

**Episodic recharge of groundwater due to
cyclonic events within the Limpopo province,
South Africa**

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ABSTRACT

Research was conducted based on long-term groundwater monitoring data to investigate the effect of cyclones on episodic recharge in the Limpopo province. Episodic recharge was mathematically defined through empirical observations, as modelling episodic recharge requires a very detailed dataset and the spatial scale of the study area rendered this modelling approach impractical. A detection algorithm based on the aforementioned episodic recharge definitions was developed and applied to boreholes with long-term historical water levels and the cyclone database along the eastern seaboard over the same periods. The correlation between cyclones making landfall, tropical storms and tropical depressions moving within 100km from Mozambique's and South African coastline were calculated with respect to the defined episodic recharge definitions. The maximum rainfall associated with the aforementioned events were also studied. Although some cyclone events do coincide with the episodic recharge events, the study showed that cyclones is not the driving factor for episodic recharge in the Limpopo province despite some evidence from long-term monitoring data that might suggest this.

Keywords: episodic recharge, cyclonic rainfall, correlation coefficient algorithm, groundwater resources

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LIST OF ABBREVIATIONS

AMD	Acid Mine Drainage
DWS	Department of Water and Sanitation
ETD	Extra-Tropical Depression
GDP	Gross Domestic Product
GRAII	Groundwater Resources Assessment Phase II
GRIP	Groundwater Resources Information Project
ITC	Intense Tropical Cyclone
mamsl	meters above mean sea level
MTS	Moderate Tropical Storm
NGA	National Groundwater Archive
RSMC	Regional Specialized Meteorological Centre
SD	Subtropical Depression
STS	Severe Tropical Storm
SWIO	South-West Indian Ocean
TC	Tropical Cyclone
TD	Tropical Depression
TD100	Tropical Depression within 100km of eastern seaboard
TS100	Tropical Storm within 100km of eastern seaboard
VITC	Very Intense Tropical Cyclone
WMO	World Meteorological Organization

1 INTRODUCTION

The following chapter provides an introduction to the research problem, the aims and objectives of the study.

1.1 Background

Recharge of groundwater occurs throughout South Africa due to seasonal precipitation infiltrating through the unsaturated zone into the saturated zone, i.e. the groundwater table. As rainfall across South Africa varies from season to season, the extent to which the groundwater resources will replenish also varies. In semi-arid areas rainfall is to a greater extent intermittent and may lead to sporadic precipitation events further limiting the estimation of seasonal groundwater levels. Groundwater recharge through precipitation events may either take place through sporadic rainfall occurrences, for example cyclonic systems and frontal weather systems transferring moist air from the oceans inland, or by periodic rainfall, such as seasonal rainfall, over a sequential period of time which may lead to a rise of the groundwater table. The latter recharge event will in most cases, permitted by hydrogeological factors, lead to an increase in groundwater levels due to the incessant nature of the surface precipitation infiltrating into the subsurface to become part of the groundwater, physically and chemically (Van Wyk, 2010; Van Wyk *et al.*, 2011). The recharge events associated with cyclonic systems that may bring continuous rainfall over successive days are unpredictable and may occur yearly or every few years.

It is speculated that episodic recharge of groundwater in the Limpopo provinces are not only attributed to seasonal rainwater infiltrating into the subsurface, as these areas are influenced by tropical storms such as cyclones which are associated with large amounts of rain that may lead to severe surface flooding and in some cases, may be the cause of the to complete recharge of the groundwater that occurs periodically.

Groundwater level monitoring data, both past and present, is available for the Limpopo province as well as the frequency and intensity of cyclones that made landfall in South Africa.

No research has been done regarding the episodic recharge of groundwater due to cyclonic events in South Africa, although research has been conducted on how episodic recharge is influenced by seasonal rainfall and the correlation between groundwater levels and seasonal rainfall.

1.2 Research Problem

Some empirical evidence exists, that episodic recharge of the Limpopo groundwater system is directly related to cyclonic events. To date no detail research has been conducted on the aforementioned phenomenon and forms the core of the research conducted.

1.3 Aims and Objectives of this Study

The main aim of the study is to try and establish a correlation between the historic episodic recharge events in the Limpopo province and the historic cyclonic events. Once these correlations have been calculated, it is possible to determine if a cyclonic event is a major driving factor in episodic groundwater recharge.

The objectives of the research are summarised as follows:

1. Obtain historic cyclone information to compile a database to be used in the analysis. This data base will contain historic dates of cyclones that made landfall as well as cyclones that were in close proximity (~100km) to the eastern seaboard of Southern Africa.
2. Compile a borehole data base of boreholes that has long-term water levels that exhibit episodic recharge occurrences. The selection of the boreholes will be dependent on the proximity (~ 10km) of rain gauges to these identified boreholes as well as the availability of rainfall data over the same time period water level monitoring took place.
3. Determine what the torrential cyclonic quantities of rainfall are and how much precipitation is required to allow total recharge of the groundwater to occur.
4. Develop an analysis algorithm that will allow the calculation of correlation coefficients between episodic recharge events and cyclonic activity. A mathematical expression is required to describe/identify episodic recharge.

1.4 Hypotheses

1.4.1 Hypothesis (H_1)

It is postulated that cyclonic rainfall is partially responsible for total recharge of groundwater within the Limpopo province, due to the fact that tropical storms such as cyclones are associated with torrential rainfall.

