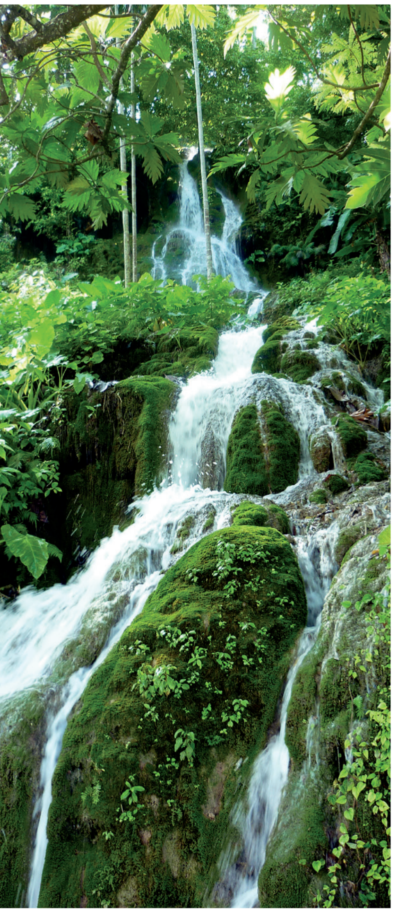
Australian Government

Geoscience Australia

Department of Climate Change and Energy Efficiency

AusAID



**Record** 2012/55 | **GeoCat** 73844

# Vulnerability assessment of climate change impacts on groundwater resources in Timor-Leste

Luke Wallace, Baskaran Sundaram, Ross S. Brodie, Sarah Marshall, Samantha Dawson, John Jaycock, Gerard Stewart and Lindsay Furness.

REPUBLICA DEMOCRÁTICA DE TIMOR-LESTE RDTL

Australian AID

International CLIMATE CHANGE ADAPTATION Initiative

Prepared for the Australian Government Department of Climate Change and Energy Efficiency **July 2012**

# Vulnerability assessment of climate change impacts on groundwater resources in Timor-Leste

PREPARED FOR THE AUSTRALIAN GOVERNMENT DEPARTMENT OF CLIMATE CHANGE AND ENERGY EFFICIENCY

BY GEOSCIENCE AUSTRALIA

July 2012

by

Luke Wallace[1], Baskaran Sundaram[1], Ross S. Brodie[1], Sarah Marshall[1], Samantha Dawson[1], John Jaycock[1], Gerard Stewart[1] and Lindsay Furness[2]

Australian Government

Geoscience Australia

Department of Climate Change and Energy Efficiency

AusAID

1. Geoscience Australia

2. BESIK project, EDTL compound, Dili, Timor Leste

**ISSN 1448-2177**
**ISBN 978-1-922103-63-5 (PDF, English)**
**ISBN 978-1-922103-64-2 (Print, English)**
**ISBN 978-1-922103-75-8 (PDF, Tetum)**
**ISBN 978-1-922103-76-5 (Print, Tetum)**

**GeoCat # 73844**

**Bibliographic reference**: Wallace, L., Sundaram, B. Brodie, R. S., Marshall S., Dawson, S., Jaycock J., Stewart G. and Furness, L., 2012. *Vulnerability assessment of climate change impacts on groundwater resources in Timor-Leste.* Record 2012/55. Geoscience Australia: Canberra.

# Executive Summary

Timor-Leste's economy and the livelihood of its people are heavily dependent on groundwater resources that are sensitive to climate change. Changes in rainfall patterns and sea level rise due to climate change are likely to put these groundwater resources at further risk. The current sustainability of groundwater in Timor-Leste is largely unknown; as are the likely effects of climate change on both the quantity and quality of available groundwater. Given expectations of reduced water availability in many regions and growing demand, pressure on groundwater resources is set to escalate in the future. It is not possible to quantify the effects of climate change on groundwater resources without first establishing a baseline understanding of how groundwater systems operate under current climate conditions. A more detailed understanding is needed of how pressures from climate change and groundwater pumping will influence the availability and quality of groundwater for management into the future.

Geoscience Australia, in partnership with the Government of Timor-Leste's National Directorate for Water Resource Management (DNGRA), Rural Water Supply and Sanitation Program (BESIK), and the Australian Department of Climate Change and Energy Efficiency (DCCEE) began the '*Assessment of Climate Change Impacts on Groundwater in Timor-Leste'* project in 2010, funded by the Pacific Adaptation Strategy Assistance Program under the Australian Government's International Climate Change Adaptation Initiative. The project aimed to build Timor-Leste water agencies' capacity for assessing, monitoring and managing groundwater resources in a changing climate.

This report is a summary of findings by Geoscience Australia in relation to the project aim and is accompanied by additional outputs on: 1) the hydrogeology of Timor-Leste; 2) groundwater monitoring and sampling guidelines; 3) geophysical survey of three case study areas; 4) GIS methodology training guide to reproduce the outputs of this project; and 5) catalogue of datasets and data records. Training and workshops were carried out in Timor-Leste on the use of monitoring tools and the analysis of groundwater information. This project has developed key resources and tools to underpin the effective assessment, monitoring and management of groundwater resources in a changing climate. Key findings are summarised below.

**Development of a National Hydrogeology Map for Timor-Leste**
A key output of the project was the development of a national hydrogeological framework and hydrogeological map. The framework outlines a method to collect, categorise, map and monitor groundwater resources by combining both knowledge and data based approaches. Furthermore, this framework has been used in this study to create a new national hydrogeological map for Timor-Leste. The 'Hydrogeological Map of Timor-Leste' is the first map produced for the country that allows aquifer types to be consistently identified at a national scale and to an international standard. Three principle aquifer types were identified: sedimentary porous rock aquifers with intergranular porosity associated with river valleys and coastal lowlands; fissured aquifers of karst formations within limestone rocks; and rocks with localised flow comprised of fractured rocks and clay sediments. The map provides a foundation for research and management of groundwater resources by systematically portraying the current national groundwater knowledge and data of Timor-Leste.

**Case Study Field Research**
The case study site approach allows for detailed analysis in representative areas to understand the properties of the different aquifer types. Three case study locations were chosen to represent the three principal aquifer types of Timor-Leste identified in the hydrogeology map. The three aquifer types focused on in this study were characterised by 1) direct observations, 2) analysis of water chemistry, and 3) ground based geophysical survey. The aim of the characterisation was to determine the fundamental properties of groundwater flow and quality in each aquifer. In addition, field surveys across Timor-Leste were undertaken to confirm and refine the national hydrogeology map.

Key research findings on the aquifers and groundwater resources include:

- The aquifers of Timor-Leste can be systematically mapped as three principal types of Intergranular, Fissured and Localised, in accordance with international guidelines;
- All aquifers show high levels of structural heterogeneity indicating groundwater flow will be affected by local factors, requiring further detailed localised analysis;
- The majority of Timor-Leste's groundwater is currently of high quality, apart from some coastal sea water intrusion, and the quantity and flow rates may vary widely;
- Intergranular sedimentary aquifers are focussed along the coast of Timor-Leste, centred around river channels, and are susceptible to reduced storage and seawater intrusion due to changes in rainfall and sea level rise, particularly in smaller water catchment areas;
- Fissured karst aquifers are principally in the east of Timor-Leste and groundwater yield is susceptible to changes in rainfall, responding rapidly (seasonally) across the broad topographic highs; and
- Localised fractured aquifers are principally in the west of Timor-Leste and groundwater yield is also susceptible to changes in rainfall, responding rapidly (seasonally) in the many localised topographic highs.

**Training of Timor-Leste Staff**

Training was conducted by Geoscience Australia to build knowledge and capacity of Timor-Leste government staff. This focused on reproducing the hydrogeology monitoring, mapping and analysis produced in the current study. The training was attended by 15 staff from relevant Timor-Leste Government Directorates (including water management, geology, environment and BESIK). Activities included: 1) groundwater fundamentals courses; 2) theory of, and hands-on training in, the use of groundwater monitoring equipment in the classroom and field; 3) theory behind national mapping of groundwater resources; 4) hands-on GIS digital mapping of national datasets; and 5) data management and analysis.

**Vulnerability Assessment of Groundwater to Climate Change**

In addition to assessing the 'impact' of climate change on groundwater resources, an assessment of groundwater 'vulnerability' to climate change effects has been made by incorporating the adaptive capacity of groundwater management in Timor-Leste. Vulnerability is a function of exposure, sensitivity and adaptive capacity as outlined in the vulnerability framework below. In the current study the vulnerability of the groundwater resources to climate change was assessed by Geoscience Australia which was then built on by Charles Darwin University (CDU; separate accompanying report, Myers et al., 2012) who assessed the vulnerability of the people that rely on these groundwater resources.

Exposure + Sensitivity

Potential Impact + Adaptive Capacity

Vulnerability

**Vulnerability Framework (Schröter et al., 2004)**

The two principal climate change hazards with the potential to impact on groundwater are 1) changes in rainfall and 2) sea level rise. While little change is predicted for total annual rainfall, the predicted prolonged dry season will place additional pressure on groundwater resources by extending the period of groundwater stress. The estimated sea level rise of 9 mm per year is much greater than the average tectonic rise of Timor of 0.5 mm per year. Increases in the sea level are likely to cause seawater to move landward and intrude into aquifers. The vulnerability of the three aquifer types against these two principal climate change hazards has been assessed through the above framework and is tabulated below.

**Overall Aquifer Vulnerability**

| Aquifer Type | Vulnerability to Rainfall Changes | Vulnerability to Sea Level Rise |
|---|---|---|
| Intergranular (Large Catchments)<br>Intergranular (Small Catchments) | Medium (PI = H, AC = H)<br>High (PI = H, AC = L) | Medium (PI = H, AC = H)<br>High (PI = H, AC = L) |
| Fissured (Topographic High)<br>Fissured (Topographic Low) | High (PI = H, AC = L)<br>Medium (PI = M, AC = M) | Low (PI = L, AC = M)<br>Medium (PI = L, AC = L) |
| Localised (Topographic High)<br>Localised (Topographic Low) | High (PI = H, AC =L)<br>Medium (PI = M, AC = M) | Low (PI = L, AC = M)<br>Medium (PI = L, AC = L) |

Vulnerability Classes: High = higher potential impact + lower adaptive capacity; Medium = comparable potential impact and adaptive capacity; Low = lower potential impact + higher adaptive capacity. PI – Potential Impact; AC – Adaptive Capacity.

The aquifers with the highest vulnerability to climate change are coastal intergranular aquifers with smaller catchment areas and both fissured and localised aquifers in topographic highs. As indicated in the key research findings above, these areas have higher ‘potential impact’ from changes in rainfall and/or sea level rise. Combined with the limited ‘adaptive capacity’, these areas have high vulnerability to the predicted climate change into the future.

**Potential Adaptation Options**

The following potential priority adaptation measures are proposed for Timor-Leste to reduce groundwater vulnerability:

- Targeted groundwater monitoring program;
- Capacity building, education and training;
- Integrated groundwater and surface water management using an adaptive management approach;
- Develop policies and legislation;
- Develop institutional and human capacity;
- Managed aquifer recharge;
- Land use change; and
- Build environment friendly infrastructure.

**Key Knowledge Gaps and Recommendations for Further Work**

Some major gaps remain in our knowledge of 1) Timor-Leste’s groundwater resources characteristics (such as the size, location, dynamics and sustainability of extraction) to be monitored and managed; 2) interactions and connectivity between groundwater and surface waters (including rivers, lakes and springs); and 3) potential threats to groundwater resources (e.g. contaminants). Future work for assessing climate change impacts should focus on:

- Detailed characterisation of principal aquifer types at local scales;
- Development of national recharge maps;
- Development of targeted monitoring network;
- Ongoing systematic groundwater monitoring; and
- Feasibility assessment of climate change adaptation options.

# Contents

# Introduction

## AIM

The aim of the '*Assessment of Climate Change Impacts on Groundwater in Timor-Leste Project'* is to build Timor-Leste water agencies' capacity for assessing, monitoring and managing groundwater resources in a changing climate. Geoscience Australia (GA) has undertaken this project in partnership with the Government of Timor–Leste's National Directorate for Water Resource Management (DNGRA), other Timor-Leste government agencies (including directorates for: water supply and sanitation; environment; geology; and GIS), Charles Darwin University (CDU), and existing programs of the Australian Agency for International Development (AusAID).

The project is an Australian Government initiative under the Pacific Adaptation Strategy Assistance Program. This program is being managed by the Australian Government Department of Climate Change and Energy Efficiency (DCCEE) and is part of the International Climate Change Adaptation Initiative.

This report is a summary of activities undertaken by Geoscience Australia in relation to the project outcomes and is accompanied by additional reports on: 1) the hydrogeology of Timor-Leste; 2) groundwater monitoring and sampling guidelines; 3) geophysical survey of three case study areas; 4) GIS methodology training guide to reproduce the outputs of this project; 5) catalogue of datasets and data records; and 6) vulnerability of people to climate change impact on groundwater (report by CDU; (Myers et al., 2012))

## NEED FOR ASSESSMENT OF CLIMATE CHANGE IMPACTS ON GROUNDWATER

East Timor's economy and the livelihood of its community are heavily dependent on groundwater resources that are sensitive to climate change (Barnett et al., 2007). Threats to water and food security from variable rainfall and seawater intrusion into groundwater reserves present serious challenges to vulnerable communities throughout the nation. Climate change is expected to affect the availability and quality of groundwater in Timor-Leste through changes in temperature, rainfall and sea-level-rise. Climate change, through changes in rainfall and temperature (potential evaporation), could cause longer periods of drought or more intense rainfall, which may result in insufficient groundwater recharge and reduced groundwater availability. Sea-level rise has the potential to drive seawater intrusion into freshwater aquifers, causing changes in groundwater flow and salinisation of water used for drinking and agriculture (Barnett et al., 2007). These changes in groundwater flow can in turn exacerbate groundwater contamination from solid waste and sewage. The effects of changes in climate on groundwater resources were highlighted in a recent DCCEE commissioned report for Timor-Leste which noted "*The most significant impact on the population during El Nino* [drought] *years is the reduced ground water availability"* (Australian Bureau of Meteorology and CSIRO, 2011).

The current sustainability of groundwater use in Timor-Leste is largely unknown. In order to quantify the effects of climate change on the quality and quantity of groundwater resources, a baseline understanding of how groundwater systems operate under current climate conditions must be established. By establishing this baseline, a more detailed understanding of how pressures from climate change and groundwater pumping will influence the availability and quality of groundwater can be developed.

## REPORT STRUCTURE

This report reviews what is currently known about groundwater and climate change in Timor-Leste as well as presenting new information for groundwater nationally, and for case study areas. An overview of Timor-Leste's physical environment is given followed by an outline of previous knowledge of groundwater resources and the predicted climate change scenarios for Timor-Leste. A new national hydrogeology map of Timor-Leste is presented as are the results of detailed analysis of case study areas with field and desk based hydrogeological techniques. The report concludes by summarising the potential vulnerability of groundwater resources to climate change in Timor-Leste and outlining key knowledge gaps.

This report is written for a wide audience including scientists, water managers and policy officers from both within and outside of Timor-Leste. For this reason the report includes explanatory information on understanding groundwater. Much of the technical details are presented in accompanying reports to simplify this summary report, which will also be translated into the local language of Tetum.

## PROJECT METHOD

This project has gone beyond an assessment of 'impact' to also assess the 'vulnerability' of groundwater resources to specific climate change hazards according to the vulnerability framework described below. The assessment of vulnerability is not a straightforward exercise, often because there is confusion concerning the precise meaning of the term 'vulnerability' and there is no single way of conceptualising and assessing vulnerability (Hinkel and Klein, 2006). This section will define vulnerability and discuss the ways in which aquifer vulnerability to climate change has been assessed within this project.

The Intergovernmental Panel on Climate Change (IPCC) has defined vulnerability in the specific context of climate change as "*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change*" (IPCC, 2007). Barnett et al. note that "*While there is no consensus on the best approach to vulnerability assessment, in general they entail considering one or more of: exposure to climate risks, susceptibility to damage, and capacity to recover.*" The essence of these definitions is captured by Voice et al. (2006) who state that "*vulnerability is a function of exposure, sensitivity and adaptive capacity*". This is the definition used by this study and project partner, Charles Darwin University. The interrelation of these three components is given in the vulnerability framework outlined below Figure 1 (Schröter et al., 2004).

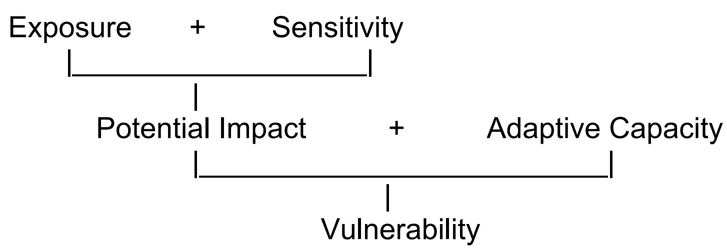



**Figure 1 Vulnerability framework (Schröter et al., 2004)**

This framework shows vulnerability is proportional to ‘Exposure’ and ‘Sensitivity’. The combination of these gives the ‘Potential Impact’ of a specific hazard on a particular system. The ‘Adaptive Capacity’ is the ability to cope with the ‘Potential Impact’ of the hazard and therefore is inversely proportional to vulnerability. That is, the higher the ‘Potential Impact’ the higher the vulnerability, whereas, the higher the ‘Adaptive Capacity’ the lower the vulnerability.

The term vulnerability can encompass a broad spectrum that could include communities, as well as the systems and assets susceptible to an adverse effect/hazard. As Klein and Nicholls (1999) have stated, “*vulnerability to impacts is a multi-dimensional concept, encompassing biogeophysical, economic, institutional and socio-cultural factors*”. This project endeavours to assess both the biogeophysical and the socio-economic impacts of climate change on groundwater resources in Timor-Leste. This report focuses on the biogeophysical vulnerability of groundwater systems (aquifers and groundwater). An accompanying report by project partners, Charles Darwin University, builds on this biogeophysical analysis to present a socio-economic vulnerability analysis of communities (Myers et al., 2012).

In this biogeophysical analysis ‘Exposure’ refers to specific climate change hazards to which an aquifer is exposed (e.g. changes in rainfall or sea level). The ‘Sensitivity’ refers to the intrinsic properties of a particular aquifer that makes it more, or less, susceptible to the effects of a specific climate change hazard. The ‘Potential Impact’ is the possible effect of climate change on an aquifer given its combined ‘Exposure’ and ‘Sensitivity’. In this context of biogeophysical systems, ‘Adaptive Capacity’ refers to the ability to manage groundwater resources to mitigate the ‘Potential Impact’ of climate change. Therefore the vulnerability of Timor-Leste’s groundwater resources in this project refers to groundwater exposure and sensitivity to climate change effects balanced against the adaptive capacity of groundwater management.

# Background

## BIOGEOGRAPHICAL CHARACTERISTICS

Timor-Leste forms the eastern half of the island of Timor, sitting adjacent to Indonesia and separated from Australia by the Timor Sea. The country is about 14,922 $km^2$ and includes the island of Atauro and the enclave of Oecussi (latitude 8° 00' to 9° 30' south and longitude 124° 00' to 127° 30' east; (Figure 2 (Asian Development Bank, 2004). The topography of the country is generally mountainous, characterised by rugged terrain and small narrow valleys (Figure 3). It has been suggested that as much as 44% of the country may have a slope of >40%. Many of these mountains are above 2,000 m elevation, Mount Ramelau the highest at 2,963 m. Timor-Leste ranges between 75 km and 100 km in width. In the north-east, uplifted coral reef stretches along the coast, and is characterised by typical karst topography.

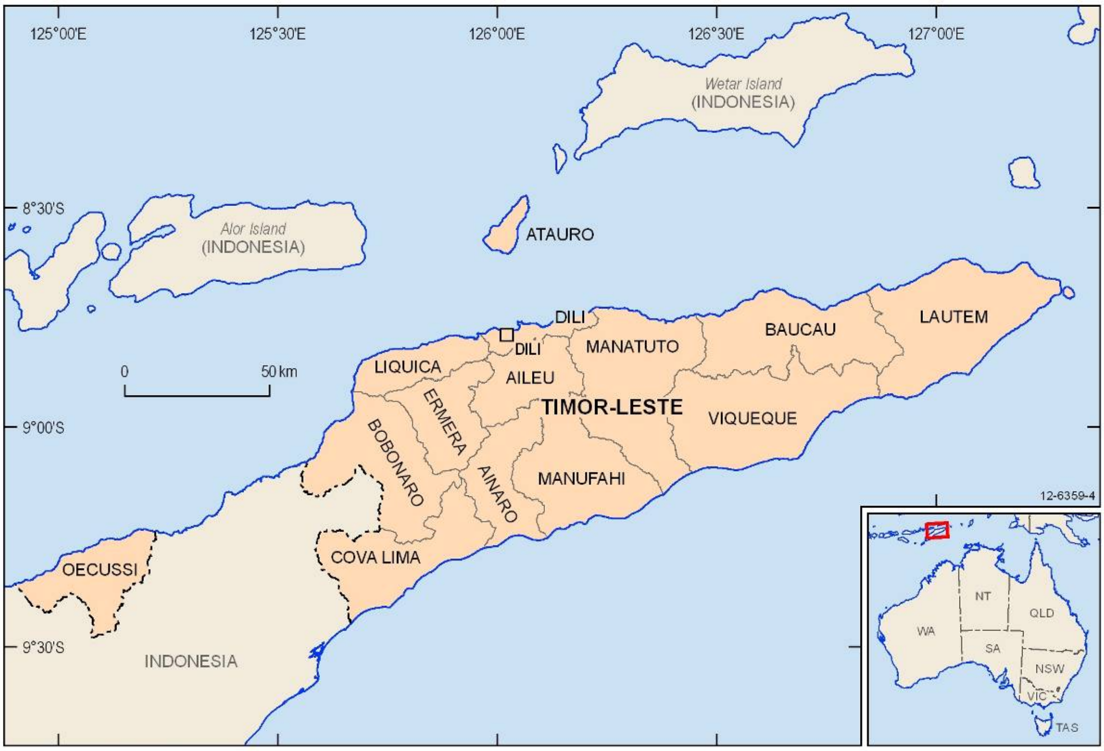



**Figure 2: Location of Timor-Leste (after Asian Development Bank, 2004)**

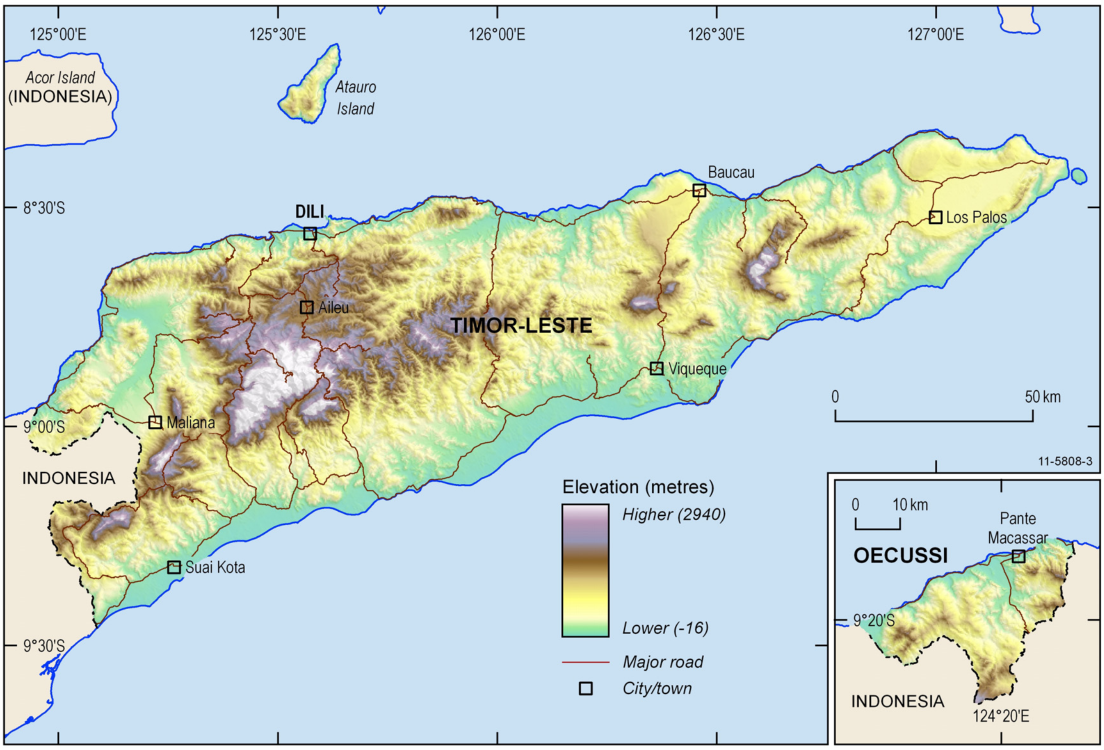



**Figure 3: Topography of Timor-Leste**

## Climate

The climate of Timor-Leste is characterised by the Asian tropical monsoonal system due to its topographic relief and geographical location. The climate of Timor-Leste can largely be divided in to two distinct seasons: the '*Wet season'* (December to May) with the wettest month January, February or May depending on the region; and the *'dry season'* (June to November) with September-October generally the driest months, also depending on the region. Further details on the current climate and future climate projections are discussed in the Climate Change in Timor-Leste section below.

## Geology

The geology of Timor-Leste is complex both compositionally and tectonically as shown in Figure 4. Compositionally, Timor-Leste contains a wide variety of rock types (igneous, metamorphic and sedimentary) with a range of textural (fine-grained and well sorted to large boulder conglomerates) and chemical (felsic to ultra-mafic) compositions. It is important to note, however, that volcanism is not a key feature of the geology in mainland Timor-Leste, in contrast to the surrounding islands. The tectonic history of Timor-Leste, which sits at the interface of the Eurasian and Australian Tectonic Plate boundaries, has received much attention and several tectonic evolution models exist. Geological work has been undertaken pre-1975 before Indonesian occupation with foreign access (Audley-Charles, 1965); 1975-1999 during Indonesian occupation with limited foreign access; and post-1999 with independence of Timor-Leste and foreign access once again possible.

Further information on the geology is given in the hydrogeology section. A detailed description of the geological features of the country relevant to groundwater are presented in the accompanying volume to this report, the Hydrogeology of Timor-Leste (Wallace et al., 2012).

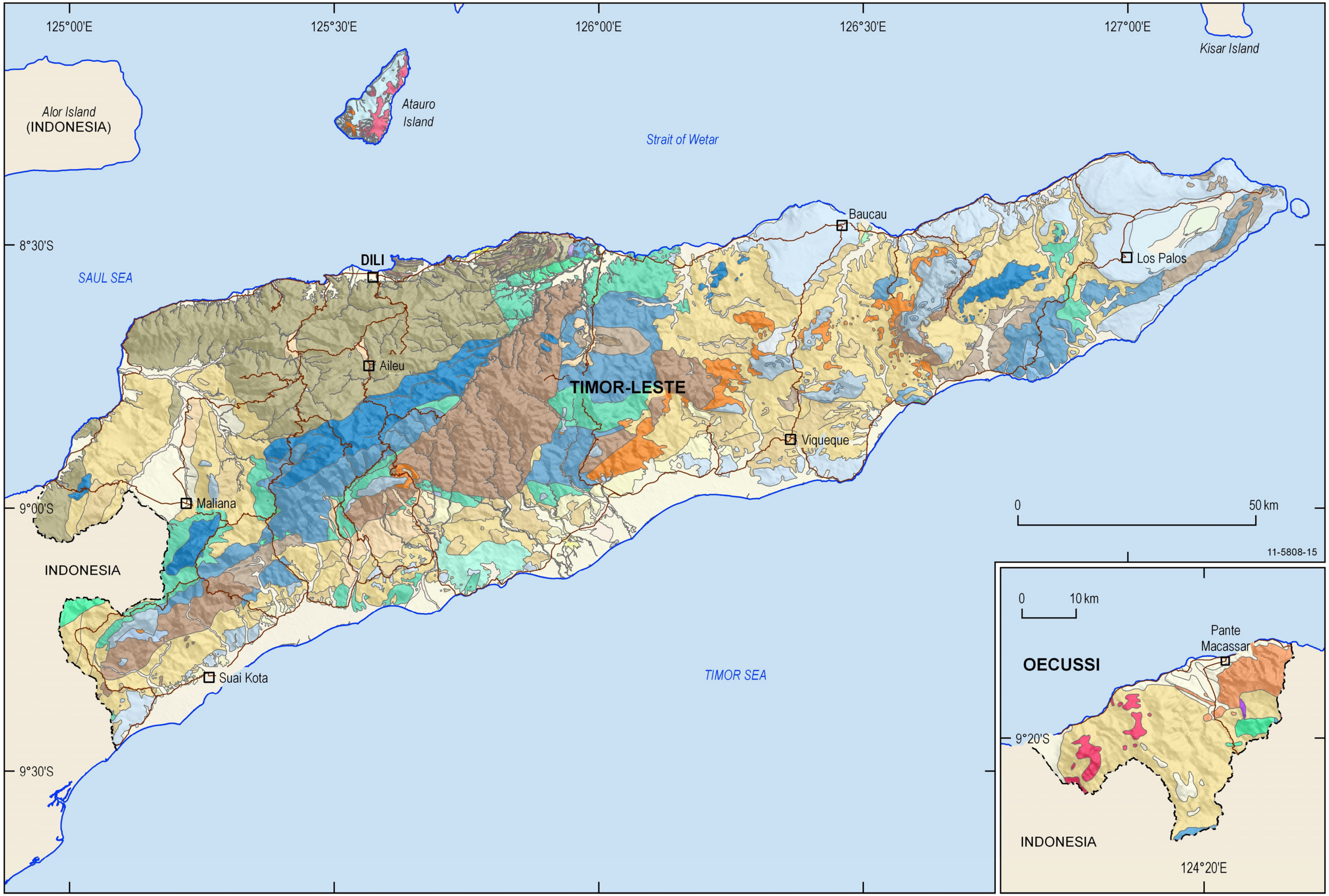



**Figure 4: Geology of Timor-Leste (Wallace et al., 2012). Note: Legend over page.**

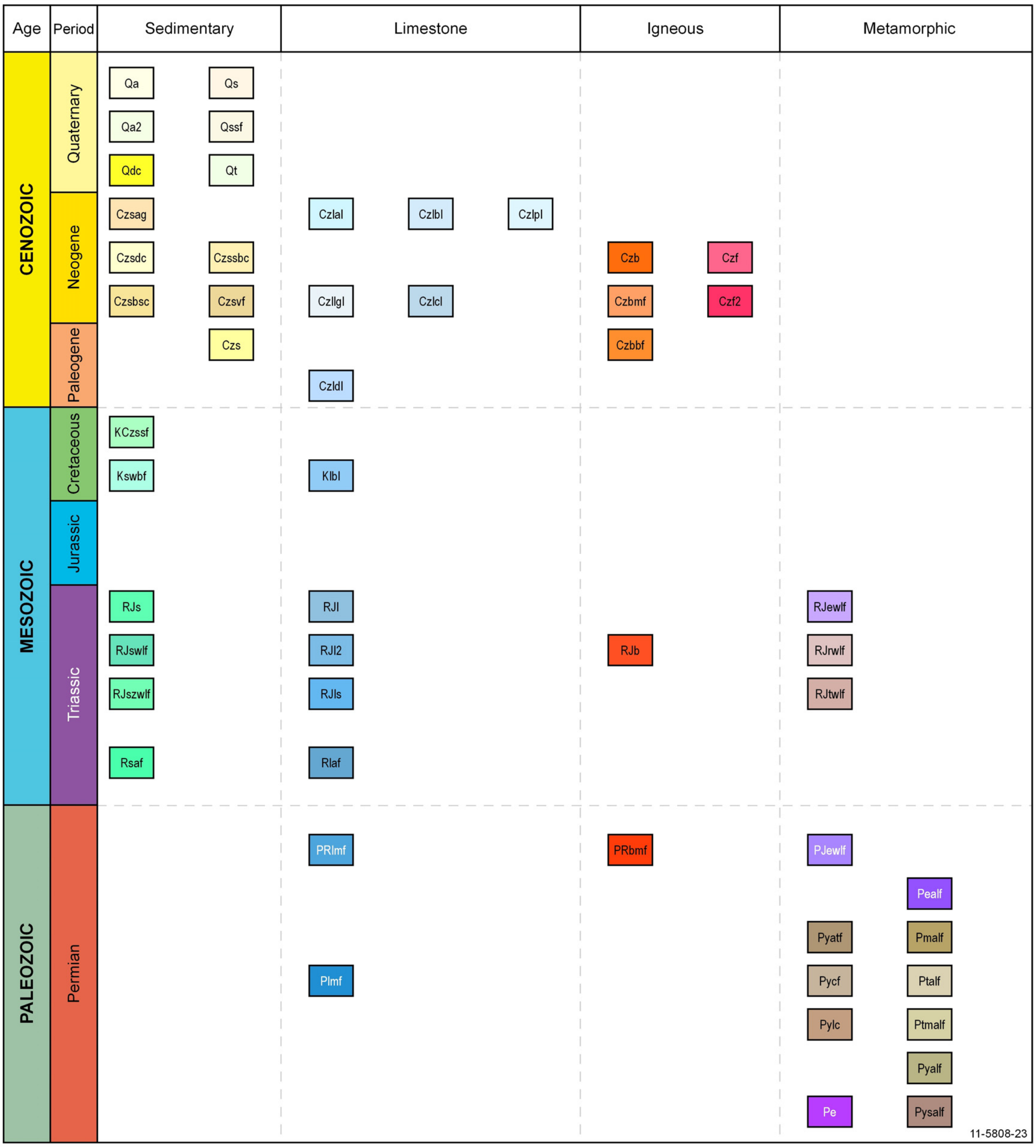



Figure 4 legend, Geology of Timor-Leste (Wallace et al., 2012).

