Catchment Hydrology and Landcover in Karst Savannas: A Case Study in East Sumba, Indonesia

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

Signature:  Date: 19/04/2024

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Publications

Other publications

Baffour, B., Aheto, J. M. K., Das, S. **Godwin, P.**, & Richardson, A. (2023). Geostatistical modelling of child undernutrition in developing countries using remote-sensed data: evidence from Bangladesh and Ghana demographic and health surveys, *Scientific Reports*, *13*, 21753. https://doi.org/10.1038/s41598-023-48980-y

Narayan, M., Evans, K., Lamsal, B., Thapa, R., Miller, J. Hobgen, S., Myers, B., Wurm, P., **Godwin, P.**, Riwu Kaho, N., & Markus, J. (2017). Deployment of Open Data Kit for Information Management for Various Engineering Projects In Rural, Indonesia. *International Research Journal of Electronics and Computer Engineering*, *3*, 1–6. https://doi.org/10.24178/irjece.2017.3.1.01

Conference presentations

Godwin, P., Duvert, C., & Lambrinidis, D. (2017). Stable isotope composition of precipitation and groundwater in a wet-dry tropics karst area (East Sumba, Indonesia) [Conference presentation]. Australasian Groundwater Conference Abstracts. Australia

Abstract

Shallow groundwater systems are a critical water source to communities in resource-poor tropical savanna regions, where karstic landscapes are particularly prone to water insecurity. There has been limited investigation into, and development of water resources in, these areas and many peoples' livelihoods are constrained by the need to travel significant distances from home in order to obtain water for household and productive use. Springs are particularly important sources of perennial household water supply. It is thus crucial to understand controls on groundwater availability in these contexts in order to support sustainable use. The aim of this study is to support land-use planning by increasing the understanding of landcover as a control on recharge to shallow groundwater in a karstic catchment of the tropical savanna in East Sumba, Indonesia, with a focus on two key research questions. (1) What are the key environmental controls on groundwater recharge in tropical karst savannas? (2) What is the influence of catchment revegetation on groundwater recharge? To address these questions, the study employs remote sensing approaches to identify trends in NDVI and its relationship with available rainfall and soil moisture; hydrochemical and isotope analyses to study flowpaths and recharge rates; and field and lab analyses of soil characteristics and infiltration potential tests in order to measure the influence of landcover on infiltration to the vadose zone.

The study finds that epikarst and groundwater storage are both used by woody vegetation in the Larawali catchment, particularly during the dry season, while soil moisture is the key water source during the wet season. Shrink-swell soil characteristics are found to be an important control on infiltration and subsequent deep drainage, and are more important than landcover during the early wet season. Following soil saturation, however, the high macroporosity that results from woody vegetation root channels promotes rapid infiltration and drainage through preferential pathways. Analyses of major ions and δ^2H and $\delta^{18}O$ established that recharge to epikarst and shallow groundwater storage is from local meteoric sources and occurs within a period of a few months. All three springs and two wells were identified as being of a Ca-HCO_3 water type. Low Mg/Ca ratios of spring and well water

provide evidence of short residence times within the karst groundwater storage and likely rapid conduit flow. The chloride mass balance found that the recharge fraction of rainfall for groundwater in the Larawali catchment is between 15% and 30%, with annual average recharge of 172 mm.

The study provides a conceptual model of the ecohydrological system of the Larawali catchment and concludes that landcover provides some control over rates of infiltration through the soil layer and into the epikarst. It is determined that woody vegetation in the catchment has, in general, a greater evapotranspiration potential than herbaceous vegetation, however, the characteristics of precipitation and the lithosphere may be more significant controls of groundwater recharge than the structural differences between woody and non-woody vegetation. It is important, therefore, to further examine functional vegetation traits in the context of land use planning, revegetation and Farmer Managed Natural Regeneration programs, and also to include local knowledge in future studies of the karst tropical savanna ecohydrological system.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

AHP .... Analytical Hierarchy Process

ANU .... Australian National University

BATAN .... Indonesian Research Organisation for Nuclear Energy

BMKG .... *Badan Meterologi, Klimatologi, dan Geofisika Indonesia* (Body for Meteorology, Climatology and Geophysics, Indonesia)

BS .... Bare Soil

CDU........................ Charles Darwin University

CHIRPS .... Climate Hazards Group Infrared Precipitation with Station data

CMB .... Chloride Mass Balance

CSIRO .... Commonwealth Scientific and Industrial Research Organisation

CV........................... Coefficient of Variation

DEA........................ Digital Earth Australia

DEM .... Digital Elevation Model

EC .... Electrical Conductivity

ENSO...................... El Niño Southern Oscillation

FMNR..................... Farmer Managed Natural Regeneration

GDEM .... Global Digital Elevation Map

GEE .... Google Earth Engine

GIMMS................... Global Inventory Modelling and Mapping Studies

GIS.......................... Geographical Information System

GMWL .... Global Meteoric Water Line

ICP-OES .... Inductively Coupled Plasma – Optical Emission Spectrometry

ICRAF .... World Agroforestry Centre

INFOCUS .... Increase Food Security within the Community through Sustainable Livelihood and Natural Resources Management System

IRED .... Rural Economic Development Project Indonesia

KOPPESDA .... *Koordinisasi Peneletian Pengelolaan Sumberdaya Alam* (Coordination of Natural Resource Management Research)

K_s .... Saturated Hydraulic Conductivity

LAI .... Leaf Area Index

LFA......................... Landscape Function Analysis

LI .... Leakiness Index

LMWL.................... Local Meteoric Water Line

MD.......................... Moderately Dry

MK.......................... Mann Kendall

MODIS .... Moderate Resolution Imaging Spectroradiometer

MW......................... Moderately Wet

NDVI .... Normalised Difference Vegetation Index

NPV .... Non-Photosynthetic Vegetation

NTT .... *Nusa Tenggara Timur* (East Nusa Tenggara)

ODK .... Open Data Kit

OLSR...................... Ordinary Least Squares Regression

PTF .... Pedotransfer Function

PUSAIR.................. Indonesian Water Resources Research and Development Centre

PV .... Photosynthetic Vegetation

PWLSR................... Precipitation Weighted Least Squares Regression

RF .... Recharge Fraction

RISTEKDIKTI .... Ministry of Research and Technology, Indonesia

S-GRAFS................ Satellite-Guided Root-zone moisture Analysis and Forecasting System

SMAP .... Soil Moisture Active Passive

SOI.......................... Southern Oscillation Index

SPI .... Standardised Precipitation Index

SPOT .... *Satellite Pour l'Observation de la Terre* (Satellite for the Observation of Earth)

SVDV .... Synchronous Vertical Dual View

UNDANA............... Universitas Nusa Cendana

UNKRISWINA ...... Universitas Kristen Wira Wacana Sumba

USA .... United States of America

USDA .... United States Department of Agriculture

VD .... Very Dry

VW .... Very Wet

WCC....................... Windowed Cross Correlation

ZMK .... Mann Kendall Trend Statistic

Glossary and Non-English terms

Epikarst	Transition zone between soil and bedrock in karst landscapes
Hydraulic conductivity	The ability of soil to conduct water
Karst	Highly soluble carbonate rock with well-developed secondary porosity
Lahan kritis	A legally defined term in Indonesia to mean degraded land with loss of ecological function
Woody vegetation	Trees and shrubs

Chapter 1. Introduction and Background

1.1. Water security challenges in karst tropical savanna environments

Tropical savanna landscapes are characterised by a highly variable climate with prolonged dry seasons associated with frequent water and food shortages and are known to support around 10 per cent of the global human population (Russell-Smith et al., 2007). In addition, karst savanna landscapes are particularly prone to water insecurity as it is difficult to characterise karst groundwater systems and identify reliable groundwater resources (Klaas, 2008; Klaas et al., 2020). Karst landscapes are those where the local carbonate geology is generally characterised by "high rock solubility and well developed secondary (fracture) porosity" (Ford & Williams, 2007). There are few hydrogeological investigations of groundwater resources in tropical karst savanna landscapes, and the drivers of groundwater yield fluxes are poorly understood. Whilst high yielding karst springs may have potential for development as a source of water for household and productive needs, and are therefore a focus for hydrogeological investigations, low to medium yielding springs can also provide critical water supplies for household and productive needs, yet they are rarely studied in detail.

Effective management of karst groundwater, including springs, requires an understanding of the sources and rates of recharge, and any potential threats to the quality and quantity of water discharging as springs, or extracted via bores and wells. Commonly in karst areas, groundwater management is directed at preventing groundwater contamination, as rapidly recharged karst aquifers are especially vulnerable (Goldscheider, 2010; Riyanto et al., 2020). Management objectives that also consider potential influences on the flux of karst groundwater recharge are arguably equally important (Bazan et al., 2013; Canham et al., 2021), however, often the research that underpins these objectives is underdeveloped (Setiawan et al., 2019).

As karst aquifers may be characterised by water that is stored and transmitted in one or more of: matrix, fractures or conduits, they can be highly heterogeneous (hydraulic conductivity varies according to position within the aquifer) and highly anisotropic (hydraulic conductivity varies with direction in the aquifer) (Ford & Williams, 2007). These spatial variations in karst aquifer characteristics make it challenging to model groundwater flow and to predict the effects of stressors on the aquifer (Palmer, 2010). There are a number of interconnected input controls to the recharge of aquifers that drain to shallow groundwater. These input controls can be broadly grouped in the spheres to which they belong: 1) the atmosphere; 2) the pedosphere; 3) the biosphere; and 4) the lithosphere (Ford & Williams, 2007; Stroj et al., 2020). Firstly, the atmospheric controls on the aquifer recharge are the amount, intensity and seasonality of precipitation received in the karst catchment, as well as the amount of evaporation (Klaas et al., 2020; Ollivier et al., 2021). Groundwater recharge in tropical aquifers originates primarily from intense rainfall events, with the proportion of rainfall that is partitioned to groundwater recharge dependent on antecedent soil moisture conditions (Jasechko & Taylor, 2015). Secondly, the pedosphere or the soil layer has an important controlling function on infiltration and can impede infiltration where soil permeability is low (Chandler, 2006; Falk et al., 2024). Thirdly, the biosphere acts as a key input control, primarily through interception, evapotranspiration and through promoting infiltration. Finally, the structure of the lithosphere (bedrock characteristics) determine the rate and direction of flow, residence time and groundwater yields (Ford & Williams, 2007) (Figure 1.1). Land-use or landcover change may have important effects on groundwater recharge, depending on the characteristics of the groundwater system including depth to groundwater and also the structure and characteristics of vegetation (Acharya et al., 2018; Benegas et al., 2021; Ilstedt et al., 2016). In order to understand the potential influence of a stressor, such as landcover change on recharge to important groundwater resources, each of these input controls and the relationships between them need to be examined. Where groundwater is the singular source of community water supply, it is fundamental that natural resource management objectives take into account the resilience of aquifers to land-use or landcover change.

In the East Nusa Tenggara (NTT) region of Indonesia, there are many anecdotes of springs disappearing when stands of woody vegetation are converted to other land-uses or conversely, springs reappearing when tree cover is re-established (Finlayson, 2016; Godwin, 2012; Hamba Pulu, 2016). This publicly understood phenomenon is one of the key drivers of revegetation projects in East Sumba, along with elsewhere in NTT. The other primary driver of revegetation projects is the requirement under provincial catchment management regulations to address what is recognised as diminishing hydrologic functions of catchments more generally (BPDAS, 2011).

The local concept of the response of spring yields to a change in tree cover in NTT conflicts with anecdotes from the Edwards plateau, a highly studied temperate karst savanna in Texas, USA. On the Edwards plateau, it is anecdotally reported that springs have reappeared following removal of invasive Ashe juniper stands (Wilcox et al., 2006). In contrast, a tropical savanna agroforestry parkland of Burkina Faso, Ilstedt et al. (2016) found that woody vegetation cover is important to enhancing infiltration and increasing groundwater recharge. As the assumed relationship between woody vegetation cover and spring yields is used as a key tenet underpinning regreening and reafforestation projects in NTT, it is critical to examine tree cover as an input control to groundwater recharge in a karst tropical savanna setting to determine if these assumptions are applicable.

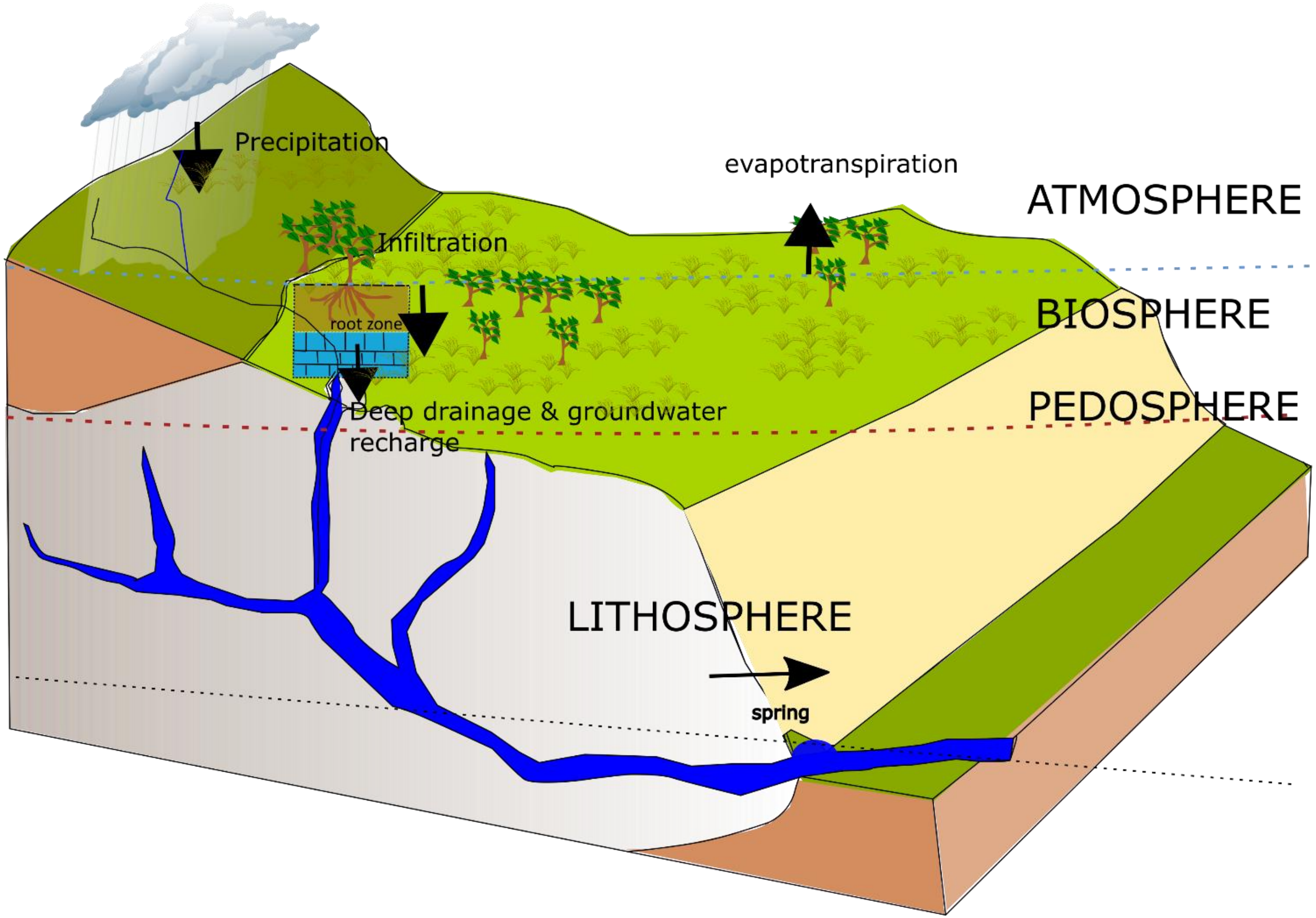

Figure 1.1. Conceptual diagram of the controls on groundwater recharge. Diagram modified from Goldscheider and Drew (2014).

1.2. Catchment management in Indonesia

There is a long history of regreening initiatives in Indonesia extending back to the 18th Century colonial era (Monk, 1997; Piggin, 2007). In post-colonial times, since 1945, the Indonesian and provincial governments have focused on the revegetation of degraded catchment areas, with integrated goals of poverty reduction, climate change mitigation and water catchment protection (BPDAS, 2011). While the key motivations of tree planting from individuals, community groups and institutions are largely economic due to the potential of deriving income from productive timber trees or food forests (Pellokila et al., 2014), the ecohydrological benefits of increasing density of woody vegetation have also been widely communicated in regards to tropical savanna environments (Ilstedt et al., 2016; Ilstedt et al., 2007).

Catchment management objectives centred around increasing woody vegetation density are common in data-scarce tropical regions. Where these objectives have been developed from generic ecohydrologic concepts, catchment management approaches may not have the intended hydrologic outcomes. Ponette-González et al. (2014) argued that catchment management actions should focus on specific structural or ecological functions of landcover that have the desired influence on a given hydrologic flux. For example, if sustaining or increasing dry season water availability is the objective in a water limited environment, then any proposals to increase woody vegetation cover should take into account potential decreases in groundwater recharge as a result of decreased throughfall and increased transpiration.

Increasing woody vegetation is a strong focus of Indonesian central government policy and programs for the management of water and land on a catchment scale. In particular, catchment management programs are directed towards restoring degraded catchments through reafforestation or regreening initiatives. In Indonesia, there is a regulatory distinction between ‘reafforestation’, which refers to increasing forest cover within legally zoned forest areas; and ‘regreening’, which refers to increasing woody vegetation cover outside forest areas (Monk, 1997). The central government impetus for reafforestation and regreening stems largely from significant problems of erosion, landslides, flooding and general soil degradation in more densely populated regions of the country (Paimin & Purwanto, 2012). There is a system in Indonesia for evaluating landscape condition on a catchment scale in order to prioritise catchments requiring the most urgent rehabilitation efforts to mitigate the effects of extreme weather events, climate change and to alleviate poverty associated with degradation of soil and water resources. Catchments designated as having large areas of degraded land with reduced ecological function (known as *lahan kritis* in Indonesia) are allocated resources for projects, such as tree planting and erosion and sediment control (BPDAS, 2011). Another key indicator of catchment degradation used in the prioritisation process is the reduction in number or yield of springs (LPPDAS, 2003).

The prioritisation of *lahan kritis* in Indonesia has important implications for the funds that are made available to provincial and lower levels of government to enable them to undertake landscape rehabilitation works (LPPDAS, 2003). If matched with an equally systematic process for examining the factors leading to reduced hydrological functions in designated *lahan kritis* zones, catchment management programs in Indonesia may be marked with higher degrees of success. There are many potential functional benefits to a catchment from reafforestation and regreening works including decreasing erosion potential, enhancing soil microbiotic activity, increasing shelter and shade for livestock and providing income potential from timber (Reku Raya, 2020). In undertaking reafforestation and regreening initiatives, it is important that the interactions between trees and the water cycle are also understood to predict the influence of a change in tree density on community water supplies.

Indonesian law requires that 30% of catchments are forested (Anwar, 2005). This regulation is tied in to government-owned forest estates and land-use zoning, which is at odds with the NTT savanna environments (Hobgen, 2015). Through the national *Rehabilitasi Hutan Lahan* (Rehabilitation of land and forest) program, funding and resources are granted to the lowest levels of government and to non-government organisations for program implementation (BPDAS, 2011; Pellokila et al., 2014). At the village level, NTT communities are increasingly being assisted by institutions to undertake land-use planning by considering their community development aspirations within the context of agroclimatic potential and hydroecological constraints (Pellokila et al., 2014). This may involve, for example, detailing the characteristics of climate, hillslopes, soils, existing land-use and land-use history, within a village, district or catchment area, as well as in evaluating future land-use scenarios (Seran Mau et al., 2017). In order to strengthen these land-use planning processes and safeguard community groundwater supplies, it is important that the potential influences of different land-uses on groundwater recharge fluxes in karst savanna landscapes are known.

1.3. Research objectives and questions

The objective of this thesis was to support land-use planning by increasing the understanding of landcover as a control on recharge to shallow groundwater in a karstic catchment of the tropical savanna in East Sumba, Indonesia. The two overall research questions for this thesis were:

1) What are the key environmental controls on groundwater recharge in tropical karst savannas?
2) What is the influence of catchment revegetation on groundwater recharge?

To address these research questions, an interdisciplinary approach was applied comprising:

1) a remote sensing study at the district and catchment scale of the response of vegetation to available moisture, including anomalous rainfall periods; and the influence of groundwater availability on vegetation productivity (Chapter 3);
2) a catchment scale study of the influence of landcover and soil characteristics on infiltration rates, which included a spatial analysis of groundwater recharge potential and an evaluation of landscape leakiness as a function of landcover (Chapter 4); and
3) a catchment scale analysis of groundwater recharge rates and recharge pathways using stable isotope hydrology and hydrogeochemistry (Chapter 5).

1.4. Significance of the research

The project is significant as there is a demand for information on land management approaches that will maintain or enhance the yields of shallow groundwater resources, yet the input controls for groundwater recharge in karst tropical savannas are not well understood. The research will contribute to understanding the unique attributes and responses in these tropical savanna karst environments, building on current global perspectives. Also at a finer scale, this evidence based research will support and inform national and provincial land management planning and policy. As the dry seasons in tropical savannas are predicted to become longer (Brown et al., 2013), and with potentially less annual rainfall available for groundwater recharge, this study provides an important contribution that will assist with the protection of community groundwater supplies.

1.5. Thesis structure

This thesis comprises six chapters, along with appendices and references. Chapters 1 and 2 delineate the research problem; Chapters 3 to 5 present this study's empirical findings; and Chapter 6 provides a discussion and analysis of the research. Each chapter is aligned with a specific research objective and associated questions, contextualised within the hydrological cycle (Table 1.1; Figure 1.2).

Table 1.1. Thesis structure.

Thesis chapter	Research objective	Research questions	Zone of the hydrological cycle in focus
Chapter 1: Introduction and background	1. To define the integrated land and water management problem in karst tropical savannas	1.1 What are the key input controls on groundwater recharge in tropical karst savannas?	Atmosphere Pedosphere Biosphere Lithosphere
Chapter 2: Introduction to the ecohydrology and hydrogeology of karst tropical savanna environments		1.2 What is the influence of woody vegetation restoration on ecohydrology in tropical karst savannas?	
Chapter 3: Response of woody vegetation to available moisture in karst tropical savanna	2. To examine the overall response of woody vegetation to changes in available moisture in the Haharu district of Nusa Tenggara Timur, Indonesia	2.1 How does woody vegetation respond to changes in soil moisture and rainfall at the landscape scale?	Atmosphere Biosphere
		2.2 How does woody vegetation at the patch scale respond to inter-annual variability of rainfall and rainfall anomalies?	
	3. To examine the specific responses of vegetation patches to moisture that had been subject to restoration in the form of Farmer Managed Natural Regeneration or tree planting.	3.1 How do sites of woody vegetation restoration respond to available moisture?	
Chapter 4: Infiltration mechanisms and landcover	4. To determine the influence of woody vegetation on infiltration patterns in a karst savanna	4.1 How do infiltration rates differ in soils under different woody and non-woody vegetation?	Pedosphere Biosphere
		4.2 How does woody vegetation influence infiltrability and promotion of autogenic recharge?	
Chapter 5: Sources and rates of groundwater recharge	5. To determine the sources and recharge rates of groundwater in the study area	5.1 What are the recharge rates and recharge fraction of rainfall for groundwaters in the study area?	Atmosphere Pedosphere Lithosphere
		5.2 What is the source of groundwater in the study area?	
Chapter 6: Potential influence of woody vegetation change on groundwater recharge in a tropical karst savanna	6. To outline the potential influence of woody vegetation change on groundwater recharge in a tropical karst savanna	6.1 To what extent does woody vegetation influence groundwater recharge potential in the tropical karst savanna study area and what are the implications for future land and water management of these landscapes?	Atmosphere Pedosphere Biosphere Lithosphere

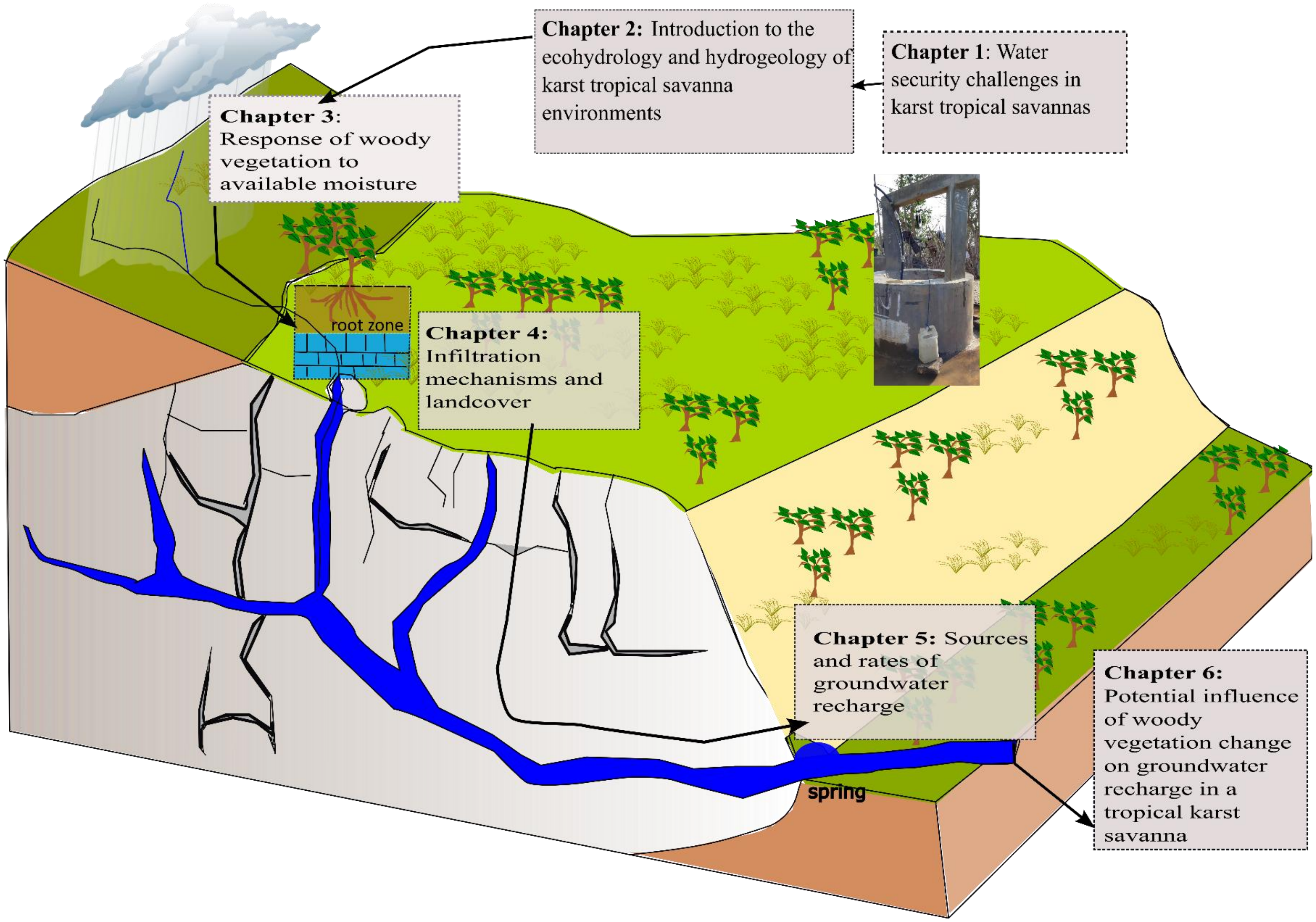

Figure 1.2. Structure of the thesis.

1.6. Study area: Larawali catchment and the Haharu district, East Sumba Indonesia

In the Haharu district of East Sumba, Indonesia, the water supply is scarce for both household and productive needs, particularly during the long dry season, which usually commences between March and May and ends between November and December (Russell-Smith et al., 2007). There has been limited investigation into and development of the water resources in the district and many peoples' livelihoods are constrained by the need to travel significant distances from their homes to obtain water for household use and for watering small-scale vegetable and grain crops (Sule & Delinom, 1989). The Haharu district has an area of 796 km^2, and is located in the northern central region of the island of Sumba (centred around 9°28' S, 119°58' E) (Figure 1.3).

The district was selected as a study area based on four primary criteria: 1) it is located within the tropical savanna climate zone and is underlain by carbonate geology; 2) it is regionally known as a district with severe water security challenges; 3) it has been the focus for regreening efforts over the last decade; and 4) it is largely accessible by road. As described in Chapter 3, the Haharu district boundary was used as a spatial boundary for analysis of the response of vegetation to available moisture. The district boundary was applied to allow for identification of longer-term district scale greening trends using MODIS (Moderate Resolution Imaging Spectroradiometer), as a result of smaller scale regreening endeavours at different locations in the district. As detailed in Chapters 4 and 5, the surface water Larawali catchment within the Haharu district was defined as the hydrological boundary for the study as it contains wells and springs that are important community water supplies relied upon by members of surrounding villages. As there are no existing data on boundaries of groundwater basins, the Larawali catchment boundary was assumed to be the drainage extent of the groundwater discharging to these community water supplies and thus investigations of infiltration mechanisms and sources of groundwater recharge were limited to this extent.

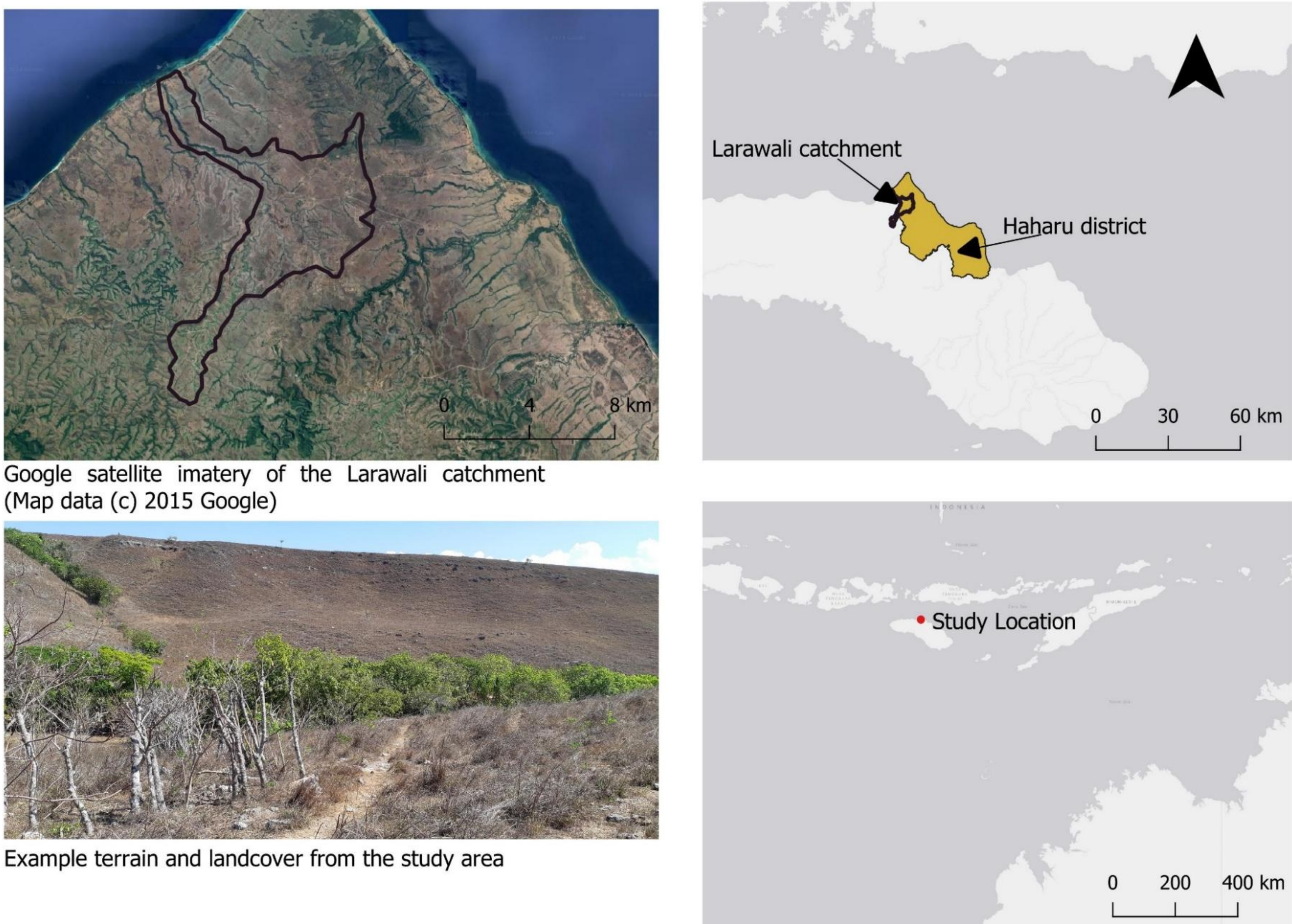

Figure 1.3. Location of the Larawali catchment, Haharu district, *Nusa Tenggara Timur* (NTT; East Nusa Tenggara).

According to an island scale water resources study undertaken by the Indonesian Water Resources Research and Development Centre (PUSAIR), the water demand in the Haharu district will equate to 546 kLday $^{-1}$ by 2025, based on a population of 6,005 (in 2012) (Herawan et al., 2014). This figure included the consideration of water needs for irrigation, livestock watering and household use. Available supply was estimated by application of the National Rural Electric Cooperative Association water balance model to estimate surface water availability, and groundwater recharge was estimated based on coefficients derived from geophysical studies. As such, the district was deemed to be in year round surplus (Herawan et al., 2014). The PUSAIR study provides an important foundation for considering the island scale water resource potential, however, there were some critical omissions and interpolations in the analysis that lead to a misrepresentation of the supply-demand challenge. One such omission is that the analysis did not consider the spatial distribution of river and groundwater supplies relative to the location of the settlements within each district.

1.6.1. Geology

The Larawali catchment is 51 km^2 and predominantly overlies the uplifted quaternary reef terrace Kaliangga formation, with a small area of Kananggar limestone and turbiditic sandstone (Mio-Pliocene) in the southern region (Figure 5.1A) (Abdullah et al., 2000; Fortuin et al., 1997; Nexer et al., 2015). It is thought that significant uplift took place on Sumba Island ~3 million years ago due to collision between the Sunda-Banda Arc and the Australian plate. It is estimated that over the past 600 years uplift has continued at a rate of between 0.40–0.55 mm per year (Chauveau et al., 2021). The terrain in this study is referred to as ‘karst’ due to the presence of sinkholes and large springs found on the Kaliangga formation. There is limited evidence of karstification at the surface within the Larawali catchment, however.

1.6.2. Soils and vegetation

The majority of soils in the Haharu district are shallow, stony, and calcareous, with relatively low to moderate clay content and associated low water holding capacity. There are some areas of heavier cracking clay soils that retain moisture for longer periods and which can become waterlogged in particularly wet periods (Monk, 1997). These calcareous soils support open grassland and acacia forest savanna. The high concentrations of calcium and magnesium in soils restrict other nutrients and limits the growth and diversity of trees, while the shallow soils support reasonably biodiverse herbaceous flora (Monk, 1997). The interspersed trees in the district tend to be even aged stands resulting from frequent disturbance by fire. The exception to this is in gullies and drainage lines with perennial water access where there are greater numbers of mature trees of mixed species. The savanna grasslands have been minimally developed for a mix of land-uses including household scale agroforestry, vegetable gardening and livestock grazing (Mulyoutami et al., 2016; Seran Mau et al., 2017). Generally, the vegetation in the district comprises a dense understory of perennial grasses: *alang alang* (*Imperata cylindrica*), kangaroo grass (*Themeda triandra*), and black speargrass (*Heteropogon contortus*) interspersed with both evergreen and deciduous trees (Monk, 1997). Additional patch scale vegetation descriptions are provided in Section 3.4.2.

1.6.3. Rainfall

There are three main rainfall regions in Indonesia, and the influence of the monsoons and El Niño Southern Oscillation (ENSO) on these regions is dependent on topography and ocean-atmospheric fluxes (Aldrian & Dwi Susanto, 2003). The island of Sumba shares a rainfall region with all of East Nusa Tenggara, Java and East Sumatra. The northwest monsoon (also known as the Indonesian-Australian Summer Monsoon or the Asian Monsoon) moves progressively to the southeast over Indonesia from September to April, arriving in the Nusa Tenggara region later than in regions to the west. From May to September, the south-easterly trade winds deliver dry Australian continental air to the region (Lau et al., 2005). Sumba is one of the driest islands in Indonesia, with mean annual rainfall between 500–1,000 mm (As-syakur et al., 2013). In East Sumba, the mean annual rainfall is 862 mm (coefficient of variation 28%) (BMKG, 2020), most of which is received during the wet season between November and May (Figure 1.4). The mean annual temperatures are 17.4 °C (minimum) to 28.5 °C (maximum) (BMKG, 2020). The main weather systems influencing the study area are the northwest monsoon (the Asian monsoon) from November to May and the dry southeast monsoon from June to September (Aldrian & Dwi Susanto, 2003). The ENSO and the Indian Ocean Dipole are known to contribute to inter-annual rainfall anomalies in East Indonesia with the strongest influence of both climate drivers occurring during the dry season.

Throughout Indonesia, springs are particularly important sources of perennial household water supply and can also be culturally and spiritually important features in a landscape (Klaas, 2008; Ratumakin et al., 2016; Siswadi et al., 2011). Within this context, it is important to understand the influence of land cover on groundwater yields to inform equitable catchment management decisions and to protect important water sources.

The proportion of tree cover has fluctuated in Sumba during the past 25,000 years in response to water stress, with abrupt changes particularly apparent during periods of dry season aridity (Dubois et al., 2014). In addition, anthropogenic landscape influences during recent times, including the use of fire and removal of trees for domestic and agricultural needs, may have enhanced this landscape change (Monk, 1997). In selected locations, however, tree density has increased in the last two decades as a result of restoration efforts (Pellokila et al., 2014; Reku Raya, 2020).

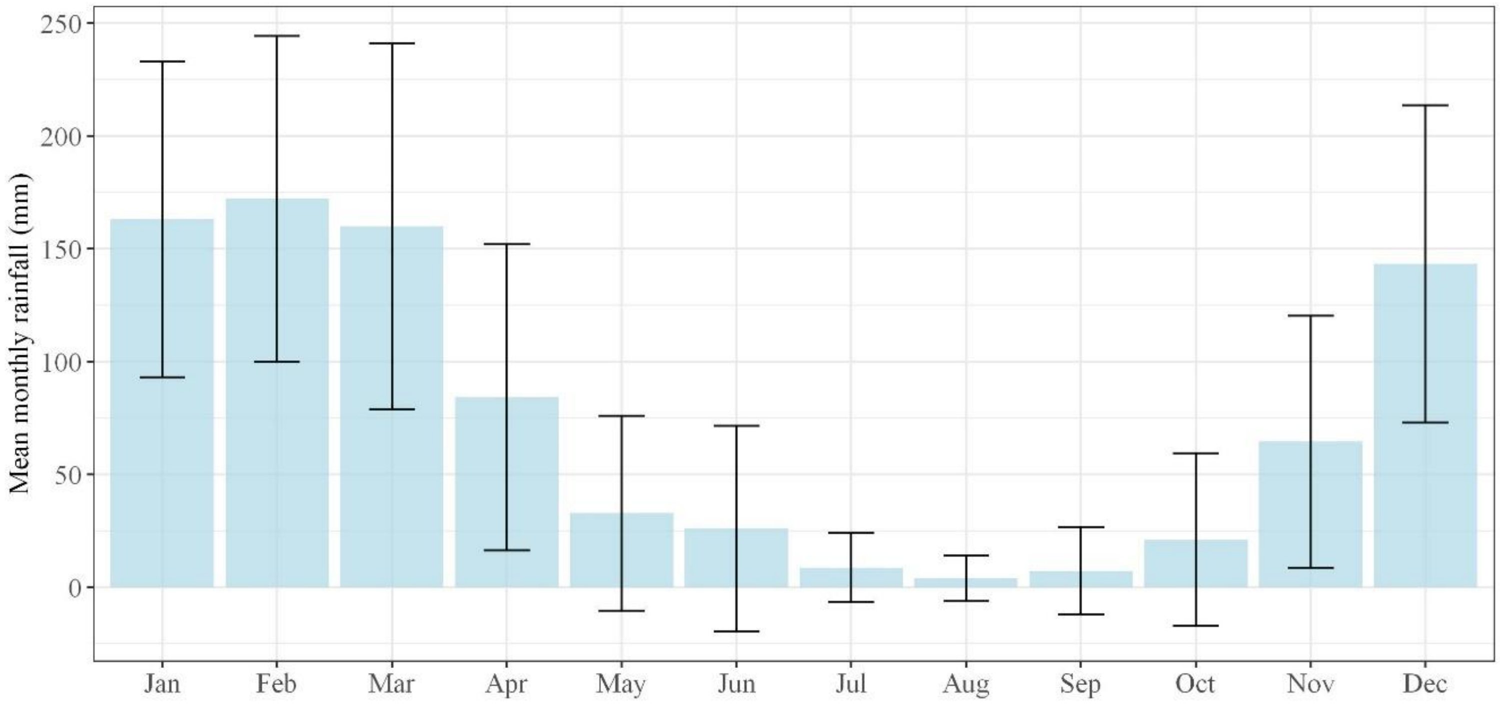

Figure 1.4. Long term monthly rainfall in Waingapu, East Sumba from 1974 to 2018. Source: BMKG, (2020). Error bars indicate 1 standard deviation.

1.6.4. Restoration activities in the Haharu district

The period of this study (2015–2020) overlapped that of three major regreening programs in the Haharu district. From 2011 to 2015, the World Vision program: Increase Food Security within the Community through Sustainable Livelihood and Natural Resources Management System (INFOCUS) implemented a combination of planting of high value tree species and Farmer Managed Natural Regeneration (FMNR). Also known as pollarding and coppicing, FMNR is a form of agroforestry, where shoots growing from tree stumps, root stock or seeds of preferred tree species are systematically pruned and managed in order to achieve an increase in woody vegetation cover (Chomba et al., 2020; Rinaudo et al., 2019). Distinct from tree planting, FMNR relies on the existing below ground tree resources to regenerate woody biomass. The INFOCUS project implemented regreening of approximately 105 ha marginal land through community forest and agroforestry projects. It was followed by the Rural Economic Development Project Indonesia (IRED) project, a partnership between World Vision, the World Agroforestry Centre (ICRAF) and Lutheran World Relief undertaken between 2015 and 2020. The INFOCUS activities implemented up until 2014 were expanded by IRED, until March 2020, which included regreening activities on 412 ha and the planting of more than 6,000 seedlings between 2018 and 2020. The IRED FMNR activities included the maintenance of local species, as well as maintaining productive timber and forage tree species (Reku Raya, 2020). The third regreening program in operation in the district consisted of a collection of tree planting projects that were implemented by non-government organisations including The Nature Conservancy, Yayasan Tananua and Koppesda involving planting of productive timber and tree crops between 2003 and 2016. The focus of these programs was climate change mitigation and the protection of spring yields (Martini et al., 2016). An absence of available digital mapping and monitoring for these programs precludes the presentation of exact statistics on locations and areas of landcover change.

1.7. COVID-19 Impact Statement

Travel restrictions associated with the COVID-19 pandemic had a substantial impact on all aspects of this project. The impacts on the individual chapters and the thesis are as follows:

Chapter 4 – Field infiltration measurements were undertaken in dry season conditions in 2018. After reviewing results of these measurements, the intention was to repeat the measurements, collect additional soil samples and record field observations at a greater number of sites and under wet season conditions in 2020. Unfortunately, the COVID-19 travel restrictions prevented further field work and the analysis of landcover as a control on infiltration is far less detailed than was originally intended. To increase our understanding of landcover and hydrology in the study area in the absence of further field data, additional desktop-based remotely sensed analyses were undertaken (Leakiness index), as well as an investigation of the applicability of using pedotransfer functions in the study area for estimating soil hydraulic properties.

Chapter 5: – The original intention of the thesis was to use stable isotopes as tracers to investigate water sources of trees. In October 2019, tree stem, soil and water samples were collected in accordance with relevant sampling protocols and were stored at the Universitas Kristen Wira Wacana lab in Sumba to await finalisation of necessary export and import permissions from the Indonesian and Australian governments. As no facility was available in Indonesia to extract xylem or soil water for stable isotope studies, so it was necessary to transport them to the Australian National University (ANU) for analysis. After travel restrictions were introduced, a local research partner was engaged in order to repeat sample collection on behalf of the project and these samples were successfully stored, with evidence of sample collection and storage shared digitally via a purpose-built Open Data Kit (ODK) Collect proforma. Conducting this field work and transporting the samples also required a protracted approval process in order to secure an extension to a foreign research permit and sample collection permit that had been issued in late 2021. In December 2021, after numerous failed attempts at transporting samples to the ANU via a third-party cold-chain courier, a research contact was engaged to deliver the samples to biosecurity officials in Australia. Unfortunately, the long transport process resulted in the samples being unviable. Prior to the COVID-19 restrictions, the intention was to transport the samples in person from Waingapu, NTT, Indonesia to Canberra, Australia, with limited delays and for samples to be analysed using a novel water extraction method at ANU. To address these unanticipated data gaps, Chapter 5 was altered to have a stronger focus on the stable isotopes in precipitation and a comparison of insights on moisture sources with other data in the region. Original research questions relating to moisture sources for trees in the study area were removed.

Local knowledge chapter (not prepared) – In early 2020, an advanced plan, including ethics approval and research design, was completed for undertaking interviews with key informants about the local understanding of the influence of trees on catchment hydrology in the study area. With the support of a local research partner, the intention was to collaborate with local researchers to collect interview data. Unfortunately, Sumba was severely impacted by the COVID-19 pandemic and this work had to be abandoned.

1.7.1. Overall thesis impacts:

Due to the absence of key information on wet season infiltration rates, tree water sources, and the local understanding of the influence of trees on catchment hydrology, it was not possible to respond to the original hypotheses for this project with the rigour that was originally anticipated. The size of the datasets were critically limited by COVID imposed travel constraints that prevented planned additional field data collection. The outcomes of this project were refocussed on analysis of the data that were obtained to understanding the recharge mechanisms of groundwater in the study area and the potential changes in infiltration as a result of woody vegetation increases.

1.8. References

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Chapter 2. Introduction to the Ecohydrology and Hydrogeology of Karst Tropical Savanna Environments

2.1. Thesis context

Chapter two describes the ecohydrological approach to understanding the influence of landcover on groundwater availability. The relevant components of the hydrological cycle are explained along with an introduction to the influence of land-use and landcover on infiltration. A brief description of the ecohydrology characteristics specific to karst geologies is provided to introduce the concepts that are explored in the results chapters.

2.2. Ecohydrology

Ecohydrology is a study of the interactions between the living environment and the hydrological cycle. The hydrological cycle is governed by inputs from precipitation and fluxes to surface water flows, recharge, groundwater storage, groundwater discharge and evapotranspiration. Each flux within the hydrological cycle is influenced by the living environment (Watson & Burnett, 1993). An ecohydrological view of a water balance provides particular focus to physical processes occurring in the vadose zone (i.e. the zone extending from the land surface to the water table) and considers the exchanges in water between rainfall, vegetation, soil moisture and groundwater (Eamus, 2006). Applying an ecohydrological framework enables us to consider the influence of revegetation on recharge to groundwater in karst tropical savanna areas. A key difference in ecohydrology between karst landscapes and systems with low permeability bedrock is the usually very shallow soil profile in karst landscapes, which is associated with limited soil water and greater fluxes into and from bedrock fractures (Chandler, 2006). Trees may influence the groundwater balance negatively or positively, by increasing evapotranspiration (a negative influence) and by potentially increasing interception and infiltration through the vadose zone (a positive influence) (Bruijnzeel, 2004). Other fluxes that may be immediately reduced by the planting of trees are runoff, soil moisture and deep drainage. The presence of trees may also increase infiltration potential and ultimately drainage to bedrock storage by increasing macroporosity (Benegas et al., 2014). The magnitude of changes to the inputs and outputs from a groundwater system due to the influence of vegetation determine whether the outcome on the groundwater balance is positive or negative. The vadose zone is a critical zone for water movement by vegetation and is the focus in the field of ecohydrology (Schwinning, 2010).

Factors influencing the groundwater and soil water use patterns of vegetation in karst landscapes are: vegetation type, rooting depth, local geology, soil thickness, structure of the epikarst[1] and proximity to surface water bodies (Schwinning, 2008). Trees with deep roots are likely to use more groundwater than shrubs and grasses under particular conditions, however, this requires either deep soils or the presence of fractures for root development. In the absence of these, shallow tree root systems develop, which cannot be differentiated from the root systems of shrubs and grasses. In this case, evapotranspiration from the epikarst will be limited (Andréassian, 2004; Schwinning, 2008). Previous studies such as Schwinning (2008), Cardella Dammeyer et al. (2016) and Ding et al. (2021) have identified the epikarst as a key zone for tree water use during average to wetter periods, with deeper groundwater located in karst fissures becoming a key water source during extended dry periods.

Fissures in the carbonate matrix of karst geologies are formed by dissolution[2] and these widen and lengthen over time, providing extended aquifer storage and/or flow pathways. In a karst system, rainfall infiltrates soil layers and travels through highly permeable drainage networks made up of fractures and pores in the carbonate matrix. Aquifers then develop in areas where highly permeable carbonate soil rests on low permeability rocks (Ford & Williams, 2007). Groundwater storage and flow in karst systems is highly heterogeneous in space and time (Palmer, 2010).

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[1] Epikarst is "the transition zone between the soil and the bedrock in karst landscapes" (Schwinning, 2008). https://doi.org/10.1007/s00442-008-1147-2 , characterised by "enhanced permeability where weathering, dissolution, and root growth have created a substrate of highly porous rock" (Bakalowicz, 2003).

[2] Atmospheric CO_2 dissolves in rainwater to form carbonic acid (H_2CO_3), which causes dissolution of calcium carbonate ($CaC0_3$) according to the following equation: $CaC0_3\,(s) + H_2CO_3\,(aq) \rightleftharpoons Ca^{2+} + 2HCO_3$ (Ford & Williams, 2007).

Karst springs occur where fractures slope towards an adjoining valley and water drains under gravity; or where there is contact between an impermeable and permeable formation (Ford & Williams, 2007). Springs can be classified according to the properties of the aquifers and the type of flow into and out of those aquifers which control their occurrence (Ford & Williams, 2007; Klaas, 2008). For example, they may be a discharge point for aquifers that are recharged by diffuse or point recharge (Klaas, 2008). Alternatively, springs can be classified according to controls on their location: 1) depression springs: where the water table intersects the surface, 2) contact spring where permeable rocks overlie rocks with low permeability, 3) fault springs: where a fault forms a boundary to groundwater flow, 4) sinkhole springs: where water dissolves limestone beneath the surface and artesian pressure is high enough to carry water to the surface, and 5) fracture springs: where groundwater following a fracture intersects the surface (such as where basalt or limestone overlies impermeable rock) (USDA, 2007, after Fetter, 2001). As springs provide important community water supplies and also support biodiverse ecosystems (Cantonati et al., 2020; Stevens et al., 2021), it is critical that the controls on fluxes in recharge and discharge are understood.

There are limited studies that have examined the groundwater dependence of vegetation specifically growing in the vicinity of karst springs, although studies such as Siswo et al. (2019) and Nugroho et al. (2021) have described the occurrence of particular species in and around springs and developed hypotheses about the ecohydrological relationships between trees and groundwater discharging from springs. A previous study identified differing degrees of groundwater dependence of riparian vegetation in a tropical savanna area of northern Australia (Lamontagne et al., 2005), where it was suggested that the level of groundwater use by vegetation was linked with position in the landscape. Lamontagne et al. (2005) identified vegetation species that were either 'obligate phreatophytes' or 'facultative phreatophytes'[3]. Facultative phreatophytes make use of both

[3] "Obligate phreatophytes send roots into or below the capillary fringe to use shallow groundwater, while facultative phreatophytes can also survive in upland environments where groundwater is not available" Naiman et al., 2005).

groundwater and soil water and can be found at higher elevations. Lamontagne et al. (2005) also noted that phreatophytic vegetation can be opportunistic during wetter periods and use relatively more surface water or soil water.

Woody vegetation use of groundwater or epikarst storage for transpiration is one mechanism under which groundwater availability for household or productive use could be affected. The other components of the water balance that are controlled by landcover must also be considered. Previous reviews have determined that in catchments with a history of woody vegetation cover, generally runoff and streamflow are negatively correlated with percentage woody vegetation cover (Bosch & Hewlett, 1982; Bruijnzeel, 2004). Conversion of forest to non-woody landcover types, for example, can result in decreased infiltration potential and a subsequent reduction in groundwater recharge (Andréassian, 2004; Bargués Tobella et al., 2014; Brown et al., 2005; Calder, 2007; Ilstedt et al., 2007). It is also known that following land cover changes in a catchment, there is a lag time before a system reaches a new ecohydrologic equilibrium and that this lag time is longer when non-woody vegetation is converted to woody vegetation, such as in the case of revegetation programs (Brown et al., 2005). The lag time also varies according to woody vegetation species and the percentage area of a catchment in which the change has occurred (Hou et al., 2023).

An understanding of the influence of landcover types (especially woody vegetation) on groundwater fluxes is important to effective integrated land and water management, as landcover change can have short and long term effects on water supply (Brauman et al., 2012). There is an inherent risk in applying generalised ecohydrologic assumptions to catchment regreening and reafforestation programs, as what is assumed about the role of landcover in providing particular water services, such as maintenance of groundwater recharge, may be misinformed (Bargués Tobella et al., 2014; Brauman et al., 2012; Bruijnzeel, 2004; Ilstedt et al., 2016; Ilstedt et al., 2007; Ponette-González et al., 2014). Some key components of the water balance that drive fluxes in groundwater recharge are described below:

2.2.1. Interception

The three main components of vegetation in a savanna environment that influence interception are the tree canopy, grass canopy and leaf litter (Tsiko et al., 2012). Trees have a higher interception capacity than grasses or bare ground (Chandler, 2006) and the degree of tree canopy interception is influenced by tree architecture including leaf diameter and canopy width (Skhosana et al., 2023). In addition to playing a role in intercepting and transpiring water in a catchment, vegetation also protects the ground from kinetic energy of rain and directs runoff (Asdak, 1995).