1.4.2 Hypothesis (H_0)

No clear correlation exists between episodic recharge and cyclonic events due to the fact that episodic recharge generally takes place during the wet season, which is also the season when cyclonic events takes place.

2 LITERATURE REVIEW

2.1 Introduction

Cyclones may be the cause of regular total recharge, and if this is the case, the areas affected by cyclonic activity must be identified in order to be able to plan the use of the water resources accordingly. In South Africa's rural areas, agriculture on a subsistence scale is of utmost importance to the survival of the inhabitants along with commercial operations that provide valuable products to the country's population, and also provide 7,2% of South Africa's gross domestic product (GDP) (Young, 2013).

2.2 Episodic Recharge

Inputs into the hydrological system at the land surface such as precipitation, irrigation, or transient surface water all travel through the unsaturated zone to recharge the saturated zone at rates that can be described as constant and episodic (Nimmo *et al.*, 2015). The two components of water movement into the saturated zone are clarified by different mechanisms. The constant rate of water flow derives from descending flow which is slow and diffusive so as to saturate the sequential fluctuations imposed at the land surface (Nimmo *et al.*, 1994). The episodic rate of water flow is explained as water which comes through pathways in the aquifer, such as fractures and cracks in the rocks, travelling fast or direct enough that some degree of flux and continues to the water table (Nimmo *et al.*, 2015). The episodicity of the recharge affects how much of the introduced water becomes part of the recharge and due to this, change in climatic events, for instance cyclones, will have a significant impact on water supply to the aquifer (Crosbie *et al.*, 2012). Nimmo *et al.* (2015) further explains that the intensity of storms may greatly affect the amount of recharge due to the fact that more water may be produced than required to rewet the dry soil which will lead to more surface runoff which will escape without becoming recharge. The conditions of the affected area that is to be recharged are influenced significantly by the soil type, underlying geology, vegetation, angle of the slope, and temperature of the area.

Episodic recharge is easier to measure in arid and semi-arid areas than in humid areas as a result of recharge easily being recognised upon inspection in arid and semi-arid regions due to that the groundwater levels will show a clear fluctuation other than in humid regions where the recharge from one event may not be distinguished from another recharge event (Healy & Cook, 2002).

Episodic recharge can be described as the recharge of groundwater that isn't attributed to regular rainfall patterns of which non-regular rainfall events include intermittently high amounts of rainfall, tropical storms, or non-seasonal rainfall events (Barnes, et al., 1992; Zhang *et al.*,

1999; Lewis & Walker, 2002; Van Wyk, 2010). Lewis and Walker (2002) continue to describe episodic recharge which occurs by means of two methods that include diffuse recharge from rainfall events and focused recharge through flood events. Robins *et al* (2013) sums episodic recharge up as an occurrence which is difficult to monitor and measure, nonetheless it is imperative to distinguish when recharge is likely to be irregular as it will considerably affect recharge potential.

Due to extremes in climate that can be attributed to global warming, stored water in arid areas can be considered as the remainder of palaeorecharge from an age when the climate was wetter than it currently is, and taking this into consideration, recharge has been considered as episodic when it occurred for millennia at a time (Commander, 2002; Cresswell *et al.*, 1999; Jacobson *et al.*, 1989). On the other hand, episodic recharge events can also only last a couple of days depending on the amount of unusual rainfall (Barnes *et al.*, 1992). Taking all of these factors into account, Crosbie *et al.* (2012) has determined that episodic recharge in semi-arid areas have a minimum recurrence interval of between 1.3 and 22 years which escalates with increasing aridity. This recurrence interval is important to ensure proper water resource planning and management and by being able to estimate the recharge of an area, long-term recharge estimate can also be made. To ultimately determine whether episodic recharge forms part of the total recharge is extremely difficult due to the fact that most recharge studies are intended to show estimate of mean annual recharge coupled with that long-term groundwater recharge and episodic recharge data is very rare (Lewis & Walker, 2002). Lewis & Walker (2002) further explain that the amount of recharge depends on the amount of rainfall, which thus assumes that areas with particularly regular rainfall patterns, large episodic recharge events are unlikely to occur. Areas thus having a very episodic rainfall regime, will have a sporadic recharge regime. Aridity of an area plays a large role in the recharge of the area as the unpredictability of rainfall surges as aridity increases which leads to the implication that rainfall becomes more irregular and episodic as aridity increases.

2.3 Factors Influencing the Infiltration Rate of Surface Water

Casenave and Valentin (1992) and Wood and Blackburn (1981) suggest that there are various factors that influence infiltration of water into the subsurface and may vary from one region to another. In most semi-arid areas, the factors influencing the infiltration rate are similar and may even influence other soil factors such as sediment production and surface runoff (Blackburn, 1975). Casenave and Valentin (1992), also put forward that the infiltration rate is vastly influenced by the surface in semi-arid areas and the influencing factors are can be arranged into order according to the influence the factor has on the infiltration rate. These factors are listed in decreasing order of influence as the following: surface crust, vegetation cover, faunal activity, surface roughness, vesicular porosity, and soil texture.