### Soils

There are four distinct soil types that occur in Timor-Leste, reflecting the regional geology. In general the soils of Timor-Leste are not very fertile, do not store water well, and are easily eroded (Figure 5). The soils located at the mouth of the River Loes, to the south of Manatuto, and to the east of Baucau, are of recent alluvial formations and are not suitable for agriculture. The soils found in the eastern regions such as in Maliana, Ainaro, and Maubisse, and to a lesser extend in Baucau, Lauten and in Los Palos are the most fertile and are suitable for agriculture. The soils of alluvial origin are confined to the coastal regions around Dili, Suai and Manatuto and are poorly drained soils. The soils present in the highlands around Ermera are rich in organic matter and suitable for agriculture.

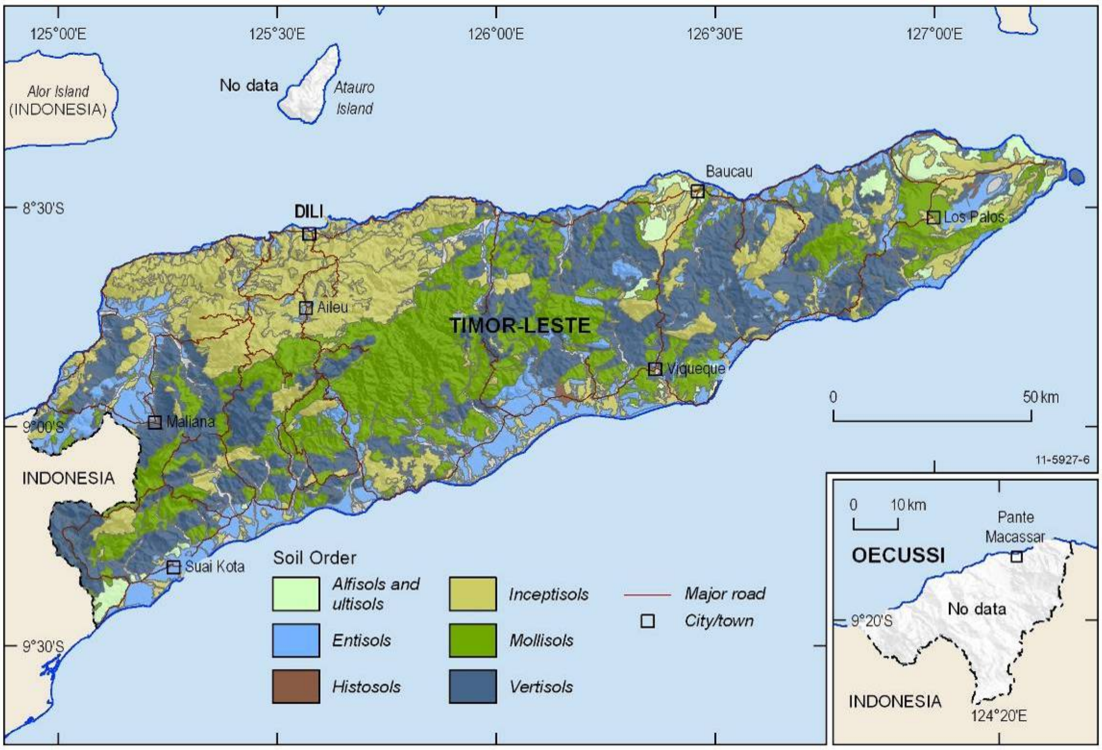



**Figure 5: Soil Order map of Timor-Leste**

### Land use

Agriculture activities are focused on maize, rice and coffee production in the many districts in Timor-Leste (Figure 6, Figure 7 and Figure 8). Maize is the most important food supply in Timor-Leste and relies on rainfall in the wet season. Rice is the second most important food crop and is mostly grown during the wet season, relying on irrigation (Figure 7). Coffee is the most important cash crop grown in Timor-Leste, accounting for approximately 90% of foreign exchange (Figure 8).

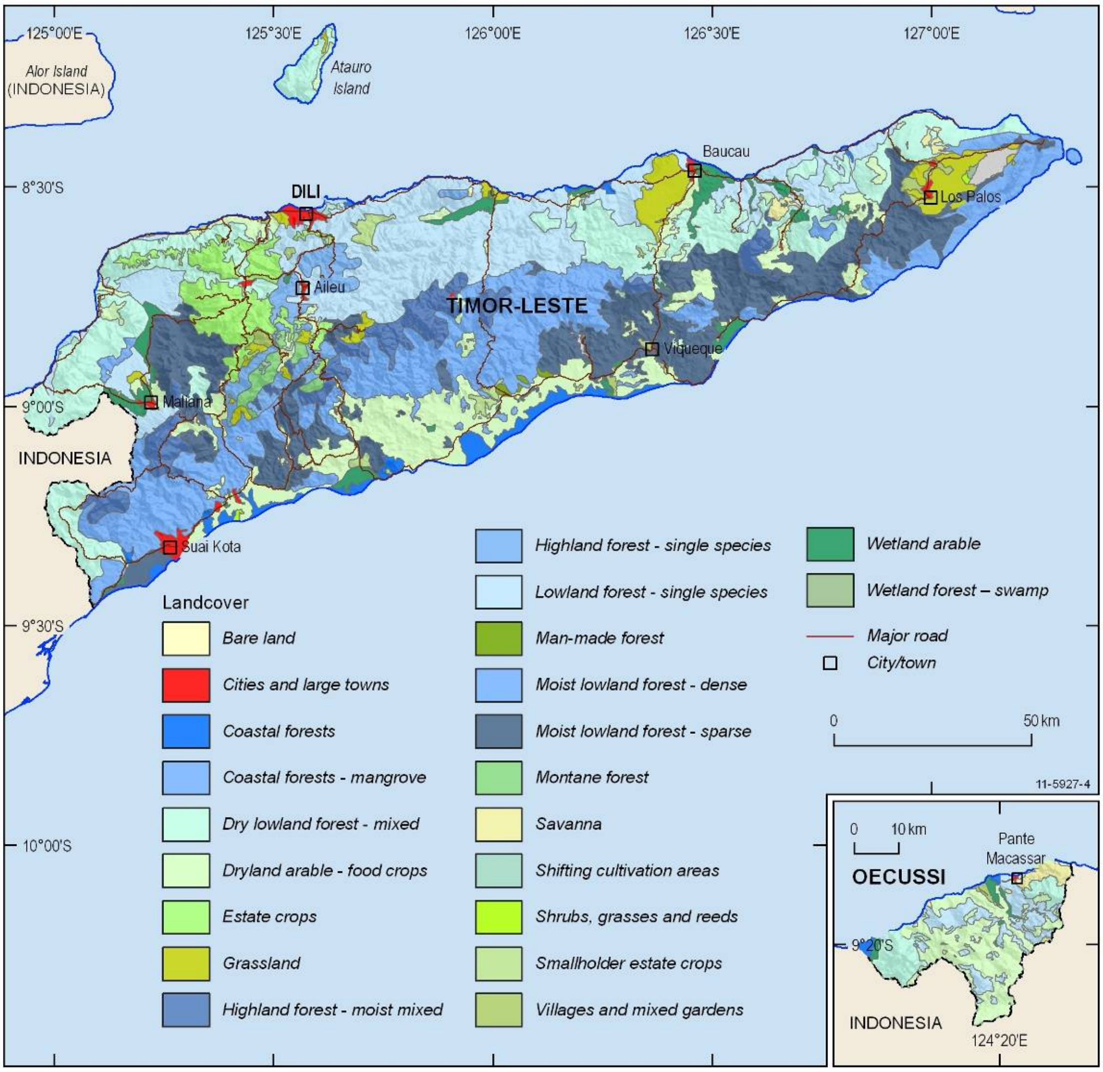



**Figure 6: Landuse map of Timor-Leste**

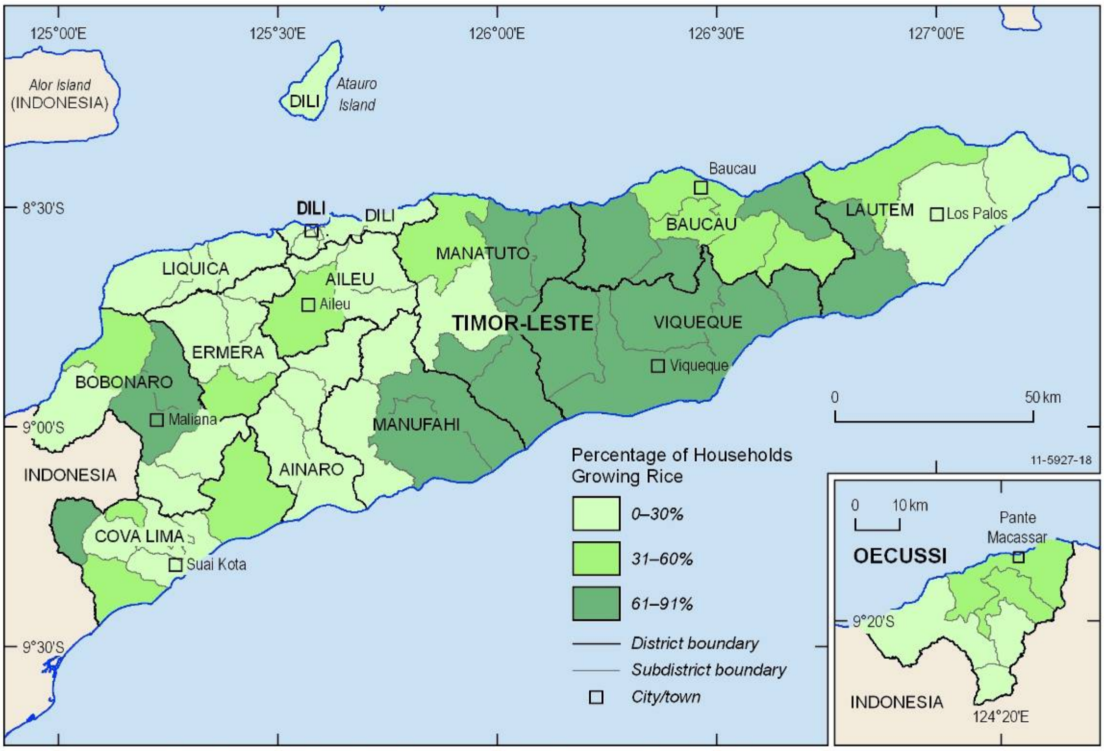



**Figure 7: Rice growing areas of Timor-Leste (Vong et al., 2006)**

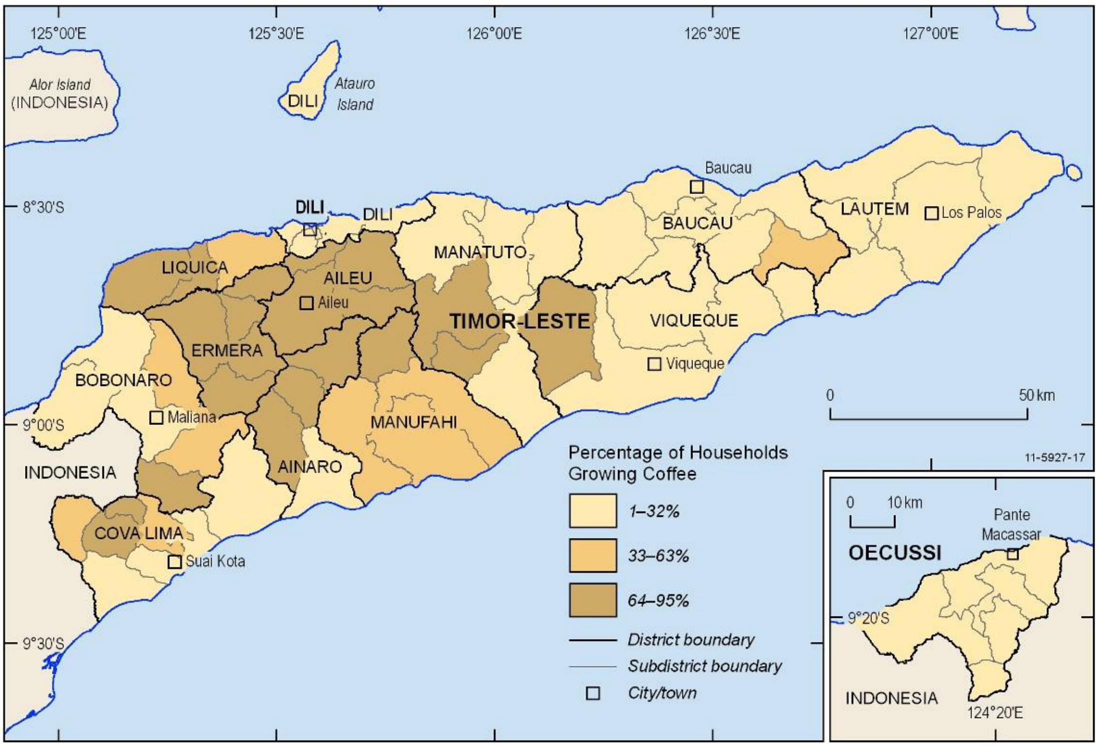



**Figure 8: Coffee growing areas in Timor-Leste (Vong et al., 2006)**

### Water Resources

Most areas of Timor-Leste oscillate between having surplus water resources to being water-stressed. During the wet season and in wetter years there are often floods and excess water whereas in the dry season and drier years, there can be areas of water stress, drought and water shortages for consumptive and agricultural use and the natural environment (Asian Development Bank, 2004; Yance, 2004; Costin and Powell, 2006). In these drier times, and to some extent during the wetter periods, surface waters are largely unavailable for use and groundwater is heavily relied on.

Although agriculture, particularly rice, has been the largest consumer of water it is predicted that, as the population grows, there will be a corresponding expansion in commercial, industrial and consumptive use (Asian Development Bank, 2004; Costin and Powell, 2006). This will place further stresses on water resources and their availability.

In addition to these stresses, past and continued forest clearing for agriculture, timber and firewood harvesting has lead to exposed soils throughout the country. In turn, these exposed soils have eroded quickly causing soil loss, high water turbidity, increased water runoff and increased flash flooding. There is also some concern that the high sediment loads could damage estuaries, offshore reefs and wetlands. Furthermore, the high sediment loads, combined with pollution in the rivers, can and have made water unfit for human consumption. Associated urban water shortages after heavy rainfall events are regular in some areas (Costin and Powell, 2006).

In these situations, when surface water becomes unusable, groundwater is relied on as a primary source of water. Water use is not widely monitored and only large commercial users are charged for the supply. There are no licensing arrangements with agricultural users nor is there regulation of, or fees imposed on, those who release wastewater into the river systems. Improved understanding and management of both the surface-water and groundwater resources of Timor-Leste is required to ensure there are not water shortages in any sector, including environmental water uses, into the future.

## GROUNDWATER AND AQUIFER SYSTEMS

'Groundwater' is water stored below the ground in spaces and cracks in the rocks and sediments. These are called pores, fractures or fissures. Groundwater is a vast resource which greatly exceeds the amount of water in rivers and lakes, both around the world and in Timor-Leste. The porous rocks and fissured/fractured rocks in which groundwater is stored and flows are called aquifers. These aquifers typically consist of sediments, limestone or fractured igneous/metamorphic rocks. Groundwater may flow relatively homogenously through an aquifer or may flow along localised preferential flow paths. The amount of 'homogenous flow' relative to 'preferential flow' within an aquifer will depend on the rock type. Some of the general properties of the typical aquifer types made of different types of rock are discussed in the following sections.

### Groundwater movement underground

Aquifers are not only a storage reservoir for groundwater, but also a pathway for water movement underground. Groundwater moves through an aquifer from its recharge areas to its discharge zones, areas where the water table is above the land surface, or until it is extracted by pumping.

Groundwater can move quickly or slowly depending on the amount of pressure available to force it through the porous aquifer materials. Groundwater moves from high to low water levels, that is, from areas of high pressure to areas of low pressure. The direction of the flow normally follows the general topography of the land surface. It may take years, decades or even centuries for water to flow through some aquifers depending on the aquifer type. In sedimentary aquifers comprising very porous materials (coarse gravel) or fractured rock with large openings (fractured basalt) flow rates are much faster. In some cases water may reside underground only a few days or weeks before reaching a discharge zone. Groundwater can be naturally discharged into streams, springs, wetlands and oceans or pumped to the surface.

### Aquifer characteristics that influence groundwater movement

Aquifers are all defined by their ability to store and transmit water at rates fast enough to supply a reasonable amount of water to wells (Fetter, 2001). Below some of the important attributes of aquifer systems are described.

#### *Hydraulic Conductivity*

The movement of groundwater through an aquifer is related to the aquifer hydraulic conductivity. Hydraulic conductivity refers to the volume of water able to flow through a section of aquifer under specific conditions (Lapidus et al., 1987). This is related not only to the properties of the aquifer, but of the groundwater itself. Groundwater composition and temperature influence hydraulic conductivity by affecting the density and viscosity of the groundwater (Fetter, 2001).

Hydraulic conductivity can be expressed by the coefficient K and can be quantified using the following formula:

$$K = \frac{-Q}{A(dh/dL)}$$

*Q = discharge (unit of volume/time e.g.* $m^3/s$*)*
*A = units of area (e.g.* $m^3$*)*
*dh/dL = hydraulic gradient (change in hydraulic head over flow length)*

This formula rearranges Darcy's Law (Fetter, 2001), describing flow of fluid through a porous medium. It is important to note that the quantity of flow is proportional to hydraulic conductivity (K) and this is dependent on the nature of the porous medium (such as its porosity and permeability) as well as the fluid passing through it (such as the viscosity and specific weight).
Assuming the same fluid properties, different types of aquifers will have different values of hydraulic conductivity as can be seen in Table 1. They will therefore allow different amounts of groundwater to pass through them. The higher values indicate higher flow.

**Table 1: Differences in hydraulic conductivities depending on sediment type (Schwartz, 1990).**

| Intergranular Sediment | Hydraulic Conductivity (m/sec) |
|---|---|
| Gravel | 3 x $10^{-4}$ to 3 x $10^{-2}$ |
| Coarse sand | 9 x $10^{-7}$ to 6 x $10^{-3}$ |
| Medium sand | 9 x $10^{-7}$ to 5 x $10^{-4}$ |
| Fine sand | 2 x $10^{-7}$ to 2 x $10^{-4}$ |
| Silt, loess | 1 x $10^{-9}$ to 2 x $10^{-5}$ |
| Clay | 1 x $10^{-1}$1 to 4.7 x $10^{-9}$ |

#### *Potentiometric Surface*

The 'potentiometer surface' refers to the potential groundwater height at any given location. Groundwater heights (relative water levels) in an aquifer are measured to determine the pressure and flow direction of groundwater in the aquifer. The height of groundwater above a base-level, such as sea level, is determined by measuring the depth to the water level and then subtracting it from the elevation above sea level. This can be used to estimate the direction of groundwater movement as groundwater flows from regions of high to low water levels. The heterogeneity of the aquifer and varying permeabilities of different sediment type should, however, be considered when estimating flow rates or directions.

### *Confining Layers*

There may be material that restricts or 'confines' water flow in an aquifer. Confining layers in aquifers have a much lower permeability than the surrounding aquifer (such as clays), which means that water may not be able to flow or only flow at a substantially slower rate. The arrangement of the confining layers within the aquifer is important in the assessment of the aquifer. This will enable an understanding of where the water is and how it may flow. An 'artesian aquifer' is one that is under great enough pressure that the water can freely flow above the land surface (Lapidus et al., 1987). This is due to the pressure that is exerted upon the water due to confining layers within the aquifer (Figure 9).

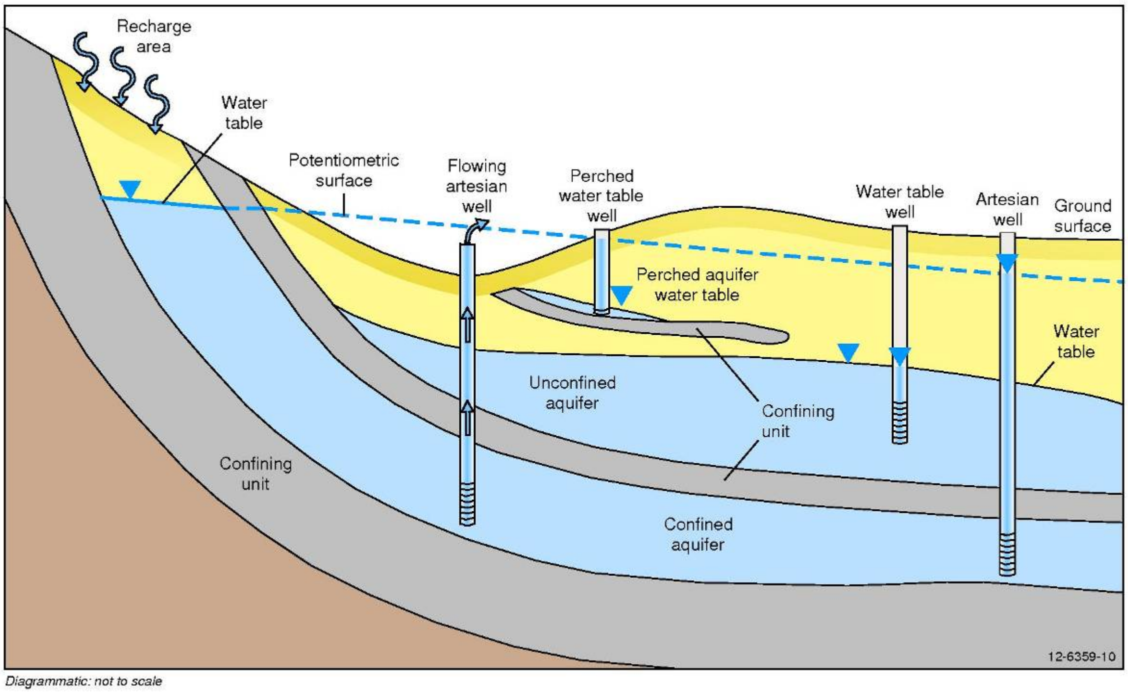



**Figure 9: A schematic diagram of confined and unconfined aquifers including flowing artesian wells (Survey)**

## Groundwater Recharge

Groundwater recharge is the replenishment of groundwater by the infiltration of surface water into an aquifer. Aquifers are recharged by direct infiltration of rainwater or by leakage from rivers and lakes (Figure 10).

Recharge mainly occurs in areas where parts of an aquifer are exposed at or close to the surface. Recharge can be diffuse (i.e. widespread over an area where permeable rocks are exposed) or local (e.g. in the case of karst landscapes, recharge is mostly through local karst features). Recharge is commonly expressed as the amount of water which fills an aquifer over a given period of time, and is usually measured in millimetres-per-year. The key factors that control groundwater recharge include: climate (the amount and intensity of rainfall and evaporation), soil and aquifer hydraulic properties, vegetation, topography, soil moisture and the spatial extent of the aquifer.

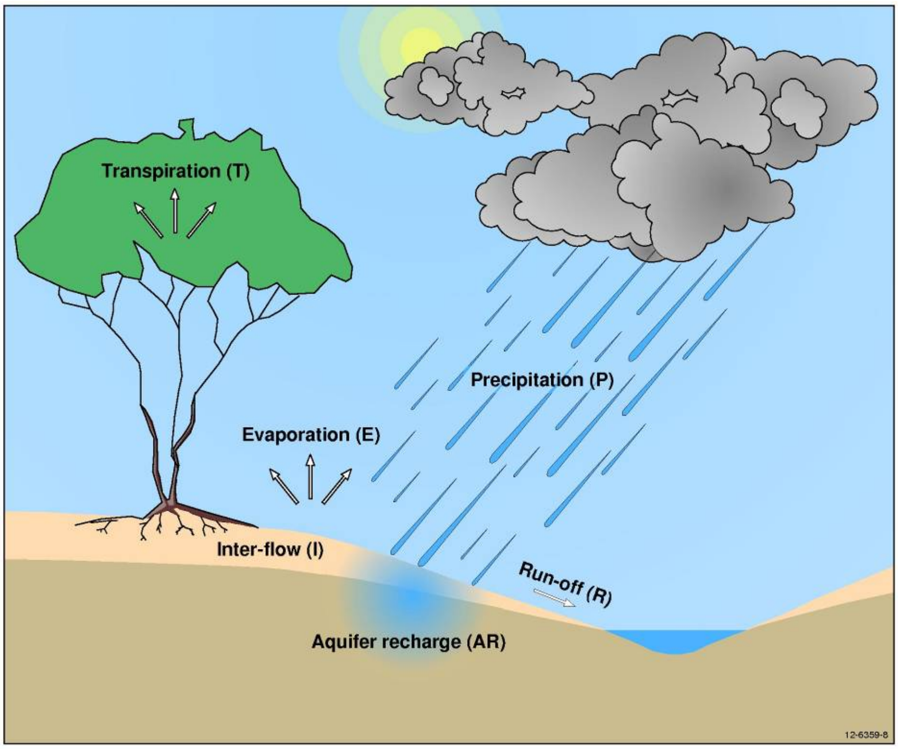



**Figure 10: Aquifer Recharge**

AR = P-R-I-E-T
Where P – Precipitation; R – Runoff;
I – Interflow; E – Evaporation;
T – Transpiration; AR – Aquifer recharge

An accurate estimation of recharge remains one of the biggest challenges for groundwater investigations. It is important to understand recharge rates because they are used to determine the sustainable yield: the volume of water that can safely be extracted from an aquifer. In the past, recharge estimates were often simply a fixed percentage of annual rainfall. While such an approach has been widely used in the past, the increasing competition for water resources means that the water availability needs to be more accurately understood.

### Groundwater-Surface water interaction

Groundwater and surface water are usually interconnected and interchangeable resources in many regions. In most cases it is actually the same water: groundwater becomes surface water, and surface water becomes groundwater. Nearly all surface water features (rivers, lakes, wetlands and estuaries) interact with groundwater. As a result, withdrawal of water from streams can deplete groundwater or, conversely, extraction of groundwater can deplete water in rivers, lakes or wetlands. Contamination of surface water can cause degradation of groundwater quality and, equally, contamination of groundwater can degrade surface water (Figure 11).

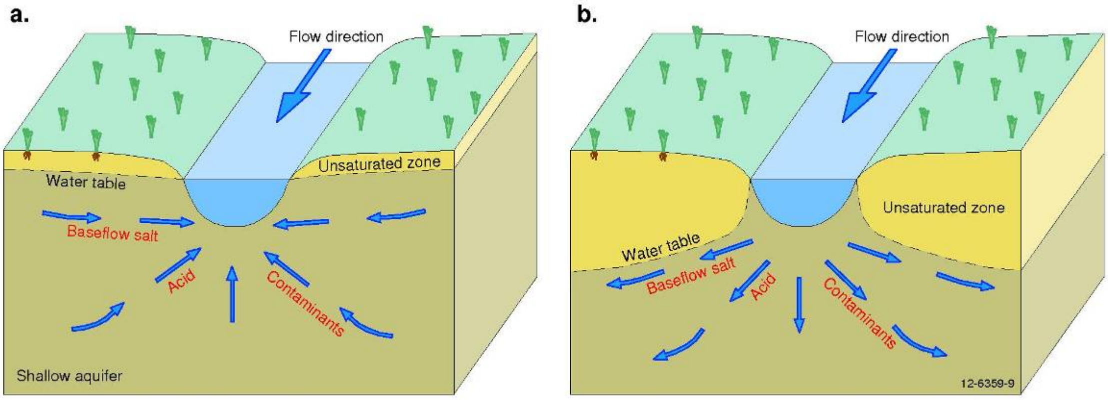



**Figure 11: Groundwater-surface water interaction and water quality (a) gaining stream (b) losing stream (Winter et al. 1998)**

### Groundwater Monitoring

Groundwater monitoring provides data on groundwater quality and quantity and is an integral part of groundwater management. Ideally groundwater monitoring should be carried out regularly in all areas where groundwater resources are extracted. Depending on the purpose of monitoring, different parameters can be tested. A separate detailed groundwater monitoring guide has been developed to accompany this report.

The main objectives of groundwater monitoring include:

- Establishing the baseline quality of groundwater occurring naturally in aquifers and assessing the impact of human activities on groundwater quality;
- Documenting any change in groundwater storage over time; and
- Assessing and predicting the response of hydrologic systems to natural climatic variations and over pumping.

## GROUNDWATER IN TIMOR-LESTE

### Groundwater Aquifers in Timor-Leste

At the commencement of this project very little information was available regarding the quantity and quality of groundwater in Timor-Leste. No detailed national groundwater studies were available and few measurements had been made. Groundwater is likely to be found beneath all land in Timor-Leste, however the groundwater resources are likely to be unevenly distributed and will vary in quality and quantity.

This project developed a national hydrogeological map of Timor-Leste. Groundwater resources of Timor-Leste have been classified into three principal aquifer types consistent with international classifications (UNESCO, 1983): sedimentary porous rock aquifers with intergranular porosity associated with river valleys and coastal lowlands; fissured aquifers of karst formations within limestone rocks; and rocks with localised flow comprised of fractured rocks and clay sediments. The descriptions of the various aquifers, aquifer characteristics and groundwater systems are presented in the hydrogeology section of this report and in further detail in the separate Hydrogeology of Timor-Leste report (Wallace et al., 2012). This hydrogeological mapping will be a valuable tool for managers, planners and groundwater users to better understand groundwater systems in Timor-Leste.

Groundwater is a critical resource in Timor-Leste. The people of Timor-Leste rely on groundwater during the dry season when most surface water dries up. Groundwater is used as a source of drinking water for urban and rural communities and for industrial and agricultural activities. Rural villages may have one or two groundwater wells which service the entire community, while many others get their water solely from natural groundwater springs. Intensive groundwater pumping occurs in the major centres for the purposes of general consumptive, industrial and agricultural use.

Groundwater in Timor-Leste is recharged by rainfall during the wet season to maintain enough storage for use during the dry season. Without regular recharge, the stored groundwater decreases. Increased demand caused by growth in population, industry and agriculture also has the potential to reduce the amount of stored groundwater. Both groundwater recharge and pumping need to be understood and, in the case of pumping, managed in Timor-Leste to ensure enough groundwater is available when needed.