2.2.2. Rooting depth

Rooting depth determines the depth from which vegetation can access soil moisture or groundwater and is generally limited by soil depth. It is generally understood that in shallow soils trees have the same evaporative potential as shrubs and grasses as both vegetation types will exploit the same water source (Andréassian, 2004). However, there may be some differences in karst environments where soils are generally shallow, but trees can also develop roots into the epikarst to access an additional store of water (Schwinning, 2010).

2.2.3. Leaf area index

While rooting depth is an important plant characteristic that determines the depth from which soil moisture or groundwater can be accessed, the best indicator of evaporative ability is thought to be leaf area index (LAI) and sapwood area (Andréassian, 2004). The LAI, which is the one sided green leaf area per unit ground surface area can be obtained from satellite imagery such as MODIS, however, separating the woody and non-woody components of vegetation in a savanna environment is challenging (Kahiu & Hanan, 2018).

2.2.4. Climate

For trees to transpire greater volumes of water than shrubs and grasses, sufficient rainfall is required to refill soil water stores and reduce soil water tension (de Blécourt et al., 2021). In addition, atmospheric evaporative demand is determined by climate parameters (i.e. temperature, wind speed, cloud cover and humidity). These climate parameters in combination with soil water availability control the evapotranspiration flux (Andréassian, 2004).

2.2.5. Age and species mix of vegetation patches

Paired catchment studies have found that peak tree water use occurs within the early growing stages of trees and that a water balance reaches a new equilibrium as trees mature or thin (Andréassian, 2004). The time required for equilibrium to be reached varies according to climate, mix of vegetation species and geology.

2.2.6. Groundwater storage

There are three components of groundwater storage: shallow root zone, deep soil storage and bedrock storage. Perched aquifers and unsaturated bedrock may be large stores with seasonal to annual residence times. Groundwater storage during the dry season following reduction in tree cover may increase or decrease depending on soil composition (and rate of infiltration) and change in evapotranspiration depends on growth rate and root maturity of trees. Groundwater-vegetation dynamics vary between wet and dry seasons as rate of evaporation changes with change in temperatures and vegetation growth rates. In the tropics, vegetation growth is faster than in temperate seasonal climates. Because of this, the influence of vegetation cover change is shorter than in seasonal climates (Asdak, 1995). In karst terrains dry season groundwater baseflow is dependent on drainage from soil moisture and drainage from bedrock storage, that is, perched aquifers are the dominant groundwater baseflow response (Chandler, 2006).

2.2.7. Land-use and landcover influence on infiltration

Permeability of the ground surface can also be affected by land-use activities. For example a history of fire can lead to hydrophobicity or impermeable layers and land tillage can lead to soil compaction which affects large pores thus decreasing soil porosity which decreases infiltration potential (Mousavi et al., 2011). The level of organic matter in soil can also influence percolation (Mousavi et al., 2011; USDA, 2007). Infiltration rates are highest in loams and much lower in fine textured soils (Mousavi et al., 2011).

The potential effects of landcover change, in particular increasing tree cover, on groundwater recharge rates are highly dependent on a number of regionally unique factors including those outlined above. Generally, trees have a positive effect on soil hydraulic conductivity and associated groundwater recharge. Some studies argue that particular densities of tree cover are required to maximise groundwater recharge. A review by Ilstedt et al. (2007) found that infiltration capacity increased on average threefold after planting trees in agricultural fields. It was noted that knowledge about rates of infiltration for different soil types and the effects of tree planting with various species and techniques is severely lacking. Ilstedt et al. (2007) argue that more information based on well-designed experiments under varied biophysical conditions in the tropics is required (Ilstedt et al., 2007).

2.3. Summary of the relevant features of karst tropical savanna environments

The input controls for groundwater recharge in karst tropical savanna environments include components of the atmosphere, biosphere, pedosphere and lithosphere. The vadose zone, also termed the unsaturated zone, of karst geologies in tropical savanna environments is the critical zone of interaction between the biosphere and the groundwater system (Cantonati et al., 2020; Schwinning, 2010). The shallow components of the vadose zone of a karst environment comprise the soil layer and the epikarst. Characteristics of the soil layer have an important influence on infiltration and deep drainage to the epikarst (Chandler, 2006), where moisture may be stored in soil-filled fissures

(Schwinning, 2010). The vadose zone is also subject to atmospheric influences including rainfall intensity, frequency and duration, and evaporation.

The characteristics of woody and non-woody vegetation growing within the drainage areas of karst tropical savanna groundwater systems may be important input controls for groundwater recharge. The specific characteristics of vegetation that influence the water balance, as listed in Section 2.2, are interception capacity, rooting depth, LAI, mix of vegetation species within a patch and the maturity of vegetation. These vegetation characteristics determine the quantum of water loss from the soil, epikarst and groundwater storage zones as evapotranspiration and subsequently the amount of water remaining that can be partitioned to groundwater storage and groundwater discharge to springs.

The high degree of heterogeneity in karst geologies means that it is challenging to predict the dynamics of subsurface flow and also to examine the influence of the atmosphere, biosphere and pedosphere as input controls to groundwater recharge. It is possible, however, through the interdisciplinary research approach described in Chapter 1, to build a conceptual model of the ecohydrological system, which includes an understanding of infiltration, groundwater recharge pathways and residence time; and to develop assumptions about the influences of land cover on groundwater availability.

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Chapter 3. Response of Woody Vegetation to Available Moisture

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The chapter has been modified slightly from the format published in the Frontiers journal for consistency with the remainder of the thesis.

3.1. Thesis context

The two objectives for Chapter 3 were (1) to examine the overall response of woody vegetation to changes in available moisture in the Haharu district; and (2) to examine the specific responses of vegetation patches to moisture that had been subject to restoration in the form of Farmer Managed Natural Regeneration (FMNR) or tree planting. These objectives were met by way of a study that computed correlations between vegetation productivity and available moisture in the form of rainfall and soil moisture. This analysis enabled identification of the influence of longer-term precipitation input to the Haharu district during a period from 1999 to 2018 on vegetation productivity and the influence of soil moisture between 2015 and 2018. Where normalised difference vegetation index (NDVI) and precipitation or soil moisture are uncoupled in the time series, a dependency of vegetation on groundwater was assumed. This study is an important component of understanding the influence of woody vegetation on groundwater recharge as the relationships that are established between NDVI, precipitation and soil moisture are proxies for groundwater use by vegetation in the Haharu district.

3.2. Abstract

Revegetation projects are an important feature of landscape restoration in Indonesian karst savannas. An understanding of the relationship between moisture availability and vegetation condition can assist with the planning and implementation of revegetation efforts. Observing interannual trends in NDVI may be an effective approach to remotely monitor the relative success of small-scale revegetation efforts. Working at vegetation restoration sites in the Haharu district of East Sumba, East Nusa Tenggara Indonesia, increasing trends in Landsat 7 NDVI were identified at two of four restoration sites using Mann-Kendall and Theil-Sen trend analyses. A key determinant of vegetation response to changing available moisture (as rainfall or soil moisture), is the degree of access to groundwater. No correlation was established between NDVI and rainfall at the three vegetation patches with access to shallow groundwater, while at rainfall dependent sites there were significant Pearson's correlations ranging between 0.52 and 0.71. There was a clear negative effect of the very dry El Niño period in the year 2005 on NDVI across all sites, but it was less pronounced at the three sites with access to shallow groundwater. Wet years, associated with La Niña events, including the year 2018 had a positive response of NDVI across all sites, while the NDVI response was lower in very wet years with annual rainfall above 1200 mm (years 2000 and 2011). A windowed cross correlation method was applied to mean values of district NDVI to examine the lag between moisture input and NDVI response for both rainfall and soil moisture between 1999 and 2018. The strongest correlation between rainfall and NDVI was identified with four months of antecedent rainfall ($r = 0.71$, $p < 0.001$), and between 2015 to 2018 two months of antecedent rainfall gave the highest correlation ($r = 0.75$, $p < 0.001$). The highest correlation between soil moisture and NDVI was identified with a one-month lag ($r = 0.40$, $p < 0.001$) followed by no lag ($r = 0.35$, $p < 0.001$). Through this study, the applicability of using NDVI, rainfall and soil moisture trend analyses to identify groundwater dependent vegetation patches and to monitor the effectiveness of vegetation restoration was demonstrated.

3.3. Introduction

Karst aquifers in savanna environments provide essential water supplies to support human populations in Asia, Africa, Australia and Central America (Goldscheider et al., 2020; Klaas, 2008; Rossatto et al., 2014; Schwinning, 2008). These environments are potentially under threat from a combination of water stress and landcover change (Sankaran, 2019). In these highly seasonal landscapes, the spatial and temporal patterns of tree water uptake remain poorly understood, yet enhanced knowledge of their dynamics is important to sustainably manage the groundwater systems (Acharya et al., 2018; Asbjornsen et al., 2011; Banks et al., 2011). In karst savannas, vegetation water use is often dependent on the moisture available in the epikarst (i.e. the zone of weathered bedrock beneath the soil layer) (Jones, 2013; Nie et al., 2012; Rossatto et al., 2014; Schwinning, 2010). Relative to a non-karst environment where infiltration to the tree root zone occurs gradually after soil saturation, groundwater recharge in karst ecosystems occurs rapidly following intense rainfall events due to the presence of large fissures or conduits (Sarrazin et al., 2018; Schwinning, 2008; Wilcox et al., 2006). The epikarst is also a key subsurface zone for groundwater recharge (Nie et al., 2012; Rossatto et al., 2014; Schwinning, 2008, 2010; Ward et al., 2013).

The presence, type and density of vegetation in recharge zones may affect fluxes of soil moisture, epikarst storage and ultimately groundwater availability (Asbjornsen et al., 2011; Bazan et al., 2013; Cardella Dammeyer et al., 2016; Huxman et al., 2005; Nie et al., 2012; Nijzink et al., 2016; Sarrazin et al., 2018). In tropical savannas, the dominant savanna tree and shrub species have evolved to transpire perennially (Eamus et al., 2000), potentially influencing deep soil water and groundwater stores, particularly during the dry season when shallow moisture sources are depleted. By exploring the dynamics between vegetation productivity and moisture availability, we can better predict the resilience of tropical karst savanna ecosystems, including moisture stores, to future environmental conditions especially the likely prolonged dry seasons, change in frequency and intensity of recharge events, continued influence of the El Niño Southern Oscillation (ENSO) (Brown et al., 2013), and changes in groundwater abstraction rates. Here these dynamics were investigated using satellite image derived Normalised Difference Vegetation Index (NDVI) surfaces and moisture trend analyses to provide preliminary insights into the response of tropical karst savanna vegetation to available moisture.

The NDVI is a proxy for productivity as it indicates photosynthetic activity by measuring chlorophyll reflectance (Aguilar et al., 2012; Fu & Burgher, 2015; Glenn et al., 2011; Glenn et al., 2010; Li et al., 2017; Souza et al., 2016). The seasonal and interannual response of vegetation condition to moisture availability is commonly studied using NDVI trend analyses, and it can indicate how vegetation condition may be affected by future climate conditions (Chamaillé-Jammes & Fritz, 2009; Fensholt & Rasmussen, 2011). It is generally found that NDVI responds to antecedent rainfall with a range of lag times between one month and several years (e.g. Chamaille-Jammes et al., 2006; Fu & Burgher, 2015; Svoray & Karnieli, 2011). Previous trend analyses have shown that rainfall anomalies (i.e. departures from long term means) may have a more significant influence on NDVI than seasonal variability (Chen et al., 2020) and that the degree of influence varies with vegetation structure (Anchang et al., 2019; Brandt et al., 2019; Gaughan et al., 2012; Kahiu & Hanan, 2018; Lucas et al., 2017; Mishra et al., 2015).

In savanna environments NDVI is commonly used to examine landscape processes (Scanlon et al., 2002 and Scanlon et al., 2005). It is recognised as a suitable index in the open savanna landscapes as it rarely reaches saturation (Archibald and Scholes, 2007), whereas in densely vegetated environments the red band may saturate, making landcover change difficult to distinguish (Huete et al., 2017). Limitations of NDVI in savanna environments include soil background effects and the different phenologies of trees and herbaceous vegetation (Wingate et al., 2019). Different timing of green-up in trees and herbaceous vegetation can limit the ability to monitor vegetation change using NDVI over short time periods, however, NDVI is an accepted vegetation index for timeseries analyses related to understanding relationships with inter-annual climate variables (Lu et al., 2003) and changes in moisture availability (Andrew et al., 2017).

The degree to which vegetation productivity is influenced by moisture relative to other environmental drivers varies spatially and temporally (Beringer et al., 2015; Lehmann et al., 2014) and vegetation communities have degrees of dependence on groundwater, subject to phenological and location characteristics (e.g. Cook & O'Grady, 2006; Lamontagne et al., 2005). Tropical savanna vegetation communities are dominated by C4 grasses, interspersed with predominantly C3 evergreen trees (Monk, 1997; Murphy & Bowman, 2012; Myers et al., 1997; Rossatto et al., 2014). During the dry season, trees and shrubs use deep soil moisture or groundwater to varying degrees as a function of plant root density and the water use strategies of individual species (Cook & O'Grady, 2006; Lamontagne et al., 2005; Rossatto et al., 2014; Schwinning, 2008; Ward et al., 2013). The degree of vegetation groundwater dependence is indicated by how closely NDVI is coupled with rainfall (Higgins et al., 2011; Rossatto et al., 2014; Sankaran, 2019), that is, where NDVI is poorly correlated to rainfall, vegetation is considered to be groundwater dependent.

Soil moisture provides a better representation of plant available water than rainfall and this parameter co-varies with NDVI at a range of lag times (Ahmed et al., 2017; Tian et al., 2019). Microwave remote sensing provides the capability for direct observation of surface soil moisture condition by analysing the microwave radiation emitted or reflected by the soil, and several microwave satellite missions have been deployed to provide continuous global scale soil moisture estimation (Ford et al., 2014; Tian et al., 2021). Root zone soil moisture, which is an important indicator of plant water availability, is widely obtained through the use of model simulations. In addition, modelled estimates of root-zone soil moisture from satellite retrievals have proved to have generally good agreement with ground data (Ford et al., 2014; Tian et al., 2019) and are therefore a valid indicator of plant available water.

There is demand for knowledge of plant available water and the associated vegetation productivity response in karst savanna landscapes of Indonesia. This demand stems from concerns of land managers about the links between soil and water resources, reduced tree cover, and biodiversity and livelihoods (Pellokila et al., 2014). Government and non-government programs have sought to improve landscape function in priority areas through regreening and reforestation. This work has focussed on sites that are particularly prone to erosion (BPDAS, 2011; Monk, 1997; Mulyoutami et al., 2016; Scott et al., 2005; Wallace et al., 2005), and in the absence of data about plant water use. Climate predictions indicate that the southernmost islands of Indonesia (e.g. East Nusa Tenggara province) will be subjected to increased durations of periods without rainfall and to higher rainfall during the early wet season (Brown et al., 2013). The El Niño Southern Oscillation will continue to be the main driver of interannual variability in rainfall across the region, with potentially greater rainfall extremes in a future warmer climate (Brown et al., 2013). Against this background, a study area was selected in the karst landscapes of Sumba (East Nusa Tenggara), which has been a focal area for land restoration programs in the period from 2009 to 2018. It is important to understand both the potential for success of these programs in the context of moisture availability, as well as any potential influences of increased tree cover on hydrology, including water availability in springs for human use. Therefore, the aim of this research was to provide insights into the response of vegetation to available moisture through analyses of NDVI, rainfall and soil moisture trends.

Our analysis aimed to characterise the interannual (1999–2018) NDVI trends at 10 patches of karst savanna vegetation and determine the influence of available moisture on these trends to inform land restoration projects. The 10 patches of savanna vegetation include three sites near a groundwater discharge point and seven sites with deep (>20 m) groundwater, four of them with active vegetation restoration activities. It was hypothesised that: 1) at the landscape scale, NDVI is correlated with soil moisture and rainfall; 2) NDVI at the three sites where groundwater is readily available is less sensitive to rainfall; 3) inter-annual variability of rainfall and rainfall anomalies are important drivers of NDVI;

and 4) positive trends in inter-annual NDVI can be detected at the four restoration sites irrespective of moisture trends.

3.4. Materials and methods

3.4.1. Study period

The NDVI response of vegetation was observed through analysis of satellite imagery between 1999 and 2018, while rainfall records from 1974 to 2018 were used to determine long-term rainfall characteristics.

3.4.2. Vegetation patch selection

Shallow groundwater sites support evergreen trees including local mango (*Buchanania arborescens),* mahogany (*Swietenia macrophylla*), teak (*Tectona grandis*), tamarind (*Tamarindus indica*) and figs (*Ficus* species), and the semi-deciduous lac tree (*Schleichera oleosa*). Away from shallow groundwater, scattered tree species include the evergreen chinese apple (*Ziziphus mauritiana),* cassia (*Senna siamea),* and deciduous gmelina (*Gmelina arborea*). At deep groundwater sites with restoration interventions, species that have been cultivated include teak, injuwatu *(Pleiogynium timoriense),* mahogany, cashew (*Anacardium occidentale*) and gmelina (Pellokila et al., 2014).

The ten 1 ha vegetation patches were selected within the district according to their depth to groundwater and land management status. Three sites are located next to groundwater discharge points, which support evergreen vegetation that has been actively conserved, maintained or restored; while the seven other sites are in areas where groundwater is unlikely to be available to trees (i.e. water table between 21 to 47 m below ground level). Out of the seven sites with deep groundwater, four are subject to managed vegetation restoration activities (Figure 3.1; Table 3.1). Soil texture at each of the 10 selected vegetation patches was sandy clay.

To determine the proportion of woody and non-woody vegetation in the study area and in 1-ha vegetation patches, a supervised classification was completed using field-verified training points of 15 landcover classes on a composite image created from the median pixel values of cloud-free multispectral Sentinel images between 01/01/2018 and 01/07/2018 at 10 m resolution in Google Earth Engine (GEE). These dates were selected to correspond with a period of field observation. The 15 landcover classes were then reclassified to a binary woody and non-woody grid, where woody pixels were defined as those dominated by C3 tree and shrub species and non-woody pixels were dominated by C4 grasses, surface water or bare ground (Appendix Table 1). Woody cover fraction for each 1 ha vegetation patch polygon was determined using Saga GIS v7.2.0 (Conrad et al., 2015) and the performance of this classification was checked against a manual delineation of woody canopy cover. Canopy cover was delineated manually by outlining canopies and summing canopy polygon areas in QGIS v3.10.6 (QGIS Development Team, 2020) using high resolution Google satellite imagery (Google & Maxar Technologies, 2018) and samples of canopy areas were ground-truthed at each site.

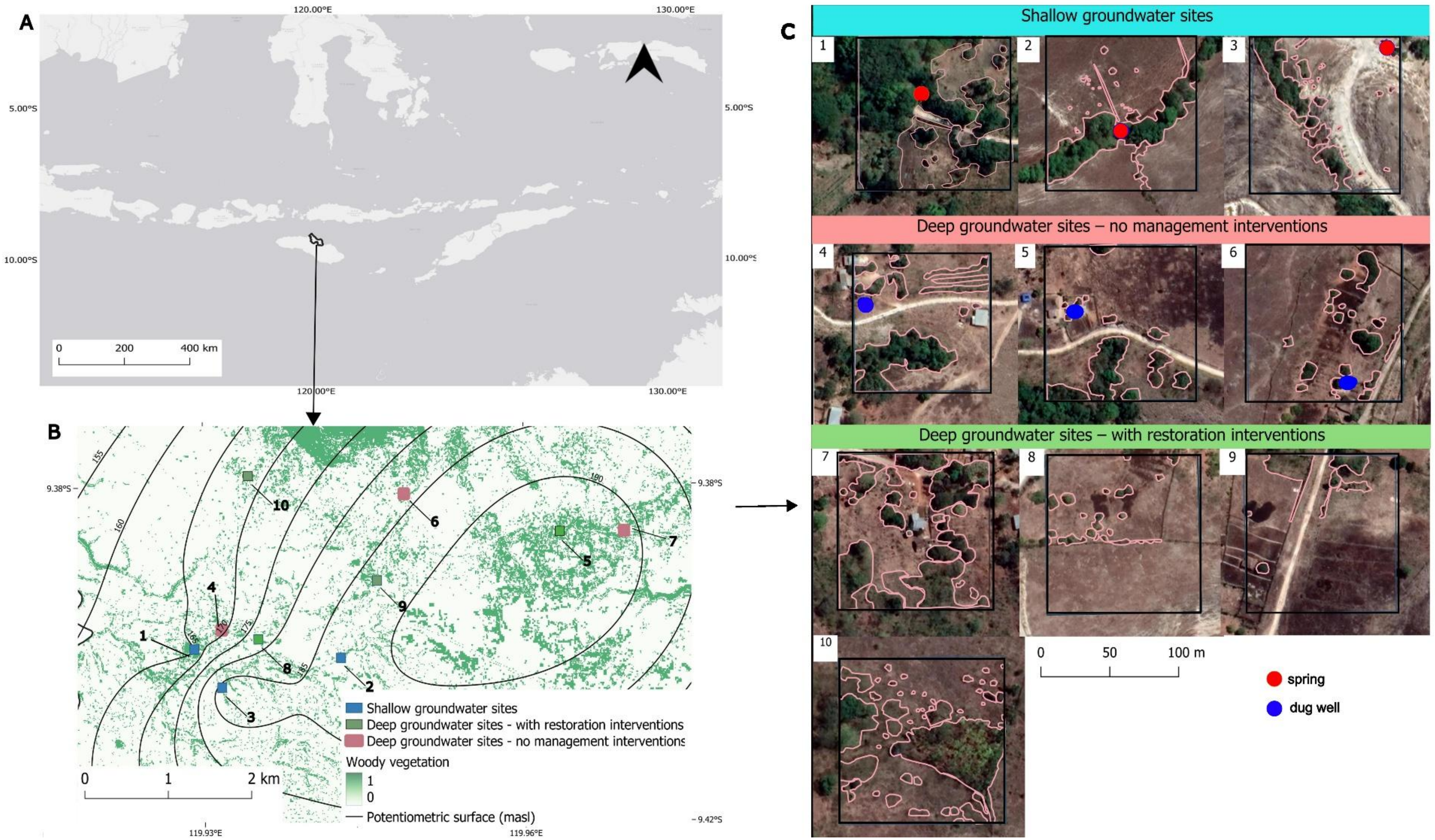

Figure 3.1. A) Location of the study area in the East Sumba regency of East Nusa Tenggara, Indonesia; B) detailed study area indicating: the location of vegetation patches, with site type code by colour; the potentiometric surface (5 m depth contours); woody and non-woody vegetation cover; C) delineation of woody canopy cover at each site on Google Satellite imagery (Map data: ©2015 Google).

Table 3.1. Description of vegetation sites.

Site name		Woody cover fraction	Woody canopy cover (%)	Patch description	Depth to groundwater (m)	Year of tree planting activities	Distance to drainage line (m)	Upstream drainage area (km²)
Shallow groundwater sites								
1.	Napu Spring	0.73	79	Spring discharge area at the base of a valley inhabited by mature trees including Ficus spp. Mangifera spp. *Swietenia macrophylla* planted for conservation activities.	0	2013	0	0.076
2.	Laikaterik Spring	0.26	30	Small discharge point in a depression at the base of a mature Ficus sp. tree. Moderate sized trees along drainage line and plantings of *Tectona grandis* and *Sweitenia macrophylla* above discharge point	0–2	2011	0	0.044
3.	Karaha Spring	0.08	21	Large mid-slope diffuse discharge line (likely a perched water table) supporting *Swietenia macrophylla* and the evergreen *Mangifera minor*.	0	2011	0	0.129
Deep groundwater sites – no management intervention								
4.	Napu Well	0.27	37	Dug well in flat area surrounded by grassland and an unknown mature evergreen tree	26	N/A	400	0.032
5.	Wunga Well 1	0.40	19	Disused dug well mid-slope, surrounded by intermediate orchard trees including *Anacardium occidentale*	21	N/A	38	0.077
6.	Wunga Well 2	0.20	14	Disused dug well mid-slope, surrounded by intermediate orchard trees including *Anacardium occidentale*	47*	N/A	30	0.018
Deep groundwater sites – with restoration interventions								
7.	Mahogany plantation	0.62	59	*Sweitenia macrophylla* plantation in upper slops flat area	29*	2011	190	0.012
8.	Cashew orchard	0.07	7	Mature *Anacardium occidentale* orchard with *Imperata cylindrica* grass understory in mid-slope flat area	20*	< 2003	250	0.122
9.	Regeneration 1	0.16	11	Mixed seasonal vegetable crops & farmer managed natural regeneration, household scale in mid-slope flat area.	56*	2013	290	0.019
10.	Regeneration 2	0.52	46	Farmer managed natural regeneration, sub-village scale, mixture of *Tectona grandis, Gmelina arborea, Senna siamea, Swietenia macrophylla* and *Pleiogynium timoriense* in mid-slope flat area.	19*	2013	340	0.017

* indicates an interpolated depth to groundwater.

3.4.3. Rainfall data

Rainfall time series data from January 1974 to December 2014 from the proximal Bureau of Meteorology (BMKG) rainfall station in Waingapu (51 km away in a straight-line from the field site) were used to establish long term regional rainfall trends. Rainfall data from the Climate Hazards Group Infrared Rainfall with Station (CHIRPS) daily 0.05° x 0.05° gridded time series product were accessed through GEE for comparison with daily local manual gauge data collected between July 2015 and June 2017 and proximal BMKG gauge data. Spearman's rank-based correlations were calculated between each of the rainfall datasets to determine the most accurate dataset to represent rainfall in the study area.

The wet season was defined as commencing on 1 November and concluding on 30 May and rainfall events outside of the wet season were classified as dry season rain. Water years were defined as the periods from 1 November of a given year to 30 October of the following year, and were then classified as very dry to very wet to assess the influence of inter-annual rainfall anomalies on NDVI (Table 3.2).

Table 3.2. Wet season classification criteria. Water years are classified according to deviation from the mean.

Condition		Classification
$R > \mu + 2\sigma$	[> 1262]	Very wet
$\mu + 2\sigma > R > \mu + \sigma$	[1038:1262]	Wet
$\mu + \sigma > R > \mu$	[840:1038]	Moderately wet
$\mu > R > \mu - \sigma$	[590:840]	Moderately dry
$\mu - \sigma > R > \mu - 2\sigma$	[367:590]	Dry
$R < \mu - 2\sigma$	[<366]	Very dry

R = annual rainfall, μ = long term mean annual rainfall and σ = standard deviation. Rainfall amounts are shown in mm. The frequency of each wet season class occurring between 1974 and 2018 was as follows: 1 very dry (VD) year, 4 dry (D) years, 22 moderately dry (MD) years, 13 moderately wet (MW) years, 3 wet (W) year and 2 very wet (VW) years (Figure 3.2A).

Historical Troup Southern Oscillation Index (SOI) data were obtained from the Bureau of Meteorology, Australia (BOM, 2021) to examine the influence of ENSO on rainfall anomalies and moisture availability. While classification of El Niño and La Niña events vary according to meteorological institution (Van Oldenborgh et al., 2021), for simplicity El Niño (La Niña) events were defined here as those with annual mean SOI below – 7 (above +7) (Figure 3.2).

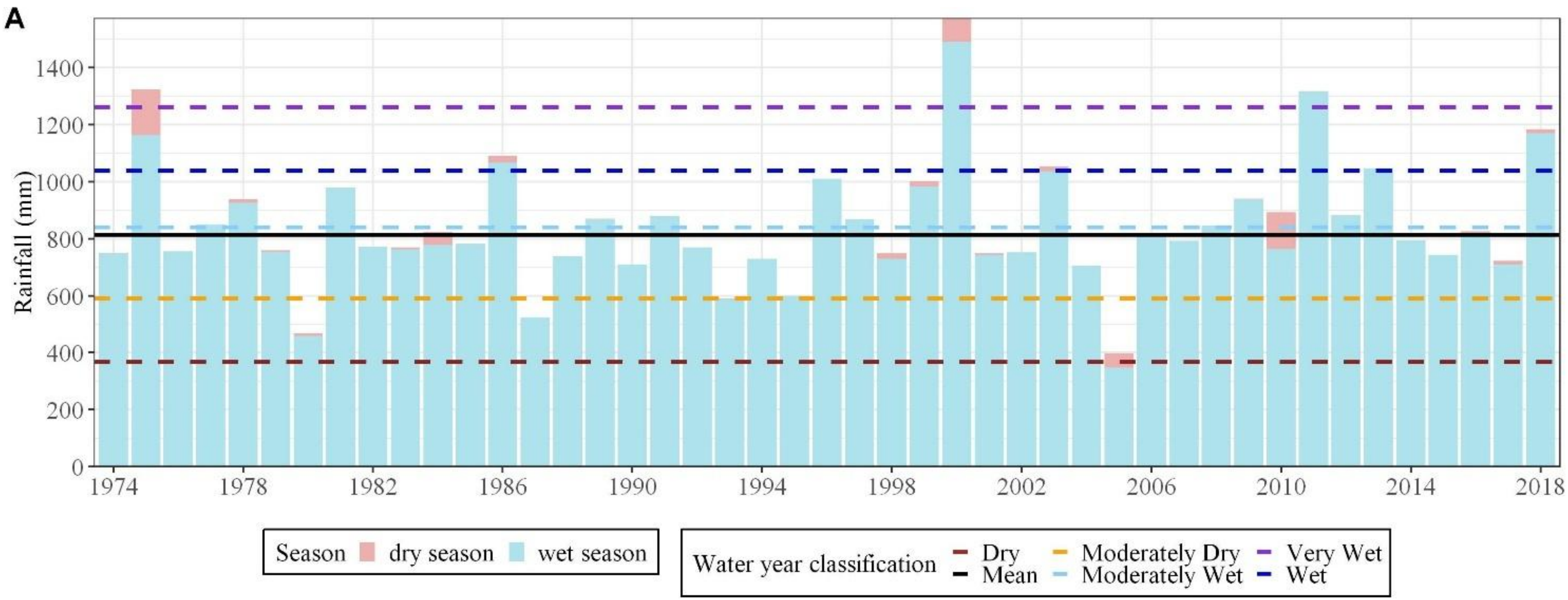

Figure 3.2. A) Wet season and dry season rainfall totals by water year from 1974 to 2018. Total wet season rainfall from November to May the following year is shown (blue bars) along with dry season rainfall between June and October (red bars). Anomalous rainfall years are identified as above the $\mu + \sigma$ (wet), $\mu + 2\sigma$ lines (very wet) or below the $\mu - \sigma$ (dry) or μ -2σ (very dry) lines.

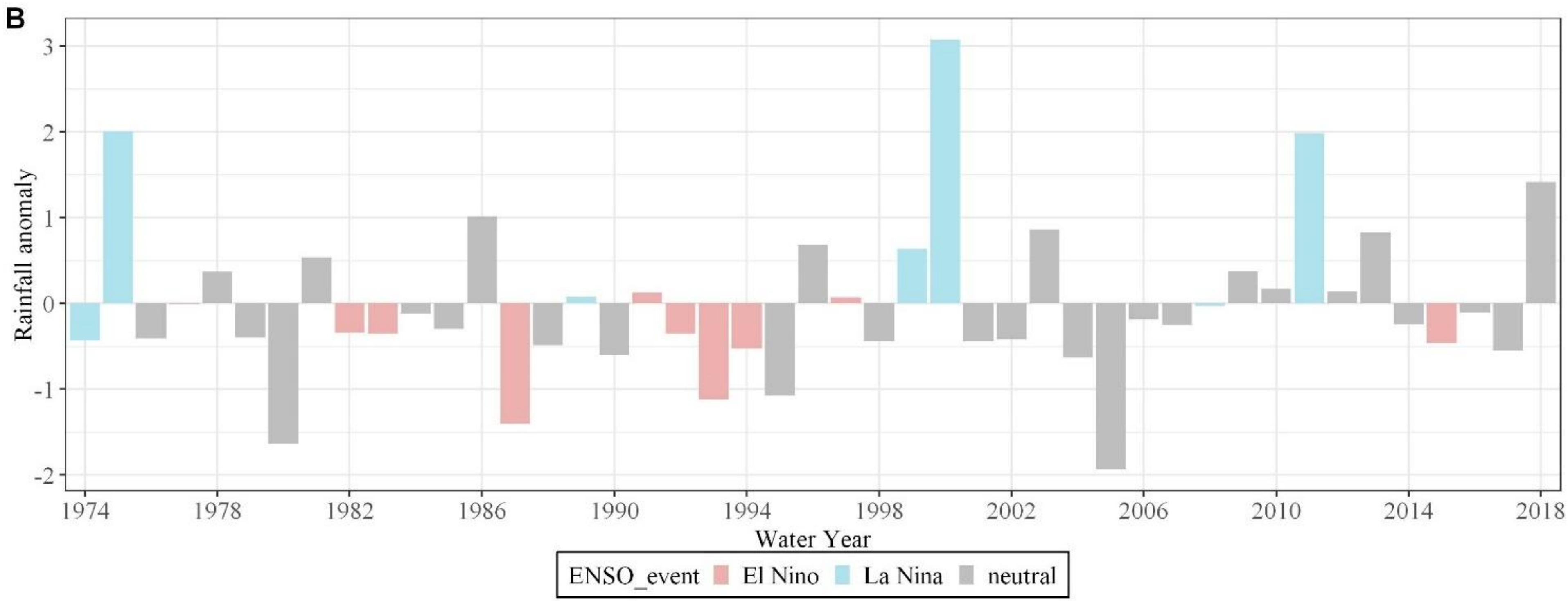

Figure 3.2. B) Rainfall anomalies and El Niño Southern Oscillation (ENSO) events by water year (1 November to 30 October the following year). El Niño, La Niña and neutral conditions are indicated by red, blue, and grey bars, respectively.

3.4.4. Soil moisture and groundwater estimate

The recent Soil Moisture Active Passive (SMAP) (Entekhabi et al., 2010) product has demonstrated superior quality in measuring surface soil moisture condition compared with other operational products (Chen et al., 2018; Chen et al., 2014; Cui et al., 2018; Kumar et al., 2018). However, soil moisture retrieved from SMAP only represents the soil moisture content at up to top 5 cm of the soil and it is incomplete in space and time. Data assimilation, which is the process of optimally combining model simulations with independent observations to improve the accuracy of model estimation (Entekhabi et al., 2010), is the most widely used approach to obtain soil moisture estimates. In this study, we derived values for surface soil moisture and root zone soil moisture from the gridded 0.1 x 0.1^{o} soil moisture time series from the Satellite-Guided Root-zone moisture Analysis and Forecasting System (S-GRAFS) (Tian et al., 2023). Surface soil moisture is measured relative to the wettest condition recorded for the site and rootzone soil water index is derived from surface relative wetness.

To characterise seasonal access to moisture for each patch, we estimated the depth to groundwater and distance to drainage lines. For depth to groundwater, the potentiometric surface across the study area was generated in Saga GIS v7.2.0 (Conrad et al., 2015) using the *Contour Lines from Points* tool (Conrad, 2014). Groundwater elevation contours were interpolated on a 30 x 30 m digital elevation surface from known mean depth to groundwater at six points (community managed wells and springs) within a 5 x 5 km area using multilevel B- Spline Interpolation (Figure 3.1B).

3.4.5. Normalised difference vegetation index data

Most published analyses of vegetation responses to rainfall in savanna landscapes are applied at a coarse spatial resolution (> 250 m), which has the advantage of long historical records and high frequency such as MODIS NDVI, Global Inventory Modelling and Mapping Studies (GIMMS) NDVI and MODIS LAI (Leaf Area Index) time series data. However, analyses at this coarse scale do not have the ability to detect small, localised fluxes in vegetation productivity, driven by fine-scale hydrological or landcover changes. In addition, measurements of NDVI at lower resolution tend to underestimate the proportion of photosynthetically active vegetation due to aggregation with surrounding less vegetated patches (Munyati & Mboweni, 2013). Thus, in this study, we extracted data from MODIS imagery for district scale analyses and from Landsat 7 imagery for patch-scale analyses. We also trialled Sentinel 2 data, but we found that insufficient cloud-free dates were available for time series analysis.

Multispectral images from Landsat (LANDSAT/LE07/C01/T1_SR, n = 360) and MODIS (MOD13A1.061, n = 434) sensors were sampled at 30 and 500 m resolution, respectively, in GEE for the period 1999 to 2018. For Landsat data the cloud and cloud shadow Quality Assurance bands were used to eliminate pixels containing cloud and red band saturation. Landsat 7 images post 31/05/2003 had some missing data due to failure of the scan line corrector, amounting to 22% data loss per scene (Loveland & Dwyer, 2012). However, this does not greatly impact NDVI time series analysis (Zhu, 2017). It is also preferable to derive NDVI consistently from Landsat 7, rather than gap-fill with data derived from Landsat 5 retrievals, as the red reflectance values differ between the two sensors (Sulla-Menashe et al., 2016; Teillet et al., 2001); and a change in orbit resulted in inconsistencies in values (Roy et al., 2016). For MODIS, the MOD13A1.061 image collection available in GEE is atmospherically corrected and masked for water, clouds and cloud shadow. The study period was set as 1999 to 2018 to provide sufficient observations for trends analyses and to coincide with collection of field observations for related studies between 2014 and 2018.

3.4.6. Statistical analyses

Statistical tests were conducted with R version 4.0.3 (R Core Team, 2020), the 'Kendall' (v2.21; McLeod, 2022), 'modifiedmk' (v1.6; Patakamuri, 2021) and 'zyp' packages (Brounaugh et al., 2023). A link to the full reproducible code is provided in the data availability statement. To investigate the temporal correlation between monthly NDVI and moisture parameters (rainfall and soil moisture), a windowed cross correlation (WCC) was applied. In the WCC method, a temporal window is selected to examine the changes in correlation between two time series (Boker et al., 2002), and this enabled us to determine the period that NDVI lags behind available moisture. The correlations between one month up to 12-month antecedent rainfall and NDVI were calculated for each vegetation patch, while a linear regression model was used between total annual rainfall and mean annual NDVI to analyse the sensitivity of each vegetation patch to changes in available moisture (adapted from Aguilar et al., 2012; Chamaillé-Jammes & Fritz, 2009; Liu et al., 2017). For soil moisture, pixel-wise correlations with NDVI were determined at the scale of the soil moisture grid (0.1 x 0.1^{o}) for the period 2015 to 2018. Results calculated on water years are referred to hereafter as 'annual' values. Because the NDVI and rainfall data were not normally distributed, a Spearman rank-based correlation test was used to identify sites where mean annual NDVI had the strongest relationship with annual rainfall.

To test for increasing or decreasing trends in monthly NDVI and rainfall time series, non-parametric Mann-Kendall (MK) trend analyses were applied. Mann Kendall analyses were chosen because they are an appropriate method for detecting trends in time series data irrespective of outliers, and are commonly used in hydrological studies (e.g. Hamed, 2008). The MK test parameters were: H_0: data are independent and randomly ordered; and H_a: there is a monotonic trend. The MK test statistic (ZMK) was calculated as for Hippel and McLeod (1994). Autocorrelation and partial correlation in the time series were tested using *acf* and *pacf* plots. When either was detected, a block bootstrap method was used in conjunction with the MK test to check for false trends (Önöz & Bayazit, 2012). The MK test statistic results are presented, along with the 2-sided p-values, where $\alpha = 0.05$, with 95% confidence intervals for the bootstrap statistics. Where significant trends were identified, the overall annual change (ΔNDVI y^{-1}) in the time series was calculated as m* 12, where m is the slope of the Theil Sen regression line for the monthly NDVI time series (adapted from Sen, 1968; Venter et al., 2020)

Minimum, maximum, mean, median and amplitude NDVI values were determined for the whole 1999:2018 Landsat time series and for subsets of the time series, based on classes of wet seasons (from very dry to very wet; Section 3.4.3). Minimum, maximum, median and mean values provide an indication of photosynthetic activity, while seasonal amplitudes provide insights into the evergreen (woody) and deciduous vegetation makeup at each vegetation patch (Forkel et al., 2013).

The Pearson's correlation between NDVI and soil moisture gridded time series at two depths (surface and root zone) was calculated for all pixels in the Haharu district polygon for the period between 2015 and 2018. Linear regression was undertaken to determine the sensitivity of the soil moisture – NDVI correlation to fraction of woody cover. All vegetation patches are located within the same 0.1^{o} x 0.1^{o} soil moisture pixel, so an inter-site comparison of soil moisture was not possible. The process for selection and preparation of datasets and methods of data analysis are summarised in Figure 3.3.

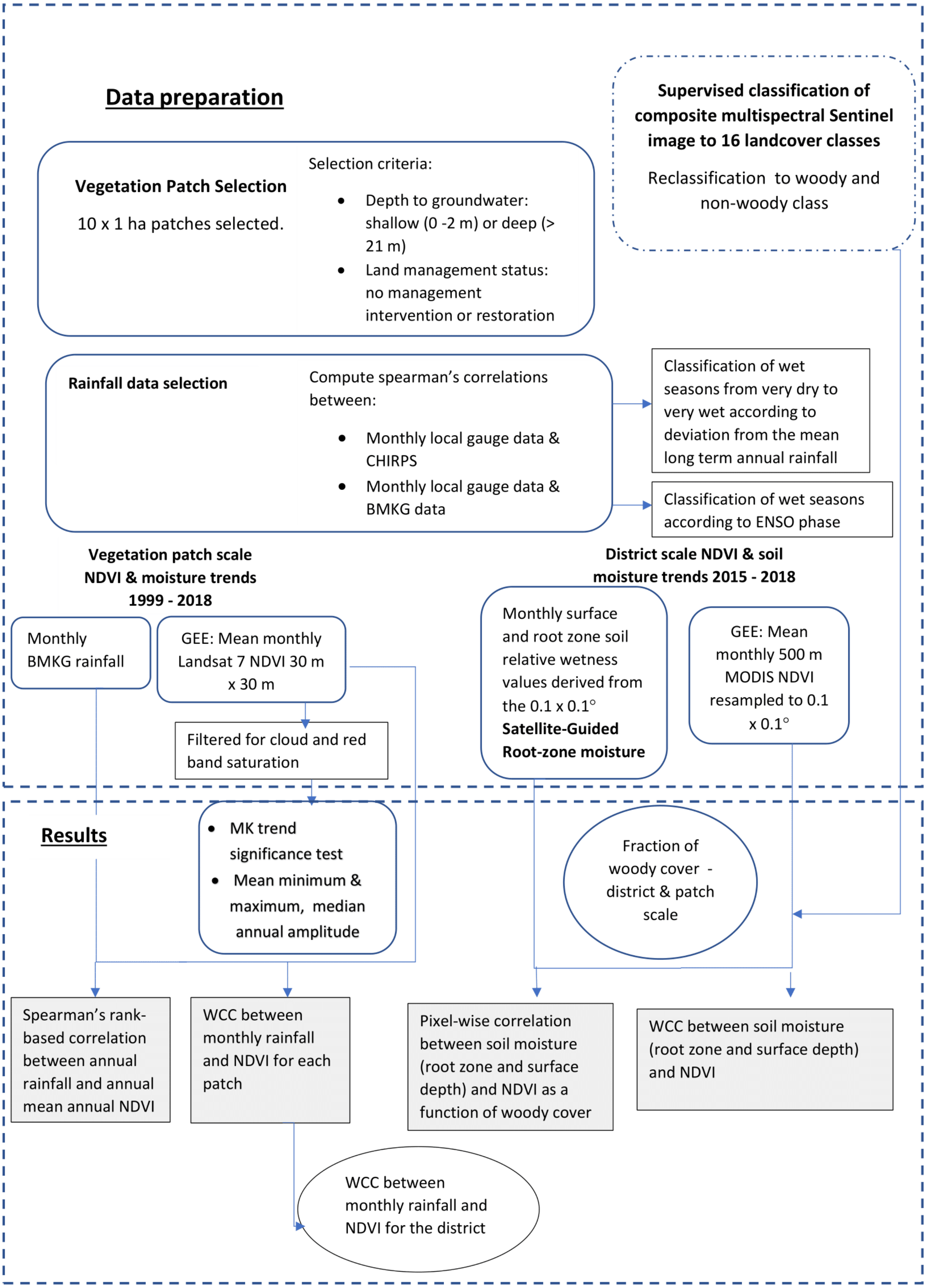

Figure 3.3. Data preparation and analysis process

3.5. Results

3.5.1. Rainfall and soil moisture trends

Monthly rainfall data in the period between May 2015 and June 2018 from both the proximal BMKG gauge and the CHIRPS gridded dataset were closely correlated with local rainfall measurements ($r = 0.87$, $p < 0.001$ and $r = 0.84$, $p < 0.001$, respectively). The BMKG gauge data were selected for use in further analyses due to the slightly higher correlation result. It was established that of the five driest years between 1974 and 2018, with rainfall anomalies ranging between -2.08 and -1.14, three coincided with El Niño events and conversely four of the five wettest years, with rainfall anomalies between +1.5 and +3.3, coincided with La Niña events (Figure 3.2). The wettest year in this record was the 2000 La Niña year, when 1478 mm was received during the wet season, with an additional 88 mm outside this period. Between 2013 and 2016, three moderately dry years were experienced. A strong El Niño event contributed to the drier than mean season in 2015, with a borderline El Niño in late 2014 contributing to late onset of the wet season and below mean rainfall (Figure 3.2B). In 2010, 32% of rainfall occurred during the dry season, while 5% of rainfall occurred in the dry season on average. In 2011, a strong and sustained La Niña event resulted in a +3.6 rainfall anomaly wet season, with > 99% of the 1318 mm of rainfall falling during the wet season period. There were no statistically significant trends in monthly rainfall using Mann-Kendall tests in the period between 1999 to 2018 (ZMK -0.03, p-value 0.43).

The effect of the negative rainfall anomaly in 2015 is reflected in soil moisture at both the soil surface and in the root zone in the dry season of 2015 with low soil water index values of 0.04 (Figure 3.4). Following this period, soil moisture returned to a peak value between 0.58 and 0.74 in the middle of each wet season and then returned to very low values at the end of the 2018 water year, despite a positive rainfall anomaly for that year.

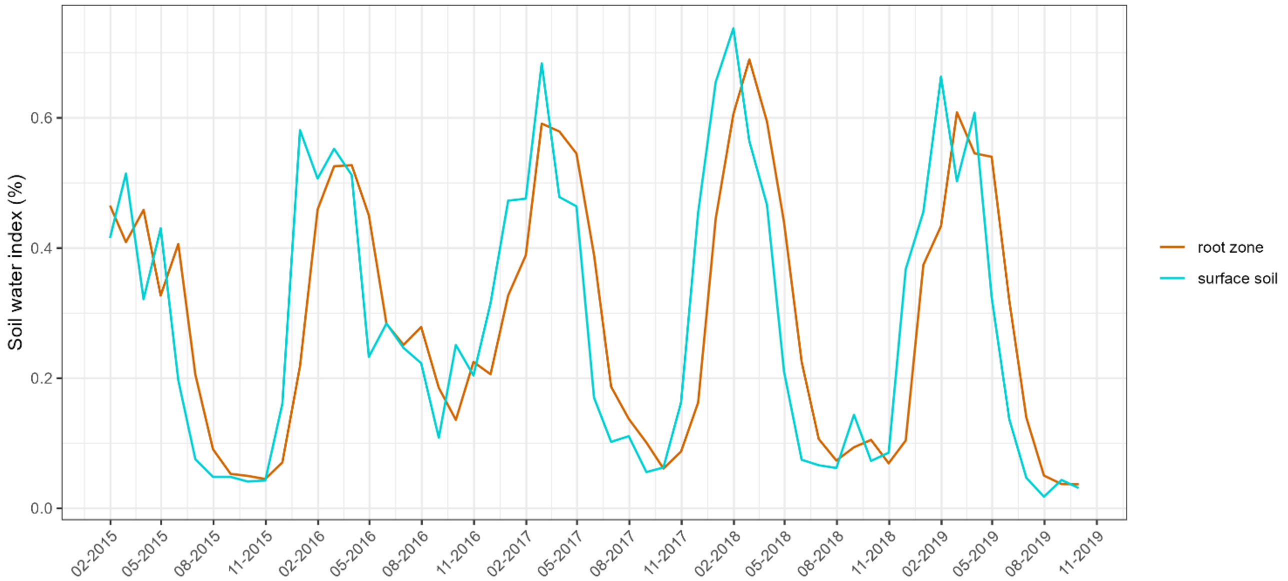

Figure 3.4. Mean monthly root zone and surface soil moisture for the study area for the water years 2015 to 2019.

3.5.2. Normalised difference vegetation index patterns and trends at the district scale

Woody landcover accounts for 45% of the district while non-woody accounts for 55% (Figure 3.5). Dense woody areas with a NDVI > 0.5 are largely confined to riparian corridors, steeper hillslopes and groundwater discharge areas (Figure 3.55). NDVI values range from -0.53 to 0.83 and the district mean value is 0.36. Woody cover has an NDVI range of approximately 0.6 to 0.8, while grass dominated landcover is < 0.5 (Figure 3.5). Negative NDVI values correspond to ephemeral water bodies in the district.

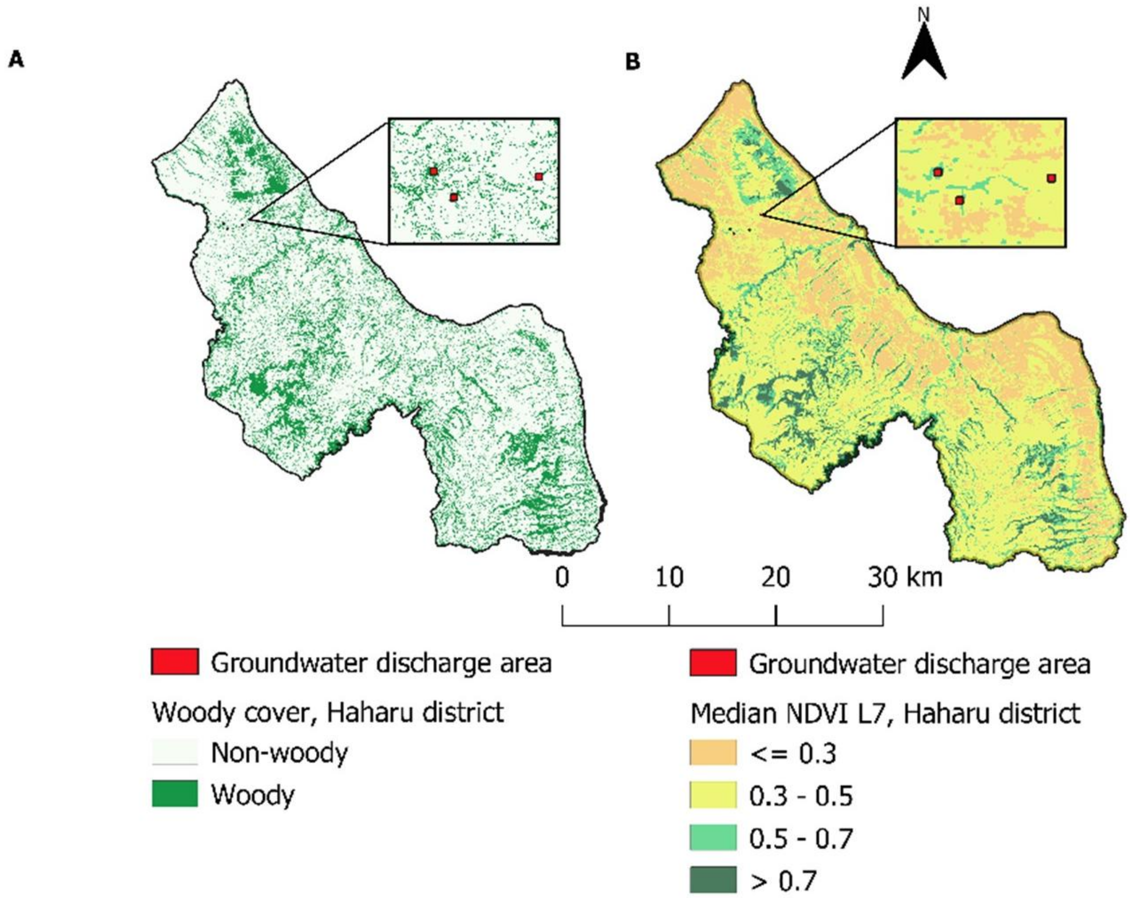

Figure 3.5. A) Binary woody and non-woody classification derived from 15 landcover classes. B) Median interannual NDVI in the Haharu district derived from Landsat 7 imagery.

As a general rule, NDVI was highest between February and April (late wet season) and lowest between September and November (late dry season). The differences in timing of minimum and maximum NDVI values derived from MODIS and Landsat 7 imagery (Figure 3.6) are explained by the number of image acquisitions. Landsat 7 repeat acquisition is 16 days, whilst near-daily for MODIS, whereby the possibility of cloud obscuration is thus vastly reduced. The Landsat spatial resolution is 70 times greater, while the acquisition rate of MODIS is greater than 30 times higher, resulting in similar standard deviation and standard error measurements, and a markedly lower coefficient of variation for MODIS NDVI (Table 3.3). At the district scale using the MK test, no significant long-term trends were identified in the mean monthly MODIS (n = 434) or Landsat 7 (n = 356) time series data from 1999 to 2018.