2.3.1 Surface Crusting

Surface crusting occurs when the soil surface dries out after rain or irrigation (National Resources Conservation Service, 2011). During rain or irrigation water droplets infiltrate soil aggregates and disband these aggregates into soil particles after which these particles settle into block surface pores. This process causes the soil surface to seal over which obstructs water from infiltrating into the subsurface. Once the soil surface dries out, the surface crusts. Various types of surface crusting can be associated with different porosities that range from high to very low depending on the type of crusting such as drying, structural, erosion, aeolian, runoff unsettling, sedimentary and gravel (Casenave & Valentin, 1992).

2.3.2 Vegetation Cover

Vegetation cover includes the living plants as well as the organic remnants which superficially rearrange the soil particles on the surface. These plants and remnants mainly protect the soil against external elements such as rain and wind. Scott (2000) states that the degree of water infiltration may be deterred, depending on the type of vegetation. Soil particles with a low specific surface area are more likely to repel water which leads to more surface runoff. Soils with a high level of organic matter are also more likely to repel water. Well covered surfaces halt the flow of surface runoff which will allow surface water to seep into the subsurface whereas soils that are exposed allow water to run off with more ease (Mohammad & Adam, 2010; Scott, 2000).

2.3.3 Faunal activity

Faunal activity affects the infiltration rate as it causes macro-porosity due to the organisms such as earthworms and termites that move within the subsurface constructing macropores. This affects the physical structure of the soil through the burrowing by the macrofauna which leads to higher water adsorption and retention (Sarr *et al.*, 2001). Burrowing by these organisms can decrease soil bulk density, increase the soil's water retention, and increase the soil's porosity which ultimately leads to a higher infiltration rate (Denning *et al.*, 1978; Eldridge, 1994; Sarr *et al.*, 2001).

2.3.4 Surface Roughness

Surface roughness is defined as irregularities on the ground ranging from 5cm to 50cm which may be either naturally made or man-made (Casenave & Valentin, 1992). The roughness of the ground surface is likely to reduce runoff and increase water storage in the soil. The angle of the slope and the continuity of the irregularities determine how much runoff can occur which can be stored (Casenave & Valentin, 1992). Surface roughness may also regulate the rate of erosion

and runoff as it is a key factor used to describe the general variation in surface elevation in terms of the soil's microrelief (Gómez & Nearing, 2005; Zheng *et al.*, 2014).

2.3.5 Vesicular Porosity

Vesicular porosity refers to the state when there are ample vesicles in the microlayers of the soils surface crusts which leads to higher porosity but does not diffuse water efficiently as these pores are not unified (Figueira & Stoops, 1983). These pores are created when air is encapsulated within the soil's microlayers due to the low soil diffusivity (Casenave & Valentin, 1992). The measurement of the vesicular porosity of a specific soil can provide a definitive indication of how poorly the soil can allow water to infiltrate. Casenave and Valentin (1992) go on to state that the number of pores within a soil can be related to the amount of runoff that can be expected from rainfall on the surface.

2.3.6 Soil texture

Soil texture can be broadly defined as the proportions of the individual soil particles in a mixture of soil (Oberthür *et al.*, 1999). The soil texture classes can range from sandy, which can be associated with a rough texture, to clayey, which can be associated with a fine texture. The texture of the classes is determined by the size of the soil particles within a mixture of soil, such as a sandy soil consists mainly of sand particles with larger dimensions whereas a clayey soil consists of mainly sand particles slighter dimensions (Casenave & Valentin, 1992).

2.3.7 Summary

Most of the factors discussed above influence macroporosity in various manners. Macropores within the subsurface influence the flow of water on the surface as well the infiltration of the water into the subsurface. The macropores structures transport water and minerals within rainwater into the soils below, and if there isn't a sufficient network of macropores present, surface runoff may increase thus decreasing the amount of solutes entering the subsoil (Larson, 1999; Weiler & Naef, 2003). Water that infiltrates into the subsoil through macropores flows rapidly and may lead to certain fragments of the soil not coming in initial contact with infiltrating water as the water will move through the shrinking cracks, worm channels, and root holes in the soil thus creating preferential flow (Flühler *et al.*, 1996; Weiler & Naef, 2003).

On the surface, infiltration rates are controlled by vegetative, edaphic, climatic, and topographic aspects from which the vegetation is the only influence that can really be controlled by anthropogenic practises (Wood & Blackburn, 1981). Wood and Blackburn (1981) continue to state that the type of vegetation and the extent thereof may alter the soil-water relationship. Vegetative cover affects numerous hydrological processes that include infiltration of water,

percolation of water, surface runoff, evaporation, transpiration, and soil water storage (Dadkhah & Gifford, 1980). Animals that graze in either a natural- or anthropogenic situation eat the vegetation and trample on the soil which has a major impact on the infiltration capabilities of the soil. Dadkhah and Gifford (1980) reason that by constant trampling of the soil, it is compacted to such an extent that vital macropores required for significant water infiltration collapse, and this leads to the soil's infiltration rate decreasing while the runoff increases.

2.4 Factors Affecting Groundwater Recharge

Groundwater recharge is influenced in various manners that can either be analysed in the field, or using laboratory methods. Groundwater recharge may differ considerably both within and between watersheds due to dissimilarities in topography, sediments, and climate in alternating areas (Nolan *et al.*, 2007). The amount of recharge is determined using various factors such as aerial photos, geology maps, a land use database, and field verification, which in some cases will all be combined to form a recharge potential zone (Yeh *et al.*, 2009). Zones with the most efficient recharge will also be most susceptible to the diffusion of pollutants in the subsurface (Shaban *et al.*, 2006).