### Impacts of groundwater extraction on water availability and quality

Groundwater is increasingly being seen as an alternative source to surface water supplies in recent years in Timor-Leste due to prolonged drought. Although groundwater provides a useful alternate source of water, it is also a vulnerable resource. When the rate of groundwater extraction exceeds the average long-term recharge rate from rainfall, groundwater levels will decline and impact on aquifer yields and quality. The impact of this decline can include the following:

- Lower yields mean less water is available for domestic water supply, stock drinking water, and irrigation;
- Springs, streams and rivers fed by groundwater may partially or completely dry up, causing both adverse human and ecological effects;
- Low flows of rivers may not be sufficient for proper dilution of discharged wastewater, resulting in greater surface water pollution;
- Increased threat of saltwater intrusion into fresh groundwater supplies in coastal regions; and
- Deterioration of groundwater quality.

To avoid irreversible damage to groundwater systems, an available extraction volume for any aquifer should be established based on the long-term sustainable yield assessment, i.e. the volume of groundwater that can be extracted annually from a groundwater basin without causing adverse effects. Groundwater extraction information for Timor-Leste is currently not available.

### Groundwater contamination

Contamination of groundwater may be associated with specific point sources or may occur over a wide area (non-point source or 'diffuse'). The sources of groundwater contamination are numerous and diverse, including: improper disposal of wastes; use and storage of chemicals; poor installation and maintenance of septic tanks; landfills; wastewater or urban runoff; and leaking or poorly located storage lagoons used by industries. Contaminants can be extremely hard to remediate, with pollution often resulting in permanent damage to the aquifer. It is better to prevent groundwater contamination than risk contamination and subsequently spend significant resources to clean it up.

## CLIMATE CHANGE AND TIMOR-LESTE

At a global scale, climate change will have a range of impacts, including changing rainfall amounts and distributions, altering seasonal patterns, sea level rise and increased extreme weather event intensity (Barnett et al., 2007; Kirono, 2010; Australian Bureau of Meteorology and CSIRO, 2011).

There is uncertainty in interpreting predicted climate change impacts at a local scale. The central reports referred to use a range of Global Climate Models (GCMs), from which they derive a mean predicted climate change impact under one or a number of future emission scenarios. As GCMs typically have a grid resolution of 100-500 $km^2$, downscaling is required for finer scale predictions. Downscaling to a grid size small enough to be applicable to Timor-Leste increases the uncertainty, particularly as the downscaling technique used may differ between models (Barnett et al., 2007; Katzfey et al., 2010). Therefore it should be recognised that there is a level uncertainty surrounding all climate change predictions, including the ones referred to here.

A recent report by DCCEE has summarised the outputs of numerous climate change studies (Australian Bureau of Meteorology and CSIRO, 2011). This report is used as the central reference for this study. Timor-Leste's current climate and future climate predictions are presented in the following sections.

### Current climate of Timor-Leste

Timor-Leste has a monsoon climate and rainfall is influenced by the West Pacific Monsoon system. It has a pronounced 'wet' season and a 'dry' season with transition period in between. The average wet season starts around December-January and lasts for three to four months, depending on the region (Tanaka, 1994). The northern part of the country, influenced by the Northern Monomodal Rainfall Pattern, has four to six months of wet season from December to May. The southern part of the country experiences the Southern Bimodal Rainfall Pattern which provides a much longer wet season of seven to nine months with two peaks, one from December and the other from May (Figure 12).

Total annual rainfall varies across the country. It ranges from 1000 mm on the northern coast, to 1500-2000 mm in the central highlands, and over 2500 mm in the higher altitude areas which are mainly located in the west of the country (Figure 13). Although in general rainfall is higher in higher altitude areas, there are some exceptions as reported by Fox (2003), who noted that the Liquica and Viqueque are at low altitudes (25 m and 46 m respectively) but with relatively high annual rainfall (1349 and 1610 mm respectively).

Total annual rainfall varies from year to year and rainfall intensity also varies considerably at any one location (Keefer, 2000). Like most tropical locations, intense downpours are common in Timor-Leste. Keefer (2000) report that rainfall intensity is usually greatest during the North West Monsoon periods (December-March) in the Northern part of the country, while in the Southern part of the country high rainfall totals were recorded during May-August.

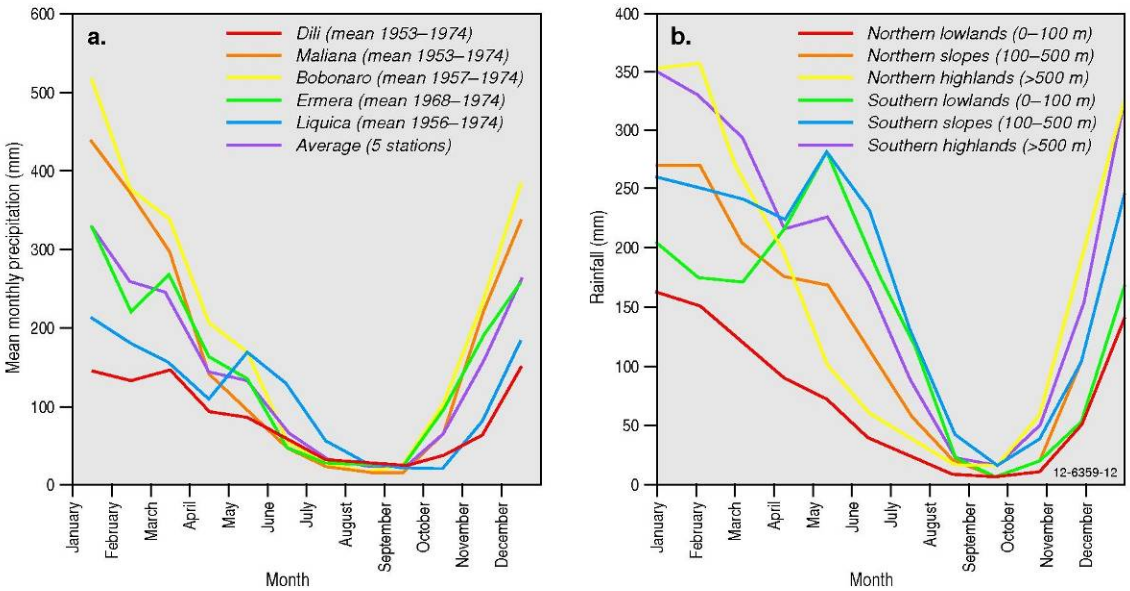



**Figure 12: Mean monthly rainfall for key regions in Timor-Leste (Barnett et al., 2007; Kirono, 2010).**

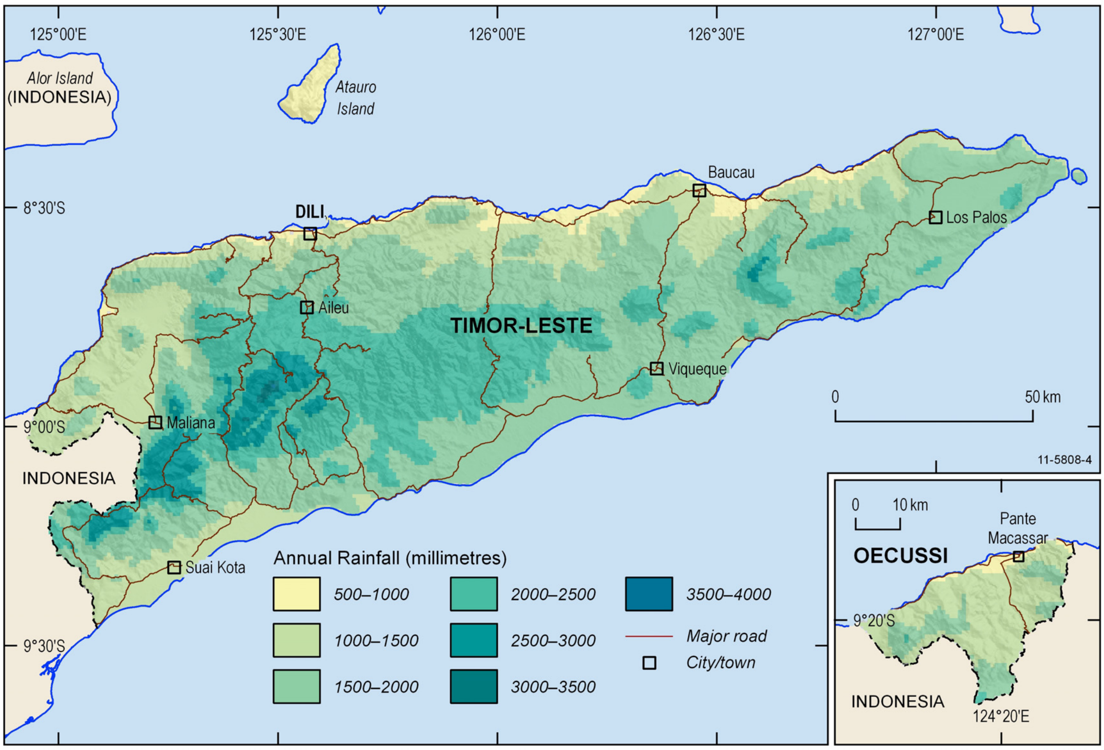



**Figure 13: Mean annual rainfall of Timor-Leste**

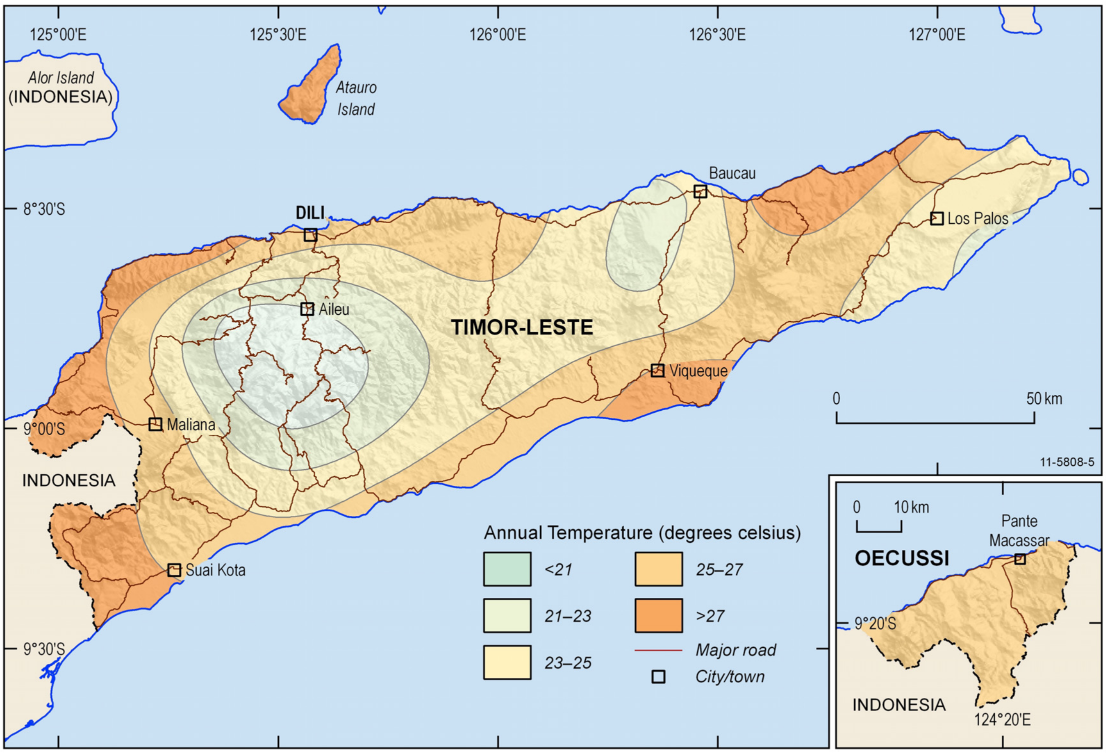



**Figure 14: Mean annual temperature of Timor-Leste**

Timor-Leste has a tropical climate in which the temperature varies little throughout the year. In general temperature decreases with altitude (Figure 14, Figure 15), the average temperature is around 27°C in coastal areas and around 22°C in the highlands. For example, in Maubisse (located at 1400 m above sea level) the annual mean temperature is 19.8°C while in Liquica (located at 25 m above sea level) it is around 27.4°C. The estimated cooling with height is around 5.5°C per 1000 m (Keefer, 2000; Yance, 2004). The diurnal (daily) temperature variation is often larger than the yearly variation. For example, at Godo and Sumbawa Besar, Sumbawa, the difference between maximum temperature (around 2-3 pm) and minimum temperature (just before sunrise) ranges from 7 to 9°C during the wet season (December to March), and up to 13°C towards the end of the dry season (Fenco Consultants, 1981; Monk et al., 1997).

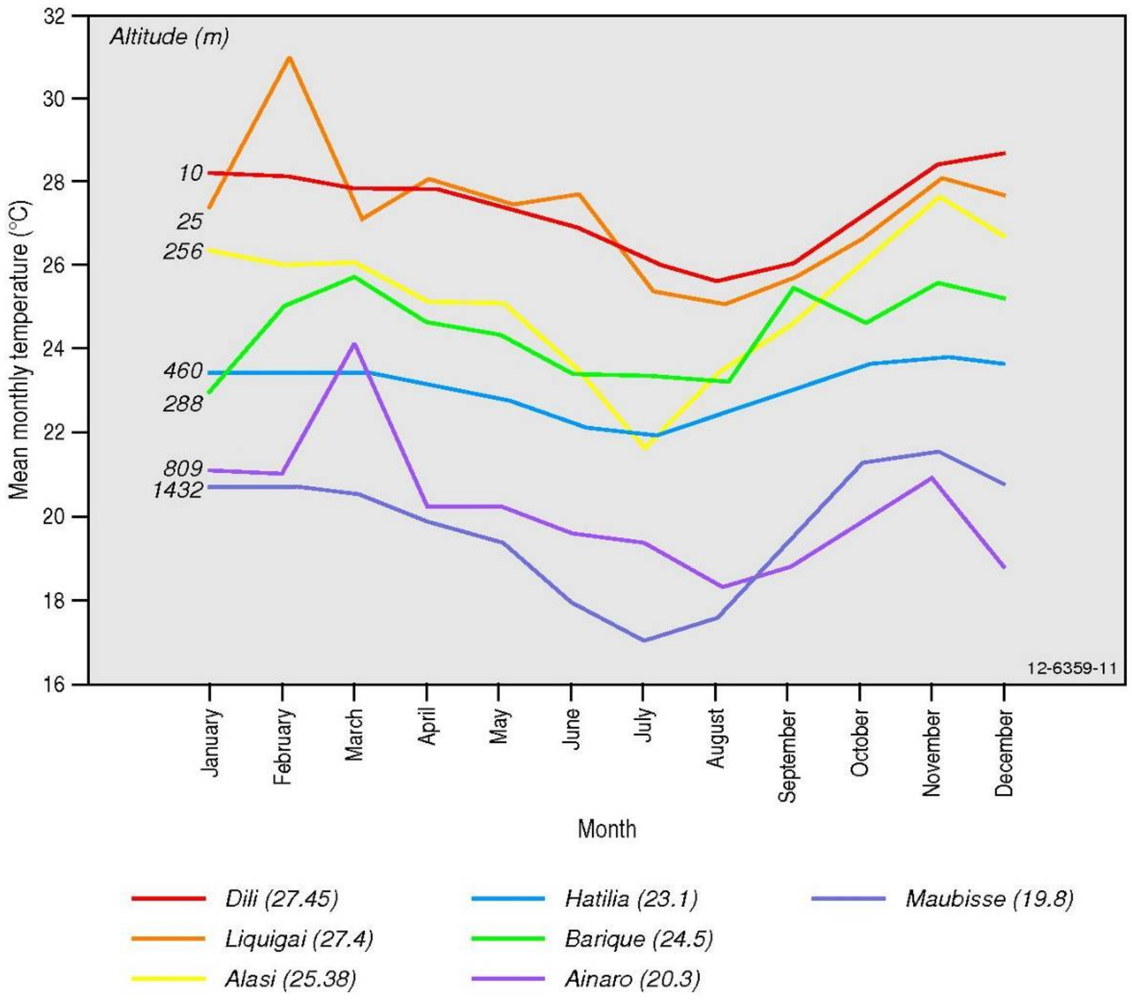



**Figure 15: Mean monthly temperature at selected sites (Fenco Consultants, 1981; Monk et al., 1997).**

Potential evaporation provides an indication of maximum possible evaporation under saturated surface conditions. It is one of the key factors of the hydrological cycle (Figure 10). Potential evaporation rates in Timor-Leste have been summarised by Yance (2004) who quoted the report of Sousa (1972) and SNC-Lavalin International (2001) which are presented below:

- Monthly evaporation ranges from 60 to 230 mm in the lowlands and between 100 to 190 mm in the highlands.

- The average daily potential evaporation was in the range of 5.2 to 6.5 mm in the lowlands and 2.6 to 4.9 mm in the midlands.
- Potential evaporation exceeds rainfall between May and October for Laga and Baucau, and between July and November in Viqueque and Ossu.

Based on rainfall and temperature Timor-Leste can be grouped as having three climatic zones (Sandlund et al., 2001) (Figure 16):

- the northern coastal zone (mean temperature >24°C, annual rainfall <1500 mm, dry season of five months);
- the mountain zone (mean temperature <24°C, annual rainfall >1500 mm, dry season of four months); and
- the southern coastal zone (mean temperature >24°C, heavier rainfall, dry season of three months).

In addition, there is large annual climatic variability present in Timor-Leste. Current rainfall patterns are dominated by the Western Pacific Monsoon and have an annual average of 1000 mm for the northern coast, 1500-2000 mm in the central highlands and over 2500 mm for the southern coast. Yet the variation of these totals can range from half to more than double the average amount and there are also very intense rainfall events which can see daily downpours equalling up to a quarter of the annual average (Monk et al., 1997). Both floods (in the wet) and droughts (in the dry) are frequent and each of these event types have effects on property, infrastructure, food production, etc. (Barnett et al., 2007).

El Niño Southern Oscillation (ENSO) also has a large impact on rainfall and thus water availability in Timor Leste. El Niño events can cause greatly reduced rainfall in some areas, increased rainfall in others, a drop in sea level (up to 20 cm) and affect the start of the wet season. Conversely, La Niña events induce a general increase in rainfall, an increase in sea height (10-20 cm), increase in wave height (up to double normal height in the south) and can again affect the timing of the wet season (Dolcemascolo, 2003; Kuleshov et al., 2009; Abbs, 2010).

A summary of Timor-Leste's current and historic climate shows the following trends (BoM CSIRO, 2011):

- Dili has a very marked wet season from December to May and a dry season from June to November;
- Sea-surface temperatures are closely related to air temperatures and show a weak seasonal cycle with highest temperatures in March and November, about 2.5ºC warmer than those in July, the coolest month;
- Air temperature trends are not presented as there is insufficient data available for the 1950-2009 period;
- Negative trends in annual and dry season rainfall at Dili Airport for the period 1952–2009 are statistically significant;
- The sea-level rise near Timor-Leste measured by satellite altimeters since 1993 is about 9 mm per year; and
- On average Dili experiences eight tropical cyclones per decade, with most occurring between November and April, however, the effect is usually weak.

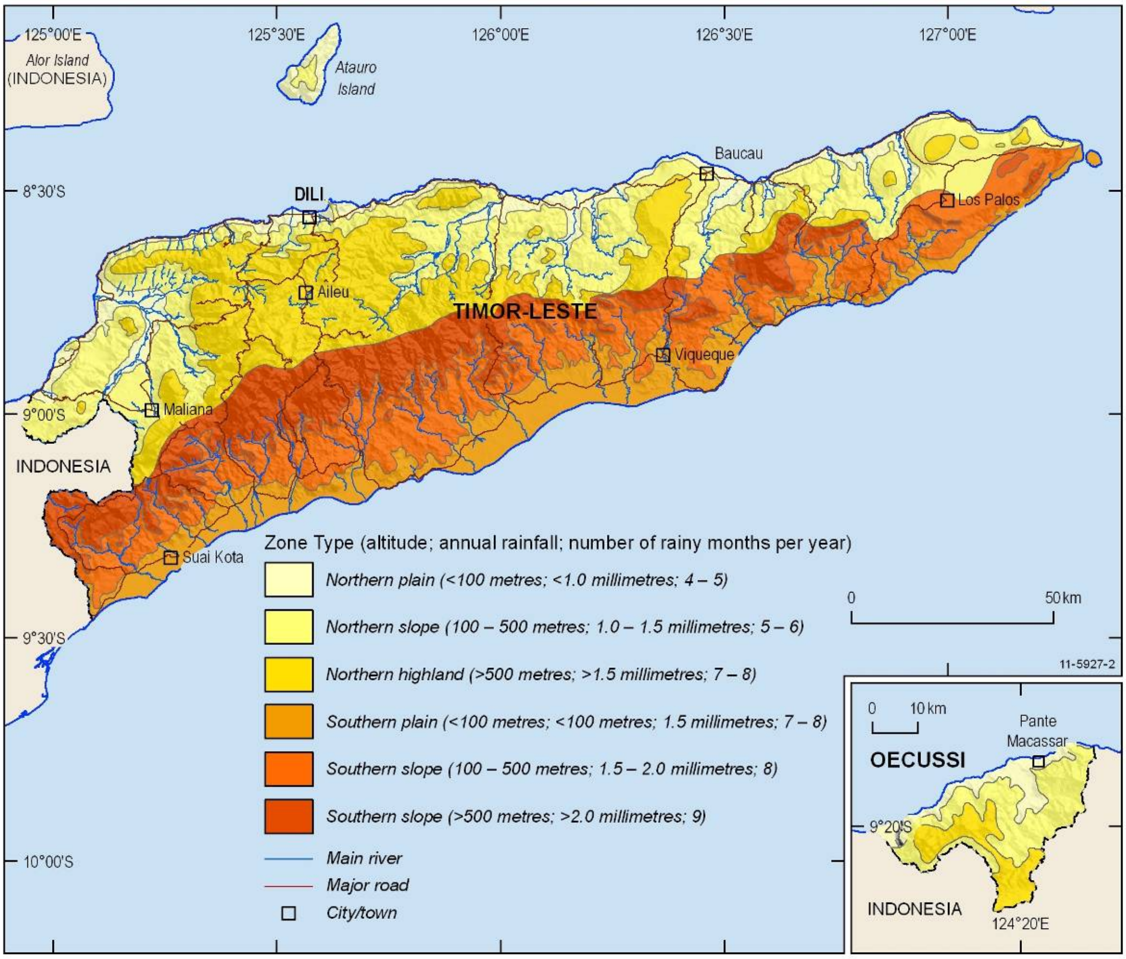



**Figure 16: Climatic zones of Timor-Leste (ARPAPET, 1996; Durand, 2006)**

## Future climate change projections for Timor-Leste

There are no specific studies of historical climate data for Timor-Leste to provide evidence of whether and how its climate has changed. The effect of climate change in Timor-Leste will manifest itself in several ways, not all of which are agreed on by all of the reports (Seeds of Life, 2004; Barnett et al., 2007; IPCC, 2007; Katzfey et al., 2010; Kirono, 2010; Australian Bureau of Meteorology and CSIRO, 2011).

Future climate predictions for the course of the 21st Century (BoM CSIRO, 2011) include the following:

- Surface air temperature and sea-surface temperature are projected to continue to increase (very high confidence);
- Wet season rainfall is projected to increase (moderate confidence);
- Dry season rainfall is projected to decrease (moderate confidence);
- Little change is projected in annual mean rainfall (low confidence);
- The intensity and frequency of days of extreme heat are projected to increase (very high confidence);
- The intensity and frequency of days of extreme rainfall are projected to increase (high confidence);
- Little change is projected in the incidence of drought (low confidence);

- Tropical cyclone numbers are projected to decline in the broad region surrounding East Timor (0–20ºS and 100ºE–130ºE) (moderate confidence);
- Ocean acidification is projected to continue (very high confidence); and
- Mean sea-level rise is projected to continue (very high confidence).

Of particular importance to groundwater impacts are rainfall, due to its effect on groundwater recharge, and sea level rise, due to the potential for seawater intrusion into coastal aquifers. Through these effects, climate change can potentially impact groundwater resources in the following ways:

- Seawater intrusion (influx of seawater into fresh groundwater) and inland migration of the fresh-saline interface;
- Seawater inundation (surface flow into low-lying areas) and the flooding of unconfined aquifers by seawater;
- Contamination of wells by storm surges and flooding of surface fittings;
- Changing recharge due to variable rainfall and evapotranspiration resulting in an altered distribution of freshwater in an aquifer;
- Changing discharge patterns that can generate waterlogged conditions and may impact on aquatic and wetland ecosystems; and
- High water table impact on infrastructure including leakage to septic tanks and sewer systems.

***Rainfall***

While little change is predicted for total annual rainfall, reduced rainfall in the dry season will place additional pressure on groundwater resources by extending the period that groundwater is relied upon. The predicted increase in the amount and intensity of rainfall in the wet season may have varied affects on groundwater recharge. Increased rainfall intensity can increase groundwater recharge, due to greater infiltration, in some environments but decrease groundwater recharge, due to increased run-off, in others. The effects of increased rainfall intensity on groundwater recharge will vary form site to site. Additionally, while the above predictions may be applicable as an average at a national scale, the effects on local areas may be substantially different. Researches showed that when less rainfall occurs nationally in El Nino years many areas have lower rainfall, however, some areas experience greater than average rainfall (Barnett et al., 2007). This indicates that on a local scale groundwater management will need to be prepared for both reduced and increased rainfall.

***Sea Level Rise***

The predicted sea level rise is likely to affect coastal aquifers. The estimated sea level rise of 9 mm per year is much greater than the average tectonic rise of Timor of 0.5 mm per year. Coastal aquifers in contact with the sea often exist in a delicate balance with the position of the freshwater/seawater interface depending on recharge of freshwater and the height of sea level. Increases in the sea level are likely to cause seawater to move landward and intrude into aquifers. This is also the case for extreme weather events that may temporarily increase local sea level and cause seawater to intrude into freshwater aquifers. Once seawater intrusion has occurred, it is very hard or impossible to reverse. Therefore even temporary sea level rise can have significant consequences for coastal aquifers.

The impacts of sea-level rise are site-specific, and the response of the transition zone between fresh water and sea water during sea-level rise will depend on the hydrogeology of the system, including the aquifer type and its geometry, aquifer parameter values (e.g. hydraulic conductivity), and system boundary conditions. Human influences such as groundwater extraction, drainage, and artificial recharge will also have an influence on the extent to which sea-level rise impacts occur and/or are mitigated.

According to the Ghyben-Herzberg groundwater relationship (which describes the relationship between the height of freshwater above sea level and the depth to the freshwater-seawater interface) every metre of freshwater above mean sea level translates 40 m of freshwater below sea level due to the difference in density between freshwater and seawater (Figure 17 a). Therefore, for example, a 50 cm rise in sea level with static groundwater levels (a relative decrease in groundwater levels of 50 cm to sea level) has the potential to cause a 20 m reduction in the freshwater availability of freshwater (Sherif and Singh, 1999), as shown in Figure 17 b.

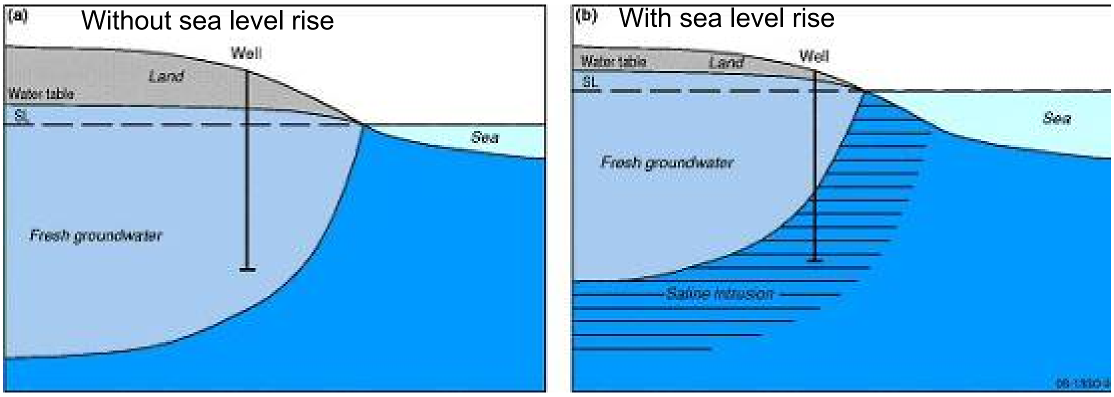



**Figure 17: Impacts of sea level rise on seawater intrusion in coastal aquifers**

Preliminary results show that low-lying areas occur around the Timor-Leste coastline, with the largest areas mostly along the southern coast (Figure 18). The coastal land lying less than 5 m above sea level (i.e. between 0 and 5 m AHD) is potentially at threat from seawater intrusion. The lowest lying coastal areas are found predominantly along the southern coast and but also in discrete locations along the northern coastal areas (Figure 18). Many coastal communities are in low lying areas, for example Dili, the capital city, and potentially at risk. The coastal communities reliant on groundwater supplies in Timor-Leste are potentially at risk but a detailed assessment is required to quantify the actual risk at each location.

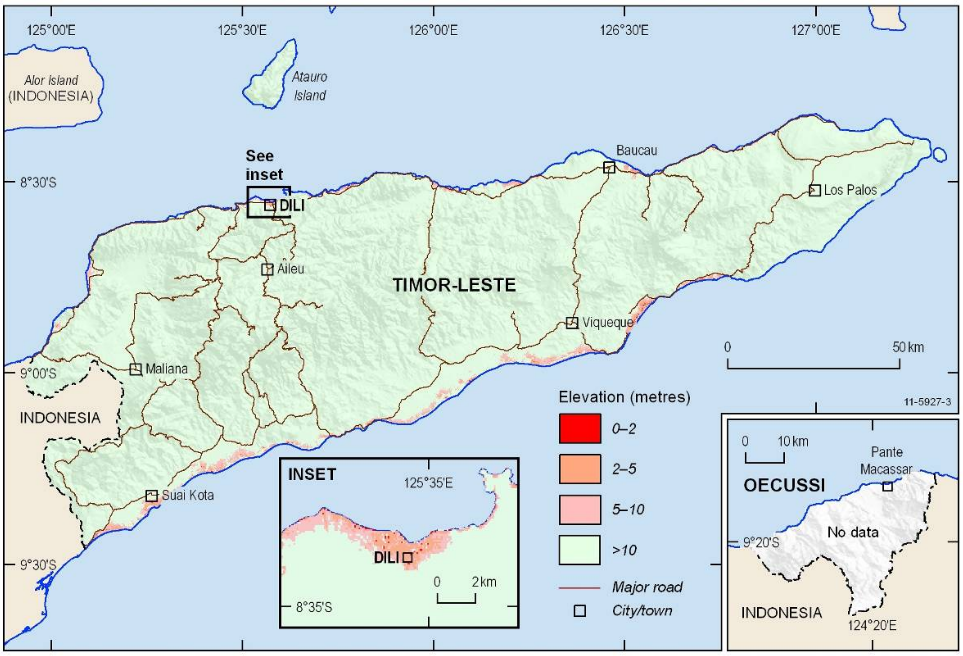



**Figure 18: Low-lying coastal land in Timor-Leste with an elevation less than 10 m AHD.**

## SUMMARY

Groundwater availability is essential to Timor-Leste; however, very little information is currently available on this resource. The hydrogeology of the country will be dependent on the interaction between geology and climate, both of which have been shown to be complex and variable. Climate change will affect groundwater into the future, principally through changes in rainfall and sea level rise. The potential effects of climate change will be changes in the amount of available groundwater as well as seawater intrusion into freshwater aquifers. Given the current limited information and complexity of geology and climate, assessing the impact of climate change on the groundwater resources of Timor-Leste requires a consistent understanding of hydrogeology at a national scale. The next section outlines the development of a new national hydrogeology map of Timor-Leste.

# Development of a national hydrogeology map for Timor-Leste

## BACKGROUND

This section provides a framework and map for classifying Timor-Leste's groundwater systematically for discovery, management and future research at a national scale. At the initiation of this project there was no pre-existing hydrogeological map of Timor-Leste. A basic 'subterranean water resources' map of Timor-Leste was produced by the Direktorat Geologie Bandung which has been presented in Monk (1997) and Durand (2006). This map shows general locations of the then known groundwater occurrences and gives a ranking (1-4) on the availability of water. However, the methods, assumptions and input information were not defined and it was not possible to directly build on the information of that map. This project proposes a new national hydrogeology map in partnership with the Timor-Leste Directorate of Water Resource Management (DNGRA), with input from other Timor-Leste directorates. The methods, assumptions and input information of the hydrogeological mapping have been outlined, along with the framework used to construct the map.