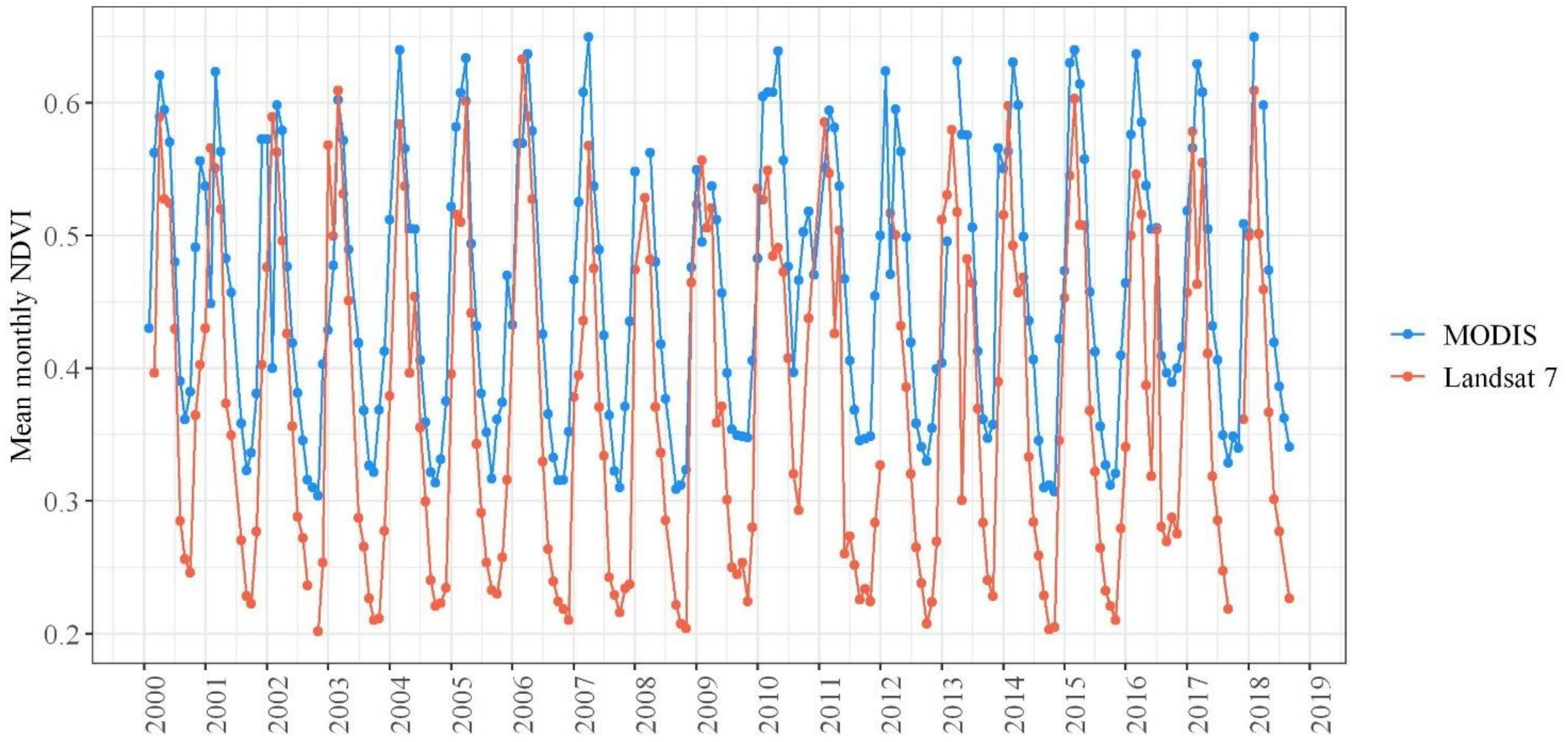

Figure 3.6. Monthly MODIS and Landsat 7 NDVI values between 2000 and 2018.

Table 3.3. Landsat 7 and MODIS mean monthly NDVI trend analysis for the Haharu district, 1999 to 2018.

	Mean	Standard deviation	Standard error	CV
Landsat 7 (LANDSAT/LE07/C01/T1_SR)	0.368	0.126	0.008	34
MODIS (MODIS/006/MOD13A1)	0.462	0.104	0.007	22

CV = Coefficient of variation.

3.5.3. Response of monthly normalised difference vegetation index and soil moisture to rainfall at the district scale

Using the WCC method with windows of one month for the period between 1999 to 2018, a lag time of four months between rainfall and the Landsat 7 NDVI monthly time series gave the highest correlation ($r = 0.71$, $p = <0.001$), with similar yet lower values for rainfall lags of 2,3, 5 and 6 months (Figure 3.77A). To compare with the available soil moisture data, the WCC for the period between 2015 and 2018 was also computed. Here it was identified that a lag of two months gave the highest correlation, followed by one month (Figure 3.7.7B). This difference is attributed to the three consecutive moderately dry years from 2015 and 2017, where response to rainfall would have been more rapid (Ahmed et al., 2017).

The cross-correlation between NDVI and soil moisture differed by soil depth. It was determined that the overall correlation between surface soil moisture (0–5 cm depth) and NDVI for all valid pixels within the district polygon was highest with a one-month lag (0.40, $p <0.001$) followed by no lag (0.35, $p <0.001$) (Figure 3.7.7D). For soil moisture in the root zone (0–1 m depth), the highest correlation was found with no lag (0.47, $p <0.001$), followed by a one-month lag (0.32, $p<0.001$) (Figure 3.7.7C). For pixels within the district where the fraction of woody cover was > 0.5, monthly NDVI was highly correlated with root zone soil moisture (between 0.82 and 0.85), while surface soil moisture was not as well correlated (between 0.48 and 0.6). The fraction of woody cover had a stronger influence on the NDVI soil moisture relationship in the root zone than in the shallow soil zone (Figure 3.7E).

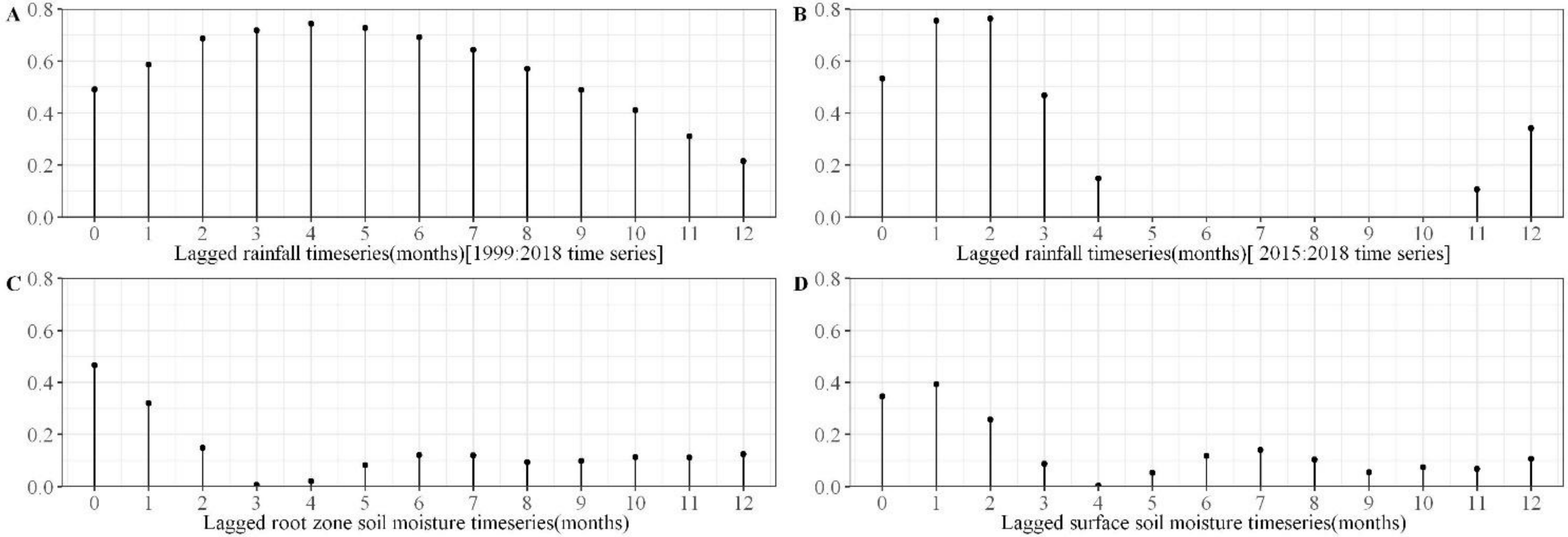

Figure 3.7. A) Cross-correlation values for monthly rainfall vs monthly Landsat 7 derived NDVI between 1999 and 2018; B) rainfall vs Landsat 7 derived NDVI between 2015 and 2018; C) root zone soil moisture vs NDVI; and D) surface soil moisture vs NDVI.

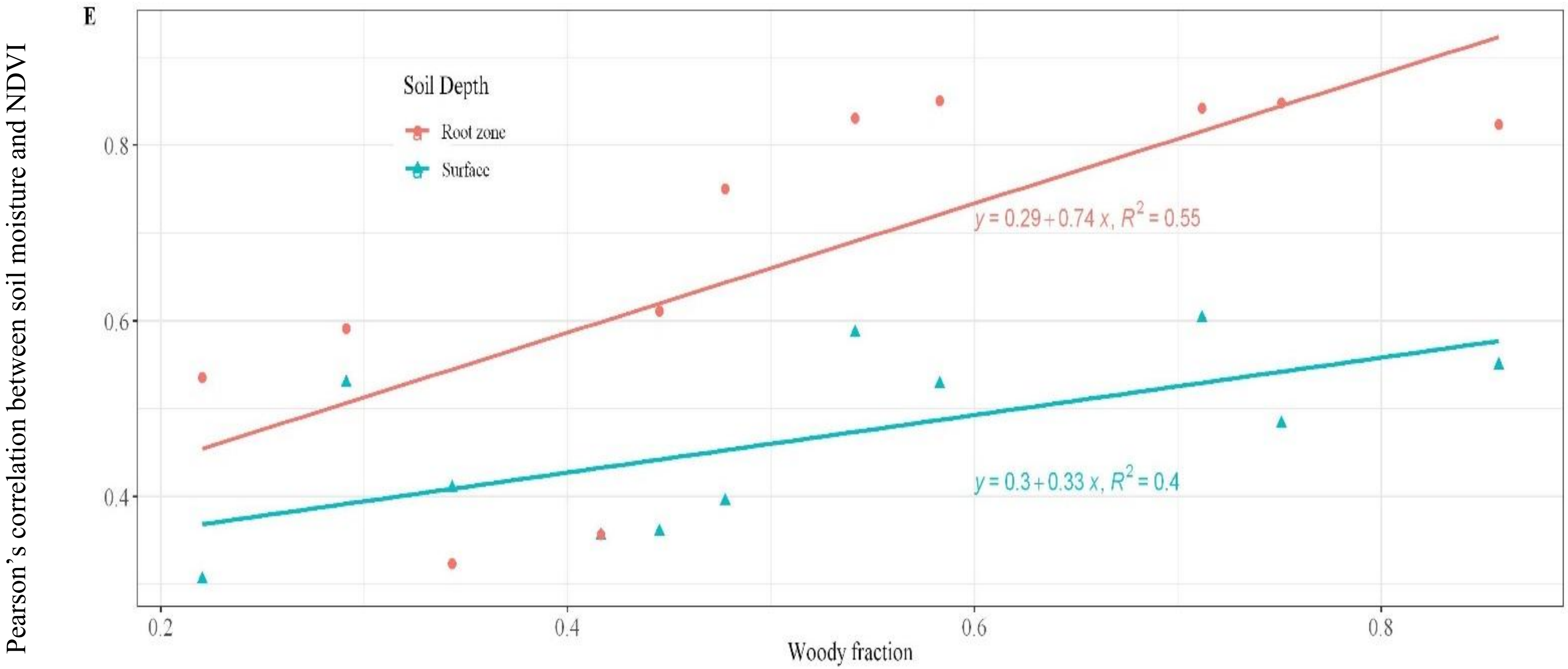

Figure 3.7. E) Correlation between soil moisture and NDVI as a function of woody fraction. Linear regression equations are shown to indicate the influence of woody fraction on the NDVI soil moisture relationship.

3.5.4. Normalised difference vegetation index trends at the patch scale

Mean and maximum NDVI were highest at a shallow groundwater site (site 1), which was also the site with the highest woody cover (Table 3.4; Figure 3.1). Aside from this result, no consistent relationship between site type and NDVI minimum, maximum, mean or amplitude values was established, nor was there a consistent influence of the fraction of woody cover on these results. A significant decreasing trend in annual NDVI amplitudes was found at a deep groundwater site with no intervention (site 4; ZMK -0.56 , p-value 0.001) and an increasing trend at a deep groundwater site with restoration intervention (site 8; ZMK 0.439, p-value 0.01). This suggests a potential change in the woody and grasscover fractions or the effect of anomalous wet periods on grass productivity at these two sites (Chamaille-Jammes et al., 2006, Kahiu and Hanan, 2018, Ma et al., 2013). No trend in NDVI amplitude was found at the remaining sites, suggesting no significant change over the study period in the woody and grasscover fractions at these sites. For mean monthly NDVI values, a significant positive trend at a shallow groundwater site (Site 1; ZMK 0.318, p-value <0.001, Δ 3.74x$10^{-4}$$y^{-1}$) and at a deep groundwater site with restoration intervention (Site 9; ZMK 0.238, p-value <0.001, Δ 2.7x$10^{-4}$$y^{-1}$) was identified. Two additional restoration sites (sites 7 and 8) had positive trends with small p-values (0.07 and 0.05, respectively), however, it could not be concluded that these were significant trends (Appendix Table 2).

Table 3.4. Mean minimum and mean maximum NDVI values from Landsat 7 by site for the 1999 to 2018 time series. In general, low positive values represent shrub and grassland (0.2 to 0.4), high positive values indicate woody cover (0.6 to 0.8).

Site Number	Site Name	Mean Minimum NDVI	Mean Maximum NDVI	Mean NDVI	Median Annual Amplitude NDVI
Shallow groundwater sites					
1	Napu Spring	0.44	0.81	0.63	0.37
3	Laikaterik_Spring	0.21	0.54	0.35	0.37
4	Karaha_Spring	0.30	0.69	0.44	0.33
Deep groundwater sites – no intervention					
2	Community_Well	0.26	0.52	0.32	0.43
5	Wunga Well 1	0.24	0.61	0.40	0.46
6	Wunga Well 2	0.30	0.64	0.48	0.39
Deep groundwater sites – with restoration					
7	Mahogany Plantation	0.27	0.69	0.44	0.47
8	Cashew_orchard	0.20	0.60	0.37	0.34
9	Regeneration 1	0.27	0.74	0.49	0.43
10	Regeneration 2	0.29	0.54	0.35	0.33

Median annual amplitude is the median difference between minimum and maximum NDVI in each water year correlation with monthly rainfall and soil moisture:

Using WCC, it was established that a lag time of two months between rainfall and the Landsat 7 NDVI monthly time series gave the highest correlation for most sites, ranging between 0.49 (site 4) and 0.76 (site 8) (Appendix Table 3). Whilst the NDVI at two of the shallow groundwater sites had low correlations with rainfall at 0, 1 and 2 month lagged rainfall, it was found that the correlation could not be predicted by site type alone, as site 2 (a shallow groundwater site) had higher correlations with lagged rainfall than deep groundwater sites.

The sensitivity of mean annual NDVI to annual rainfall at each site is indicated by the slope of their linear regression (Table 3.5). As anticipated, shallow groundwater sites were least sensitive to rainfall, with regression slopes <1.2 and no significant correlation between the two variables (Pearson's correlations between -0.24 and 0.30). The deep groundwater sites were much more sensitive to rainfall (regression slopes between 0.14 and 0.48 and Pearson's correlations between 0.52 and 0.71); and groundwater site with restoration interventions were the most sensitive of all sites (Table 3.5). The

R^2 values for the linear regressions were relatively low due to the high interannual variability of NDVI, however, the relationships were significant ($\alpha = 0.05$) for all but one deep groundwater site (Table 3.5).

Table 3.5. Linear regression of mean annual NDVI versus total annual rainfall at vegetation patches grouped by site type, from 1999 to 2018.

Site Number	Site Name	Slope ($x10^{-2}$)	R^2	p-Value	Pearson's Correlation	p-Value
Deep groundwater sites – with restoration intervention						
7	Mahogany Plantation	4.2	0.49	<0.001	0.70	<0.001
9	Regeneration 1	3.7	0.23	0.02	0.52	0.02
8	Cashew orchard	3.1	0.48	<0.001	0.71	<0.001
10	Regeneration 2	3.1	0.14	0.06	0.62	0.003
Deep groundwater sites – no intervention						
6	Wunga Well 2	2.7	0.32	0.01	0.60	0.005
4	Community_Well	2.6	0.36	<0.001	0.63	0.003
5	Wunga Well_1	2.5	0.25	0.01	0.54	0.01
Shallow groundwater sites						
2	Karaha Spring	1.2	0.04	0.21	0.30	0.21
3	Laikaterik Spring	0.8	0.01	0.36	0.21	0.36
1	Napu Spring	-1.9	0.01	0.30	-0.24	0.30

The slope and adjusted R^2 and p-values are presented for each vegetation patch in decreasing order of slope value.

It was established that there was no significant correlation between annual NDVI and annual rainfall at shallow groundwater sites. All remaining sites had significant correlations ranging between 0.52 and 0.71 (Table 3.5). Annual NDVI at deep groundwater sites had the highest Pearson's correlation and Spearman's rank-based correlation with rainfall, with no clear split between the sites with or without restoration intervention (Table 3.5; Figure 3.8.8).

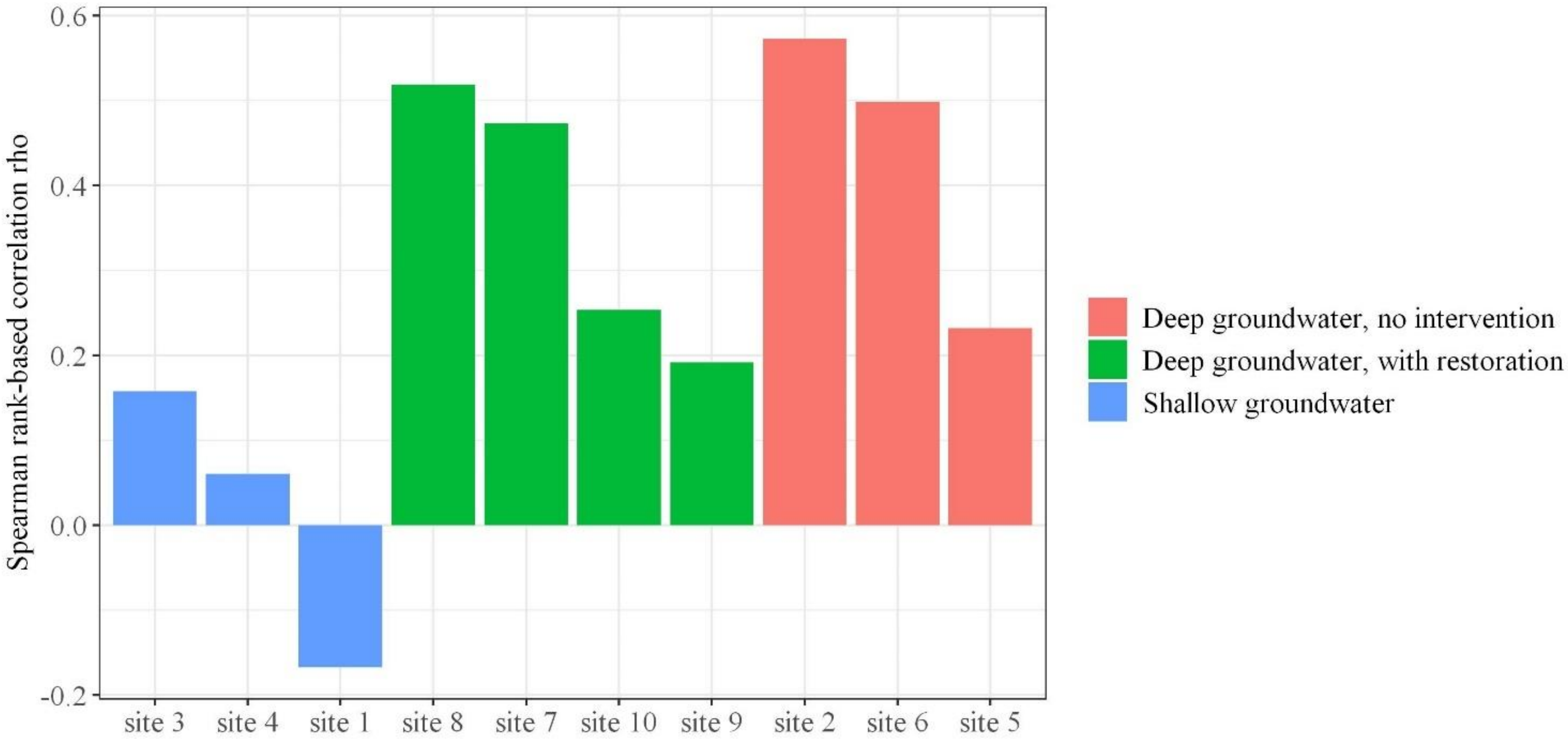

Figure 3.8. Spearman's rank-based correlation of annual NDVI vs annual rainfall for each site. Bars are grouped by site type.

3.5.5. Response of normalised difference vegetation index to anomalies of wet season rainfall

Most years in the study period had moderate to wetter than long term mean rainfall. We could not identify clear differences in the response of NDVI amplitudes to rainfall anomalies by site type. However, differences in the mean, median and interquartile ranges of NDVI by site type were established in response to annual rainfall classes. Mean and median NDVI was highest for shallow groundwater sites across the whole period and all wet season classes. The range of NDVI values for shallow groundwater sites was significantly higher than other site types in the moderately dry (MD) and very dry (VD) periods. For the deep groundwater sites both with and without restoration intervention, there was a significant difference in NDVI in the W period relative to the whole study period, indicating a positive influence of additional rainfall on NDVI at these sites. For all site types, there was a statistically significant difference between median values in the VD period relative to W. Mean and median values in the VW period were lower than W for all site types (Figure 3.9.9), which can be explained by a decrease in NDVI in the late wet season in the VW period (Appendix Figure 1). It was found that NDVI peaks were earlier in the VW and W years compared with the VD year. The NDVI in the VD year had a short single peak, suggesting a short growing season while the VW year had a drop in NDVI in the late wet season (April), followed by a recovery in May (Appendix Figure 1). A threshold volume of annual rainfall in the order of 1200 mm (between 1 and 2 standard deviations above mean rainfall) was identified, beyond which any additional rainfall had a neutral or negative effect on NDVI (Appendix Figure 2).

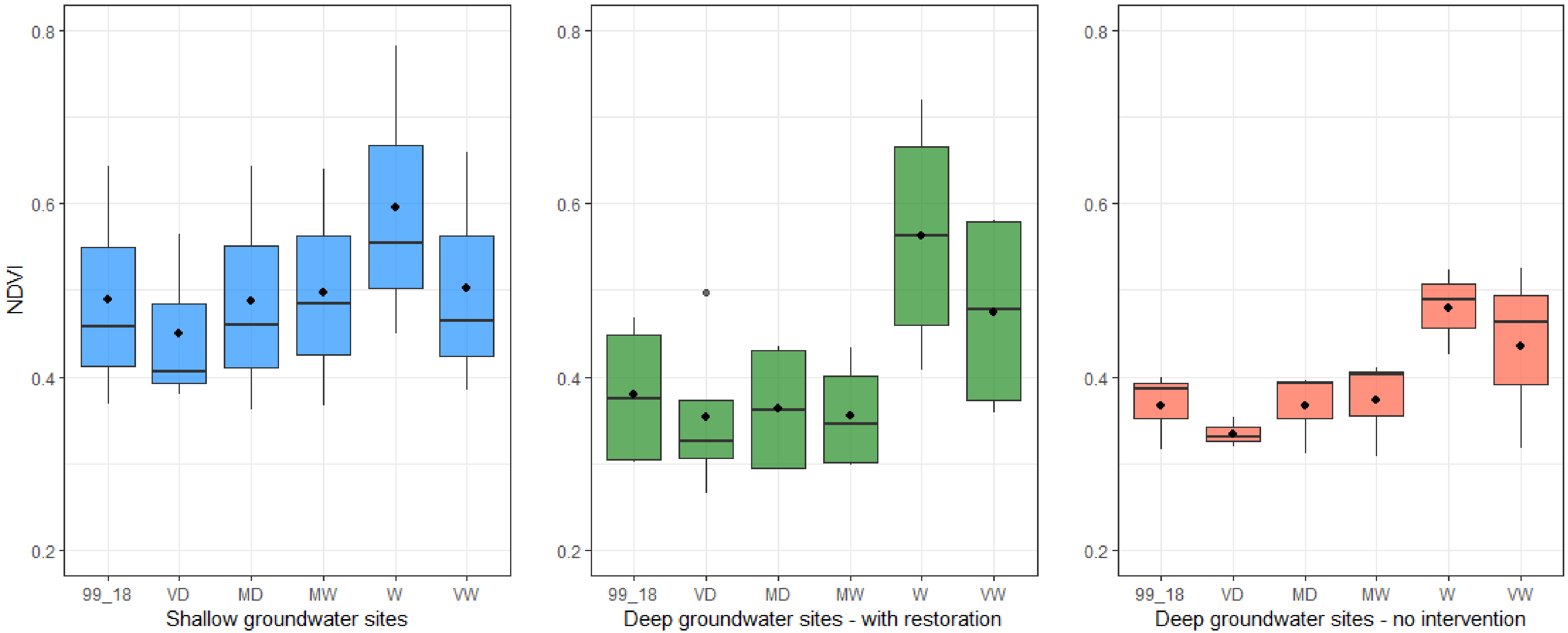

Figure 3.9. Distribution of median annual NDVI values for the entire study period (99-18); very dry (VD); moderately dry (MD); moderately wet (MW); wet (W); and very wet (VW) years. Boxes span the interquartile range, lines denote the median, circles denote the mean, whiskers represent the 10th and 90th percentiles, and outliers are represented by grey circles.

3.6. Discussion

3.6.1. Response of normalised difference vegetation index reliably linked to rainfall and soil moisture

The results of this study show that in tropical karst savanna areas subject to high rainfall seasonality, the NDVI correlation to rainfall can reliably be linked to the presence of subsurface moisture. Specifically, where subsurface moisture is depleted, the correlation between NDVI and rainfall will be high and vice versa. In line with our first hypothesis, it was established that root-zone soil moisture was correlated with NDVI in the corresponding (lag0) and preceding month (lag1). Shallow soil moisture was also correlated with NDVI, although not as strongly. These findings agree with previous studies such as Ahmed et al. (2017), who used the 0.5º global monthly soil moisture data and GIMMS NDVI3g to identify correlations between NDVI and soil moisture in the Sahel region of Africa. The study found that the highest correlation between the two variables was between lag0 and lag1 and that south of the study region, where mean rainfall is higher, longer lag times gave the highest correlations. Ahmed et al. (2017) also identified that during a wetter phase the lag time that gave the highest correlation was greater compared with a more normal phase of rainfall. The relationship between soil moisture and NDVI during more normal periods of rainfall could not be tested in this study, given the short soil moisture time series and this is noted as a limitation. The data in this study showed that the strength of the correlation between soil moisture and NDVI increased in line with woody cover fraction. The correlation between woody cover, soil moisture and NDVI has previously been reported, for example in Tian et al. (2019) who found that surface soil moisture is more strongly correlated with NDVI of grasslands and deep soil moisture is more closely correlated with NDVI in sites with higher woody fractions (shrub and forest sites). Our finding of a rapid response of NDVI to soil moisture corresponds with results of cross-correlation analyses of soil moisture and the 1-km GIMMS NDVI3g in Australia from 1996 to 2005 (Chen et al., 2014). It is important to note that in our study soil moisture had reasonable correlation with NDVI, particularly where woody fractions are higher. However, soils on the study sites are shallow (approximately 30 cm deep), mostly with limited water storage capacity. Therefore, during the early to mid dry season, the soil moisture index may represent moisture in the epikarst, the zone between soil and bedrock in karst environments (Querejeta et al., 2007; Schwinning, 2008). This zone is rapidly recharged and more resistant to evaporation than the soil zone (Swaffer, 2014). Carbonate bedrock can provide accessible sources of water for plants with sufficiently deep roots during dry periods. However, the available water content is dependent on the characteristics of the rock such as its primary porosity (Estrada-Medina et al., 2013; Nardini et al., 2021). The roots of some of the dominant tree species in our study sites have been observed to grow into deep fractures in the bedrock to access moisture (J Meha, February 4, 2019, personal communication).

3.6.2. Groundwater access reduces sensitivity to rainfall inputs

While soil moisture provides the most accurate representation of plant available moisture, antecedent rainfall also provides an indication of moisture availability. At the patch scale in our study, NDVI was most strongly correlated with two to six months of antecedent rainfall (lag2 to lag6), however, there was a clear decoupling between NDVI and antecedent rainfall at the three sites with shallow groundwater access, in accordance with our second hypothesis. This result is attributed to the fact that tree growth at these sites was much less dependent on rainfall inputs (Ma et al., 2013). Furthermore, it was established that NDVI was consistently higher at sites with shallow groundwater access, which is comparable to findings by O'Grady et al. (2011) that LAI increased with groundwater access (NDVI is a function of LAI; Carlson & Ripley, 1997). This is explained by the concept of ecological optimality, where ecosystems evolve to equilibrate with available moisture (Schymanski et al., 2009). While vegetation productivity is water-limited in tropical savanna systems (Eamus et al., 2000), the vegetation patches at our sites with groundwater access were less susceptible to short-term rainfall anomalies, as their hydraulic architecture likely evolved with available groundwater (Eamus et al., 2016). These sites, while less vulnerable to short-term dry periods, may be influenced by more severe dry phases or longer term changes in rainfall patterns (Ma et al., 2013), which are likely to determine the volume of recharge and discharge to and from the groundwater store. Analysis of the relationship between NDVI and rainfall identified that the response of plant productivity to rainfall amounts was not uniform across vegetation patches. However, additional rainfall had a greater positive effect on sites with no groundwater availability to trees. This reflects the findings of Ma et al. (2013) at savanna sites in northern Australia, where they reported that while rainfall pulses drive savanna vegetation greening responses in general, sites with access to deep soil water or groundwater exhibit less seasonal and interannual changes in enhanced vegetation index or LAI.

3.6.3. El Niño events reduce vegetation productivity

It is valuable to relate the reported rainfall anomalies in the study region to ENSO events as a useful predictor of the impacts of ENSO on rainfall and vegetation productivity in the future. Climate studies have found that El Niño events generally occur every 2-5 years, and that La Niña events are usually at least 7 years apart, but are variably spaced (Wolter & Timlin, 2011). Previous studies, including Kurniadi et al. (2021) and Supari et al. (2018) found that in Indonesia, ENSO has a more significant influence on rainfall during the dry season than the wet season. Consistent with these studies, it was established that most La Niña events resulted in higher rainfall totals and greater proportions of annual rainfall falling in the dry season. It was also found that most El Niño years resulted in lower than mean rainfall in the study area. More importantly, our results show that the vegetation productivity of this karst tropical savanna ecosystem was significantly impacted by strong El Niño events but recovered when followed by wetter periods resulting from La Niña conditions (Figure 3.2 B and Figure 3.9). This finding supports our third hypothesis that interannual rainfall variability and anomalies are important drivers of NDVI in tropical karst savannas. Protracted dry periods may lead to significant reduction in vegetation productivity and a long recovery period at both groundwater dependent sites (due to a reduction in groundwater recharge) and at rainfall dependent sites due to the absence of soil moisture (Chiloane et al., 2022). The wettest periods in the time series, the 2000 and 2011 La Niña years, did not contribute to significant changes in productivity. Annual rainfall thresholds for NDVI responses, such as the 1200 mm that was identified have been reported in related studies (e.g. Ahmed et al., 2017; Al-Bakri & Suleiman, 2004; Fu & Burgher, 2015; Nicholson & Farrar, 1994). Nicholson et al. (1990) reported that NDVI was insensitive to rainfall above approximately 1100 mm per year or 200 mm per month across a range of vegetation types, including grassland/shrubland in a study of GIMMS NDVI3g response to rainfall in the Sahel and East Africa from 1982 to 1985. Nicholson and Farrar (1994) established that on sandy soils in the semi-arid savanna of Botswana there was a threshold amount of approximately 500 mm per year or 50-100 mm per month, illustrating a large variation in NDVI response of savanna vegetation due to site effects including latitude, mean rainfall trends and soil type. Our study investigated the NDVI response to moisture at sites with consistent soil type, latitude and annual rainfall as it was focussed on a small district scale and observed the variation in responses in relation to access to groundwater and vegetation management activities.

In karst savannas, it has been found that maintenance of groundwater levels, and thus maintenance of vegetation productivity of groundwater-dependent sites, is dependent on successive wet periods (Cardella Dammeyer et al., 2016). Longer time series that include a greater number of ENSO events resulting in rainfall anomalies would provide greater ability to predict vegetation response to climate conditions. While not considered in this study, other climate drivers including the Indian Ocean Dipole (IOD) can influence dry season rainfall between June and November in Indonesia (Kurniadi et al., 2021). However, ENSO remains the main driver of interannual variability in the western Pacific monsoon rainfall (Kurniadi et al., 2021).

3.6.4. Effect of vegetation restoration on long-term normalised difference vegetation index trends

While it was found that there was no increasing or declining long-term trend in NDVI at the district scale, our results at the patch scale identified two sites with significant increasing interannual

NDVI trends (an increase of 3.74×10^{-4} NDVI yr^{-1} and 2.7×10^{-4} NDVI yr^{-1} at sites 1 and 9, respectively). Both sites are subject to woody vegetation conservation and restoration (Pellokila et al., 2014). The increasing NDVI trends are attributed to the restoration activities that commenced in 2013 at both sites. No positive trends at the other sites with restoration activities were identified and this could be related to lower intensity of tree planting, less seasonal intercropping with cash crops or less effective tree management approaches and/ or mitigating factors such as damage from fire and livestock (Pellokila et al., 2014; Reku Raya, 2020). It would be valuable to repeat the analysis at additional restoration sites within the study region to establish whether positive trends could be detected above the background regional greening trend.

Studies on long-term background NDVI trends in the region have provided varying results. Between 2000 and 2010 in Australia, a decline in both rainfall and NDVI was identified across 90% of the continent using 1 km resolution 10-day SPOT-derived (*Satellite Pour l'Observation de la Terre*) NDVI surfaces (Liu et al., 2017). The study by Liu et al. (2017) examined the effect of a severely dry period on vegetation in Australia and therefore did not explore the effect of the 2011 La Niña event. In spanning a period that included the 2011 wet event (1982 to 2011), B. Chen et al. (2014) found that the majority of the Asia-Australia region had no significant trend in monthly 0.25 degree resolution NDVI derived from the GIMMS dataset, with smaller areas showing an annual growth rate of 6.22×10^{-4}. In Indonesia specifically, de Jong et al. (2011) reported a decreasing trend from 1981 to 2006 by using a linear model of NDVI residuals, also derived from GIMMS NDVI3g.

Beyond identifying overall NDVI trends in the region, Wu et al. (2013) attempt to distinguish between background greening and revegetation efforts and suggest that an annual increase in MODIS NDVI of 6.0×10^{-4} between the years 2000 and 2010 in the Beijing–Tianjin Sand Source Region may be due to an effective ecological restoration program. This increasing trend was not found to be significant, however. Wu et al. (2013) also acknowledged that it is difficult to separate the effects of climate change and human activity on changes in NDVI in their study. More recently, Song et al.

(2022) used multiple linear regressions to investigate the effects of climate change and ecological restoration on NDVI in China and found that there was an annual increase in NDVI of 1.7×10^{-3} from 1999 to 2015 and that afforestation had a relative contribution of > 75 % of NDVI increases in most areas. Using residual trend analysis, Liang et al. (2023) monitored MODIS and GIMMS NDVI increases resulting from planting efforts in ecological reserves in China between 1982 and 2018 and identified annual growth rates up to 5.3×10^{-3}.This large range of annual increases in NDVI in the Asia-Australia region from a minimum of 2.7×10^{-4} in our study to a maximum of 1.7×10^{-3} reported in China, suggests that the choice of imagery, spatial and temporal scale and statistical methods affects NDVI results. The variation in these methods likely influences the ability to accurately identify the response of vegetation to changes in moisture availability, especially in the karst savanna environment where trees are scattered.

3.6.5. Limitations of the study

This study was able to clearly differentiate the NDVI response of groundwater dependent vegetation patches from those reliant on rainfall, as well as detect the effect of managed vegetation restoration efforts at two sites. However, there remain some uncertainties about the relative contributions of climate and human intervention to changes in NDVI at each site and it would be valuable to apply methods such as in Liang et al. (2023) and Song et al. (2022) to assess the key driving factors in NDVI increases. In addition, the findings in this study would be strengthened with an investigation of the correlation between soil moisture and rainfall in the study area over the full length of the study period, as well as changes in temporal dynamics between soil moisture and NDVI during extreme wet and dry years.

3.7. Conclusions

This study provides foundational insights into the relationship between available moisture and vegetation productivity in tropical karst savannas. It was shown that interannual rainfall variability and rainfall anomalies related to ENSO are important drivers of NDVI, such that, a deviation from the usual ENSO patterns may result in major changes to vegetation productivity. Additionally, it was established that the NDVI-rainfall relationship serves as a reliable indicator of shallow groundwater access and groundwater-dependent ecosystems, as areas where NDVI trends are decoupled from rainfall, in particular during drier periods. Through use of MK trend analyses of Landsat 7 NDVI data, we identified a generally increasing trend at some, but not all, sites with managed restoration of woody vegetation.

3.8. References

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Chapter 4. Infiltration Mechanisms and Landcover

4.1. Introduction

The ecohydrology of karst savannas has recently been of research interest due to potential water management challenges associated with woody plant encroachment (Acharya et al., 2018; Leite et al., 2020; Schwinning, 2008; Swaffer, 2014; Wilcox et al., 2006; Williams et al., 2006). While it has long been assumed that an increase in the density of woody plants in a savanna environment would result in increased transpiration and reduced groundwater recharge, previous studies have demonstrated that the presence of shrubs and trees generally enhances infiltration and reduces runoff (Benegas et al., 2021; Leite et al., 2020; Marquart et al., 2020; Wilcox et al., 2006). Woody cover is also known to encourage meso-faunal activity, which creates biopores that leads to higher rates of infiltration through preferential pathways (Chandler, 2006; Eldridge & Freudenberger, 2005; Ilstedt et al., 2007; Marquart et al., 2020). In karst environments, trees can also enhance secondary porosity by enlarging rock fractures with their roots (Pawlik et al., 2023). Shrubs and herbaceous plants develop extensive shallow root systems to obtain soil water, while trees may extend roots up to six metres into the karst fissures (Geekiyanage et al., 2019).

The influence of woody cover on infiltration is dependent, however, on plant species and land management practices. Where organic matter under woody cover is removed or burnt for example, infiltration capacity of soils is reduced (Bonell et al., 2010; Ghimire et al., 2014). Trampling by livestock is also commonly known to decrease the size and abundance of macropores and reduce infiltration capacity (Bonell, 2005; Ghimire et al., 2014). Inherent soil properties, such as soil texture and soil pH combined with land cover and land management are important determinants of infiltrability (Bargués-Tobella et al., 2024; Hodnett & Tomasella, 2002; Marquart et al., 2020) and woody cover may not have a universally significant influence on infiltrability relative to soil properties (Falk et al., 2024).

In savanna environments, soil texture, organic matter, land-use and landcover are all important components of soil infiltrability (Bargués-Tobella et al., 2024; Bargués Tobella et al., 2014; Falk et al., 2024). In addition, the broader landscape characteristics of lithology, drainage density and slope and landcover are useful predictors of infiltrability and groundwater recharge (Ahmed et al., 2021; Arulbalaji et al., 2019; Yeh et al., 2016). Finally, the distribution of woody vegetation within a catchment area may have an important influence on rainfall partitioning (Bargués Tobella et al., 2014; Ludwig et al., 2005; Rodríguez-Lozano et al., 2023) and ultimately infiltration to groundwater recharge zones (Bargués Tobella et al., 2014).

There are many studies in the tropics concerned with the influence of afforestation or agroforestry on infiltration capacity which find that soil infiltrability increases relative to baseline conditions (Ilstedt et al., 2007), however, these studies do not explore the effect of the spatial distribution of scattered trees along a catchment and overall landscape function. The concept of Landscape Function Analysis (LFA), as developed by Tongway and Hindley (2004) provides a framework to conceptualise landscapes as patterns of vegetation patches, where rainwater accumulates and inter-patches where rainwater is lost as Hortonian overland flow. LFA also highlights the importance of patch and inter-patch characteristics in controlling the movement of resources within the landscape from source to sink locations. In connection with the LFA concepts, Ludwig et al. (2002) developed a method to measure landscape degradation as a 'leakiness index' (LI), to determine the capacity of a landscape to obstruct overland flow, enabling infiltration to the soil or groundwater reservoirs. The LI is premised on the role of vegetation patches in increasing soil infiltrability and surface roughness (Crompton et al., 2023; Ludwig et al., 2007).

Deriving an index of leakiness for a landscape defined by surface water catchment boundaries is a valuable exercise to evaluate the influence of land management changes over time or for comparison of multiple study areas (Ludwig et al., 2007; Rodríguez-Lozano et al., 2023). In addition to this catchment scale assessment of leakiness, to assess the effect of land management on groundwater recharge potential, it is critical to predict the locations of highest potential for groundwater recharge within the study area. This enables a focus for point-scale evaluation of infiltrability. In the absence of field data that delineate groundwater recharge zones such as tracer studies or geophysical surveys, it is a common approach to apply GIS based multi-criteria analyses for prediction of groundwater recharge potential within a study area (e.g. Agarwal & Garg, 2016; Ahmed et al., 2021; Arulbalaji et al., 2019; Chowdhury et al., 2009). A range of multi-criteria analysis techniques have been used within data scarce study areas to delineate groundwater recharge potential zones (Ahmed et al., 2021) including weighted linear combination method (Senanayake et al., 2016; Yeh et al., 2016), weighted multi influencing factor (Magesh et al., 2012), and Analytical Hierarchy Process (AHP) (e.g. Agarwal & Garg, 2016; Andualem & Demeke, 2019; Arulbalaji et al., 2019; Chowdhury et al., 2009; Kaliraj et al., 2014). The AHP approach to multi-criteria analyses is accepted as a rigorous method as it assumes minimal bias due to the multi-stage process of deriving weights for each criterion. Each criterion is allocated a priority and is added to a pairwise comparison matrix. Priorities are then normalised using a geometric mean and the logic of priorities is validated using a consistency ratio (Krejčí & Stoklasa, 2018; Saaty, 1987).

As inputs to a multi-criteria analysis of groundwater recharge potential, the commonly included thematic layers are drainage density, lineament density, slope, lithology, soil type and landcover as each of these are known to have an influence on rainfall partitioning, infiltration and ultimately groundwater recharge (Ahmed et al., 2021; Arulbalaji et al., 2019; Yeh et al., 2016). Gridded thematic layers are classified to a consistent scale and are then overlaid in a Geographical Information System (GIS) to derive a composite value of groundwater recharge potential. The resulting map provides a low-cost foundation for decision makers and for further field-based investigations of groundwater resources (Ahmed et al., 2021).

Most of the factors contributing to groundwater recharge potential are a product of landscape evolution. Drainage density is a result of the permeability of bedrock (Cotton, 1964) while slope, lithology and soil type all relate to geological history. Landcover, however, is the result of geology, climate, and also anthropogenic influence (Ellis, 2021; Sankaran, 2019). To optimise groundwater recharge potential in water scarce environments, it is critical to understand the influence of landcover and land-use. There are a number of published studies on the influence of land-use and landcover types on soil hydraulic properties and water retention characteristics (e.g. Eldridge & Freudenberger, 2005; Falk et al., 2024; Leite et al., 2020; Marquart et al., 2020; Zhu et al., 2022). Ilstedt et al. (2016) developed a theory of optimum tree cover to maximise groundwater recharge from infiltration in the seasonally dry tropics. The theory was based on a water balance model with soil water drainage and sap flow measurement data as inputs, and the study finds that the configuration and management protocols for trees in an agroforestry environment are important to maximise infiltration in the seasonally dry tropics. The effect of woody cover on infiltration rates was also studied by Eldridge and Freudenberger (2005), who found that both early-stage infiltration (sorptivity) and later (steady state) stages of infiltration were higher under shrubs than grasses. The positive effect of woody cover on infiltration is a consistent finding in studies concerned with the influence of woody vegetation on ecohydrology in savanna environments (Benegas et al., 2021; Benegas et al., 2014; Ilstedt et al., 2016; Leite et al., 2020; Wilcox et al., 2022). The effect of woody vegetation and inherent soil characteristics on ecohydrology in karst savanna environments specifically needs to be understood as the soil zone has the potential to impede rapid infiltration and percolation to a highly permeable bedrock (Ford & Williams, 2007).

Karst geology is defined as soluble rock with high secondary porosity, usually carbonate rock. These geologies are highly heterogeneous and made up of networks of fissures and cavities (Ford & Williams, 2007). Karst soil layers are generally shallow and rocky, and in many cases hydraulic conductivity through the soil layer is slower than through fissures and cavities in the rock mass (Acharya et al., 2018; Chandler, 2006; Leite et al., 2020). In this context, the soil layer can be considered a barrier to infiltration if it is characterised by high bulk density or has a large clay fraction

(Saxton & Rawls, 2006). Hydraulic conductivity, defined as the ability of soil to transmit water (Davie, 2008) is governed principally by inherent soil properties including clay content (Kennett-Smith et al., 1994) and pore geometry and connectivity (Davie, 2008). In addition, land management activities that influence soil nutrients, aggregate stability, bulk density and porosity are important factors in determining soil hydraulic conductivity (Ilstedt et al., 2016; Ilstedt et al., 2007; Sirimarco et al., 2018).

Land management, in particular with respect to management of woody vegetation, has an important influence on soil properties (Bargués-Tobella et al., 2024) due to changes in organic matter (Ilstedt et al., 2007) nutrients (O'Connell & Sankaran, 1997), changes in soil structure due to compaction from livestock (Martínez & Gilabert, 2009) or machinery (Nawaz et al., 2013) and porosity changes due to an increase or decrease in biopores (Eldridge & Freudenberger, 2005; Marquart et al., 2020). There is potential to maintain or rehabilitate soil structure to enhance infiltrability through land management initiatives (Ilstedt et al., 2007). While individuals and community groups are largely economically motivated to participate in regreening efforts, there is strong evidence of the benefits to hydrological function from increased woody vegetation (Benegas et al., 2021; Benegas et al., 2014; Ilstedt et al., 2016).

As infiltration is only one component of the water balance, it is critical that the influence of landcover change on the inter-related components of interception and evapotranspiration are also considered (Ghimire et al., 2014). The difference between additional infiltration and evapotranspiration is commonly referred to as the 'infiltration-trade-off' (Bonell, 2010; Bruijnzeel & Bonell, 2005; Ilstedt et al., 2016; Krishnaswamy et al., 2013). Ilstedt et al. (2016) demonstrated that at intermediate tree densities in savanna environments, vertical percolation of rainfall was highest at the edges of tree canopies and that increase in infiltration relative to treeless scenarios was higher than increases in tree water use. Furthermore, in karst regions, infiltrating rainwater can quickly flow through bedrock fractures into groundwater reservoirs or conduits to groundwater discharge points (Yang et al., 2016). The objective of this study, which follows a chapter on groundwater recharge pathways, was to evaluate the change in vegetation cover between 2015 and 2022 within a tropical karst savanna case study area and assess the influence of revegetation efforts on infiltration. The study was focused on the research questions: 1) how 'leaky' is the catchment according to landscape function principles; 2) how do infiltration rates differ in soils under tree canopies and grass; 3) how do infiltration rates differ according to inherent soil properties; and 4) how reliable are pedotransfer functions in predicting soil hydraulic properties?

4.2. Materials and methods

4.2.1. Study site

The boundary for this study of infiltration was the Larawali surface water catchment. A description of soils and catchment morphometry is included below as background to infiltration and groundwater recharge potential within the study area.

4.2.1.1. Soils and vegetation

There are limited published data on soil classifications for the study area, with most soil studies limited to coarse mapping. The United States Department of Agriculture (USDA) soil classification system is used in this study for easy reference to prior studies in the region. Soils are classified as belonging to two great subgroups Haplustepts: a carbonate rich free-draining inceptisol and Haplustolls: mollisols occurring in wet-dry tropical conditions. Both soil types are formed from carbonate lithologies and have limited development (Mulyani et al., 2013; Scheffe et al., 2015; Soil Survey Staff, 1999). The study area is dominated by savanna vegetation, that is predominantly grasses and sedges and few tall trees. Regular burning practices are thought to maintain the savanna vegetation communities (Sanchez, 1976). The Larawali catchment has small areas of scrub land or low woodland in the northern region of the catchment above the village of Wunga as well along the lower section of the Larawali river channel. The majority of the catchment is grassland, with approximately 13% woody vegetation cover (Figure 4.1).

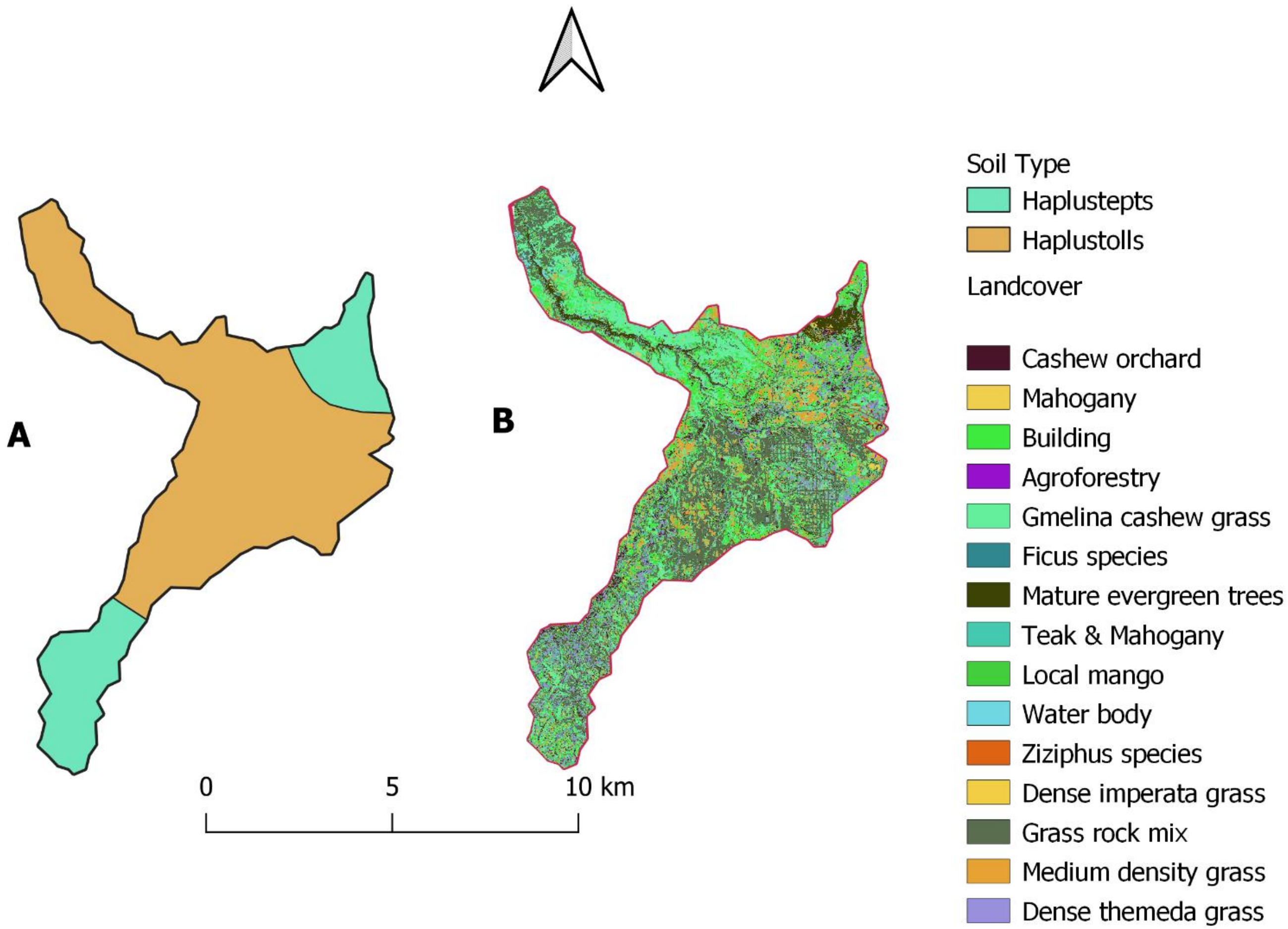

Figure 4.1. A) Soil subgroups and B) catchment landcover, derived from a supervised classification of composite Sentinel images (10 m resolution).

4.2.1.2. Catchment relief and slope

Catchment relief, defined as the difference between the highest and lowest points in the catchment area is 426 m, while the mean catchment relief (the difference between mean catchment elevation and the outlet elevation) is 207 m. The catchment has a relatively elongated shape and a linear longitudinal profile, which is attributed to a high rate of coastal uplift relative to the rate of bedrock erosion (Nexer et al., 2015). The majority of the Larawali catchment area is relatively flat, with 44% of the catchment area level to gently inclined (less than 6 °) and an additional 50% of the catchment moderately inclined (between 6° and 18°) (Figure 4.2).

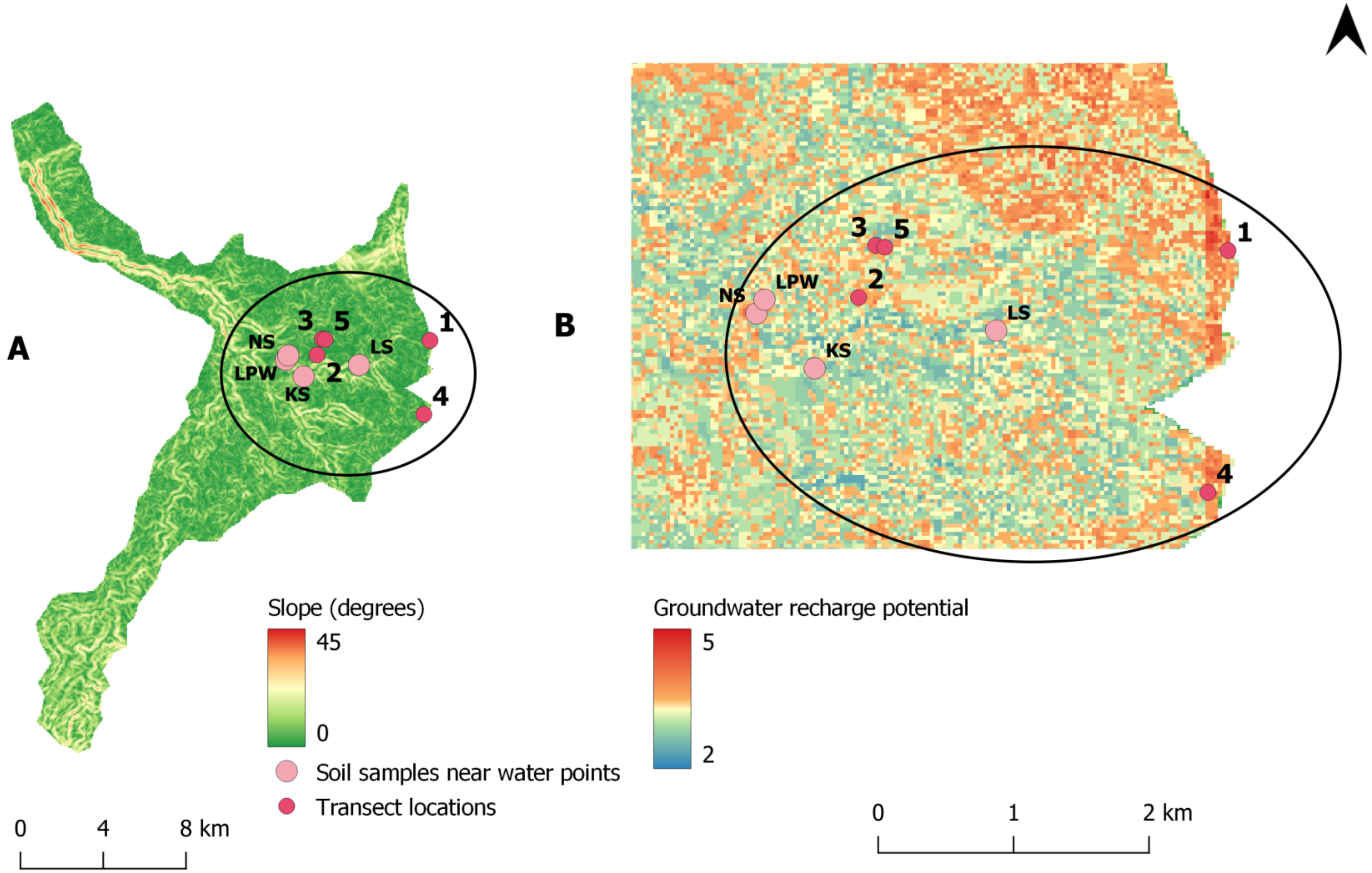

Figure 4.2. A) Plot locations (numbered 1:5) and soil samples near water points with underlying slope; B) Plot and soil sampling locations with underlying groundwater recharge potential.