Groundwater recharge may be categorized as diffuse or focussed with each method of recharge operating on its own separate set of mechanisms (Nolan *et al.*, 2007; Scanlon *et al.*, 2006). Diffuse recharge refers to surface water originating from precipitation that infiltrates and percolates through the unsaturated zone into the saturated zone and usually occurs over large areas (Scanlon *et al.*, 2006; De Vries & Simmers, 2002). Diffuse recharge also may uncommonly occur in arid and semi-arid regions but usually occurs in humid areas where shallow water tables and gaining streams are habitual (Nolan *et al.*, 2007; Ng *et al.*, 2009). Focused recharge occurs when surface water descends down the surface into any waterbody on the surface such as a lake, stream, or canal (Nolan, Healy, Taber, Perkins, Hitt, & Wolock, 2007). According to Ritorto *et al.* (2009) spring originating in karst structures below surface may be attributed to focussed recharge as this type of recharge is associated with losing streams which thus allows water to flow in these subsoil conduits. As focussed recharge occurs through surface flow of water, the water will always flow to the lowest point in the area such as a depression or sinkhole from which where it recharges the subsoil through fractures in most cases (Scanlon *et al.*, 2006). Yeh *et al.* (2009) further state that due to that surface water flow according to gravitational forces, groundwater potential zone with the highest recharge potential will be situated in an area downstream in the basin due to the gravelly sands found in the bottom of valleys.

2.4.1 Rainfall

Rainfall is the most important recharge controlling factor as without it no natural recharge would be able to occur. This input into the soil has various characteristics that play a role in recharge such as the duration, the intensity, and distribution spatially thereof (Connelly *et al.*, 1989). The report by Connelly *et al.* (1989) also specified that rainfall may be intercepted by vegetation before it reaches the soil. Rainfall interception is the rain that falls on vegetation which then evaporates before it ever reaches the soil below and is prone to increases in areas that have thick vegetation canopies over the soil such as forests (Klaassen *et al.*, 1998). In times of prolonged precipitation, the vegetation will act as a reservoir for water after only when this vegetal reservoir is full, the water will run down the vegetation and fall onto the soil (Klaassen *et al.*, 1998).

2.4.2 Evapotranspiration

Evapotranspiration accounts for the largest share of a catchment's water balance as all plants require moisture and extract this moisture from the soil through the plant's roots and thus the amount of vegetation has a direct influence on the amount of evapotranspiration (Connelly *et al.*, 1989; Brümmer *et al.*, 2012). According to a study done by Shukla and Mintz (1982) about two thirds of all precipitation can be accounted for by land-surface evapotranspiration. In a study done by Zhang *et al.* (2001) it was found that areas that are covered by forests will have a higher evapotranspiration than areas that are only covered by grass, and that there are various factors such as rainfall interception, net radiation, advection, turbulent transport, leaf area, and plant-available water capacity that act as key controllers for evapotranspiration. Vegetation dries the soil by extract water therefrom, and when the plant available water is less than the transpiration demand of the vegetation, the plants become stressed and are only able to extract a fraction of the demand which in effect affects the plant's growth (Brümmer *et al.*, 2012).

2.4.3 Surface Evaporation

Surface evaporation is one of the main aspects when taking the relationship between soil and atmosphere into account (Teng *et al.*, 2014). The amount of free water available at the potential moist soil surface is considered to be the potential evaporation and may be influenced by temperature, wind, humidity, atmospheric pressure and the amount of sunlight per day (Connelly *et al.*, 1989; Teng *et al.*, 2014). All these influencing factors make it difficult to precisely determine the amount of water available to evaporation at the surface, as well as the amount of water being evaporated. All of the water removed from the soil by surface evaporation is thus no long potential recharge in the soil (Connelly *et al.*, 1989). Recharge from rainfall will directly be influenced by the surface evaporation rate which is very influential in semi-arid areas (Meredith *et al.*, 2015).

2.4.4 Surface Runoff

Runoff is dependent on various factors which may influence the amount of groundwater recharge individually or as a collective. Runoff is influenced by surface roughness, the gradient of the slope, the faunal cover, the type of overland flow which may either be rill or sheet flow, the type of channel flow which may either be turbulent or laminar flow, the surface water storage capacity, and the amount of rainfall (Connelly *et al.*, 1989; Harbor, 1994; Arnaez *et al.*, 2007). Infiltration of surface water into the subsurface will increase when a larger amount of water is available to the soil for a longer period of time by means of water collecting in ponds or any depression on the surface (Connelly, Abrams, & Schultz, 1989).

2.4.5 Infiltration

Infiltration is when water enters into the subsurface and controls various factors of surface water flow (Franzluebbers, 2002). According to Radke & Berry (1993) infiltration's characteristics upon analysis give a good indication of changes in a soil's physical and biological properties. Various factors influence infiltration of surface water such as soil moisture content, slope of the landscape, soil structure and texture, entrapped air, vegetation cover, soil management, and organic matter content (Connelly, *et al.*, 1989; Radke & Berry, 1993; Bharati *et al.*, 2002). If no cracks exist on the surface due to surface crusting water will run off the surface and not infiltrate into the subsurface (Novák *et al.*, 2000).