The production of this map was conceived in 2010 as a component of a Department of Climate Change and Energy Efficiency (DCCEE) and AusAID funded project '*Assessment of climate change impacts on groundwater resources of East Timor*' conducted by GA in partnership with the Timor-Leste Government Directorate DNGRA. The absence of a national hydrogeology map for Timor-Leste has restricted the management and research of aquifers and groundwater resources in the past. A proposal by GA to produce a new national hydrogeology map as part of a framework for groundwater management within the current project was supported by the funding bodies and Timor-Leste Government Directorates. The UNESCO (1983) international legend for hydrogeological mapping has been followed in the production of this framework to ensure consistency of the mapping of aquifers and groundwater resources within Timor-Leste and internationally.

## INTRODUCTION

A hydrogeology framework has been developed to allow Timor-Leste to manage groundwater resources into the future. The framework outlines the steps needed to develop an understanding of groundwater resources. This framework has been tailored to the current limited amount of groundwater data available in Timor-Leste and to accommodate more detailed data in the future. The framework has also been used by this project to develop a national hydrogeology map of Timor-Leste. The 'Hydrogeology of Timor-Leste', presented here at a scale of 1:250,000, is a new hydrogeological map of the country. This hydrogeology framework and mapping represents a significant step forward for the future discovery, management and research of Timor-Leste's aquifers and groundwater resources in a context of changing climatic conditions, population growth and industry development.

Firstly, this section outlines a framework of steps needed to understand the hydrogeology of a given area. This is followed by further detail on the process of hydrogeological mapping, factors that influence hydrogeology and the mapping of the hydrogeology of Timor-Leste.

## HYDROGEOLOGY FRAMEWORK

The new hydrogeology framework is designed to simply and clearly demonstrate how existing information can be built on to produce consistent and detailed information and maps for groundwater managers. The framework takes into account the current limited groundwater information by showing how surrogate datasets can be used for initial assessments (knowledge approach). It also allows for high amounts of detailed and site-specific groundwater information to be incorporated into the national scale (data approach). The new hydrogeology framework is outlined below and is followed by the steps taken by this project to apply the framework to Timor-Leste with the production of the national hydrogeological map.

### Hydrogeology Framework Method

The framework method outlined here contains two major phases. These phases are aligned with the two phases of the current project: 1) knowledge driven assessment and 2) data driven assessment. The knowledge driven assessment of Phase 1 has produced a new national hydrogeology map from the limited data available. The data driven assessment of Phase 2 has added new site specific hydrogeological data from Timor-Leste. The framework method for Phase 1 is discussed in steps 1-4 and the following Phase 2 method is outlined in steps 5-8 below and shown in Figure 19.

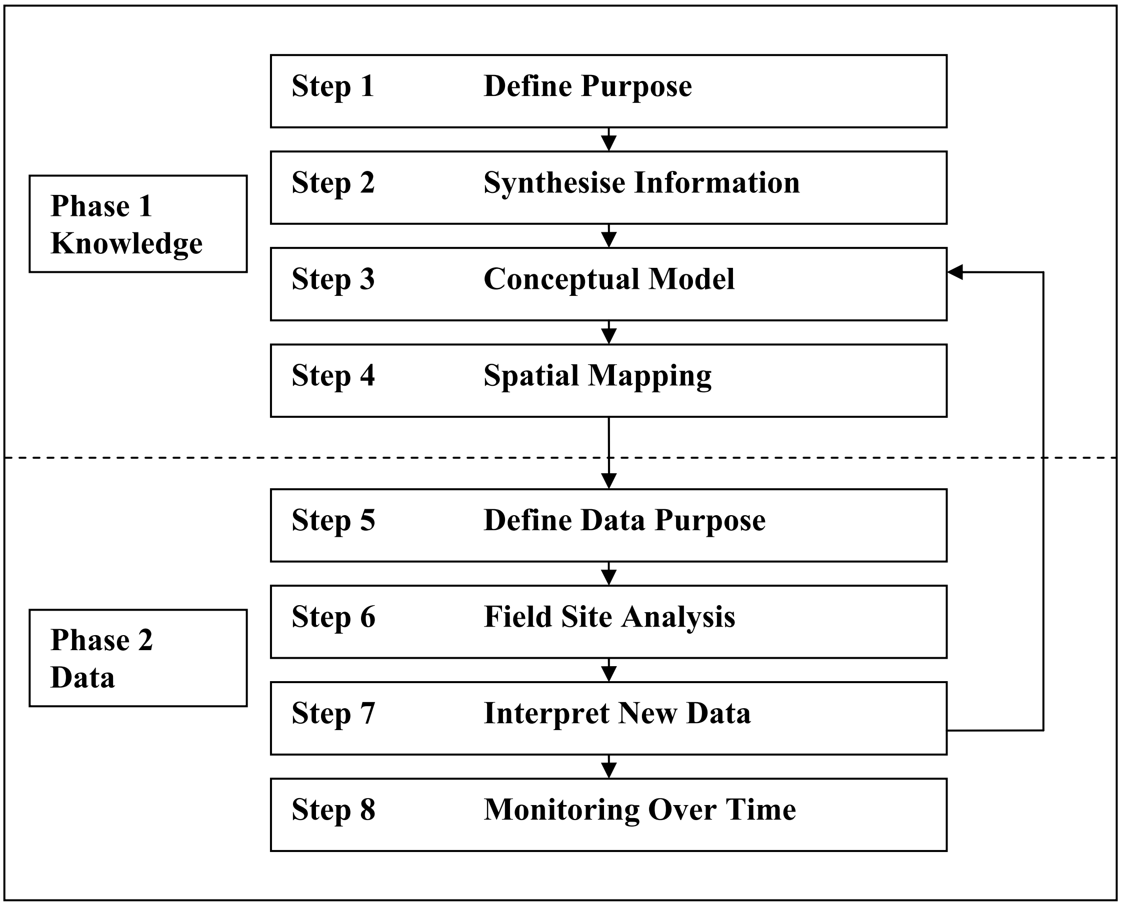



**Figure 19: Hydrogeology framework combining ‘knowledge’ and ‘data’ driven approaches.**

*Phase 1*
In the first step of the knowledge approach of phase 1, the framework needs to be applied to a clear and specific purpose. In outlining the purpose it is important to identify i) what the end product is for, ii) what the end product will look like, and iii) how the end product will be used. In the case of this project the framework is to i) characterise the hydrogeology of aquifers, ii) in the form of a map and descriptive text, and iii) primarily used for the management and prospectivity of groundwater resources.

The second step is to identify and synthesise all the available information, knowledge and datasets related to the purpose, in this case hydrogeology. As no hydrogeology map of Timor-Leste is available, surrogate information and datasets need to be used. A surrogate is any information that can be used to understand hydrogeology in the absence of hydrogeological data. Useful datasets for hydrogeology are geology, topography and any water cycle information such as rainfall, evaporation and runoff. Some of these datasets are available for Timor-Leste and have been used for this purpose.

The third step is to build a conceptual understanding or model of the hydrogeology systems of interest. Here the information and datasets collected in the second step, above, are interpreted. This requires specialist knowledge that is available in textbooks, literature and manuals as well as from experienced staff and locals (local knowledge). This step involves outlining the processes that control the hydrogeological systems of interest against the typical properties expected for a given aquifer.

The fourth step is to draft a new map or conceptual understanding of the topic at hand, in this case a new hydrogeology map. The hydrogeology map needs to incorporate all of the above steps addressing: 1) the purpose; 2) a synthesis of information available; and 3) a conceptualisation of the systems being described. Including all three of these steps will ensure the draft captures all available and relevant information. There are likely to be some gaps in the information available. This is typical and it needs to be clearly stated with any new map what information was used and what information was not available. The steps involved in creating any new map should be set out so that someone else could create exactly the same map from the same information. The final part of the fourth step is to have the draft reviewed by people knowledgeable in the subject matter. The more critical the review of the draft map the more useful the final map will be.

*Phase 2*
The second phase of the framework method focuses on the data driven assessment of hydrogeology. The data assessment of phase 2 should occur after the knowledge assessment of phase 1. This is because the data assessment both uses information from the knowledge assessment and also feeds back into the knowledge assessment. That is, the hydrogeological data collected from specific sites works interactively with the national scale hydrogeological map.

The fifth step of the framework, the start of the data approach of phase 2, is to determine what the purpose of the groundwater measurement is. A number of recognised standard groundwater measurements are available for different settings and for different purposes. Once the purpose of the measurement has been decided, such as water quality, quantity or vulnerability to climate change, a standard measurement regime can be started (a groundwater monitoring guide accompanies this report).

The sixth step is the selection of suitable case study field sites to sample. Field locations should be selected on the basis of need, such as the greatest benefit to the greatest number of people, but also on the type of aquifer. As different aquifer types may behave differently it is important to understand a variety of aquifer types. Site selection will be important for initially understanding unknown aquifer properties. Over time as more and more sites are studied and data collected the properties of Timor-Leste's aquifers will become much better known.

The seventh step is to apply the findings of new data collection to compare with the national hydrogeology map and understand sites that have not yet been assessed. While it may not be possible to compare two different types of aquifer, such as sandstone and limestone, it is possible to infer, to some extent, the properties within an aquifer type, such as two similar sandstones. The case study sites can be used to add detail to the national hydrogeology map and also to understand similar aquifers that have not yet been measured.

The eighth step is to continue monitoring over time. This is one of the most important steps. While measurement of a field site at one time produces a lot of information about the condition of groundwater, it is just as important to understand how the groundwater quality and quantity changes over time from month to month, year to year and decade to decade. Using these trends in groundwater quality and quantity, over time groundwater managers can start to predict and manage groundwater into the future, including for climate change.

The same assessment framework method described above for hydrogeology can also be used for mapping groundwater vulnerability to climate change. In this case the purpose, surrogate datasets, knowledge and site analysis would focus on groundwater vulnerability to climate change. The most important dataset for any groundwater vulnerability assessment is a national hydrogeology map. As no such map was available for Timor-Leste, this project has developed a hydrogeology map to be used for management and vulnerability assessments. With this map the framework method described above can be followed. However the knowledge base surrounding vulnerability studies can be complex as vulnerability assessments can be used for many different purposes. The approach for this vulnerability assessment of groundwater is stated in the introduction of the report (see Figure 1, vulnerability framework).

## HYDROGEOLOGY MAPPING

The remainder of this section covers the development of the hydrogeological map for Timor-Leste following steps 1-7 of the framework method described above. The body of this section summarises the major findings and information from the development of the map. The majority of datasets, interpretations and step-by-step methods used for this section are presented in the accompanying hydrogeology report.

### International Standards

The 'Hydrogeological Map of Timor-Leste' has been developed in accordance with the 'International Legend for Hydrogeological Maps' produced by the United Nations Educational, Scientific and Cultural Organisation (UNESCO, 1983). The UNESCO legend has been produced as a universal guide to the display of hydrogeological maps to ensure a consistent standard. The UNESCO legend outlines a standard set of symbols, patterns and colours which have specific hydrogeological meanings and are internationally recognised.

Hydrogeological maps have been defined as maps that depict the extent of aquifers along with geological, hydrogeological, meteorological and surface water features that may influence or aid the understanding of the groundwater system (UNESCO, 1983). The scale of these maps may be international, national, regional or local, and may vary from small scale (less than 1:1,000,000) to large scale (greater than 1:250,000). The use of standardised dataset formats, symbols and scales in the Timor-Leste hydrogeology map facilitates comparison and mutual knowledge sharing between countries.

The Hydrogeological Map of Timor-Leste and UNESCO based legend have been produced as part of a framework to represent a general national hydrogeological map. The general hydrogeological map covers a range of different environments, rather than a specialised map produced solely to highlight a few particular environments or characteristics. The production of specialised maps, in addition to the hydrogeological map, is also important for local areas and may require the use of non-standard symbols, patterns or colours for specific purposes. However, the UNESCO legend guidelines strongly recommend the preparation of a general hydrogeological map, such as the one being produced in this project, as a base before producing further specialised maps.

### Purpose

The purpose of a hydrogeological map is to enable the distinction of areas according to their hydrological character in relation to geology (UNESCO, 1983). This hydrogeology map of Timor-Leste has been created to serve multiple purposes relating to aquifer and groundwater management. The map not only provides a baseline for managing groundwater in response to climate change scenarios, but is also applicable to a broad range of groundwater uses and management purposes. The principal addition to the current map is the concept of groundwater 'prospectivity'. Groundwater prospectivity combines the aquifer flow system style (i.e. sedimentary, karst or fractured rock) with the potential flow rates for groundwater extraction to produce a map that shows where usable groundwater resources may occur. The map produced for this project incorporates groundwater prospectivity and can be used, at a national scale, for purposes including:

- Assessment of the impacts of climate change on groundwater;
- Managing extraction of groundwater under changing dry and wet periods;
- Designing appropriate monitoring programs for groundwater quality and quantity;
- Providing a basis to calculate sustainable yields for current population and industry; and
- Assessment of future domestic, agriculture and industry groundwater use.

### Compilation

The compilation of the hydrogeology map of Timor Leste, in accordance with the UNESCO (1983) international legend for hydrogeological maps, combines both knowledge-driven and data-driven approaches. The knowledge-driven approach has used knowledge of typical groundwater behaviour in geological settings combined with the Timor-Leste geology map (and other supporting datasets such as topography etc) to produce surrogates for groundwater aquifers. The data-driven approach has utilised available groundwater data in Timor-Leste from previous research, groundwater monitoring, field trips and local knowledge to characterise aquifers. In the data-driven approach, data has been collected from case studies to extend information into similar aquifer styles. The current project uses the knowledge and data approaches interactively to build an understanding of Timor-Leste aquifers. This information is combined using geographic information systems (GIS) to map and display aquifer characteristics (details of the GIS method and data inputs are given in accompanying reports).

Data was collected in-country in partnership with DNGRA and with the support of Timor-Leste Government Directorates, UNDP and RWSSP (BESIK). Geology and topography are the principal national digital GIS datasets used for the hydrogeology map. Data for specific aquifers was limited and included some groundwater level measurements and local knowledge about the flow rate and seasonality of groundwater spring discharge in different aquifer systems.

Drafts of the hydrogeology maps produced by the current project, as well as the input datasets, have been reviewed by relevant experts to ensure the maps are robust and remain useful into the future. Correspondence with Prof. Mike Audley-Charles, who has spent most of his working life producing the current maps and knowledge of Timor-Leste's geology, has assured the validity of the GIS version of his original maps. Reviewers of the hydrogeology map include Dr. Phil Commander, an experienced hydrogeologist and co-author of the present 'Hydrogeology of Australia' map published in 1987. Additionally, drafts of the hydrogeology map have been presented internally within GA and distributed to immediate stakeholders and project partners (DNGRA, DCCEE, PASAP, UNDP, RWSSP) for comment. The project team has sought the highest level reviews and criticism of the hydrogeology map to ensure the quality and effectiveness of the final product.

### Limitations

The current study has produced a hydrogeological framework and a hydrogeology map with detail appropriate for national scale display. The accuracy of a hydrogeology map, produced according to the hydrogeological framework, relies on the amount and quality of groundwater information (data and knowledge) available. To date the availability of groundwater information on Timor-Leste is limited. For this reason, the creation of the hydrogeology map is being undertaken in conjunction with field-based groundwater and aquifer assessments. These field based assessments have targeted different aquifer systems to provide additional data to ground-truth and modify the current map. The map reflects the hydrogeology of Timor-Leste at a national scale, including information derived from case study analysis.

As the present map classification is intended for differentiation of major aquifer types at a national scale, further detailed studies, beyond the life of this project, will be required to gain additional information to produce separate maps at the local aquifer scale. Through providing a national framework for the classification of aquifers, the hydrogeology map assists in the identification of sites for such further detailed studies. These future detailed site specific case-studies will complement the national scale map. The use of digital GIS analysis by this project allows more detailed future studies to be entered and viewed as an overlay with the national map.

## INFLUENCES ON HYDROGEOLOGY IN TIMOR-LESTE

The flow and storage of groundwater is controlled by geology, topography and the water cycle. It is particularly important to understand the properties of the geological materials which form groundwater aquifers. A background of the properties of different styles of aquifers and how they interact with groundwater is presented below.

### Geology

The geology of Timor-Leste is complex both in composition and tectonic activity. An overview of the history of geological work in Timor-Leste is provided in the accompanying hydrogeology report (United Nations, 2003). While there are a number of different theories on the details of Timor-Leste's geological evolution there are several general concepts which are largely agreed and can be summarised in four stages:

1) Formation and deformation (including metamorphism) of deep marine sediments on the Australian Plate (occurring in the time periods of Permian to Pliocene);
2) Covering of deep marine sediments with thick clays (Bobonaro Scaly Clays) produced from an underwater sediment gravity slide during the tilting of the area of Timor at the start of continental collision between Eurasian and Australian Plates (during the Cenozoic time period);
3) Emplacement of older metamorphic, sedimentary and igneous rocks, from the Eurasian Plate, thrust over younger rocks during the collisions of the Eurasian and Australian Plates; and
4) Formation of limestone coral reefs, sedimentary alluvial terraces and floodplains on top of all other geological materials (Cenozoic to present).

This has produced the current surface geology exposure in Timor-Leste which consists of Australian Plate sediments overlain by a range of continental collision emplaced Eurasian Plate rocks with limestone and recent sediments sitting on top.

Several national geology maps exist for Timor-Leste (Audley-Charles, simplified geology, ESCAP and a compilation geology maps based on Audley-Charles). The maps differ in the level of detail of geological materials and structures but show broadly consistent geological features across the country. The national geology map chosen for use in this study is principally based on the work of Audley-Charles (1965) and has the most detailed outlines of geological units and the greatest number of geological subdivisions. Structural information (i.e. faulting, fracturing, folding, etc) and structural cross-sections are not provided with this map but have been inferred from other maps.

Geological maps can present a volume of information using international standard conventions of ordering and colour. As the geology map existing in Timor-Leste had no interpretive order, the geology was displayed as unorganised random colours. This project has relabelled the geological map symbols into 'age-rock type-formation name' and reorganised the geological units into a legend of age against rock type. For example the map symbols of the Baucau Limestone would be: Age – Cenozoic (**Cz**), rock type – limestone (**l**), formation name – Baucau Limestone (**bl**), which is shortened to **Czlbl**. These major rock types have also been recoloured against rock type and age divisions. While the international conventions have been followed, the map has been tailored to Timor-Leste's unique geology. The changes to relabel and colour the geology map were made to make the map more readable and allow greater interpretation by an international audience. This also allows the map to be interpreted from a hydrogeological perspective. The full details of all geological units are presented in the accompanying hydrogeology report.

## HYDROGEOLOGY OF TIMOR-LESTE

This section outlines the properties of Timor-Leste's principal hydrogeological divisions and their spatial distribution on a national scale.

### Principal Hydrogeological Divisions

Three principal aquifer types have been identified for the purposes of the national map: intergranular porosity, fissured porosity and localised flow. The detailed geological descriptions from (Audley-Charles, 1965) and others have been used here to classify the geology into these three hydrology units based on rock texture, fracturing, lithology, age, extent and thickness. Intergranular porosity is assigned to rocks where groundwater flow will occur in pore spaces between sediment grains. Intergranular porosity has largely been allocated to sedimentary rocks where the unit is principally composed of grainsizes greater than silt, including conglomerates. Fissured porosity has been assigned to units that have consistent interconnected flow paths throughout the rock. Fissured porosity has been given to rocks that are principally composed of limestone and known to have karst features. Localised flow is assigned to rocks where porosity is not pervasive but occurs along discreet zones within a unit. Two principal rock types were classified as having localised flow: fractured rocks, where porosity is restricted to fractures, localised confining units, where rocks are dominated by clay and porosity is restricted to localised coarser sedimentary horizons. The rock types that make up the three principal hydrological divisions are summarised below with detailed descriptions given in the accompanying volume, Hydrogeology of Timor-Leste.

### Intergranular Porosity (Sedimentary)

The intergranular porosity hydrogeology sub-division (blue) includes sedimentary rocks of ages from the Triassic-Jurassic, Cretaceous and Cenozoic, and are present throughout Timor-Leste. Extensive deposits of sedimentary rocks and unconsolidated sediments are concentrated along the coast of Timor-Leste, forming sedimentary plains, but these deposits are also present within several inland depressions such as in the east near Lake Surubeco, south-west around Same, and in the west near Maliana. Smaller sediment deposits are present throughout Timor-Leste within drainage lines which become larger towards the coast. To reflect the potential hydrological difference in these sedimentary environments, the intergranular porosity sub-division has been further separated into higher potential yield (sedimentary plains) and lower potential yield (drainage line river valley sediments).

### Fissured Porosity (Karst)

The fissured porosity hydrogeology sub-division (green) largely consists of the limestone rocks with karstic textures, which range in age from Permian to Cenozoic, and occur throughout Timor-Leste. The older limestone (Permian to Cretaceous) is particularly prevalent in the central mountains that run the length of the country from east to west. The younger limestone (Cenozoic) predominantly occurs closer to the coast, particularly prominent in the eastern half of the country. These rocks are known to produce substantial groundwater resources. Within the fissured porosity sub-division, the younger limestone has been given a higher potential yield, to reflect the known high karst features and volumes of groundwater flow, and the older limestone a lower potential yield due to the metamorphism and more fractured nature of these rocks.

### Localised Porosity

The localised flow hydrogeology sub-division combines two principal and very different rock types of fractured rocks (buff) and confining units (brown). Both these classifications may produce localised flow, but will do so for different reasons. The groundwater flow within fractured rocks will be focussed along fractures, with the rock itself having little primary porosity. The clay-rich confining units will focus groundwater along courser sedimentary horizons where, locally, groundwater will flow through sand and gravel beds. As the localised porosity units do not have consistent flow throughout, the prospectivity is lower in these areas. That is, just because groundwater flow is high in one area there is no guarantee that groundwater flow will be high in an adjacent location. The fractured and confining localised classifications are discussed below.

#### *Fractured Localised Porosity*

The fractured localised porosity classification consists of the fractured, metamorphosed and crystalline igneous rocks of Timor-Leste which range in age from Pre-Permian to Cenozoic. These rocks are concentrated in the west of the country but are also present as smaller outcrops throughout. The metamorphosed rocks are mapped as extensive units and incorporate a large number of different lithologies. The heating from metamorphism has partially re-crystallised minerals, to form the current coherent folded and fractured rocks. The crystalline igneous rocks are predominantly mafic volcanic exposures through the central Timor-Leste mainland and felsic volcanic exposures on Atauro Island. The coherent metamorphosed and crystalline igneous rocks will have little primary porosity and groundwater will be focused along fractures formed after deposition. This is likely to produce groundwater flow that is localised around areas with greater amounts of fracturing. Although groundwater will have localised flow, the potential yields of water could be high in isolated areas, such as is evident in the high flow rates of some groundwater springs.

#### *Confining Units Localised Porosity*

The confining units classification of the localised porosity sub-division is made up of fine grained, clay-rich, non-metamorphosed sediments which range in age from Triassic to Cenozoic. These clays are distributed throughout Timor-Leste, with the younger Cenozoic clays forming thick continuous layers that overly older rocks. Clay-rich sediments do not have high groundwater flows as the fine clay particles fill the rock pores and prevent water flow. As these clay-rich sediments often act as a barrier to groundwater flow they are known as confining units. They will likely have low groundwater flow themselves, and will also act as confining layers over other aquifers. These units, although predominantly clay-rich, contain a wide range of other materials including sands and conglomerates. Some of these coarse sedimentary horizons may act as conduits from groundwater flow, creating some localised porosity. Locally these porous horizons may be an important source of groundwater but the prospectivity of groundwater within these clay-rich confining units will be very low.

### Hydrogeology Map of Timor-Leste

The spatial distribution of the principal hydrogeological units of Timor-Leste has been mapped to represent the aquifers and their characteristics relevant to groundwater (Figure 20, Figure 21 and Figure 22).

The solid colour of the hydrogeology map represents aquifer types. Aquifer type has been assigned based on texture and lithology of geological formations. The classification of aquifer types assumes that, for the most part, coarse grained sedimentary units are dominated by intergranular porosity (blue), karst limestone units are dominated by fissured porosity (green), fractured rocks are dominated by localised porosity (buff), and fine grained sedimentary clay units may have some localised porosity but largely act as confining units (brown). It is important to note that geological formations can contain a number of rock types that may have different porosities. The aquifer type classifications have been assigned based on the dominant rock types for national scale presentation.

The shade of the solid blue (intergranular aquifers) and green (fissured aquifers) colours of the hydrogeology map reflects the potential yield of the aquifer. The potential yield of an aquifer is an estimate of the likely amount of usable groundwater an aquifer may have. In the absence of any groundwater data for many aquifers, potential yield is estimated based on the size and age of the aquifer. The size of an aquifer is particularly important for the alluvial intergranular aquifers where the sediments have a wide range of thicknesses and widths, from small river channels to large sediment planes. The smaller river channels (approximately 1-10 m thickness) are classed as Intergranular Porosity, Lower Potential Yield (light blue) to reflect the lower amount of water storage compared with the larger alluvial planes (approximately 10's to 100's of metres thickness) which are classed as Intergranular Porosity, Higher Potential Yield (dark blue). The age of aquifers is more important for the karst fissured aquifers where older metamorphosed limestone has less karstic features than younger limestone. The older limestone has been classed as Fissured Porosity, Lower Potential Yield (light green) to reflect the potentially lower groundwater flow while the younger limestone with potentially higher groundwater flows are classed as Fissured Porosity, Higher Potential Yield (dark green).

The hydrogeology map also distinguishes between aquifers with localised and pervasive groundwater flow. Aquifers with pervasive groundwater flow (intergranular-blue and fissured-green) are more likely to have widely available groundwater, with high prospectivity for potential wells. Aquifers with localised groundwater flow (fractured rock-buff and confining units-brown) would require much more precise planning of any potential new wells to find groundwater. The localised groundwater flow is separated into fractured rocks (buff) and clay-rich sediments (brown). The fractured rocks are likely to have high potential groundwater flows but only along localised fractures and are classed as Localised Porosity, Higher Potential Yield. The clay-rich sediment are more likely to act as confining units rather than aquifers but may have some localised groundwater flow and are classed as Localised Porosity, Potential Confining Unit.

The lithology of the aquifers is represented by patterned symbols. The lithology is derived from the surface geology map of Timor-Leste for the major hydrogeology aquifer types. The major lithological groupings represented are clays, sands, conglomerates, limestone, basalt and ultra-mafic. These are represented with their standard patterns in grey overlying the aquifer types.

Site specific groundwater information has been added to the hydrogeology map as data has been collected during this project. This includes contours of groundwater flow, groundwater flow directions, groundwater springs, and groundwater quality, which are depicted with violet symbols in accordance with the UNESCO legend. This additional groundwater information allows greater interpretation of individual aquifer groundwater trends on a national scale.

In addition to the hydrogeology map a groundwater potential yield map has been created for Timor-Leste (Figure 23, Figure 24 and Figure 25). This map shows higher (dark blue) and lower (light blue) potential yield of groundwater regardless of lithology or aquifer type. This map has been created to simplify the potential occurrence and yield of all groundwater. This map has also been used in the Charles Darwin University report as a surrogate for aquifer sensitivity.

National datasets relevant to groundwater are included as inset maps, at a 1:1,000,000 scale, on the large hydrogeology map wall poster. Information relevant to groundwater includes rainfall, temperature, topography and geology. This information becomes too complex to display when overlain on the hydrogeology map and has been kept separate to allow the viewer to compare maps without obscuring the primary aquifer features.

Cross sections of hydrogeology and geology have been drawn through Timor-Leste with a vertical exaggeration of 1:10. These give an illustration of the distribution of aquifers with depth. This aids in understanding the potential interactions between aquifers and the sub-surface extent of aquifer types. The cross sections show that the majority of the young limestone is restricted to near surface while the older limestone is extensive at depth. They also show that many of the alluvial sediments overlap to form extensive intergranular aquifers on the south coast.

The principal hydrogeological divisions and interpretations of hydrology for each geological unit are described below.

