survey conducted in six locations, it is found that the organisational frameworks of Mamar are typically similar one another.

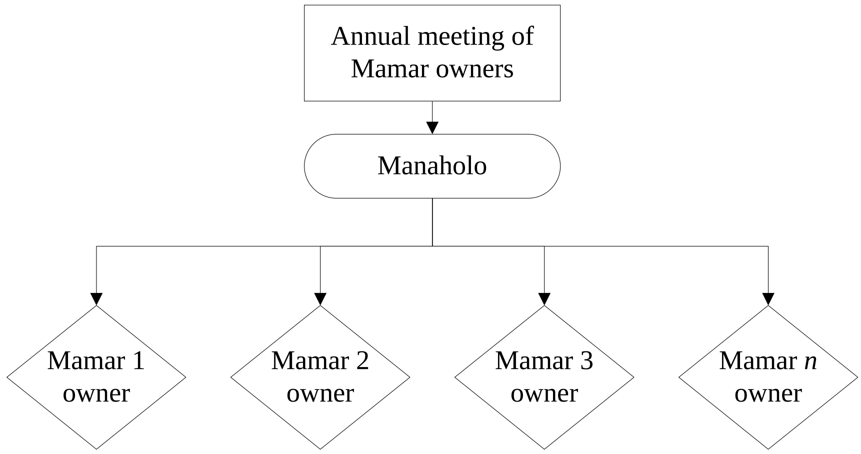

Figure 4 – 12. Organisational framework in Mamar institution

Annual meeting is held by all Mamar's owner to mainly select *manaholo*. This meeting takes place once in a year in an agreed spot inside of the Mamar plantation normally at *rumah jaga* or guard house (Figure 4 – 13). The time when meeting is held is always in a day before wet season commences. This time is obviously selected by *manaholo* with an approval from the committee of the landlords. After being selected in the annual meeting, *manaholo* then works for one year before the next annual meeting being held.

Figure 4 – 13. *Rumah jaga* (guard house) inside Mamar plantation area in Inaoe Village

4.4.2. Organisational mechanism and working relationship

Practically, *manaholo* is the key actor in managing water regulation over Mamar spring. Once *manaholo* is selected, most of managerial rights over water are transferred from land owners to *manaholo*. In the framework of Mamar system, *manaholo*'s duties and responsibilities, ranging from socially and technically protecting the spring to dispute resolution, are described in Section 4.4.3.2.

The administrative interaction of all actors is outlined in a set of regulation which is always being a subject of change in annual meeting by all plantation owners. Primarily, the regulation affirms general rules used in Mamar system. It weighs the severity of infringement and amount of fine that needs to be paid by the culprit.

In most cases, all actors interacted in Mamar system are relatives. This family relationship keeps the Mamar system run as a persuasive style organisation where any disagreement is consoled as a family matter. However, any infringement over regulation will definitely end up in penalty in which its magnitude may be decided according to offender’s economic condition. Here, the regulation basically serves as a legal guideline that binds all land owners.

4.4.3. Stakeholders and their roles

4.4.3.1. Committee of landlords

This committee consists of all owners of land surrounding the pertinent spring. Those who have legal access to occupy the land are automatically appointed as members of the committee. The owners of the land usually come from family from high social status such as king (*manek*), king’s guards, and other prominent figures in the village. Therefore, the ownership of the land reflects owners’ social strata in the society. These people gain direct benefit from spring water to irrigate their lands, on which profitable plantations grow. In the past, the rich and superior ruled in Rote Island providing the monarch to retrieve most of judicial rights in their territory. Those rights include jurisdictional control on land tenure, which gave them privilege to annex land surrounding the spring.

4.4.3.2. Manaholo

Manaholo is a local title for a person that has an authority to control and manage the Mamar. This particular function is given by committee of landlords as *manaholo* is elected by all landlords in the annual meeting of the committee. The annual meeting usually takes place in dry season just before wet season commences. Figure 4 – 14 shows two *manaholos*, working in a Mamar site, in an interview during the field investigation.

Figure 4 – 14. Two *manaholos* during interview at Mamar site in Inaoe Village

Manaholo's main function is to ensure that Mamar's law and order are accurately enforced in Mamar. The rule commonly applied in Mamar is explained in Section 4.3.4. *Manaholo*'s main duty is done through patrolling the whole Mamar areas everyday on foot. Therefore, in some areas where the area is so big, there are more than one *manaholo* to work. The area of each *manaholo* working on is then decided according to decision by the committee of landlords.

Principally, *manaholo* is the party that involves in Mamar site mostly every time. *Manaholo*'s patrolling function requires *manaholo* work almost 24 hours a day in Mamar site. In this case this function aims at securing Mamar site from theft especially when it is dark. Thieves often occur in Mamar site as this lucrative piece of land is the richest zone in a village which attracts criminal intents to take place. Among seized thieves owners of Mamar are often found (Klaas, 2006). In this regard, the same penalty applies on each affront without discriminating the offenders. Fine is decided by *manaholo* and the verdict acts as final decision on the indictment. Consequently, all matters related with Mamar are decided by *manaholo* alone (Bellan, 2006). Within Mamar physical boundaries, whenever dispute arises, *manaholo* is the key person to decide the issue. Its power to regulate cases limits other parties to seek legal resolution in regular court system run by the local government. Conflict settlement that took place in Mamar site is resolved by *manaholo*.

Overall, each stakeholder has different roles in the framework of Mamar System. Those roles are generally similar in all villages in Rote Island. However, particular minor functions attached to a stakeholder may exist or be absent in some areas. This modification may occur to address local cultural differences as well as physical situation such as topographical dissimilarity and the extent of water quantity.

4.4.4. Rule in Mamar institution and its enforcement mechanism

4.4.4.1. Distribution of water

As being described in section 4.3.3, water flows by gravity throughout Mamar site. Water emerged from spring spreads out coating the surrounding areas which are practically plantation area. Therefore, for purpose of irrigating plantation areas there is no specific diversion system to convey water. As a result *manaholo* works without a specific task to manage water distribution for all plantation spots. However, in big spring where the spring is fortified with cemented wall such as in Ba'a, water use may extend to irrigate farmland. For this purpose cemented channel exists to bring water to distant farmland locations. In Londalusi and Mokdale Village, iron pipes are used to carry water from Mamar spring for drinking purpose. In this manner, when water is utilised beyond the area of plantation which are water consumption and irrigation schemes, government's interest is applied. Consequently, *manaholo* only works in the boundaries of Mamar areas.

Most Mamar sites are covered by dense canopy of trees. Decaying braches and leaves fall and pile up on the ground due to natural tree decomposition or torrential wind that sometimes occurs during wet season. As a result, this often leads to obstruction on water passages which results in inefficiency in water distribution to all members' plantation area. Uneven distribution frequently ends in conflict among members. Therefore, *manaholo* has a right to ask all members to come in a certain day to clean up the site. On the particular day all land owner should come and work together to clean waterways and remove fallen tree braches. In areas where wells for drinking water exist for the whole community, these people also jointly work to do the cleaning.

4.4.4.2. Sanction and control mechanism

Generally, the most infringement case occurs in Mamar spot is theft. A thief usually comes into a plantation area in the night, taking advantage of darkness, to pinch plantation products (Bellan, 2006). Fruits that are commonly being targeted are coconut and betel. Both types of fruits have a high economic value in the market. Another type of offence is harvesting of plantation products by its owner without approval by *manaholo*. In this case, land owner enters his/her plantation area and collects plantation fruits. In the regulation, every land owner cannot go into their piece of land without a consent from *manaholo*. The breach against this regulation breach is categorised serious as it implies heavy penalty (Klaas, 2006). The penalty is basically paying fine that ranges from an animal such as pig or goat to being prohibited to enter his or her own Mamar for a period of time. The last type of penalty is considered severe as an owner cannot benefit from their own plantation product.

4.5. People perspective on Mamar system

Local perspective on existing management over natural resources is important in order to evaluate present practice, recommend solutions and accommodate positive change in the future. Direct feedback gathered from inhabitants is substantial to determine issues at grass root scale and to seek answer for resolution.

During the field investigation in Rote Island, a social survey was carried out to determine general perspective of inhabitants towards Mamar System. The survey took place in five villages (Figure 4 – 15) using questionnaires, discussion and interview methods.

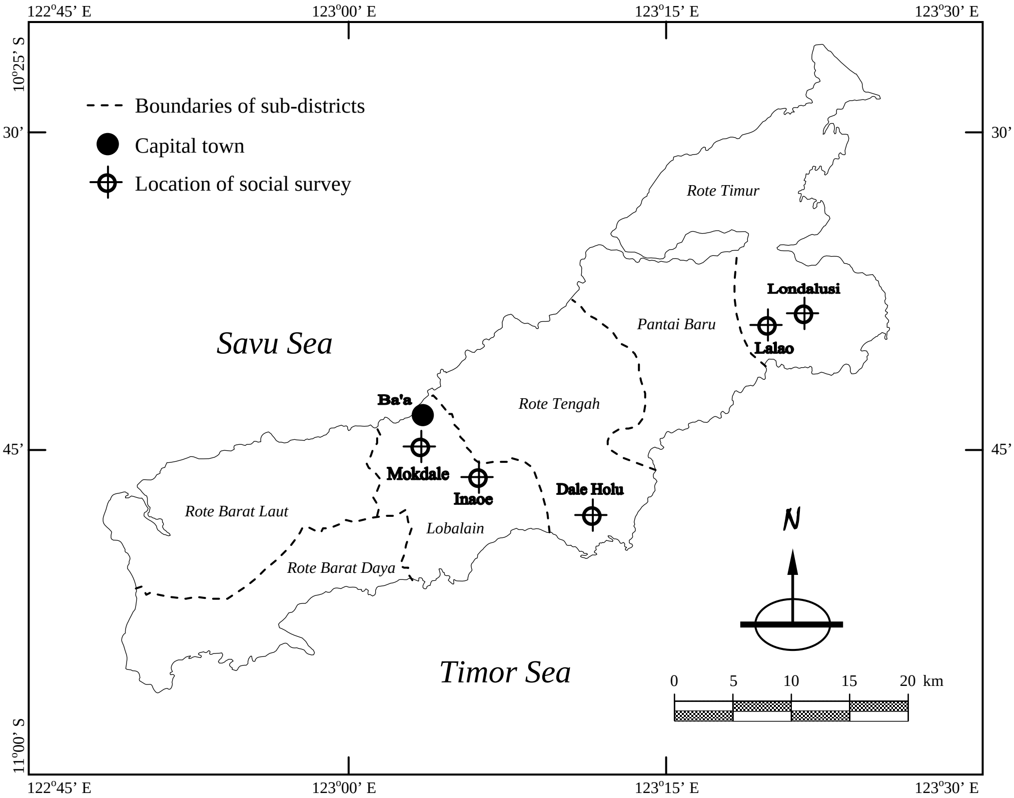

Figure 4 – 15. Location of social survey in Rote Island

The questionnaires and interview involved 33 people whose social status ranges from inhabitants (91%) to *manaholo* (9%). Among the respondents, 79% are male (26) and 21% are female (7). Questions were designed to address the issue of people perception on Mamar System regarding its organisational framework and mechanism, administrative tools, evaluation mechanism. Figure 4 – 16 and 4 – 17 shows interview and discussion session during field survey. The analysis of the social survey is presented in Annex E, and the summary is presented in this section.

Figure 4 – 16. Interview session in Lalao Village

Figure 4 – 17. Discussion session in Dale Holu Village

Generally, most respondents (64%) believe that water scarcity does not occur in their village. In the discussion, they argued that at present water provision from Mamar springs is adequate to supply their need.

The survey also shows that Mamar springs possess a significant value in respondents' point of view as all participants (100%) considered it valuable in providing water for household's uses, vegetations and livestock. All participants (100%) also believed that they entirely relied upon water provision from Mamar springs.

Concerning Mamar System performance, 94% respondents believed that it has effectively worked to manage the usage and conservation of the springs in their village. This applies to all aspects of Mamar System, i.e.: organisational framework, organisational mechanism, administrative tools, evaluation mechanism, and water distribution in Mamar System. In general, despite there was disparity in respondents' perception towards Mamar System's performance, it is concluded that they will keep on supporting the Mamar System in their village.

4.6. Conclusion

1. In general, this chapter focuses on the social aspects of the management of Mamar spring. This comprises of water uses, organisational framework and mechanism in Mamar System and people's perspective on the system. The understanding of Mamar System as an indigenous knowledge that socially and culturally roots in Rote Island's society in this chapter is then complemented with technical aspects of the Mamar system in previous chapter (Chapter 3) in order to design appropriate conservation strategies in the framework of sustainable water management in Chapter 5.