2.4.6 Macro Catchment Influences

Macro catchment influences are considered to be the land uses in the areas surrounding the catchment which may influence the amount of recharge (Connelly *et al.*, 1989). Urban development and agriculture land uses attribute to the largest portion of land use practises and are continuously expanding thus placing more pressure on the environment. According to a study done by Tilman *et al.* (2001) the world's agricultural land uses will increase by up to 50% within the next 40 years. In agricultural practises where the crop or vegetation is irrigated the amount of recharge increases due to irrigation water directly infiltrating into the subsoil (Scanlon *et al.*, 2005). This increase in agricultural land use will significantly affect the groundwater recharge patterns due to crops and pastures requiring larger amount of water, therefore depriving the aquifers below of substantial amounts of water.

2.4.7 Hydrogeological Factors

Hydrogeological factors are the factors that may limit the transfer of water from the surface to the unsaturated zone to the saturated zone and beyond (Connelly *et al.*, 1989). The subsurface geology is rarely uniform which leads to layers of varying permeability and thus water will infiltrate into an aquifer at differing rates depending on the subsurface geology (Cherkauer &

Ansari, 2005). Cherkauer and Ansari's (2005) study also illustrated that impermeable layers may limit water movement totally in which case water may move laterally according to gravity or create a new aquifer on top of the confining layer. Porosity, specific yield and permeability also influence recharge as these characteristics have an impact on how much water is retained as recharge (Brassington, 2007). According to Brassington (2007) these factors mostly relate to unconsolidated materials and sedimentary rock which between them create the majority of aquifers. Porosity is the amount of water rocks can hold within its pores which is proportional to the volume of rock containing pores (Brassington, 2007). Porosity does not provide a direct indication of how much water can be extracted from the rock as the surface-tension forces around the individual grains will retain water (Kumar & Bhattacharjee, 2003). The portion of the water that is extracted from the aquifer is specific yield (unconfined systems) or storativity (confined systems) and is dependent on the grain size of particles, the sorting of these particles, and the porosity (Kumar & Bhattacharjee, 2003). Hydraulic conductivity requires the same factors as porosity to determine it with the exception that hydraulic conductivity is the measurement of how fast water will flow through the rock (Brassington, 2007). Porosity and storage coefficient have a complex relationship in solid rocks as cementation and compaction in unconsolidated material reduces specific yield, whereas fracturing in solid rock increases it (Kumar & Bhattacharjee, 2003). Brassington (2007) provides a table analysis of the representative values of porosity and specific yield in basic aquifer materials.

Table 1 - Porosity and specific yield for various materials

Material	Porosity (%)	Specific yield (%)
Coarse gravel	28	23
Medium gravel	32	24
Fine gravel	34	25
Coarse sand	39	27
Medium sand	39	28
Fine sand	43	23
Silt	46	8
Clay	42	3
Loess	49	18
Peat	92	44
Fine-grained Sandstone	33	21
Medium-grained Sandstone	37	27
Limestone	30	14
Dolomite	26	-
Siltstone	35	12
Mudstone	43	-
Shale	6	-
Basalt	17	-
Schist	38	26
Weathered Gabbro	43	-
Weathered Granite	45	-

2.4.8 Geological Influence on Groundwater Levels

Throughout the Limpopo province geological settings differ as the province is home to some of the world's oldest geological formations. Upon surface water infiltrating into the subsurface, the influence that the site-specific geology has on water levels differs too. Some geological formations will allow groundwater to flow quickly through it while other formations have lower transmissivities due to being impermeable (Krásný, 1993), containing few or small fractures (MacDonald *et al.*, 2005), and having a low hydraulic conductivity (Sánchez-Vila *et al.*, 1996).

The different lithologies found at the various boreholes include Amphibolite and Serpentine (metamorphic, mafic, & ultramafic rock), Carbonate rocks, Felsic and Intermediate rocks, Granite Gneiss, Granulite (from Siliciclastic rocks), Mafic and Ultramafic volcanic rocks, and Siliciclastic rocks.

2.4.8.1 Amphibolite and Serpentine Rocks

Amphibolite and Serpentine rocks (metamorphic, mafic, & ultramafic rock) are found in the Pietersburg- and Gravelotte groups. The Pietersburg group is geologically characterised by ultramafic metavolcanic rocks including serpentinite, serpentized metapyroxenite and peridotite, talcose rocks, and chlorite talc schist along with amphibolite schist, banded ironstone, and quartzitic schist (Stettler *et al.*, 1988). The Gravelotte group is the broad term used for the Murchison Greenstone Belt (MGB) (Jaguin *et al.*, 2013) which is geologically characterised in the southern part by amphibolites (of which some facies are metamorphosed), hornblende and biotite schists, deformed amphibolite gneisses, gabbros-anorthosites, tonalities, and volcanic breccias (Vearncombe, 1988; Leyland & Witthüser, 2008). These respective geologic groups contain many fractures and have high densities and high hydraulic conductivities which allows groundwater to flow through these hard-rock aquifers at differing rates depending on the size of the fractures (Stettler *et al.*, 1988). Groundwater that flows in these lithologies has a high transmissivity rate.