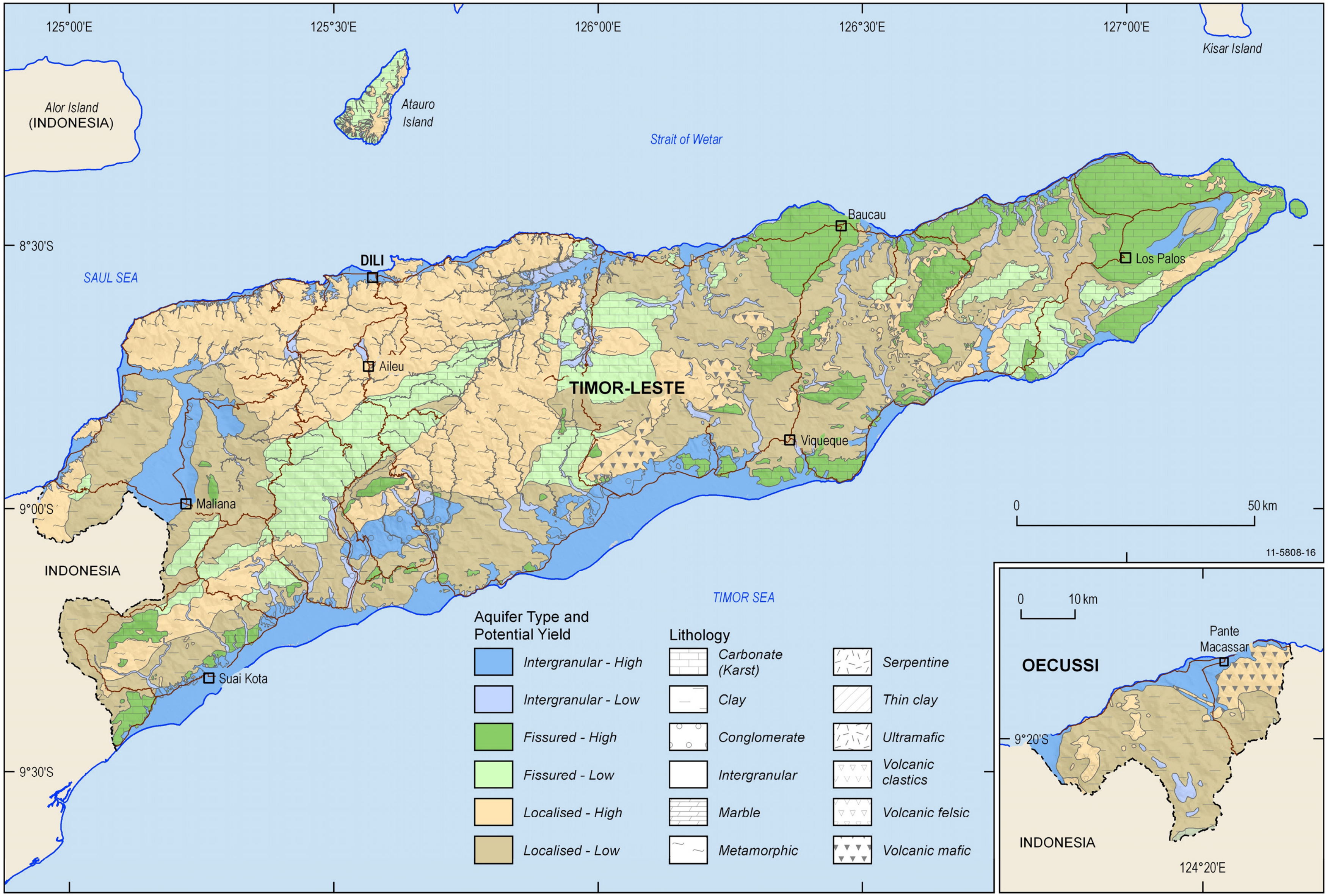



**Figure 20: Hydrogeology map of Timor-Leste**

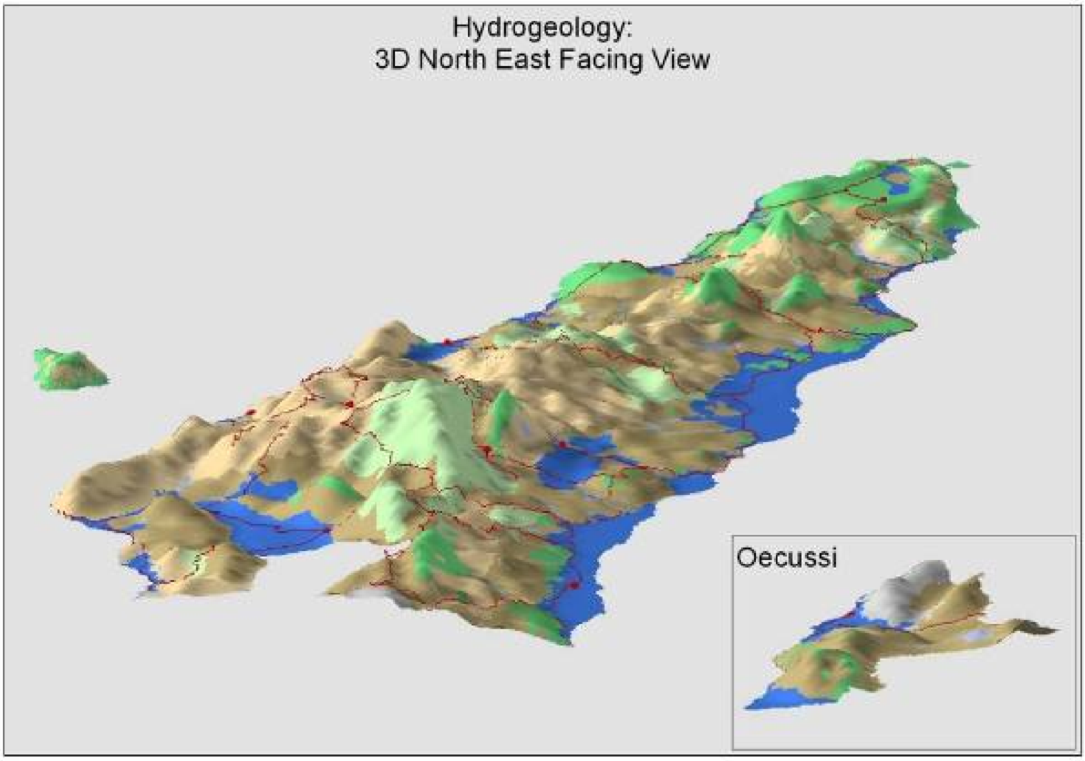



Figure 21: 3D North East Facing View of the Hydrogeology of Timor-Leste

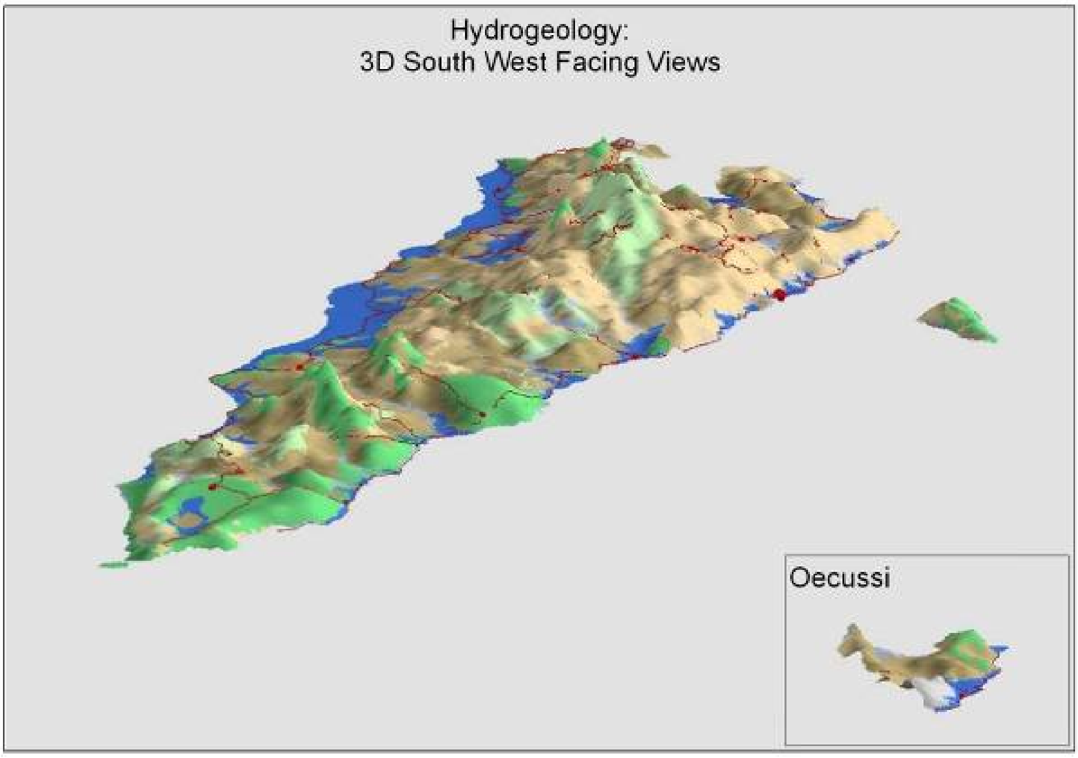



Figure 22: 3D South West Facing View of the Hydrogeology for Timor-Leste

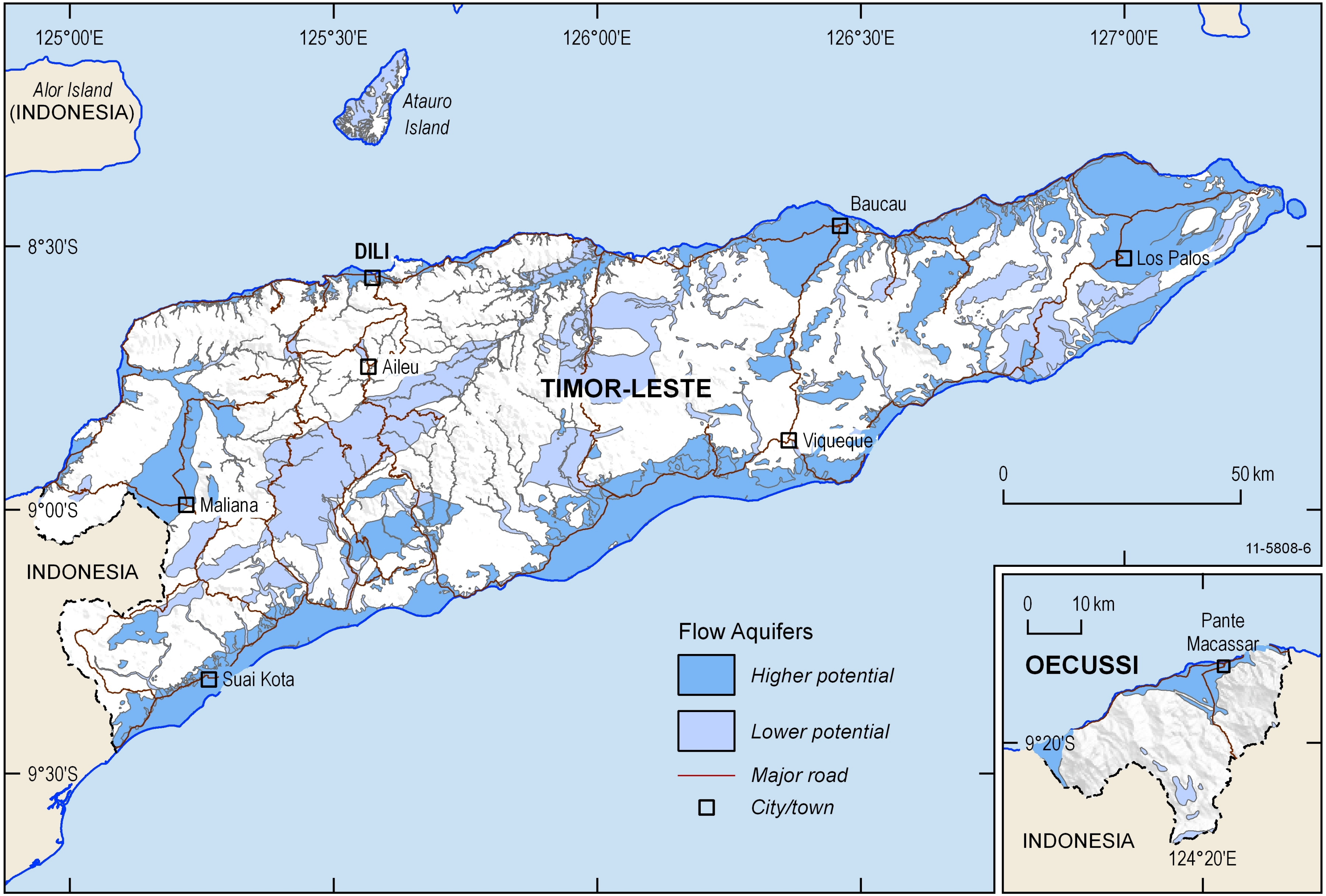



**Figure 23: Hydrogeology map of Timor-Leste showing potential aqufer yield**

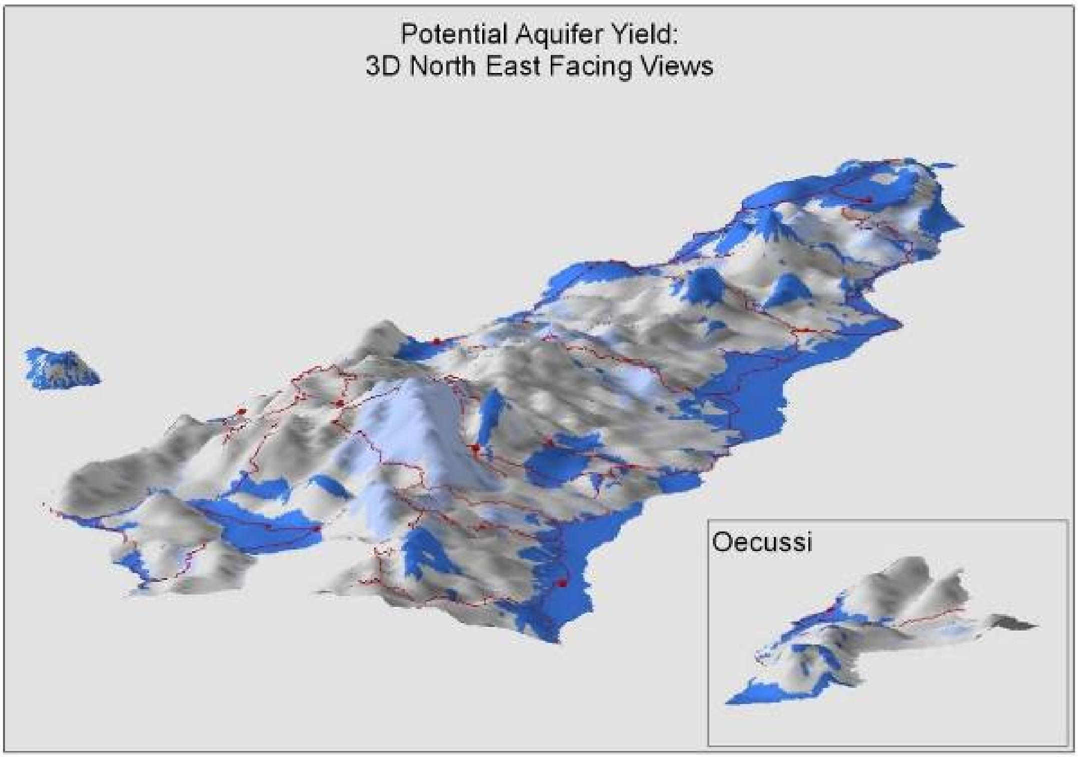



**Figure 24: 3D North East Facing View of potential aquifer yield hydrogeology map of Timor-Leste**

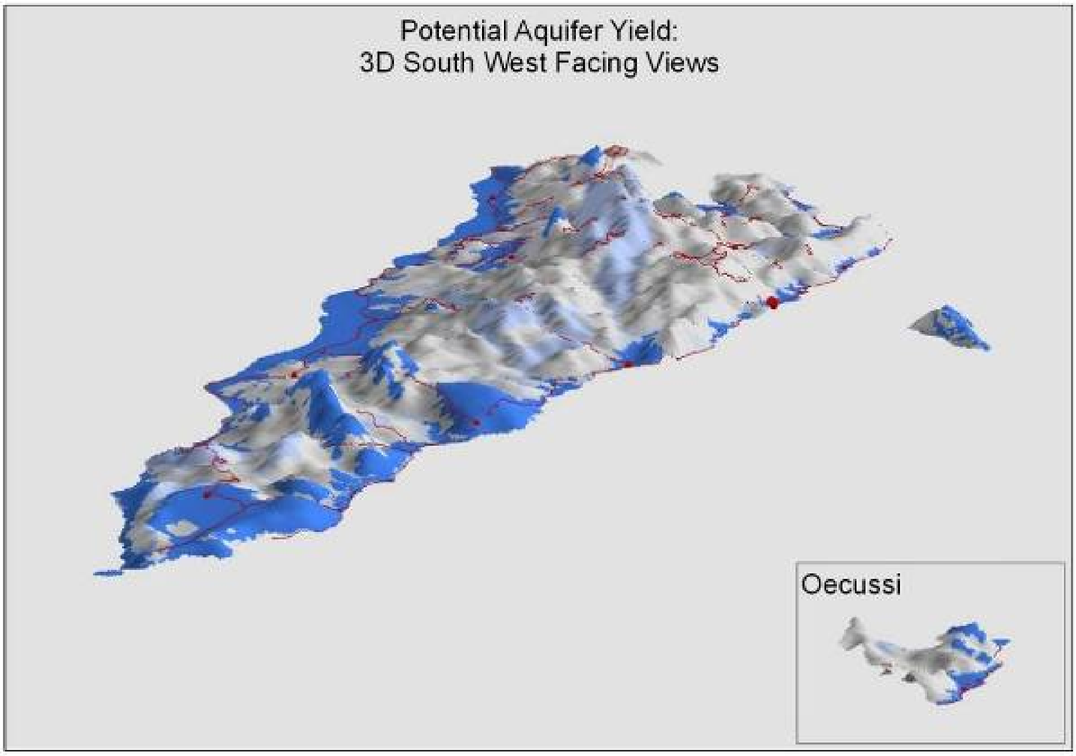



**Figure 25: 3D South East Facing view of potential aquifer yield hydrogeology map of Timor-Leste**

## KEY FINDINGS FROM HYDROGEOLOGY OF TIMOR-LESTE

The hydrogeological framework and new Hydrogeology Map of Timor-Leste provide a means for understanding groundwater at a national scale. The hydrogeological framework outlines clear steps to start understanding and monitoring groundwater. This was developed, firstly, through a knowledge based approach to use the best available hydrogeological knowledge to interpret surrogate information (such as geology) with the currently limited available groundwater information. The data based approach has also been used to incorporate new data collected by this project and the details of this work are presented in the following case study section. The map provides a foundation for research and management of groundwater resources by systematically portraying, for the first time, the current national groundwater knowledge and data of Timor-Leste.

This section has demonstrated that:

- A simple knowledge and data driven framework can be used to build an understanding of the hydrogeology of Timor-Leste.
- A new national hydrogeology map of Timor-Leste can be created from the sparse groundwater information available. By systematically following a hydrogeology framework, the detailed geology, other relevant datasets available and fieldwork can be simplified to represent and map the three major aquifer subdivisions of Timor-Leste.

An separate aquifer yield/sensitivity map has been created from the new hydrogeology map based on typical flow measurements to allow a national vulnerability assessment of Timor-Leste (this map has also been used to assess vulnerability of people in the accompanying CDU report (Myers et al., 2012), Chapter 6 38-40pp).

# Case Study Hydrogeology

## INTRODUCTION

Detailed case studies are required to characterise the main hydrogeology sub-divisions of Timor-Leste. This section presents analysis from fieldwork activities in Timor-Leste. The case study site approach allows for detailed analysis in representative areas to understand the properties of the three distinct aquifer types. This was undertaken to validate the desk-based conceptual framework and map outlined in the previous chapter and to improve understanding of the characteristics of the principal hydrogeological divisions. It is essential that a base-level understanding of these resources is established as a foundation for any future monitoring. Regular monitoring will be required to improve our understanding of this resource and how external influences (i.e. climate, infrastructure, social factors) will affect the resource.

## CASE STUDY LOCATIONS

Three case study locations were chosen to represent the three principal aquifer types of Timor-Leste identified in the hydrogeology map. These are 1) intergranular aquifers (alluvial) at Dili, 2) fissured aquifers (karst) at Baucau and 3) localised aquifers (fractured) at Aileu. While the project initially envisaged only two case study sites, coverage of all three of the main aquifer types was pursued to allow a comprehensive comparison of these different groundwater environments (Figure 26).

### Intergranular Aquifer (Sedimentary): Dili Aquifer

The sedimentary aquifer of Dili was selected as the case study site for Intergranular Aquifers. The groundwater use from intergranular aquifers ranges from high extraction through constructed bores and open wells to no extraction. The Dili aquifer is an example of a high potential yield intergranular coastal aquifer that is currently undergoing high rates of extraction. This intergranular aquifer was chosen due to the high population density and extraction rates from the water resources. Aquifers with these pressures require the most immediate attention in terms of groundwater management and potential impact of climate change on livelihoods (Figure 27).

### Localised Aquifer (Fractured rock): Aileu Aquifer

The regional fractured aquifer of the Aileu Formation around the Aileu district, south of Dili, was selected for the Localised Aquifer (fractured) case study site. The Aileu Formation is an extensive metamorphosed unit that forms a large portion of Timor-Leste's fractured rocks. This aquifer is not densely populated like Dili but represents a significant portion of the population of Timor-Leste due to its large extent. As water is typically taken from springs, with little extraction from bores and wells, the population is reliant on fluctuating natural processes (such as recharge) for their water. This aquifer was chosen due to the large population supported over a large area and the susceptibility to natural processes that will be affected by climate change (Figure 28).

### Fissured Aquifer (Karst): Baucau Aquifer

The limestone aquifer of the Baucau Limestone, containing the major town of Baucau (Timor-Leste's second largest town), was selected for the Fissured Aquifer (Karst) case-study. The Baucau Limestone is a young limestone with high-potential yield that supplies water to the dense population of Baucau. This area does not typically use bores or wells as groundwater extrudes from natural springs. This style of karst aquifer covers a large area of eastern Timor-Leste. Baucau was chosen due to the large extent of young limestone and because it supplies a dense population from groundwater springs that may be susceptible to natural climatic variations (Figure 29).

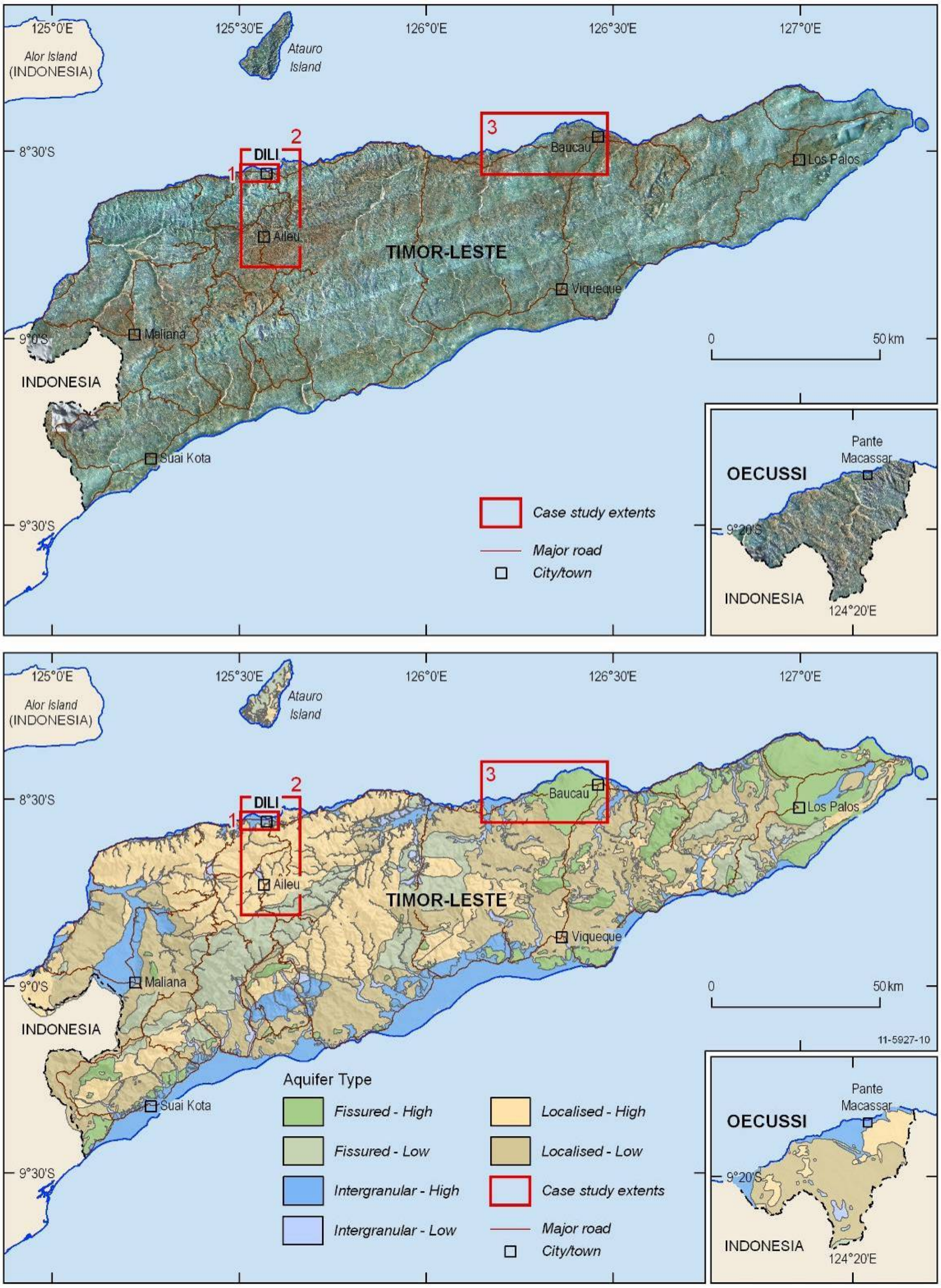



**Figure 26: Terrain and aquifer maps of Timor-Leste showing three case study areas of Dili, Aileu and Baucau representing the three dominant aquifer types of intergranular, localised and fissured**

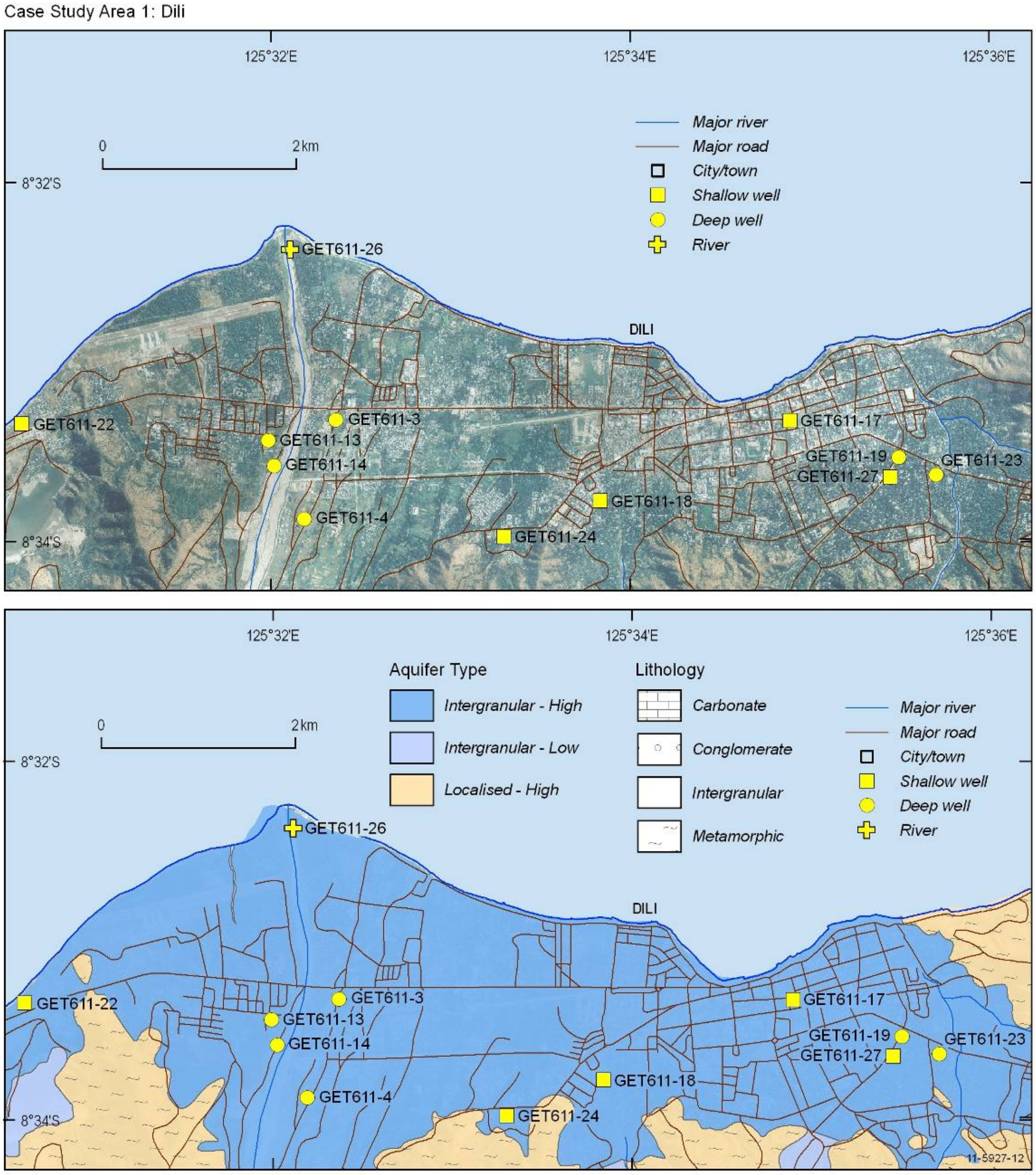



**Figure 27: Terrain and aquifer maps of the Dili case study area with sample locations**

Case Study Area 3: Aileu

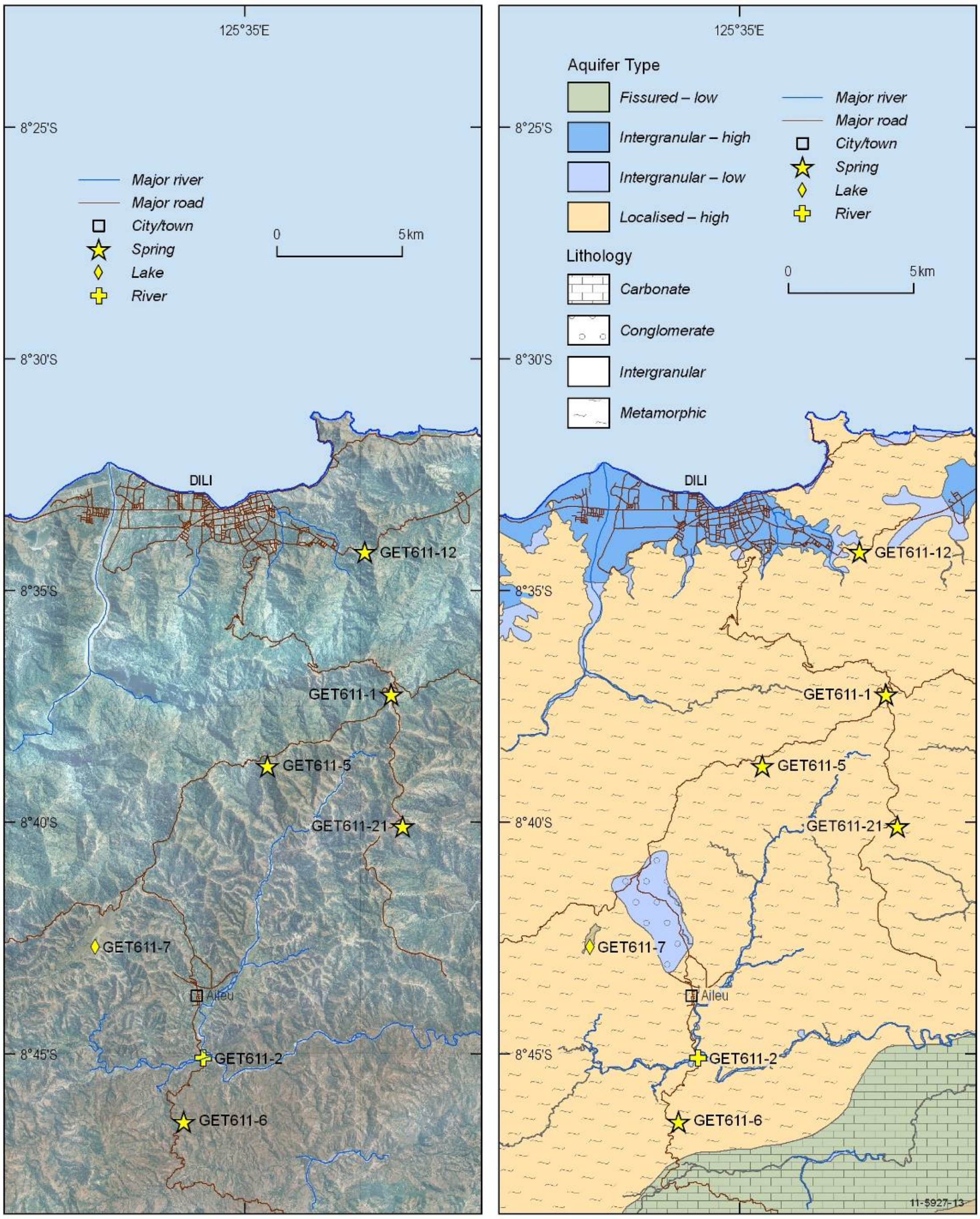



**Figure 28: Terrain and aquifer maps of the Aileu case study area with sample locations**

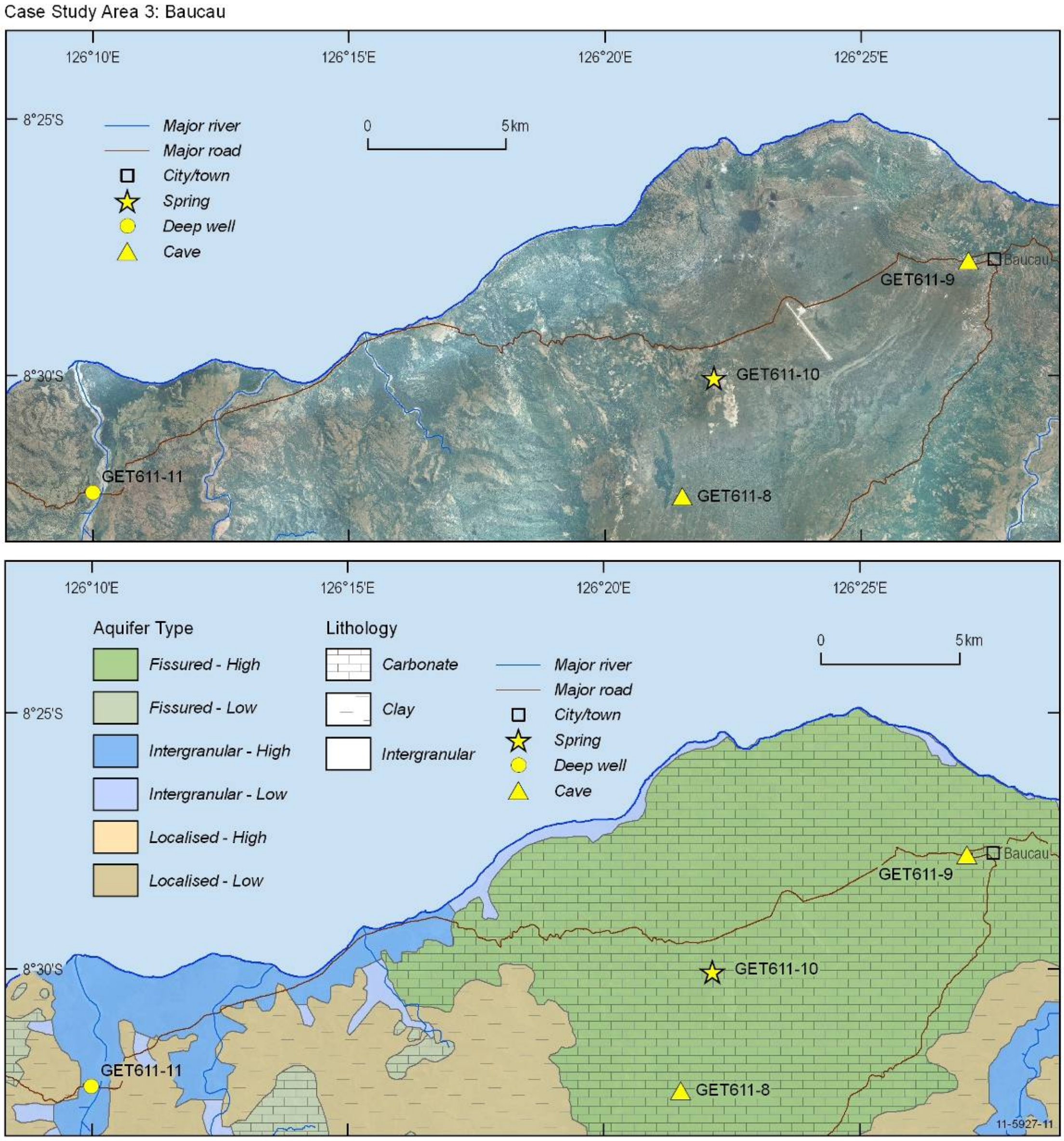



**Figure 29: Terrain and aquifer maps of the Baucau case study area with sample locations**

## CASE STUDY-AQUIFER CHARACTERISTICS

The three principal aquifer types (Table 2) were characterised by direct observations, analysis of water chemistry, and geophysical techniques. The aim of the characterisation was to determine the fundamental properties of groundwater flow and quality in each aquifer. This information was then used to assess the potential impacts of climate change on each aquifer type as well as a vulnerability assessment. The results of observational, chemical and geophysical analysis are presented below for each aquifer type.