2. Water is a significant natural resource in the karstic-dominated island of Rote. Continuous supply of spring water is crucial as surface water is very limited in dry season. Therefore, community developed and maintains a system which is locally acknowledged as Mamar System that regulates and manages aspects of water use in order to cope with spatially and quantitatively limited water sources.

3. In this study, Mamar System is defined as a local knowledge and practice of water management in Rotenese society in Rote Island to conserve karstic groundwater spring in order to primarily provide sufficient water for plantation and drinking water for the community living surrounding it.

4. Originally, the Mamar System was constructed surrounding monarchy system in Rote Island because spring was considered as culturally a precious and sacred object in the kingdom. A situation, which the spring belonged to the *manek* and therefore the imperial families and their components enjoyed privilege of accessing to water spring as well as utilising it for especially their plantation areas, has changed since the independence of Indonesia when the absolute control over the spring by the *manek* was given back to the inhabitant.

5. Mamar spring has two major functions, i.e. primary functions, which refer to basic life supporting and economic roles in the community, and secondary functions which comprise of administrative, social and ecological functions. Basic life supporting function consists of provision of drinking water for people, plants and animals, while economic functions are given by harvest products of Mamar plantation, adjacent to the spring that plays important role as important sources of income of the community. Secondary functions are creating a communal harmony in the society, accommodating

social gathering and providing water for sustaining the Mamar ecosystem in where people live.

6. Spatially, Mamar springs is not evenly distributed due to heterogeneity of geological pattern across Rote Island. Karst springs in this island are mostly situated in Rote Timur Sub-district (24 springs), whereas the least numbers are shared among Rote Barat Daya, Lobalain and Pantai Baru Sub-districts (7 springs). Most of springs are remote from transportation infrastructure creating difficulty for access and data acquisition.

7. The importance of Mamar spring directs inhabitants to protect the spring. Physically, there are two types of spring protection, i.e. cement fortified pool and water tank. Both types, that work as temporary reservoir, are determined by two main factors, namely technical characteristics of the spring (water discharge and soil type) and social value (the extent primary and secondary functions are fulfilled).

8. Spring water is utilised by different users and uses. People use the water for domestic purpose, livestock, small-size farm, plantation and rice farm. Concerning water distribution, generally there is no pipe system that conveys water directly from a spring to houses. Therefore for consuming and using it, people come to the spring.

9. Organisationally, Mamar System consists of the owners of Mamar plantation and *manaholo*. Annual meeting takes place to mainly select *manaholo* and review the overall performance of the system. *Manaholo* is the main actor in managing water regulation over Mamar spring. Manaholo’s main duty is done through patrolling the whole Mamar areas everyday on foot to ensure that Mamar’s law and order are accurately enforced in Mamar site. *Manaholo*’s duties and responsibilities ranges from socially and technically protecting the spring to dispute resolution in which *manaholo* retains right to persecute the trespassers, decide the type of penalty or fine. As a water controller, *manaholo* is

responsible for managing the distribution of water from spring, thus coordinating the landowners to clean up the spring.

10. Social survey was performed to identify inhabitants' perspectives on existing management of Mamar System over the spring. The survey took place in five villages using questionnaires, discussion and interview methods. Generally, most respondents (64%) believe that water scarcity does not occur in their village. The survey shows that all participants considered Mamar valuable in providing water for household's uses, vegetations and livestock, thus relied upon water provision from Mamar springs. Overall, concerning Mamar System performance (i.e.: organisational framework, organisational mechanism, administrative tools, evaluation mechanism, and water distribution), 94% respondents believed that it has effectively worked to manage the usage and conservation of the springs in their village. It is concluded the inhabitants will keep on supporting the Mamar System in their village.

Chapter 5

WATER CONSERVATION STRATEGY

5.1. General

In this chapter several factors that can play significant roles in shaping future state of water availability in Rote Island are explained. Those factors, including population growth (part 5.2.1), human activities (part 5.2.2), land use change (part 5.2.2) and potential effect of climate change on the hydrologic cycle in this island (part 5.2.2) are argued to have potential direct relation with water provision through Mamar springs. Those factors need to be carefully addressed in order to map a condition where there is a balance between water demands and water accessibility over time on this island. Therefore, in part 5.3 by simulating and analysing a water balance projection, a number of prospective measures are then described with the aim of alleviating threat of water scarcity in Rote Island by incorporating means of the persistent traditional Mamar system.

5.2. Potential trade-offs

Mamar spring is the main source of water in Rote Island. The typical karst characteristics of the land that covers over 60% of Rote Island (Section 3.3.2) as well as a short period of wet season that is only last for about four months which are December to March (Section 3.2.2) preclude the availability of surface water such as river and lake. Therefore, together with other one-quarter of the world's population that are fed by or live in karst groundwater areas (Ford & Williams, 1989), people living in this island heavily rely on the perennial supply of groundwater that emerges as mamar springs.

However, there are some factors that pose threats to the capability of mamar spring to supply adequate water for the whole communities in Rote Island. An increase in population in the form of augmented immigration and birth rate could trigger a rise in basic demands i.e. food, water and housing. This increase could consequently put an immense pressure on natural resources that are already limited in this island. Higher demand of natural resources may subsequently trigger land use change that converts natural recharge area of for groundwater to agriculture and settlement areas. Meanwhile, amplified demand on water as a coherent consequence of increased population may exacerbate the problem, as water might be overused beyond its physical capacity that is directly linked with recharge performance of the land.

The relationships of the potential factors that pose threat to Mamar are presented in Figure 5 – 1. In this flowchart, the connections among each factor are described in arrows by which it is explained that one problem occurs as a result of preceding factor. It is shown that all factors have direct and indirect implication to the state of water balance variables that govern hydrologic process in this karstic island. Anthropogenic factors have direct correlation with water balance parameters, i.e. rainfall, infiltration, run-off and evapotranspiration. Furthermore, a potential of hydrologic impact of global warming may contribute to the change in water balance of Rote Island (Section 2.4.2). Any changes occurs in the state of water balance of the karstic groundwater may result in a reduced water recharge capacity to karst aquifer, by which water is stored and conveyed to mamar springs. As a result, the capacity of spring to supply water for the community is degraded as groundwater supply from karst aquifer is depleted. This condition may also to some extent has potential to reduce the functions of Mamar System which is developed as water institution that manages the mamar karstic springs (Section 4.2.3). And ultimately, as water supply from mamar springs declines water scarcity may be intensified and ends in water insecurity in the communities of Rote Island.

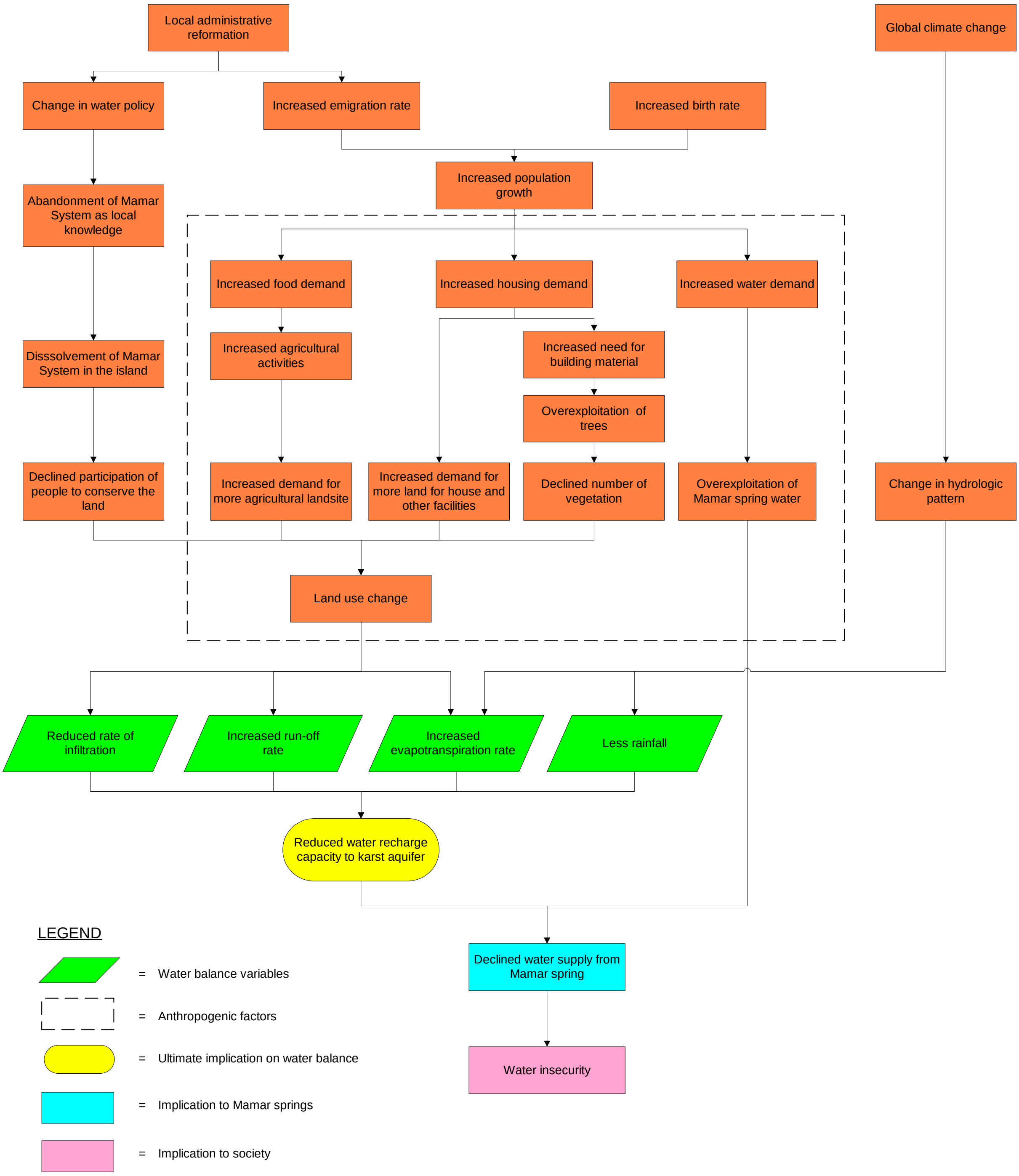

Figure 5 – 1 Potential trade-offs over water provision from Mamar springs

The detail explanation of each factor that poses risk to Mamar spring is presented in Section 5.2.1.

5.2.1. Population growth

Increase of population gives additional burden to natural resources such as water. Total water requirement in term of quantity is magnified as population grows. Therefore, demand for bigger water consumption soars as population growth rate rises. A projection by Gardner-Outlaw & Engelman (1997) shows that a direct correlation is present between population and water withdrawals. In their report, within the last sixty years world population tripled while rate of water abstraction follows the same trend. The United Nations has predicted the acuteness of threat on water as by 2050 there will be 7 billion people in sixty countries suffering water shortage (UN, 2003). While its quantity drops in conjunction with other human-driven factors that significantly influence it, water is at brink of its limitation in supplying basic needs for the world.

Urbanization might be the potential threat to the availability of water in Rote Island. The recent census between 2002 and 2004 shows of that population grew significantly due to immigration in Lobalain Sub-district in where the capital of the regency is situated (Section 2.2.2). Unlike other five sub-districts, Lobalain experienced this irregular growth rate since a transfer of the governance status of Rote Island took place in 2002. In that year, Rote Island gained a new authority as regency replacing the previous status which was sub-disctrict. The shift in governance level in this island brought direct changes in economic and administration settings. Nevertheless, its new “governmental cloth” has attracted more people to immigrate from other island. Migrants mainly come and settle in Rote Island as public servants and traders. Contributing to an increase in total annual population growth rate from 1.5% to 2.33%

between 2002 and 2004 respectively, this trans-island migration brings a heavy strain as settlement areas expands and so does water demands in Rote Island. This situation can be clearly seen in the capital of the regency where water problems that were previously severe have become even more acute, especially when it deals with drinking water service provided by the local Water Agency.

The increase in number of population in Rote Island is apparent in the capital area but not in rural areas. Nevertheless, this figure may eventually expand to other parts of the island especially where soil is fertile and the economic potential can subsequently be an appeal to further migration. Moreover, among the most promising land in Rote Island are areas where Mamar springs are located. The population growth by which its rate is increased can be a big obstacle for future sustainable water management of this island.