4.2.2. Calculating Landscape leakiness

As well as the catchment's shape and relief, land-use and landcover have an important role in controlling the proportion of rainfall that is retained in the catchment and that has the potential to infiltrate and become groundwater recharge. The landscape LI is a measure of one component of landscape function developed by Ludwig et al. (2002) to assess how efficiently a landscape retains water and nutrients using remotely sensed landcover imagery. Landscape leakiness is based on the principle that functional landscapes with well distributed vegetation patches retain water and sediments, whereas dysfunctional landscapes will 'leak' a higher proportion of these resources. This study uses the index with a focus on water retention and to determine the catchment scale water retention potential as a function of landcover. As water retention (the inverse of runoff) is proportional to infiltration and groundwater recharge, it is valuable to determine a landscape leakiness baseline for the study area and evaluate how it has changed over time as a function of landcover change. The original LI method was modified by Ludwig et al. (2007) to take into account flow direction based on a digital elevation model (DEM), and this is the method used here. The index is calculated as follows (Equation 1):

$$LI = 1 - \left[\frac{Lmax - Lcalc}{Lmax - Lmin}\right]^k$$

(Equation 1)

where *Lcalc* is calculated leakiness, *Lmax* is maximum leakiness and *Lmin* is minimum leakiness. *Lcalc* is computed from progressive flow values, *pi*,*j*, where *pi*,*j* for each pixel is the sum of the contributions of flows from adjoining pixels at higher elevations (Ludwig et al., 2007). *Lcalc* in this study was computed in Saga GIS v7.8.2 (Conrad et al., 2015) as the maximum annual bare soil (BS) percentage (derived from the grid shown in Figure 4.3A) * flow accumulation (Figure 4.3B for each year in the study period. *Lmax* was computed as maximum flow accumulation at the outlet and *Lmin* was assumed to be 0 as per Ludwig et al., 2007.

To obtain *Lcalc*, mean annual Landsat derived fractional cover (Geoscience Australia Landsat Fractional Cover Collection 3) was acquired from Digital Earth Australia (DEA), via the DEA Sandbox[4]. The product consists of four bands: photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV) and BS. Pixel values in each band represent the percentage of each respective cover type. Mean annual values were computed for each band for the years 2015 to 2022. A total vegetation fraction was obtained by summing the PV and NPV grids (Figure 4.3C). A grid of flow accumulation for each pixel within the catchment was derived from the ASTER Global Digital Elevation Map (GDEM) DEM using the Flow Accumulation (Top Down) module in Saga GIS v7.2.0 with the deterministic 8 flow routing method (Conrad, 2016). An annual catchment mean total fractional vegetation cover (PV + NPV) was calculated for each year in the study period for comparison with the LI. In addition, as a rapid evaluation of the fraction of woody vegetation cover, the average minimum PV was computed for each year.

[4] The jupyter notebook used to run scripts within the DEA sandbox can be found here: http://www.hydroshare.org/resource/9b9d54b9363b48fab86c148271710c06

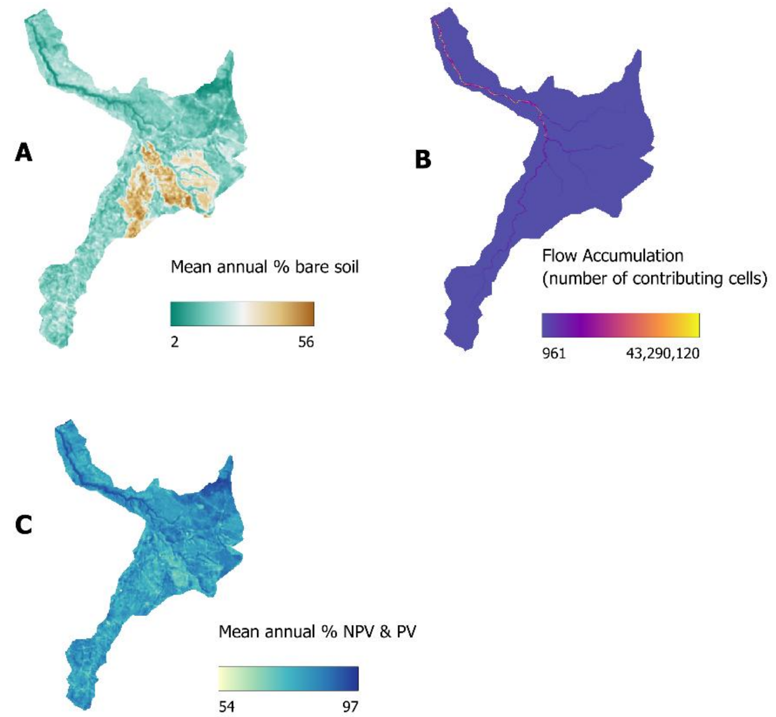

Figure 4.3. Input grids to the Leakiness Index computation: (A) Mean annual % bare soil; (B) Flow Accumulation; and (C) Mean annual % NPV & PV

4.3. Spatial analysis of groundwater recharge potential and study design

To predict locations of high groundwater recharge potential, and select locations for infiltration analyses within the catchment, a weighted overlay analysis of slope, drainage density, landcover, geology and soils was carried out in QGIS v3.28.7 (QGIS Development Team, 2020 (QGIS Development Team, 2020) (Figure 4.4). Weights for each layer were selected by way of the commonly applied Analytical Hierarchy Process (Agarwal & Garg, 2016; Ahmed et al., 2021; Kaliraj et al., 2014) where the degree of relative importance to groundwater recharge of each layer is determined in a pairwise matrix on the Saaty scale of 1 to 9. The geometric mean of values for each layer is computed and then normalised according to the sum of geometric means for all layers (Krejčí & Stoklasa, 2018). These layers were processed, classified and weighted according to Table 4.1 and Table 4.2).

Table 4.1. Raster layers used in a weighted criteria evaluation to predict groundwater recharge potential.

Grid name	Processing notes	Influence on groundwater recharge
Slope in degrees (Class 1–6)	Derived from the ASTER GDEM Version 3 (ASTGTM). Local depressions in the DEM were filled using the Wang Liu Fill Sinks tool (Wang and Liu, 2006) in Saga GIS v7.2.0 (Conrad et al., 2015) and subsequently referred to as the filled DEM.	While field experiments have identified varying degrees of influence of slope on infiltration, dependent on landcover, soil types and rainfall intensity (Morbidelli et al., 2018), it is assumed here that slope negatively influences infiltration potential and is the most important of the five factors considered.
Drainage density ($km.km^{-2}$)	Derived from the filled DEM with channels created by the Saga GIS v7.2.0 basic terrain analysis and threshold of Strahler order 2 streams. The channels layer was Intersected with grid of 1 km^2 to create a drainage density grid with values between 0 and 13.	Drainage density, defined as the length of stream channel per unit area of the catchment is commonly used as an indication of the resistance of the catchment to erosion. Drainage density is known to be inversely proportional to infiltration (Horton Robert, 1945).
Landcover	Landcover mapping was prepared using a supervised classification of a composite Sentinel image in Google Earth Engine (described in Chapter 2). The 10 m resolution landcover grid was resampled to 30 m and then reclassified with values from 1 to 6.	Infiltration potential has been shown to be generally higher under woody landcover than herbaceous cover (Eldridge & Freudenberger, 2005; Li et al., 2008; Marquart et al., 2020; Wilcox et al., 2022)
Geology	Derived from Effendi and Apandi (1981).	Geology influences infiltration potential, primary and secondary porosity and storage characteristics. The Kananggar formation has low primary and secondary porosity in contrast to the Reef terraces, which have high secondary porosity. The reef terrace formation has a much higher potential for groundwater recharge (Sule & Delinom, 1989).
Soils	Adapted from Mulyani et al. (2013)	Haplustolls are slightly weathered parent material, have high infiltration rates, are free draining and have low water holding capacity. Haplustepts are freely draining calcareous inceptisols.

DEM: Digital Elevation Model; GDEM: Global Digital Elevation Map.

Table 4.2. Schedule of weightings used in the weighted overlay.

Raster layer	Value	Weight	Contribution to groundwater recharge potential	Value
Slope (degrees)	0° to 0°35'	0.27	Very High	6
	0°36' to 1°45'		High	5
	1°46' to 5°45'		Medium	4
	5°46' to 18°		Low	3
	18°01' to 30°		Very Low	2
	30°01' to 45		Limited	1
Drainage density (km/km^2)	0 to 2.0	0.17	Very High	6
	2.01 to 4.0		High	5
	4.01 to 6.0		Medium	4
	6.01 to 8.0		Low	3
	8.01 to 10.0		Very low	2
	>10.0		Limited	1
Landcover	Cashew orchard	0.2	Very High	6
	Mahogany		Very High	6
	Building		Limited	1
	Agroforestry		High	5
	Gmelina, Cashew, Grass mix		High	5
	Ficus species		Very High	6
	Mature evergreen trees		Very High	6
	Teak and mahogany		Very High	6
	Local mango		Very High	6
	Water body		Very High	6
	Ziziphus species		Very High	6
	Dense imperata grass		Medium	4
	Grass rock mix		Very low	2
	Medium density grass		Low	3

Raster layer	Value	Weight	Contribution to groundwater recharge potential	Value
	Dense themeda grass		Medium	4
Geology	Quarternary reef terraces	0.17	High	6
	Kananggar formation (tuffaceous mudstone, volcaniclastic turbidites)		Medium	3
Soils	Haplustepts (sandy loam)	0.2	Medium	4
	Haplustolls (silty loam)		Low	2

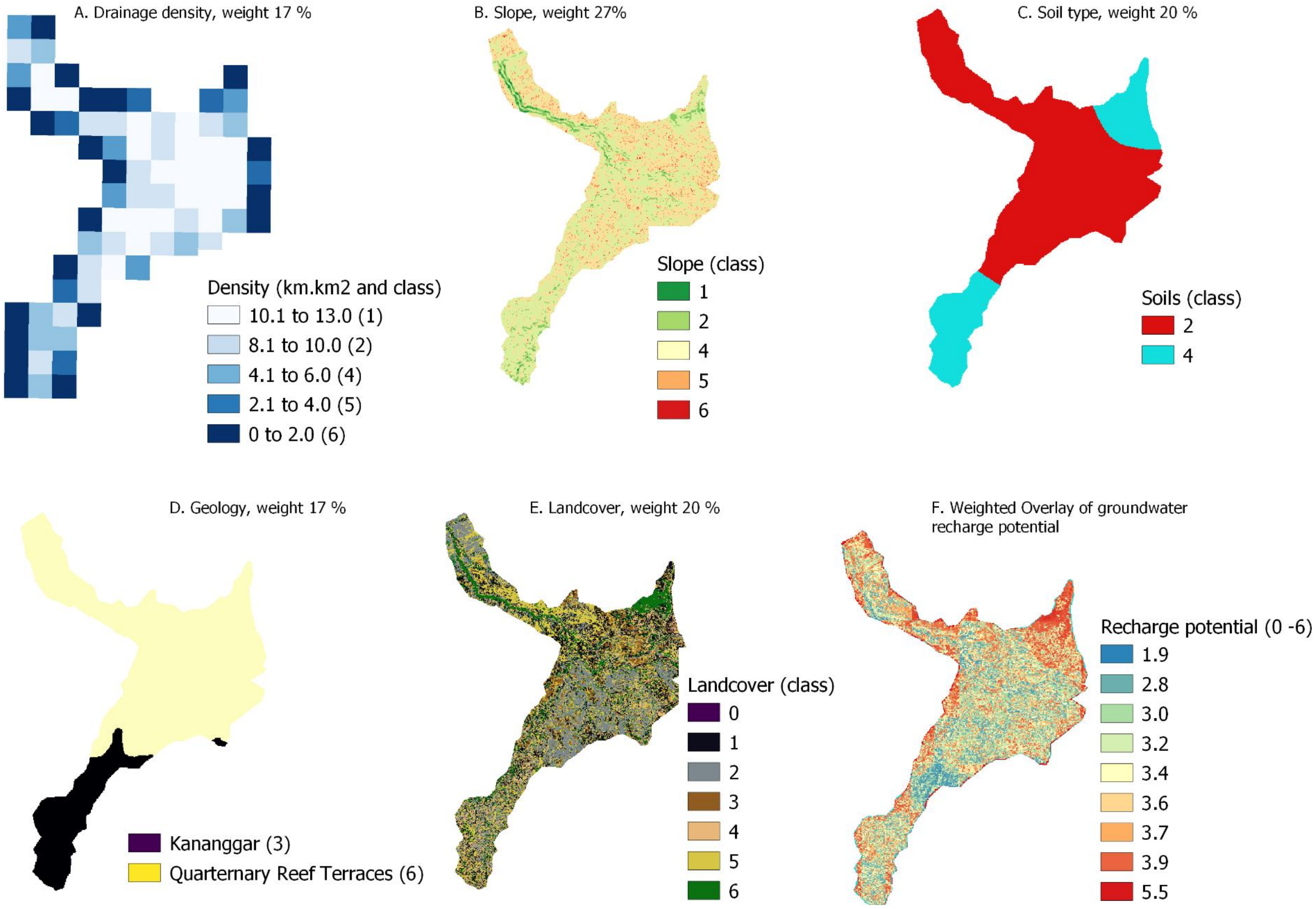

Figure 4.4. Weighted overlay analysis of groundwater recharge potential. Grids A to E are input layers and grid F is the resulting grid of groundwater recharge potential.

4.4. Soil Infiltration measurements

Saturated soil hydraulic conductivity is a key parameter that governs infiltration and groundwater recharge potential. Five plots for infiltration measurements that were on level to gently inclined slopes of Haplustoll soils within the identified regions of high groundwater recharge potential were selected based on ease of access by vehicle (Figure 4.2). At each site, 3 to 4 infiltration measurements were taken at level points, with a representation of sites under grass landcover and at a tree canopy edge[5]. At each of these points, measures of sorptivity and steady state infiltration rate were made using CSIRO disc permeameters. A key advantage of the CSIRO disc permeameters is the ability to adjust the water supply potential via the attached bubbling tower to compare infiltration measurements between ponded and negative supply potential (Perroux & White, 1988) (Figure 4.5A). Measurements in this study were conducted at potential – 40 mm to measure flow through matrix pores of < 0.75 mm in diameter (Perroux & White, 1988), and + 10 mm tension, to measure flow through all pores, including macropores created by roots, soil fauna and from shrinkage in clay soils (Eldridge & Freudenberger, 2005; Perroux & White, 1988) (Figure 4.5B). Where vegetation (grass, shrub or tree) was present, it was trimmed to approximately 5 mm in height. Soil samples were taken 250 mm from the infiltration measurement location using bulk density tubes and these were capped, double bagged and kept cold until analysis at Universitas Nusa Cendana, Kupang. Bulk density and volumetric soil moisture content measurements were made in the laboratory to enable saturated soil hydraulic conductivity calculations. Infiltration measurements were undertaken in the early dry season (June 2018) when soil water deficit was approaching its maximum. Therefore in soils with shrink-swell properties, these measurements were made when cracks had their maximum aperture. Observations of mean crack widths and depths (where possible), soil water status, presence of roots, ped size, sand soil colour at each point were recorded. It was hypothesised that infiltration rates under

[5] At some sites, the number of measurement points was limited by available water, which had to be hand-carried in drums, to refill the water reservoir for the disc permeameter.

tree canopy sites would be significantly higher than that under grassed sites in accordance with findings of related studies (Eldridge & Freudenberger, 2005).

Figure 4.5. A) Ponded disc permeameter setup; B) Unsaturated disc permeameter setup (infiltration with -40 mm negative supply potential). r_0 (the disc radius) is delineated on each permeameter.

A tipping bucket rain gauge and TinyTag data logger were installed in December 2016 and recorded 2 minute rainfall intensity values until June 2018.

4.5. Pedotransfer function values to compute hydraulic conductivity

Due to logistical constraints relating to flooding as well as travel restrictions during the COVID-19 pandemic that prevented repeat field infiltration measurements and obtaining a sufficiently large number of samples, a review of available pedotransfer functions (PTF) was conducted to identify the validity of using derived saturated hydraulic conductivity values based on soil texture. Modelled soil hydraulic properties have been developed from a range of methods that are all based on the van Genuchten model of water retention. Using the van Genuchten model (van Genuchten, 1980), methods ranging from linear regression to machine learning approaches are used to estimate hydraulic conductivity from predictive inputs including particle size distribution, bulk density, pH, EC (Electrical Conductivity) and organic carbon (Minasny & Hartemink, 2011). While PTFs are widely used to obtain estimates of soil hydraulic conductivity amongst other soil hydraulic properties in the absence of sufficient field measurements, obtained estimates vary notably depending on the choice of training data and input parameters (Hodnett & Tomasella, 2002; Minasny & Hartemink, 2011; Minasny & McBratney, 2000; Tomasella & Hodnett, 2004). Many published PTFs are developed on soils data from temperate regions and modelled soil properties may not be valid for tropical soils (Bargués-Tobella et al., 2024; Tomasella & Hodnett, 2004). A key difference with soils in tropical environments is that soils with high clay content are relatively more permeable than temperate soils with comparable clay content. The higher permeability of clay soils in tropical environments is due to the continual leaching of major cations, resulting in low pH and a concentration of sesquioxides in the B horizon, which may which bind with clay minerals to create larger stable micro-aggregates. For less developed tropical soils, including inceptisols, differences in actual and predicted hydraulic conductivity values may be more closely related to soil macropore structure that is not accounted for in PTFs (Ottoni et al., 2019) and pH may not have a significant effect (Falk et al., 2024). Here the predicted values of saturated soil hydraulic conductivity (K_s) from PTFs were compared with values calculated from field and lab measurements. To maximise reproducibility, the selection of PTFs was limited to those with a freely available application or R package that could be easily run (Table 4.3).

Table 4.3. Selected pedotransfer functions (PTF) for estimating saturated hydraulic conductivity (K_s).

Model citation	**Jena et al., 2021**	**Minasny and McBratney, 2002**	**Kearney & Maino, 2018a**	**Kearney & Maino, 2018b**	**Kearney & Maino, 2018c**
Model source	Model provided along with guided use of the free Waikato Environment for Knowledge Analysis (Weka) Version 3.8.3 environment	Neuroman Application	NicheMapR package, model 0 (Cosby et al., 1984)[6]	NicheMapR package, model 1 (Cosby et al., 1984)	NicheMapR package, model 1 (Campbell, 1985)
Model type	Random forest algorithm	Artificial neural networks	Univariate regression	Multivariate regression	Unknown
Predictive inputs	Fractions of clay, silt, fine sand and coarse sand; geometric mean diameter, d60, d10, Cu	Fractions of clay, silt, fine sand, coarse sand, bulk density.	Fractions of clay, silt and sand; bulk density	Fractions of clay, silt and sand; bulk density	Fractions of clay, silt and sand; bulk density
Source of training data	Tropical savanna region of India	Australia	USA	USA	Unknown

[6] Documentation for NicheMapR provides an explanation of model parameters (https://rdrr.io/github/mrke/NicheMapR/man/pedotransfer.html)

4.6. Lab analysis of soil physicochemical properties

4.6.1. Particle size distribution

Soil particle size distribution was obtained via laser diffraction using a Malvern Mastersizer 2000 at the Australian National University Fenner School for Environment and Society laboratory. All soil samples were sieved to < 1mm and deionised water was used as a dispersant. Particle sizes were defined according to the USDA classification as follows: clay = <2µm, silt = 2 to 50 µm, fine sand = 50 to 250 µm and coarse sand is 250 to 2000 µm. The 10th and 60^{th} percentile particle size values along with the volume weighted mean particle size were also recorded, as these were used as inputs to the selected PTFs. Following initial measurements of particle size using deionised water only as a dispersant, analyses were repeated with the addition of 1g/L of Calgon (sodium hexametaphosphate) according to the Mastersizer 2000 user manual. Soil texture was also estimated by the field texture method (McDonald & Isbell, 2009).

4.6.2. Soil pH and electrical conductivity

Soil pH and electrical conductivity (EC) were measured according to the 1:5 soil: water suspension standard method (Rayment & Higginson, 1992). Values of pH and EC were obtained for one topsoil sample per infiltration measurement plot from 1:5 soil water suspensions. Additional samples could not be analysed due to weight restrictions in transporting samples by air from the study area to Kupang.

4.6.3. Bulk density, soil water content and saturated hydraulic conductivity

Bulk density was measured in the Civil Engineering lab at Universitas Nusa Cendana in June 2018. Weights of bulk density tubes containing soil samples were recorded and then dried at 105°C for 48 hours. Equations 2 to 5 (Perroux & White, 1988) were used to calculate bulk density, gravimetric water content, volumetric water content and saturated soil hydraulic conductivity, respectively.

$$\text{Bulk density (gcm}^{-3}\text{)} = \text{Mass of dry soil (g) / Volume of bulk density tube (cm}^3\text{)}$$

(Equation 2)

$$\text{Gravimetric water content (g.g}^{-1}\text{)} = \text{Mass of wet soil – Mass of dry soil (g) / Mass of dry soil (g)}$$

(Equation 3)

$$\text{Volumetric water content} = \text{Gravimetric water content (gg}^{-1}\text{) * bulk density (Mgm}^{-3}\text{)}$$

(Equation 4)

Saturated hydraulic conductivity (K_s (mmh^{-1})):

$$K_{s = \frac{q}{\pi r_0{}^2}} - \frac{4bs_0^2}{\pi r_0(\theta_0 - \theta_n)}$$

(Equation 5)

where $q/\pi r_0^2$ is the steady state flow rate in mm h^{-1}, r_0 is the radius of the ring, θ_0 is the final volumetric moisture content, θ_n is the initial volumetric moisture content and b is approximately 0.55. Where sorptivity measurements are very high and initial soil moisture content is low, hydraulic conductivity calculated using this equation becomes negative and these results were discounted.

4.7. Linear Shrinkage

Linear shrinkage measurements were carried out on one soil sample from each of the five infiltration measurement sites at the Civil Engineering laboratory, Universitas Nusa Cendana, Kupang according to the standard method for engineering purposes (AS 1289.C4.1-1977). As noted above, the number of samples transported to the lab was limited due to air travel weight restrictions. The purpose of conducting linear shrinkage tests was to determine the influence of soil moisture conditions on the shrink-swell behaviour of soils.

4.8. Results

4.8.1. Leakiness Index

The LI for the Larawali catchment decreased over the study period of 2015 to 2022 from 0.16 to 0.12. The decrease in LI was not linear, and showed a non-significant decreasing trend (Mann Kendall's tau -0.619, p-value 0.07). There was an increase in mean total vegetation fractional cover across the catchment in 2022 relative to the 2015 baseline, although there was no overall trend in these mean values (Figure 4.6). The change in fraction of woody vegetation cover followed a similar pattern to the total vegetation cover, and was found to increase from 12.3 (baseline) to 18.9 (2022) (Figure 4.7).

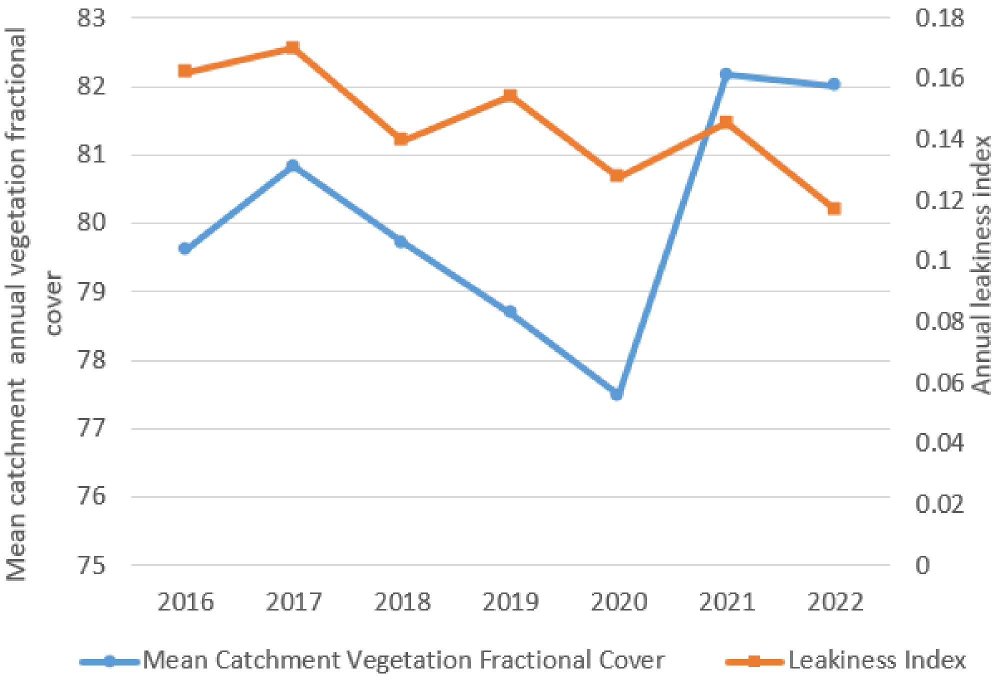

Figure 4.6. Annual Leakiness index and mean catchment vegetation fractional cover.

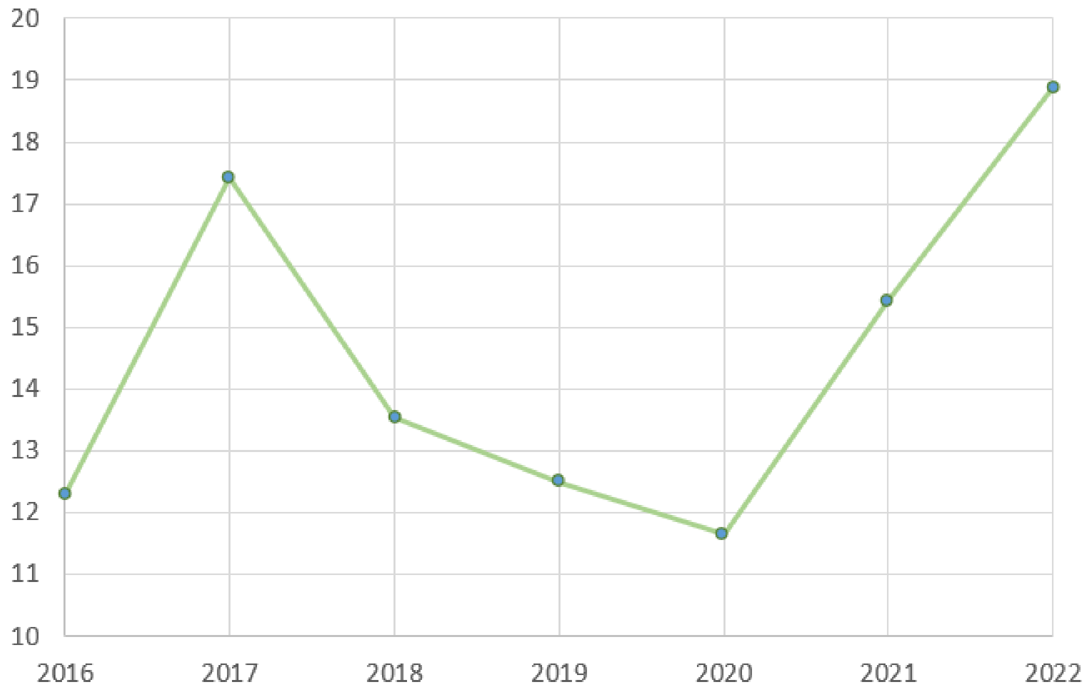

Figure 4.7. Fraction of woody vegetation cover by year calculated as the catchment average annual minimum photosynthetic vegetation (PV).

4.8.2. Infiltration & hydraulic conductivity

4.8.3. Infiltration rates according to landcover

Steady state infiltration rates under ponded conditions (+10mm water supply potential) were higher under tree canopy sites than grass sites. Our hypothesis that the mean infiltration rate under tree sites would be significantly higher than that under grassed sites was supported by a one-tail t-test ($p = 0.04$, $\alpha = 0.05$). Under negative tension conditions (-40 mm supply potential), however, the highest rates were recorded at grassed sites (Figure 4.8). Sorptivity rates (infiltration rates recorded during the wetting up phase in the first 10 minutes of measurement) under both ponded and negative tension conditions were higher at grasses sites. The mean sorptivity ratio (the ratio of sorptivity under ponded to negative tension conditions) was higher at grassed sites than treed sites (Figure 4.8E). This ratio is an indication of the role of macropores in governing infiltration and at the grassed sites, represents large and deep cracks evident in the surface soil profile (Figure 4.9).

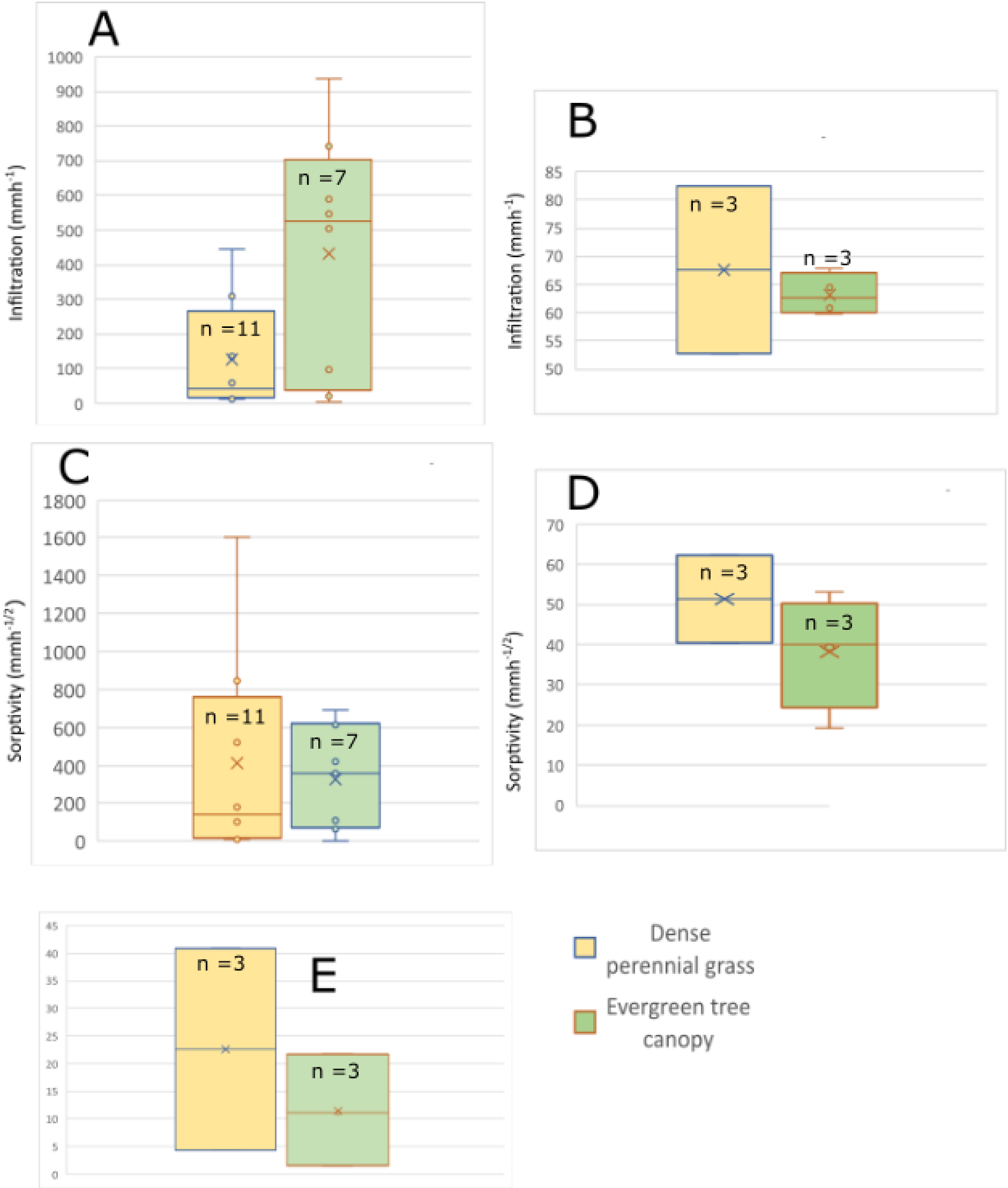

Figure 4.8. A) Steady state infiltration rates by landcover type under ponded conditions; B) steady state infiltration rates under negative tension; C) sorptivity rates under ponded conditions; D) sorptivity rates under negative tension; and E) sorptivity ratios by landcover type. Median and mean values are indicated by lines and crosses, respectively.

Figure 4.9. Example of desiccation cracks in vertisols of the study area.

The median infiltration rate we recorded using the ponded disc permeameter was 98.5 mmh^{-1} and 526 mmh^{-1} for sites with grass cover and tree cover, respectively. The maximum rainfall intensity we measured was 59 mmh^{-1} (on 27 February 2017). At this intensity, runoff would theoretically occur at five of the ten grassed sites, and 2 of the 8 tree canopy sites. The average intensity of all rainfall events recorded between December 2016 and June 2018 was 4 mmh^{-1}. As infiltration measurements were conducted during the dry season, infiltration capacity (reported as steady state infiltration rates), is comparative to early wet season rainfall events. The mean early wet season rainfall intensity recorded between 15 December 2016 and 28 February 2017 was 3.2 mmh^{-1}, well below the measured steady state infiltration rate for all sites. An analysis of daily rainfall records from 2004 to 2015 at the proximal rainfall station in Waingapu found that the majority of big rainfall events (> 30 mmd^{-1}) occurred between December and February, with the largest proportion of big rainfall events (22%) occurring in February. It is argued therefore, that the rainfall intensities recorded during the study period represent a sample of average peak wet season conditions and that Hortonian overland flow is unlikely, or very rarely to occur within the predicted groundwater recharge area.

4.8.4. Lab soil property results

4.8.4.1. Bulk density

A one-tailed t-test found that grassed sites had significantly higher bulk density values than treed sites (p-value 0.002, α=0.05), however, it is noted that this result is from a small number of samples (Figure 4.10; Table 4.4).

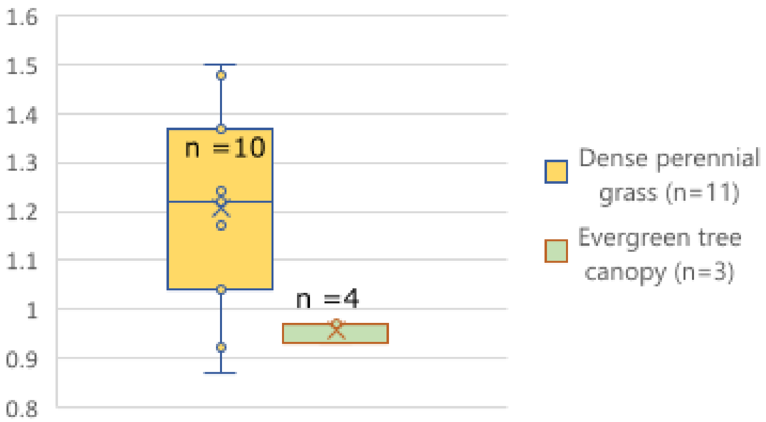

Figure 4.10. Bulk density (Mgm-3).

Table 4.4. Bulk density and soil water content results.

Plot and sample point	Landcover	Bulk density (Mgm-3)	Initial volumetric water content (cm^3 cm^{-3})	Final volumetric water content (cm^3 cm^{-3})
T1.1	Tree canopy	0.93	0.13	0.43
T2.2	Grass	1.04	0.18	0.44
T2.3	Grass	1.24	0.15	0.74
T3.1	Grass	0.87	0.15	0.80
T3.2	Grass	1.22	0.17	0.75
T3.3	Grass	0.92	0.13	0.62
T3.4	Grass	1.24	0.15	0.74
T4.1	Grass	1.22	0.59	0.80
T4.2	Grass	1.50	0.26	1.03
T4.3	Tree canopy	1.37	0.23	0.82
T4.4	Grass	1.48	0.29	0.98
T5.1	Tree canopy	0.97	0.11	0.60
T5.2	Grass	1.17	0.14	0.73
T5.3	Tree canopy	0.97	0.15	0.60

4.8.4.2. Particle size distribution

Soil samples from the infiltration measurement sites had low percentages of clay-size particles (between 0 and 2%) and all samples were at least 50% sand. Samples taken from the groundwater discharge point locations mostly had higher clay percentages, and there was no trend with increasing depth (Table 4.5). There was no difference in the results of particle size distribution following addition of Calgon as a dispersant. The results of soil texture estimation by the field texture method suggested much higher percentages of clay in samples taken at infiltration measurement sites with textures including loam, clay loam and clay.

Table 4.5. Particle Size Distribution results from laser diffraction.

Site	Soil depth (cm)	% Clay (<2µm)	% Silt (2–50 µm)	% Sand (50–2000 µm)
Soils taken at infiltration measurement sites				
1.1	Surface	2	32	66
1.2	Surface	0	13	86
3.4	Surface	2	40	58
3.4	Surface	0	16	83
3.4	Surface	1	35	64
3.4	Surface	1	44	55
5.1	Surface	0	19	81
5.1	Surface	1	37	63
Soil samples taken at groundwater discharge points				
1.2	115-130	10	72	18
1.2	145-160	6	71	24
1.2	145-160	8	81	11
1.2	235-250	11	87	2
2.2	10-20	4	60	37
2.2	90-110	3	64	33
3.1	75-90	0	42	57
3.2	65-80	3	75	23
3.3	50-70	5	86	9
3.3	115-120	3	74	22

4.8.4.3. Linear shrinkage

Linear shrinkage results demonstrate the decrease in length (as a %) of soils from wet to dry states, representing the shrink-swell behaviour of vertisols and formation of desiccation cracking in dry conditions. Cracks provide preferential flow pathways for a front of infiltrating rainwater and depending on the characteristics of the soil, the cracks may close within the first rainfall event (Favre et al., 1997; Hodnett & Bell, 1986). Despite low percentages of clay particles found via laser diffraction, high percentages of linear shrinkage were found for four of the five sites in particular (sites 1 to 4), demonstrating the potential for significant changes in soil macro and microporosity between wet and dry conditions.

Table 4.6. Linear shrinkage results.

Site	Site Description	Percent shrinkage	Image of dried sample
1	Grass cover	16	
2	*Anacardium occidentale* tree canopy edge	15	
3	Goat grazing, *Anacardium occidentale* canopy edge	13	
4	3 m from base of *Ziziphus mauritiana* tree	20	
5	*Anacardium occidentale* orchard	9	

4.8.4.4. pH and electrical conductivity

Results of analysis of pH and EC of soil samples from infiltration measurement sites and groundwater point sites are shown in

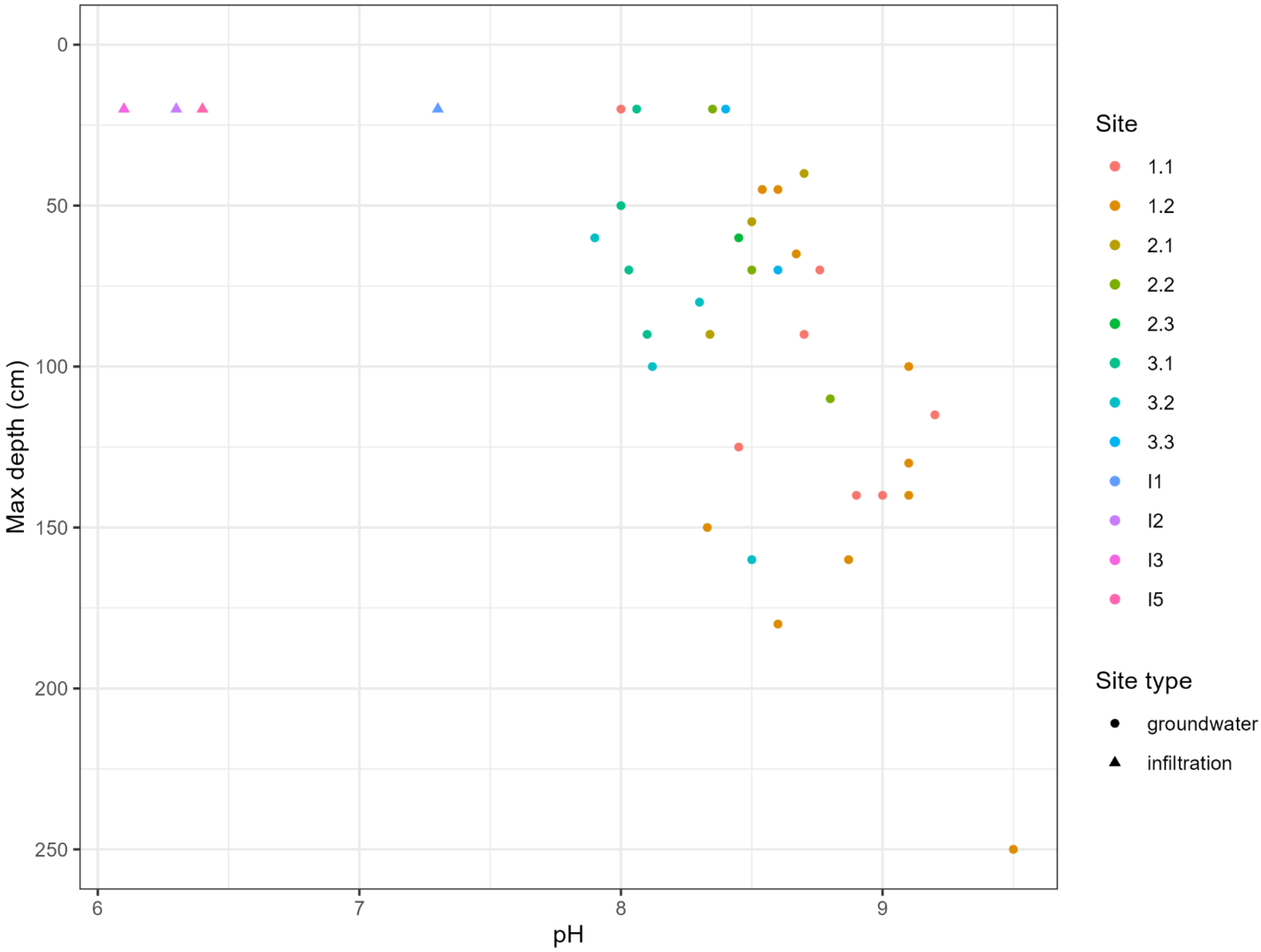

Figure 4.11A)A and

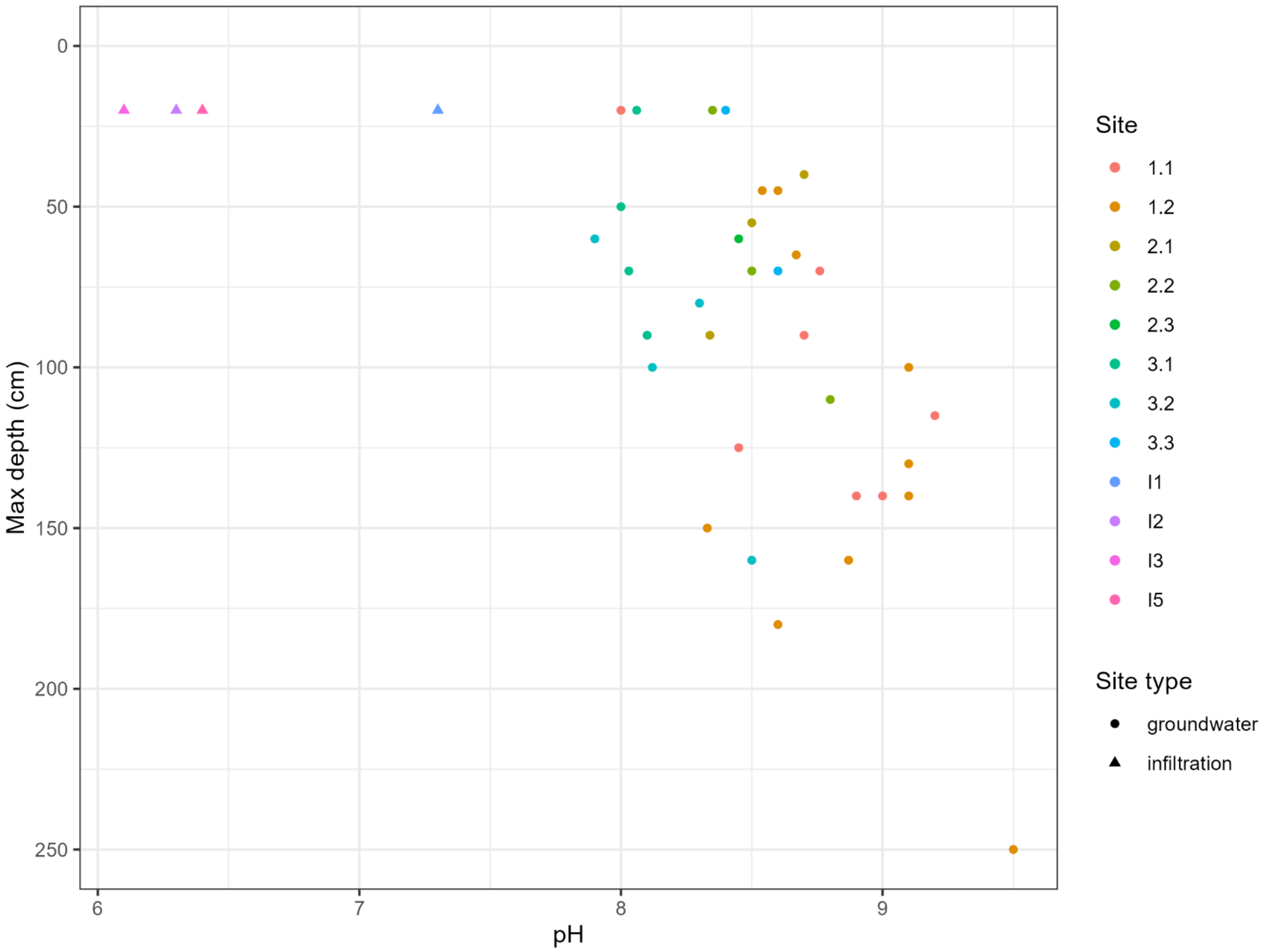

Figure 4.11A)B, respectively. There are low pH values (in the range of 6.1 to 7.4) at the infiltration sites and higher pH (range of 7.9 to 9.5) close to the groundwater sites. At the groundwater sites there was no consistent trend in pH with depth. There was also a large difference in the EC results between the infiltration measurement sites and the groundwater discharge sites, with much higher EC values found at the infiltration measurement sites.

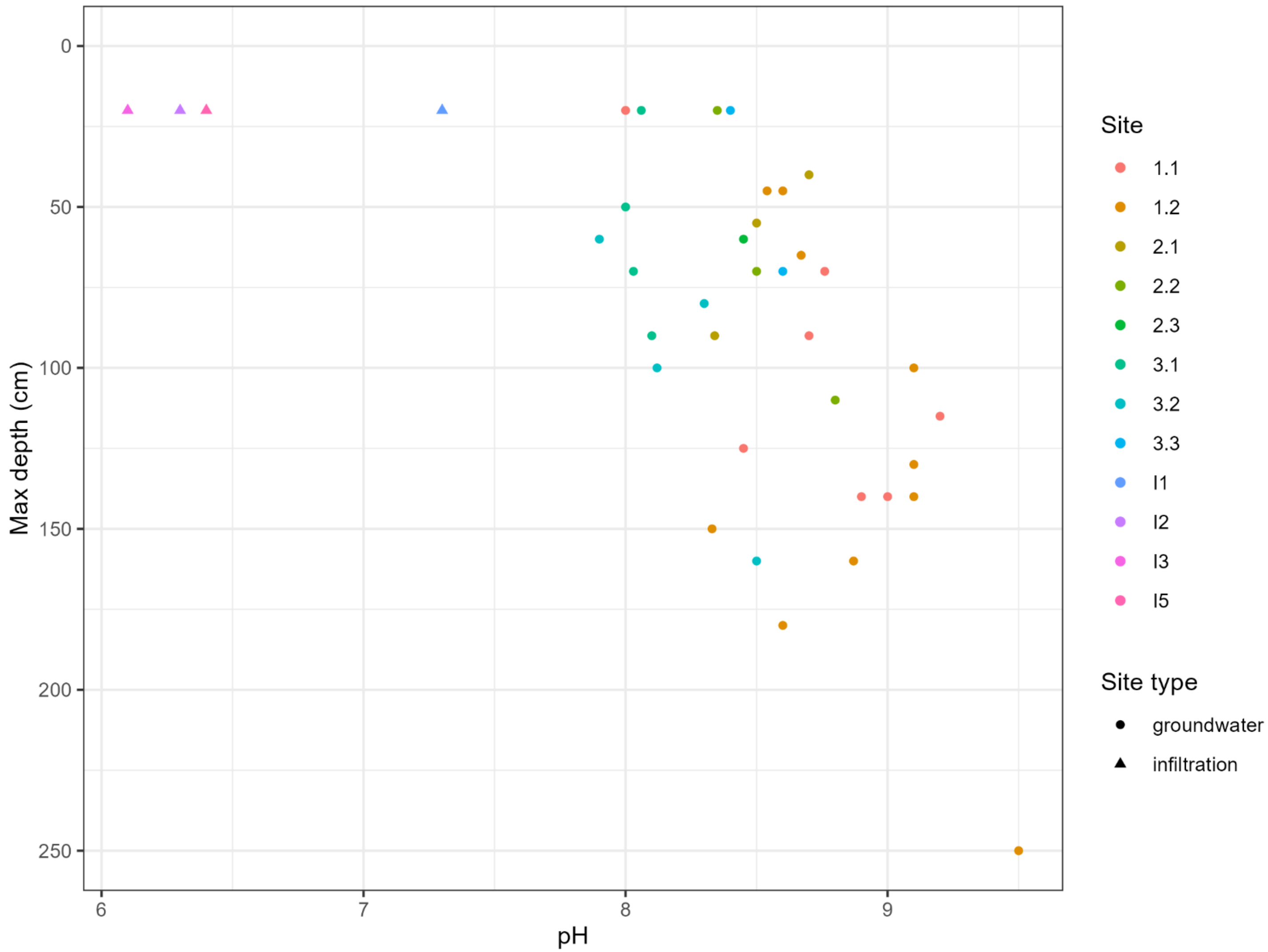

Figure 4.11A). 1:5 Soil Water suspension pH results by site and depth.

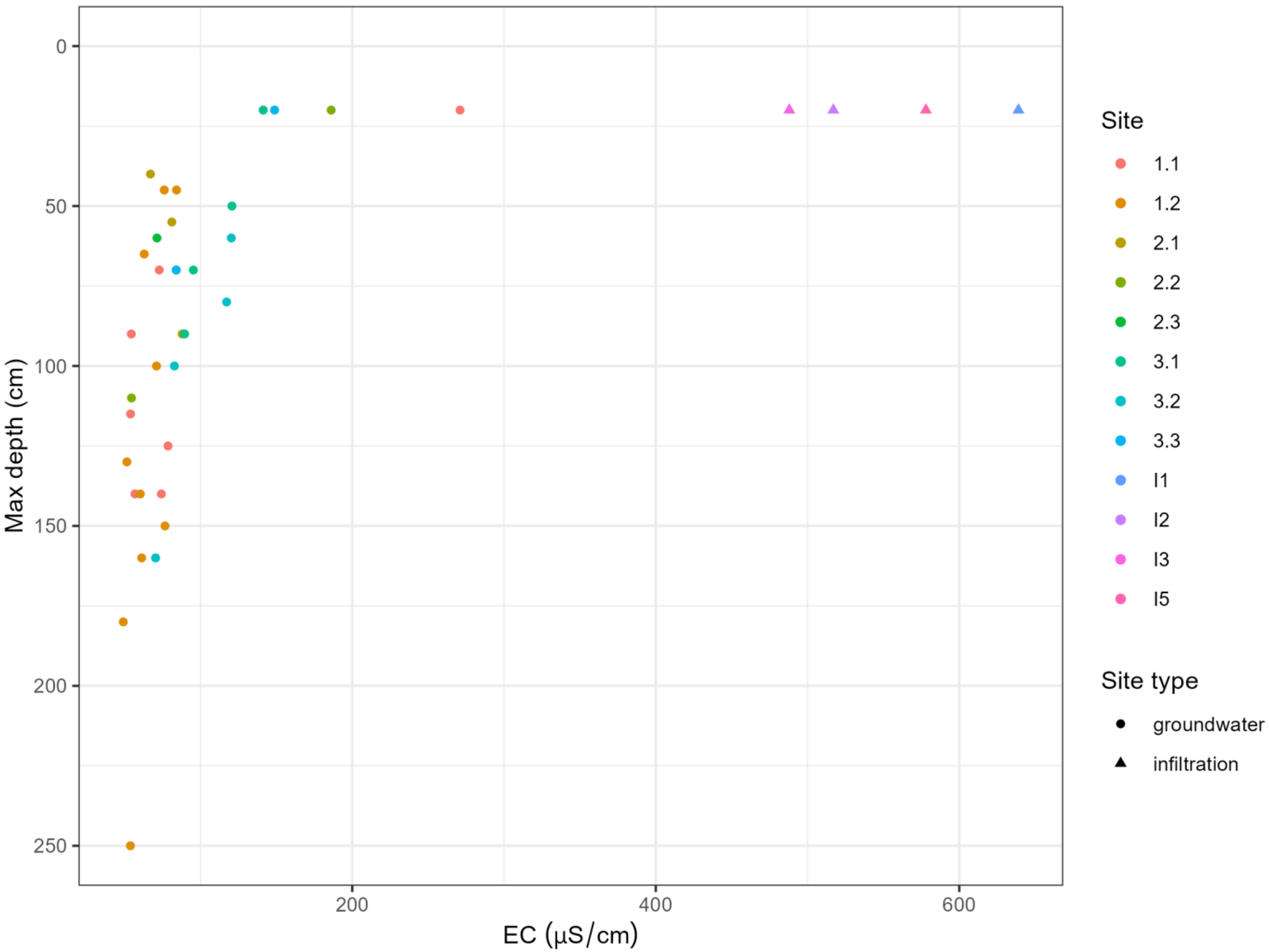

Figure 4.11 B) 1:5 Soil water suspension electrical conductivity (EC; μscm^{-1}) results by site and depth.