**Table 2** Three case study areas for the three principal aquifer types in Timor-Leste

| Aquifer | Location | Rock type | Area (approximate) |
|---|---|---|---|
| Intergranular | Dili | Sedimentary | 18 $km^2$ |
| Localised | Aileu | Fractured rock | 1250 $km^2$ |
| Fissured | Baucau | Limestone | 240 $km^2$ |

### Intergranular Aquifer (Dili Aquifer)

Intergranular aquifers are composed of sediments with groundwater filling the spaces between sediment grains. The types of sediments that form an aquifer influence the properties of the aquifer and its ability to store and transmit groundwater. For this reason it is important to understand the sediments themselves.

The sediments of the Dili Aquifer have been mapped as Quaternary age alluvium. The alluvium ranges in composition throughout Timor-Leste, reflecting the surrounding geology. The texture of these sediments varies, but is typically unconsolidated and moderately poorly sorted silts to cobbles. Much of the alluvium is undifferentiated Quaternary sediments, but in many areas the alluvium forms part of defined units, such as the Suai Formation, Ainaro Gravels and Dilor Conglomerate. It rests over all other older rocks and is present throughout Timor-Leste river valleys and coastlines.

Prior knowledge of the hydrogeology of Timor-Leste is limited. The most comprehensive appraisal of the water resources in Timor-Leste is of the Dili aquifer in *'The Study on Urgent Improvement Project for Water Supply System in East Timor'* produced by the Japan International Cooperation Agency (JICA, 2001). The current study builds on the results of the JICA as well as other hydrological and geological studies on Timor-Leste. Frequently referenced in the JICA report was the document titled 'Hydrogeology of Dili and Suai' produced by the Indonesian Government in 1993, which Geoscience Australia did not have access to.

The Dili Aquifer is the source of groundwater for the capital city. It extends approximately 9 km east to west and 3 km north to south on the country's northern coast. The sediments comprising the aquifer are thought to be provided predominantly by the major Comoro River but also the smaller Maloa and Benamau Rivers, and deposited as a merged delta. The Comoro River has a total catchment area of approximately 207.3 $km^2$ (JICA, 2001).

The aquifer is accessed by 14 deep bores (~80 m depth), which are situated around the Comoro River well field, in west Dili and in the Kuluhun and Bidau well fields in east Dili. The hydrological characteristics of the Dili aquifer are separated into the characteristics of the Comoro Well Field and Kuluhun and Bidau Well Fields individually (JICA, 2001). They interpret the vertical thickness of the Comoro alluvial fan to be from 82 – 130 m, with an increasing thickness to the north towards the coast. The aquifer is thought to be semi-confined by lenses of interconnected impermeable silts and clays and it is noted that the upper-basement rock is highly weathered mica schist (up to approximately 50 m). Groundwater discharge is considered directly related to rainfall and head height of water is likely strongly linked to seasonal fluctuations. The sediments comprising the Kuluhun and Bidau well fields have been described as colluvium and overlapping alluvial fans decreasing from cobbles and boulders at the base of the hills to coarse sands and gravels towards the coastline (JICA, 2001). One of the most notable features of the Dili Aquifer(s) is variation between basement depths. In the Kuluhun and Bidau well fields, the maximum depth of the aquifer is approximately 80 m, but in parts the aquifer is only up to 10 m thick.

This coastal alluvium, which Dili sits on, has been distinguished from other, thinner, river alluvial deposits by the width of the deposit and the steepness of the terrain. The coastal alluvium hydrogeology of the Dili area is classified here as 'Intergranular Flow, Higher Potential Yield'. This classification reflects that the inter-granular groundwater flow is likely to be high and the greater thickness of the units at the coast is likely to result in higher potential yields.

In this study the Dili Aquifer sediments can be shown to be related to the (1) sediment source, (2) sediment transportation, and (3) sediment deposition. These three processes are outlined below in terms of the Dili Aquifer.

(1) Sediment source

The sediment comprising the Dili Aquifer has been eroded from the hills that fringe the city of Dili itself. The rocks that constitute these hills are known as the Aileu Formation. The Aileu Formation consists of slates, phyllites, meta-quartzites, mica schists, amphibole schists and some rare marbles (Sjapawi, 1996). The rocks have been strongly deformed and metamorphosed (Grady, 1981) with metamorphic grade increasing northwards. These are inferred to represent metamorphosed Pre-Mesozoic and Mesozoic sediments (Sjapawi, 1996).

The aquifer contains a high variability of sediment types ranging from clays and silts to cobbles and boulders. Units are approximately 0.2 – 2 m thick and changes in the unit type can be abrupt. Units containing coarse and moderately sorted sediments are highly porous with little cementing. Such units may contribute to localised areas of high-groundwater flow due to their high permeability.

On the other hand, the aquifer also contains clays and finer grained silt sediments with lower permeability. These units may act as confining units, inhibiting flow. It is important to note that the clay units, while common, were not always continuous and in some cases are less than 5 m long. Therefore these may not represent one continuous confining unit but rather multiple small confining units over discrete intervals with an unknown distribution.

(2) Sediment transportation

The Dili Aquifer is delta fed by high energy braided rivers that transport sediment to the aquifer. The formation of these rivers and the creation of the Dili aquifer is a result of the geological uplift of the region. The creation of topography as Timor began to emerge above sea-level created the potential energy that drives the erosion of material down slope.

Braided rivers form because there is too much sediment to be carried by the energy of the fluvial system or if the banks are highly erodible (Schwab, 1996). Some features common to braided rivers include steep gradients, abundant coarser sediments (mostly sand and gravel) and rapid discharge fluctuations (Schwab, 1996). Braided rivers shift rapidly (Schwab, 1996) and the Comoro is likely to have followed a different trajectory throughout time, depositing sediments all through the Dili plain. Therefore localised units of coarser sediment may be distributed unevenly amongst the finer grained clays.

(3) Sediment deposition

The morphology of the aquifer is analogous to a coarse grained delta system. It has formed by rapid deposition of sediments as the high energy rivers meet the flat coastal plains. In the plan view, deltas are often triangle in shape, and are wedge-shaped in cross section. There is a wide range of grain sizes in deltas, which usually become finer away from land. It is likely that the Dili aquifer is composed of a number of deltas each associated with a fluvial system forming discrete and overlapping aquifers. These aquifers will be of varying sizes and characteristics depending of the sediment load that the river is able to carry and deposit.

Overall the sedimentology results of this study suggest that the aquifer is composed of highly heterogeneous materials. This is due to the wide range of source materials from which the sediments are eroded, the wide range in grain size carried by the high energy alluvial transport, and the abrupt deposition of sediments at the coast.

Groundwater level heights for the Dili area roughly reflected topography. Bores furthest from the coast have the highest potentiometric surface (taken from reference sea-level height). The height may also be related to distance from the Comoro River in the western bores.

### Localised Aquifer (Aileu District)

Fractured rocks are rocks that contain multiple discontinuities. The localised aquifer fractured rocks have little primary intergranular porosity due to metamorphism and do not form caves like the carbonate rocks. This means that groundwater flow is restricted to fractures within the rock mass.

Fractures develop in metamorphic rocks like the Aileu formation due to shrinkage during dewatering of sediments, tectonic movement, and pressure relief due to erosion of overburden rock. The amount of fracturing may decrease with depth and groundwater movement is largely concentrated in the upper 100m or so of rock. Folding and faulting can produce very complicated aquifers where the recharge, discharge and flow of groundwater are hard to predict. One complication is that faults may act as either pathways for groundwater movements or as barriers to flow. Fractures may develop due to regional or localised factors, can form in any direction as fracture sets, and may or may not be interconnected. This means that the amount of groundwater flow is likely to change from one site to the next and knowledge of the local geology is required.

The Aileu Formation is a Permian age sequence of hard metamorphosed (heated) deep marine sediments at least 1000 m thick. The formation is composed of inter-bedded mudstone and sandstone that has been subsequently 'baked' by metamorphism forming hard, coherent rocks. These rocks form a large outcrop that has been faulted horizontally (thrust fault) into its current position and makes up the majority of north-west Timor-Leste.

The hydrogeology of the Aileu Formation is classified here as 'Localised, Higher Potential Yield'. The metamorphosed rocks will have little inter-granular flow and the majority of groundwater is present in more localised fractures and faults, forming springs. The high degree of fracturing and faulting indicates that the localised springs may have high groundwater flow. Little information is available for springs of the fractured rock localised aquifer of the Aileu district.

Springs were found to be common throughout the Aileu district fractured rock but varied in distribution, flow rate and seasonality of flow. Springs were found to occur at a range of elevations from the base to near the peaks of the mountainous terrain. Individual springs, typically with flow rates from 0.1 – 2.0 l/s, were found throughout higher elevations of local topography. However, individual springs quickly formed streams down slope. Measuring the contribution of groundwater discharge to an established stream is significantly more difficult than the measurement of isolated springs. Thus it was not possible to measure the individual flow rate contribution of groundwater outflows at lower levels in the topography. It was noted, however, that many streams gained considerably in flow down slope indicating that significant contributions of groundwater are being made to river flow.

It was found during the dry season sampling that many springs had lowered flows and some had dried out. This is typical for the Aileu fractured rock district and demonstrates the strong seasonality of springs at higher elevations. The increase in streams down slope form the combination of spring outflows also shows that streams are largely groundwater fed during the dry season. This is likely to be the reverse in the wet season with streams flowing into aquifers. This shows that groundwater levels (and the springs it feeds) are highly sensitive to rainfall at higher elevations as are the interactions between surface water and groundwater.

### Fissured Aquifer (Baucau Aquifer)

Carbonate rocks may have primary porosity (similar to intergranular aquifers) or secondary porosity (sink holes, fissures and caves) that forms within the carbonate rocks after deposition. The secondary porosity is often the greatest transmitter of water in carbonate rocks.

Primary porosity in carbonate rocks can be variable. Deposition of clastic carbonates or the development of carbonate reefs can produce high primary porosity, and thus potential water flow, due to the interconnected pore spaces. Chemically precipitated carbonate rocks may have very little primary porosity due to the lack of available pore space to transmit water.

Secondary porosity is formed by the enlargement of bedding planes, fractures and faults due to the dissolution of carbonate by water. Over time this dissolution forms sink holes and caves. As more groundwater flows through the larger fissures these become enlarged faster than other areas and consequently receive more groundwater. This results in openings becoming larger along the flow path with fewer fissures carrying more of the groundwater flow. Groundwater may start as diffuse flow but will end up concentrated in larger caves. This favouring of larger openings over smaller ones results in a high degree of heterogeneity in carbonate rocks (i.e. some areas will have high flow via caves whereas an adjacent area may have very limited flow).

The position, orientation and direction of cave systems that carry groundwater will depend on the original bedding plains, fractures and faults within the carbonate rock. A carbonate rock with a low density of fissures may strongly influence the development of caves as there are only a few pathways for the water to flow. Carbonate rocks with a high density of fissures will allow groundwater to find more pathways and therefore a more direct route through the rock.

The Baucau Limestone is a 100-500 m thick, shallow marine/beach limestone of Pliestocene to Recent age. It is principally composed of reefs and is highly karstified (cavernous) and terraced. The Baucau Limestone is widespread throughout the eastern half of Timor-Leste and groundwater yields are known to be high throughout this formation.

The Baucau Limestone is largely a coral-reef limestone with the principal lithologies within the limestone being: coral-reef limestone; carbonate conglomerate (calcirudites); carbonate sands (calcarenites); and pebbly sandstones. The limestone has formed as a series of raised beaches, the terraces marking the stages of uplift over time. The Baucau Limestone rests unconformably over the Viqueque Formation, forming prominent terraces that stretch outwards towards the shore-line with decreasing elevation. The top terraces are the oldest limestones of this formation, with the youngest currently forming at the foot of the coastal cliffs. The limestone forms large domed hills and plateaus in the east of Timor-Leste that rise up to 500 m elevation. It is also highly karstified with prominent large caves common.

The hydrogeology of the Baucau Limestone is classified here as ‘Fissured, Higher Potential Yield’. The highly karstified limestone has high yielding groundwater springs that flow year round. This is a known high yielding aquifer, which supports a number of communities, including Timor-Leste’s second largest town, Baucau.

Spring flow rates and seasonality were strongly correlated with altitude in the Baucau Limestone while spring distribution was found to be variable (this may also be the case for the fractured rock but could not be confirmed as flow rates could not be measured at lower elevations due to the presence of streams). Spring flow rates generally increased at lower elevations in the old town of Baucau. Spring flows at higher elevations were lower and in many cases had stopped flowing at the time of sampling in the dry season. This demonstrates that the higher plateau area of Baucau is highly sensitive to changes in rainfall. The position of springs appears to be linked to local heterogeneous variations in the karst landscape and is not evenly distributed. With largely no streams or surface water in the karst landscape the water cycle is dominated by groundwater.

### Field observations overview

The field observations discussed above show that the three dominant aquifer types are, as anticipated, physically distinct resulting in unique hydrogeological characteristics. The field observations also show that all three aquifers have high levels of internal physical heterogeneity. The intergranular aquifer of the Dili area has a complex distribution of clay confining units and sand-cobble grain size aquifers, the coarser material predominantly concentrated around the dominant river channels. The localised fractured rock aquifer of the Aileu district is composed of a wide variety of metamorphosed rocks with mountainous topography. The complex composition and topography of the fractured rock aquifer is reflected in the complex distribution of groundwater springs. The fissured aquifer of the Baucau area is composed of multiple generations of limestone that have risen out of the ocean over time. The complex interconnection of cave systems through the multiple limestone layers, combined with topography, result in the heterogeneous distribution of springs. Additionally, all aquifers appear to have prominent seasonal variations of groundwater levels associated with seasonal rainfall and strong groundwater-surface water relationships.

## WATER CHEMISTRY RESULTS

The chemical results for fieldwork conducted in Timor-Leste are discussed below for the case study sites from each of the principal aquifer types. The major ions chemistry is summarised in a Piper plot and Durov diagram (Figure 30 and Figure 31) and are discussed for each case study area separately below.

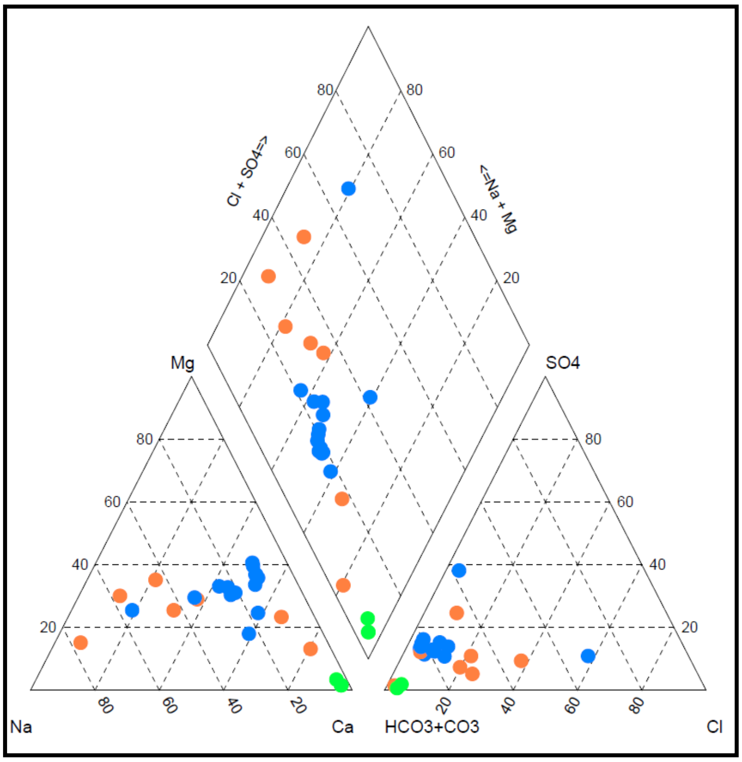



**Figure 30: Piper plot of major element water chemistry for intergranular (blue), localised (orange) and fissured (green) aquifers**

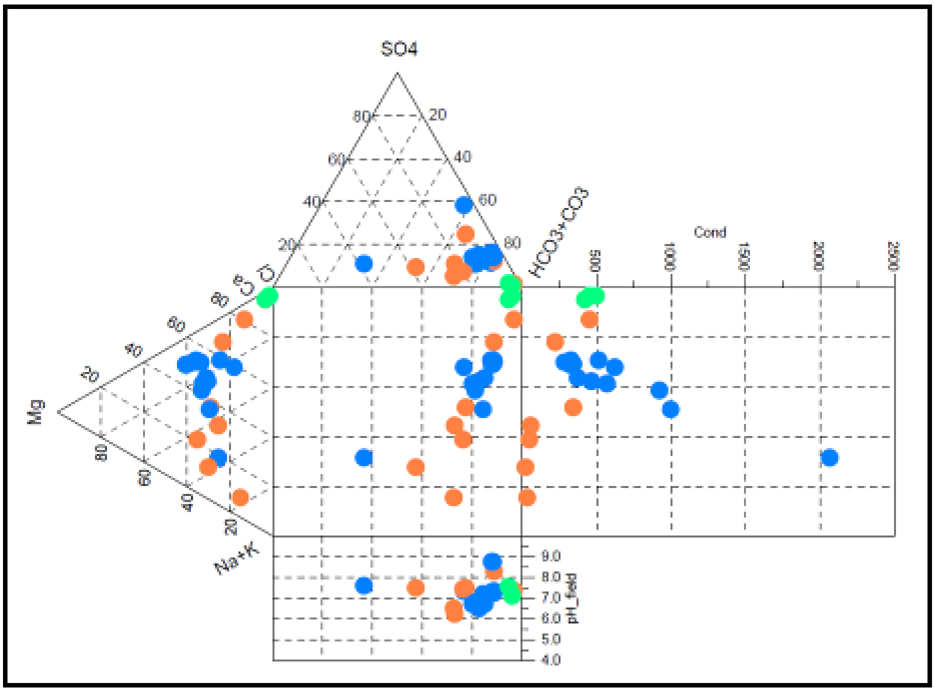



**Figure 31: Durov diagram with major elements, salinity and pH for intergranular (blue), localised (orange) and fissured (green) aquifers**

## Intergranular Aquifer (Alluvial)

### *Field Parameters*

Both the river samples and deep wells have similar calcium carbonate values of approximately 150 mg/L while the shallow bores value is approximately double with a value of 332 mg/L. Sample GET611-24 contains the greatest value, with 454 mg/L $CaCO_3$. The median value of eastern samples (171 mg/L) is higher than the total median value (166 mg/L) and the value in the west is lower (140.6 mg/L).

Sulphides are low across all samples and 9 of the 14 (64 %) contain values below-detection-limit (BDL). The river samples contain a marginally higher median value of sulphide than both the shallow and deep bores, both of which are BDL. The river samples have a median value of 0.015 mg/L. Reduced iron ($Fe^{2+}$) values are low across all samples with a range of BDL – 0.03 and median values for deep, shallow and river samples as BDL, 0.01 and 0.01 mg/L respectively. Total iron concentrations, on the other hand, are greater with median values of 0.02, 0.16 and 0.41 respectively for deep bore, shallow bore and river samples.

Turbidity values are very low for both deep and shallow bores demonstrating that the samples contain minimal suspended solids. The river samples have somewhat greater turbidity with a median of 16 FTU (Formazin turbidity unit) between them.

The EC (electrical conductivity) across all samples is low, which is related to the concentration of salts in the water. All samples contain values below 1000 µS/cm except for sample GET611-22, which has a value of 2063 µS/cm. Shallow bore samples contain a median value of 921 µS/cm, approximately three times the deep bore and river sample median values of 334 and 335 µS/cm respectively. The EC median value of the eastern samples (419.5 µS/cm) is higher than that of the western samples (231 µS/cm) and the total median value (374 µS/cm).

The recommended guideline value for pH is 6.5 – 8.5. All samples from deep and shallow bores contained values within this guideline, with median values of 7.3 and 7.2 respectively. The river samples, in contrast, contain higher pH values with a median value of 8.8. This indicates that the river samples contain alkaline water. pH is moderately lower in the eastern deep samples with a median value of 6.6 compared to the west, which is more alkaline with a value of 7.3.

The range of Eh (Redox Potential) for all samples is 5 – 178 mV. The median values for deep bore, shallow bore and river samples are 157, 55 and 100 mV respectively. Both the western median and the eastern median are similar for Eh with values of 140.5 and 167.5, respectively.

Temperatures across all samples vary from 25.7 – 31.0 °C. Deep bore samples contain the coolest water at the time of sampling, with a median value of 26.1 °C, while shallow bore and river samples are moderately warmer with values of 28.0 °C and 28.5 °C respectively. The eastern deep wells have a moderately higher temperature (27.1 °C) than the western deep wells (26.0 °C).

Dissolved oxygen (DO) has a range of 6.4 – 103.5 %. This high value is in a river sample, which contain higher values of DO due to their exposure to air, but may be an over estimation due to the difference of the calibration solution. DO increases in percentage from shallow bores to deep bores to river samples with median values of 30.6, 52.7 and 93.5 % respectively. The western deep wells have a higher dissolved oxygen content with a median value of 63.7 % compared to the eastern median value of 49.5 %.

***Major Elements***

The piper plots show that the groundwater anion composition is dominated by (with approximately 80 %) $HCO_3^-$ + $CO_3^{2-}$ and low in $Cl^-$ or $SO_4^{2-}$ anions. The cation composition is dominated by $Ca^{2+}$ (approximately 60 – 80 % of cations). The groundwater does contain some more enriched in $Na^+$ and $Mg^{2+}$ cation values. Overall the combined piper plot shows that groundwater compositions are calcium- sodium- or magnesium- bicarbonate/carbonate water types. As can be seen from the combined projection of cations and anions, the Dili samples contained a mixed signature on a line that is directly between the karst and fractured rock samples. This indicates that the ionic composition of the groundwater is very closely related to the source rock material of the sediments.

***Trace Elements***

Overall the samples show low concentrations of trace elements. The majority of the elements analysed for trace elements (72 % of samples) contain median values (BDL). Most element concentrations are considerably below the recommended guideline value for health. One sample (GET611-24) approached the recommended guideline value of arsenic (0.01 mg/L) with a concentration of 0.007 mg/L and manganese of (0.5 mg/L) with a concentration of 0.487 mg/L.

The majority (37 of the 50) of samples analysed for trace elements (silver, bismuth, erbium, europium, gadolinium, titanium, beryllium, gallium, cadmium, hafnium, tellurium, cobalt, holmium, caesium, chromium, indium, lanthanum, lutetium, thorium, cerium, neodymium, praseodymium, nickel, samarium, lead, terbium, antimony, thulium, selenium, ytterbium, yttrium, thallium, zirconium, vanadium, iron and mercury) had concentrations (BDL).

Aluminium, uranium, copper, rubidium, lithium and tin were below detection limit in the majority of samples and are at very low concentrations in the Dili aquifer with maximum values of 0.01, 0.001, 0.01, 0.008, 0.014 and 0.002 mg/L respectively. Some trace elements that were detected but were below recommended health guidelines for water include boron, strontium, barium, manganese, molybdenum and zinc with total median values of 0.23, 0.31, 0.01, 0.004, 0.001 and 0.047 mg/L respectively.

Trace element concentrations in deep bores, shallow bores and river samples were compared at specific locations. Shallow bores typically display higher trace element concentrations than the deep bores with higher median values recorded for arsenic, boron, strontium, barium, uranium, copper, rubidium, lithium, manganese and zinc. The two river samples collected show low trace element concentrations with no elements exceeding regulatory guidelines. Most water samples (92 %) show median values below the detection limits of the laboratory. The four elements that have been detected in the river samples are aluminium, strontium, barium and lithium.

Median element concentrations were calculated to compare the four deep samples in the west (Comoro well field) with the two in the east (Kuluhun well field). In this analysis 6 of the 7 elements detected (aluminium, strontium, barium, copper, lithium and zinc) are higher in the eastern.

***Nutrients***
The results show that, in the Dili Aquifer, some groundwater nutrient concentrations are approaching, however do not reach, the recommended guidelines for health. Ammonia concentrations are low across all samples. 3 of the 14 samples (21.4 %) are BDL and the values range from BDL – 0.2 mg/L N. Deep bores have the highest median values of 0.03 mg/L N. Nitrate values are approaching recommended guideline values in some samples with a range of 0.02 – 7.5 mg/L N. The highest value, GET611-18 is a shallow well of just 6 m near the centre of Dili. The closest sample location to GET611-18 is GET611-24.GET611-24 is also in the centre of Dili but is 24 m deep and has a significantly lower nitrate concentration of 1.1 mg/L N. Shallow samples have higher median values overall with a value of 3.1 mg/L N compared to deep samples containing a median value of 0.32 mg/L N.

All samples contain nitrite values BDL. Phosphate values are low with 2 of the 14 samples (14.3 %) below detection limit and a range of values from 0.01 – 0.05 mg/L P. Deep, shallow and river samples all have equal median values of 0.02 mg/L P. Total Oxidised Nitrogen: as N are similar to nitrate values with the highest median value of 3.1 mg/L N occurring from the shallow samples. The range of all samples is from 0.02 – 7.5 mg/L N.

***Pesticides***
All three samples tested: two deep wells and one river sample (problems in site access restricted the attainment of a shallow well sample) contain no concentrations above detection limit for the 109 different pesticides tested for.

### Localised Aquifer (Fractured)

***Field Parameters***
The conductivity of all fractured rock water samples are low ranging from 35.7 to 454.0 µs/cm. The pH of the fractured rock springs range from 6.24 to 7.49. The lake and river water samples have higher pH values of 7.50 and 8.29 respectively. These are similar to the water guideline range of pH 6.5 to 8.5. Redox potential (Eh) ranges from 63 to 187 mV. Dissolved oxygen (DO) has a wide range from 26.2 to 87.5 % saturation. This variation does not necessarily reflect the sampling from surface waters and springs. While both the river and the lake do have high DO, the spring samples can have equally high DO or low DO. This may be due to the diverse nature of individual springs. Temperature of waters ranges from 17.3 to 25.4 ºC. Cooler waters are associated with springs at higher elevations while the higher temperatures are from springs at lower elevations as well as surface waters of the lake and river samples.

***Major Elements***
The major anions of the fractured rock waters are dominated by carbonate. Carbonate has a wide range of values throughout the fractured rock of 10.8 to 246.0 mg/l. The highest carbonate value is associated with a spring GET611-2 that is near limestone units from another formation. The river sample, close to spring GET611-2, also has higher carbonate value of 97.6 mg/l which is likely due to the catchment containing a carbonate-rich source material. One other spring sample GET116-12 within the fractured rock, near Dili, has a high carbonate value of 146.0 mg/l. Apart from these three samples, two of which are associated with carbonate formations, the fractured rock waters have a much lower range of 10.8 to 22.2 mg/l. The molar ratio of carbonate to chloride and sulfate ions is consistently greater than 50% and typically greater than 70% but show a greater spread of values than the karst or sedimentary aquifers.

The major cation ratios for the fractured rock are spread between $Ca^{2+}$, $Na^{+}$ and $Mg^{2+}$ end members. Concentrations of major cations are generally low with $Ca^{2+}$ ranging between 0.7-79 mg/l, $Na^{+}$ 3.6-47.6 mg/l and $Mg^{2+}$ 0.8-21.6 mg/l. The higher concentration values are present within the spring GET611-6 and river GET611-2 sites at the southern extent of the Aileu Formation fractured rock, adjacent to older limestones, and the spring site GET611-12 at the northern extent of the Aileu Formation, adjacent to alluvial sediments.

The anion + cation section of the Piper plot shows the range in the distribution of water samples from the Ca-HCO3 dominance of GET611-6 and GET611-2 to Na-HCO3 dominance within the remainder of the fractured rock. As $Na^{+}$ becomes the dominant cation $Cl^{-}$ ratios also increase.

***Trace Elements***

The majority of trace elements in the fractured rock are below the laboratory detection limits and all are below health guidelines. Of the trace elements detected, the higher concentrations tend to be in the lake sample GET611-7. This appears to be partly due to the turbidity of the waters in the lake at the time of sampling with trace elements being contained within suspended solids rather than in the dissolved fraction. These results indicate that the waters of the Aileu Formation fractured rock area are generally low in trace elements and there are no regional trace element contributions.

***Nutrients***

Nutrients P in the form of phosphate, and N, in the form of ammonia and nitrate, are present in the fractured rock aquifer but largely in low concentrations. Concentrations of P in water samples range from 0.01-0.24 mg/L and are below detection limit in sites GET611-6, GET611-7, and GET611-12. Concentrations of N are below detection limits in surface waters in all forms with the springs ranging in concentration from 0.01-0.04 mg/L ammonia as N and from 0.03-0.71 mg/L nitrate as N. Nitrite was below detection limit at all sites.

### Fissured Aquifer (Karst)

***Field Parameters***

The conductivity of the waters from the karst aquifer of the Baucau Limestone is consistently low, ranging from 422-497 µS/cm. The pH also shows little variance from neutral ranging from 7.18-7.56. Eh sits between 100-151 mV and DO ranges from 59.9-83.0 % saturation.

***Major Elements***

The major element molar ratios from the Piper plot show that the karst aquifer is dominated by Ca-HCO3 type waters with greater than 90% of ions dominated by $Ca^{2+}$, relative to $Na^{+}$ and $Mg^{2+}$; and $HCO_3^{-}$, compared with $Cl^{-}$ and $SO_4^{2-}$. Unlike the sedimentary and fractured aquifer types the karst aquifer has little variation in major ion composition.