5.2.2. Land-use change

According to Turner, Moss, & Skole (1993) land use change is categorised as land cover conversion and land cover modification. The difference between the two categories is that the earlier denotes total replacement of land cover with another type while the change in land use in the latter category does not transform the main type of land use. However, despite the level of change described in the two categories, land use change contributes to the modification of hydrologic characteristics of a particular area.

Any changes to soil-atmospheric behaviour may lead to environmental problems. Ford & Williams (1989) suggested that compared to other type of landscape, karst areas are more vulnerable to numerous types of environmental problems, especially those that relate with water. Unlike non-karst aquifers that are generally covered by overlying or less-permeable rock formations or soils, those in karst terrain are often exposed directly to surface without a low permeability cover (Kaçaroğlu, 1999). Therefore, the only protective coverage of the karst surface is vegetation. Consequently, any conversion or modification on land use that lead to removal of covering vegetation in a karst area may result in the surface being uncovered and as a result the overall karst system may be prone to water loss due to run-off (Gillieson, 1996). As vegetated areas being anthropogenically transformed to impermeable areas such as settlement, roads and buildings, land capacity to let water infiltrates decreases. Consequently, there is little supply to karst aquifer from both allogenic and autogenic areas through recharge process. Thereby, karstic springs may experience water shortage throughout the year.

Another potential consequence as a result of change in land use is water contamination. The physical characteristic of karst drainage system that mainly consists of large opening and diffuse secondary porosity governs the actual process of water travelling from the surface to the outlets such as springs. Any pollution discharged into karst area may be rapidly transported due to porous media of carbonate rocks. In conduit flow aquifer, where groundwater travels in turbulent flow (Shuster & White, 1971) pollutants may experience less attenuation mechanisms such as chemical reactions, adsorption, ion exchange and bioremediation (Kaçaroğlu, 1999) due to lack of available surface area and sufficient time to conduct those alleviating procedures (Ford & Williams, 1989). Therefore in karst areas, land use change can be hazardous to groundwater quality (Jiang, Zhang, Yuan, Zhang, & He, 2006).

One possible environmental impact due to land use change in karst areas caused by human activities is presented by Li, Shao, Yang, & Bai (2008) who studied karst desertification in karst area in China. Their study shown that change in land cover has a strong impact on karst landscape degeneration. Meanwhile, Sauro (1993) concluded that exploitation of karst areas such as deforestation, farming and stone quarrying right after the erection of settlement site contributed to soil erosion, complete desertification and problems of sewage and solid waste disposal. Concerning water quality, he found that chloride and nitrate level in karst springs and wells adjacent to urban areas are much higher than that in upland waters.

Change in land use due to increased population growth is predicted to take place in Rote Island. Based on observation and discussion with a prominent figure in Mokdale Village (Panie, 2006) during field investigation, it is concluded that in the capital of Rote Island more buildings were built from 2002 onwards than that before 2002. Settlement and government compound areas expand towards southeast where the recharge area for the spring watershed is situated. It is clearly seen that the significant increase of population creates strong pressure to build more structures and thereby change the shape of land. Furthermore, once the compound is finally finished than it may attract sectors such as business and services to convert the bare land into a set of impermeable zones upstream. Without any proper measures this condition may result in a significant change in the hydrologic cycle of the area in a way that the water recharge capacity of the karst aquifer is reduced. Consequently, lack of water storage in aquifer may result in a declined groundwater supply from Mamar Spring.

5.2.3. Global climate change

According to the climate projection by Intergovernmental Panel on Climate Change (IPCC, 2007a) that employs seven scenarios the global average sea surface temperature will increase by 0.6 to 4.0 ^{o}C between 2090 and 2099 relative to temperature in 1999. Locally, Rote Island is projected to experience a 1.5 to 2 ^{O}C temperature increase in the same time framework (IPCC, 2007c). It is also expected that mean rainfall in Rote Island between December and

March will increase by 0.2 mm/day however during dry period it decreases by 0.1 mm/day (IPCC, 2007b).

The change in climate condition in Rote Island to some extent may change the recharge pattern with regards to karst environment. The increased temperature leads to an increase of evapotranspiration, thus reducing the recharge rate on a watershed scale. Although there is an increase in rainfall in wet season it is argued that without any conservative precaution on land coverage in recharge area most water may become runoff rather than infiltrate into karst. It is also possible that the increase in precipitation is presented as intense and extreme rainfalls that suggests an increased chance of flash flooding rather than as steady rain which helps maximise infiltration (IPCC, 2007b). Moreover, an increased in evapotranspiration in Rote Island might be counted as a trigger for more severe water depletion at Mamar springs during dry season.

5.2.4. Abandonment of local knowledge

Incorporation of indigenous knowledge on managing natural resources such as groundwater is crucial for building a strong foundation that in the long-term serves as a basis for conservation. As noted by Burke & Moench (2000), the step to acknowledge local context is an efficient way to better manage groundwater resources. A case study from the Andean Region of Ecuador (Cremers, Ooijevaar, & Boelens, 2005) shows that when policy makers fail to recognise and embrace the significant value of local water rights and knowledge access to water by all users is endangered. Bridgewater & Arico (2002) underlines that preservation of biodiversity requires a cultural control that shares its manifestation in the form of indigenous knowledge.

In Rote Island, the demographic outline has been changing dramatically since the administrative reformation in which the old status of "sub-district" expanded to a new administrative status as regency. The change started to draw more assets to the island as rapid as number of immigrants. Urbanisation pressure potentially perpetuates the problem with a stricter government law that confines water usage of mamar spring and role of Mamar System to maintain the springs. Moreover, those who live with natural resources are ones that are most capable for preserving them (Agrawal, 2001). Inhabitants and their knowledge of managing Mamar springs are important value in the community. Lack of acknowledgement of this local wisdom from the government may create a gap between the society and achieving sustainable water use based on local knowledge. At the end, as the system that has been embraced for generations is neglected, the participation of people living next to springs in conservation measures may decline.

5.3. Conservation strategies

Water insecurity in many places of the world has become a problem that without any cure could trigger other problems such as health, sanitation, poverty and food insecurity problems. It is predicted that 25% of world population live in countries that are affected by lack of freshwater (Gardner-Outlaw & Engleman, 1997). People living in karst area are more likely to be susceptible from water shortage due to physical characteristics of carbonate rocks in which water stored in its porous media may evaporate quicker than that of impermeable soils. Other factors such as rapid economic growth and increased population rate could put tremendous pressure on karstic water sources to supply enough water to the society. Consequently, without appropriate conservation strategies the provision of water from karst landscape that covers 7-12% of the earth terrain (Drew, 1999) is at stake.

Rote Island's karstic springs, called Mamar, that has been playing a vital role in water supply needs for the society could also face the situation above. The identification of potential trade-offs described in Section 5.2 shows that there are several main factors that potentially contribute to the decline in water supply from Mamar springs. Those factors, namely changes in local water policy, increased population and global climate change, could result in a decrease in water recharge capacity to karst aquifer and thereby reduced flows from springs. As inhabitants depend on Mamar springs for water supply needs, the ultimate implication to society is potential water insecurity. Therefore, it is imperative that conservation strategies on Rote Island are undertaken in order to overcome this potential consequence. In this study conservation strategies are drawn in the framework of sustainable water management that suits Rote Island's physical and societal conditions which is described in the following Section.

5.3.1. Concept of sustainable water management

The concept of sustainable water management refers to the term of sustainability in Bruntland Commission's Report on in which sustainable development was principally characterised as human's effort to meet the needs of the present generation without compromising the needs of future generations (WCED, 1987). When it is related to water as primary source of living for all people, this definition implies an impartial distribution of water over time which takes into account the same quantity and quality of water for users at any time, and over space which aim at reaching all locations. Meanwhile, the ability to manage water as a crucial natural resource entails a comprehensive set of concerns to administer water in a way that accommodate ecological, economical, technical and societal acceptance of a broader society (Bernhardi, Beroggi, & Moens, 2000). Therefore the basic principles of sustainable water management can be summarised as a way or process to manage available water with proper ecological, economical, technical and societal concerns by giving recognition of future generation's right to utilise the same quantity and quality of water.

Sustainable water management approaches vary spatially, as they should address communities with different social backgrounds and locations with diverse physical characteristics. In Rote Island's context, sustainable water management approach is considered to be the one that needs not only to adopt local knowledge which is Mamar System but also to articulate the special physical land characteristics into best conservation strategies. Therefore, any water preservation concept need to be designed in order to be relevant with the characteristics of karst system in Rote Island, the societal pattern of the community and the plausibility of the impact of global climate change in the island.

To address the needs of embracing the concept of sustainable water management in coping with potential trade-offs as described in Section 5.2, several conservation strategies that are manifested in proposed measures are designed and explained in the following sections.

5.3.2. Proposed measures

In order to protect karstic groundwater in the framework of sustainable water management in Rote Island several proposed measures are recommended. These measures that are presented in Figure 5 – 2 are designed to encourage an integrated approach in watershed scale in order to facilitate sustainability in the area. The formulation of proposed measures takes into account characteristics of karst areas in Rote Island (Chapter 3), existing indigenous practice of natural resource management called Mamar System (Chapter 4) and potential trade-offs as described in Section 5.2. Each measure correlates with others to an extent that one supports others, thus all components of the proposed measures are linked in an integrated relationship as described below.

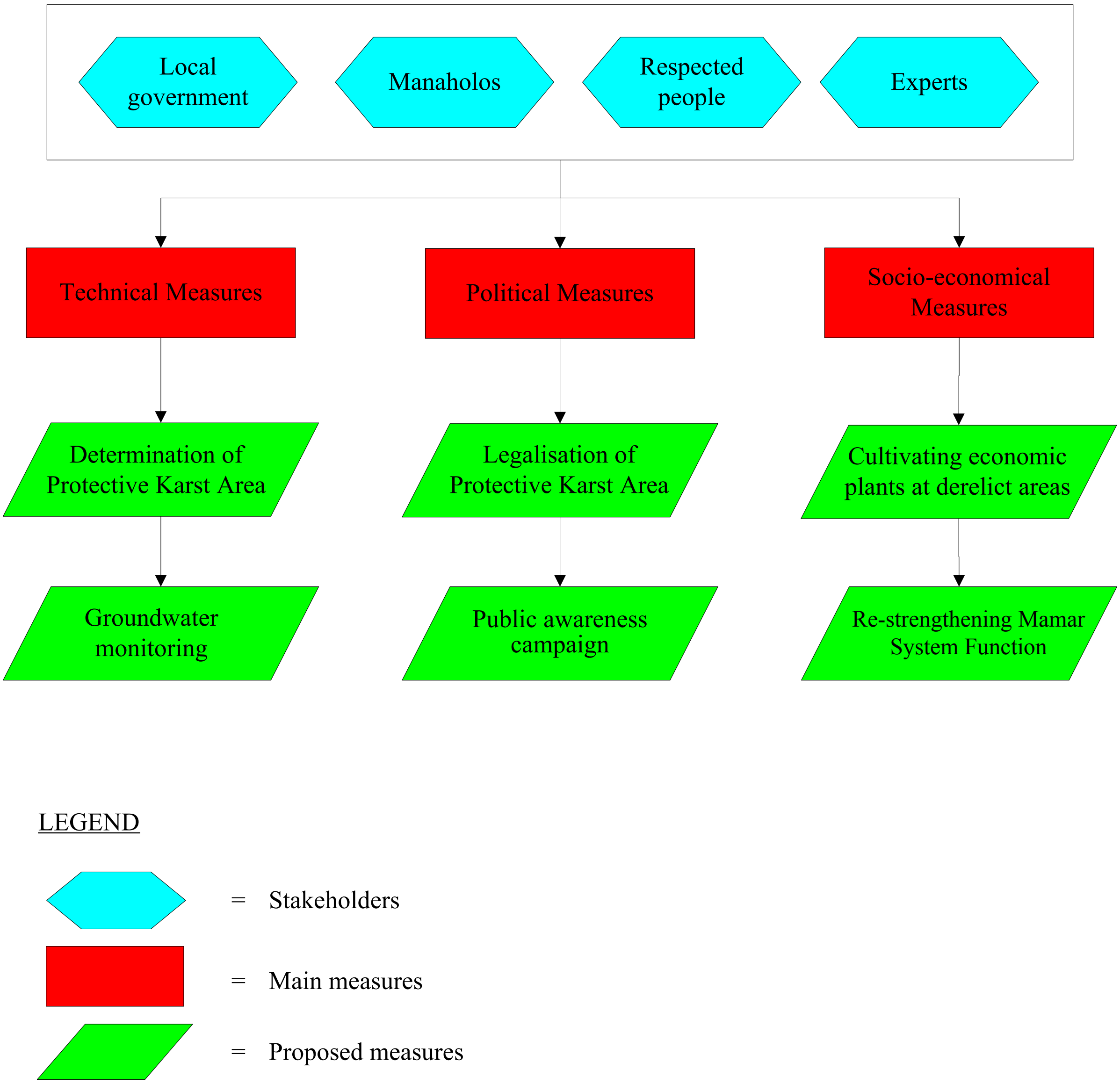

Figure 5 – 2 Proposed measures for sustainable water management in Rote Island

5.3.2.1. Technical measures

a. Determination of Protective Karst Area (PKA)

Establishment of protection zones is the first option undertaken in several cases in karst areas in the world (Afrasiabian, 2007; Escolero et al., 2002). The concept of protective karst areas, that is often called vulnerability and risks map (Nguyet & Goldscheider, 2006), has been widely used to become a foundation of policy formulation of karst protection in several European countries (Andreo et al., 2006; Gogu, Carabin, Hallet, Peters, & Dassargues, 2001; Goldscheider, 2005). In this study conservation strategies were applied with respect to catchment areas of springs or wells. It is assumed that, with regard to the hydrologic cycle in karst areas, the groundwater recharge process initially starts upstream where precipitation occurs (see Figure 3 – 33). Water then infiltrates and feeds the aquifer which retains and transports it to the adjacent outlets. The determination of outer borders of protective karst zone needs to comply with the principle that precipitation falls on points where water, through both primary (allogenic denundation), and secondary porosities (autogenic denundation) reaches a karst aquifer and emerges as springs or wells. Those points are then drawn to form a single karst watershed.