4.8.5. Calculated and modelled saturated hydraulic conductivity

There were limitations in calculating hydraulic conductivity using the disc permeameter method (Perroux & White, 1988). Where sorptivity values were very high due to the presence of cracks in shrink-swell soils, resulting K_s were negative. All tree canopy sites had high sorptivity rates due to the presence of macropores resulting from root channels and no valid K_s values were obtained. For the grassed sites, values ranged between 10 and 305 mmh^{-1} (Table 4.7).

Table 4.7. Hydraulic conductivity calculations.

Site name	Landcover type	Sorptivity (mmh$^{-1/2}$)	Steady state infiltration (mmh^{-1})	K_s (mmh^{-1})					
				Field based	PTF Jena et al. (2021)	PTF Minasny and McBratney (2002)	PTF Kearney and Maino (2018) a[1]	PTF Kearney and Maino (2018) b[2]	PTF Kearney and Maino (2018)c[3]
1.1	Tree canopy	35	5.73	-24.45*	5.27	167.4	42.84	156.6	34.7
2.2	Dense perennial grass	419	444	-4381*					
2.3	Dense perennial grass	15	14	12	5.10	43.95			
3.1	Minimal grass cover	58	25	-42*					
3.2	Dense perennial grass	8	12	10					
3.3	Dense perennial grass	14	24	23					
3.4	Minimal grass cover	361	137	-1154*	7.14	56.1	41.04	48.96	32.29
4.1	Dense grass	1602	3496	-4055*					
4.2	Dense grass	105	309	119					
4.3	Tree canopy	355	505	-2912*					
4.4	Dense grass	844	1221	-6151*					
5.1	Tree canopy	108	742	-4*	7.40	89.29	39.6	120.6	30.67
5.2	Grass	687	547	305					
5.3	Tree canopy	616	936	-5277*					

K_s: Saturated hydraulic conductivity; PTF: Pedotransfer function.

*Hydraulic conductivity cannot be validly calculated using the (CSIRO, 1988) method where sorptivity rates are very high.

[1] PTF based on univariate regression (Cosby et al., 1984).

[2] PTF based on multivariate regression (Cosby et al., 1984).

[3] PTF based on Campbell (1985).

Grey shading indicates that the applicable particle size distribution data were not available as inputs to the PTF.

4.9. Discussion

4.9.1. How has catchment leakiness changed over time?

The potential for the Larawali catchment to retain rainwater increased over the study period according to the LI. The LI results imply that the runoff connectivity within the catchment has reduced relative to the 2015 baseline. In the case that rainfall intensity exceeds infiltration capacity, the influence of vegetation patches will be less significant (Crompton et al., 2023), however, the results of this study show that in early wet season conditions at least, this does not occur.

The LI is a measure of structural connectivity, (i.e., it enables an evaluation of the landscape's ability to retain resources as a function of topography and vegetation pattern), however, it does not take into account rainfall characteristics or soil permeability. The addition of information on rainfall intensity and soil permeability enables an evaluation of functional connectivity (Crompton et al., 2023). While model development was out of the scope of this study, the combined results of a catchment-scale LI calculation and point-scale rainfall and infiltration studies provide a logical foundation for simulation of the rainfall-runoff components of a catchment-scale water balance. To calculate LI, the bare soil fraction of each 30 m^2 within the catchment was used to compute the fraction of accumulated flow in each cell that would be transported to downstream cells. This computation assumes that bare soil patches have much greater runoff potential than vegetation patches. It was not feasible to test this assumption in this study as the overall grass cover was medium to dense at all plots and dense at most infiltration sites. Two sites were recorded as having 50% grass cover and 50% bare soil. The remaining sites had medium to dense grass cover, which needed to be trimmed prior to placement of the disc permeameter. While a large range in infiltration rates was found within the grass cover sites, the rate was not found to be a function of the density of grass cover. Total vegetation cover was calculated to increase from 80% to 82%, and the fraction of woody vegetation cover is estimated to have increased from 12% to 19%, however, the method of disaggregation of woody vegetation from the fractional cover results requires further attention (Whitley et al., 2017).

4.9.2. How does landcover influence infiltration?

Infiltration rates under ponded conditions were significantly higher at tree canopy sites compared to grass sites, which supported the hypothesis. When infiltration was restricted to matrix pores with the use of suction (-40 mm supply potential), higher rates of sorptivity and steady state infiltration were measured at grass site than tree canopy sites, which suggests that macropores created by tree root channels (Bargués-Tobella et al., 2024) are the main driver of infiltration rates during ponded conditions under tree canopies. However, the calculated sorptivity ratio (also known as a macroporosity index) was found to be higher at grass sites than tree canopy sites, suggesting that macropores in fact played a more important role than matrix flow in governing infiltration under grasses than under trees. It is noted, however, that sorptivity and steady state infiltration under tension were not measured at all sites, due to limitations in transporting sufficient water to the sites to fill the water reservoirs for both ponded and unsaturated infiltration measurements. To reach soil saturation and enable measurement of steady state infiltration rates, between 10 and 20 L of water was required per infiltration measurement point. The water used for these measurements was collected in 25L drums from the closest accessible point of the river. Drums had to be carried by hand some distance to the measurement points. The need for large volumes of water to carry out infiltration measurements is a disadvantage of the CSIRO disc permeameter method in remote savanna conditions.

The other limitation in results obtained from infiltration measurements in the field is that these measurements were made during the dry season when desiccation cracks were at their maximum aperture. Cracks in the surface soil profile were important preferential infiltration pathways and resulted in very high sorptivity values. The measured infiltration, sorptivity and K_s values therefore relate to macroporosity and not to the soil matrix. (Bonell et al., 2010) encountered similar limitations in a study of reforestation on the Western Ghats of India, noting the challenges of accurately measuring K_s in the dry season and in the presence of desiccation cracks. The study concluded that landcover change did not influence K_s on black soils as hydraulic characteristics were a function of inherent soil properties. However, on red and laterite soils, reforestation resulted in higher K_s at shallow depths. It is important to consider potential differences in infiltration with antecedent soil moisture conditions in vertisols.

4.9.3. Limitations of calculating saturated hydraulic conductivity from infiltration measurements conducted in dry conditions

Infiltration measurements were conducted in June 2018, which is the early dry season in the study area. At this time there were fine to coarse cracks present in the soil matrix which provided preferential flow paths for the wetting front during infiltration rate measurements. The results reported here for sorptivity and steady state infiltration are representative of infiltration conditions during the early wet season when the first rainfall events are received, yet the calculated K_s values are high as the method that was applied is dependent on sorptivity and initial soil moisture (Equation 5) (Foley et al., 2006). Infiltration measurements were conducted until an apparent steady-state flow rate. However, according to Foley et al. (2006) it may take several hours to reach a fully wet soil profile and thus reach steady-state flow. For this reason, to obtain an accurate calculation of K_s using the disc permeameter method (Perroux & White, 1988), infiltration measurements should be conducted after a period of pre-wetting or, in the case of this study area, during the wet season. Pre-wetting would result in lower infiltration rates due to pores being partly or completely filled. In this study, infiltration rates and calculated K_s was governed strongly by macroporosity. In the presence of macropores, water movement is governed by gravity, known as bypass flow, rather than by permeability of the soil matrix (Ruy et al., 1999). In spite of the high degree of macroporosity observed in soils in this study created by root channels and through desiccation cracking, the measured infiltration rates were within the same range as those reported by Jones and Banner (2003), also in tropical soils overlying an uplifted coral reef terrace.

4.9.4. What effect do inherent soil properties have on infiltration?

While the design of this study aimed to evaluate the influence of landcover on infiltrability by selecting sites of uniform slope and soil sub-group, a large degree of heterogeneity was identified in soil texture and the occurrence of desiccation cracking. Soils in karst regions are known to be particularly heterogeneous and the application of PTFs based on soil texture may not be reliable (Zhang et al., 2021). In karst regions, bedrock fractures can be filled with soil material of varying textures, usually of higher clay content with depth. This means that K_s close to the soil surface may be very high, generally exceeding rainfall intensity, and will decrease considerably with depth (Yang et al., 2016). This study measured infiltration and sorptivity rates in the shallow soil profile and soil samples were obtained from the soil surface up to a depth of 2.5 m at some sites. The particle size distribution results from the laser diffraction method, which included high percentage of sand, were unexpected. With repeated lab analyses of particle size distribution of soil samples using an alternative method, it may be possible to determine a trend in the distribution of clay particles with soil depth. Subsequently the use of a PTF based on particle size such as those listed in Table 4.3 would provide an indication of changes in K_s with depth. The results of particle size analysis used in this study did not find that clay particles increased uniformly with soil depth in this study as would be expected. It may be that the presence of organic matter in soil samples falsely skewed the results of particle size to the coarse fraction. Ideally these analyses would be repeated following the pre-treatment methods that improve the dispersion of soil particles (Zimmermann & Horn, 2020).

At groundwater discharge sites both EC and pH generally increased with soil depth. The increase in pH with depth is attributed to greater proportions of calcite derived from the coral reef geology, relative to the higher proportions of plant-derived organic matter in shallow soil samples. Soil pH and EC are known to have non-linear relationships with $K_{s.}$ As pH increases with depth in the soil profile, K_s generally decreases, however, particle size also contributes to the K_s value, so both factors must be included in estimations of K_s (Ali et al., 2019). The effect of EC on K_s is driven largely by excess Na, which contributes to dispersion of clay particles within the soil matrix

4.9.5. Limitations of pedotransfer functions

The K_s was estimated for available particle size distribution and bulk density data. There was a large range of the resulting estimated values and these values also differed significantly from the values calculated from field infiltration measurements. There are a number of limitations of using the selected PTFs to estimate $K_{s.}$ These include that the results of particle size analyses using laser diffraction is dependent on the methods of soil pre-treatment and dispersion. Particle size distribution is a key determinant of water infiltration. However, without appropriate pre-treatment of soil samples, or use of an appropriate dispersion method during laser diffraction analysis, the particle size distribution could be artificially skewed to the coarser end due to the presence of water-stable aggregates of clay particles (Zimmermann & Horn, 2020).

Due to the small number of results of measured K_s it was not possible to generate a PTF using data from this study or to determine the soil characteristics that had the most significant influence on K_s. With additional measurements of infiltration in the field, data from this study could be used as inputs to a mixed-effect model to evaluate the relative influence of soil texture, macroporosity, pH and landcover on determining K_s in a karst tropical savanna setting.

4.10. Conclusions and management implications

From a structural perspective, the Larawali catchment has a low water resource loss potential as measured by LI, which decreased from 0.16 to 0.12 over the study period. In the same period, the average fraction of catchment vegetation cover has increased by 2% from 80 to 82%. The fraction of woody vegetation cover is estimated to have increased from 12% to 19%, however, the disaggregation of woody vegetation from the fractional cover results requires further attention. From a functional perspective, the results of this study supported the hypothesis that infiltration rates are higher under tree canopies than grass canopies, however, logistical constraints combined with the dry soil moisture conditions of field measurements hindered the ability to demonstrate results that were statistically significant. This study also concludes that inherent soil properties may have more influence over infiltration and groundwater recharge potential than landcover. In particular, the shrink-swell properties of vertisols have a drastic influence on K_s in different soil moisture conditions. Finally, while PTFs have the potential to provide estimates of soil hydraulic properties without the need to undertake time-consuming field measurements of infiltration, for accurate results it is important to 1) select a model with training data from comparable soil conditions; and 2) validate the model with field data. Neither of these conditions were possible given the constraints of this study.

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Chapter 5. Sources and Rates of Groundwater Recharge

5.1. Introduction

In karst savanna landscapes, due to short wet seasons and the absence of major surface water drainage development, groundwater discharge features are crucial water sources for rural communities. Karst savanna landscapes by and large coincide with limited development and poor socio-economic indicators due in part to the biophysical constraints on agricultural and industrial development including thin and rocky soils (Mulyoutami et al., 2016; Schwinning, 2008). The lack of data relating to these karst groundwater systems and associated springs is problematic for water resource planning. Approximately 25% of the global population is dependent on drinking water from karst aquifers (Ford & Williams, 2007) and investigation and development of groundwater resources are required in these areas to improve access to safe drinking water and sanitation and to enhance climate resilience. Groundwater resources in karst savanna landscapes are most often recharged by episodic events over a short wet season (Swaffer, 2014) so spring yields are susceptible to climate variability and climate change. Their environments may also be subject to frequent fire events and widespread landcover change, which can induce changes in the groundwater balance (Chandler, 2006).

Where there is a demand to understand the reliability of groundwater supplies, studies using geochemical approaches are an important contribution to provide a base understanding of the origins and the rate of groundwater recharge (Querejeta et al., 2007). In particular, using stable isotopes in water in combination with major ion analyses is a common approach in groundwater recharge studies (e.g. Acikel & Ekmekci, 2021; Beal et al., 2019; Chimenti et al., 2023; ElGhawi et al., 2021; Tweed et al., 2020).

There have been few investigations of isotopes in precipitation in Indonesia. Belgaman et al. (2016) investigated the temporal variability of stable isotopes in precipitation as well as the influence of climate drivers on stable isotopes values. No strong relationships were established between climate drivers and stable isotopes in precipitation in the eastern part of Indonesia, although the authors found a correlation with phases of the Madden Julian Oscillation in the western region of Indonesia. The study recommended the development of additional monitoring sites within Indonesia to improve understanding of stable isotopes in the region (Belgaman et al., 2016). To date, however, there is only one published study containing precipitation isotope data from the tropical savanna zone of Indonesia (Manta et al., 2022).

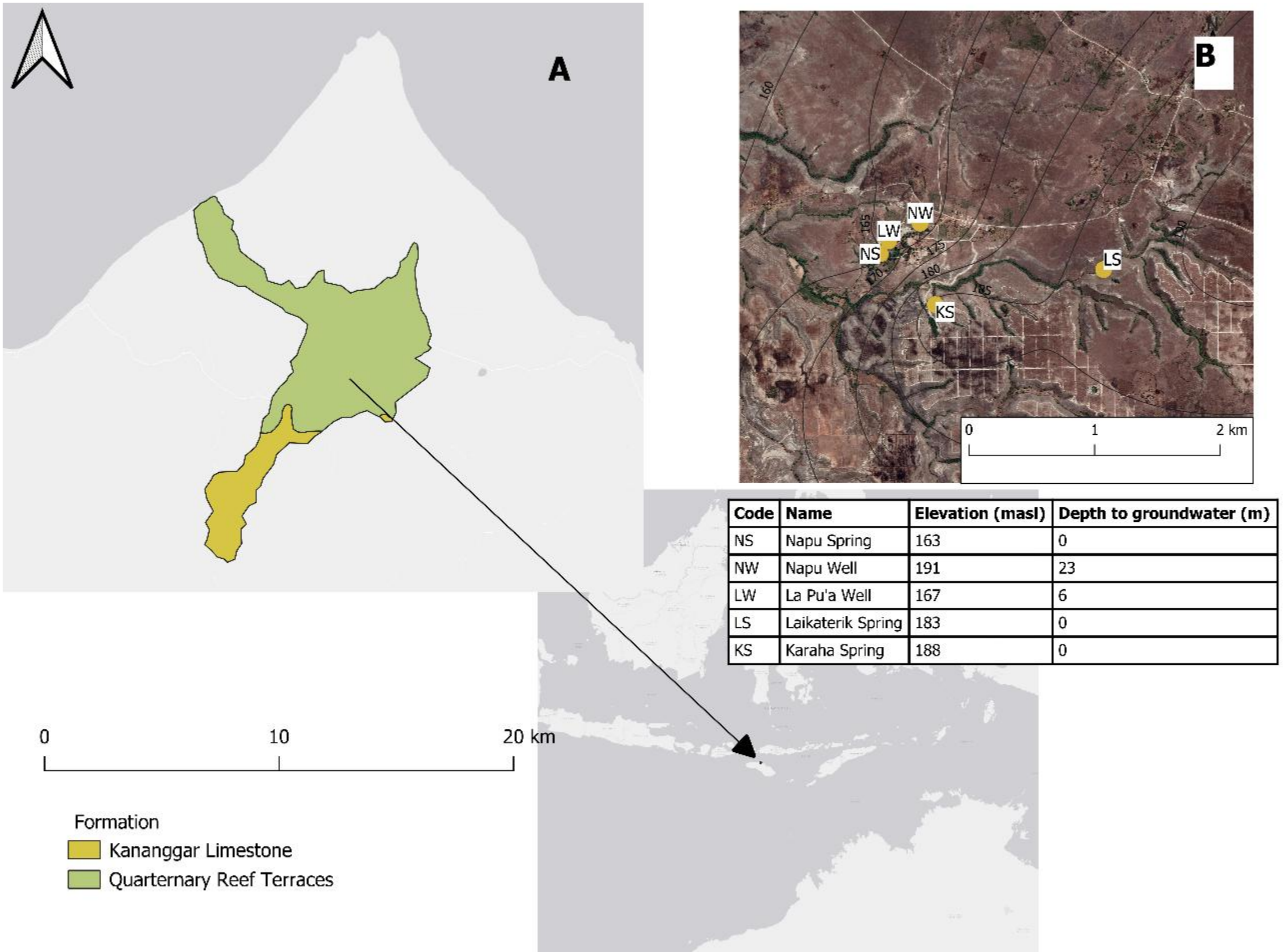
Combining stable isotopes and major ion analyses can help further constrain potential sources and flowpaths of groundwater recharge (e.g. Somaratne, 2014). For example, in a karst environment, groundwater recharged by point sources such as sinkholes and fissures will have a water type more closely related to rainwater, whereas recharge from diffuse sources will be more enriched in salts and have a stable isotopic composition with a higher ratio of ^{18}O:^{16}O and ^{2}H:H (Acikel & Ekmekci, 2021; Chimenti et al., 2023; ElGhawi et al., 2021; Somaratne, 2014). In addition, the comparison of chloride (Cl^-) concentrations in rainfall and groundwater can be used to estimate long-term average groundwater recharge rates (Allison & Hughes, 1978; Clark, 2015). Understanding the sources and flow paths of springs is a prerequisite to their sustainable management. Manta et al. (2022) used hydrochemistry and stable isotope ratios to investigate groundwater recharge zones in Raimanuk on the island of Timor in East Nusa Tenggara, Indonesia, however, did not consider recharge rates.

Here major ion chemistry and stable isotope hydrology methods were employed to investigate the origins and recharge rates of groundwater and associated springs in a karst savanna in East Sumba, Indonesia. The key objectives of this study were to 1) generate a baseline of hydrochemical and stable isotope data to inform the origins and dominant pathways of groundwater discharging into three main springs and two water supply wells across the area; and 2) estimate the recharge rates for these five groundwater features. The outcomes of this study will provide a basis for further quantitative investigation of water supply features and the related karst aquifers and insight into the potential influence of landcover management on the groundwater balance.

5.2. Methods

5.2.1. Hydrogeology

Infiltration and flow through the limestone Kaliangga (Quarternary reef terrace) strata in the study area is assumed to be dominated by secondary porosity, that is fissures, shafts and sinkholes, however, the degree of karstification within the Larawali catchment area of the Kaliangga formation is not known. The majority of groundwater on the island of Sumba, however, is reported to be cavern and fissure water, discharging as unconfined karst springs (Inamoto & Sayama, 1993). The source of water and rate of recharge for discharge features in the Larawali catchment had not previously been studied. Five groundwater features are the focus of this study, including three springs and two wells (Figure 5.1B). Each of the features are daily sources of water supply for households from surrounding villages.



Code	Name	Elevation (masl)	Depth to groundwater (m)
NS	Napu Spring	163	0
NW	Napu Well	191	23
LW	La Pu'a Well	167	6
LS	Laikaterik Spring	183	0
KS	Karaha Spring	188	0

Figure 5.1. A) Geology of the study area; B) Location of groundwater discharge sites, indicated by code. Contour lines delineate the interpolated potentiometric surface in metres (asl).

The Larawali catchment area is comprised of steep gullies with ephemeral creek systems and two main springs at low points where the water table meets the surface (Laikaterik and Napu springs). There is also one mid-slope contact spring or perched water table (Karaha Spring), which likely overlies impermeable clay-rich sediments. All three springs are perennial seeps with average annual yields estimated to be between 0.5 to 1 L sec^{-1}. Yields cannot be easily measured as the Napu Spring has been covered with a spring box and is pumped to an overhead tank, while the other two springs discharge to small pools that could not be purged due to local water demands. The two wells that were studied are dug community water supply wells at 6 metres and 23 metres depth for the La Pu'a and Napu wells, respectively (Figure 5.1B). These wells likely intercept large fissures.

5.2.2. Sample collection

Nine sites within the Larawali catchment of the Haharu district in Sumba, Indonesia were sampled during two consecutive wet seasons between 2016 and 2018 and again in the 2019-2020 wet season. The nine sites were comprised of three rainfall collection sites (Napu, Waingapu and Wunga), the three springs described above (Laikaterik, Napu and Karaha), two wells (Napu and La Pu'a) and one river site (Table 5.1). A total of 65 rainfall samples were collected between December 2016 and April 2020, including 31 storm event samples, four monthly composite samples and 30 weekly composite samples (Table 5.1). All rainfall samples were collected using a custom-made rainfall accumulation sampler, based on the design of (Groning et al., 2012) (Figure 5.2). Composite rainfall samples were accumulated in a 3L HDPE (High Density Polyethylene) sample bottle over one month. At the end of the month the accumulated sample was transferred into a 60mL sample bottle with no headspace. Storm event samples were collected by filling directly with rainfall from the air, or by emptying collected rainwater from the manual rain gauge into a sample bottle following a storm event. Samples were collected from Waingapu in addition to Napu, in the event that access to the rainfall accumulation sampler in Napu was not possible due to COVID-19 travel restrictions or other issues relating to road access.

The number of groundwater samples that were collected throughout the study period and analysed for stable isotopes and major ions were 61 and 44, respectively (Table 5.1). The difference in numbers analysed resulted from logistical constraints, where headspace was introduced into some sample bottles prior to analysis. Spring samples were collected as close as possible to the spring vent, or in the case of Napu Spring, from the outlet of the spring box, while well samples were collected using a Hydrasleeve passive sampler to gain a sample that had not be subjected to evaporative influence, without the need to purge the well first. While it is not known at what level within the well formation water enters the well, the water in the bottom is assumed to be most representative of groundwater.

Samples for stable isotopes were collected in 60 mL polyethylene (PE) bottles, filtered in the field using a 0.45μm syringe filter, filled to the top and sealed with electric tape to prevent any evaporation. For major ion analyses, samples were collected in clean and dry PE or glass bottles and also filtered in the field using a 0.45mm syringe filter. Samples for cation analyses were acidified in the field to $pH < 2$ using HNO_3. Where possible, samples were transported on ice and refrigerated at 4°C until analysis. Due to logistical complications in transporting samples from the study area to labs in Australia, some samples were not kept at 4°C, as required by sampling protocols, and these are indicated in the results.

For each sample, pH, EC and temperature were measured in the field using handheld sensors (TPS WPPLS003) and total alkalinity were determined where possible using a digital alkalinity titrator within 24 hours of sampling. Where HCO_3^- measurements were not done in the field, HCO_3^- was calculated using a charge balance with all remaining major ions.

Table 5.1. Water sampling sites, Larawali catchment.

Sampling Site Name	Sample Site symbol	Water source type	Sampling method	Stable isotopes sample count	Major ions sample count
Napu Rain	NR	Rain	Composite rain collector (accumulated sample)	17	19
Napu Rain	NR	Rain	Storm event sample	27	1
Wunga Rain	WR	Rain	Composite rain collector	4	2
Waingapu Rain	WR	Rain	Composite rain collector	15	12
Waingapu Rain	WR	Rain	Storm event sample	2	0
Total rainfall samples				**65**	**34**
Larawali River	LR	River	Surface sample	5	2
Karaha Spring	KS	Natural spring	Collected from as close to spring vent as possible	13	10
Laikaterik Spring	LS	Natural spring		11	15
Napu Spring	NS	Spring cistern		11	7
La Pu'a Well	LW	Well	Hydrasleeve from well bottom	7	2
Napu Well	SN	Well		19	10
Total groundwater samples				**61**	**44**

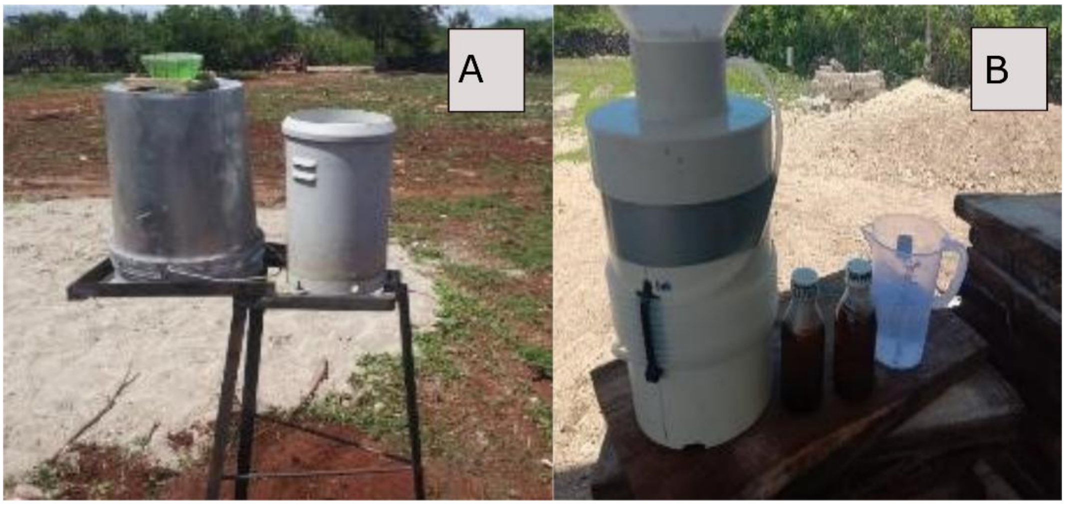


Figure 5.2. A) Rain accumulation sampler used in 2016 and 2017; B) Rain accumulation sampler used to collect weekly composite samples in 2019–2020

5.2.3. Rainfall measurements

Tipping bucket rain gauges equipped with Tinytag data loggers were installed at Napu village (9°23’46”S 119°55’41”E) and Wunga village (9°23’09”S 119°57’24”E) to record rainfall amount, frequency and intensity. Longer term rainfall data were sourced from the proximal Indonesian meteorological bureau weather station in Waingapu (9°40’32”S 120°18’19”E). Monthly and water year standard precipitation index (SPI) was calculated for monthly rainfall to indicate the intensity of the wet season. Water year totals were calculated as the sum of rainfall from 01 November in a given year until 30 October the following year. SPI was calculated as in (Mckee et al., 1993):

$$SPI = \frac{(P - \mu\mathrm{P})}{\sigma\mathrm{p},}$$

(Equation 6)

where P is monthly precipitation, μP and σ_{p} are the long-term average and standard deviation of precipitation for a given month, respectively.

5.2.4. Stable isotope analyses

Water samples were analysed by cavity ring-down spectrometry (Picarro L2130-i) for hydrogen (δ^2H) and oxygen (δ^{18}O) stable isotope ratios at the Environmental Chemistry and Microbiological Unit, Charles Darwin University, Darwin for samples collected until 2017 and subsequently at the Research School of Biology, Australian National University. All δ^2H and δ^{18}O ratios are reported relative to the Vienna Standard Mean Ocean Water and expressed in per mill (‰) (Gonfiantini, 1978) Sampling precision for samples and standards was between 0.04 and 0.07 ‰ for δ^{18}0 and between 0.29 to 0.39 ‰ for δ^2H.

5.2.5. Major ion analyses

The concentrations of the following ions were determined: boron, calcium, iron, potassium, magnesium, sodium, fluoride, chloride, nitrite, bromide, nitrate, sulphate and phosphate. Major cations were measured in the Research School of Earth Sciences laboratory at the Australian National University using an Agilent 5110 SVDV ICP-OES (Synchronous Vertical Dual View Inductively Coupled Plasma – Optical Emission Spectrometry), and major anions with a Dionex Ion Chromotograph. Piper plots were generated in Python using D-Piper (Moreno Merino et al., 2021) to group waters by hydrochemical type.

Molar ratios of Mg^{2+}:Ca^{2+} are commonly applied in hydrological studies of karst areas, as the ratio of $^+$ reflects the degree to which groundwaters are effected by dissolution processes and therefore are an indication of groundwater residence time (De Filippi et al., 2021). As the dolomite mineral ($CaMg(CO_3)_2$, dissolves two orders of magnitude slower than calcite ($CaCO_3$), a higher Mg^{2+}:Ca^{2+} ratio is an indicator of less rapid and diffuse discharge (Setiawan et al., 2020; Stroj et al., 2020). In dolomite the ratio approaches 1, while in s ($CaCO_3$) the ratio is generally 0.5–1 (Setiawan et al., 2020). Higher Ca^{2+} are an indication of conduit discharge, while Mg^{2+} dominant waters relate to slower diffuse discharge (De Filippi et al., 2021).

5.2.6. Development of a local meteoric water line

A local meteoric water line (LMWL) was initially generated using the δ^2H and δ^{18}O values of all 65 rainfall samples. The 30 weekly composite samples from 2019 and 2020 were then excluded from the results due to errors that were introduced through sample handling in the period between sample collection and stable isotope analysis. These errors were associated with necessary steps that were taken to meet biosecurity requirements, including the introduction of headspace to allow for gas expansion in sample bottles prior to gamma irradiation as well as storing samples at room temperature for an extended period of time. A precipitation amount weighted least squares regression (PWLSR) was calculated from the remaining 36 rainfall samples. Daily rainfall totals were used as weights for storm event samples, and monthly totals for accumulated monthly samples as per (Hughes & Crawford, 2012). The slope and intercept of the LMWL are compared to other precipitation stable isotope data within the region to contribute insights into precipitation moisture sources in the study area and to address an identified data need (Belgaman et al., 2016). The deuterium excess (d-excess = δ^2H – 8 δ^{18}O) was derived as an indicator of the degree of secondary evaporation in precipitation (Dansgaard, 1964). The d-excess provides an indication of evaporation that relates to the Global Meteoric Water Line (GMWL) (where secondary evaporation is limited, the d-excess approaches the GMWL intercept of 10). A related measure, the line-conditioned excess (lc-excess), identifies the deviation of δ^2H from the LMWL (Landwehr & Coplen, 2004). Lc-excess is calculated as δ^2H – a*δ^{18}O – b, where a and b are the coefficients of the LMWL. A negative lc-excess value is an indication of an evaporation effect in a water sample (Landwehr & Coplen, 2004; Sprenger et al., 2017). Finally, the non-parametric Spearman's rank-based correlation tests were used to assess the relationship between rainfall amounts and stable isotope ratios.

5.2.7. Chloride mass balance

Average annual recharge was estimated using a steady state chloride mass balance (CMB) of groundwater, which is a reliable method for estimating long-term mean annual recharge rates (Crosbie et al., 2010; Jones et al., 2000). Chloride that has been deposited on the land surface from precipitation concentrates in the unsaturated zone, as it is not taken up by plants, it then ultimately concentrates in groundwater. The long-term recharge fraction (RF) of rainfall was calculated as:

$$RF = \frac{Cl_p^-}{Cl_{gw}^-},$$

(Equation 7)

where Cl_p^- is chloride concentration in rainfall and Cl_{gw}^- is the chloride concentration in groundwater (Schmidt et al., 2013). This method assumes that there are no other sources of Cl^- in groundwater. The geogenic contribution of chloride is known to be negligible in carbonate aquifers (Schmidt et al., 2013), while potential anthropogenic sources of Cl^- in the catchment, including animal manure, synthetic fertilisers and pit latrines, were located sufficiently far from the sampling points for these to be negligible. Annual groundwater recharge rates for each spring and well were estimated from long-term average annual precipitation from the proximal Indonesian meteorological station at Waingapu (51 km southeast) and the RF. Extreme results of Cl^- that were obtained in rainfall samples were discounted in calculating Cl^-_p as it is assumed that these samples had not been adequately filtered prior to transport to the lab. While rainfall samples had been collected in Waingapu as well as Napu (Section 5.2.2) the Cl^- results from Waingapu were not used to determine mean annual Cl- deposition (PClp), as Waingapu is approximately 60 km southeast of Napu and the predominant moisture sources for Napu are from the northwest (Aldrian & Dwi Susanto, 2003).

5.3. Results

5.3.1. Rainfall characteristics

Longterm mean annual rainfall statistics were discussed in Chapter 2. Here the monthly and annual rainfall data are described for the study period (2016–2020). All but one of the four wet seasons during the study period were drier that the long-term average with an SPI ranging between -0.11 and -0.72. Late 2017 and early 2018 had wetter than average monthly rainfall, culminating in a total wet season SPI of +1.19 (Figure 5.3). The maximum rainfall intensity measured was 59 mmh^{-1} (on 27 February 2017). The average intensity of all rainfall events recorded between December 2016 and June 2018 was 4 mmh^{-1}. The maximum daily precipitation amount recorded was 95 mm (on 11 January 2018). The mean daily precipitation amount during the wet season months in this period (November to April) was 8 mm.

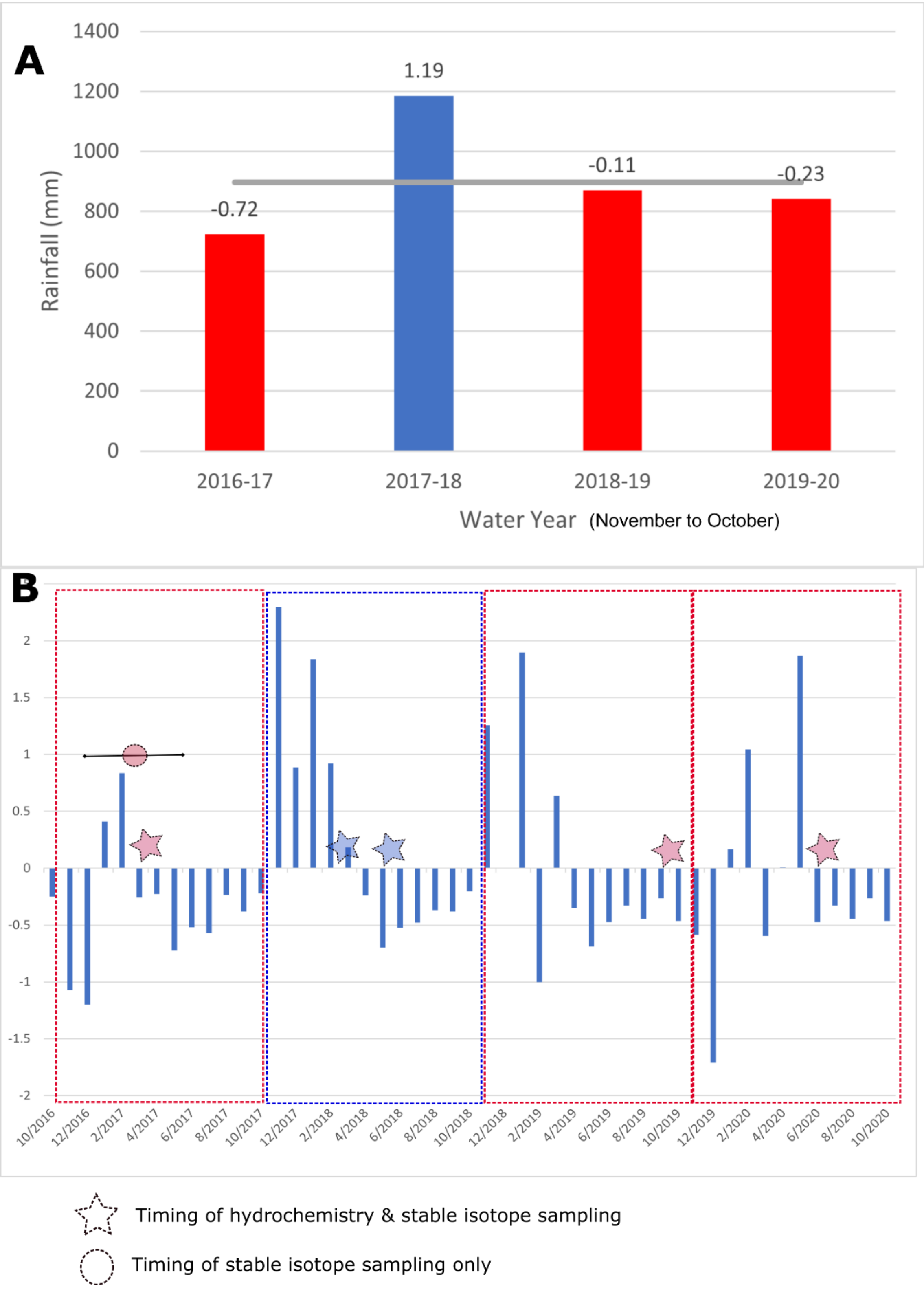


Figure 5.3. A) Water year standardised precipitation index (SPI) for wet seasons between 2016 and 2020. The grey horizontal line indicates the longterm annual mean rainfall for the study area. B) SPI for Waingapu monthly rainfall between 2016–2020. Timing of sampling campaigns are indicated for reference.

5.3.2. Hydrochemistry

All groundwater sites (both wells and springs) were found to be closely grouped and of Ca-HCO_3 type, while rainwater samples were of mixed type. River water was also Ca-HCO_3 type but was more enriched in Mg^{2+} than groundwater (Figure 5.4; Table 5.2).

There is no clear differentiation in water type between springs and wells from the plot of major cations (Ca+Mg vs Na+K; Figure 5.5). There are some small variations, however, in cation ratios between sites and seasons. The Laikaterik spring has the most pronounced seasonal response, and it also has in general a much higher ratio of Ca+Mg to Na+K, than other sites. The Karaha spring and Napu Well have generally lower concentrations of all four cations in the wet season (Figure 5.5A). Cl^- in water samples differed by season, with some higher concentrations returned during the March to April 2018 sampling period (Figure 5.5B). This sampling period occurred at the end of a bigger than average wet season.

Mg/Ca molar ratios ranged from 0.03 to 0.1. The mean values for all wells and springs were between 0.05 and 0.06. These results suggest short residence time in a limestone karst aquifer (Setiawan et al., 2020). While there was some variation in the range of values of Mg/Ca ratio with each water year the median value was 0.5 for all three water years that were sampled (2016–2017, 2017–2018 and 2019–2020) (**Error! Reference source not found.**; Table 5.3). Reduced Ca^{2+} in March and June 2018 suggests a dilution effect of the wetter than average November 2017 to March 2018 period (SPI +1.19, Figure 5.2). The median Ca^{2+} values for all wells and springs in the 2016, 2017 and 2019 water years were 6.06, 4.62 and 5.50, respectively.

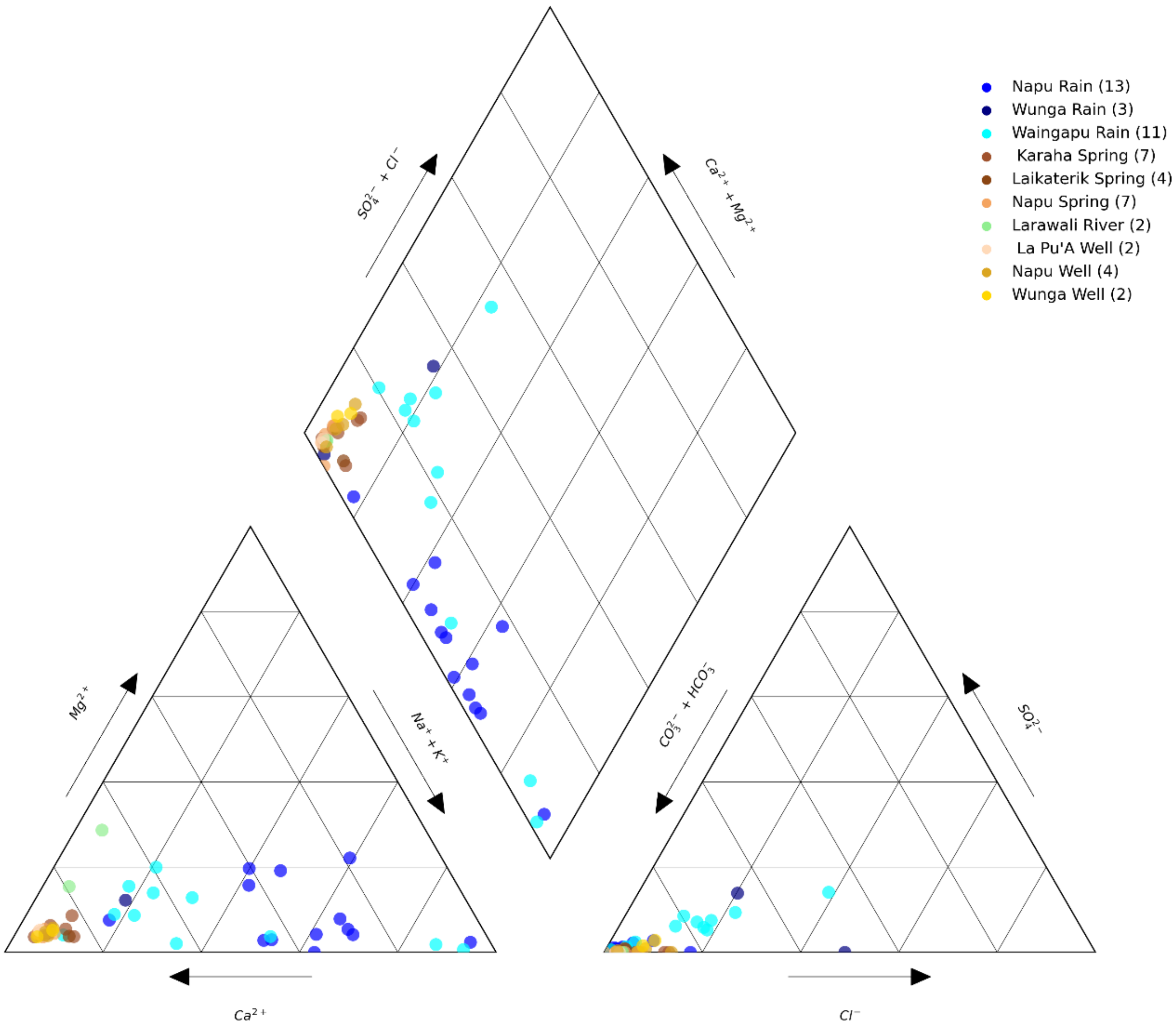


Figure 5.4. Piper diagram of major ions in samples collected between 2016 and 2020 coloured according to site.

Table 5.2. Hydrochemistry results for groundwaters and river water samples.

Site	B^+	Ca^+	Fe^{2+}	K^+	Mg^{2+}	Na^+	Fl^-	Cl^-	Br^-	NO3-	$SO4^{2-}$	$PO4^{2-}$	$HCO3^-$	EC (µs/cm)	Temp (°C)	pH
Karaha Spring	0.03	4.33	0.00	0.03	0.23	0.27	0.00	0.35	0.00	0.02	0.02	0.00	4.07	397	29.3	8.2
Napu Spring	0.03	6.24	0.00	0.05	0.30	0.31	0.00	0.41	0.00	0.06	nd	nd	6.55	498	28.2	7.1
Laikaterik Spring	0.03	5.30	0.00	0.09	0.27	0.22	0.00	0.33	0.00	0.01	0.03	nd	6.36	486	28.2	7.1
La Pu'a Well	0.00	5.63	0.00	0.02	0.31	0.24	0.00	0.21	0.00	0.04	nd	nd	7.16	501	20.4	7.4
Napu Well	0.03	4.62	0.00	0.02	0.22	0.27	0.00	0.39	0.00	0.12	0.01	0.02	4.57	403	29.8	7.5
Larawali River	0.00	3.60	0.00	0.04	1.52	0.24	0.01	0.22	0.00	0.01	nd	nd	5.24	318	28.1	8.1
Upper Larawali River	0.00	4.65	0.00	0.04	0.88	0.26	0.01	0.21	0.00	0.01	nd	nd	nd	382	31.2	7.6

All concentrations of ions are reported in $meqL^{-1}$. nd indicates no data. EC = Electrical conductivity.

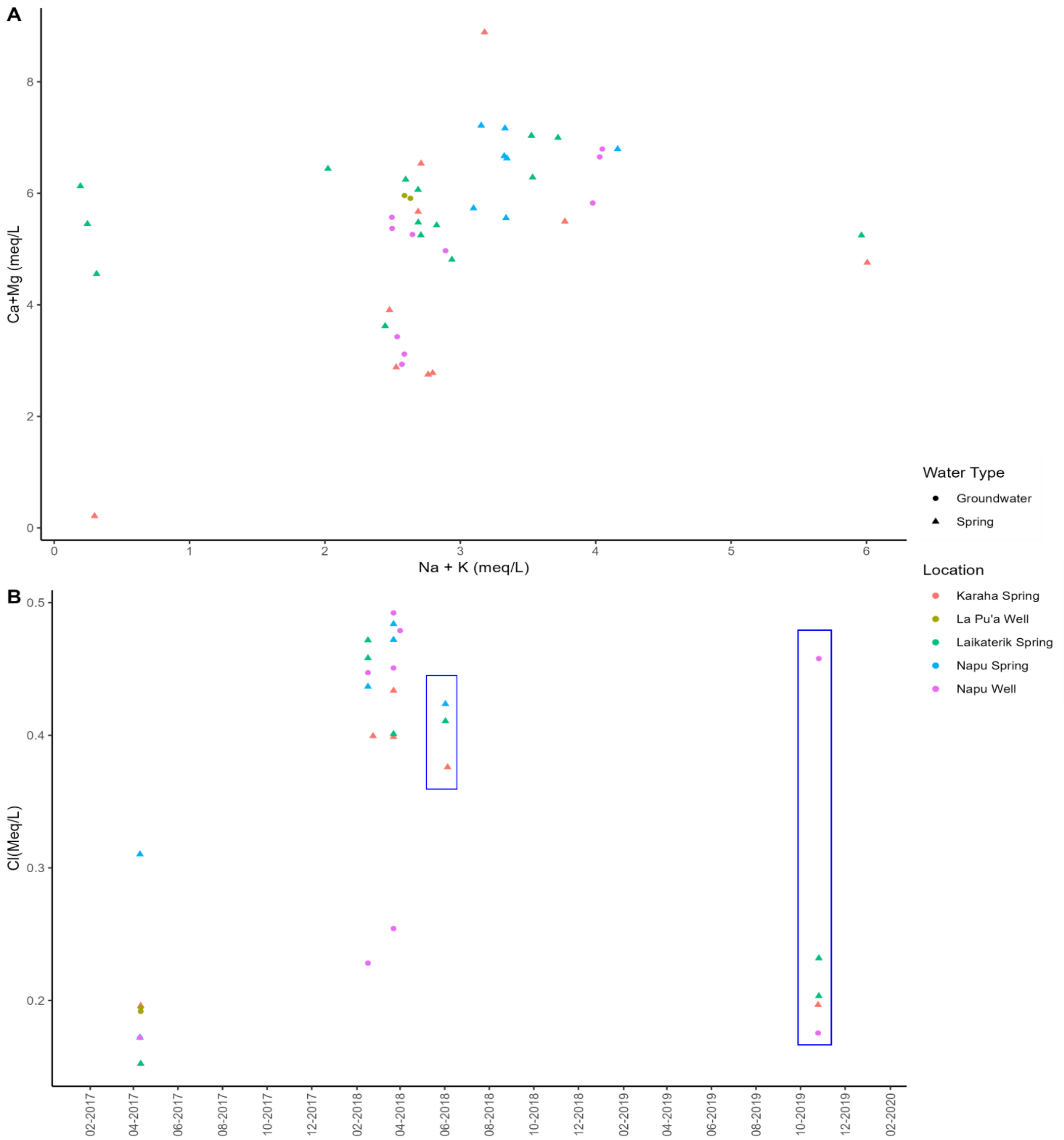


Figure 5.5. Spring, groundwater and river sample major ion results. A) Major cations B) Chloride values. Dry season Chloride values are identified by blue rectangles, the remaining samples were collected during wet season conditions.

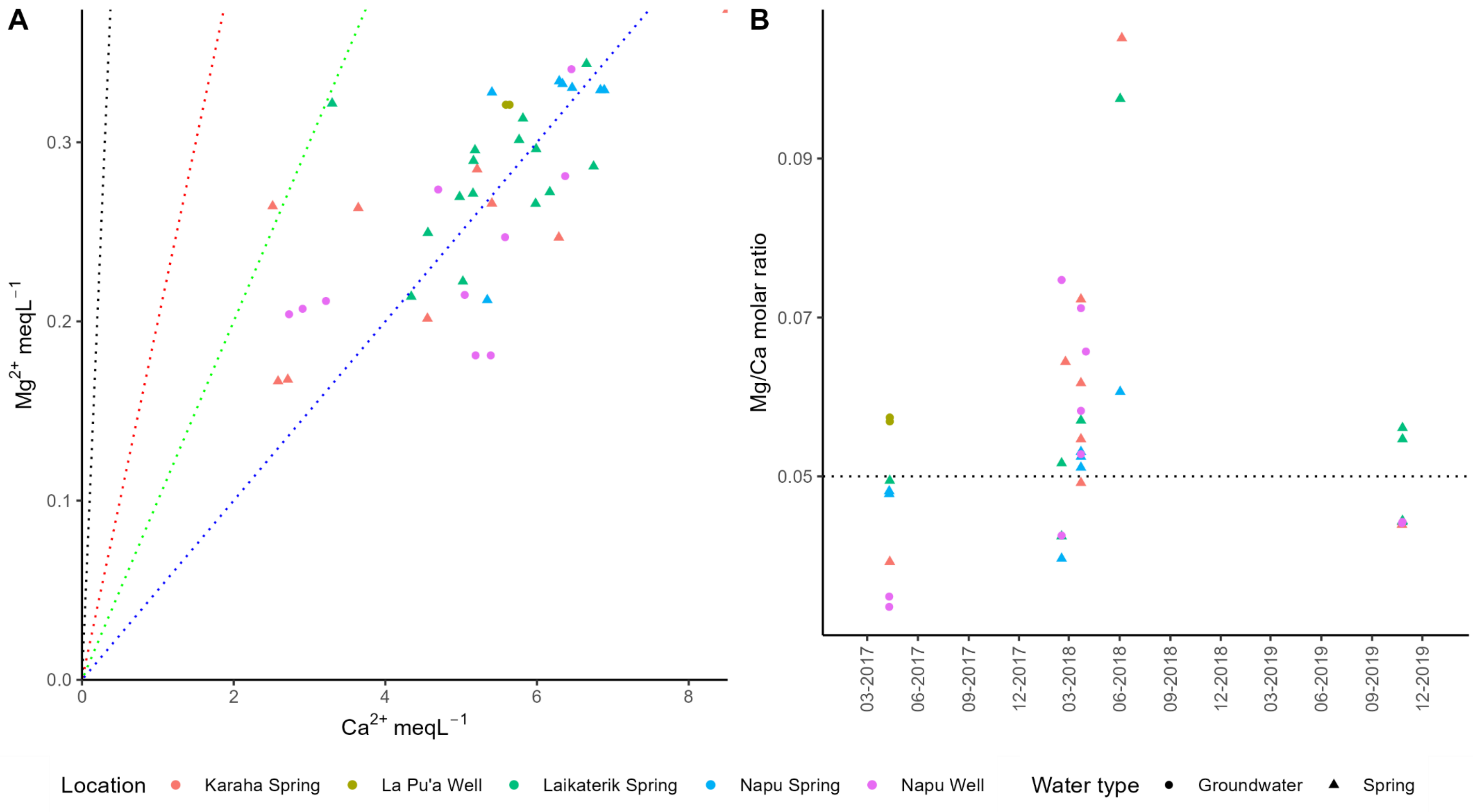


Figure 5.6. A) Mg/Ca ratios in meq/L for all groundwater and spring samples. Dashed lines indicate Mg/Ca ratios of 0.05, 0.1, 0.5 and 1. A ratio of approximately 1 indicates dolomite dissolution; B) Seasonal results of Mg/Ca ratios. The dashed line indicates the median value for each sampling season.

Table 5.3. Mean values of Ca^{2+}, Mg^{2+} and their molar ratio.

Site	Mean Ca^{2+}(meqL^{-1})	Mean Mg^{2+}(meqL^{-1})	Mean Mg2+:Ca2+	CV Mg2+:Ca2+
Napu Spring	6.22	0.31	0.05	0.13
Napu Well	4.76	0.23	0.05	0.28
Laikaterik Spring	5.39	0.28	0.05	0.24
La Pu'a Well	5.61	0.32	0.06	0.01
Karaha Spring	4.60	0.25	0.06	0.34

CV = Coefficient of variation.

5.3.3. Chloride mass balance

A large range of Cl^- values for both groundwater sites and for rainfall was established for all samples collected between 2016 and 2020 (Figure 5.6). It is noted that the small range in Cl^- for La Puá well was based on two samples only. For samples either collected, analysed or both after 2018, Cl^- values were found to be higher (in the range of 0.4 to 0.45 meqL^{-1}) while the maximum value for any site for samples collected and analysed in 2017 was 0.3 meqL^{-1}, with a mean value of 0.2 meqL^{-1}.