Concentrations of most major elements increase slightly with decreasing elevation ($Cl^{-}$ 5.1-5.9 mg/L, $SO_4^{2-}$ 1.2-3.4 mg/L, $Mg^{2+}$ 0.9-1.8 mg/L, and $Na^{+}$ 3.0-3.3mg/L. However the most abundant major ions $Ca^{2+}$ and $HCO_3^{-}$ do not share this trend and show variable concentrations with decreasing elevation having ranges of 82.6-100.0 mg/L and 218.0-262.0 mg/L respectively.

***Trace Elements***

Apart from Strontium and Barium, all trace elements analysed are at or below detection limits at all three sites of the karst aquifer. The concentrations of Strontium and Barium are low and range from 0.221-0.656 mg/L and 0.006-0.016 mg/L respectively.

***Nutrients***

Apart from nitrate, all P and N nutrients analysed (phosphate, ammonia and nitrite) where at or below detection limit. Nitrate is consistently low in all samples ranging from 1.1-1.4 mg/L as N.

### Seawater Signatures

Plotting $Na^+$ and $Ca^{2+}$ ratios against $Cl^-$ can be used to assess the similarity of waters to seawater ratios (Figure 32 and Figure 33). The graphs below show that only one of the coastal sedimentary groundwater samples is consistent with a seawater signature. This sample is near the Tasitolu salt lakes and in an area of seawater intrusion. This shows that the seawater-affected groundwaters plot on the seawater trend line. As none of the other coastal groundwater samples plot on the seawater signature this indicates that seawater is not interacting with groundwater resources close to the current main operating bores of Dili. However, it does show that seawater intrusion is occurring within close proximity of groundwater supplies and could be exacerbated by changes in the hydrogeology regime (i.e. changes in sea level and groundwater recharge).

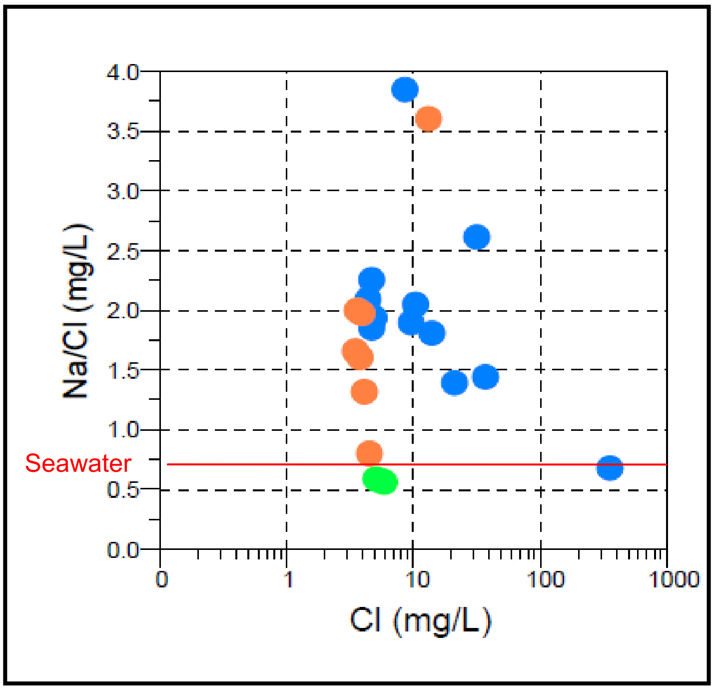



**Figure 32: Seawater signature Na/Cl ratio against Cl trends for intergranular (blue), localised (orange) and fissured (green) aquifers**

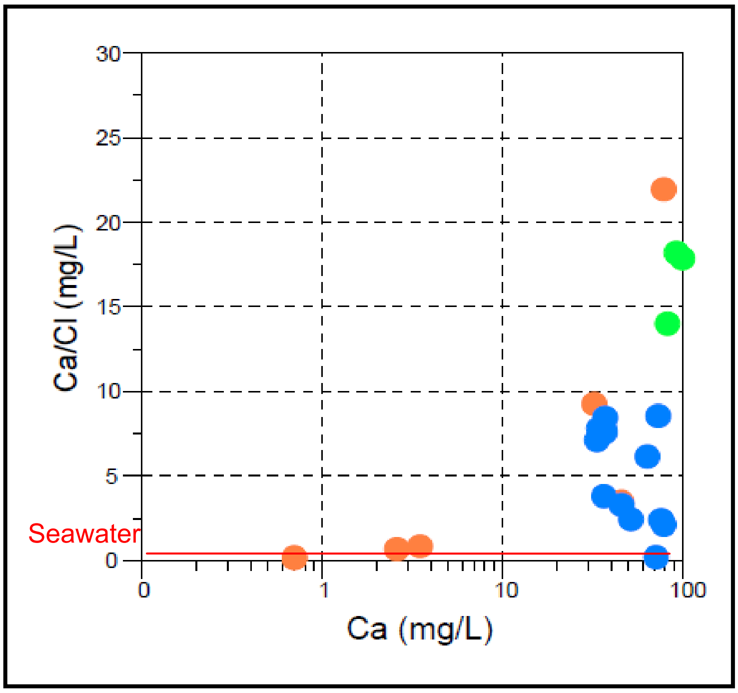



**Figure 33: Seawater signature Ca/Cl ratio against Cl trends for intergranular (blue), localised (orange) and fissured (green) aquifers**

### Chemistry results overview

Overall the chemistry of the Dili intergranular aquifer, Aileu localised fractured rock aquifer and Baucau Limestone fissured karst aquifer shows water that is fresh and free from any unsafe major element, trace element, nutrient or pesticide concentrations. EC values show the majority of aquifers have low salt content but that a sample near the Tasitolu salt lakes in Dili contains saltier water and this area should be monitored to follow any encroachment on fresh groundwater. This shows that Tasitolu, where recharge from rivers is minimal, is much saltier than areas directly adjacent to major rivers. This suggests that the degree of seawater intrusion is inversely proportional to the amount of river flow. There is a difference in chemistry between the shallow and deep water samples in the Dili aquifer indicating that there is a separation between deep confined and shallow unconfined aquifers. There is also a difference in chemistry between East and West sites in the Dili area indicating that the different catchments have produced distinct aquifers centred around the major rivers.

## GEOPHYSICS

A geophysical technique, the time domain electromagnetic (TDEM) method, was used in each of the case study locations to assist in the assessment of aquifer geometry and characteristics. This technique measured apparent conductivity to infer the presence or absence of groundwater and the salinity of the groundwater. For the full details of methods and results refer to the accompanying Geophysics Report.

### Intergranular Aquifer (Dili)

The geophysical survey of the Dili Aquifer ran in lines from the foothills to the coast (north to south) and from the Comoro River (west) to the Maloa and Benamau Rivers (east). The results show a high degree of variations in aquifer architecture both with depth and laterally. The soundings in the area of the Comoro river channel indicate a minimum depth to bedrock of 150 m. The soundings also indicate a shallow unconfined aquifer from around 0 – 40 m depth with a zone of clay lenses between 40 – 60 m depth, separating the shallow aquifer from a deeper confined (semi-confined) aquifer from around 60 to >150 m. In the east, towards Maloa and Benamau rivers, the soundings indicate a shallower depth to bedrock of around 50 – 100 m. These interpretations are largely consistent with the work done by JICA (2001). The veritable responses from soundings indicate internal compositional variations within each aquifer suggesting multiple overlaying lenses of sands/gravels and clays/silts rather than homogeneous continuous aquifers and confining layers. Soundings from the middle of the Dili aquifer area, between the major rivers of the east and west, indicate much higher concentrations of clays and smaller potential aquifer zones. These results indicate a general architecture of the Dili delta sediments consisting of two main aquifer zones centred around the main east and west river channels with variable clay lenses throughout. These clay lenses form a semi-confining layer in places.

The geophysical results also show the presence of high conductivity (highly saline water) within these coastal aquifers, adjacent to seawater. One highly conductive site is Tasitolu which sits adjacent to the Dili aquifer. This geophysical evidence combined with direct chemical analysis shows that seawater is saturating sediments proximal to major aquifers used to supply Dili. Additionally, a conductive zone below the mouth of the Comoro river at around 120 m depth may indicate the position of the freshwater/seawater interface. This indicates that the main aquifer system sits in connection with seawater and that the groundwater could be susceptible to seawater intrusion with changes in groundwater extraction, recharge or sea-level-rise.

### Localised Aquifer – fractured rock (Aileu)

Several individual (point) soundings were made on fractured rocks of the Aileu formation above Dili. These largely showed low conductivity indicating that the groundwater present is fresh, although the amount of water may be limited. Several soundings showed a slight increase in conductivity between 10 – 25 m depth indicating groundwater may be concentrated at shallow levels with flow focused in surface fracture sets between these depths. This is consistent with typical groundwater flow in fractured aquifers were fractures are concentrated closer to the surface.

### Fissured Aquifer – Karst (Baucau)

Geophysical survey lines were run north-south and east-west above a cave system on the Baucau plateau. The geology shows that the Baucau Limestone sits over a thick clay sequence with the limestone thinner on the plateau and thicker towards the coast. The geophysics gives a consistent low conductivity response for around 0-30 m depth with higher conductivity below 30m to a depth of around 100 m. These results indicate, at this site on the plateau, around 30 m of limestone aquifer (low conductivity) sitting above around 100 m of impermeable clays (higher conductivity), which is consistent with the anticipated aquifer structure. The results also show that the limestone has a slightly higher conductivity at around 15 m, indicating the presence of groundwater in the limestone above the limestone/clay interface. This is consistent with the observed flow of groundwater in cave systems below the survey area.

## KEY FINDINGS FROM CASE STUDY INVESTIGATIONS

The results of this study form direct observation, water chemistry analysis and geophysics. These results have been used to characterise the fundamental properties of the main aquifer system types of Timor-Leste. The principal findings of this work are:

*Intergranular Aquifers:*

- The Dili aquifer is highly heterogeneous and likely to have zones of preferential flow. Rather than containing large areas of homogeneous sand, the aquifers have many clay lenses which will require more detailed investigation to determine architecture for water prospectivity. As the Dili delta sediments formed by similar processes to many of the coastal alluvial deposits, other similar aquifers in Timor-Leste are likely to have the same heterogeneous characteristics;

- The unconsolidated alluvial aquifers of Dili were found to be centred around the dominant river systems. This predictability assists in the exploration of groundwater in Dili and additionally appears to be a common characteristic in coastal alluvial aquifers of Timor-Leste; and
- Seawater intrusion adjacent to major intergranular aquifers adjoining the coast appears to be common. Seawater intrusion seems to be prevented in the major aquifers due to the higher groundwater recharge associated with the dominant river systems. This indicates that regular flow from the dominant rivers currently controls seawater intrusion at present sea levels. Changes to river runoff, groundwater recharge or sea level may exacerbate seawater intrusion.

*Localised Aquifers:*

- In the localised aquifers of the Aileu fractured rocks, groundwater is concentrated near surface (permeability of the rocks decreases with depth) making localised flow likely to be dominant over regional flow;
- Springs discharging from local flow systems within the fractured rock show seasonal variation in groundwater flow in topographic highs (with many springs drying out) indicating that springs require recharge on an annual basis to be sustained and will therefore be susceptible to climate change; and
- Rivers in the localised fractured rock aquifer areas are fed by groundwater in the dry season showing that surface water in the dry season is also dependant on groundwater.

*Fissured Aquifers:*

- Springs discharging from the fissured limestone of the Baucau area show seasonal variations in topographic highs (plateaus) but permanent flows at lower topographies. This shows variability in the reliability of groundwater flow and the potential response to climate change across one aquifer resource type;
- Groundwater is principally near surface in limestone Baucau plateau due to underlying impermeable clays. This restricts the potential storage of groundwater in the karst aquifer system.

*All Aquifers:*

- Interaction of groundwater between aquifers appears to be important but was beyond the scope of this study and requires further detailed analysis;
- Interaction between surface water and groundwater also appears to be important, as demonstrated by the importance of river recharge for mitigating sea water intrusion and stream flow dependence on groundwater discharges via springs, but further investigation was beyond the scope of this study and requires further detailed analysis; and
- The high heterogeneity and localised nature of many of the aquifers assessed here indicate that local factors will be important to the character of groundwater flow and that climate change impacts associated with changed rainfall and/or sea level rise are likely to have immediate impacts on groundwater resources.

# Vulnerability Assessment of Climate Change on Groundwater Resources in Timor-Leste

Groundwater constitutes a significant freshwater supply in Timor-Leste. Climate change is expected to put additional pressure on available water resources from population growth, including urbanisation and economic and land-use change. The effect of climate change on water resource availability is one of the most challenging aspects of long-term sustainable water management. Although a number of studies have focused on climate change impacts on surface water resources, climate change effects on groundwater availability and quality have not been systematically addressed.

A systematic and succinct vulnerability analysis is presented below. This is followed by further details on the impacts and management of groundwater in a changing climate.

## GROUNDWATER VULNERABILITY ANALYSIS

Using the vulnerability framework previously outlined in the Introduction of this report, the results of this study can be used to describe climate change effects on aquifers. The principal components of vulnerability addressed in this study are the combination of aquifer 'Exposure' and 'Sensitivity' to a hazard to give the 'Potential Impact' of climate change. Combined with the 'Adaptive Capacity' to cope with the 'Potential Impact', the vulnerability of an aquifer to climate change can be estimated. The principal climate change hazards are outlined below followed by an analysis of the exposure (Table 3), sensitivity (Table 4), potential impact (Table 5), adaptive capacity (Table 6), and finally vulnerability of aquifers to climate change (Table 7).

Exposure + Sensitivity

Potential Impact + Adaptive Capacity

Vulnerability

**Vulnerability framework (as shown in Figure 1; Schroter et al., 2004)**

### Climate Change Hazards

The two principal climate change hazards to aquifers in Timor-Leste are 1) changes in rainfall and 2) sea level rise.

***Change in rainfall patterns***

A shift in climatic conditions has the potential to change the frequency and timing of rainfall (recharge) events, thus altering groundwater recharge regimes and thereby affecting groundwater availability. The extent to which groundwater availability is altered for a particular aquifer system will be dependent on the nature of climate change at the relevant location, and the sensitivity of recharge processes to those changes in climate. The Timor-Leste climate change projections indicate that an increasing proportion of rain will fall in intense events during the wet season and that there will be more prolonged dry seasons (BoM CSIRO, 2011).

The predicted increased intensity of rainfall may increase or decrease groundwater recharge depending on local factors. Additional work is required to assess the effect of increased rainfall intensity on aquifer groundwater resources. Increased periods of droughts, however, will almost certainly result in groundwater stress; as will the flow-on effects of increased use of groundwater to augment surface water supply during dry periods. This will especially be the case if there is the expected need for extra water that accompanies population growth and the expansion of agricultural and industrial activities. The predicted extended dry season is currently the clearest groundwater hazard to aquifers from climate change associated with rainfall , and the focus of this analysis.

#### *Sea level rise*

Sea level rise will change the dynamic balance of the groundwater-seawater interface and can cause seawater intrusion into freshwater aquifers. This may permanently affect groundwater quality making it unusable. In addition to subsurface seawater intrusion, sea level rise may also result in the permanent surface inundation of low-lying coastal regions and increase the frequency and intensity of temporary inundation through the occurrence of storm surges. This can also result in the intrusion of seawater into freshwater aquifers through downward seepage.

### Exposure

Exposure is the degree to which an aquifer comes in contact with a particular climate change hazard.

#### *Change in rainfall patterns*

All aquifers rely heavily on rainfall for groundwater recharge and may be exposed to changing rainfall. The potential change in rainfall distribution is unknown and it is not possible to predict which areas will have greater or less rainfall. As the general prediction is for roughly similar total annual rainfall, with a longer dry period and more intense wet period, it is likely that all aquifers will be exposed to changing rainfall.

#### *Sea level rise*

Intergranular aquifers are concentrated along the coastline of Timor-Leste. The process of weathering, transport and deposition of alluvial sediments in the mountainous terrain has resulted in Timor-Leste being largely skirted by a strip of intergranular aquifers that enter the sea. The proximity and connection of intergranular aquifers with the sea, combined with their low topographic relief, gives this aquifer type a high level of exposure to sea level rise.

While the older fissured karst aquifers are completely removed from the coast, the young fissured karst aquifers are common along the coastline in the east of Timor-Leste. However, uplift has raised the large portion of the young fissured aquifers away from the sea and only the topographic lows of steeply terraced platforms are in contact with the sea. The relatively small portion of the area of fissured aquifers in contact with the sea and steep relief give the fissured karst aquifers lower exposure to sea level rise.

The larger proportions of the localised fractured rock aquifers are inland, only contacting the coast along the north-east margin. Due to the mountainous topography, only a relatively thin strip of high relief localised aquifers are in contact with the sea and, like fissured aquifers, the exposure, compared with the area of the aquifer, is relatively small.

**Table 3: Exposure**

| Aquifer Type | Exposure to Rainfall Changes | Exposure to Sea Level Rise |
|---|---|---|
| Intergranular (Large Catchments)<br>Intergranular (Small Catchments) | High<br>High | High<br>High |
| Fissured (Topographic High)<br>Fissured (Topographic Low) | High<br>High | Low<br>Low |
| Localised (Topographic High)<br>Localised (Topographic Low) | High<br>High | Low<br>Low |

Exposure Classes: High; Medium; and Low.

## Sensitivity

Sensitivity relates to the intrinsic properties of an aquifer to resist the effects of climate change.

### *Change in rainfall patterns*

Intergranular aquifer sensitivity to rainfall change will depend on the size of the catchment area that feeds the aquifer. All intergranular aquifers will respond to rainfall through the amount of groundwater recharge from rivers, direct rainfall and adjacent aquifers. As the amount of groundwater recharge affects the balance of the seawater/freshwater interface, changes in rainfall will have a strong influence on the potential for seawater intrusion (as much influence as sea level rise). Intergranular aquifers with smaller catchment areas are shown to have significantly less recharge and are likely to be much more sensitive, responding rapidly to changes in rainfall. This indicates that intergranular aquifers with large catchment areas will be sensitive to changes in rainfall and those with smaller catchment areas will be highly sensitive.

Changes in rainfall for fissured karst aquifers will affect topographic highs more than topographic lows. While all areas of fissured aquifers will be affected by changes in rainfall, higher topographies have been shown to respond very rapidly and can dry out within one dry season. These higher topographies will be very sensitive to changes in rainfall, particularly the extended dry periods.

Like fissured aquifers, the localised fractured rock aquifers are more sensitive to rainfall changes at topographic highs due to the low groundwater storage resulting in rapid response between recharge and drying out of springs. Localised fractured aquifers will be sensitive with topographic highs being highly sensitive.

### *Sea level rise*

Coastal intergranular aquifers sit in balance with a seawater/freshwater interface that is dependent on the sea level. Increases in sea level will tend to push the seawater interface landward. Areas with small catchment areas were found to have more landward seawater interfaces and will be more susceptible to sea level rise. As the majority of intergranular aquifers in Timor-Leste are along the coast they will have a high sensitivity to sea level rise.

Like the intergranular aquifers, the effects of fissured karst aquifers will likely depend on the discharge flow rates of groundwater from catchment areas. The steep profiles and large inland area of fissured aquifers are likely to make them less sensitive to the effects of sea level rise.

Localised fractured rock aquifers have a similar connection with the sea as fissured aquifers, with high topographic relief, but potentially have less groundwater discharge and may be somewhat sensitive to sea level rise.

**Table 4: Sensitivity**

| Aquifer Type | Sensitivity to Rainfall Changes | Sensitivity to Sea Level Rise |
|---|---|---|
| Intergranular (Large Catchments)<br>Intergranular (Small Catchments) | Medium<br>High | High<br>High |
| Fissured (Topographic High)<br>Fissured (Topographic Low) | High<br>Medium | Low<br>Medium |
| Localised (Topographic High)<br>Localised (Topographic Low) | High<br>Medium | Low<br>Medium |

Sensitivity Classes: High; Medium; and Low.

## Potential Impacts

Potential impacts of a hazard on an aquifer are the combination of the exposure of an aquifer to a hazard and the sensitivity of the aquifer to that hazard.

### *Change in rainfall patterns*

Intergranular aquifers receive recharge directly as well as from streams and other aquifers. Extended dry periods will prolong periods without groundwater recharge and impact aquifers by producing lower groundwater levels. This will affect the groundwater storage, extraction of groundwater, sustainable yields, and the seawater/freshwater interface. The highest impact will be on aquifers with small catchments, with less potential recharge, and the effects are likely to occur more rapidly. However, all intergranular aquifers will be impacted by changes in rainfall.

Longer dry seasons are likely to cause reduced flows from fissured karst aquifer springs. The potential impact will be rapid and greater in topographic highs where springs dry out, extending periods of extreme water stress.

Localised fractured rock aquifers are likely to experience similar potential impacts to fissured aquifers with greater impact on springs in topographic highs. Additionally, the rivers that are fed by groundwater in topographic lows of the localised aquifers will receive less groundwater discharge, reducing flows.

### *Sea level rise*

Intergranular aquifers have both high exposure to sea level rise and are sensitive to seawater intrusion. The aquifers with smaller catchment areas have greater sensitivity and will have high potential impact. However, aquifers with large catchment areas are associated with highly utilised aquifers and the potential impacts will have greater consequences for the population making the potential impact high.

With low exposure to the sea and little groundwater extraction at sea level, the potential impacts of sea level rise are small on fissured karst aquifers apart from right on the coast. Localised fractured rock aquifers are expected to have a similar response to the fissured aquifers with relatively low potential impacts from sea level rise.

**Table 5: Potential Impacts**

| Aquifer Type | Potential Impacts to Rainfall Changes | Potential Impacts to Sea Level Rise |
|---|---|---|
| Intergranular (Large Catchments)<br>Intergranular (Small Catchments) | High (E = H, S = M)<br>High (E = H, S = H) | High (E = H, S = H)<br>High (E = H, S = H) |
| Fissured (Topographic High)<br>Fissured (Topographic Low) | High (E = H, S = H)<br>Medium (E = H, S = M) | Low (E = L, S = L)<br>Low (E = L, S = M) |
| Localised (Topographic High)<br>Localised (Topographic Low) | High (E = H, S = H)<br>Medium (E = H, S = M) | Low (E = L, S = L)<br>Low (E = L, S = M) |

Potential Impact Classes: High = higher exposure + sensitivity; Medium = lower sensitivity even if some exposure is present; and Low = lower exposure + sensitivity. E – Exposure; S – Sensitivity.

## Adaptive Capacity

Adaptive capacity refers to the management of the hazard and how the threat can be minimised. Different groundwater management options are suitable for the different hazards and aquifer types. Management options are outlined in more detail after the vulnerability analysis.

### *Change in rainfall patterns*

Intergranular aquifers have a number of management options due to the greater infrastructure in coastal areas and access to greater stream flow during the wet season. In areas were groundwater is currently being extracted, management of extraction rates can be instigated. Additionally, recharge can be enhanced by managed aquifer recharge in the wet season by capturing rainfall and stream waters. Managed recharge will be assisted in areas that have larger catchments and can utilise more surface waters.

Spring flows from fissured karst aquifers, especially in the topographic highs where springs seasonally dry up, will largely rely on rainfall, making management options limited. The capacity for managed groundwater recharge in higher topographies during the wet season is also limited due to the low storage capacity in these areas. The supply of water in topographic highs will increasingly rely on alternative sources of water such as piped water or relocation of people.

Localised fractured rock aquifers will have similarly constrained management options as fissured aquifers. As the groundwater naturally extrudes from the rock, reduced recharge could lead to greater seasonality in spring flow and water supply in topographically high areas may depend on the piping of water or redistribution of people.

### *Sea level rise*

Seawater intrusion can be managed actively in intergranular aquifers by reducing groundwater extraction or artificially pumping fresh recharge water into the aquifer. Passive management may include increasing surface water recharge through infiltration pits. This adaptation will only be possible if fresh water is available for this purpose. Reduced rainfall will exacerbate the potential of seawater intrusion from sea level rise. Additionally, surface inundation (via increased storm surge frequency and extent) and subsequent downward seepage of seawater can potentially be managed by conserving mangroves or through installation of tidal barrages.

Management options are reduced for fissured karst aquifers and localised fractured rock aquifers due to the absence of well infrastructure. There is little adaptive capacity for these aquifers to sea level rise and seawater intrusion (though, as noted above, the area affected in these aquifers is likely to be small).

**Table 6: Adaptive Capacity**

| Aquifer Type | Adaptive Capacity to Rainfall Changes | Adaptive Capacity to Sea Level Rise |
|---|---|---|
| Intergranular (Large Catchments)<br>Intergranular (Small Catchments) | High<br>Low | High<br>Low |
| Fissured (Topographic High)<br>Fissured (Topographic Low) | Low<br>Medium | Medium<br>Low |
| Localised (Topographic High)<br>Localised (Topographic Low) | Low<br>Medium | Medium<br>Low |

Adaptive Capacity Classes: High; Medium; and Low.

### Vulnerability

Vulnerability is the combination of the potential impacts of climate change and the adaptive capacity to offset the effects according to the vulnerability framework described above. The vulnerabilities for each aquifer environment in response to changes in rainfall and sea level rise are tabulated below.

#### *Change in rainfall patterns*

The vulnerability of intergranular aquifers to rainfall changes is dependent on the catchment area. A medium vulnerability has been assigned to intergranular aquifers with larger catchments due to the potential impact of reduced recharge during extended dry periods combined with the larger potential to manage the effects. High vulnerability is assigned to intergranular aquifers with smaller catchment areas due to the greater potential and rapid onset of the potential impacts.

Fissured and localised aquifer vulnerabilities are both dependent on topography. Topographic highs in both aquifer types are assigned a high vulnerability due to the rapid drying of springs and high gravity-driven flow during dry periods as well as limited adaptation options.

#### *Sea level rise*

As with changes in rainfall, the vulnerability of intergranular aquifers to sea level rise is dependent on catchment size. Aquifers with small catchments are assigned a higher vulnerability due to the potential impacts and high sensitivity of aquifers and lower capacity to adapt. Aquifers with larger catchments have less sensitivity and greater adaptive capacity and are assigned a medium vulnerability.

While fissured and localised aquifers have limited adaptation options they also have limited contact with the sea and high topographic relief that reduce the potential impact of sea level rise and are assigned low vulnerabilities.

**Table 7: Overall Aquifer Vulnerability**

| Aquifer Type | Vulnerability to Rainfall Changes | Vulnerability to Sea Level Rise |
|---|---|---|
| Intergranular (Large Catchments)<br>Intergranular (Small Catchments) | Medium (PI = H, AC = H)<br>High (PI = H, AC = L) | Medium (PI = H, AC = H)<br>High (PI = H, AC = L) |
| Fissured (Topographic High)<br>Fissured (Topographic Low) | High (PI = H, AC = L)<br>Medium (PI = M, AC = M) | Low (PI = L, AC = M)<br>Medium (PI = L, AC = L) |
| Localised (Topographic High)<br>Localised (Topographic Low) | High (PI = H, AC =L)<br>Medium (PI = M, AC = M) | Low (PI = L, AC = M)<br>Medium (PI = L, AC = L) |

Vulnerability Classes: High = higher potential impact + lower adaptive capacity; Medium = comparable potential impact and adaptive capacity; and Low = lower potential impact + higher adaptive capacity. PI – Potential Impact; AC – Adaptive Capacity.

## POTENTIAL ADAPTATION OPTIONS FOR THE IMPACTS OF CLIMATE CHANGE ON GROUNDWATER IN TIMORE-LESTE

Continuing water scarcity and climate change are placing pressure on groundwater reserves and the security of supply in Timor-Leste. The overarching aim of developing adaptation options is to make the Timorese people more resilient to climate change, recognising their high dependency on groundwater resources. Adaptation measures will be focused on reducing the vulnerability of groundwater systems to climate change and promoting sustainable water resource management. These measures will build on existing strategies and plans for water resource management within Timor-Leste including the National Priorities process. The following potential priority adaptation measures are proposed for Timor-Leste to reduce groundwater vulnerability:

***Integrated groundwater and surface water management using an adaptive management approach* -** Recognising that surface water and groundwater resources are fundamentally connected means that management of these resources needs to be coordinated. It is recommended to develop an integrated water resources management approach rather than a sectoral approach. Integrated management aims to ensure that the use of one water resource does not adversely impact on the other. It involves making decisions based on impacts for the whole hydrologic cycle. As an example water can be stored in the aquifer for use during droughts by increasing recharge during times of above-average water availability. As such, an aquifer can be a water source during dry periods, and a storage reservoir during wet periods.

***Targeted groundwater monitoring program* -** A targeted monitoring program is essential for managing any groundwater system. Groundwater monitoring provides information about groundwater availability and quality and it is an integral part of water management. Ideally groundwater level and quality monitoring should be carried out regularly in all areas where groundwater resources are extracted for use.

***Land use change* -** changing land use and land management practices may provide an opportunity to enhance recharge, to protect groundwater quality and to reduce groundwater losses from evapotranspiration. Changing crop type and improving water use efficiency provide an adaptation option for mitigating climate change impacts. Changes in land use should not result in adverse impacts to other parts of the environment.

***Build environmental friendly infrastructure -*** to protect water sources (springs, streams, wells, etc) and to provide safe water supply during climate change extreme event periods.

***Capacity building, education and training -*** to improve community and stakeholder understanding of climate risks and their capacity to participate in management responses and/or generate, modify or apply adaptations. Improve water source data collection and monitoring including meteorological data, water quality, water sources depletion and long-term water source availability in a climate change context.

***Develop policies and legislation -*** to protect critical surface and groundwater resources in an integrated manner leading to resilience to climate change.

***Develop institutions and human capacity -*** to adapt to the impacts of the climate change on water resources.

***Managed aquifer recharge (MAR) -*** Managed aquifer recharge is a method of adding a water source, such as recycled water, to an aquifer under controlled conditions. The main purpose of aquifer recharge is to store excess water for later use, while improving water quality by recharging the aquifer with high quality water. MAR is increasingly being considered as an option for improving the security and quality of water supplies in areas where they are scarce due to climate change. It offers several potential benefits, including storing water underground for future use, securing and enhancing water supplies, improving groundwater quality, preventing saltwater from intruding into fresh coastal aquifers, stabilising or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, and enabling reuse of waste or storm water.

## CHALLENGES AND CONSTRAINTS ON GROUNDWATER MANAGEMENT ADAPTATION

Groundwater availability is strongly influenced and constrained by the local geographical and climatic environment. Management of Timor-Leste's groundwater resources will need to take into account the monsoonal recharge events as well as the relatively small size of aquifers. Large seasonal variations in groundwater levels due to variation in rainfall will need to be incorporated into management plans as an ongoing stress. These seasonal variations also highlight that the small scale of aquifers in Timor-Leste is likely to lead to relatively rapid climate change impacts on groundwater.

Groundwater management is an essential component of overall water management in Timor-Leste. Management of groundwater resources requires knowledge of the potential threats and the processes that drive them, including climate change. Effective management of groundwater will require a monitoring framework and action plans for management scenarios. Informed groundwater management guidelines that capture and communicate groundwater knowledge from communities, NGOs, planners, policy-makers and groundwater projects are needed. Given the current limited knowledge of groundwater, as well as imminent climate change impacts, these guidelines will need to be updated regularly, as new information is made available. The challenge will be to build the capacity and resources for efficient groundwater management in a changing climate.

Ongoing groundwater monitoring is crucial to groundwater management: understanding groundwater systems and preventing potential threats to groundwater relies on complete monitoring data. To identify the effects of climate change, monthly monitoring data is required for years to decades. There is strong potential for improvements in groundwater monitoring capacity in Timor-Leste as datasets are currently incomplete. Additionally, monitoring currently takes place at the site of groundwater extraction, giving no warning of potential threats until the effects impact the supply network. Groundwater monitoring needs to take place with dedicated observation wells to provide warning of potential threats before the impacts reach extraction wells.

The key challenges are to:

- Develop groundwater monitoring networks that target the potential threats;
- Build in-country technical capacity and resources to carry out the work;
- Develop guidelines that support informed monitoring of groundwater; and
- Develop national policies and programs to address groundwater knowledge gaps and foster best practice management.