In the context of Rote Island, PKA is determined using the concept described above towards which hydrogeological characteristics of the karst landscape is used. Here, it is concluded that the karst system is governed by a mixture of autogenic and allogenic karst (Section 3.6.3). Therefore, the area where both types of karst that initiate infiltration occur is described as PKA (Figure 5 – 3). In this concept, protective karst area basically starts upstream where infiltration takes place by both diffuse and point ways. This area is crucial in determining the quantity and quality of groundwater that emerges downstream as spring. Therefore, since any negative modification by which vegetations are removed and waste disposal takes place in this area could result in a decline of safe water supply, any further settlement expansion into this area is restricted or prohibited. This issue is afterwards explained in Section 5.3.2 2.1. (Legalisation of protective karst area). Furthermore, in order to augment the recharge rate in PKA, subsequent measures such as reforestation, explained in Section 5.3.2.3.2. (Cultivating plants at diffuse recharge area) are recommended to be undertaken. In addition, the determination of PKA requires a set of hydrological data of which at the moment is insufficient. Therefore groundwater monitoring at Mamar springs is a prerequisite for a proper PKA design (5.3.2.1.2).

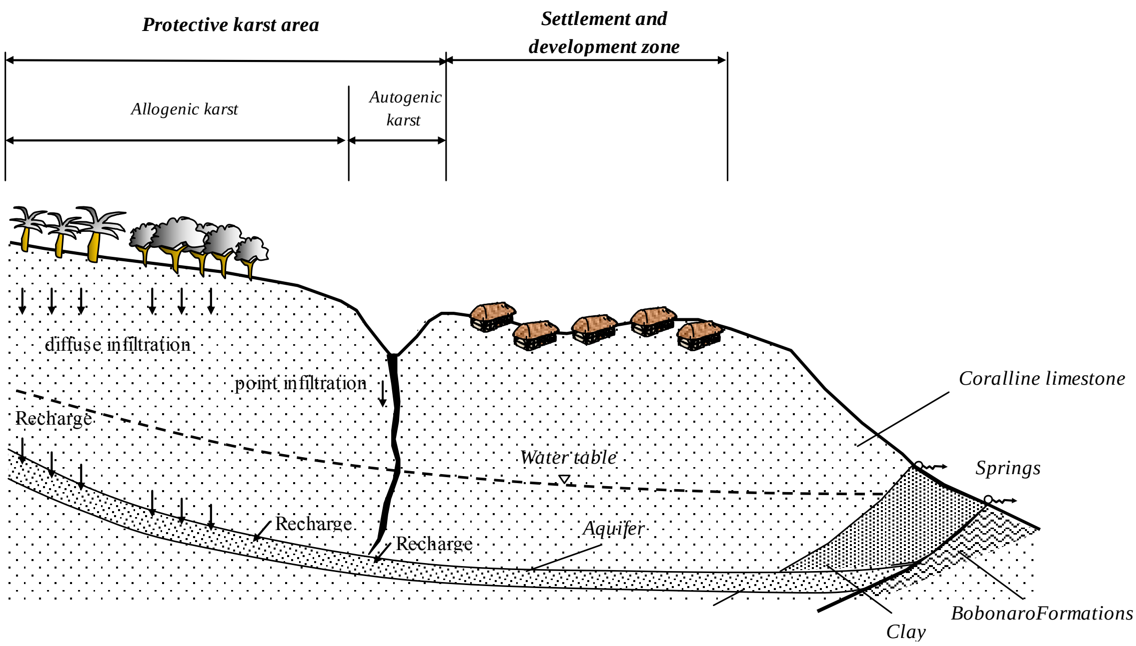

Figure 5 – 3 Concept of protective karst area (PKA) in Rote Island

In the determination of PKA, Participatory Approach is recommended to be used in order to have common ground for resource planning and implementation, to reduce conflict and bring more affluent result (Tam, 2006). In designing PKA, all stakeholders are promoted to collectively share their viewpoints and interest in a free and equal communication. In the discussion forum that is advised to be facilitated by the government, the *manaholos* could describe their functions and territories as well as past and recent Mamar springs' physical condition. The government could explain overall regional development plan within a specific time frame, while experts could justify the initiation and processes of karst system and the implication of anthropogenic activities in karstic springs' watershed. Furthermore, respected people who are usually religious and customary leaders could share the tradition and religious viewpoints.

b. Groundwater monitoring at Mamar springs

Knowledge of hydrogeological system of a specific area is a precondition for appropriate conservation strategies (Nguyet & Goldscheider, 2006). The knowledge is built upon thorough analysis of a set of data available for pertinent area. In karst areas, several places i.e. springs, cave streams, and wells, are the only suitable location to monitor the quality and quantity of groundwater (Quinlan & Koglin, 1989). Data such as springs' water discharge taken from continuous groundwater monitoring is important to determine characteristics of groundwater recharge process. Several studies employing groundwater monitoring that examined both physical and chemical properties of karstic groundwater were used to achieve efficient and appropriate design of groundwater protection strategies (Afrasiabian, 2007; Escolero et al., 2002; Plagnes & Bakalowicz, 2001).

Periodic data available on water discharge at spring as aquifer outlet can be used as a technical tool to describe recharge pattern throughout the year. Better understanding of karst spring behaviour that is demonstrated by the recharge pattern during both dry and wet season can subsequently support decision making process and raise awareness of the society. Meanwhile, supporting chemical analysis on springs' water quality determines not only karstification or karst dissolution process but also the potential present and future hazards that may modify the groundwater quality.

At the moment in Rote Island, there is no periodic discharge and water quality data at spring level. Lack of groundwater monitoring is argued to be an administrative problem more than a technical problem, as methods are well established to obtain such data. This issue is suggested to be driven by insufficient local knowledge of karst's hydrogeological behaviour in which recharge process and springs interact. The existing local knowledge discontinues at a premise that during wet season water is abundant at spring and on the other hand water level at springs' pool declines in the dry season (Otto, 2006; Roen, 2006). The questions on how it happens and what the causes are not resolved due to lack of understanding of hydrologic cycle in karst area. This issue, which originates from lack of supporting data and analysis, consequently hampers implementation of sustainable water management in karstic areas of Rote Island.

In order to alleviate data deficiency of water properties in the framework of karst spring in Rote Island, this study recommends frequent groundwater monitoring at Mamar springs. This task can be performed by both inhabitants and technical officials from the government. It is proposed that a water level board be installed at spring's pool to measure water level by which discharge can be determined. This simple technique can be executed voluntarily by locals whom in the context of Mamar System, can be selected by *manaholos*. Water gauging can be done periodically such as two-week or three-week recording. Government's officials, who in Rote Island's administrative function work for BAPEDALDA (Environment Regional Environment Impact Management Agency), can assist the selected inhabitants to read the board and record it in a log book. Furthermore, water sampling for groundwater chemical analysis can be performed by the same government's officials who visit the site at the same regular interval as that in water level gauging.

5.3.2.2. Political measures

a. Legalisation of protective karst area (PKA)

There is an urgent requirement to facilitate finalisation of legal aspect of PKA. After being confirmed by all stakeholders as depicted in Figure 5 – 2, it is recommended that the final draft of PKA be implemented with legal means. The government, through its Regional BAPPEDA (Regional Development Planning Agency), who mainly works as a coordination agency in regencial platform, can adopt PKA into its regional strategic plan (*Rencana Strategis Daerah*). This plan projects and integrates overall development strategies from all agencies in Rote Island. The plan is then translated in a formal-legal language as Perda (Regional Regulation).

Perda consists of a list of regulations that is used by the regional government to manage its territory. It contains a set of rules concerning social, economical and political aspects including its implementation mechanisms as well as enforcement processes to ensure its implementation. Likewise in other parts of Indonesia, Perda is the highest regencial regulation in Rote Island. It is issued by BAPPEDA prior or following an endorsement by the head of regency (*Bupati*). With regard to PKA, some points that can be addressed in Perda are restricted land-use modification in PKA, restricted groundwater extraction in the catchment area, long-term reforestation schemes in karst recharge areas and strategic waste disposal system.

b. Public awareness campaign for adaptive society on sustainable water management

People and natural resources are two main parts that are closely interrelated. People can live and make use of the resources, while at the same time they can protect them. They need to realise that their attitude towards natural resources as well as its surrounding area determines their continuation to sustain their life and the next generation. Therefore the recognition and understanding of the particular water conservation area is crucial in the context of sustainable water management. The knowledge of the particular system can be attained in an environmental education in the society. Education can create awareness, communicate information, coach knowledge, cultivate habits and skills and promote values (Mogome-Ntsatsi & Adeola, 1995).

In Rote Island context, awareness campaign is recommended to be facilitated by the regional government. To address the “young generation” who will take future responsibility of the conservation in the area, environmental education can be included in regional curriculum in primary and secondary schools. Meanwhile *manaholos* and regional government can actively transfer the conservation messages through community education in neighbouring meetings in local level. Teachers in the classroom and *manaholos* in the communal meetings can deliver a strong message of conservation-led attitudes by describing the importance of understanding the hydrologic cycle in karst areas, its relationship with water security and the impacts of anthropogenic activities in the catchment areas. Better understanding of water conservation concept could lead to an awareness of the importance of spring protection which at the end could create positive attitudes and a personal commitment to preserve it.

5.3.2.3. Socio-economical measures

a. Strengthening Mamar System

As described in Chapter 4, Mamar System is institutionally a system that consists of *manaholo* as the water manager and landowners, whose main function is to regulate and manage the Mamar spring and the plantation area that encircle it. In local scope, Mamar System plays crucial role in ensuring equal water usage among inhabitants and conservation measures at spring site. Therefore empowering Mamar System is an option that is recommended in this study.

It is recommended that the regional government promote a coordination of all Mamar System in Rote Island. The coordination can initially take place with identification of all springs including the local Mamar institution that administers it. Then, an annual meeting attended by representatives of each Mamar spring can be organised by the government. In this meeting, economic, social and technical issues regarding Mamar Spring can be discussed. Problems related with spring management and their conservation measures can be shared among the participants by the examining contribution of government officials from water and conservation division, i.e. Bapedalda. The outcome of the meeting would be a significant input for regional authority to assess current policy concerning groundwater protection as well as other economic and social policies.

b. Cultivating economic plants at diffuse recharge area

Ecologically, reforestation measure is a method to conserve the land by which it accommodates more water to penetrate the earth, thus entering the aquifer during recharge process. Therefore, the absolute benefit of reforestation in hydrologic cycle is that it accentuates infiltration by increasing the quantity of water percolating down to the water table (Allen & Chapman, 2001).