The annual mean Cl^- concentration in precipitation for Napu was 0.03meqL^{-1} (n = 19), while for Waingapu it was 0.05 meqL^{-1} (n = 10). The highest recharge fraction (0.30) was found at La Pu'a well, however as noted above, this result is from two samples only, both of which were collected in the 2016-17 wet season. The annual recharge at La Pu'a well is estimated to be 259 mm. The remaining four groundwater sites had recharge fractions between 0.15 and 0.19 with annual recharge estimates between 132 and 169 mm (Table 5.4). The average recharge estimate for all wells and springs was 172 mm, with an Interquartile Range (IQR) of 27 mm.

Table 5.4. Annual recharge estimates from chloride mass balance values.

Groundwater Site	Annual Average Cl (meqL^{-1})	n	Recharge Fraction	Annual average recharge estimate (mm)
Karaha Spring	0.36	8	0.16	142
La Pu'a Well	0.20	5	0.30	259
Napu Well	0.30	6	0.19	169
Laikaterik Spring	0.32	3	0.18	158
Napu Spring	0.38	6	0.15	132

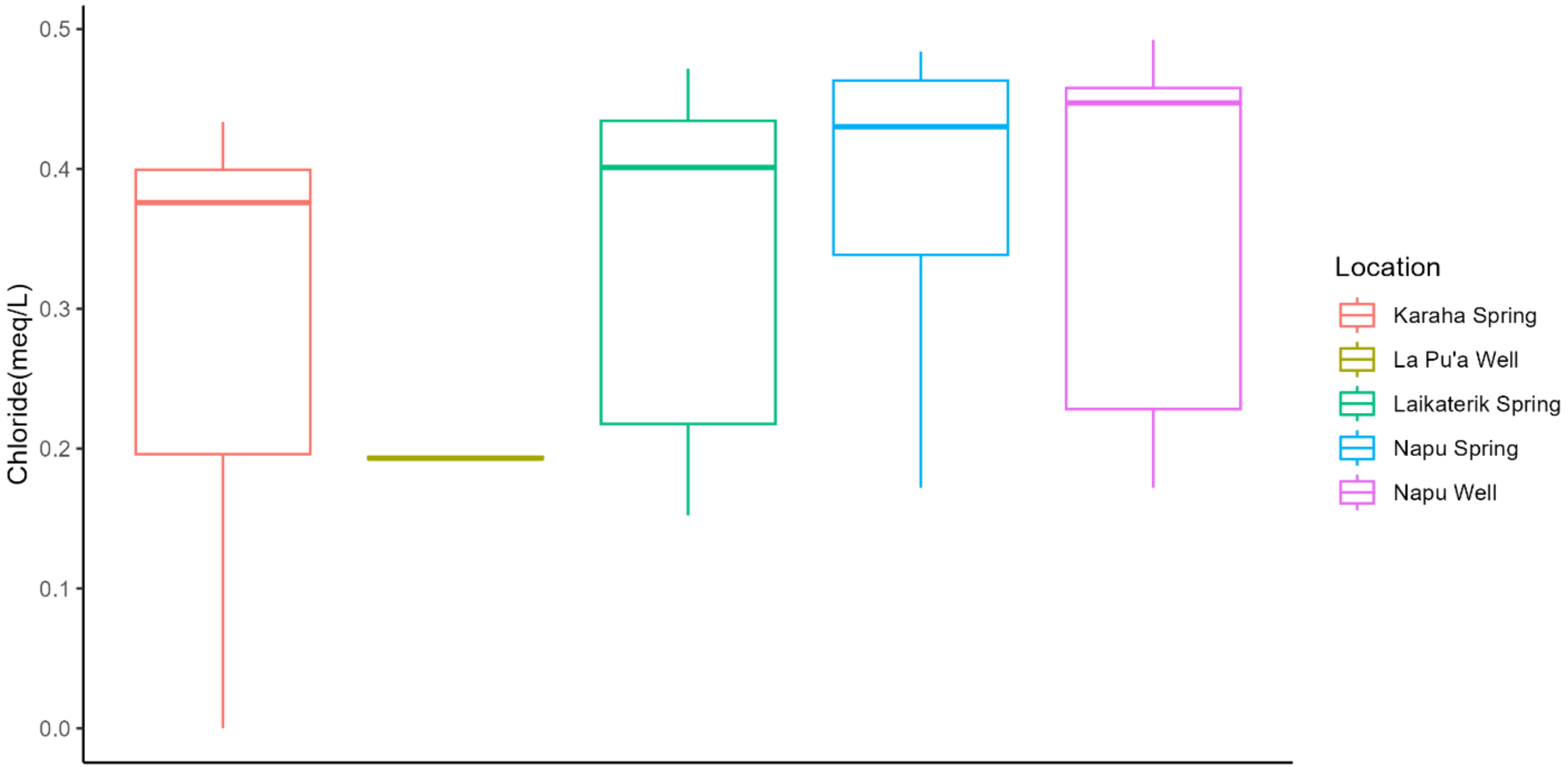


Figure 5.6 B). Chloride concentrations of all groundwater and rainwater samples from 2016–2020

5.3.4. Local meteoric water line and stable isotopes in groundwater

The stable isotope values for all rainfall samples collected between December 2016 and April 2020 are provided in supplementary material (Appendix Table 4). The range of $\delta^{18}O$ and $\delta^{2}H$ values in precipitation was from -11.4‰ to -2.4‰ and -80.4‰ to -0.5‰, respectively. The slope and intercept of the precipitation amount weighted LMWL was found to be $\delta^{2}H = 8.29\ \delta^{18}O + 15.01$ (Figure 5.7). Results from samples collected in 2019–2020 showed evidence of fractionation within sample bottles due to excessive headspace and temperature fluctuations during sample storage (Appendix B). These samples were excluded from calculation of the LMWL

There are no published data on stable isotopes in precipitation within a 400 km radius of the study area. There are, however, LMWLs that have been published based on varying numbers of samples from studies in Indonesia: Denpasar, Bali (approximately 520 km WNW) (Ardana et al., 2023; Belgaman et al., 2016), Raimanuk, Timor (approximately 545 km E) (Manta et al., 2022), and Makassar, Sulawesi (470 km N) (Belgaman et al., 2016); and in Australia: Darwin (approximately 1,250 km SE) (Hollins et al., 2018; Munksgaard et al., 2019). The study area is in the same climate zone as Darwin, and Raimanuk, while Makassar and Denpasar are in the wetter tropical monsoon and tropical rainforest climate zones, respectively (Peel et al., 2007) (Table 5.5; Figure 5.8).

The slope and intercept of the LMWL are larger than the GMWL, suggesting no sub-cloud evaporation processes have occurred. Both the slope and intercept of the LMWL are close to the slopes and intercepts from Darwin (Munksgaard et al., 2019) and Denpasar (Ardana et al., 2023). The Makassar and Denpasar (Belgaman et al., 2016) regression lines, however, have smaller slopes and intercepts than the LWML and plot below the GMWL (Figure 5.8).

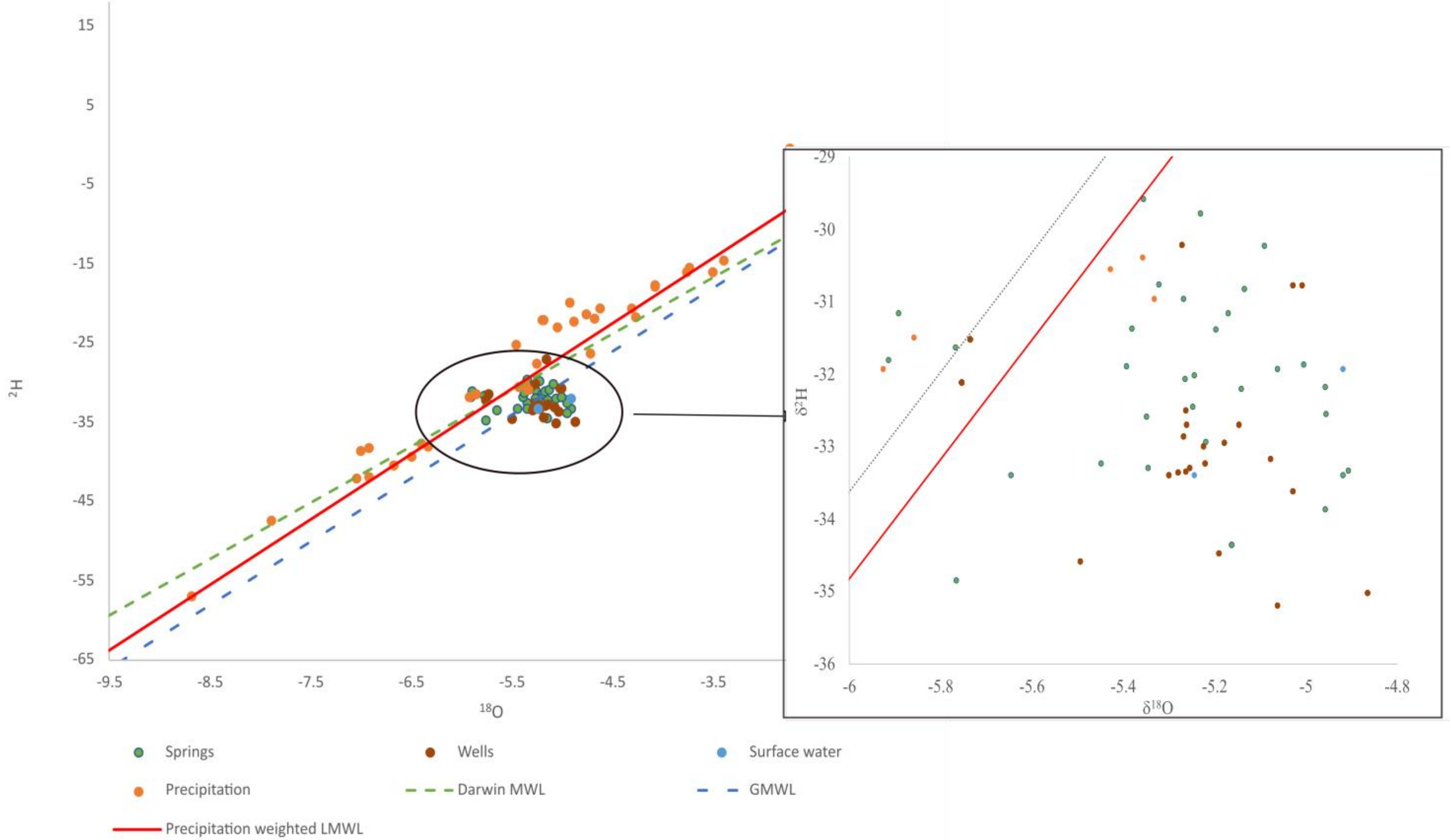


Figure 5.7. Dual isotope plot showing the local meteoric water line (LMWL) obtained from 36 rainfall samples at the study site (Napu, East Sumba, Indonesia) as well as spring and groundwater samples. The global meteoric water line (GMWL) and Darwin meteoric water lines are also shown. The slope of the LMWL was 8.29 and intercept was 15.01. The plot on the right shows distribution of groundwater samples specifically, which were in the range $\delta^{18}O$ -5.92:-4.87 and $\delta^{2}H$ -35.2:-29.59.

Table 5.5. Local meteoric water lines from related studies in the Indonesia – Australia region.

Stable isotopes in precipitation monitoring station	**Köppen-Geiger climate classification**	**Monitoring period**	**Precipitation Weighted Least Squares Regression (PWLSR)**	**Number of samples**	**Reference**
Napu (Sumba)	Aw	2016–2018	8.45 δ18O + 16.35	36	This study
Raimanuk (Timor)	Aw	2021	8.12 δ18O + 11.95	4	Manta et al. (2022)
Darwin	Aw	1962–2014	7.82 δ18O + 10.27	N/A[1]	Hollins et al. (2018)
Darwin	Aw	2014–2017	8.11 δ18O + 14.81	252	Munksgaard et al. (2019)
Denpasar	Af	2020–2021	8.58 δ18O + 19.88	5	Ardana et al. (2023)
Denpasar	Af	2002–2010	7.1 δ18O + 9.8 [2]	~ 2920	Belgaman et al. (2016)
Makassar	Am	2002–2010	7.1 δ18O + 4.7 [2]	~ 2920	Belgaman et al. (2016)

[1]Number of samples not specified, however, the study was based on the full GNIP (Global Network of Isotopes in Precipitation) record available for Australian stations.

[2]Authors did not specify if these values are based on precipitation weighted Ordinary Least Squares Regression (OLSR) or unweighted OLSR

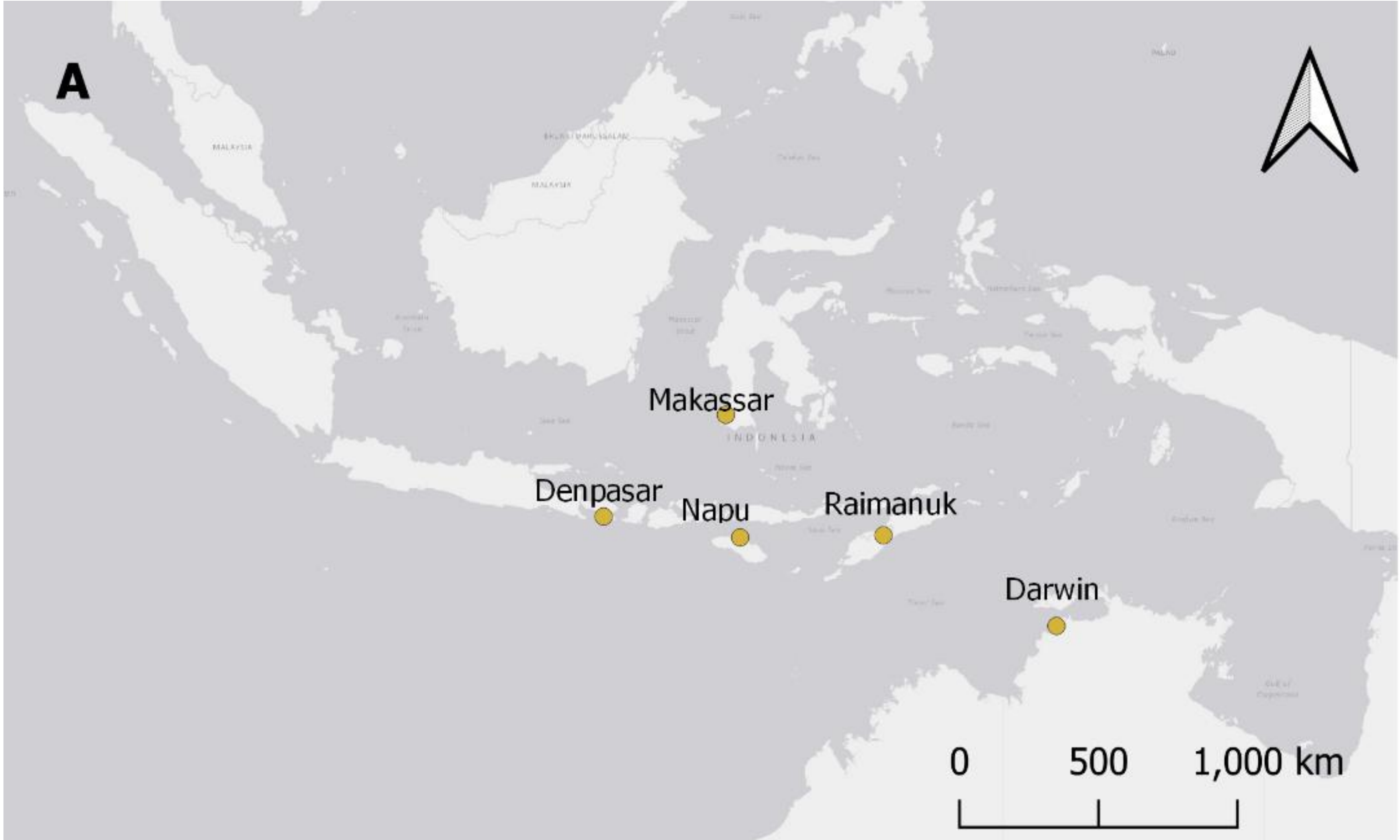


Figure 5.8. A) Napu Local Meteoric Water Line (LMWL) in relation to existing regional data.

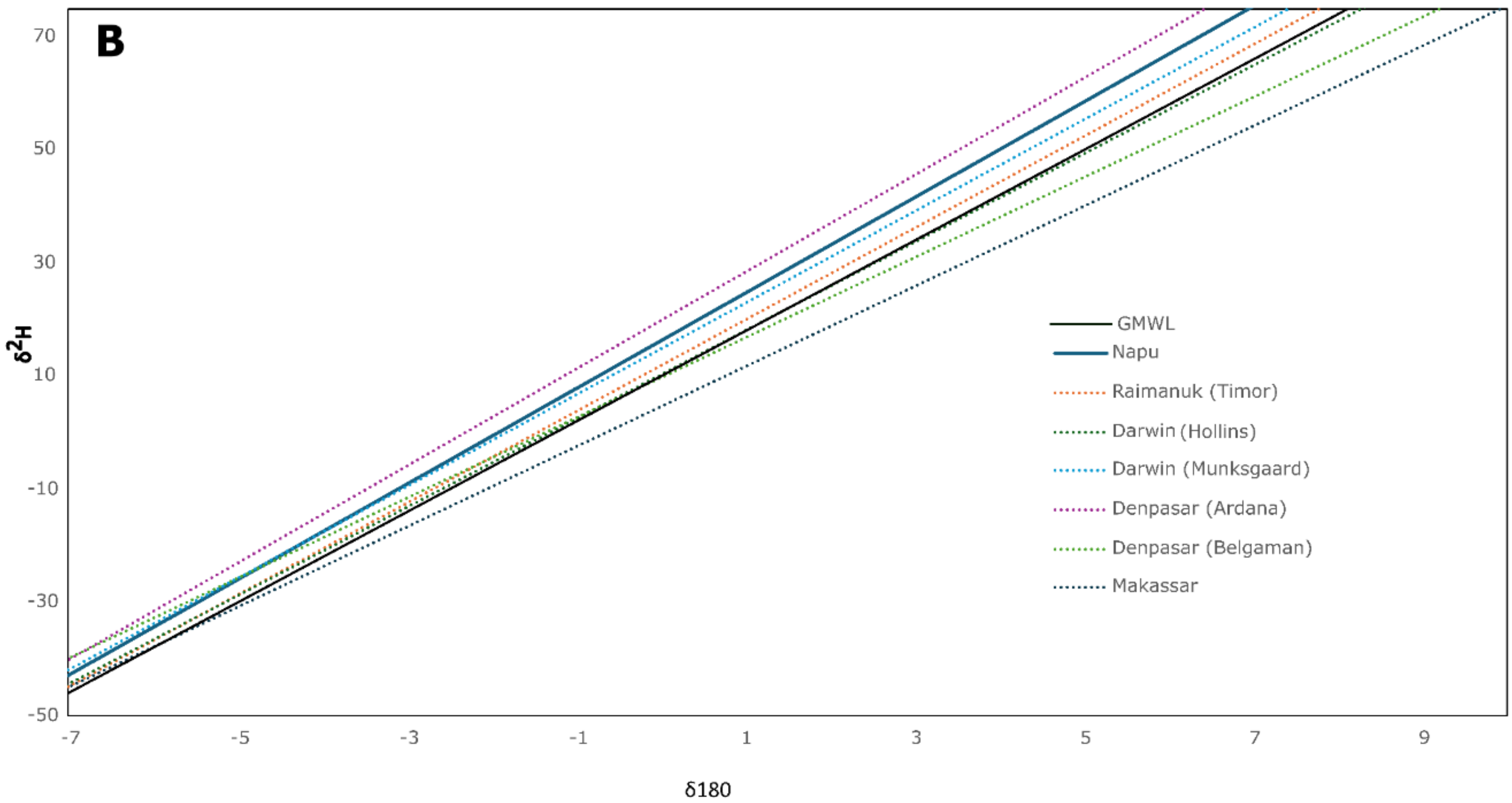


Figure 5.8. B) The Napu Local Meteoric Water Line (LMWL; blue) obtained in this study and Global Meteoric Water Line (GMWL; black) are indicated with solid lines and other LMWLs are indicated by dashed lines.

No secondary evaporation processes were indicated by d-excess results, which ranged from 10.54 to 21.38 ‰, with a median value of 14.45 ‰. Higher d-excess and lc-excess values were returned for samples from 2018 compared to 2017. The lc-excess ranged from -2.8 to 6.2 ‰., with a median of 0.2 ‰. No relationship was found between rainfall amount and $\delta^{18}O$ or $\delta^{2}H$, and a weak negative correlation was returned for d-excess, lc-excess and rainfall amount (rho -0.41, p-value 0.02 and rho -0.43, p-value 0.01, respectively) (Figure 5.9A).

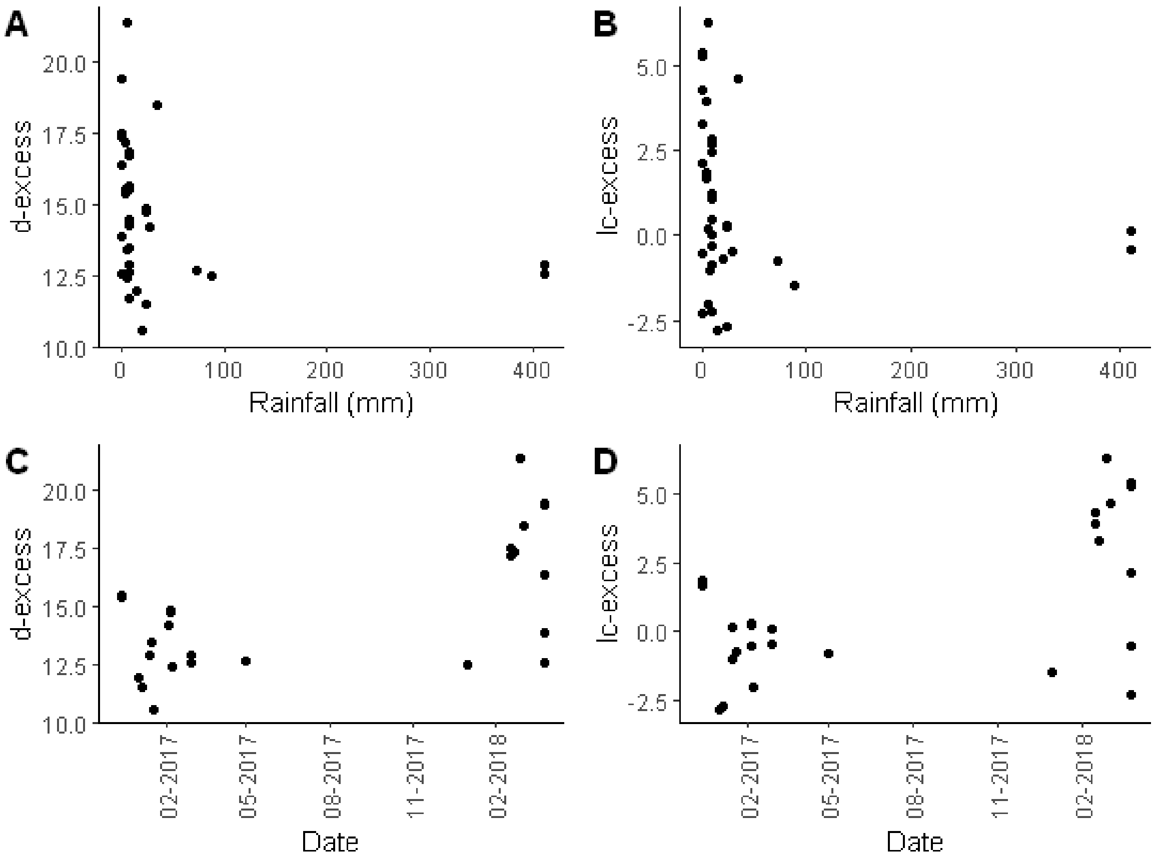


Figure 5.9. A) d-excess as a function of rainfall amounts; B) d-excess by date; C) lc-excess as a function of rainfall amount; D) lc-excess by date. d-excess and lc-excess are expressed in ‰

The range of $\delta^{18}O$ and $\delta^{2}H$ in wells and springs was much narrower than in precipitation. $\delta^{18}O$ ranged from -5.92 to -4.91 ‰ and $\delta^{2}H$ ranged from -34.85 to -29.59 ‰. The small range in isotope values in groundwater samples can be explained by mixing of water from different precipitation events. Most groundwater samples fell below the LWML, showing some effect of evaporative enrichment, with lc-excess ranging from -10.23 to 2.84 (Figure 5.7). The range and median of $\delta^{18}O$ values in spring waters was 1.01 and -5.23 ‰, respectively, while the $\delta^{2}H$ range and median was 5.26 and -32.01 ‰, respectively. For wells, the range and median values of $\delta^{18}O$ were similar to springs at 1.30 and -5.23 ‰, respectively. The range of $\delta^{2}H$ was larger at 8.22 ‰ and the median value was similar to springs at -32.50 ‰. Median values of $\delta^{18}O$ and $\delta^{2}H$ were slightly enriched in the 2018 water year relative to the 2017 water year. This could be due to the effect of mixing of lower intensity precipitation events, which tend to result in more enriched stable isotope signatures. A minor seasonal signal in $\delta^{18}O$ is indicated by the more enriched values in groundwater during the dry season (a difference of 0.29 ‰), however, as the maximum measurement precision for $\delta^{18}O$ is 0.07 ‰, this seasonal difference is not considered significant (Figure 5.10). There was also a seasonal and inter-annual difference suggested in lc-excess, with more negative values in groundwaters sampled during the dry season, suggesting a higher effect of evaporation during the drier months, and in the 2016-17 water year. It was not possible to determine if there was a seasonal influence in wells as no valid dry season results for wells were obtained.

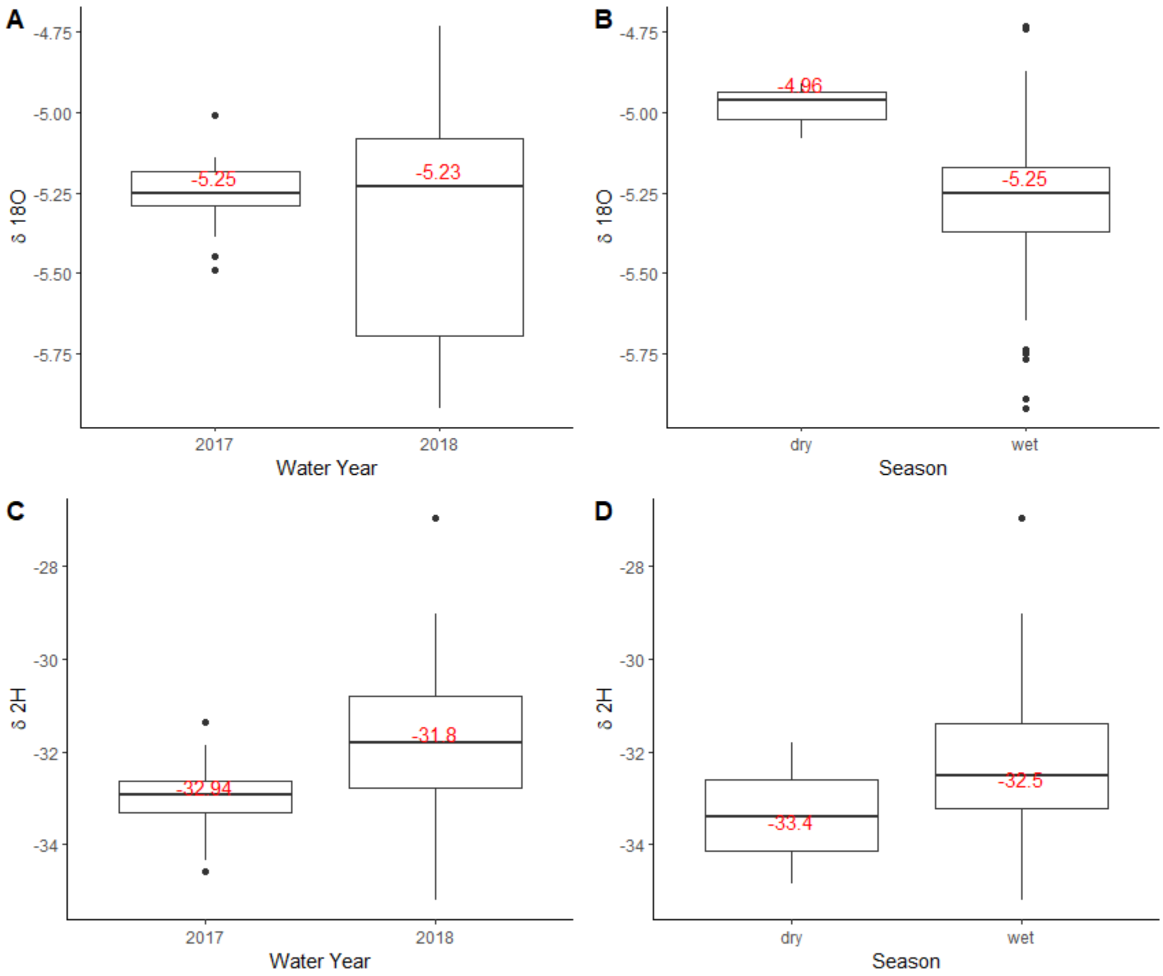


Figure 5.10. Seasonality of spring and groundwater stable isotope A) δ18O by water year; B) δ18O by season; C) δ2H by water year; and D) δ2H by season. All values are expressed in ‰. Median values are indicated by lines inside the boxplot and in red text

Overall, the mean statistics for individual wells and springs show that there is limited spatial or temporal variation in the stable isotope ratios of groundwater (Table 5.6).

Table 5.6. Mean stable isotope statistics for wells and springs.

Site	d^{18}O ‰	CV	d^{2}H ‰	CV	lc_excess
Karaha Spring	-5.22	0.04	-32.25	0.04	-4.51
Laikaterik Spring	-5.40	0.06	-31.76	0.03	-2.45
Napu Spring	-5.32	0.05	-32.98	0.04	-4.38
La Pu'a Well	-5.23	0.01	-33.13	0.01	-5.31
Napu Well	-5.34	0.06	-32.25	0.06	-3.44

CV indicates coefficient of variation for δ^{18}O and δ^{2}H ‰, respectively.

5.4. Discussion

5.4.1. Rapidly recharged groundwater sources for wells and springs

The results of major ion and stable isotope analyses indicate that the groundwater sources for the three springs and two wells in this study are rapidly recharged. There was no major distinction between water types between each of the springs and wells suggesting that their Ca-HCO_3 dominant geochemistry results from localised recharge (i.e. recharge originating from infiltration of precipitation directly above the aquifer). The very low Mg/Ca molar ratio for all groundwater and spring samples also supported a model of rapid flow to the discharge points via limestone conduits (Setiawan et al., 2020). Wet season groundwaters are relatively depleted in solutes, which suggests that recharge occurs rapidly as preferential flow through fissures in the limestone and that there is rapid flow to discharge points through conduits. While in the dry season, more concentrated solutes in groundwater represent flow to wells and springs that have accumulated solutes from limestone dissolution processes (Pratama et al., 2021). An insignificant seasonal signal is indicated in groundwater stable isotope ratios, with more enriched isotopes during the dry season, however, additional dry season sampling is required to validate this. Higher Cl^- values that were returned during early 2018 following a wetter period could indicate a memory effect from the drier 2017 period and a mixing with older matrix water (Arbel et al., 2010). This lag between periods of heavy rainfall and a dilution response on the groundwater, suggests a groundwater residence time in the order of a few months, and indicate that at least some recharge is diffuse. Repeat sampling under a range of hydrometeorological conditions would provide further insight into these seasonal dynamics. It is recognised that karst recharge is highly complex (Dar et al., 2021; Jones et al., 2000) and that data gaps in this study resulting from compromised samples preclude detailed interpretations of the hydrochemistry of the wells and springs in the study area. Nevertheless, the close grouping of water types and stable isotope signatures characterise the groundwater as responsive to local precipitation within a relatively short time period of a few months.

Of equal relevance to water management, is the fraction of precipitation that translates to recharge of groundwater. This study found that wells and springs are recharged with between 15% and 30% of rainfall and this agrees with a study of another tropical Pleistocene coral reef aquifer in Barbados (Jones et al., 2000). Recharge fractions are dependent on a number of factors including rainfall frequency and duration, landcover, soil texture and available infiltration pathways (Somaratne, 2014). It is noted from results of this study that recharge rates calculated from a CMB are highly sensitive to different input values of mean Cl^-_p and Cl^-_{gw}, illustrating the need to have both precipitation and groundwater samples that represent the breadth of variation in moisture sources and precipitation intensities. If more extreme Cl^- results were excluded from calculation of the recharge fraction and recharge rate for the Karaha Spring for example, the results would change from 0.14 to 0.28 and 129 to 247 mmy^{-1}, respectively. It should also be noted that annual rainfall in the study area is highly variable (CV = 0.29) so as this study has established that recharge corresponds with rainfall within the same water year, recharge amount would also fluctuate significantly on an annual basis.

The Indonesian Water Resources Research and Development Centre (PUSAIR) determined that in the study area, the annual coefficient of recharge, also known as the recharge fraction of rainfall, is dependent on annual rainfall. In the study area, the coefficient of recharge used as an input to water balance models was 0.01 for the coral reef terrace formation where rainfall < 1500 mmy^{-1}. In the Haharu district specifically, where the study area is located, the coefficient was 0.02. Whether inclusive or exclusive of the potentially elevated Cl^- results in our study, the estimates still suggest that the recharge fractions for the two wells and three springs in the study area are significantly higher (by a factor of ten) than the coefficients applied by PUSAIR, meaning that the groundwater supply is more reliable than indicated in the PUSAIR report (Herawan et al., 2014).

5.4.2. Stable isotopes in precipitation not linked with rainfall amounts

The results of this study supported the regional trend in the tropical savanna region of the Asia-Pacific that event-based stable isotope ratios in precipitation are not closely related to rainfall amounts

(Belgaman et al., 2016). The ‘amount effect’ has been used to explain stable isotope compositions with high ratios of light to heavy isotopes, where intense rainfall events deliver water that is depleted in the heavy isotopes (^{18}O and ^{2}H). This is due to reevaporation of falling rain, diffusive exchanges with surrounding water vapour and recycling of subcloud layer vapour (Risi et al., 2008). In Southeast Asia, however, stable isotope compositions of precipitation are generally more closely correlated with moisture sources and transport patterns and not the amount of local precipitation events (Aggarwal et al., 2004). The ‘amount effect’ is generally not evident at short time scales, as the atmospheric processes that determine the stable isotope ratios in precipitation may have longer time scales, or take effect at large spatial scales (Kurita, 2013; Zwart et al., 2018). Munksgaard et al. (2020) also found that in the tropical region of Australia there was limited correlation between isotope signatures of daily precipitation and rainfall amounts, yet noted that the relationship may be identified on a monthly scale. In our study area there is little to no precipitation outside the wet season, so moisture sources are likely to be unaffected by continental loss and more closely reflect South China sea sources (Aldrian & Dwi Susanto, 2003). It was not possible to examine whether a relationship exists between monthly rainfall amounts and accumulated monthly stable isotope samples, due to the small number of viable accumulated monthly samples that were analysed ($n = 4$).

Precipitation from spatially and temporally variable moisture sources is depleted in heavy isotopes while oceanic moisture sources with limited continental loss are relatively enriched (Ingraham, 1998). As the study area is located close to the ocean, the result of slightly enriched stable isotope ratios in precipitation relative to the GMWL is expected. Precipitation events further inland are subject to greater kinetic fractionation or the ‘continental effect’ and are more depleted the further the water is from its oceanic source (Ingraham, 1998). The LWML obtained from results of this study is comparable to the PWLSR results from Darwin, Australia (Munksgaard et al., 2019), Denpasar, Indonesia (Ardana et al., 2023) and Raimanuk, Indonesia (Manta et al., 2022).

A large range of $\delta^{18}O$ and $\delta^{2}H$ values in precipitation were reported in this study, and while the compromised samples that were collected in 2019-2020 were excluded from the calculation of the LMWL due to issues with sample handling, it is recognised that extremes of both $\delta^{18}O$ and $\delta^{2}H$ in precipitation can be representative of a unique moisture source, or climate or synoptic event (Hollins et al., 2018). The narrow range of stable isotope ratios in groundwater is explained by groundwater being recharged predominantly by larger rainfall events with more depleted $\delta^{18}O$ signatures (Clark, 2015).

The study period was characterised by three out of four drier than average years. A clearer signal of the drier than average 2016–2017 water year followed by the wetter than average 2017–2018 might have been expected in the concentrations of solutes and in the stable isotope ratios (Pratama et al., 2021), however, the limitations of insufficient sample numbers and temporal resolution prevented any robust conclusions on the seasonal characteristics of recharge to groundwater in the study area. Monthly sampling of groundwater and precipitation that spans at least three water years is recommended to capture the differences in hydrochemistry and stable isotope signatures from varying precipitation events. Collection of bulk monthly precipitation samples are recommended to validate the PWLSR as the larger and more intense precipitation events have a bigger influence on the coefficients of the LWML (Munksgaard et al., 2020).

5.5. Conclusion and management implications

Wells and springs are in the Larawali catchment of East Sumba, Indonesia are responsive to local precipitation events within a short time frame, most likely as preferential flow through conduits in the karst limestone matrix. The fraction of rainfall that is partitioned to groundwater recharge is estimated to be between 15% and 30% in the study area and recharge would fluctuate significantly on an annual basis relative to rainfall amounts. Moisture sources for precipitation in East Sumba are common to previously studied sites in Darwin (Australia) to the East and Denpasar (Bali, Indonesia) to the west. This catchment-scale study contributes insights into recharge processes for important community groundwater supplies within a karst tropical savanna regional context. The key implications are that land management within close proximity to wells and springs may have an influence on the fraction of rainfall that flows through preferential pathways in the karst matrix and ultimately on the yields that are discharged. As there is no evidence of regional input to groundwater, or groundwater with a long residence time in the study area, local landcover changes that affect rainfall partitioning at the land surface and in the soil zone are most relevant to endeavours at sustaining groundwater supplies.

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Chapter 6. Discussion and Conclusions: The Influence of Landcover on Groundwater Recharge in Tropical Karst Savanna Landscapes

6.1. Introduction

The objective of this study is to support land use planning by increasing the understanding of landcover as a control on spring water availability. The thesis met this objective by addressing the following research questions:

1) What are the key environmental controls on groundwater recharge in tropical karst savannas?
2) What is the influence of catchment revegetation on groundwater recharge?

To address these two research questions, a study area was selected in the karst tropical savanna region of East Sumba, Indonesia and an interdisciplinary approach was applied comprising:

1) a remote sensing study at the district and catchment scale of the response of vegetation to available moisture, including anomalous rainfall periods; and the influence of groundwater availability on vegetation productivity (Chapter 3);
2) a catchment scale study of the influence of landcover and soil characteristics on infiltration rates, which included a spatial analysis of groundwater recharge potential and an evaluation of landscape leakiness as a function of landcover (Chapter 4);
3) a catchment scale analysis of groundwater recharge rates and recharge pathways using stable isotope hydrology and hydrogeochemistry (Chapter 5).

There is a need to safeguard community groundwater supplies in karst tropical savanna landscapes, such as in the Larawali catchment of East Sumba, due to the absence of surface water during long dry seasons. It is particularly important to sustainably manage groundwater resources in the context of a changing climate with predicted shorter, more intense wet seasons and longer periods without rainfall (Brown et al., 2013), and it is critical that the controls on groundwater recharge of community groundwater sources are understood. In Indonesia, as with elsewhere in the tropics, woody revegetation is a key focus of land rehabilitation from an institutional perspective and revegetation targets are often linked to hydrologic service objectives (Ponette-González et al., 2014). This study documents the moisture inputs, infiltration mechanisms and recharge pathways for the shallow groundwater system in the Larawali catchment (Chapters 4 and 5) and examines the response of woody vegetation to available moisture (Chapter 3) as insights into the potential influence of woody vegetation on the hydrological cycle.

6.2. Key findings

6.2.1. Epikarst storage and groundwater are a primary source of water for woody vegetation in the Larawali catchment

The analysis of the response of NDVI to changes in moisture availability in Chapter 3, together with hydrogeochemical results presented in Chapter 5, demonstrated that shallow groundwater located in the upper, highly weathered layers of the karst formation (i.e., the epikarst) supports perennial primary production in woody vegetation. This conclusion can be made as woody vegetation vigour, measured as NDVI, was not well correlated with rainfall in vegetation patches that were in close proximity to spring vents, or in locations where the depth to groundwater was known to be 6 m or less. Woody vegetation vigour was also maintained at these sites during very dry periods, suggesting that tree roots had access to a more perennial source of water.

By examining monthly NDVI and rainfall time series, this study also demonstrated earlier peaks in vegetation greenness at patches with shallow groundwater access, as well as longer growing seasons, than in sites with deep groundwater only, illustrating the difference in groundwater and rainfall dependency of these sites. It was determined through an analysis of root zone soil moisture and NDVI by landcover type that woody vegetation responded to the presence of root zone soil moisture immediately, or with a lag of up to one month, while grass-dominated vegetation patches had a much weaker response to moisture at that depth.

While this thesis did not include the monitoring of water table depth, the approach of examining NDVI trends at vegetation patches that have a known mean depth to groundwater and relating changes in NDVI to rainfall anomalies strongly suggests groundwater usage during dry periods. Using similar methods of Landsat NDVI time series analyses within a 20 m buffer around wells and accumulated water year rainfall, Aguilar et al. (2012) reported that NDVI was a reliable indicator of groundwater availability in a temperate island location, noting a high correlation between NDVI and groundwater availability during dry periods. Aguilar et al. (2012) employed water table depth data in examining the availability of groundwater to vegetation. The study found that NDVI of the dominant woody species was strongly correlated with availability of water in a freshwater lens during dry periods. Also including water table data in NDVI time series analyses, Lv et al. (2013) related NDVI peaks to water table depth in a desert location of China, finding that NDVI was correlated with the presence of groundwater to a depth of 5 to 10 m. In California, USA, Rohde et al. (2024) identified a negative correlation between depth to groundwater and NDVI by computing the Z-score for time series of dry season NDVI between 1985 and 2022. The Californian study identified that tree rooting depth can be used as a proxy for depth to groundwater, noting that phreatophytes generally distribute roots in the capillary fringe, which is above the water table, so depth to groundwater is often within ~1 m of maximum rooting depth. Supported by these findings in related studies of correlations between NDVI and groundwater availability, and the analysis of NDVI and moisture time series in this study of the Larawali catchment, it is feasible to propose that deep rooted woody vegetation within the catchment likely reduces the local groundwater store, particularly during dry periods.

The original research design of this study included an analysis of sources of xylem water in woody vegetation, however, as outlined in the COVID-19 Impact Statement (Section 1.7), while all the sampling was completed for this component of Chapter 5, the samples could not be analysed due to constraints relating to sample storage and transport. Consequently, this study did not contribute direct evidence of the water sources of trees in the Larawali catchment. It did, however, identify that woody vegetation remains productive during anomalously dry periods in sites with shallow soils, and therefore demonstrates a degree of dependence on groundwater or epikarst storage. This inference of dependence on a deeper moisture source is a valuable contribution to understanding the ecohydrology of a karst tropical savanna area. The validity of developing assumptions about vegetation water sources from NDVI – rainfall time series analyses has been reviewed in brief by Eamus et al. (2015), who argued that the effect of the mixed phenologies of trees and grasses (i.e., differences in timing of green-up) within a pixel may inhibit the ability to distinguish groundwater dependence. It is argued here that the use of the 30-m resolution Landsat 7, as well as a field calibrated classification of woody and non-woody dominated pixels enabled a greater confidence in any assumptions made regarding groundwater dependence.

In a karst savanna environment, the source of transpiration water could be one or more of shallow soil moisture, root zone soil moisture, epikarst storage or water in the saturated zone (Figure 6.1). Use of groundwater stored in soil-filled karst fissures by deep rooted woody savanna vegetation is a documented phenomenon that has been studied by examining stem water isotope ratios (Schwinning, 2008, 2010). Carrière et al. (2020) determined through isotope tracing and leaf water potential analyses in a temperate karst location in France that during periods of water stress, woody vegetation in karst environments relied on relatively higher proportions of deep vadose zone water. In a karst tropical savanna agroforestry area of Mexico, Querejeta et al. (2007) showed that trees accessed water from bedrock storage in the upper 2–3 m of bedrock during the dry season and did not access groundwater. The findings of deeper vadose zone water used by Carrière et al. (2020) was explained by a combination of site and species variables, while Querejeta et al. (2007) attributed the absence of groundwater in xylem water in their study to a limestone barrier impenetrable to tree roots. Rooting depth in the epikarst is an important variable that influences the amount of epikarst storage and can impede drainage to deeper groundwater (Schwinning, 2010). In this study, it is proposed that during the wet season the primary water source for woody vegetation is epikarst storage (between approximately 0.5 and 2 m below the surface), while during the mid to late dry season, water is sourced from the saturated zone since epikarst storage is subject to evaporation and is diminished over the course of the dry season (Ding et al., 2018).

The rooting depth of vegetation is known to be a key determinant of its water use potential (Andréassian, 2004), yet it is a difficult variable to predict (Schwinning, 2010). Jochen Schenk (2008) noted that there is little known about rooting systems of plants on shallow soils over bedrock, however, a literature review of rooting depths in water limited environments from different areas of the globe established that the mean rooting depth of woody vegetation over bedrock was 7.9 m (Jochen Schenk & Jackson, 2002). There is a growing body of evidence of the importance of bedrock moisture storage as a source of water for woody vegetation and a review of field studies by McCormick et al. (2021) established that it is a key resource that can be drawn down during extended dry periods. In this study of groundwater recharge and landcover in the Larawali catchment, it is assumed that the use of epikarst storage and shallow groundwater (at ~6 m depth) by woody vegetation reduces the amount of deep drainage to the saturated zone, particularly in the dry season (Figure 6.1).

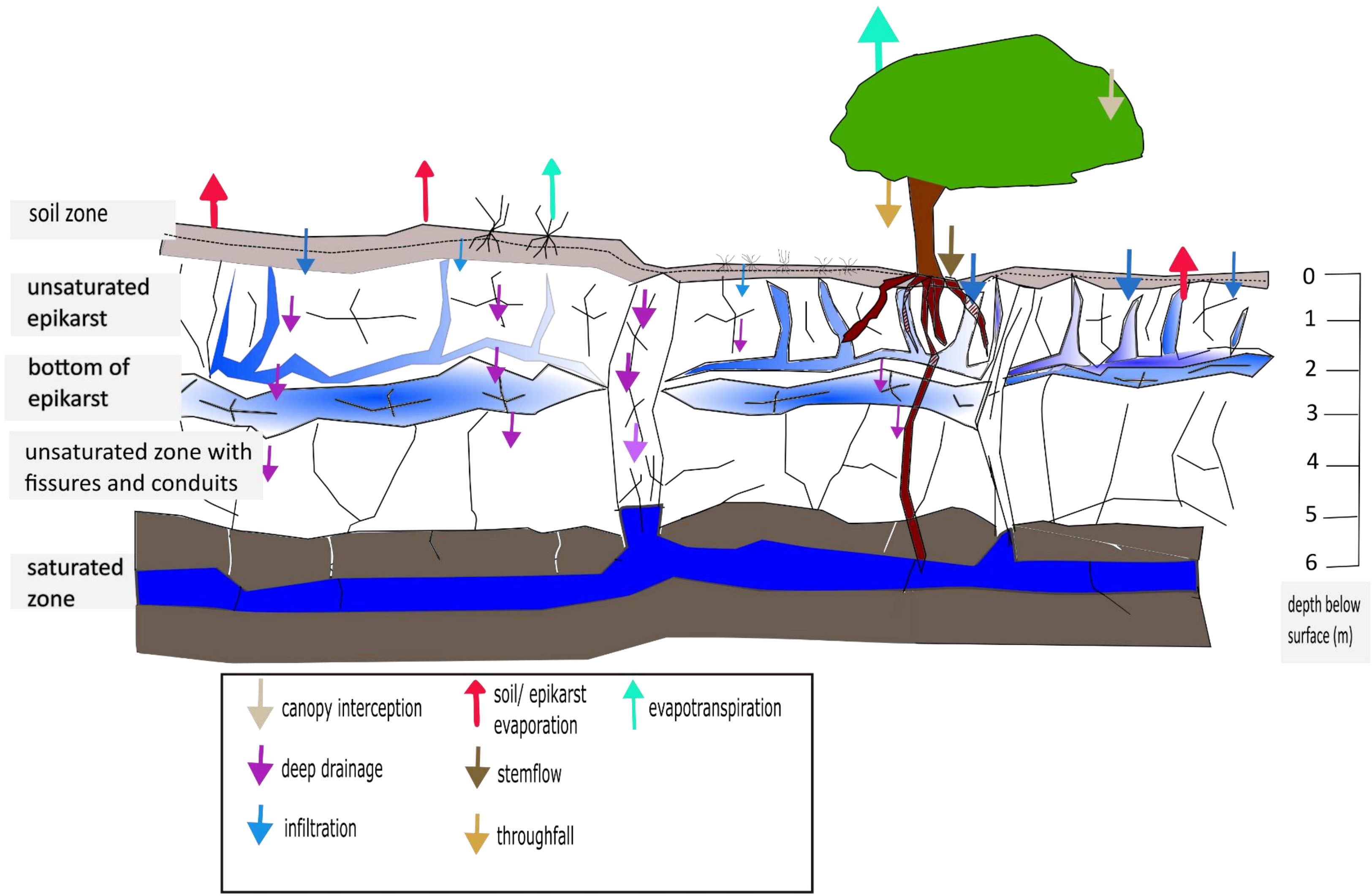

Figure 6.1. Conceptual model of hydrological fluxes in the study area representative of dry season conditions . Adapted from Dörfliger et al. (1999).

A review by Geekiyanage et al. (2019) summarised the woody vegetation water dependencies in karst environments from 15 studies in China, the USA, and Australia. The review determined that woody vegetation can be dependent on either soil moisture, epikarst storage, groundwater or fog, and that trees may use a drought deciduousness strategy. A recent study in a karstic area in southwest China using stable isotopes and sap flow measurements determined that the main source of water for the dominant tree species during the wet season was soil moisture, while during the dry season, transpiration rates were reduced and water was sourced from groundwater (Wu et al., 2021). Again in southwest China, Ding et al. (2018) identified a large range in the proportions of groundwater use by eight different woody plant species on dolomite outcrops, finding that it was difficult to draw conclusions on the difference between evergreen and deciduous plant groundwater use. Ding et al. (2018) noted that groundwater use by woody vegetation varies according to site and individual plants due to the high heterogeneity of the karst matrix. The woody vegetation species in the Larawali catchment are a mixture of evergreen and deciduous species (Sections 1.6.2, 3.4.2 & 4.2.1.1) and the species have varying leaf morphologies and rooting depths. The NDVI analysis included in this study demonstrated that woody vegetation patches continue to be productive during dry periods. It is therefore possible to conclude that woody vegetation employs similar water use strategies as has been found in previous karst studies, such as dimorphic root structures to access both shallow and deeper moisture sources (Ding et al., 2018), and will thus have a negative influence on epikarst storage and deeper groundwater recharge.

6.2.2. Groundwater recharge in the Larawali catchment is influenced by climate, lithology and landcover

With the knowledge that epikarst storage or groundwater storage are key water sources for woody vegetation in the Larawali catchment, it is important to then summarise what this study found in relation to the controls on inputs to the epikarst and groundwater storages. The role of ENSO on rainfall patterns in the tropical savanna region of Indonesia was described in Chapter 3. El Niño events are characterised by short, intense wet seasons, while La Niña events are associated with higher overall rainfall and greater proportions of dry season rainfall. Thus, ENSO patterns are a key determinant of available moisture for groundwater recharge (Arjasakusuma et al., 2018; Brown et al., 2013; Kurniadi et al., 2021; Supari et al., 2018). The results presented in Chapter 5 established that in the Larawali catchment, between 15% to 30% of rainfall is partitioned to groundwater recharge. As annual rainfall can vary from as little as 540 mm to as much as 1,400 mm (BMKG, 2020), annual groundwater recharge could vary from 77 to 420 mm. This high variability in recharge amounts has implications on the reliability of water supply for domestic and productive uses for communities in the Larawali catchment, with depth to groundwater likely to increase during extended dry periods, leading to a reduction in yields from springs and wells.

This study also showed that the dug wells and springs used for community water supply in the Larawali catchment are recharged within a few months following periods of rainfall, and therefore short-term changes to the ecohydrological system will influence the availability of groundwater at these five sources of extraction by communities of Larawali. The short transit times in the vadose and saturated zones identified from hydrogeochemical analyses in Chapter 5 suggested that there is limited storage in the epikarst or deeper conduits supplying the springs and wells. There is the potential, therefore, for a large-scale increase in the existing woody vegetation density to result in a reduction in spring discharge through increased groundwater use for transpiration.

The results of infiltration measurements presented in Chapter 4 demonstrated that both grass cover and woody vegetation cover enhance infiltration into the shallow soil layer though high macroporosity as a result of root channels. Infiltration rates beneath woody vegetation canopies were found to be significantly higher that grass canopies under ponded conditions, which represented early dry season conditions. However, under both vegetation types the infiltration rates were higher than maximum recorded rainfall intensity, suggesting that the vegetation structural types did not provide a critical control on infiltration. During the early wet season, there is little to no potential for runoff to occur on level to gently sloping sites within the predicted groundwater recharge zones, indicating that the majority of rainfall is partitioned initially to infiltration. Infiltration rates and hydraulic conductivity are governed by the high level of macroporosity during the early dry season. Macropores in the Larawali catchment are a combination of biopores, which are caused by root channels from grass, tree and shrub roots; and from desiccation cracks, which occur in the vertic inceptisols that predominate the catchment.