2.4.8.2 Carbonate Rocks

Carbonate rocks are found in the Malmani subgroup in the Chuniespoort group. The Malmani subgroup is geologically characterised by dolomite, chert, and limestone with some areas even containing quartzite which is very well preserved due to metamorphism (Sumner & Grotzinger, 2004; Sumner & Beukes, 2006). The geologic formations containing carbonate rocks have high porosities but do not have high specific yield as groundwater flows through these formations with relative ease. Storativity in carbonate rocks is increased when a carbonate rock formation is underlined by an impermeable layer which allows the groundwater to have a high transmissivity rate, but doesn't allow the groundwater to seep further into the subsurface, thus

creating an unconfined aquifer, and when a carbonate rock formation is compartmentalised between impermeable layers, a confined aquifer is created (Durand, 2012).

2.4.8.3 *Felsic and Intermediate Rocks*

Felsic and Intermediate rocks are found in the Kwaggasnek Formation in the Rooiberg Group, and in the Turfloop Granite. The Kwaggasnek Formation is geologically characterised by volcanic rocks such as ilmenite, magnetite, rhyolite, dacite, agglomerates, and quartzite xenoliths with sporadic basaltic andesite and shale (Schweitzer *et al.*, 1995; Buchanan *et al.*, 1999; 2002). The Turfloop Granite is geologically characterised as being a massive batholithic intrusion which has an adamellitic to granodioritic composition that contains granite which is coarse-grained to porphyritic (Stettler *et al.*, 1988; Mothetha, 2009). Felsic rocks have a high silica content of more than 65% with intermediate rocks having a silica content of between 53% and 65% (Monroe *et al.*, 2007), thus creating very hard rock composites. Fractures within these rocks cause groundwater to move under high pressure, and may contain a high hydraulic conductivity (Buchanan *et al.*, 1999). Surface water infiltrates slowly into areas with felsic and intermediate rocks as water can only infiltrate into this rock through fractures unless the rock is already well weathered and contains a lot of fractures (Williams *et al.*, 1993).

2.4.8.4 *Granite Gneiss*

Granite Gneiss is found in the Hout River Gneiss and in the Goudplaats Gneiss. The Hout River Gneiss comprises of leucocratic biotite gneiss of granodioritic to tonalitic composition with granite and quartz-veins intruding into it (Stettler *et al.*, 1988; Holwell & McDonald, 2006; Mothetha, 2009). The Goudplaats Gneiss is geologically characterised by gneiss containing xenoliths, banded gneiss, and migmatite linked with leucocratic granite (De Bruijn *et al.*, 2005; Mothetha, 2009). When granitic gneiss weathers sufficiently it creates an environment for an aquifer to have a high hydraulic conductivity (Morrice *et al.*, 1997). In a study done by Katsuyama *et al.* (2005) an observation was made that more than 45% of the total annual rainfall in that specific area infiltrated into the granite bedrock as the soil material above was also weathered from granitic bedrock. In areas that are dominated by granitic gneisses, groundwater will accumulate on top of the bedrock in unconsolidated weathered bedrock material which will then seep into fractures in the bedrock (Taylor & Howard, 1999). Granite gneiss has a relative low density at between 2560 – 2700 kg/m³ but has a very high resistivity when unfractured and a far lesser resistivity when fractured (Stettler *et al.*, 1988). This high resistivity implies that groundwater will have a very high resistance to flow into an unfractured granitic gneiss bedrock area where as groundwater will be able to flow into weathered fractured bedrock areas.

2.4.8.5 Granulite

Granulite (from Siliciclastic rocks) is found in the Malala Drift group in the Beit Bridge Complex and in the Goudplaats Gneiss. The Malala Drift group is geologically characterised by quartzofeldspathic gneiss, biotite schist, amphibolitic gneiss, quartzites and pelite but is mainly gneissic (Nel & Nel, 2009; Rigby *et al.*, 2011). The Goudplaats Gneiss is geologically characterised by gneiss containing xenoliths, banded gneiss, and migmatite linked with leucocratic granite (De Bruijn *et al.*, 2005; Mothetha, 2009). Granulite is a high grade metamorphosed rock that originates in conditions of high temperature and moderate pressures from gneisses to form fine-grained light coloured quartzofeldspathic granulite (Bromley *et al.*, 1999). As granulite is fine-grained, it is porous and may have a high transmissivity rate as well as a high specific storage capacity.

2.4.8.6 Mafic and Ultramafic Volcanic Rocks

Mafic and Ultramafic volcanic rocks are found in the Main Zone, Zoetveld Subsuite, and Molendraai Magnetite Gabbro in the Rustenburg Layered Suite (RLS) in the Bushveld Complex, and in the Letaba Formation in the Lebombo Group. The Main Zone is geologically characterised by norites, gabbronorites, anorthosites, tholeiitic basalt, and pyroxenite in magmatic transitional zones (Barnes & Maier, 2002; Harris *et al.*, 2005). The Zoetveld subsuite, which is in the Lower Zone of the BLS, is geologically characterised by harzburgite-pyroxenite, harzburgite, and pyroxenite (Hulbert & von Gruenewaldt, 1982). The Molendraai Magnetite Gabbro, which is in the Upper Zone of the RLS, is geologically characterised by magnetite gabbro, magnetites, gabbronorites, anorthosites, diorites, and anorthosites (Barnes & Maier, 2002; Reid & Basson, 2002; Kinnaird & Iain McDonald, 2005). The Letaba formation is geologically characterised by picrites, picritic basalt, basalt, and scarce andesite (Riley, *et al.*, 2004; Olivier *et al.*, 2011). In mafic and ultramafic volcanic rocks fractures within the rock increase nearby contact zones between formations and contact zones nearby intrusions (Matter *et al.*, 2006). Matter *et al.* (2006) continue to state that hydraulic properties of fractured hard-rock formations depend on various attributes such as the fracture distribution, orientation, frequency and interconnectivity. Highly weathered and fractured volcanic rock may have a high transmissivity which also may be increased by the grain size of the rock in the formation (Yidana *et al.*, 2011). In a study done by Jalludin & Razack (2004) it was discovered that certain mafic and ultramafic volcanic rocks exhibit higher transmissivity the younger the rock is, while lower transmissivities were measured in older rock formations. Fractures in mafic and ultramafic volcanic rocks tend to be at a higher dip angle which implies that when boreholes are drilled in order to abstract groundwater, high levels of drilling accuracy must be achieved in order to strike a sustainable water vein (Matter *et al.*, 2006).