In karst landscape, recharge process is mainly governed by physical characteristics of the surface and drainage system underneath (see Section 2.3.3). With regard to recharge process, it is concluded in Section 3.6.3 that Rote Island is controlled by the mixture of autogenic and allogenic systems. Characterised by the heterogeneity of both permeable and impermeable formations, this recharge system is governed by point and diffuse recharges. Unlike point recharge type of inundation, diffuse recharge area is characterised with a complex primary drainage that is built by heterogenous porous karst media such as carbonate and dolomite (Shuster & White, 1971). Here, infiltration occurs in a slower rate than that in point recharge area. In this area, land cover plays crucial role in retaining water after precipitation before it reaches the surface. Water then infiltrates slowly into the ground and through the karstic compact drainage it feeds into the aquifer (White, 1969). Without vegetation as the natural cover of karst area, water is flushed away as run-off before it reaches into the ground. Therefore, the extent of vegetation in diffuse recharge area is very important to mainly act as buffer zone for water before it interacts with the earth surface and appropriately penetrates the soil.

A case study from karst areas of Sewu Hills in Java, Indonesia, which is mainly characterised by coral reef limestone complex (Haryono & Day, 2004) shows that reforestation is a sustainable option for recharge in a carbonate area. After its introduction in the late 1980's the reforestation has brought a significant transformation of land use in this area. Trees planting scheme in the recharge area has addressed inhabitants' basic needs of energy, food and timber amid severe drought and population growth (Nibbering, 1999).

After assessing and delineation of PKA in a watershed of particular Mamar spring, reforestation can take place in the defined diffuse recharge area. The fundamental rationale that underlays reforestation measures is not only the physical concept of hydrologic cycle but also economic purposes. The selection of local vegetation needs to take into account the concept that the improvement of inhabitants' livelihood is the most important long-term objective in efforts to enhance natural resources management in developing countries (Merrey, Drechsel, Vries, & Sally, 2005). Type of vegetation can vary among different fruit-ripen trees, such as coconut (*Cocos nucifera*), Palm (*Borassus flabellifer*), betel palm (*Areca catechu*), banana (*Musaceae*) and mango (*Mangifera*), which in turn can strengthen local's economy. Those trees are common in this island because they comply with Rote Island's climatological and soil characteristics (BPS, 2004).

Kahembi (Schleichera oleosa) is also recommended to be another option for reforestation due to it's densely canopy and highly adaptation with tropical karst environment, such as that in Rote Island (Russell-Smith, Djoeroemana, Maan, & Pandanga, 2007) and economic value as it hosts highly valued burrowing beetle larva (*Laccifer lacca Kerr*) that has become a profitable exported product in Indonesia (Juspan, 2004).

5.4. Conclusion

1. Generally, this chapter explains the strategies needed to be undertaken to ensure the Mamar in Rote Island performs its capability to supply adequate and safe water to the

whole community. The analysis starts with the identification of potential factors, including population growth, human activities, land use change and potential effect of climate change on the hydrologic cycle in this island, that pose threat to the state of Mamar. Then, the water conservation strategies, consisting of technical, political and economical measures, are formulated in the framework of sustainable water management.

2. The increase of population especially in the form of immigration is suggested to put burden to karst landscape as settlement and business areas could expand into the recharge area of the karst system. Immigration, which is mainly driven by a new administrative statue of the island could also increase demand on water that is mainly sourced from karst springs.

3. Karst system is more vulnerable to any changes occur at the surface. Therefore, land use change, due to increased demand for settlement and business areas as population increases, is suggested contribute to the modification of hydrologic characteristics of the karstic areas in Rote Island. Land use could bring detrimental impact to the existence of Mamar spring as infiltration rate decreases due to vegetation removal and contaminants are transported through porous carbonate layers to the springs which may reduce groundwater quality.

4. It is suggested that change in global climate has impact to the raise of sea surface temperature (1.5 to 2 ^{O}C) between 1090 and 2099 at the area adjacent to Rote Island. The prediction also suggests a decrease in dry season (0.1 mm/day) and an increase in mean rainfall in wet season (0.2 mm/day) and. The change may impact the recharge pattern of the karst area in this island as the increased temperature leads to an increase of evapotranspiration, thus reducing the recharge rate on a watershed scale. Meanwhile, the increase of rainfall is suggested to be present as intense and extreme rainfalls that

suggests an increased chance of intense runoff rather than as steady rain which helps maximise infiltration.

5. The indigenous knowledge of managing water from karstic spring, called Mamar System, is suggested to be at stake as immigration pressure, that could lead to increased demand on space and natural resources, potentially influence people's attitude and value toward the system. People may abandon the wise use of Mamar spring while the government may take over the managerial aspects of the Mamar from *manaholo*.

6. It is concluded that all factors that pose threat to Mamar have direct and indirect implication to the state of water balance variables that govern hydrologic process in this karstic island. Any changes occurs in the state of water balance of the karstic groundwater may result in a reduced water recharge capacity to karst aquifer which end at reduction of capacity of spring to supply water, thus creating water insecurity in the communities of Rote Island.

7. It is concluded that conservation strategies, which in this are drawn in the framework of sustainable water management that suits Rote Island's physical and societal conditions, need to be designed and implemented in order to overcome the potential tradeoffs.

8. Sustainable water management in karstic groundwater of Mamar System is defined as a way or process to manage available karstic spring water with proper ecological, economical, technical and societal concerns by giving recognition of future generation's right to utilise the same quantity and quality of water. This concept is then accentuated and manifested in several proposed measures, covering technical, political and economical aspects. The formulation of proposed measures takes into account characteristics of karst areas in Rote Island (Chapter 3), existing indigenous practice of natural resource management called Mamar System (Chapter 4) and potential trade-offs

as described in Section 5.2. Each measure is designed to correlate one to another in an integrated relationship.

9. The proposed measures are technical measures, including determination of Protective Karst Area (PKA) and groundwater monitoring at Mamar springs, political measures, including legalisation of PKA and public awareness campaign for adaptive society on sustainable water management, and socio-economical measures, including strengthening of Mamar System and cultivation of economic plants at diffuse recharge area.

10. Establishment of PKA is proposed in order to physically protect the recharge area of the pertinent karstic spring by determination of borders of protective karst zone that is categorised as mixed of allogenic denundation and autogenic denundation as concluded in Chapter 3. PKA acts as a reserve area in where no physical development activities are allowed to take place. The protection of the recharge area consequently ensures a proper natural water transport from this area to the springs and to prevent any soil and water contamination in this area.

11. Finalisation of legal aspect of PKA is required through Regional Regional Development Planning Agency (BAPPEDA). It is recommended that PKA be adopted into RENSTRA (Regional Strategic Plan), which is then translated in a formal-legal language as Perda (Regional Regulation).

12. In order to gain a comprehensive knowledge of hydrogeological karst system in Rote Island as one of the prerequisites for designing appropriate conservation strategies, periodic groundwater monitoring is recommended. The monitoring is aiming at collecting both physical and chemical properties of the spring. This task is suggested be performed by *manaholo* or local inhabitants after being trained by the government's officials.

13. Realising the importance of Mamar System in the society, it is recommended to strengthen Mamar System by promoting coordination of all Mamar System in Rote Island. The government is suggested to accommodate the coordinative functions which are accentuated through regular meeting that discusses economic, social and technical issues regarding Mamar Spring.

14. In order to encourage inhabitant to conserve the Mamar spring using economic mean, it is recommended that profitable plants be cultivated at diffuse recharge area. The reforestation could physically assist alleviated infiltration and thus improving water recharge to the karst aquifer. Those trees could bring a long term benefit for the inhabitants as their fruit products can be sold in market thus improving their livelihood.

Chapter 6

SUMMARY AND SUGGESTIONS FOR FURTHER STUDY

In this chapter the summary of the study and the key findings presented in this thesis are extracted.

6.1. Summary of the thesis

The main objectives of this study are to assess the Mamar including its hydrogeological system, water allocation and distribution, interaction patterns and social benefit for the community in Rote Island and to develop recommendation based on the analysis above towards sustainability of water use. In order to achieve the objectives, the study presents findings from available literatures, field investigation including visual examination on geomorphology and water measurement at Mamar springs and social survey which aims at understanding people's perceptions and attitudes towards Mamar System.

A theoretical and analytical foundation of karst system with regard to Rote Island is presented in Chapter 2 and 3 respectively. The climatological, hydrogeological, hydrochemical and water balance analyses, in which data from literature are employed, are presented to better understand the physical circumstance of karst system in the study area. The study progresses to clarify the literature findings by conducting field investigation at seven locations in Rote Island. The summary of the findings which have been validated during the field survey are as follow:

- Climatologically, Rote Island Rote Island is characterised by a typical monsoonal climate characterised by two distinct seasons, which are dry season (April to November) and wet season (December –March). This climatic state is influenced by its geographic position by which it is situated between two main continents which are Australia and Asia and two oceans, which are Pacific and Indian Oceans. The characteristics of rainfall, mean daily sunshine and temperature of this island influence the water balance of the study area, in which evapotranspiration, runoff and infiltration are quantified. The result shows that the availability of water especially during dry season is at stake as groundwater storage drops significantly. Therefore, although maintaining a perennial supply for the society, Mamar springs are hydrologically susceptible to experience significant decrease of water discharged especially in dry season.

- Geohydrologically, Rote Island is categorised as karst island in which karst characteristics dominate. The data from bores and field investigation highlight the extensive carbonate layers, combined with other rock formations, i.e. Bobonaro, Noele, Aitutu Formations, and alluvial deposit, present in this Island. The indication of carbonate and bicarbonate components which represent limestone and dolomite occurrence in soil stratum is verified in hydrochemistry analysis using groundwater sample from the bores.
- After analysing hydrogeology data available from five bores and conducting field survey in seven villages in Rote Island, a conceptual model is built based on arguments on the relation between geological formation and spring initiation, the relation between theory of Rote Island's genesis and spring initiation, the conceptualisation of groundwater recharge process, and the conceptualisation of aquifer characteristics in Rote Island
- The conceptual model suggests that the type of karst aquifer in Rote Island differs spatially which is determined by geological formation in the pertinent area and timely which is determined by seasonal fluctuation of water table related with water input which is rain that functions as an input for recharge process in the area determines the amount of

water discharged at spring. Consequently, this karst system is susceptible as it could respond rapidly to natural and anthropogenic processes.

The findings and arguments presented above basically provides technical approaches to mainly understand the recharge process in karst area of Rote Island which significantly determines the physical behaviour of Mamar spring which is one of the objectives of this study. The comprehension of physical Mamar springs in this chapter is then complemented with social aspects of the Mamar system which is derived from social survey in five villages. The summary of the findings during social survey that provides a comprehensive of the Mamar System is as follow:

- Water from spring is important for the whole community of Rote Island as it continuously provides water. Its functions that range from primary functions (basic life supporting and economic roles in the community) and secondary functions (administrative, social and ecological functions) construct its significant value in the community. As a result, the spring is exclusively managed is a certain knowledge that suits with local tradition.

- The local knowledge by which the community manage the spring water and its ecosystem is called Mamar System developed and maintains a system which is locally acknowledged as Mamar System which is, in this study, defined as a local knowledge and practice of water management in Rotenese society in Rote Island to conserve karstic groundwater spring in order to primarily provide sufficient water for plantation and drinking water for the community living surrounding it. The Mamar system including its organisational arrangement and mechanism, stakeholders and their roles and rules employed to sustain the system is presented in Chapter 4 by emphasizing the importance of the system in maintaining water management in the villages.

- The result of the social survey shows that all participants considered Mamar valuable in providing water for household’s uses, vegetations and livestock, thus relied upon water provision from Mamar springs. Concerning Mamar System performance (i.e.: organisational framework, organisational mechanism, administrative tools, evaluation mechanism, and water distribution), most respondents believed that it has effectively worked to manage the usage and conservation of the springs in their village. It is concluded the inhabitants will keep on supporting the Mamar System in their village.

Presented as the answer of the first objective of this study, the understanding of Mamar System as an indigenous knowledge that socially and culturally roots in Rote Island’s society in Chapter 4 is then complemented with technical aspects of the Mamar system in Chapter 3 in order to design appropriate conservation strategies in the framework of sustainable water management in Chapter 5.

In chapter 5 the second objective of this study is answered. This chapter explains the strategies needed to be undertaken to ensure the Mamar in Rote Island performs its capability to supply adequate and safe water to the whole community. The summary of the analysis and recommendation is as follow:

- The analysis starts with the identification of potential factors, including population growth, human activities, land use change and potential effect of climate change on the hydrologic cycle in this island, that pose threat to the state of Mamar.