Results of linear shrinkage tests presented in Chapter 4 demonstrated a large volume change in soils with changes in soil moisture, indicating a relatively high proportion of clay minerals in the soil, although this conflicted with the particle size distribution results. As noted earlier, it is suggested that repetition of particle size distribution analyses with an alternative method would return results with higher percentages of clay fractions, as recommended by Zimmermann and Horn (2020). The shrink-swell properties of soils in the Larawali catchment cause rapid infiltration preferentially through desiccation cracks on commencement of the wet season. As the wet season progresses, soil macroporosity and hydraulic conductivity are much reduced as cracks close, and infiltration rates are therefore also reduced (Seghieri, 1995). It is when desiccation cracks have closed due to soil saturation that the biopores created by root channels are likely to become the primary preferential flow pathways and have an important control on rainfall partitioning and the infiltration flux (Eldridge & Freudenberger, 2005). Figure 6.2 depicts a conceptual diagram of the expected differences between early wet season and mid to late wet season. As the primary porosity of the fine-textured soils is low, the key pathways for infiltration during the mid to late wet season are via macropores from root channels. Repeated infiltration measurements are required for an increased understanding of the infiltration rates and mechanisms in the Larawali catchment during the mid to late wet season. In order to monitor the change in soil volume and aperture of desiccation cracks, monthly infiltration and soil moisture measurements during the wet season would be ideal.

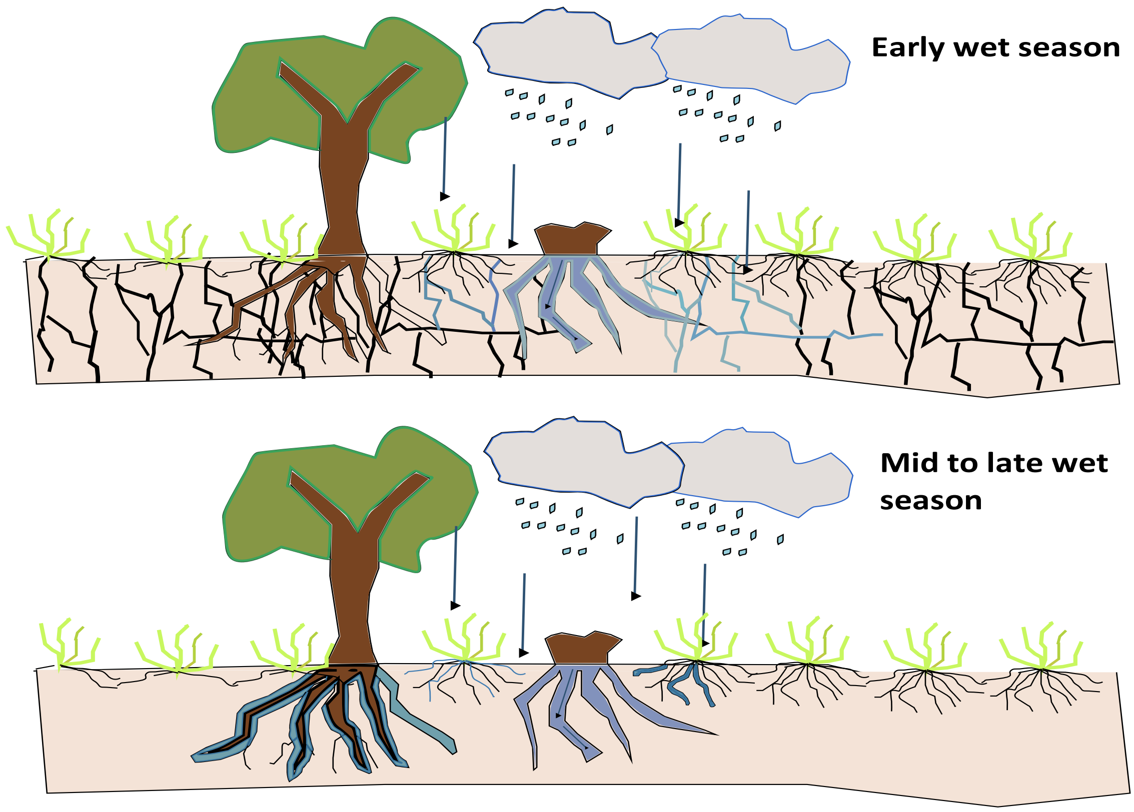

Figure 6.2. Conceptual diagram of the temporal difference in infiltration preferential pathways.

In the early wet season desiccation cracks (represented as thick black lines) dominate the soil macroporosity. In the mid to late wet season when cracks have closed, the main pathways for rapid infiltration are through macroporosity from root channels.

6.2.3. The potential influence of rooting depth and canopy architecture on groundwater recharge in the Larawali catchment

It was not within the scope of this study to measure the rooting depth or characterise canopy architecture of landcover within the study area, although these two vegetation characteristics have an important influence on the fluxes of transpiration and interception, respectively, as noted in Section 2.2 and as identified by authors such as Andréassian (2004), Schwinning (2010) and Chandler (2006). Studies within Indonesia have documented the distributions and diversities of tree species in groundwater discharge areas and discussed the potential influence of tree root systems on groundwater fluxes (e.g. Siswo et al., 2019). Noting the common occurrence of tree roots in fractured rock, Siswo et al. (2019) suggested that groundwater recharge may be enhanced by tree roots enlarging rock fractures and cited the possibility of hydraulic lift by trees that results in increased water storage and spring discharge. However, Siswo et al. (2019) did not study any mechanisms or patterns of water use, but instead focussed on the ecology of the phreatophytic vegetation. Nugroho et al. (2021) also described species occurring in a spring catchment area and made recommendations for catchment rehabilitation that were focussed on hydrologic objectives, discussing the differences in water retention capacity and infiltration potential resulting from vegetation cover change. They suggested that particular tree species, especially *Ficus* contribute to water 'storage' in the catchment, however, did not discuss the relevant hydrologic fluxes including infiltration, evapotranspiration, deep drainage and groundwater recharge. Both Siswo et al. (2019) and Nugroho et al. (2021) are examples of available literature that relies on descriptive ecological studies alone and does not examine the hydrologic exchanges between vegetation, groundwater and the atmosphere.

In order to predict how the evapotranspiration flux may have changed as a result of increased vegetation cover during this period, we can draw on insights from related ecohydrological studies. The Edwards Plateau savanna is a highly studied carbonate aquifer in Texas, USA, which has experienced increasing encroachment by Ashe juniper trees over the last century. Through the application of stable isotope hydrology, Schwinning (2008) established that juniper roots on the Edwards Plateau sourced water from the epikarst, thereby resulting in a level of reduced recharge to aquifer storage. However, Schwinning (2008) acknowledged that further investigation of recharge mechanisms is required in order to determine the quantum of this effect. Based on ecohydrological relationships from the same study area, Wilcox et al. (2006) developed a classification of hydrological sensitivity to woody plant cover, noting that sites with shallow soils, shallow groundwater and permeable geology will be most affected by changes in woody cover. The Larawali catchment has two of the characteristics of a site that should have higher hydrological sensitivity to changes in woody vegetation cover according to the classification of Wilcox et al. (2006): shallow cracking clay soils and fractured limestone geology. In areas of the Larawali catchment where soil water drainage occurs rapidly through cracks in soils, it is assumed that increases in water storage in soil-filled fissures of the epikarst is also rapid. As this water is beyond the rooting depth of most herbaceous plants, only woody plants that can affect the flux within the epikarst storage. It has been observed, however, on the Edwards Plateau that if woody plants are removed, an initial pulse of increased deep drainage as a result of decreased epikarst water use leads to more groundwater recharge in the short-term, however, the groundwater use potential of colonising herbaceous vegetation in the longer term may return the system to similar hydrological conditions (Cardella Dammeyer et al., 2016). Cardella Dammeyer et al. (2016) also argued that the structure of the epikarst and karst matrix are key determinants of deep drainage and groundwater recharge irrespective of vegetation cover and that geology coupled with precipitation characteristics may be the major control on groundwater availability.

The importance of vegetation cover in controlling groundwater recharge is dependent on a number of environmental variables. By measuring soil water drainage and sap flow in a tropical savanna area of Burkina Faso, Ilstedt et al. (2016) established that intermediate tree cover provides an effect of increased soil hydraulic conductivity and subsequent increased infiltration and groundwater recharge. They determined that accumulated drainage was faster and higher in areas close to trees than those further away from trees and predicted that groundwater recharge would be over four times higher in a scenario with 10 trees ha^{-1} relative to no trees. Importantly, however, Ilstedt et al. (2016) noted that where soils were too porous for overland flow to occur, as was reported during early wet season conditions in the Larawali catchment, the effect of increased tree cover would be small or negative. In this case, any change in groundwater recharge would be determined by the difference between the increase in vegetation water use and decrease in soil evaporation.

The partitioning of rainfall to components of the water balance is notably affected by landcover through changes to infiltration and transpiration and can also shift considerably due to changes in interception. For example, Honda and Durigan (2016) reported that in southwestern Brazil approximately 97% of rainfall reaches the ground in an open savanna, while in a closed forest this was reduced to 80%. The amount of rainfall that is intercepted by woody vegetation canopies is proportional to tree basal area, as reported by Honda and Durigan (2016) and Skhosana et al. (2023). Both studies found that the woody plant encroachment of open savanna areas increased the partitioning of rainfall to interception, however, this effect was reduced in the event of heavy rainfall. During heavy rainfall a greater proportion of rainfall is partitioned to stemflow and less is lost as interception. Skhosana et al. (2023) found interception loss was approximately halved during heavier rainfall events (>20 mm), relative to small rainfall events (<10 mm). Plant functional traits including leaf type and number of stems also influences rainfall partitioning, with fine leaved woody vegetation capable of intercepting a greater proportion of rainfall than broad-leaved types and stemflow increasing in proportion to the number of stems or tree basal area (Skhosana et al., 2023). The influence of plant functional traits on rainfall partitioning in the Larawali catchment is discussed below (Section 6.2.4).

6.2.4. The potential influence of different woody vegetation species on groundwater recharge in the Larawali catchment

In the Larawali catchment, the choice of woody vegetation selected for tree planting or for FMNR has primarily focussed on the income earning potential of the species. Many species, such as Teak and Mahogany, are broad leaved evergreen trees that are grown to a medium size before being harvested (Reku Raya, 2020). Under these conditions, the potential for evaporation losses as a result of canopy interception would be less than in the fine leaved woody encroachment scenarios examined by Honda and Durigan (2016) and Skhosana et al. (2023). Other woody vegetation species that are commonly selected for revegetation programs or managed through FMNR in NTT are the multi-purpose species: *Leucaena leucocephala, Gliricidia sepium* and *Sesbania grandiflora.* All three woody plants are deep-rooted leguminous shrubs or trees with fine leaved canopies. These species are favoured by farmers and graziers in NTT for their ability to survive in relatively dry conditions (Koehuan, 2022), increase soil nitrogen, enhance soil infiltration and provide a source of forage for stock (Mulyoutami et al., 2018). An additional preferred woody species for revegetation in NTT is *Lannea coromandelica*, which is a stem succulent species.[7] While *L. coromandelica* is a popular species for its application as a living fence in NTT, it is locally known to have high water demands (Mulyoutami et al., 2018). In Western Thailand, a study of leaf phenology (Kaewthongrach et al., 2019) established that *L. coromandelica* is drought deciduous and sheds its leaves earlier than other tropical dry forest species. As a stem succulent, *L. coromandelica* has low wood density and can store large amounts of water to sustain transpiration during dry periods (Kaewthongrach et al., 2019). The functional traits of these woody species, such as canopy and root architectures, and their influence on hydrology requires further consideration. There is a need to continue bridging the gap between knowledge from the plant physiology discipline that examines water use strategies such as these and the fields of hydrology and karst hydrogeology to better understand the potential influence of woody vegetation on groundwater recharge. This gap in research approaches when understanding exchanges between biota and groundwater systems was previously identified by Cantonati et al. (2020), with respect to all groundwater dependent ecosystems. Here, it is argued that there is a critical gap in karst environments specifically where interdisciplinary research approaches that expand on methods used in this study can contribute to integrated land and water management planning processes.

Differences in the interception potential and water use strategies of woody vegetation may have an important influence on groundwater recharge where the density of woody vegetation is increased. In addition, it is important to note the role of woody vegetation cover in providing shade, thereby reducing soil evaporation. In a study of groundwater use by two tree species on a karst aquifer in the Mediterranean climate of southern Australia, Swaffer (2014) it was established that soil evaporation was the biggest water loss from the system, with soil evaporation highest at bare soil sites followed by under *Allocasuarina verticillata* and lowest under *Eucalyptus diversifolia.* The lower soil evaporation rates under the *E. diversifolia* are explained by its more closed canopy and provision of shade and

[7] Stem succulent plants store water and conducts photosynthesis in their stems.

shelter from the wind relative to the more open *A. verticillata* (Swaffer et al., 2014). While Swaffer et al. (2014) found that there was a difference in transpirations rates between the two individual tree species, the evapotranspiration rates under plots of *E. diversifolia* and *A. verticiallata* were similar, which was attributed to an ecological adaptation to the drier conditions.

The adaptations of vegetation to drought conditions have been observed in seasonally dry environments, where the 'hydraulic architecture' is determined by minimum moisture availability (Eamus et al., 2000). It is the leaf area and basal area of woody vegetation along with root characteristics that determine water use potential. These woody vegetation characteristics also provide shelter from solar radiation and wind, which reduce soil evaporation. It is important to understand the water use strategies and evapotranspiration potential of existing woody vegetation species in the Larawali catchment, as well as those proposed for revegetation and FMNR projects as related studies suggest the presence, type and density of woody vegetation in the catchment will influence groundwater recharge. There is a wealth of local knowledge in NTT of the seasonal responses of vegetation to available moisture as well as water relations between competing plant species (Klaas, 2008; Lusiana et al., 2008; Mulyoutami et al., 2018; Mulyoutami et al., 2016). In planning catchment rehabilitation or regreening activities in karst tropical savanna areas, such as the Larawali catchment, local knowledge of ecohydrology should be considered in combination with insights presented in this study relating to the controls on groundwater recharge. In the future, interdisciplinary research approaches that triangulate local knowledge with contemporary ecohydrological knowledge are needed to obtain information that enables effective and sustainable catchment management.

6.2.5. The potential influence of catchment revegetation on groundwater recharge in tropical karst savannas such as the Larawali catchment

This study has determined that during between 2015 and 2022 the annual average proportion of rainfall that was partitioned to runoff should have decreased. This was determined by calculation of the catchment Leakiness Index (Chapter 4), with the decrease in runoff attributed to an overall increase in catchment vegetation cover. It is difficult to directly attribute the increase in vegetation cover entirely to tree planting and FMNR projects due to the absence of mapping and monitoring data for these sites. However, it was possible to relate significant interannual NDVI trends at two sites at the patch scale to woody conservation and restoration efforts (Chapter 3). The health and productivity of restored vegetation sites can reliably be monitored at a patch scale through the use of remotely sensed NDVI, which is achievable with freely available satellite imagery that can be processed using cloud computing and analysed with relatively simple statistical techniques. With increasingly available higher resolution satellite imagery, such as longer time series of Sentinel-1 and Sentinel-2 imagery, the accuracy with which changes in woody vegetation cover can be monitored will also improve (Zhang et al., 2019). The ability to monitor changes in woody vegetation cover and the relationship with available moisture is particularly important in the context of large-scale land-use change.

This study coincided with a period of transitional land use change in the Larawali catchment. While the study was focused on the influence of regreening projects on catchment hydrology, by coincidence, the level of agricultural activity in the catchment was lower than it historically had been, due to alternative employment opportunities in the adjacent Kadahang catchment. A commercial irrigated plantation of *Ricinus communis* (castor bean) was established in 2015 and became the primary employer of working age members of Napu village (Hamba Pulu, 2016). Because of this, livestock grazing and productive agroforestry activities in the Larawali catchment were largely abandoned. The implication of this change in land use was that fractional vegetation cover was relatively high (over 82% in 2021; Section 4.8.1), with limited bare soil. From the perspective of catchment function, this high level of cover of both herbaceous and woody vegetation meant that there is limited potential for rainfall to be lost from the catchment as runoff, and this is represented in the decreasing trend in Leakiness Index. While woody and herbaceous vegetation are integral to reducing runoff, it is also important to consider the potential evapotranspiration water losses from the catchment resulting from additional woody vegetation.

The potential influence of woody vegetation on groundwater recharge in the Larawali catchment was inferred in this study by examining the input controls to groundwater recharge, as the water balance components including evapotranspiration were not quantified. This study primarily focused on the influence of vegetation on the infiltration flux and the sources of transpiration water, as extrapolated from NDVI-moisture relationships.

It is clear from the results presented in this study and insights drawn from related studies (such as Eamus et al., 2000; Eamus et al., 2015; Querejeta et al., 2007) that land cover does influence the hydrology of karst tropical savanna environments, especially during the dry season and early wet season. It cannot be concluded here that the influence of woody vegetation on groundwater recharge is distinct from that of herbaceous vegetation, rather, it is proposed that vegetation cover in general is important for maintenance of soil structure, including soil macropores that promote rapid infiltration. In the future in NTT, it will be important to balance the demands of agricultural intensification and landscape function in order to maximise the partitioning of rainfall to infiltration, deep drainage and groundwater recharge. The hydrologic influence of practices such as soil scraping and removal of mixed tree-grass savanna vegetation for intensive agricultural developments should be carefully monitored and there is potential for the research approaches presented here to contribute to a monitoring strategy.

6.2.6. Limitations and recommendations for further research

This study used an ecohydrological perspective to investigate the influence of landcover on groundwater recharge in the study area. This was an applicable approach to the research questions, given the challenges of undertaking research in the Sumba context, for instance, the absence of existing hydrogeological data, the remoteness from laboratory facilities and the need for non-invasive investigation methods that had minimal disturbance to community water supplies. It is noted that the research approach did not include investigations of sub-surface processes, with the exception of hydrogeochemistry, which provided indications of the rate and scale of recharge processes. To further characterise the limestone groundwater system in the study area, additional studies of recharge and discharge processes are needed and it is recommended that the following methods would be appropriate to the biophysical and socio-cultural contexts:

6.2.6.1. Repeated analyses of NDVI and soil moisture relationships

This study used available soil moisture time series data from 2015 to 2018. To examine the relationship between soil moisture and woody vegetation productivity under different rainfall regimes, repeated analyses of NDVI and soil moisture relationships with longer time series of surface and root-zone soil moisture data would provide a more robust understanding of responses to available soil moisture.

6.2.6.2. Repeated studies of hydrogen and oxygen isotopes

For a detailed understanding of the response of springs to precipitation events, high frequency sampling of hydrogen and oxygen isotopes during the wet season would provide the best information. In combination with automatic data loggers that record physicochemical parameters, the recharge and discharge mechanisms of the shallow Larawali groundwater system could be better understood. Applicable research methods are described in Stroj et al. (2020). The use of the monthly sampling of springs and wells for the radioisotope tritium during the wet and dry seasons would also provide additional insights into the residence time of groundwater in the system (Allison & Hughes, 1978).

6.2.6.3. Repeated studies of major ions in the wet and dry seasons

In a small island field environment, such as the Haharu district of East Sumba, the challenge of transporting equipment to and samples from the field remains a challenge and therefore high frequency sampling is difficult, however, by strengthening research partnerships between local institutions and established research institutions elsewhere in Indonesia, there is potential to improve hydrogeochemical capability in the region. There are a number of facilities in Indonesia with the capacity to analyse for major ions and isotopes of hydrogen and oxygen in water. High frequency sampling and analyses for major ions as well as isotopes will provide greater confidence of the nature of conduit transport and groundwater residence time in the Larawali catchment.

6.2.6.4. Stable isotope studies in stem water

Due to the logistical and regulatory challenges associated with exporting water, soil and plant material from Indonesia, analyses of the sources of tree water were not completed in this study. This is a critical gap in understanding the ecohydrology of the karst tropical savanna environment and it is therefore a priority for future research. At the time of this research, a facility to extract water from plant stems and soil water within Indonesia for stable isotope studies could not be identified, however, it is proposed that through partnerships between research institutions in Australia such as Charles Darwin University and the Australian National University; and Indonesian institutions such as the Indonesian Research Organisation for Nuclear Energy (BATAN), a methodological approach to analyses of tree water sources within Indonesia could be established. It is argued that this would provide a key contribution to the demand for knowledge of the influence of woody vegetation on catchment hydrology.

6.2.6.5. Measurement of field capacity of soils

Groundwater recharge takes place once the field capacity of soils is exceeded (i.e. the threshold at which water in larger soil pores has been drained away by the force of gravity of soils). It is therefore important to measure the field capacity of soils in the study area to determine the threshold for deep drainage to groundwater. Field and modelling approaches to understanding this component of karst groundwater recharge have been described by Hartmann et al. (2021).

6.2.6.6. Electrical resistivity surveys

In this study, mapping was produced of locations of highest groundwater recharge potential within the Larawali catchment. Through the use of hydrogeochemistry. it was determined that recharge occurs as a relatively rapid diffuse process that occurs over a period of months through the limestone matrix and that water is transmitted to discharge points via limestone conduits (Section 5.4). In order to gain additional insight into the geological structures governing recharge and discharge processes, the use of electrical resistivity studies in the assumed recharge zones could be explored. Electrical resistivity studies are a widely accepted approach to obtaining information on geological structures and the presence of aquifers. Electrical resistivity surveys were completed elsewhere in Sumba as part of the PUSAIR study into the potential of water resources in Sumba (Herawan et al., 2014). One survey was conducted on the Kaliangga formation in west Sumba to identify groundwater close to the city of Tambolaka, finding groundwater at a depth of approximately 30 m. The value of conducting electrical resistivity surveys in the Larawali catchment is that it is a non-invasive technique that can identify the characteristics of limestone, for instance, whether it is compact limestone, which has high resistivity; saturated karstified limestone, with lower resistivity; or dry karstified limestone, which has intermediate resistivity (Ford & Williams, 2007). Obtaining information about the nature of the limestone in the Larawali catchment would contribute to the understanding of recharge zones and recharge pathways, which would be a valuable contribution to land use planning as well as potentially provide opportunities to construct additional wells where groundwater is identified.

6.3. Conclusions

This study contributes to a demand for an increase in the knowledge of catchment hydrology in karst tropical savannas and the controls on groundwater recharge; finding that landcover provides some control over rates of infiltration through the soil layer and into the epikarst. Woody vegetation in general has a greater evapotranspiration potential than herbaceous vegetation in the Larawali catchment, however, the characteristics of precipitation and structure of the epikarst and deeper karst matrix may be more significant controls of groundwater recharge than the structural differences between woody and non-woody vegetation. Under saturated soil conditions, woody vegetation provides greater soil infiltration potential than herbaceous vegetation due to the high macroporosity associated with large root channels, however, in early wet season conditions, soil characteristics are the dominant control of rainfall partitioning at the soil surface.

Repetition of the methods applied in this study, along with application of additional studies, as listed in Section 6.2.6 are needed to further increase our understanding of the ecohydrology of the karst tropical savanna environment. Furthermore, the local understanding and experience of the importance of trees in regulating the hydrology of the karst tropical savanna environment as well as providing additional ecosystem services, should be systematically researched within an ecohydrological research framework. This would enable the development of management recommendations that are appropriate to the socio-ecological context and that have the greatest potential in achieving the desired hydrological service objectives of land management programs.

6.4. References

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Appendices

Appendix A: Chapter 3 supplementary figures and tables

Appendix Table 1. Landcover classes and reclassification to woody/herbaceous landcover classification.

Dominant landcover class	ID	Woody (1) / Herbaceous class (0)
Cashew trees	1	1
Mahogany trees	2	1
Agroforestry (mixed immature trees and vegetables)	3	0
Gmelina and cashew trees	4	1
Themeda grass	5	0
Mature Ficus species	6	1
Mature evergreen tree species	7	1
Teak and mahogany	8	1
Mature local mangifera	9	1
Surface water	10	0
Ziziphus mauritiana	11	1
Imperata grass	12	0
Bare ground or rock	13	0
Mixed grass	14	0
Vegetable plot	15	0

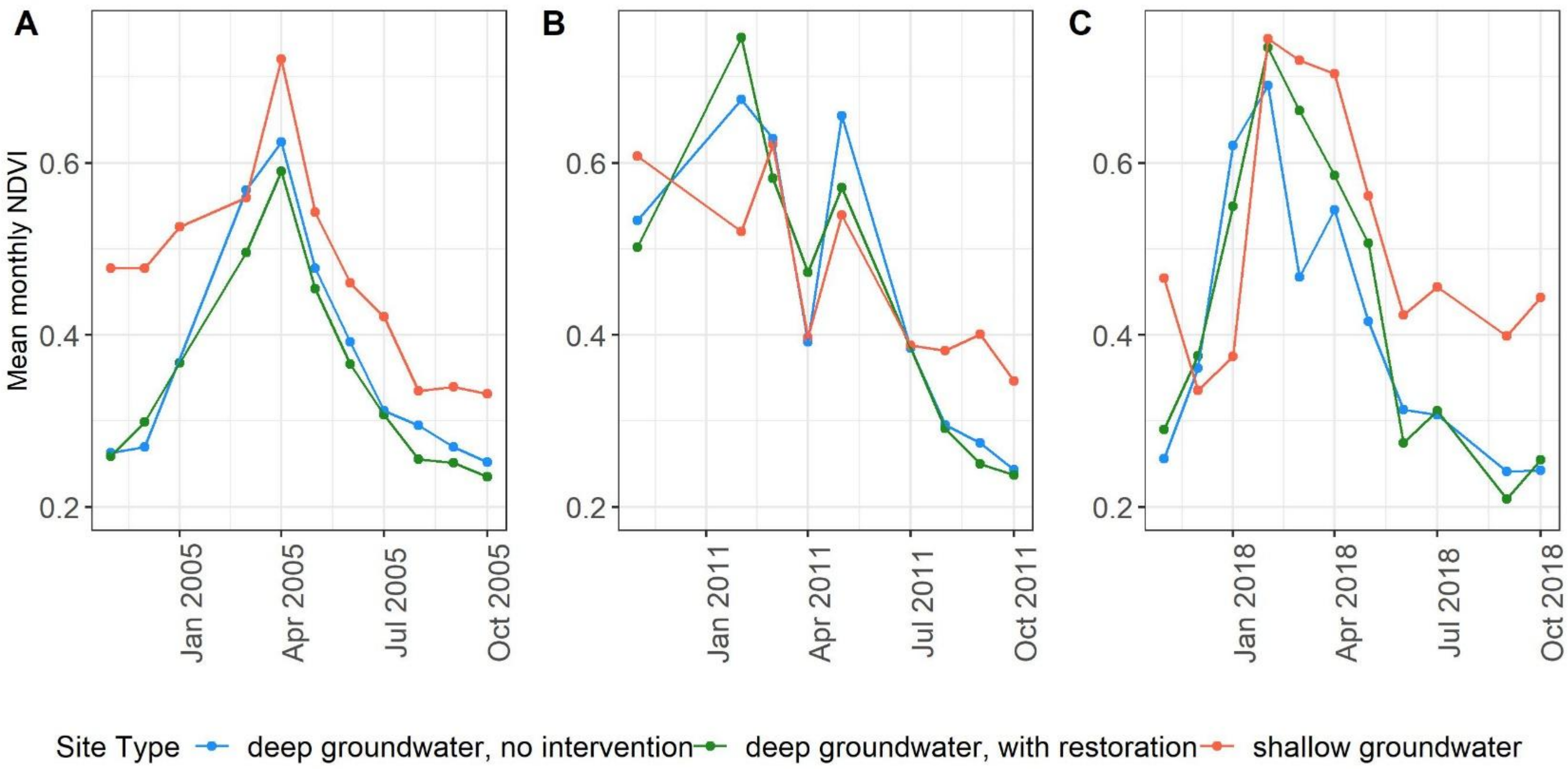
Appendix Table 2. Mean monthly NDVI trends at vegetation patches.

Site Number	Mann Kendall's tau	2-sided p-value	Sen's slope	Intercept
Shallow groundwater sites				
1	0.318*	2.2×10^{-16}	3.11×10^{-5}	0.181
2	0.067	0.196	NA	NA
3	-0.0093	0.85	NA	NA
Deep groundwater sites – no management intervention				
4	0.02	0.70	NA	NA
5	-0.050	0.32	NA	NA
6	0.011	0.83	NA	NA
Deep groundwater sites – with restoration interventions				
7	0.095	0.07	NA	NA
8	0.103	0.05	NA	NA
9	0.238*	7.75×10^{-6}	2.24×10^{-5}	0.122
10	0.0746	0.155	NA	NA

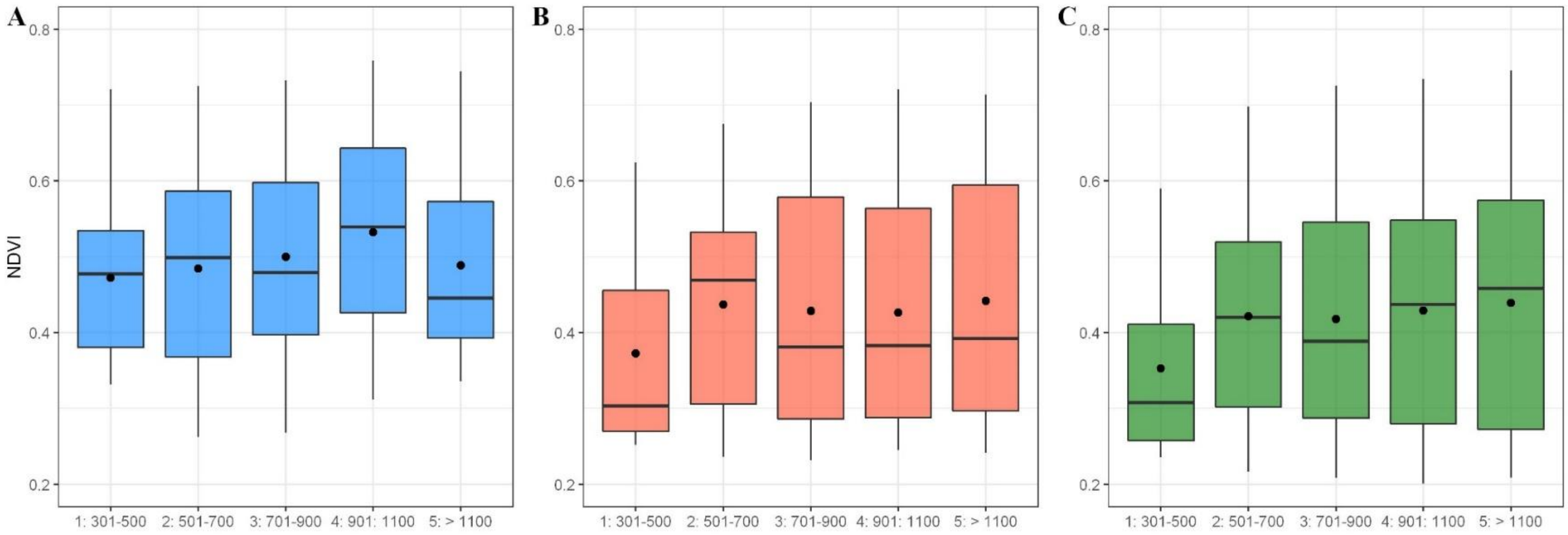
Mann Kendall's tau indicates the magnitude and direction of any trend in the NDVI time series The 2-sided p-value indicates if the trend is statistically significant ($\alpha = 0.05$). Significant trends are indicated by an *. NA: Not applicable.

Appendix Table 3. Pearson's correlation (r) of monthly NDVI by lagged monthly rainfall time series (0, 1 and 2 month lags).

	Rainfall time series monthly lag (months)		
Site number	**0**	**1**	**2**
Shallow groundwater sites			
1	0.36	0.45	0.495
2	0.511	0.601	0.676
3	0.459	0.557	0.642
Deep groundwater sites – no intervention			
4	0.546	0.519	0.488
5	0.433	0.551	0.67
6	0.575	0.689	0.754
Deep groundwater sites – with restoration			
7	0.463	0.577	0.7
8	0.558	0.654	0.759
9	0.47	0.658	0.62
10	0.49	0.573	0.633



Appendix Figure 1. Mean monthly NDVI by site type in a A) Very Dry, B) Very Wet and C) Wet year.



Appendix Figure 2. Boxplots of monthly NDVI according to rainfall bin for: A) Shallow groundwater sites; B) Deep groundwater sites without intervention; and C) Deep groundwater sites with restoration. Rainfall bins are in 300 mm intervals.

Appendix B: Chapter 5 supplementary tables and figures

Appendix Table 4. Results of stable isotopes in precipitation.

Location	Date	$d^{18}O$ VSMOW	$d^{2}H$ VSMOW
Waingapu	27/03/2018	-5.19	-22.10
Waingapu	27/03/2018	-5.19	-22.12
Napu	28/2/2018	-2.74	-0.54
Napu	21/2/2018	-5.05	-23.05
Waingapu	27/03/2018	-4.92	-19.97
Napu	17/2/2018	-7.01	-38.61
Napu	17/2/2018	-6.92	-38.20
Napu	13/12/2016	-5.93	-31.93
Napu	13/12/2016	-5.86	-31.50
Napu	5/01/2017	-4.72	-26.24
Napu	2/01/2017	-3.51	-16.13
Napu	Composite December 2017 – Napu	-5.36	-30.39
Napu	15/01/2017	-5.43	-30.55
Napu	16/01/2017	-6.92	-41.94
Napu	19/01/2017	-11.36	-80.34
Napu	8/02/2017	-4.27	-21.74
Napu	6/02/2017	-4.09	-17.99
Napu	6/02/2017	-4.07	-17.73
Wunga	Composite February 2017 – Wunga	-8.68	-56.88
Napu	5/02/2017	-3.77	-16.00
Napu	Composite February 2017 – Napu	-6.68	-40.54
Napu	nd	-7.05	-42.14
Napu	nd	-3.74	-15.59
Napu	nd	-5.25	-27.55
Napu	nd	-4.68	-21.95
Napu	nd	-5.33	-30.96
Napu	nd	-6.34	-38.11
Napu	nd	-4.76	-21.41
Napu	nd	-4.89	-22.31
Napu	nd	-6.41	-37.79
Napu	nd	-7.89	-47.49
Wunga	Composite April 2017 – Wunga	-6.50	-39.34
Napu	5/03/2018	-5.46	-25.18
Wunga	27/03/2018	-4.63	-20.66
Wunga	27/03/2018	-4.31	-20.61
Napu	27/03/2018	-3.4	-14.66
Napu	23/12/2019	-1.20	5.41
Napu	23/12/2019	-1.14	4.51
Napu	23/12/2019	-1.23	4.75

Location	Date	d^{18}O VSMOW	d^{2}H VSMOW
Napu	30/12/2019	-1.22	3.25
Napu	8/01/2020	-4.60	-31.11
Napu	15/01/2020	-2.34	-5.60
Napu	23/01/2020	-2.08	-4.34
Napu	15/02/2020	-5.64	-42.74
Napu	28/02/2020	-6.18	-39.00
Napu	7/03/2020	-5.04	-27.61
Napu	14/03/2020	-8.75	-61.77
Napu	22/03/2020	-6.27	-39.00
Napu	28/03/2020	-2.63	-8.99
Napu	18/04/2020	-4.03	-17.39
Waingapu	23/12/2019	0.49	8.58
Waingapu	30/12/2019	-2.29	-23.34
Waingapu	6/01/2020	-7.76	-55.60
Waingapu	15/01/2020	-3.72	-17.11
Waingapu	15/01/2020	-3.00	-13.19
Waingapu	23/01/2020	-1.33	-4.21
Waingapu	8/02/2020	-2.66	-7.61
Waingapu	15/02/2020	-7.37	-48.85
Waingapu	22/02/2020	-7.05	-52.59
Waingapu	28/02/2020	-4.14	-35.12
Waingapu	7/03/2020	-5.56	-36.80
Waingapu	14/03/2020	-9.33	-64.24
Waingapu	22/03/2020	-6.95	-38.33
Waingapu	11/04/2020	-8.14	-57.82

nd: no date.

Appendix C: Project administrative approvals

Biosecurity: Permit 0001244224

Australian Government
Department of Agriculture and Water Resources

Permit to import conditionally non-prohibited goods
This permit is issued under *Biosecurity Act 2015* Section 179 (1)

Permit: 0001244224

Valid for: multiple consignments between 3 April 2017 and 9 December 2018

This permit is issued to: Ms Penelope Godwin
29 Nelumbo Street
Rivett ACT 2611
Australia

Attention: Ms Penelope Godwin

This permit is issued for the import of Biological products (Non-standard goods).

Exporter details:	Various exporters
Country of export:	Various countries

This permit includes the following good(s). Refer to the indicated page for details of the permit conditions:

1. Soil and water samples		
End use:	In-vitro	
Country of origin:	Various countries	
Permit Conditions:	Soil or water samples and related material for destructive analysis	Page 3

NOTE: Where a good has more than one set of permit conditions please read each set to determine which set of permit conditions applies to a specific consignment.

-- End of commodity list --

This permit is granted subject to the requirement that fees determined under section 592(1) are paid.

Tran Tang
Delegate of the Director of Biosecurity   Date: 24 April 2017

T +61 2 6272 3933
F +61 2 6272 5161
18 Marcus Clarke Street
Canberra City ACT 2601
GPO Box 858
Canberra ACT 2601
agriculture.gov.au
ABN 24 113 085 695

Important information about this permit and the import of goods

Note: This permit covers Department of Agriculture and Water Resources biosecurity requirements. It is your responsibility to ensure all legal requirements relating to the goods described in this import permit are met. While you should rely on your own inquiries, the following information is provided to assist you in meeting your legal obligations in relation to the importation of the goods described in this import permit.

Authority to import

You are authorised to import the goods described in this import permit under the listed conditions.

Compliance with permit conditions and freedom from contamination

All imports may be subject to biosecurity inspection on arrival to determine compliance with the listed permit conditions and freedom from contamination. Imports not in compliance or not appropriately identified or packaged and labelled in accordance with the import conditions they represent may be subject to treatment, export or destruction at the importer's expense, or forfeited to the Commonwealth.

Compliance with other regulatory provisions

Additionally, all foods imported into Australia must comply with the provisions of the *Imported Food Control Act 1992*, and may be inspected and/or analysed against the requirements of the Australia New Zealand Food Standards Code.

All imports containing or derived from genetically modified material must comply with the *Gene Technology Act 2000*.

It is the importer's responsibility to identify and ensure they have complied with all requirements of any other regulatory organisations and advisory bodies prior to and after importation. Organisations include the Department of Immigration and Border Protection, the Department of Health, Therapeutic Goods Administration, Australian Pesticides and Veterinary Medicines Authority, the Department of the Environment, Food Standards Australia New Zealand and any state agencies such as Departments of Agriculture and Health and Environmental Protection authorities. Importers should note that this list is not exhaustive.

Change of import conditions

Import conditions are subject to change at the discretion of the Director of Biosecurity. This permit may be suspended or revoked without notice.

Notification of import

Notification of the import must be provided to the Department of Agriculture and Water Resources for all imported goods other than goods imported as accompanied baggage or goods imported via the mail and not prescribed under *the Customs Act 1901*. Notification must be consistent with the Biosecurity Regulation 2016.

Valid import permit

The importer must hold a valid import permit when the goods are presented for clearance.

The importer must verify that an import permit has been issued in relation to the consignment by one of the following means:

i. The positive identification of the import permit to the Department of Agriculture and Water Resources at the time that the goods are being processed for biosecurity clearance, such as by presenting the import permit.

OR

ii. Any form of physical, digital or verbal correspondence presented with information that allows an import permit to be identified.

Provision of required documentation

All required documentation must accompany each consignment. Alternatively, necessary documentation will need to be presented to the Department of Agriculture and Water Resources at the time of clearance. In order to facilitate clearance, airfreight or mail shipments should have all documentation securely attached to the outside of the package, and clearly marked "Attention Department of Agriculture and Water Resources". Documentation may include the import permit (or import permit number), government certification and invoice.

If the product description on the import permit varies from the identifying documentation provided for clearance, the importer is responsible for providing evidence to the biosecurity officer that the import permit covers the goods in the consignment.

Any documentation provided must comply with the Department of Agriculture and Water Resource's minimum documentation requirements policy.

Permit conditions

It is the importer's responsibility to ensure that the following permit conditions are met in relation to each consignment. Where more than one set of permit conditions is shown for a good please read each set of conditions to determine which applies to a specific consignment.

1. Soil or water samples and related material for destructive analysis

This section contains permit conditions for the following commodity (or commodities):

1.	Soil and water samples

1.1. Biosecurity Pathway

a. Materials imported using this Import Permit are for chemical, physical or destructive analysis only. The isolation or culturing of microorganisms, or growing of any plant material is not permitted.

b. Samples must be directed to and held at AA class 5.1 and/or 5.11 or higher approved arrangement site.

c. 1. The products are for use at the following approved arrangement site

Australian National University (A0073)
Research School of Earth Sciences Lab G7, Jaeger Building 1, Mills Road
ACTON ACT 0200

Australian National University (A1318)
Room B35 Jaeger Building 4 Research School of Earth Sciences Mills Road ANU
ACTON ACT 0200

Charles Darwin University (C1012)
Building Yellow 2 Casuarina Campus
CASUARINA NT 0810
.

The level of containment must be at least biosecurity containment level 1 or higher.

The goods and their derivatives shall not be removed from these sites without the prior written approval of a biosecurity officer, except in the case of disposal, treatment or export. These sites must have current approval, at the time of importation, from the department. The site must be approved as a class 5 approved arrangement site.

Where more than one approved arrangement site (AA site) is listed, the samples may be transferred between the listed sites.

It is the importer's responsibility to ensure that the goods are labelled '*in vitro* use only' or equivalent on the smallest packaged unit prior to transferring material between AA sites.

OR

2. The imported commodity may be directed for treatment using one of the department approved treatments[1] before release from biosecurity control.

[1] **Department of Agriculture and Water Resources approved treatment methods**

Soil samples (and related material):

1. dry heat treatment at 160 °C for 2 hours (if the sample does not exceed 500 g in weight), or
2. heat treatment in an autoclave at 121 °C, 15 psi for 30 minutes, or 134 °C, 15 psi for 4 minutes, or
3. gamma irradiation at 50 kGy.

Water samples (and related material):

1. heat treatment in an autoclave at 121 °C, 15 psi for 15 minutes, or 134 °C, 15 psi for 4 minutes, or
2. gamma irradiation at 50 kGy, or
3. heat treatment at a minimum core temperature of 100 °C for at least 30 minutes.

d. The following destructive analysis methods are also acceptable for soil, sediment and water samples (and related material):

1. Complete acid digestion using a combination of one or other of concentrated hydrochloric (HCl 32-37%/~12M), nitric (HNO_3 65-70%/16M), perchloric ($HClO_4$ ~70%/11M), sulphuric (H_2SO_4 95- 98%/~18M) and hydrofluoric (HF 40-48%/~27M) acid in either:

1.1. a microwave digestion system at ≥ 150 °C and ≥ 15 psi for at least 20 minutes, or

1.2. heating block at a minimum of 100 °C for at least 30 minutes.

The following methods of analysis completely destroy the sample or are otherwise equivalent to approved treatments for biosecurity waste:

1. High temperature combustion (> 600 °C).
2. Atomic absorption spectrometry (AAS) where the sample is atomised using a flame atomiser, or graphite furnace.
3. Thermoluminescence dating in which the sample material is progressively heated from 110 °C to at least 350 °C (excludes low temperature thermoluminescence).
4. Induction coupled plasma (ICP) linked to mass spectrometer or optical emission spectrometer (ICP-MS or ICP-OES).
5. Gas chromatography/mass spectrometry (GC-MS).
6. Thermal ionisation/MS (TIMS).
7. Electron ionisation/MS.
8. Atmospheric pressure chemical ionisation/MS.

e. **Post entry/end use conditions**

1. This import permit allows for the importation of goods for *in vitro* laboratory studies only.
2. This import permit does not permit the direct or indirect exposure of the imported materials or derivatives to animals or plants.
3. On completion of work all imported materials and the direct or indirect derivatives thereof shall be disposed of by export, or by Department of Agriculture and Water Resources approved treatment methods (as listed above) or other methods approved in writing by the Director of Biosecurity.
4. Records of transfer, treatment, disposal and release of all imported items must be retained by the AA site for Department of Agriculture and Water Resources audit purposes.
5. It is the importer's responsibility to ensure compliance with all international (e.g. International Air Transport Association (IATA)) and domestic requirements concerning the safe handling, transport and labelling of biological material.
6. It is the end user's responsibility to ensure that all laboratory products are used in accordance with the current AS/NZS 2243 Safety in Laboratory standards and Office of the Gene Technology Regulator (OGTR) requirements.

f. **Conditions of Administration**

1. Documents must be provided with each consignment which:

   1.1. identify the consignment e.g. entry number

   1.2. identify all goods being imported as part of this consignment e.g. invoice or waybill or importer's manifest

   1.3. describe the goods being imported (where not clear). Example 1: Product XRab = Purified protein derived from rabbits. Example 2: Product AX = Synthetic antibiotic. Example 3: Comte = Cheese.
2. For further information please contact:

   Regional - Clearance assistance: http://www.agriculture.gov.au/about/contactus/phone/regional

   Canberra - Administrative assistance or technical assistance: email imports@agriculture.gov.au (See Attachments) or phone 1800 900 090

g. Under the Biosecurity Charges Imposition (General) Regulation 2016 and Chapter 9, Part 2 of the Biosecurity Regulation 2016, fees are payable to the Department of Agriculture and Water Resources for all services. Detail on how the department applies fees and levies may be found in the charging guidelines.

h. Non-commodity information requirements for imported cargo also apply, please refer to the BICON case Non-Commodity Cargo Clearance.

Timber packaging, pallets or dunnage associated with the consignment may be subject to inspection and treatment on arrival, unless sufficient evidence of a Department of Agriculture and Water Resources approved treatment is provided.

All documentation presented to the department to assist in determining the level of biosecurity risk posed by transportation pathways and packaging must also meet the requirements of the non-commodity case.

--------------------------------- End of permit conditions ---------------------------------

Delegate of the Director of Biosecurity
Tran Tang Date: 24 April 2017

Import Services Team contact details

Import Services Team

Phone: 1800 900 090

Email: imports@agriculture.gov.au

Australian Government
Department of Agriculture, Water and the Environment

Permit to import conditionally non-prohibited goods
This permit is issued under *Biosecurity Act 2015* Section 179 (1)

Permit: 0005318205

Valid for: multiple consignments between 10 August 2021 and 10 August 2023

This permit is issued to: Ms Penelope Godwin
29 Nelumbo Street
RIVETT ACT 2611
Australia

Attention: Ms Penelope Godwin

This permit is issued for the import of Plant and Plant Products (Non-standard goods).

Exporter details:	Specific exporter/s
Exporter contact:	Universitas Kristen Wira Wacana Sumba Jl. R. Soeprapto Npo. 35 WAINGAPU SUMBA TIMUR 87113 Indonesia
Country of export:	Indonesia

This permit includes the following good(s). Refer to the indicated page for details of the permit conditions:

1. Plant material, seeds, or grains or both for in-vitro use		
Description:	Plant stems for in vitro research	
Country of origin:	Indonesia	
Permit Conditions:	Plant material samples requiring gamma irradiation	Page 3

NOTE: Where a good has more than one set of permit conditions please read each set to determine which set of permit conditions applies to a specific consignment.

-- End of commodity list --

This permit is granted subject to the requirement that fees determined under section 592(1) are paid.	
Adam Zur Delegate of the Director of Biosecurity	Date: 10 August 2021

T +61 2 6272 3933
F +61 2 6272 5161
18 Marcus Clarke Street
Canberra City ACT 2601
GPO Box 858
Canberra ACT 2601
agriculture.gov.au
ABN 34 190 894 983

Important information about this permit and the import of goods

Note: This permit covers Department of Agriculture, Water and the Environment biosecurity requirements. It is your responsibility to ensure all legal requirements relating to the goods described in this import permit are met. While you should rely on your own inquiries, the following information is provided to assist you in meeting your legal obligations in relation to the importation of the goods described in this import permit.

Authority to import

You are authorised to import the goods described in this import permit under the listed conditions.

Compliance with permit conditions and freedom from contamination

All imports may be subject to biosecurity inspection on arrival to determine compliance with the listed permit conditions and freedom from contamination. Imports not in compliance or not appropriately identified or packaged and labelled in accordance with the import conditions they represent may be subject to treatment, export or destruction at the importer's expense, or forfeited to the Commonwealth.

Compliance with other regulatory provisions

Additionally, all foods imported into Australia must comply with the provisions of the *Imported Food Control Act 1992*, and may be inspected and/or analysed against the requirements of the Australia New Zealand Food Standards Code.

All imports containing or derived from genetically modified material must comply with the *Gene Technology Act 2000*.

It is the importer's responsibility to identify and ensure they have complied with all requirements of any other regulatory organisations and advisory bodies prior to and after importation. Organisations include the Department of Home Affairs, the Department of Health, Therapeutic Goods Administration, Australian Pesticides and Veterinary Medicines Authority, Food Standards Australia New Zealand and any state agencies such as Departments of Agriculture and Health and Environmental Protection authorities. Importers should note that this list is not exhaustive.

Change of import conditions

Import conditions are subject to change at the discretion of the Director of Biosecurity. This permit may be suspended or revoked without notice.

Notification of import

Notification of the import must be provided to the Department of Agriculture, Water and the Environment for all imported goods other than goods imported as accompanied baggage or goods imported via the mail and not prescribed under *the Customs Act 1901*. Notification must be consistent with the Biosecurity Regulation 2016.

Valid import permit

The importer must hold a valid import permit at the time when the goods are brought or imported into Australian Territory.

The importer must verify that they hold a valid import permit in relation to the consignment by providing positive identification to the Department of Agriculture, Water and the Environment, by either:

i. Submitting (or providing) the permit for biosecurity clearance.

OR

ii. Providing any physical, digital or verbal information that allows the permit to be identified at the time of biosecurity clearance.

Provision of required documentation

All required documentation must accompany each consignment. Alternatively, necessary documentation will need to be presented to the Department of Agriculture, Water and the Environment at the time of clearance. In order to facilitate clearance, airfreight or mail shipments should have all documentation securely attached to the outside of the package, and clearly marked "Attention Department of Agriculture, Water and the Environment". Documentation may include the import permit (or import permit number), government certification and invoice.

If the product description on the import permit varies from the identifying documentation provided for clearance, the importer is responsible for providing evidence to the biosecurity officer that the import permit covers the goods in the consignment.

Any documentation provided must comply with the Department of Agriculture, Water and the Environment's minimum documentation requirements policy.

Permit conditions

It is the importer's responsibility to ensure that the following permit conditions are met in relation to each consignment. Where more than one set of permit conditions is shown for a good please read each set of conditions to determine which applies to a specific consignment.

1. Plant material samples requiring gamma irradiation

This section contains permit conditions for the following commodity (or commodities):

1.	Plant material, seeds, or grains or both for in-vitro use Product Description:	 Plant stems for in vitro research

1.1. Biosecurity Pathway

a. The following conditions allow for the importation of not knowingly infected plant material which will be subject to mandatory gamma irradiation on arrival.

b. The species listed below have been determined to pose an unacceptable risk and must not be imported as mail (including items posted using an international postal Express Mail Service) or within accompanied baggage:

Apium graveolens (Celery seed)	*Foeniculum* spp. (Fennel seed)
Arachis hypogaea (Peanuts)	*Glycine max* (Soybean)
Cajanus cajan (Pigeon pea)	*Lens culinaris* (Lentils)
Capsicum spp. (Dried chillies/capsicum)	*Oryza sativa* (Rice)
Carthamus tinctorius (Safflower seed)	*Phaseolus* spp. (Bean seed)
Cicer arietinum (Chickpeas)	*Pisum sativum* (Pea seed)
Coriandrum sativum (Coriander seed)	*Triticum aestivum* (Wheat)
Cucurbita spp.; *Cucumis* spp.; *Citrullus* spp. (Cucurbit seed)	*Vicia faba* (Faba bean)
Cuminum cyminum (Cumin seed)	*Vigna* spp. (Mung beans, cowpeas)

c. The quantity of the material imported must not exceed what can be securely stored in the AA site.

d. Each consignment must be accompanied by a list of the botanical names (minimum genus) of all specimens, or if the specimens are unidentified, a numerical identifier and collection data.

e. Each consignment must be free of live insects, soil, and other contamination of quarantine concern prior to arrival in Australian territory.

f. Any packaging used with the consignment must be clean and new.

g. The importer must contact the Department of Agriculture, Water and the Environment regional office in the first point of entry, to confirm all arrangements for inspections and treatments of consignments.

h. Consignments should have the above documentation securely attached to the outside of the package and clearly marked "Attention Quarantine". Note: a second copy of all required documentation should be enclosed in the outer layers of the packaging in case the external documents are dislodged during transit. Alternatively, the necessary documentation will need to be presented to the department at the time of clearance.

i. Mail shipments must be addressed in the following manner:
Importer's Name
C/O- Department of Agriculture, Water and the Environment Nursery stock/Seeds unit
Department of Agriculture, Water and the Environment physical address in your region.

j. Air freight shipments (including courier) must use the following goods description when lodged in the Integrated Cargo System:
"FOR RESEARCH - IMPORT PERMIT ATTACHED"

k. All imported material must be presented to a biosecurity officer for inspection on arrival.

l. Following inspection, consignments must be securely packaged to the satisfaction of the biosecurity officer prior to movement to approved arrangement site.

m. Following verification inspection, the consignment must be forwarded directly to an approved arrangement site for mandatory gamma irradiation at 25 kGy.

Note: If soil is detected, the consignment is subject to gamma irradiation treatment of 50 kGy (5 Mrad) at the quarantine approved treatment premises.

If live insects are found during the inspection they will be identified by a Department of Agriculture, Water and the Environment entomologist and the consignment will be fumigated with methyl bromide. Treatment for live insects must be carried out prior to any other treatment that may be required. Treatment will be carried out at the importer's expense.

n. Following gamma irradiation treatment the consignment may be released to the importer by a biosecurity officer.

o. Under the Biosecurity Charges Imposition (General) Regulation 2016 and Chapter 9, Part 2 of the Biosecurity Regulation 2016, fees are payable to the Department of Agriculture, Water and the Environment for all services. Detail on how the department applies fees and levies may be found in the Charging guidelines.

p. In addition to the conditions for the goods being imported, non-commodity concerns must be assessed including container cleanliness, packaging and destination concerns, and may be subject to inspection and treatment on arrival. Please refer to the Non-Commodity Cargo Clearance BICON case for further information.

---------------------------------- End of permit conditions ----------------------------------

Delegate of the Director of Biosecurity
Adam Zur

Date: 10 August 2021

Australian Government
Department of Agriculture, Water and the Environment

Permit to import conditionally non-prohibited goods
This permit is issued under *Biosecurity Act 2015* Section 179 (1)

Permit: 0005595477

Valid for: multiple consignments between 10 August 2021 and 10 August 2023

This permit is issued to: Ms Penelope Godwin
29 Nelumbo Street
RIVETT ACT 2611
Australia

Attention: Ms Penelope Godwin

This permit is issued for the import of Biological products (Standard goods).