2.4.8.7 Siliciclastic Rocks

Siliciclastic rocks are found in the Black Reef Formation, Pretoria Group, and the Duitschland Formation in the Chuniespoort Group in the Transvaal Supergroup, the Swaershoek- and Alma formations in the Nylstroom Subgroup, and Clarens Formation in the Karoo Supergroup. The Black Reef Formation is geologically characterised by quartz-pebble conglomerates, quartz veins, pelite, and quartzite (Wronkiewicz & Condie, 1990; Fuchs *et al.*, 2016). The Pretoria Group is geologically characterised by sandstone, mudrock, diamictite, chert-conglomerate, shale, chert-breccia, quartzite, diabase, and pelite (Moore *et al.*, 2001; Gerya *et al.*, 2003). The Duitschland Formation is geologically characterised by diamictite, mudrock, chert-breccia, dolomitic mudrock, minor dolomite, and interstratified quartzite (Eriksson & Reczko, 1995; Eriksson *et al.*, 2001; Moore *et al.*, 2001). The Swaershoek Formation is geologically characterised by sandstone, shale, intermittent trachyte, quartzite, banded-chert, conglomerate, and sporadic intrusive diabase (De Kock *et al.*, 2006; Maré *et al.*, 2006). The Alma Formation is geologically characterised by wackestone, shale, intrusive dolerite, mudstone, conglomerate, arenite, arkosic sandstone, granite clasts, and quartzite (Eriksson *et al.*, 1997; De Kock *et al.*, 2006). Siliciclastic rocks have a relative low density of about 2600 kg/m^3 as these rocks have mostly volcanoclastic properties which also allows groundwater to flow through these formations with at a high rate of transmissivity (Morin, 2005). In Siliciclastic rocks, the porosity and permeability decreases with an increase in depth as these deeper zones are under higher pressure constraints which compresses grains and through this process, produces new minerals that serve as cement to the surrounding particles (Hutcheon, 1983; Morad *et al.*, 2000). As Siliciclastic rocks have varying grain sizes, these rocks' permeability and porosity will also differ, as the smaller the grain sizes, the lower the intergranular permeability will be, and the larger the grain sizes, the higher the intergranular permeability will be, which leads to varying transmissivities in these rocks (Runkel *et al.*, 2006; Lang *et al.*, 2015).

2.4.9 Rain Water Chemistry

Water's chemical composition can have an immense role in the determination of the origin of the water as rainwater and groundwater have different compositions due to varying factors influencing the water. In a study done by Lacaux *et al.* (1992) it was found that by analysing the chemical composition of rainwater it is possible to trace the sequential and spatial development of the atmospheric precipitation's chemistry along with the chemical species present in the atmosphere. These chemistry analyses also allow the determination of the origin of the precipitation as each ecosystem tends to show different chemical characteristics (Mphepya *et al.*, 2006). South Africa's rain water originating from dry savanna has chemistry primarily sourced from terrigenous sediments and nitrogen oxides respectively, which originate from soil emissions and ammonia emissions from domestic animals (Lacaux *et al.*, 1992; Mphepya *et al.*,

2004). According to a study done by Mphepya *et al.* (2004) there are five major sources that control precipitation's chemical composition which include, marine, terrigenous, nitrogenous, biomass burning and anthropogenic sources.

Rainwater that originates from the evaporation of seawater is likely to have a higher chloride concentration than rainwater originating from inland water sources (Appelo & Postma, 2005). According to Appelo and Postma (2005) the chloride concentration in rainwater originating from seawater will be between 10-15 mg/L which is similar to highly diluted seawater, and due to the dominance of these seawater composites in the rainwater, remnants of the seawater composites can be found in rainwater thousands of kilometres from the ocean. The diluted seawater content found in the rainwater originate from marine aerosols that form from liquid droplets that form when gas bubbles burst at the ocean's surface (Blanchard & Syzdek, 1988). As a result of seawater largely influencing the rainwater's composition, the concentration of the saltwater particles will be the highest the closest to the shoreline with decreasing effect the further inland the rainwater precipitates (Appelo & Postma, 2005). Other factors inland may influence the chloride content within the rainwater such coal-fired power plants of which there are many close the eastern seaboard of South Africa (Wagner & Kenneth, 1989). Typical distribution of rain water chloride is shown in Figure 1.