- Increase of population due to immigration is suggested to put burden to karst landscape as settlement and business areas could expand into the recharge area of the karst system. Karst system is more vulnerable to any changes occur at the surface. Therefore, land use change, due to increased demand for settlement and business areas as population increases, is suggested contribute to the modification of hydrologic characteristics of the karstic areas in Rote Island by which infiltration rate decreases leading to water shortage at springs and contaminants are transported through porous carbonate layers to the springs which may reduce groundwater quality. The impact of change in global climate on Rote Island is expected which may result in change in the recharge pattern of the karst area in this island as the increased temperature leads to an increase of evapotranspiration, thus reducing the recharge rate on a watershed scale. The increased need upon water due to increased population may result in abandonment of Mamar System which is the indigenous knowledge of managing water from karstic spring.

- It is concluded that all factors that pose threat to Mamar have direct and indirect implication to the state of water balance variables that govern hydrologic process in this karstic island. Any changes occurs in the state of water balance of the karstic groundwater may result in a reduced water recharge capacity to karst aquifer which end at reduction of capacity of spring to supply water, thus creating water insecurity in the communities of Rote Island.

It is concluded that conservation strategies, which in this are drawn in the framework of sustainable water management, need to be designed and implemented in order to overcome the potential tradeoffs. The conservation strategies that suits Rote Island's physical and societal conditions is presented in Chapter 5 and summarised as follow:

- Technically, establishment of Protective Karst Area (PKA) is proposed in order to physically protect the recharge area of the pertinent karstic spring by determination of borders of protective karst zone that is categorised as mixed of allogenic denundation and autogenic denundation. The protection of the recharge area is suggested to ensure a proper natural water transport from this area to the springs and to prevent any soil and water contamination in this area. To support an improved knowledge of hydrogeological karst system in Rote Island as one of the prerequisites for designing appropriate conservation strategies, periodic groundwater monitoring is recommended which aims at collecting both physical and chemical properties of the spring.

- Politically, the finalisation of legal aspect of Protective Karst Area (PKA) is important through appropriate administrative means in Rote Island in order to strengthen the preservation of the recharge area. Wider participation of the community to support the overall measures is suggested to be achieved through dissemination of information that encourage better understanding of the karst characteristics in Rote Island
- Socio-economically, a coordination of all Mamar System in Rote Island is recommended through regular meeting that discusses economic, social and technical issues regarding Mamar Spring to strengthen Mamar System's capability to manage the spring and its ecosystem. it is recommended perform reforestation at recharge area with profitable plants that could improve inhabitants' livelihood in order to gain continuous participation of inhabitants to conserve the mamar ecosystem.

6.2. Suggestions for further study

In order to achieve an enhanced understanding of karst characteristics that govern the recharge process to Mamar springs, the following potential studies are considered suitable for further research:

- A detailed geological study that aims at identifying the actual geological stratum over the Rote Island. There is only two studies recorded which is insufficient to build overall understanding of how different formations of rock interact. The study will emphasize on locations where two or more formations geologically collide and determine its relation with the occurrence of Mamar springs which in Rote Island are mostly found in this locations.

- A study at spring scale which aims at investigating the relationship of discharge at spring and the rainfall based on a continuos and complete climatological and hydraulic data. This study will result in spring hydrographs that will show the hydrogeology response of Mamar springs to components of karst landscape such as recharge process, karst aquifer, dissolution process, drainage pattern, infiltration capacity and actual runoff.

- A study on modelling the interactions of various critical factors that determine the capability of Mamar springs to ensure continuos water supply to the society. The model which is designed as a real-time interactive program is intended to be used as a decisive tool by policy makers to determine in a complex data input covering physical karst landscape behaviour of Rote Island, prediction on climatological variables with regard to global climate change and modification in demographic and land use change in Rote Island.

REFERENCES

ABM. (2008). Mean daily sunshine (hours) for Darwin Airport (1951-2008): 014015: Australian Bureau of Meterology.

Abram, N. J., Gagan, M. K., Liu, Z., Hantoro, W. S., McCulloch, M. T., & Suwargadi, B. W. (2007). Seasonal characteristics of the Indian Ocean Dipole during the Holocene epoch. *Nature, 445*(18), 299 - 302.

Afrasiabian, A. (2007). The importance of protection and management of Karst water as drinking water resources in Iran. *Environmental Geology52, 4*, 673-677.

Agrawal, A. (2001). Common property institutions and sustainable governance of resources. *World Development, 29*(10), 1649–1672.

Aldrian, E., & Djamil, Y. S. (2008). Spatio-temporal climatic change of rainfall in East Java Indonesia. *International Journal of Climatology, 28*, 435-448.

Aldrian, E., & Susanto, D. (2003). Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *International Journal of Climatology, 23*(12), 1435-1452.

Allen, A., & Chapman, D. (2001). Impacts of afforestation on groundwater resources and quality *Hydrogeology Journal, 9*(4), 390-400.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements; FAO Irrigation and Drainage Paper No.56*. Rome, Italy: FAO.

Allred, K., & Allred, C. (1997). Development and Morphology of Kazumura Cave, Hawaii. *Journal of Cave and Karst Studies, 59*(2), 67-80.

Andreo, B., Goldscheider, N., Vadillo, I., Vías, J. M., Neukum, C., Sinreich, M., et al. (2006). Karst groundwater protection: First application of a Pan-European Approach to vulnerability, hazard and risk mapping in the Sierra de Líbar (Southern Spain). *Science of The Total Environment, 357*(1-3), 54-73.

Appelo, C. A. J., & Postma, D. (2005). *Geochemistry, groundwater and pollution, 2nd ed.* Leiden: A.A. Balkema.

Ashok, K., Guan, Z., Saji, N. H., & Yamagata, T. (2004). Individual and Combined Influences of ENSO and the Indian Ocean Dipole on the Indian Summer Monsoon. *Journal of Climate, 17*(16), 3141–3155.

Audley-Charles, M. G. (1968). The geology of Portuguese Timor. *Geological Society of London Memoir, 4*, 1-76.

Bakalowicz, M. (1975). Géochimie des eaux karstiques et kartification. *Annales de Spéléologie, 45*(1), 28-35.

Ball, J. E., & Luk, K. C. (1998). Modeling spatial variability of rainfall over a catchment. *Journal of Hydrologic Engineering, 3*(2), 122-130.

Bappeda (Cartographer). (2004). *Rencana tata ruang wilayah (RTRW) Kabupaten Rote Ndao: Penggunaan lahan eksisting*

Bauer, S., Liedl, R., & Sauter, M. (2003). Modeling of karst aquifer genesis: Influence of exchange flow. *Water Resources Research, 39*(10), SBH6 1-12.

Baumgartner, A., & Reichel, E. (1975). *The World Water Balance*. Munchen: R.Oldenbourg-Verlag.

Beach, T., Luzzadder-Beach, S., Dunning, N., & Cook, D. (2008). Human and natural impacts on fluvial and karst depressions of the Maya Lowlands. *Geomorphology, In Press, Accepted Manuscript*.

Bernhardi, L., Beroggi, G. E. G., & Moens, M. R. (2000). Sustainable Water Management through Flexible Method Management. *Water Resources Management, 14*(6), 473–495.

BMG. (2007). *Rainfall Data in six meteorological stations in Rote Island: In Indonesian*. Kupang: Biro Meteorologi dan Geofisika.

Bonacci, O., & Magdalenić, A. (1993). The Catchment Area of the Sv. Ivan Karst Spring in Istria (Croatia) *Ground Water, 31*(5), 767-773.

BPS. (2002). *Rote Ndao dalam angka, BPS Kabupaten Kupang*. Kupang: Badan Pusat Statistik Kabupaten Kupang.

BPS. (2004). *Rote Ndao dalam angka, BPS Kabupaten Kupang*. Kupang: Badan Pusat Statistik Kabupaten Kupang.

Bras, R. L. (1990). *Hydrology : an introduction to hydrologic science*. Reading, Mass.: Addison-Wesley.

Bridgewater, P. B., & Arico, S. (2002). Conserving and managing biodiversity sustainably: The roles of science and society *Natural Resources Forum, 26*(3), 245-248.

Brouwer, H. A. (1922). Geologische onderzoekingen op het Eiland Rotti: Jaarb. v.h. Mijnwezen in Ned.Oost-Indië. *Verhand (1920), 3e ged.*, 70-77.

Burke, J. J., & Moench, M. H. (2000). *Groundwater and society: Resources, tensions and opportunities*. New York: United Nations.

Chahinian, N., Moussa, R., Andrieux, P., & Voltz, M. (2005). Comparison of infiltration models to simulate flood events at the field scale. *Journal of Hydrology, 306*(1-4), 191-214.

Chamalaun, F. H., & Grady, A. E. (1978). The tectonic development of Timor: A new model and its implications for petroleum exploration. *Australian Petroleum Exploration Association Journal, 50*, 102-108.

Chen, G., Pan, W., Sa, L., Han, J., & Guan, W. (2005). Application of prediction techniques in carbonate karst reservoir in tarim basin. *Applied Geophysics, 2*(2), 111-118.

Chiew, F. H., & Leahy, C. P. (2003). Comparison of Evapotranspiration Variables in Evapotranspiration Maps for Australia with Commonly Used Evapotranspiration Variables *Australian Journal of Water Resources, 7*(1), 1-11.

Chu, X., & Mariño, M. A. (2005). Determination of ponding condition and infiltration into layered soils under unsteady rainfall. *Journal of Hydrology, 313*(3-4), 195-207.

Cremers, L., Ooijevaar, M., & Boelens, R. (2005). Institutional reform in the Andean irrigation sector: Enabling policies for strengthening local rights and water management *Natural Resources Forum, 29*(1), 37-50.

Currens, J. C., & Graham, C. D. R. (2004). Flooding of Sinking Creek, Garretts Spring karst drainage basin, Jessamine and Woodford counties, Kentucky, USA *Environmental Geology, 22*(4), 337-344.

D'Arrigo, R., Wilson, R., Palmer, J., Krusic, P., Curtis, A., Sakulich, J., et al. (2006). Monsoon drought over Java, Indonesia, during the past two centuries. *Geophysical Research Letters, 33*, L04709 04701-04704.

D'Arrigo, R., & Wilson, R. (2008). El Niño and Indian Ocean influences on Indonesian drought: implications for forecasting rainfall and crop productivity. *International Journal of Climatology, 28*(5), 611-616.

D'Arrigo, R., Wilson, R., Palmer, J., Krusic, P., Curtis, A., Sakulich, J., et al. (2006). The reconstructed Indonesian warm pool sea surface temperatures from tree rings and corals: Linkages to Asian monsoon drought and El Niño–Southern Oscillation *Paleoceanography, 21*, PA3005.

Dingman, S. L. (2002). *Physical hydrology* (2nd ed.). Upper Saddle River, NJ: Prentice Hall.

Diskin, M. H., & Nazimov, N. (1996). Ponding time and infiltration capacity variation during steady rainfall. *Journal of Hydrology, 178*(1-4), 369-380.

Doorenbos, J., & Pruitt, W. O. (1975). *Guidelines for Predicting Crop Water Requirements; FAO Irrigation and Drainage Paper No.24*. Rome, Italy: FAO.

Doorenbos, J., & Pruitt, W. O. (1977). *Guidelines for Prediction of Crop Water Requirements; Irrig. And Drain. Paper no. 24* (2nd ed.). Rome, Italy: FAO.

Dreiss, S. J. (1989). Regional scale transport in a karst aquifer: 1. Component separation of spring flow hydrographs. *Water Resources Research, 25*(1), 117-125.

Drew, D. P. (Ed.). (1999). *Karst Water and Human Activities: An overview* (Vol. 20). Rotterdam, the Netherlands: A. A. Balkema.

Droogers, P., & Allen, R. G. (2002). Estimating reference evapotranspiration under inaccurate data conditions. *Irrigation and Drainage Systems, 16*(1), 33-45.

Dunham, R. J. (1962). Classification of carbonate rocks according to depositional texture. In HAM, W. E. (ed.), Classification of carbonate rocks. *American Association of Petroleum Geologists Memoir, 1*, 108-121.

Eberhard, S. M. (2004). *Ecology and hydrology of a threatened groundwater-dependent ecosystem: The Jewel Cave karst system in Western Australia. PhD thesis.* Murdoch University, Western Australia.