Exporter details:	Various exporters

This permit includes the following good(s). Refer to the indicated page for details of the permit conditions:

1. Soil and water samples		
End use:	In vitro use or in vivo use in laboratory organisms	
Country of export:	Various countries	
Country of origin:	Various countries	
Permit Conditions:	Soil and water for mandatory treatment	Page 3

NOTE: Where a good has more than one set of permit conditions please read each set to determine which set of permit conditions applies to a specific consignment.

-- End of commodity list --

This permit is granted subject to the requirement that fees determined under section 592(1) are paid.

Tim Carswell
Delegate of the Director of Biosecurity Date: 10 August 2021

T +61 2 6272 3933
F +61 2 6272 5161
18 Marcus Clarke Street
Canberra City ACT 2601
GPO Box 858
Canberra ACT 2601
agriculture.gov.au
ABN 34 190 894 983

Important information about this permit and the import of goods

Note: This permit covers Department of Agriculture, Water and the Environment biosecurity requirements. It is your responsibility to ensure all legal requirements relating to the goods described in this import permit are met. While you should rely on your own inquiries, the following information is provided to assist you in meeting your legal obligations in relation to the importation of the goods described in this import permit.

Authority to import

You are authorised to import the goods described in this import permit under the listed conditions.

Compliance with permit conditions and freedom from contamination

All imports may be subject to biosecurity inspection on arrival to determine compliance with the listed permit conditions and freedom from contamination. Imports not in compliance or not appropriately identified or packaged and labelled in accordance with the import conditions they represent may be subject to treatment, export or destruction at the importer's expense, or forfeited to the Commonwealth.

Compliance with other regulatory provisions

Additionally, all foods imported into Australia must comply with the provisions of the *Imported Food Control Act 1992*, and may be inspected and/or analysed against the requirements of the Australia New Zealand Food Standards Code.

All imports containing or derived from genetically modified material must comply with the *Gene Technology Act 2000*.

It is the importer's responsibility to identify and ensure they have complied with all requirements of any other regulatory organisations and advisory bodies prior to and after importation. Organisations include the Department of Home Affairs, the Department of Health, Therapeutic Goods Administration, Australian Pesticides and Veterinary Medicines Authority, Food Standards Australia New Zealand and any state agencies such as Departments of Agriculture and Health and Environmental Protection authorities. Importers should note that this list is not exhaustive.

Change of import conditions

Import conditions are subject to change at the discretion of the Director of Biosecurity. This permit may be suspended or revoked without notice.

Notification of import

Notification of the import must be provided to the Department of Agriculture, Water and the Environment for all imported goods other than goods imported as accompanied baggage or goods imported via the mail and not prescribed under *the Customs Act 1901*. Notification must be consistent with the Biosecurity Regulation 2016.

Valid import permit

The importer must hold a valid import permit at the time when the goods are brought or imported into Australian Territory.

The importer must verify that they hold a valid import permit in relation to the consignment by providing positive identification to the Department of Agriculture, Water and the Environment, by either:

i. Submitting (or providing) the permit for biosecurity clearance.

OR

ii. Providing any physical, digital or verbal information that allows the permit to be identified at the time of biosecurity clearance.

Provision of required documentation

All required documentation must accompany each consignment. Alternatively, necessary documentation will need to be presented to the Department of Agriculture, Water and the Environment at the time of clearance. In order to facilitate clearance, airfreight or mail shipments should have all documentation securely attached to the outside of the package, and clearly marked "Attention Department of Agriculture, Water and the Environment". Documentation may include the import permit (or import permit number), government certification and invoice.

If the product description on the import permit varies from the identifying documentation provided for clearance, the importer is responsible for providing evidence to the biosecurity officer that the import permit covers the goods in the consignment.

Any documentation provided must comply with the Department of Agriculture, Water and the Environment's minimum documentation requirements policy.

Permit conditions

It is the importer's responsibility to ensure that the following permit conditions are met in relation to each consignment. Where more than one set of permit conditions is shown for a good please read each set of conditions to determine which applies to a specific consignment.

1. Soil and water for mandatory treatment

This section contains permit conditions for the following commodity (or commodities):

1.	Soil and water samples

1.1. Biosecurity Pathway

a. Prior to release to the importer the material must be subjected to one of the following treatments at a department approved facility:

Soil samples (and related material)

1. Dry heat treatment at 160°C for 2 hours (if the sample does not exceed 500g in weight), or
2. Heat treatment in an autoclave at 121°C, 15psi for 30 minutes, or
3. Heat treatment in an autoclave at 134°C, 15psi for 4 minutes, or
4. Ionising radiation to a level that achieves a minimum absorbed dose of 50 kGy.
5. All samples must be directed to an approved arrangement site class 4.1 or 12.3 for dry heat treatment, class 8.3 for autoclave heat treatment or class 4.2 for ionising irradiation.

Water samples (and related material)

1. Heat treatment in an autoclave at 121°C, 15psi for 30 minutes, or
2. Heat treatment in an autoclave at 134°C, 15psi for 4 minutes, or
3. Heat treatment at a minimum core temperature of 100°C for at least 30 minutes, or
4. Ionising radiation to a level that achieves a minimum absorbed dose of 50 kGy.
5. All samples must be directed to an approved arrangement site class 4.1 or 12.3 for heat treatment, class 8.3 for autoclave heat treatment or class 4.2 for ionising irradiation.

Where the importer is also the treatment provider:

1. The samples must be treated within 72 hours of release to the importer.
2. The samples must not be used for any type of laboratory analysis (including microbial isolation) until treated.
3. The samples must be kept in a secure area, with no animal access, until treated.
4. All records of treatment must be maintained for audit purposes.

Where the treatment provider is not the importer:

1. The samples must be kept in a secure area, with no animal access, until treated.
2. All records of treatment must be maintained for audit purposes.

b. Please note that any treatment applied may have adverse effects on the goods.

c. These goods or any derivatives must not be distributed, sold or used for:

1. animal consumption, or

2. use as bioremediation agents or fertiliser, or
3. growing purposes, or
4. veterinary therapeutic use.

d. **Commercial administrative conditions**

Documents must be provided with each consignment which:

1. identify the consignment (if non-personal) e.g. entry number
2. identify all goods being imported as part of this consignment e.g. invoice or waybill or importer's manifest
3. describe the goods being imported (where not clear).

   e.g. 1: Product XRab = Purified protein derived from rabbits

   e.g. 2: Product AX = Synthetic antibiotic

   e.g. 3: Comte = Cheese.

e. Under the Biosecurity Charges Imposition (General) Regulation 2016 and Chapter 9, Part 2 of the Biosecurity Regulation 2016, fees are payable to the Department of Agriculture, Water and the Environment for all services. Detail on how the department applies fees and levies may be found in the Charging guidelines.

f. In addition to the conditions for the goods being imported, non-commodity concerns must be assessed including container cleanliness, packaging and destination concerns, and may be subject to inspection and treatment on arrival. Please refer to the Non-Commodity Cargo Clearance BICON case for further information.

---------------------------------- End of permit conditions ----------------------------------

Foreign research permit

KEMENTERIAN RISET, TEKNOLOGI, DAN PENDIDIKAN TINGGI
SEKRETARIAT PERIZINAN PENELITIAN ASING
Jl. M.H. Thamrin No. 8, Jakarta 10340 - Gedung 2 BPPT, Lantai 20
Telepon : 021-3162222 ext. 9777 & 9797, Faksimili : 021-39836180
Homepage: www.ristekdikti.go.id Email : frp@ristekdikti.go.id

SURAT IZIN PENELITIAN
(LETTER OF RESEARCH PERMIT)
Nomor : 406/SIP/FRP/E5/Dit.KI/XII/2016

Kementerian Riset, Teknologi, dan Pendidikan Tinggi dengan ini menerangkan bahwa berdasarkan rapat Tim Koordinasi Pemberian Izin Penelitian Asing (TKPIPA Nomor : 11B/TKPIPA/E5/Dit.KI/XI/2016, tanggal 23 November 2016), telah diberikan izin untuk mengadakan penelitian di Indonesia kepada peneliti berikut :

(The Ministry of Research Technology and Higher Education hereby state that based on the Foreign Research Permit Coordinating Team (TKPIPA) meeting above, a permit to conduct research activity in Indonesia is granted to the following) :

Nama ***(Name)***	:	**Ms. Penelope Bronwyn Godwin**
Tempat dan tanggal lahir ***(Place and date of birth)***	:	Australia, 6 Januari 1984
Warga Negara ***(Nationality)***	:	Australia
Jabatan ***(Position)***	:	PhD Student
Institusi ***(Institution)***	:	Charles Darwin University
Email ***(email)***	:	penelope.godwin@cdu.edu.au
Alamat ***(Address)***	:	29 Nelumbo St, Rivett, ACT, 2611 Australia
Nomor Paspor ***(Pasport no.)***	:	N1006520
Judul Penelitian ***(Research Title)***	:	*"Catchment hydrology in the Wet Dry Tropics –what are the drivers of spring yield variability in East Sumba, Indonesia"*
Tujuan Penelitian ***(Research Objective)***	:	Untuk mengaktifkan perlindungan arus air dengan mengkonsolidasikan pengetahuan lokal yang ada dan menghasilkan pengetahuan hidrologi baru yang meningkatkan pemahaman kita tentang keseimbangan neraca mata air dan pengaruh inisiatif manajemen tutupan lahan
Bidang Penelitian ***(Field of Research)***	:	Ekologi
Lama Penelitian ***(Research Duration)***	:	12 (dua belas) bulan, mulai 6 Desember 2016 ***(month, starting from)***
Daerah Penelitian ***(Research Location)***	:	NTT (Sumba Timur)
Mitra Kerja ***(Counterpart)***	:	Universitas Nusa Cendana (Dr. Jokobis J. Messakh)

dengan ketentuan sebagai berikut ***(with the following norms as stated in the following)*** :

1. Melaporkan kedatangan dan maksud penelitiannya kepada pemerintah daerah, instansi keamanan setempat serta instansi pemerintah terkait lainnya dengan menunjukan Surat Izin Penelitian ini, segera setelah ia tiba ditempat tujuannya. Peneliti asing juga harus melaporkan diri sebelum meninggalkan daerah penelitiannya kepada Pemerintah Daerah, Mitra Kerja di Indonesia, instansi keamanan dan instansi pemerintah terkait lainnya.
(The foreign researcher should report his/ her arrival and his/ her purpose of activities to the Local Governments and other local authorities, as soon as he/ she arrive by showing this Letter, and reporting back before leaving the area)
2. Berbuat positif terhadap bangsa Indonesia, dan mentaati peraturan-peraturan hukum yang berlaku di Indonesia, khususnya yang berlaku di daerah penelitiannya. Untuk penelitian yang dilakukan pada kawasan konservasi di Indonesia, perlu perhatian khusus, terutama pasal-pasal yang harus dipatuhi pada Surat Ijin Masuk Kawasan Konservasi (SIMAKSI).
(To conduct positively towards Indonesian people, to obey the rules, especially those in the area of research. Research in conservation areas should obey the rules as stated in the Permit for Entering Conservation Area- SIMAKSI)
3. Menjaga tata tertib, keamanan, kesopanan dan kesusilaan serta menghindari pernyataan-pernyataan baik dengan lisan maupun tulisan/ lukisan yang dapat melukai/ menyinggung perasaan, adat istiadat atau menghina agama, dari sesuatu golongan penduduk di Indonesia.
(The foreign researcher should perform good/ agreeable manner, tolerant, and obey all custom rules in every area in Indonesia)

4. Memberikan Laporan....
(The foreign researcher has to submit a progress report ....)

4. Memberikan Laporan Kemajuan setiap 3 (tiga) bulan sekali, dan Laporan Akhir sebelum meninggalkan Indonesia, kepada Kementerian Riset, Teknologi, dan Pendidikan Tinggi.
   (The foreign researcher has to submit a progress report in every three month and final report once he/ she finishes the research project in Indonesia)
5. Tidak dibenarkan membawa barang-barang atau bahan-bahan yang menurut peraturan yang berlaku dilarang untuk dibawa ke luar negeri, kecuali dengan izin instansi yang berwenang menurut peraturan yang berlaku.
   (It is prohibited to bring any specimen/ samples abroad without the stakeholder permission)
6. Apabila penelitian yang akan dilakukan diperkirakan akan menghasilkan hak milik *Intellectual Property Rights* (IPR) seperti paten, hak cipta dan merk harus dibuat perjanjian tertulis dengan Mitra Kerja, dengan memperhatikan peraturan Perundang-undangan yang berlaku di Indonesia.
   (The foreign researcher should make an agreement with the counterpart for any patent, intellectual property rights, brand, and registered mark as resulted from the research, referring to the existing Indonesian law)
7. Diwajibkan bagi peneliti asing dan mitra kerja di Indonesia untuk mempublikasikan bersama hasil penelitiannya baik berupa Jurnal nasional maupun internasional.
   (To publish jointly with the Indonesian researcher, the result of the research in an International or National Journals)
8. Memberikan salinan dari tulisan-tulisan (Thesis/Disertasi, Makalah, Laporan atau Publikasi lain) mengenai hasil penelitiannya tersebut kepada Kementerian Riset, Teknologi, dan Pendidikan Tinggi.
   (To submit copies of research result include thesis/ dissertation, paper, report, or another publication to Ministry of Research, Technology, and Higher Education)
9. Memberikan 1 (satu) copy foto-foto, slide/microfilm dan film/video casette, casette sebagai hasil penelitian kepada Kementerian Riset, Teknologi,dan Pendidikan Tinggi (kalau ada).
   (To submit one copy of photo, slide/ microfilm, video cassette, and cast as research result to Ministry of Research, Technology, and Higher Education)
10. Surat Keterangan Izin Penelitian ini hanya berlaku selama visa dari Direktorat Jenderal Imigrasi R.I dan Surat Keterangan Jalan dari Polisi masih berlaku.
    (This Letter is only valid as long as the Visa from the Directorate General of Immigration RI and Travelling Permit from the Police Head Quarter are valid)
11. Permohonan perpanjangan dan atau perubahan daerah penelitian harus diajukan kepada Kementerian Riset, Teknologi, dan Pendidikan Tinggi selambat-lambatnya satu bulan sebelum Surat Izin Penelitian habis masa berlakunya dengan melampirkan surat rekomendasi dari mitra kerja di Indonesia.
    (Extention of this Permit, or amandement of Location, should be requested to the Ministry of Research, Technology, and Higher Education, at the latest one month before expiry date of the Research Permit Letter, with recommendation letter from the counterpart)
12. Setelah penelitian selesai diharapkan supaya Surat Izin Penelitian ini dikembalikan kepada Direktur Jenderal Penguatan Riset dan Pengembangan selaku Ketua Tim Koordinasi Pemberian Izin Penelitian Asing.
    (At the end of the research, this Letter of Research Permit should be returned to the Director General of Strengthening for R&D, acting as the Head of Foreign Research Permit Coordinatimg Team)
13. Penelitian yang menggunakan Kapal Riset, pesawat survey udara, atau wahana apapun di wilayah Teritorial RI dan ZEE, serta wilayah udara RI, harus juga memperoleh *Security Clearance* dan didampingi *Security Officer.*
    (Research using Vessel Research, Airborne Survey Flight, or any other vehicles in Indonesian territorial and EEZ as well as aerospace territory, should obtain Security Clearance and accompanied by Security Officers)
14. Izin Penelitian dapat dibatalkan/ dicabut apabila Peneliti Asing melakukan pelanggaran terhadap peraturan perundangan yang berlaku.
    (Annulment and/ or revocation of the permit shall be applied if the foreign researcher violates the provisions of the prevailing laws and regulations)

Demikian **Surat Izin Penelitian Nomor : /SIP/E5/Dit.KI/XII/2016, tanggal Desember 2016,** untuk dapat dipergunakan sebagaimana mestinya. Kami mohon dengan hormat kiranya instansi-instansi Pemerintah/Swasta maupun perorangan yang dihubungi untuk memberikan bantuannya kepada yang bersangkutan sesuai dengan peraturan yang berlaku.

(Herewith the Letter of Research Permit is issued to be used accordingy. We request the Government and private Institution or individual that receive the bearer of this letter to provide assistance in accordance with the rules)

Dikeluarkan di ***(Issued in)*** : **J A K A R T A**
Tanggal ***(date)*** : **Desember 2016**

KEMENTERIAN RISET, TEKNOLOGI, DAN PENDIDIKAN TINGGI

a.n. Ketua Tim Koordinasi Pemberian Izin Penelitian Asing
Direktur Pengelolaan Kekayaan Intelektual/selaku Sekretaris TKPIPA
(on behalf of The Head of Foreign Research Permit Coordinating Team)

KEMENTERIAN RISET, TEKNOLOGI, DAN PENDIDIKAN TINGGI
DIREKTORAT JENDERAL PENGUATAN RISET DAN PENGEMBANGAN

Dr. Sadjuga, M.Sc

Penerima Surat Izin Penelitian
(Bearer of Permit Letter)

METERAI TEMPEL
2AD2DAEF069437207
6000 ENAM RIBU RUPIAH

Ms. Penelope Bronwyn Godwin

FRM.APP.19/I-13/REV.01

Australian Government
Department of Agriculture and Water Resources

TREAT, MOVE, ISOLATE OR DESTROY GOODS

Biosecurity Act 2015

Reference Number: NA18004814

GAURNV SHARMA
UNKNOWN, , 0000

Flight or Vessel Particulars:	Location:
AI302	Sydney Kingsford Smith Airport 02 8016 8500

Service Fee		Receipt Number	

Description:	Weight/No:	Origin of Goods:	Declared value:	Action :
Other vegetable & vegetable products,	252 Grams	India	$	Destruction

Biosecurity Officer:
The goods(s) listed above were inspected at Sydney Kingsford Smith Airport on 16/01/2018. I am an authorised biosecurity officer. I have assessed the goods and I suspect on reasonable grounds that there is an unacceptable level of biosecurity risk associated with the goods. On that basis, I direct you to carry out the following biosecurity measures, in accordance with s.138 of the *Biosecurity Act 2015* (**Act**).

Non Compliance with this Direction
Failure to comply with this direction is an offence against the Act and you may be liable for a civil penalty.

Morgan, Dena 16/01/2018

Biosecurity Officer — Signature — Inspection Date

Treatment directions: *Biosecurity Act s.133*

☐ The goods are directed to be treated (s.133) as specified.

Destruction direction: *Biosecurity Act s.136*

☑ The goods are directed to be destroyed (s.136) as specified.

Move (*Biosecurity Act s.132)* or Isolate *(Biosecurity Act s.137(1))* Goods Direction

☐ The goods are directed to be moved to the place specified above.

☐ The goods are directed to be isolated at the place specified above and on the conditions specified in the below condition/comments section.

Collection Location:

Australian Government
Department of Agriculture
and Water Resources

RELEASE FROM BIOSECURITY CONTROL

Biosecurity Act 2015

Reference Number: NA18048147

To importer, consignee, owner or person in possession or control of the animals, plants or goods	
PENELOPE GODNIN 29 NELUMBO STREET RIVETT, ACT, 2611 0431971309	
Flight or Vessel Particulars:	**Location:**
QF44	Sydney Kingsford Smith Airport 02 8016 8500

Description:	Weight/Number:	Origin of Goods:	Declared value:
Other contaminated goods, water contaminated	19 Units	Indonesia	$

Dear Importer,

The Department of Agriculture and Water Resources has assessed the goods you have imported. These items meet current biosecurity import requirements and are hereby released from biosecurity subject to permit conditions.

Detailed biosecurity information is available on the Department of Agriculture and Water Resources website http://www.agriculture.gov.au/biosecurity.

If you have any questions, please contact the Biosecurity Detained Goods Officer on 02 8016 8500.

Date of issue: 13/06/2018

Cambridge, Warwick
Biosecurity Officer

12 Dr Saxena.

Research permit letter

KEMENTERIAN RISET DAN TEKNOLOGI/
BADAN RISET DAN INOVASI NASIONAL
DEPUTI BIDANG PENGUATAN RISET DAN PENGEMBANGAN
Gedung B.J. Habibie Lantai 19 – 20, Jalan M.H. Thamrin No. 8, Jakarta 10340
Telepon 021-3162222 Ext. 9702, 9782, 9707; Faksimile 021-3101728

RISTEK-BRIN

SURAT IZIN PENELITIAN
(LETTER OF RESEARCH PERMIT)
Nomor : 35/E5/E5.4/SIP.EXT/2020

Perpanjangan I

Kementerian Riset dan Teknologi/Badan Riset dan Inovasi Nasional dengan ini menerangkan bahwa berdasarkan rapat Tim Koordinasi Pemberian Izin Penelitian Asing (TKPIPA Nomor : 3B/TKPIPA/E5/Dit.KI/III/2020, tanggal 31 Maret 2020), telah diberikan izin untuk mengadakan penelitian di Indonesia kepada peneliti berikut :

(The Ministry of Research and Technology/ National Agency for Research and Innovation hereby state that based on the Foreign Research Permit Coordinating Team (TKPIPA) meeting above, a permit to conduct research activity in Indonesia is granted to the following) :

Nama ***(Name)***	:	**Ms. Penelope Bronwyn Godwin**
Tempat dan tanggal lahir ***(Place and date of birth)***	:	Australia, 06 Januari 1984
Warga Negara ***(Nationality)***	:	Australia
Jabatan ***(Position)***	:	PhD Student
Institusi ***(Institution)***	:	Charles Darwin University
Email ***(email)***	:	penelope.godwin@cdu.edu.au
Alamat ***(Address)***	:	29 Nelumbo St Rivett ACT, 2611, Australia
Nomor Paspor ***(Pasport no.)***	:	PA6415121
Judul Penelitian ***(Research Title)***	:	*"Catchment hydrology in the Wet Dry Tropics –what are the drivers of spring yield variability in East Sumba, Indonesia"*
Tujuan Penelitian ***(Research Objective)***	:	Untuk mengaktifkan perlindungan arus air dengan mengkonsolidasikan pengetahuan lokal yang ada dan menghasilkan pengetahuan hidrologi baru yang meningkatkan pemahaman kita tentang keseimbangan mata air dan pengaruh inisiatif manajemen tutupan lahan
Bidang Penelitian ***(Field of Research)***	:	Ekologi
Lama Penelitian ***(Research Duration)***	:	Perpanjangan 12 (dua belas) bulan, mulai 5 Agustus 2020 ***(month, starting from)***
Daerah Penelitian ***(Research Location)***	:	NTT (Sumba Timur)
Mitra Kerja ***(Counterpart)***	:	Universitas Nusa Cendana (Dr. Jokobis J. Messakh)

dengan ketentuan sebagai berikut ***(with the following norms as stated in the following)*** :

1. Melaporkan kedatangan dan maksud penelitiannya kepada pemerintah daerah, instansi keamanan setempat serta instansi pemerintah terkait lainnya dengan menunjukan Surat Izin Penelitian ini, segera setelah ia tiba ditempat tujuannya. Peneliti asing juga harus melaporkan diri sebelum meninggalkan daerah penelitiannya kepada Pemerintah Daerah, Mitra Kerja di Indonesia, instansi keamanan dan instansi pemerintah terkait lainnya.
(The foreign researcher should report his/ her arrival and his/ her purpose of activities to the Local Governments and other local authorities, as soon as he/ she arrive by showing this Letter, and reporting back before leaving the area)
2. Berbuat positif terhadap bangsa Indonesia, dan mentaati peraturan-peraturan hukum yang berlaku di Indonesia, khususnya yang berlaku di daerah penelitiannya. Untuk penelitian yang dilakukan pada kawasan konservasi di Indonesia, perlu perhatian khusus, terutama pasal-pasal yang harus dipatuhi pada Surat Ijin Masuk Kawasan Konservasi (SIMAKSI).
(To conduct positively towards Indonesian people, to obey the rules, especially those in the area of research. Research in conservation areas should obey the rules as stated in the Permit for Entering Conservation Area- SIMAKSI)
3. Menjaga tata tertib, keamanan, kesopanan dan kesusilaan serta menghindari pernyataan-pernyataan baik dengan lisan maupun tulisan/ lukisan yang dapat melukai/ menyinggung perasaan, adat istiadat atau menghina agama, dari sesuatu golongan penduduk di Indonesia.
(The foreign researcher should perform good/ agreeable manner, tolerant, and obey all custom rules in every area in Indonesia)

4. Memberikan Laporan....
(The foreign researcher has to submit a progress report ....)

4. Menyerahkan laporan kemajuan setiap tiga bulan sekali, dan Laporan Akhir sebelum meninggalkan Indonesia, kepada Kementerian Riset dan Teknologi/Badan Riset dan Inovasi Nasional.
(The foreign researcher has to submit a progress report in every three month and final report once he/ she finishes the research project in Indonesia)
5. Tidak dibenarkan membawa barang-barang atau bahan-bahan yang menurut peraturan yang berlaku dilarang untuk dibawa ke luar negeri, kecuali dengan izin instansi yang berwenang menurut peraturan yang berlaku, dan dilengkapi dengan perjanjian alih material/*Material Transfer Agreement* (MTA).
(It is prohibited to bring any specimen/ samples abroad without the stakeholder permission and should be equipped by Material Transfer Agreement signed by all parties)
6. Apabila penelitian yang akan dilakukan diperkirakan akan menghasilkan hak milik *Intellectual Property Rights* (IPR) seperti paten, hak cipta dan merk harus dibuat perjanjian tertulis dengan Mitra Kerja, dengan memperhatikan peraturan Perundang-undangan yang berlaku di Indonesia.
(The foreign researcher should make an agreement with the counterpart for any patent, intellectual property rights, brand, and registered mark as resulted from the research, referring to the existing Indonesian law)
7. Diwajibkan bagi peneliti asing dan mitra kerja di Indonesia untuk mempublikasikan bersama hasil penelitiannya baik berupa Jurnal nasional maupun internasional.
(To publish jointly with the Indonesian researcher, the result of the research in an International or National Journals)
8. Memberikan salinan dari tulisan-tulisan (Thesis/Disertasi, Makalah, Laporan atau Publikasi lain) mengenai hasil penelitiannya tersebut kepada Kementerian Riset dan Teknologi/Badan Riset dan Inovasi Nasional.
(To submit copies of research result include thesis/ dissertation, paper, report, or another publication to Ministry of Research and Technology/ National Agency for Research and Innovation)
9. Memberikan 1 (satu) copy foto-foto, slide/microfilm dan film/video casette, casette sebagai hasil penelitian kepada Kementerian Riset dan Teknologi/Badan Riset dan Inovasi Nasional (kalau ada).
(To submit one copy of photo, slide/ microfilm, video cassette, and cast as research result to Ministry of Research and Technology/ National Agency for Research and Innovation)
10. Surat Keterangan Izin Penelitian ini hanya berlaku selama visa dari Direktorat Jenderal Imigrasi R.I dan Surat Keterangan Jalan dari Polisi masih berlaku.
(This Letter is only valid as long as the Visa from the Directorate General of Immigration RI and Travelling Permit from the Police Head Quarter are valid)
11. Permohonan perpanjangan dan atau perubahan daerah penelitian harus diajukan kepada Kementerian Riset dan Teknologi/Badan Riset dan Inovasi Nasional selambat-lambatnya satu bulan sebelum Surat Izin Penelitian habis masa berlakunya dengan melampirkan surat rekomendasi dari mitra kerja di Indonesia.
(Extention of this Permit, or amandement of Location, should be requested to the Ministry of Research and Technology/ National Agency for Research and Innovation, at the latest one month before expiry date of the Research Permit Letter, with recommendation letter from the counterpart)
12. Setelah penelitian selesai diharapkan supaya Surat Izin Penelitian ini dikembalikan kepada Deputi Bidang Penguatan Riset dan Pengembangan selaku Ketua Tim Koordinasi Pemberian Izin Penelitian Asing.
(At the end of the research, this Letter of Research Permit should be returned to the Deputi of Strengthening for Research and Development, acting as the Head of Foreign Research Permit Coordinatimg Team)
13. Penelitian yang menggunakan Kapal Riset, pesawat survey udara, atau wahana apapun di wilayah Teritorial RI dan ZEE, serta wilayah udara RI, juga harus memperoleh *Security Clearance* dan didampingi *Security Officer*.
(Research using Vessel Research, Airborne Survey Flight, or any other vehicles in Indonesian territorial and EEZ as well as aerospace territory, should obtain Security Clearance and accompanied by Security Officers)
14. Izin Penelitian dapat dibatalkan/ dicabut apabila Peneliti Asing melakukan pelanggaran terhadap peraturan perundangan yang berlaku.
(Annulment and/ or revocation of the permit shall be applied if the foreign researcher violates the provisions of the prevailing laws and regulations)
15. Pelaksanaan penelitian dalam masa pandemik COVID-19 harus mematuhi protokol kesehatan yang diterbitkan oleh Kementerian Kesehatan dan instansi lain yang berwenang.
(Implementation of fieldwork in the pandemic of COVID-19 time shall follow the Health Protocol issued by Ministry of Heathl and other authorized agencies)

Demikian **Surat Izin Penelitian Nomor : 35 /E5/E5.4/SIP.EXT/2020, tanggal 5 Agustus 2020,** untuk dapat dipergunakan sebagaimana mestinya. Kami mohon dengan hormat kiranya instansi-instansi Pemerintah/Swasta maupun perorangan yang dihubungi untuk memberikan bantuannya kepada yang bersangkutan sesuai dengan peraturan yang berlaku.
(Herewith the Letter of Research Permit is issued to be used accordingly. We request the Government and private Institution or individual that receive the bearer of this letter to provide assistance in accordance with the rules)

Dikeluarkan di *(issued in)* : **J A K A R T A**
Tanggal *(date)* : **5 Agustus 2020**

KEMENTERIAN RISET DAN TEKNOLOGI/BADAN RISET DAN INOVASI NASIONAL

Penerima Surat Izin Penelitian
(Bearer of Permit Letter)

a.n. Deputi Bidang Penguatan Riset dan Pengembangan
Direktur Pengelolaan Kekayaan Intelektual

MATERAI
RP. 6.000,-

Ms. Penelope Bronwyn Godwin

Prof. Dr. Heri Hermansyah, ST., M.Eng, IPU

Biological materials transfer agreement

KEMENTERIAN RISET, TEKNOLOGI DAN PENDIDIKAN TINGGI

UNIVERSITAS NUSA CENDANA

LABORATORIUM RISET TERPADU

Jl. Adisucipto Penfui, Kupang 85001, NTT Telp. 0380 881580, Fax 0380 881674
Website http://www.undana.ac.id

NON – COMMERICAL

BIOLOGICAL MATERIAL TRANSFER AGREEMENT

No. 133 /UN15.L1/TU/2019

This biological Material Transfer Agreement is made on this day, by and between:

Universitas Nusa Cendana, an Indonesian government institution existing under the laws of the Republic of Indonesia, having its registered office at Jalan Adisucipto, Penfui, Kupang, Nusa Tenggara Timur, Indonesia.

Prof. Ir. Herianus J.D. Lalel, MSI, PhD as Head of Integrated Laboratory of Universitas Nusa Cendana, and Dr. Jakobis Johanis Messakh, S.Pd, M.Si., domiciled at Jalan Adisucipto, Penfui, Kupang, Nusa Tenggara Timur, Indonesia (hereinafter referred to as "PROVIDER").

WITH

Charles Darwin University (CDU) which is existing under the laws of Australia, having its registered office at Ellengowan Drive, Casuarina. NT 0910, Australia, represented by Professor David Young, in this matter acting in his capacity as the Dean, College of Engineering, IT and Environment of Research, CDU (hereinafter referred to as "RECIPIENT").

In consideration of the RECIPIENT'S covenant and premises contained herein, the PROVIDER's intent is to transfer to the RECIPIENT materials as follows:

Sample material	**Maximum number of samples**	**Parameter of interest**
Soil	150	Stable isotopes of soil water, bulk density, clay mineralogy and particle size
Plant stem	120	Stable isotopes of xylem water
Fresh water	45	Stable isotopes, tritium and chloride
Rain water	44	Stable isotopes, tritium and chloride

for the sole purpose of the study and for specific assays as described in the Research Plan (Appendix 1), which shall be an integral part of this agreement, upon the terms and conditions hereinafter appearing:

A. DEFINITIONS

In this agreement, unless the context otherwise requires, all words beginning with capital letters and defined herein below shall have the following meaning:

1. Agreement: Means this agreement and any Appendices thereto;

2. Research Plan/Protocol : Means detailed plan of study to be undertaken as described in Appendix 1.

3. Materials: Means samples of organism or non-organism; whereas organism samples or parts thereof, such as zoological, botanical and microbial specimens, populations, or any other biotic component of ecosystems, progeny, unmodified and modified derivatives thereof, genetic resources including genetic material (DNA or RNA), genetic information {sequence of bases, including but not limited to DNA or RNA or protein(sequence of amino acid)), natural derivatives (biological extracts) containing metabolites and metabolite information (including but not limited to chemical structures and biosynthetic pathway) and its modification; whereas Non organism samples from raw environmental (including soil, water, litter, gut contents, and any other abiotic components), that contain (and results in isolated microorganism) organism or parts of an organism and its natural derivatives (biological extracts) containing metabolites and metabolite information (including but not limited to chemical structures, enzymes and biosynthetic pathways) and their modifications, and functional units of heredity that include, genetic information (sequence of bases, including but not limited to DNA or RNA or protein), and its modification, which shall be an integral part of this Agreement.

4. Modified Materials: Means substances, information and cells; whereas substances include genetic materials and enzymes; whereas information include biochemical pathways or chemical structures or genetic information, genetic code, or DNA sequences; whereas cells include mutants; created by RECIPIENT which contain and/ or incorporate and/ or originated from the Materials and/or the use of the Materials.

5. Permanent loans: Means selected materials transferred to the RECIPIENT that might be kept for an indefinite period of time by the RECIPIENT under its best effort; some of the material(s) are returnable to and/or revocable by the PROVIDER in the circumstances of Article E of this Agreement.

6. Research Plan: Means the Research Plan described in Appendix A to this Agreement.

7. Scientist: Means the Scientist of either party as identified in this Agreement.

B. OWNERSHIP OF BIOLOGICAL MATERIALS

The RECIPIENT acknowledges that rights, title rights, title and interests of Materials are the Property of The Republic of Indonesia and the PROVIDER shall retain ownership of Materials.

C. USE OF MATERIALS

1) The RECIPIENT has agreed to use Materials and Modified Materials:

a) Solely for purposes as formulate in the Research Plan as further described in the Appendix 1;
b) In accordance with the terms of this Agreement and all applicable laws, statutes and regulations, e.g:
    i) Material to be transferred are obtained during the field work in Indonesia by the RECIPIENT and Indonesian Collaborator(s)/ or PROVIDER with prior valid permission from the Indonesian authorities.
    ii) Material from protected species under Indonesian laws and regulation and/ or species listed in CITES Appendix 1 or/and II and/ or species listed in the lUCN Red List of Threatened Species can only be transferred with prior valid permission from Ministry of Environment and Forestry, Republic of Indonesia.

2) The RECIPIENT has agreed to use Materials for geochemical analysis only. No taxonomic botanical, zoological, phylogenetic, microbiological or bioprospecting studies will be conducted with Materials. **The following text is not applicable to this research.**
~~The RECIPIENT has agreed to use materials for taxonomical studies only:~~

~~a) RECIPIENT, for being Eligible, shall provide proofs that (s)he belongs to a high standard zoological museum and/or herbarium and/or a high standard microbial facilities or distinguished university equipped with facility to preserve the Materials. Therefore materials can only be loaned permanently and deposited at the RECIPIENT'S institution where the safety of specimens can be ensured.~~

~~b) For botanical studies (optional):~~

~~i) Fertile plant materials (i.e. standard herbariums specimens) will be distributed according to the following: First set: Deposited in Herbarium Bogoriense (BO). If a single copy only is made, it may be loaned to a specialist outside Indonesia for identification, for a duration of 6 months (extendable), and must eventually be returned. Holotype specimens must be finally stored in BO. Second set: Sent to RECIPIENT as a permanent loan from the people of Indonesia. Third set: If a local, provincial-level herbarium exists (and is active, properly curated, and accessible to the public), this set will be deposited thcre. Subsequent sets: To be distributed as permanent loan to other foreign herbaria following discussions among the parties; different taxa have different priorities for distribution. The specimens are permanent loan from the people of Indonesia.~~

~~ii) Frequently, botanical work requires the collection parts of plants (such as seeds, cuttings, roots, bulbs, corms, leaves, plant tissue culture or any other material of plant) and/ or fertilematerial (fallen leaves, twigs, fruits) which are vital for plant identification. BO has begun a separate reference collection, and requests that where possible two sets of vouchers are collected. One set will be deposited with BO and the other set may be exported, to appropriate locations for identification and storage. iii) Export of permanent loan to foreign herbaria is for the explicit purpose of i) obtaining accurate identification, ii) encouraging in-kind exchanges of material from foreign herbaria to BO, iii) back up collection of Indonesian plant records and/or specimens should BO ever be destroyed or damaged by fire or other natural disaster.~~

~~c) For Zoological studies (optional):~~

~~i) MZB have the privilege to select these specimens from the collection to be loaned and transferred to the RECIPIENT if the complete copies of field catalogues are available to MZB.~~

~~ii) All zoological Materials designated as types (liolotype and paralypes) will be treated according to International Convention as follows: the holotype and some of the~~

paratypes are deposited at MZB, while some other of the Paratypes will be shared with the RECIPIENT. Some specimens might be distributed to other recognized depositories as stipulated under separate agreement and shall be kept in good condition.

ill) For collection management purposes, the RECIPIENT might attach their own labels containing registration numbers without removing the original or MZB labels and new registration numbers shall be reported to MZB. iv) For the loan material. The RECIPIENT, under its best effort, is responsible for identification and shall share all relevant information with the PROVIDER.

d) For phylogenetic studies (optional):

i) Selected materials shall be transferred in the form of PCRs and/ or extracted DNA only for the purposes of the research plan/protocol. ii) In the circumstances that DNA Analysis (DNA extractions, RNA extractions, PCRs Sanger sequencing and next generation sequencing) cannot be done in Indonesian laboratory, the analysis can be done in the appointed laboratory abroad by Indonesian researcher(s) with financial support of RECIPIENT, and/or by RECIPIENT regarding prior written consent of The Parties.

e) For Microbiological studies (optional):

i) Materials shall be prepared in duplicate and storage in the PROVIDER'S institution.

ii) Any microbial isolates and genetic materials including but not limited to DNA or RNA or proteins successfully obtained from raw environmental (including soil, water, litter, gut contents, and any others abiotic components) materials by RECIPIENT are owned by PROVIDER and further may be used by RECIPIENT for research purposes. lit) Microbial resources shall be deposited in Indonesian Culture Collection (InaCC), even though the isolation is conducted in other countries.

iii) RECIPIENT shall have prior written approval from PROVIDER in order to deposit isolated microbial strains both in providing country or other country in the Public Culture Collection. Once microbial strains are approved to be deposited in public Culture Collection, a specific MTA for third party (Appendix 3) shall be accompanied with the microbial strains. v) RECIPIENT has agreed to use and report project collection code in the assigned form for all isolates successfully obtained in the project (Appendix 4).

iv) vi) RECIPIENT assumes all risk and responsibility in connection with the receive, handling, storage, disposal and use of the materials. The RECIPIENT is solely responsible for compliance with all applicable guidelines, regulation and law and respect to health, environmental and security risks. vii) RECIPIENT shall report annually the status of Materials and/or isolated microbial strains to PROVIDER.

f) For Bioprospecting studies (optional): i) In the circumstances analyses cannot be done in Indonesia, selected materials may be transferred to RECIPIENT in the form of suitable material (e.g. dried plant material, extract, etc.) ii) RECIPIENT shall destroy any Materials left in the end of the project with proof of Certificate of Disposal or return to PROVIDER (Optional: each arrangement is .selected in regard of the study the parties about to conduct jointly. As if the study is regarding botany, then the parties choose the arrangement for botanical studies only, as if the parties study about above all studies, then the parties choose all above arrangements).

3) The RECIPIENT has agreed not to:

a) Transfer, distribute or disclose by any means, either international or accidental, Materials or the use thereof, to any other party, except as expressly stated in Appendix 1, for the sole purpose of the Research Plan under the supervision of the Scientists;
b) Use Materials for any purpose other than as expressly stated in Appendix 1.
~~c)~~ Specific to the permanent loans, these materials shall not be available for loan as they will be destroyed after the completion of geochemical analysis. ~~be open for public at the end of the project, or at another time mutually agreed by the RECIPIENT and PROVIDER in the Research Plan / Protocol~~.

4) Parties have agreed that for the shipping fees will be the responsibility of the RECIPIENT.

D. THE RESEARCH PLAN

1) The Research Plan shall be developed together by Parties. In the Research Plan, Parties will be represented by the Scientist. The role and responsibilities of Scientists shall be further described in the Research Plan.
2) Parties agree to provide best effort to conduct researches, tests and the experiments related to the Research Plan within the jurisdiction of the Republic of Indonesia, using available national capabilities and resources.
3) The RECIPIENT shall transfer, in confidence, to the PROVIDER any and all data, records and results derived from Materials and Research Plan, including detailed records of direct use of Materials. The schedule and form of this transfer will be as detailed in the Research Plan.

E. RETURN OF THE MATERIALS – the following text is not applicable to this research, because samples will be destroyed once geochemical analysis is complete.

~~1) The RECIPIENT has agreed to safely archive Materials such as extracted DNA and silica dried material, perpetually under the conditions in this MTA. The materials and all of the data, records, and results derived from Materials and Research Plan/ Protocol must be shared to the PROVIDER at a mutually agreeable time following a request from the PROVIDER.~~
~~2) In case of any of the above provisions regarding Materials are violated by the RECIPIENT and this violation is not instantly acknowledged and addressed by the RECIPIENT to the satisfaction of the PROVIDER, the PROVIDER may request in writing to the RECIPIENT to return any Materials, and all of the data, records, and results derived from Materials and Research Plan/ Protocol, and the RECIPIENT has agreed to fulfil the request within one (1) month of the written request.~~
~~3) Regarding materials designated as permanent loan material, PROVIDER may request return of loan permanent material in writing from RECIPIENT in the event when materials deposited in PROVIDER become damaged or loss due to natural catastrophic event e.g. earthquake or fire and/ or riot and/ or civil commotion.~~

F. MODIFICATIONS – the following text is not applicable to this research as samples will be destroyed one the geochemical analysis is completed

~~1) The PROVIDER shall retain partial ownership of Modifications as co-owner with the RECIPIENT.~~
~~2) Any modifications made from the Materials shall be reported to the PROVIDER, and shall not be provided to any third party without prior written consent from the PROVIDER.~~
~~3) The proportion of the ownership of Modifications shall be stipulated in a separate agreement.~~

4) ~~If at any time, any product or process derived from Materials shipped under the terms of this Agreement, whether or not such product or process is subject to intellectual property protection, is identified as having potential commercial use, the RECIPIENT and/ or other Receiving Institutions shall immediately cease all further research and activity undertaken in connection with the materials and shall promptly notify the PROVIDER. The RECIPIENT and/ or other Receiving Institutions shall be prohibited from continuing to engage in the activity for which the commercial potential was identified until it has entered into a written agreement with the PROVIDER pertaining to the use of Materials and benefit-sharing~~

G. INTELLECTUAL PROPERTY RIGHTS

1) The RECIPIENT acknowledges that Materials or Modified Materials are or maybe the subject of patent applications. Nothing in this Agreement grants any implied or expressed license or right under any patents or any know-how or trade secrets or other proprietary rights to use Materials or Modified Materials or any product or process related thereto for profit-making or commercial purposes, including but not limited to, production, sale, screening or product design.
2) Materials requested for commercial use shall not be shipped until Parties have reached a written agreement on Intellectual property rights and sharing of benefits.
3) The RECIPIENT shall be ceased and prohibited in further activities analysing materials from which the commercial potential was identified until it has entered into a writing agreement with PROVIDER to determine the inventor and pertaining to the use of genetic heritage and benefit sharing.

H. PUBLICATION

1) Any publication resulted from this collaboration using materials of Indonesian Biodiversity shall be authored and/or co-authored by PROVIDER and RECIPIENT.
2) PROVIDER and RECIPIENT have the right to review proposed publications of results obtained under this MTA prior to publication.
3) PROVIDER and RECIPIENT agree not to publish scientific results gathered under this MTA without the other party's consent.
4) PROVIDER shall contribute at least in the writing of anything related to the Materials and introduction regarding the Materials of origin to ensure that the co-authorship comply with international code of co-authorship.
5) Portions of data shall be published in Indonesian relevant journals or other relevant journals the PROVIDER and RECIPIENT agreed upon.
6) PROVIDER and RECIPIENT agree to acknowledge the Government of Indonesia as the source of Materials in all publications.

I. CONFIDENTIALITY

The RECIPIENT shall treat in confidence any information relating to Materials and/or Modified Materials save for information that is in the public domain through no fault of their obligation herein. Such information shall include, without limitation, any specific, technical, trade or business information of the PROVIDER.

J. DISCLAIMER OF WARRANTY

1) The PROVIDER makes no representations, conditions or warranties, either expressed or implied with respect to any use of Materials or Modified Materials.

2) The PROVIDER shall not be liable for loss whether direct, consequential, incidental or special (and whether arising from the use, handling, storage, defect, error, fault or failure to perform with respect to Materials or Modified Materials).
3) Except to the extent prohibited by law, the RECIPIENT'S use, storage or disposal of the Materials is allowable. The PROVIDER shall not be liable to the RECIPIENT by any other Party, caused by the RECIPIENT's use, storage or disposal of the MATERIALS. The RECIPIENT should provide an annual report summarizing the RECIPIENT's use of the Materials.
4) Nothing in this agreement shall be construed as a warranty or representation by the PROVIDER that materials, Modified Materials or Inventions are or will be free from infringement of intellectual property rights of any third party.
5) The RECIPIENT has agreed that all persons listed in the Research Plan from (CDU) are under the direct responsibility of the RECIPIENT, and the actions of such persons, and consequences thereof, with respect to Materials and Research Plan are thereby considered the full responsibility of the RECIPIENT.

K. INDEMNITY

1) The RECIPIENT hereby jointly and severally agrees and undertakes to indemnify, hold harmless and defend the PROVIDER against any and all claims, actions and damages, liabilities, loss whatsoever (including all legal costs and expenses on a full indemnify basis) arising out of or resulting from directly, the possession, use and/or storage of any of the Materials and Modified Materials or any reason of any breach of the terms herein by the RECIPIENT.
2) In no event shall the PROVIDER be liable for consequential or incidental damages arising from breach or breaches of this agreement.
3) No action, whether in contract or tort (including negligence) or otherwise arising out of or connection with this Agreement may be brought by the PARTIES more than six (6) months after the cause of action has occurred.

L. TERMINATION

1) This Agreement will terminate on the earliest of the following date: (a) on the completion of the implementation activities set forth in the Research Plan as described in the Appendix 1, or (b) in thirty (30) days' written notice by either party to another.
2) In addition, the PROVIDER may terminate this Agreement if it is of the view that the RECIPIENT is in breach of any of the terms hereof and such breach, if capable of being remedied by the RECIPIENT after thirty (30) days' written notice by the PROVIDER.
3) Upon termination of this Agreement as provided above, the RECIPIENT shall discontinue its use of the Materials and Modified Materials and will, upon direction from the PROVIDER, return and/ or destroy any remaining Materials and Modified Materials, including but not limited to, all of the data, records, and results derived from the Materials and Research Plan/ Protocol.
4) Clauses C, E, F, G, H, I, and J of this Agreement shall survive the termination of this Agreement howsoever caused.

M. ARBITRATION

1) Any and all disputes in connection with this Agreement shall, so far as is possible, be settled amicably between Parties.
2) Failing such an amicable settlement, any and all disputes, controversies, and conflicts arising out of, or in connection with this Agreement, or its performance, shall be finally settled by

arbitration in accordance with the Rules of Arbitral Procedure of The Indonesian National Board of Arbitration ("BANI"), which rules are deemed to be incorporated by reference into this clause The Arbitration proceedings shall take place in Jakarta and shall be conducted in English.

3) Parties agree that the Panel or Arbitrators shall consist of three (3) arbitrators, the Provider and the RECIPIENT shall respectively have the right to appoint one (1) arbitrator and should one party fail to appoint its arbitrator in fourteen (14) days from the appointment of the first arbitrator, then such arbitrator shall be appointed by the BANI. The two (2) arbitrators so appointed shall jointly appoint the two (2) arbitrators fails to appoint the third arbitrator in fourteen (14) days from the appointment of the second arbitrator, then such third arbitrator shall be appointed by the BANI.
4) The decision of the Panel of Arbitrators shall be final, binding, and incontestable and may be used as a basis for judgment thereon in Indonesia or elsewhere. It shall include a determination as to which of Parties shall pay the costs of the arbitration.
5) Neither Party shall be entitled to commence or maintain any action in a court of law upon any matter in dispute until such matter shall have been submitted and determined as herein before provided, except for the enforcement of such arbitration.
6) Pending the submission to arbitration and thereafter until the Panel of Arbitrator publishes its award, except for the Termination set forth in Clause L of this Agreement, Parties shall continue to perform all their obligations under this Agreement without prejudice to a final adjustment in accordance with the said award.

N. NOTICE

1. Address

   Any notice required or permitted to be given hereunder shall be in writing and may be given by personal delivery, registered mail, facsimile if confirmed on the same day in writing by registered mail, with postage fully prepaid or facsimile to the following address:

a. PROVIDER

Institution: Universitas Nusa Cendana

Facsimile: +62 (0380) 881674

Email: info@undana.ac.id

Scientist: Dr. Jakobis Messakh

Email: yapmessakh@gmail.com

b. RECIPIENT

Institution: Charles Darwin University

Manager Research Grants and Business Development

Ellengowan Drive, Casuarina NT 0810, Australia

Email rgbd@cdu.edu.au; david.young@cdu.edu.au

Scientist: Ms Penelope Bronwyn Godwin

Email : Penelope.Godwin@cdu.edu.au

2. Receipt
   Any notice so given shall be deemed to be received in case of facsimile, forty-eight (48) hour after dispatch, or in case of a letter upon receipt, or fourteen (14) days after posting, whichever is sooner, for mail sent between any countries, upon receipt or seven (7) days after posting, whichever is sooner,

3. Service
   To prove service of Notice, it shall be sufficient to prove that a letter, e-mail, or facsimile containing the notice was properly addressed and properly dispatched or posted.

O. GOVERNING LAWS

This Agreement shall be construed, governed, interpreted and applied in accordance with the laws of the Republic of Indonesia.

P. VARIATIONS

This Agreement may only be varied by written agreement signed by both parties.

Q. COUNTERPARTS

This Agreement may be executed in counterparts, which together forms one document.

PROVIDER	RECIPIENT
UNIVERSITAS NUSA CENDANA	CHARLES DARWIN UNIVERSITY
LABORATORIUM RISET TERPADU UNIVERSITAS NUSA CENDANA	
______________________________	______________________________
Prof. Herianus J. D. Lalel Date: 16/9/19	Professor David Young Dean, College of Engineering, IT and Environment Date: 4/4/19
Witnessed by,	**Witnessed by,**
Universitas Nusa Cendana Date: 16/9/19	Danielle Choveaux Charles Darwin University Date: 4/4/19
…………………………………….	…………………………….
Scientist	**Scientist**

PROVIDER

UNIVERSITAS NUSA CENDANA

Professor Herianus Lalel

Date: 16/9/19

Witnessed by,

Dr. Jakobis J. Messakh.

universitas nusa cendana.

Date: 16/9/19

Scientist

RECIPIENT

CHARLES DARWIN UNIVERSITY

Professor David Young

Dean, College of Engineering, IT and Environment

Date: 4/4/19

Witnessed by,

Danielle Choveaux

Charles Darwin University

Date: 4/4/19

Scientist

Sample collection permit

LEMBAGA ILMU PENGETAHUAN INDONESIA
(INDONESIAN INSTITUTE OF SCIENCES)
SEKRETARIAT KEWENANGAN ILMIAH KEANEKARAGAMAN HAYATI
(SECRETARIAT OF SCIENTIFIC AUTHORITY FOR BIODIVERSITY)

LIPI

Gedung Pusat Pemanfaatan dan Inovasi Ilmu Pengetahuan dan Teknologi
Cibinong Science Center, Jl. Raya Jakarta - Bogor Km. 47, Cibinong 16912
Telp. (+62 21) 8791 7216/7219
Fax. (+62 21) 8791 7221
E-mail: skikh@mail.lipi.go.id

Nomor : B-2965/IV/KS.01.04/4/2021 Cibinong, 15 April 2021
Lampiran : -
Perihal : Rekomendasi Pengangkutan Sampel Air, Tanah, dan Batang Tanaman Dari Kecamatan Haharu, Sumba Timur ke Darwin, Australia a.n. Penelope B. Godwin (*Charles Darwin University*)

Yth.
Kepala Kantor Hubungan Internasional
Universitas Nusa Cendana
Jl. Adisucipto, Penfui Kotak Pos 1212, Kupang 85001
Email: puskomundana@yahoo.com

Menindaklanjuti surat Saudara No. 09/UN15.IRO.1/KP/2021 tanggal 16 Maret 2021 (yang kami terima tanggal 8 April 2021) perihal permohonan Izin Pengiriman Sampel Air, Tanah, dan Batang Tanaman ke Darwin Australia sebagai bahan penelitian Sdr. Penelope B. Godwin (mahasiswa S3 dari Universitas Charles Darwin, Australia yang bermitra dengan Universitas Nusa Cendana) yang berjudul "*Catchment Hydrology and Landcover in Tropical Karst Savannas: A Case Study in East Sumba, Indonesia*", pada prinsipnya kami **dapat memberikan rekomendasi** pengangkutan sampel yang dikoleksi dari wilayah karst Sumba Timur ke Universitas Charles Darwin, Australia berupa:

- Sembilan liter air tanah dari asal mata air dan sumur masyarakat
- Empat kilogram tanah dari wilayah karst
- Tanaman domestik dari perladangan masyarakat ukuran 20 x 10 cm sebanyak satu boks

Semua sampel wajib diradiasi gamma dan hanya akan digunakan untuk keperluan sebagaimana pengajuan izin penelitian yang dikeluarkan oleh Kemenristek/BRIN dengan tidak ada yang dikembangkan ke arah bioprospektif dan sisa sampel akan dimusnahkan.

Demikian rekomendasi ini kami sampaikan. Atas perhatian dan kerjasamanya, kami ucapkan terima kasih.

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