# Knowledge Gaps and Recommendations

## KEY WATER MANAGEMENT ISSUES IN TIMOR-LESTE

Timor-Leste's economy and the livelihood of its communities are heavily dependent on groundwater resources. Continuing water scarcity and climate change are placing pressure on groundwater reserves and the security of supply in Timor-Leste. Recently, the East Timor National Adaptation Programme of Action (NAPA) identified food and water security as the most important national priority. In addition, an Independent Progress Review of the Timor-Leste RWSSP undertaken in April 2010 indicates that "continued work by RWSSP and DNSAS on issues of water resource management and source protection is necessary to ensure sustained supply of water to communities".

Significant groundwater resources are present in parts of the country, some of which are being exploited in an uncoordinated manner. Communities face dwindling access to water during the dry season, when surface waters dry up, often relying solely on groundwater. These groundwater springs that many communities rely on can also be influenced during the dry season and may be reduced considerably in flow or cease altogether.

Unfortunately, there is very limited groundwater expertise within DNGRA or the Timor-Leste Government. This lack of capacity is a serious limitation in allowing the uptake of the benefits of the GA-CDU project, which then impacts on the future management, policy development and planning. There is an ongoing and urgent need to develop the groundwater skills, technical capacity and available knowledge for DNGRA and the Timor-Leste Government to ensure the sustainability of water resources through effective assessment, monitoring, management, regulation and decision-making that is based on sound evidence.

## KNOWLEDGE GAPS

There are some major gaps remaining in our knowledge of 1) Timor-Leste's groundwater resource characteristics (such as the size, location, dynamics and sustainability of extraction); 2) interactions and connectivity between groundwater and surface waters (including rivers, lakes and springs); and 3) potential threats to groundwater resources (e.g. salt water intrusion and other contaminants). More specifically, knowledge gaps in the understanding of East Timor groundwater systems include:

- Paucity of national data on groundwater location, availability and quality;
- Poor understanding of groundwater systems, springs and surface water connectivity;
- Poor understanding of groundwater recharge and quality under current climate and the likely effects of climate change;
- Limited understanding of seasonal climate variations and water storage options;
- Limited understanding of coastal groundwater resources in low lying areas and potential threats to the resource, in particular salt water intrusion into fresh groundwater reserves due to over-use and climate change; and
- Lack of standardised approaches to groundwater use, assessment and management.

These groundwater knowledge gaps inhibit policy development, water planning and groundwater management and are further exacerbated by limited technical capacity.

## RECOMMENDATIONS

A number of applied research, capacity building and communication activities are proposed to ensure effective management of groundwater resources and source protection in Timor-Leste. A wide range of benefits for Timor-Leste communities are anticipated from the proposed activities. These activities will ultimately help to develop national water management policy and governance arrangements in Timor-Leste.

### Proposed key applied research activities:

- Monitoring strategy and development of monitoring bores;
- Undertake groundwater resource assessments in targeted priority areas to improve the understanding of groundwater systems, including their relationships to springs and surface water connectivity under current climatic conditions;
- Investigate the impacts of seasonal and decadal climate variability on groundwater recharge, groundwater availability and groundwater quality including springs;
- Initiate and establish data collection and information storage systems for water resources that target the key management objectives for the water resource;
- Assess the vulnerability of coastal groundwater resources currently affected by seawater intrusion and potentially at risk in the future as a consequence of over-use and sea-level rise due to climate change;
- Assess opportunities for appropriate use of Managed Aquifer Recharge (MAR), such as storage and reuse of excess surface runoff as an alternate water supply option.
- Filling in groundwater resource knowledge gaps via Timor-Leste hydrogeological mapping and measurement;
- Evaluate the usefulness of various groundwater assessment tools such as remote sensing, geophysics and hydrochemistry for assessing and managing groundwater resources;
- Review of current water management practices, policies and supply for Timor-Leste, and an assessment of an Integrated Water Resources Management approach rather than a sectoral approach;
- Review of current NGO and donor activities and their alignment with a sector-wide approach to funding water resource management – currently ad hoc and not necessarily aligned with governmental and community priorities; and
- Further work on assessing water security vulnerability in rural communities, particularly those identified through the current project as low-yielding water-insecure aquifers.

### Proposed key capacity building and institutional strengthening activities:

***Short term immediate needs:***

- Training in water source data collection and monitoring including meteorological data, water levels and quality, groundwater database development and GIS mapping;
- Technical training on groundwater assessment monitoring, management and other skills for identified staff within Timor-Lester Government;
- Provision of assistance, mentoring and training in policy and governance to DNGRA and Timor-Leste Government staff;
- Develop institutional and human capacity to adapt to the negative impacts of climate change on water resources;
- Addressing vulnerable people’s rights including women in water-related legislation, including integrating these groups in decision making about water legislation and water resource management; and
- Raising public awareness about groundwater resources and its use as a water supply.

***Long-term capacity building in groundwater management through: (5 yrs or more)***

- Develop relevant curriculum for inclusion in the Faculty of Agriculture, Faculty of Engineering, Faculty of Education within the National University of Timor Loro Sae and the Dili Institute of Technology.
- Build the capacity of relevant teaching staff within these institutions in groundwater technical skills and knowledge
- Provision of tertiary higher education and technical scholarships to grow the human resource base for the long term.

**Proposed key communication activities:**

- Awareness raising activities aimed at increasing uptake of water harvesting within rural and urban communities to reduce depletion of water resources (groundwater, surface water including springs);
- National Water Summit – as a focal point for gathering all Timor-Leste Government agencies, NGOs, donors, educational institutions, community representatives, and other stakeholders with an interest in water resources to disseminate the outcomes of the current project, raise the profile and status of DNGRA, and highlight the importance of sustainably managing water resources; and
- Identification and development of effective linkages between key Timor-Leste directorates with expertise relevant to water management including GIS, water analysis and environmental analysis.

# References


Abbs, D., 2010. The impact of climate change on the climatology of tropical cyclone in the Australian region. CSIRO Marine and Atmospheric Research Report,. *Australian Journal of Soil Resources*.

ARPAPET, 1996. Agroclimatic Zones of East Timor, Indonesia-Australia Development Cooperation Agricultural and Regional Planning Assistance Program East Timor, Dili, Timor.

Asian Development Bank, 2004. Integrated Water Resource Management "Water for All - Water for Growth", Asian Development Bank TA:TIM 3986 Timor-Leste Integrated Water Resources Management Technical Assistance. Asian Development Bank, Dili, Timor-Leste.

Audley-Charles, M., 1965. The Geology of Portuguese Timor. *Memoirs of the Geological Society of London*, **4**, 4-84.

Australian Bureau of Meteorology and CSIRO, 2011. Climate Change in the Pacific: Scientific Assessment and New Research. Volume 1: Regional Overview. Volume 2: Country Reports.

Barnett, J., Dessai, S. and Jones, R., 2007. Vulnerability to Climate Variability and change in East Timor. *Ambio*, **36**(5), 372-379.

Costin, G. and Powell, B., 2006. Situation Analysis Report: Timor-Leste. In: Australian Water Research Facility; Brisbane (Editor). International Water Centre,, pp. 87.

Dolcemascolo, G., 2003. Climate Risk and Agriculture in Timor Loro'Sae. *In: Report of a Seminar Barbados, July 24 – 25, Adaptation to Climate Change and Managing Disaster Risk in the Caribbean and South-East Asia. 2003. Asian Disaster Preparedness Center (ADPC)/Inter-American Development Bank/CDERA.*

Durand, F., 2006. East Timor, a country at the crossroads of Asia and the Pacfic: A geo-historical atlas. IRASEC (Research Institue on Contemporary Southeast Asia), Bangkok, 198 pp.

Fenco Consultants, 1981. Sumbawa Water Resources Development Planning Study. Hydrology Report, Technical Report No. 2. Directorate General of Water Resources Development, Ministery of Public Works, Jakarta.

Fetter, C.W., 2001. Applied Hydrogeology. Pearson Education International, New Jersey.

Fox, J.J., 2003. Drawing from the past to prepare for the future: responding to the challenges of food security in Timor-Leste. In: Helder da Costa, Colin Piggin, Cesar J da Cruz and J.J. Fox (Editors), Agriculture: New Directions for a New Nation - Timor-Leste. ACIAR Proceedings No. 113.

Grady, R.F.B.A.E., 1981. Deformation and metamorphism of the Aileu Formation, north coast, East Timor and its tectonic significance. *Journal of Structural Geology*, **3**(2), 25.

Hinkel, J. and Klein, R.J.T., 2006. Integrating knowledge for assessing coastal vulnerability to climate change. *In*: L. McFadden, R.J. Nicholls and E.C. Penning-Rowsell (Editors), *Managing coastal vulnerability: An integrated approach (draft chapter forthcoming)*, Elsevier Science, pp.

IPCC, 2007. Summary for Policymakers. *In*: M.L. Parry, O. F.Caniani, J.P. Palutikof, P.J.v.d. Linden and C.E. Hanson (Editors), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, pp. 7-22.

JICA, 2001. Japan International Cooperation Agency: The study on urgent improvement project for water supply system in East Timor.

Katzfey, J., McGregor, J., Nguyen, K. and Thatcher, M., 2010. Regional Climate Change Projection Development and Interpretation for Indonesia, The Centre for Australian Weather and Cliamte Research; A partnership between CSIRO and the Bureau of Meteorology, Canberra.

Keefer, G., 2000. Report on the Restoration of Meteorlogical Network - Timor Loro'Sae, United Nations Transitional Administration in Timor-Leste, Dili.

Kirono, D., 2010. Climate change in Timor-Leste - a brief overview on future climate projections, CSIRO, Canberra.

Klein, R.J.T. and Nicholls, R.J., 1999. Assessment of coastal vulnerability to climate change. *Ambio*, **28**(2), 182-187.

Kuleshov, Y., Min, F.C., Qi, L., Chouaibou, I., Hoareau, C. and Roux, F., 2009. Tropical cyclone genesis in the Southern Hemisphere and its relationship with ENSO. *Ann. Geophys.*, **27**, 2523-2538.

Lapidus, D.F., Winstanley, I., MacDonald, J. and Burton, C., 1987. Collins internet-linked dictionary of geology. HarperCollins London, 480 pp.

Monk, K., de Fretes, Y. and Lilley, G., 1997. The ecology of Nusa Tenggara and Maluku. The ecology of Indonesia series, V. Periplus Editions, Singapore, 965 pp.

Myers, B., Fisher, R., Paul, T., Wurm, P. and Campbell, A., 2012. The Vulnerability of Groundwater Resources to Climate Change in Timor-Lest. *Prepared by Research Institute for the Environment and Livelihoods, Charles Darwin University for the Australian Government, Department of Climate Change and Energy Efficiency, Canberra*.

Sandlund, O.T., Bryceson, I., Carvalho, D.d., Rio, N., Silva, J.d. and Silva, M.A., 2001. Assessing Environmental Needs and Priorities in Timor-Leste: Issues and Priorities, United Nations Development Programme (UNDP), New York: UNDP.

Schröter, D., Metzger, M.J., Cramer, W. and Leemans, R., 2004. Vulnerability assessment - analysing the human-environment system in the face of global environmental change, Kalmar University, Sweden.

Schwab, D.R.P.F., 1996. Sedimentary Geology. W. H. Freeman and Company, New York, 575 pp.

Schwartz, P.A.D.F.W., 1990. Physical and Chemical Hydrogeology. John Wiley and Sons, Inc., Canada, 824 pp.

Seeds of Life, 2004. Current Conditions and predicted changes to rainfall and temperature in Timor-Leste due to climate change, Seeds of Life,, Dili.

Sherif, M.M. and Singh, V.P., 1999. Effect of climate change on sea water intrusion in coastal aquifers. *Hydrological Processes*, 13, 1277-1287.

Sjapawi, T.A.R.M.E.M.d.S.B.H.H.A., 1996. Structural and Depositional History of East Timor. *Proceedings, Indonesian Petroleum Association*, 25th Silver Anniversary Convention, 295 - 311.

SNC-Lavalin International, 2001. Feasibility and Engineering Study in Respect of Rehabilitation of Identified Irrigation Schemes in East Timor. In: Agricultural Affairs Department (Editor). United NationsTransitional Administration in East Timor (UNTAET).

Sousa, E., 1972. Escobo duma Caracterizacao Agroclimatic da Provincia de Timor. In: M.d.E.A.d. Ultramar (Editor). Comunicacoes - Missao de Estudos Agronomicos do Ultramar, Dili.

Survey, C.G., Groundwater Atlas of Colorado.

Tanaka, M., 1994. The onset and retreat dates of the Austral summer monsoon over Indonesia, Australia and New Guinea. *J. Met. Soc. Japan*(72), 255-267.

UNESCO, 1983. International legend for hydrogeological maps - revised edition. In: UNESCO Technical Document (Editor). UNESCO Technical Document. UNESCO, pp. 51.

United Nations, 2003. Geology and Mineral Resources of Timor-Leste, *Atlas of Mineral Resources of the ESCAP Region*, United Nations, pp.

Voice, M., Harvey, N. and Walsh, K., 2006. Vulnerability to Climate Change of Australia's Coastal Zone: Analysis of gaps in methods, data and system thresholds., Report to the Australian Greenhouse Office, Canberra, Australia.

Vong, A., Lopes, S., Silva, M.d. and Neupert, R., 2006. Population Projections 2004-2050: Analysis of Census Results. In: National Statistics Directorate (Editor). National Statistics Directorate; Timor-Leste,, pp. 80.

Wallace, L., Sundaram, B., Brodie, R.S., Dawson, S. and Furness, L., 2012. Hydrogeology of Timor Leste, Geoscience Australia.

Yance, S., 2004. Assessment of water availability and water demand in Timor-Leste at river basin level, Asian Development Bank, Dili.

# Appendix 1: Preliminary Analysis of Additional Products Relevant to Climate Change Impacts on Groundwater

This is a preliminary analysis of an additional product of a national groundwater recharge map. The proposal has now been accepted by stakeholders and funding bodies. The final outputs will be presented in the national hydrogeology map of Timor-Leste to be produced in October 2012.

## NATIONAL POTENTIAL GROUNDWATER RECHARGE MAP

Recent climate change predictions (Barnett et al., 2007; Kirono, 2010; Australian Bureau of Meteorology and CSIRO, 2011) indicate changes in rainfall in Timor-Leste. The projections also indicate an increasing proportion of rain will fall in intense events. A shift in the climatic conditions has the potential to change the frequency and timing of recharge events altering the groundwater recharge regime. Understanding the impact of climate change on groundwater recharge in Timor-Leste requires an understanding of how the regularity and magnitude of larger rainfall events changes, as well as changes to average conditions.

A national potential groundwater recharge map would show the critical areas where Timor-Leste's aquifers are recharged by rainfall. Groundwater recharge is typically not uniform and discrete recharge areas are relied upon to supply water to an aquifer system. This map would be used to show the locations where changes in rainfall will most affect groundwater resources. This would allow for the development of management options such as Managed Aquifer Recharge to adapt to climate change impacts.

Two of the initial input datasets to this aquifer recharge map in the current study have already been used as a proxy for groundwater sensitivity to reduced water availability in the current study, (Myers et al., 2012) Chapter 6, 38-40pp. The aquifer yield/sensitivity map presented in the current report (above) was combined with the rainfall map to show areas with higher and lower water availability (Myers et al., 2012), Chapter 6, 38-40pp. Given the limited amount of information available to the project, this is a useful first approximation of vulnerable areas as rainfall and aquifer yield are the primary sources of water. However, to account for the complexities of groundwater recharge, additional datasets are required.

During the course of the current study Geoscience Australia were granted access to the fundamental datasets needed for groundwater recharge estimates by Timor-Leste Government Directorates. These include rainfall, landcover, topography and soils which have been reclassified and combined with the hydrogeology map produced in this report. The reclassified national input maps (Figure 34, Figure 35, Figure 36, Figure 37 and Figure 38) and a draft national groundwater recharge map (Figure 39) are presented below. The draft recharge map shown is a one-to-one overlay of the critical datasets (five input datasets ranked from 1-3 giving a recharge map with a ranking from 5-15), the actual recharge will require further analysis of the relative contributions of the datasets to recharge for the Timor-Leste environment.

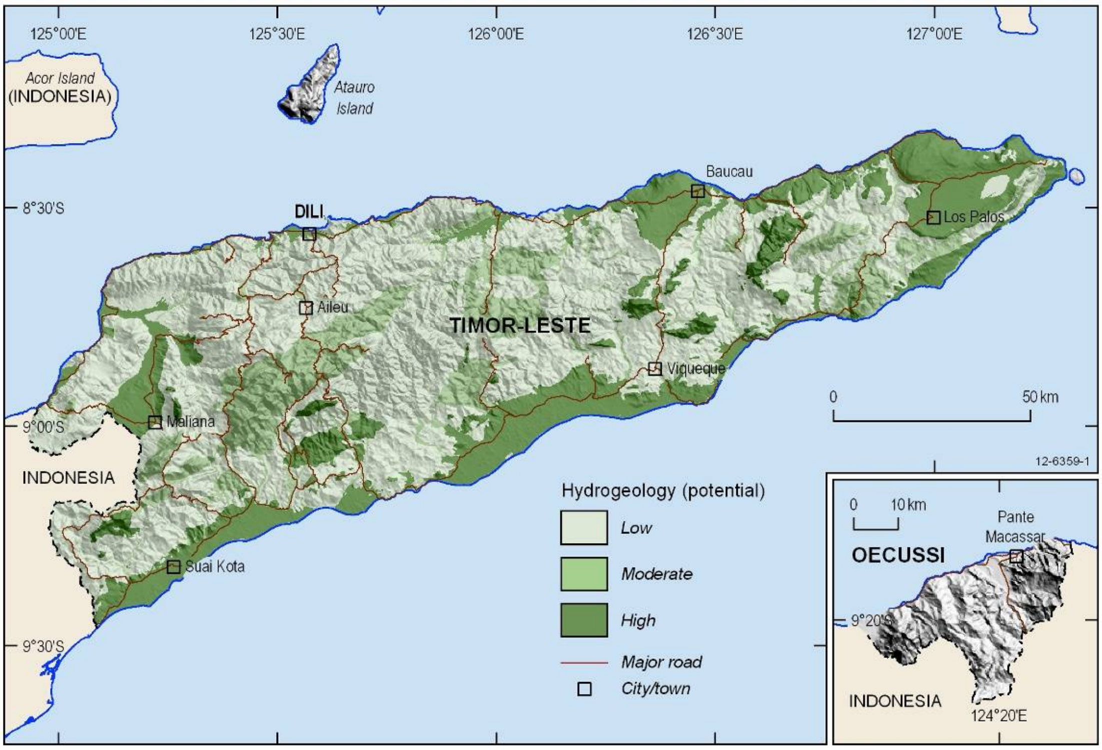



**Figure 34: Groundwater recharge map input data - reclassified hydrogeology**

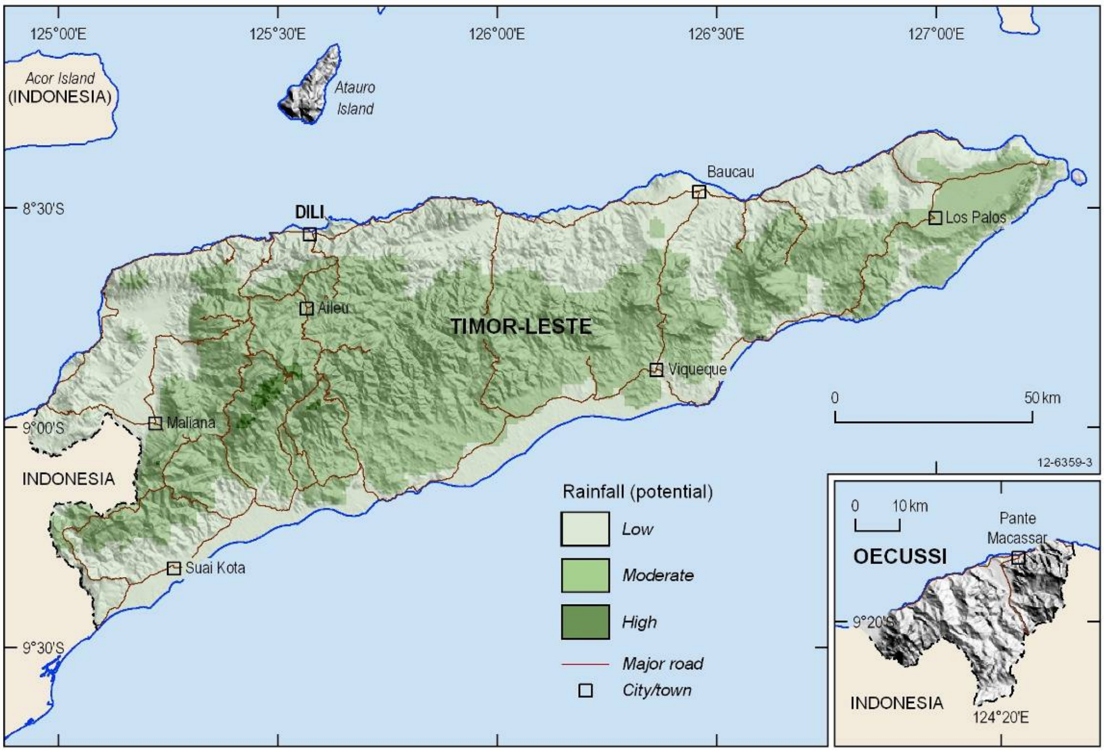



**Figure 35: Groundwater recharge map input data - reclassified rainfall**

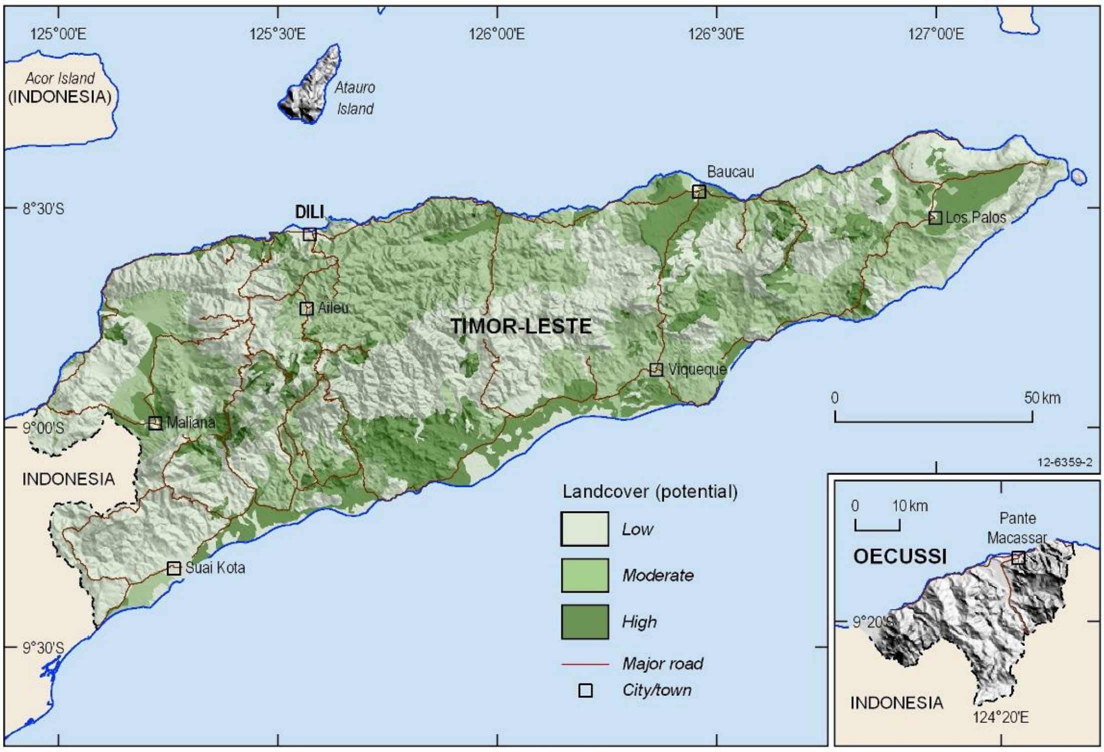



**Figure 36: Groundwater recharge map input data - reclassified landcover**

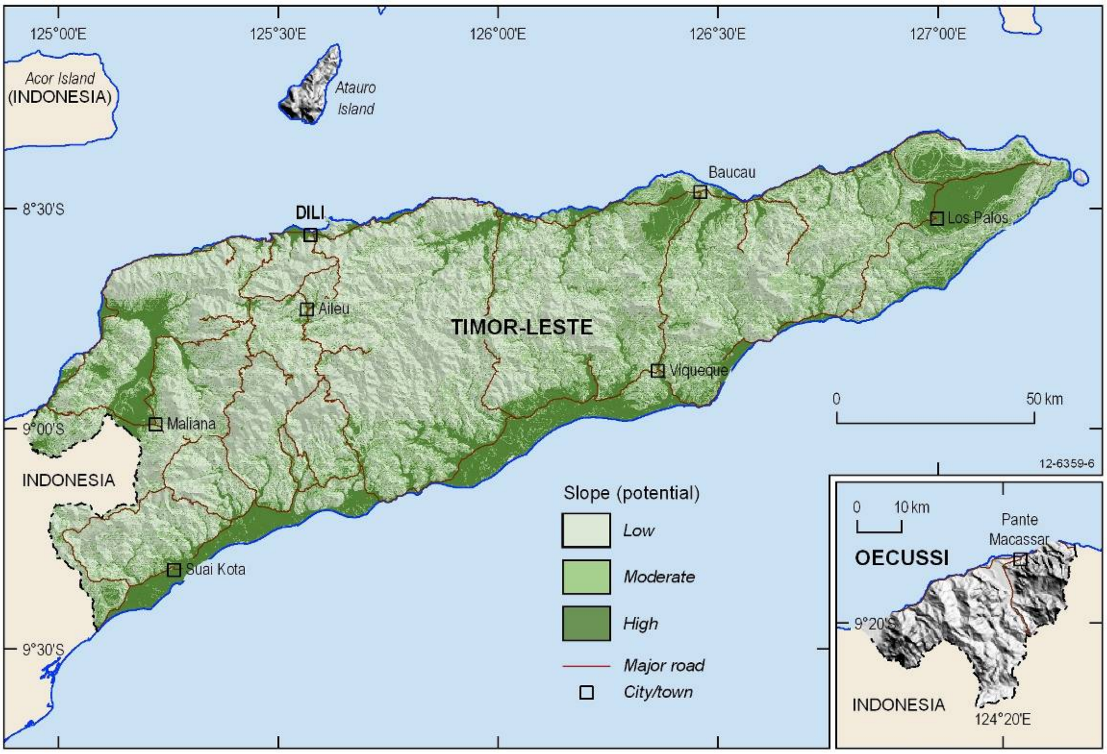



**Figure 37: Groundwater recharge map input data - reclassified topography: slope**

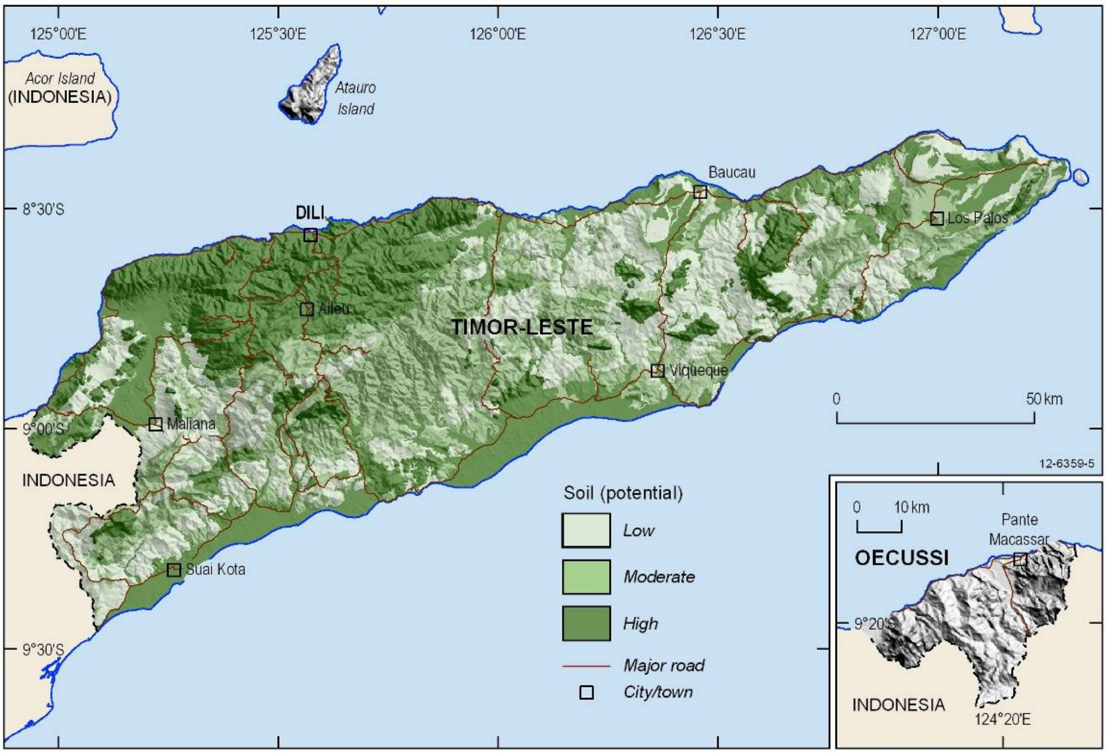



Figure 38: Groundwater recharge map input data - reclassified soil type

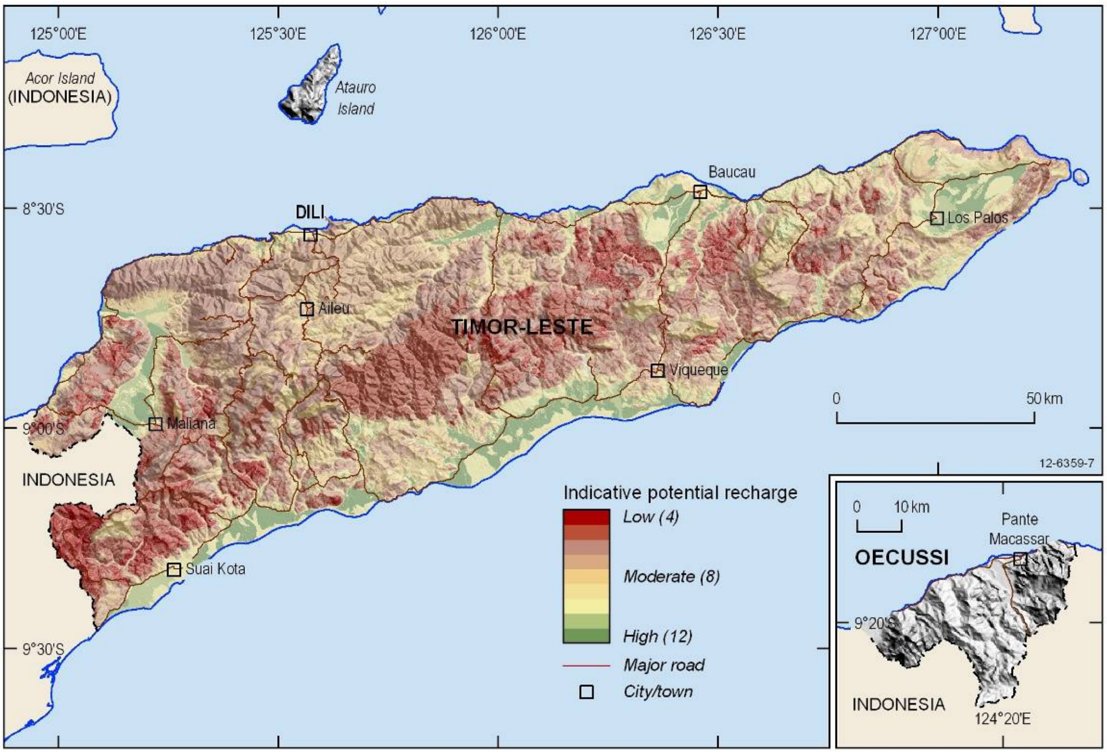



Figure 39: Draft groundwater recharge map – composite datasets 1:1 ratio