Escolero, O. A., Marin, L. E., Steinich, B., Pacheco, A. J., Cabrera, S. A., & Alcocer, J. (2002). Development of a Protection Strategy of Karst Limestone Aquifers: The Merida Yucatan, Mexico Case Study *Water Resources Management, 16*(5), 351-367.

ESDD. (2003). *Atlas of mineral resources of the ESCAP region Volume 17*: ESDD.

Fandry, C. B., & Steedman, R. K. (1989). An investigation of tropical cyclone-generated circulation on the North-West Shelf of Australia using a three-dimensional model. *Ocean dynamics, 42*(3-6), 307-341.

Fendek, M., & Fendekova, M. (2005). Transboundary Flow Modeling: The Zohor Depression of Austria and the Slovak Republic *Ground Water, 43*(5), 717-721.

Ford, D. C., & Williams, P. W. (1989). *Karst geomorphology and hydrology*. London: Unwin Hayman.

Ford, D., & Williams, P. (2007). *Karst Hydrogeology*. West Sussex: John Wiley & Sons.

Frank, E., Wicks, C., Mylroie, J., Troester, J., Alexander, J. E. C., & Carew, J. (1998). Geology of Isla de Mona, Puerto Rico. *Journal of Cave and Karst Studies, 60*(2), 69-72.

Gardner-Outlaw, T., & Engleman, R. (1997). *Sustaining Water, Easing Scarcity: A Second Update*. Washington DC: Population Action International.

Ghebreyesus. (2000). The community-based malaria control programme in Tigray, northern Ethiopia: A review of programme set-up, activities and impact. *Parassitologica, 42*, 255-290.

Gillieson, D. S. (1996). *Caves : processes, development, and management* Oxford: Blackwell Publishers.

Gogu, R., Carabin, G., Hallet, V., Peters, V., & Dassargues, A. (2001). GIS-based hydrogeological databases and groundwater modelling. *Hydrogeology Journal, 9*(6), 555-569.

Goldscheider, N. (2005). Karst groundwater vulnerability mapping: application of a new method in the Swabian Alb, Germany *Hydrogeology Journal, 13*(4), 555–564.

Govindaraju, R. S., Kavvas, M. L., Jones, S. E., & Rolston, D. E. (1996). Use of Green-Ampt model for analyzing one-dimensional convective transport in unsaturated soils. *Journal of Hydrology, 178*(1-4), 337-350.

Granger, R. J. (1989). An examination of the concept of potential evaporation. *Journal of Hydrology, 111*(1-4), 9-19.

Gray, D. M. (1973). *Handbook on the principles of hydrology with special emphasis directed to Canadian conditions in the discussion, applications and presentation of data*. Port Washington, N.Y.: Water Information Centre, Inc.

Gray, W. M. (1998). The formation of tropical cyclones. *Meteorology and Athmospheric Physics, 67*(1-4), 37-69.

Hamada, J. I., Yamanaka, M. D., Matsumoto, J., Fukao, S., Winarso, P. A., & Sribimawati, T. (2002). Spatial and temporal variations of the rainy season over Indonesia and their link to ENSO. *Journal of the Meteorological Society of Japan, 80*, 285-310.

Hamilton, W. (1979). Tectonics of the Indonesian Region. *United States Geological Survey Professional Paper, 1078*, 33-41.

Hamilton, W. (Cartographer). (1978). *Tectonic map of the Indonesian region, Scale 1:5,000,000, Map 1- 875-D*

Hargreaves, G. H., & Samani, Z. A. (1985). Reference crop evapotranspiration from temperature. *Journal of Applied Engineering in Agriculture, 1*(2), 96-99.

Hargreaves, G. L. (1994). Defining and using reference evapotranspiration. *Journal of Irrigation and Drainage, 120*(6), 1132-1139.

Hargreaves, G. L., Hargreaves, G. H., & Riley, J. P. (1985). Agricultural benefits for Senegal River basin. *Journal of Irrigation and Drainage Engineering, ASCE, 111*(2), 113-124.

Harris, R., Kaiser, J., Hurford, A., & Carter, A. (2000). Thermal history of Australian passive margin cover sequences accreted to Timor during Later Neogene arc-continent collision. *Journal of Asian Earth Sciences, 18*, 47-69.

Haryono, E., & Day, M. (2004). Landform differentiation within the Gunung Kidul Kegelkarst, Java, Indonesia. *Journal of Cave and Karst Studies, 66*(2), 62-69.

Haylock, M., & McBride, J. (2001). Spatial Coherence and Predictability of Indonesian Wet Season Rainfall. *Journal of Climate, 14*(18), 3882-3887.

Hendon, H. H. (2003). Indonesian Rainfall Variability: Impacts of ENSO and Local Air–Sea Interaction. *Journal of Climate 16*(11), 1775–1790

Hok, T. S. (1927). *Over de samestelling en het ontstaan van krijt en mergel-gesteenten van de Molukken: Jaarb. v. h. Mijnewezen in Ned. Oost-Indie, Verhand. (1926)*.

Horton, R. (1933). The role of infiltration in the hydrologic cycle. *American Geophysical Union Transactions, 14*, 446–460.

Hose, L. D., & Pisarowicz, J. A. (1999). Cueva de Villa Luz, Tabasco, Mexico: Reconnaissance Study of an Active Sulfur Spring Cave and Ecosystem. *Journal of Cave and Karst Studies, 61*(1), 13-21.

Hromodka, T. V., & Whitley, R. J. (1994). A stochastic integral equation analog of rainfall-runoff processes for evaluating modeling uncertainty *Stochastic Environmental Research and Risk Assessment, 8*(4), 259-268.

Hussain, M., Al-Khalifah, F., & Khandaker, N. I. (2006). The Jabal Al Qarah Caves of the Hofuf Area, Northeastern Saudi Arabia: A Geological Investigation. *Journal of Cave and Karst Studies, 68*(1), 12-21.

Inoue, M., & Welsh, S. E. (1993). Modelling seasonal variability in the Wind-driven Upper-layer Circulation in the Indo-Pacific Region. *Journal of Physical Oceanography, 27*(5), 683-696.

IPCC. (2001). *Climate Change 2001. The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge, UK.: Cambridge University Press.

IPCC. (2007a). *Climate Change 2007: Synthesis Report. Contribution of Working Group to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) at IPCC Plenary XXVII (Valencia, Spain, 12-17 November 2007)*. Cambridge, UK.: Cambridge University Press.

IPCC. (2007b). *Climate Change 2007:The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge, UK.: Cambridge University Press.

IPCC. (2007c). Summary for Policymakers. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M.Tignor & H. L. Miller (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jacobs, A. F. G., Heusinkveld, B. G., & Lucassen, D. C. (1998). Temperature variation in a class A evaporation pan. *Journal of Hydrology, 206*(1-2), 75-83.

Jafar, S. A. (1975). Calcareous Nannoplankton from the Miocene of Rotti, Indonesia. *Koninklijke Nederlandse Akademie van Wetenschappen, Verh., Afd. Natuurkunde, Eeste Reeks, 28*, 99.

Jakucs, L. (1977). *Morphogenetics of karst regions: Variants of karst evolution*. Budapest Akademiai Kiado.

James, L. D. (1972). Hydrologic modeling, parameter estimation, and watershed characteristics. *Journal of Hydrology, 17*(4), 283-307.

Jaquet, O., Siegel, P., Klubertanz, G., & Benabderrhamane, H. (2004). Stochastic discrete model of karstic networks. *Advances in Water Resources, 27*(1), 751–760.

Jennings, J. N. (1987). *Karst geomophology*. New York: Basil Blackwell.

Jensen, D. T., Hargreaves, G. H., Temesgen, B., & Allen, R. G. (1997). Computation of ETo under nonideal conditions. *Journal of Irrigation and Drainage Engineering, ASCE, 123*(5), 394-400.

Jensen, M. E., Burman, R. D., Allen, R. G., & American Society of Civil Engineers. Committee on Irrigation Water Requirements. (1990). *Evapotranspiration and irrigation water requirements : a manual*. New York, N.Y.: The Society.

Jiang, Y., Zhang, C., Yuan, D., Zhang, G., & He, R. (2006). Impact of land use change on groundwater quality in a typical karst watershed of southwest China: a case study of the Xiaojiang watershed, Yunnan Province *Journal of Geographical Sciences, 16*(4), 405-414.

Jong, C. d., Cappy, S., Finckh, M., & Funk, D. (2008). A transdisciplinary analysis of water problems in the mountainous karst areas of Morocco. *Engineering Geology, 99*(3-4), 228-238.

Juspan. (2004). *Cultivation of Kutu Lak (Laccifer lacca Kerr): Production, Marketing and Contribution to Farmers' Income (In Indonesia).* Universitas Kristen Satya Wacana, Salatiga, Indonesia.

Kaçaroğlu, F. (1999). Review of groundwater pollution and protection in karst areas. *Water, Air and Soil Polution, 113*, 337-356.

Kaplan, A., Cane, M. A., Kushnir, Y., Clement, A. C., Blumenthal, M. B., & Rajagopalan, B. (1998). Analyses of global sea surface temperature 1856–1991. *Journal of Gephysical Research, 103*(C9), 18,567–518,589.

Karig, D. E., Barber, A. J., Charlton, T. R., Klemperer, S., & Hussong, D. M. (1987). Nature and distribution of deformation across the Banda Arc-Australian collision zone at Timor. *Geological Society of America Bulletin, 98*(18-32).

Kiraly, L. (1998). Modeling karst aquifers by the combined discrete channel and continuum approach. *Bulletin of Hydrogeology, 16*, 77-98.

Kumar, S., & Jab, S. C. (1982). Application of SCS Infiltration Model. *Journal of the American Water Resources Association, 18*(3), 503-507.

Lemeur, R., & Zhang, L. (1990). Evaluation of three evapotranspiration models in terms of their applicability for an arid region. *Journal of Hydrology, 114*(3-4), 395-411.

Li, T.B., Shao, J.A., Yang, H., & Bai, X.Y. (2008). The relations between land use and karst rocky desertification in a typical karst area, China. *Environmental Geology*.

Liu, Z., Groves, C., Yuan, D., & Meiman, J. (2004). South China Karst Aquifer Storm-Scale Hydrochemistry *42*(4), 491-499.

Lucia, J. F. (1999). *Carbonate reservoir characterization* (Vol. Springer-Verlag). Berlin.

Maramathas, A. J., & Boudouvis, A. G. (2006). Manifestation and measurement of the fractal characteristics of karst hydrogeological formations. *Advances in Water Resources, 29*(1), 112-116.

Martínez, J. M. M., Alvarez, V. M., González-Real, M. M., & Baille, A. (200). A simulation model for predicting hourly pan evaporation from meteorological data. *Journal of Hydrology, 318*(1-4), 250-261.

Martini, R., Zaninetti, L., Lathuillière, B., Cirilli, S., Cornée, J. J., & Villeneuve, M. (2004). Upper Triassic carbonate deposits of Seram (Indonesia): palaeogeographic and geodynamic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology, 206*, 75-102.

Martini, R., Zaninetti, L., Villeneuve, M., Corne´e, J.-J., Krystyn, L., Cirilli, S., et al. (2000). Triassic pelagic deposits of Timor: palaeogeographic and sea-level implications. *Palaeogeography, Palaeoclimatology, Palaeoecology, 160*, 123-151.

McBride, J. L., & Nicholls, N. (1983). Seasonal Relationships between Australian Rainfall and the Southern Oscillation. *Monthly Weather Review, 111*(10), 1998-2004.

McVicar, T. R., Van Niel, T. G., Li, L., Hutchinson, M. F., Mu, X., & Liu, Z. (2007). Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *Journal of Hydrology, 338*(3-4), 196-220.

Merrey, D. J., Drechsel, P., Vries, F. W. T. P. d., & Sally, H. (2005). Integrating "livelihoods" into integrated water resources management: taking the integration paradigm to its logical next step for developing countries *Regional Environmental Change 5*(4), 197-204.

Miller, T. E. (1996). Geologic and Hydrologic Controls on Karst and Cave Development in Belize. *Journal of Cave and Karst Studies, 2*(2), 100-120.

Mogome-Ntsatsi, K., & Adeola, O. A. (1995). Promoting environmental awareness in Botswana: the role of community education *The Environmentalist, 15*(4), 281-292.

Monteith, J. L. (1965). Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London, 281*, 277-329.

Morel-Seytoux, H. J. (1981). Application of Infiltration Theory for the Determination of Excess Rainfall Hyetograph. *Journal of the American Water Resources Association, 17*(6), 1012-1022.

Morozov, V. (2007). Lower and Middle Carboniferous oil-bearing limestones of southeastern Tatarstan and reconstruction of the paleoenvironment of their formation. *Lithology and Mineral Resources, 42*(1), 68-74.

Morton, F. I. (1983). Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal of Hydrology, 66*(1-4), 1-76.

Mylroie, J. R., & Mylroie, J. E. (2007). Development of the carbonate island karst model. *Journal of Cave and Karst Studies, 69*(1), 59-75.

Naylor, R. L., & Battisti, D. S. (2007). Assessing the risks of climate variability and climate change for Indonesian rice agriculture. *Nat. Acad. Sci.*

Nguyet, V. T. M., & Goldscheider, N. (2006). A simplified methodology for mapping groundwater vulnerability and contamination risk, and its first application in a tropical karst area, Vietnam *Hydrogeology Journal, 14*(8), 1666-1675.

Nibbering, J. W. (1999). Tree planting on deforested farmlands, Sewu Hills, Java, Indonesia: Impact of economic and institutional changes *Agroforestry Systems, 46*(1), 65-82.

Nicholls, N. (1984). The Southern Oscillation and Indonesian Sea Surface Temperature *Monthly Weather Review, 112*(3), 424–432.

Nicholls, N. (1985). Predictability of interannual variations of Australian seasonal tropical cyclone activity. *Monthly weather review, 113*, 1144-1149.

Nicholls, N. (1995). All-India Summer Monsoon Rainfall and Sea Surface Temperatures around Northern Australia and Indonesia *Journal of Climate, 8*(5), 1463–1467

Nicholls, N., McBride, J. L., & Ormerod, R. J. (1982). On Predicting the Onset of the Australian Wet Season at Darwin. *Monthly Weather Review, 110*(1), 14–17.

Nolan, B. T., Healy, R. W., Taber, P. E., Perkins, K., Hitt, K. J., & Wolock, D. M. (2007). Factors influencing ground-water recharge in the eastern United States. *Journal of Hydrology, 332*(1-2), 187– 205.

Otto, A. (2006). Previous and Present Water Management of Oemau Spring in Mokdale Village. In D. Klaas (Ed.). Ba'a.

Palmer, A. N. (2000). Hydrogeologic control of cave patterns. In A. Klimchouk, D. C. Ford, A. N. Palmer & W. Dreybrodt (Eds.), *Evolution of Karst Aquifers* (pp. 77-90). Huntsville: Speleogenesis Nat Speleol Society.

Panie, S. P. (2006). Previous and Present Water Management of Oemau Spring in Mokdale Village. In D. Klaas (Ed.). Baa.

PAT. (1992). *Pemboran sumur eksplorasi / test well di Pulau Rote dengan total kedalaman 762 m / 10 sumur, No: 1513/KU.01.04.02-WB/V/92*. Kupang: Dep-PU, Proyek Irigasi NTT.

Patra, K. C. (2001). *Hydrology and water resources engineering*. Boca Raton, FL: Narosa Publishing House/CRC Press.

Plagnes, V., & Bakalowicz, M. (2001). The protection of karst water resources: the example of the Larzac karst plateau (south of France) *Environmental Geology, 40*(3), 349-358.

Polak, M. (2000). The botanical diversity in the Ayawasi area, Irian Jaya, Indonesia. *Biodiversity and Conservation, 9*, 1345-1375.

Ponce, V. M., & Hawkins, R. H. (1996). Runoff Curve Number: Has It Reached Maturity? *Journal of Hydrologic Engineering, 1*(1), 11-19.

Postma, C. A. J., & Postma, D. (2005). *Geochemistry, groundwater and pollution, 2nd ed.* Leiden: A.A. Balkema.

PU. (1992). *Laporan pemboran sumur eksplorasi/test well di Pulau Rote dengan total kedalaman 762 m / 10 sumur oleh CV. Citra Utama, Semarang*. Kupang: Departemen Pekerjaan Umum, Proyek Irigasi Nusa Tenggara Timur - PAT NTT Wilayah Barat.

Qannam, Z. (2003). *A hydrogeological, hydrochemical and environmental study in Wadi Al Arroub Drainage Basin, South West Bank, Palestine* TU Bergakademie Freiberg, German, Freiberg.

Quinlan, J. F., & Koglin, E. N. (1989). Ground-Water Monitoring in Karst Terranes: Recommended Protocols and Implicit Assumptions. In N. Environmental Monitoring Systems Laboratory Las Vegas (Ed.) (Vol. EPA 600/X-89/050, pp. 1-88): U.S. Environmental Protection Agency.

Raeisi, E., & Karami, G. (1997). Hydrochemographs of Berghan Karst Spring as Indicators of Aquifer Characteristics. *Journal of Cave and Karst Studies, 59*(3), 112-118.

Rana, G., & Katerji, N. (1998). A Measurement Based Sensitivity Analysis of the Penman-Monteith Actual Evapotranspiration Model for Crops of Different Height and in Contrasting Water Status *Theoretical and Applied Climatology, 60*(1-4), 141-149.

Rangin, C., Jolivet, M., & Pubellier, M. (1990). The Tethys Pacific Working Group: A Simple model for the tectonic evolution of Southeast Asia and Indonesia region for the past 43 million year. *Bulletin of Soc. Geol. Fr., 6*, 889-905.

Reasi, E., & Karami, G. (1997). Hydrochemographs of Berghan karst spring as indicators of aquifer characteristics. *Journal of Cave and Karst Studies, 59*(3), 112-118.

Riedel, W. R. (1952). Tertiary Radiolaria in western Pacific sediments. *Göteborgs Kungl. Vetensk.- o. Vitterh.- Samh. Handl.,, 6*(3), 1-18.

Riedel, W. R. (1953). Mesozoic and late tertiary radiolaria of Rotti. *Journal of Paleontology, 27*(No.6), 805-813.

Roen, J. (2006). Previous and Present Water Management of Nioen Spring in Londalusi Village. In D. Klaas (Ed.). Londalusi.

Rosidi, H. M. D., Tjokrosapoetro, S., Gafoer, S., & Suwitodirdjo, K. (Cartographer). (1981). *Geologic map of the Kupang-Atambua, Timor, Scale 1:250,000*

Rothpletz, A. (1891). The Permian, Triassic, and Jurassic Formations in the East-Indian Archipelago (Timor and Rotti). *The American Naturalist, 25*(N0.299 (Nov., 1891)), 959-962.

Russell-Smith, J., Djoeroemana, S., Maan, J., & Pandanga, P. (2007). Rural Livelihoods and Burning Practices in Savanna Landscapes of Nusa Tenggara Timur, Eastern Indonesia *Human Ecology, 35*(3), 345–359.

Sarino, & Serrano, S. E. (1990). Development of the instantaneous unit hydrograph using stochastic differential equations *Stochastic Environmental Research and Risk Assessment, 4*(2), 151-160.

Sashida, K., Munasri, Adachi, S., & Kamata, Y. (1999). Middle Jurassic radiolarian fauna from Rotti Island, Indonesia. *Journal of Asian Earth Science, 17*(4), 561-572.

Sauro, U. (1993). Human impact on the karst of the Venetian Fore-Alps, Italy. *Environmental Geology, 21*, 115-121.

Sen, Z. (1998). Average areal precipitation by percentage weighted polygon method. *Journal of Hydrologic Engineering, 3*(1), 69-72.

Sherman, L. K. (1932). Streamflow from rainfall by the unit graph method. *Engineering News-Record, 108*, 501-505.

Shuster, E. T., & White, W. B. (1971). Seasonal fluctuations in the chemistry of limestone springs: A possible means for characterizing carbonate aquifers *Journal of Hydrology, 14*(3), 93-128.

Soenarto, B. (2002). Pendugaan geolistrik lapangan di Bolok dan Sikumana, Kupang, NTT. *JLP*.

Soenarto, B. (2004). Identifikasi keberadaan air tanah dan keluaran air daerah karst di Kabupaten Sumba Barat. *JLP, 18*(54), 12-24.

Steiner, J. L., Howell, T. A., & Schneider, A. D. (1991). Lysimetric evaluation of daily potential evapotranspiration models for grain sorgum. *Agronomy Journal, 83*, 240-247.

Stöckle, C. O., Kjelgaard, J., & Bellocchi, G. (2004). Evaluation of estimated weather data for calculating Penman-Monteith reference crop evapotranspiration. *Irrigation Science, 23*(1), 39-46.

Sweeting, M. M. (1995). *Karst in China: its geomorphology and environment*. Berlin: Springer.

Szilagyi, J., Harvey, F. E., & Ayers, J. F. (2003). Regional Estimation of Base Recharge to Ground Water Using Water Balance and a Base-Flow Index. *Ground Water, 41*(4), 504-513.

Tam, C.L. (2006). Harmony Hurts: Participation and Silent Conflict at an Indonesian Fish Pond *Environmental Management, 38*(1), 1-15.

Teegavarapu, R. S. V., & Chandramouli, V. (2005). Improved weigthing methods, deterministic and stochastic data-driven models for estimation of missing precipitation records. *Journal of Hydrology, 312*, 191-206.

Temesgen, B., Allen, R. G., & Jensen, D. T. (1999). Adjusting temperature parameters to reflect well-water conditions. *Journal of Irrigation and Drainage, ASCE, 125*(1), 26-33.

Terry, J. P. (2005). Karst distribution and controls on Yoron-Jima, an emerged reef island in sub-tropical Japan. *Journal of Cave and Karst Studies, 67*(1), 48-54.

Todini, E., & Bossi, A. (1986). PAB (parabolic and backwater) an unconditionally stable flood routing scheme particularly suited for real time forecasting and control. *Journal of Hydrologic Research, 24*(5), 405-424.

Trajkovic, S. (2007). Hargreaves versus Penman-Monteith under Humid Conditions. *Journal of Irrigation and Drainage Engineering, ASCE, 133*(1), 38-42.

Turner, B. L., Moss, R. H., & Skole, D. L. (1993). *Relating land use and global land-cover change: a proposal for an IGBP-HDP Core Project*. Stockholm: International Geosphere-Biosphere Programme.

UN. (2003). *Water for people: Water for life, World Water Development Report*. Barcelona: UN (United Nations), World Water Assessment Programme.

Unny, T. E., & Karmeshu. (1984). Stochastic nature of outputs from conceptual reservoir model cascades. *Journal of Hydrology, 68*(1-4), 161-180.

USDA. (1971). Hydrology Guide for Use in Watershed Planning. In *National Engineering Handbook, Section 4, !hpplement A, Soil Conservation Service.*: U.S. Department of Agriculture.

U.S.S.C.S. (1972). *National Engineering Handbook*: U.S. Soil Conservation Service.

Veni, G., DuChene, H., & Crawford, N. C. (2001). *Living with karst : a fragile foundation*. Alexandria: American Geological Institute.

Ventura, F., Spano, D., Duce, P., & Snyder, R. L. (1999). An evaluation of common evapotranspiration equations. *Irrigation Science, 18*(4), 163–170.

Viessman, W., & Lewis, G. L. (1996). *Introduction to Hydrology*. New York: HarperCollins College.

Waltham, T., Bell, F. G., & Culshaw, M. G. (2005). Rocks, dissolution and karst. In *Sinkholes and Subsidence* (pp. 1-23). Berlin Heidelberg: Springer.

Wanielista, M., Kersten, R., & Eaglin, R. (1997). *Hydrology: Water quantity and quality control. 2nd ed.* New York: John Wiley & Sons.

Ward, A. D., & Trimble, S. W. (2004). *Environmental hydrology* (2nd ed.). Boca Raton, FL: Lewis Publishers.

WCED. (1987). *Our Common Future*. New York: Oxford University Press.

Weiss, M., & Gvirtzman, H. (2007). Estimating Ground Water Recharge using Flow Models of Perched Karstic Aquifers. *Ground Water, 45*(6), 761–773.

White, W. B. (1969). Conceptual Models for Carbonate Aquifers *Ground Water, 7*(3), 15-21.

White, W. B. (2003). Conceptual models for karstic aquifers. *Speleogenesis and Evolution of Karst Aquifers, 1*(1), 1-6.

Wu, Y., Jiang, Y., Yuan, D., & Li, L. (2007). Modeling hydrological responses of karst spring to storm events: example of the Shuifang spring (Jinfo Mt., Chongqing, China) *Environmental Geology*, 1-9.

Xiao, H., & Weng, Q. (2007). The impact of land use and land cover changes on land surface temperature in a karst area of China. *Journal of Environmental Management, 85*(1), 245–257.