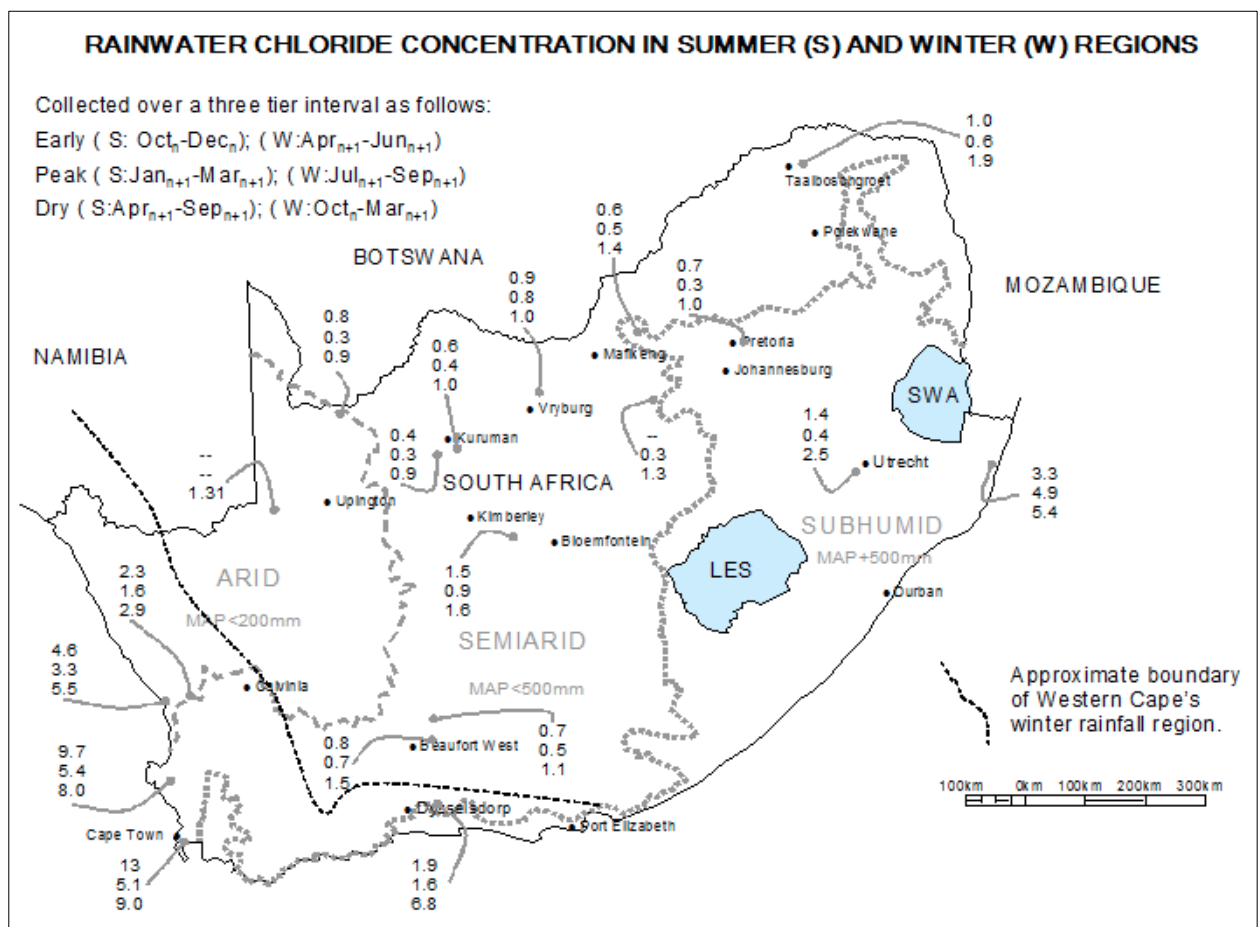


Figure 1 - Rain water chloride concentrations (taken from Van Wyk, 2010)

Inland precipitation differs from marine precipitation as it originates from different sources. By analysing the chemistry of each type of rainwater, a comparison between the two rain waters can be derived in order to be able to distinguished which type of rain water is present in groundwater recharge at the time of an event. Very few studies exist on inland and marine rain water in Southern Africa, which makes it difficult to draw a correlation between the two when groundwater recharge is involved.

A thorough study was done by Mphepya *et al.* (2004) at Skukuza from July 1999 to June 2002, and by Mphepya *et al.* (2006) at Louis-Trichardt from July 1986 to June 1999 in order to determine the chemical composition of the rainwater, along with the contributing sources of the rainwater's chemistry. The study at Skukuza's data was captured and analysed during the dry and wet season in order to create a yearly mean, whereas the study at Louis-Trichardt's data was captured as an entirety only to create a yearly mean. The average pH was calculated from volume-weighted mean of H^+ for Skukuza and Louis-Trichardt respectively (Table 2, Mphepya *et al.*, 2004; Mphepya *et al.*, 2006). From each rain event, the volume-weighted mean chemical composition was used. Volume-weighted mean is calculated by using the ionic concentration C_n and the depth of the rainfall H_n , measured in mm of the rainfall event's data collected to be combined into Equation 1.

$$Mean_{vw} = \frac{\sum C_n H_n}{\sum H_n} \quad (1)$$

where,

$$\begin{aligned} Mean_{vw} &= \text{Volume weighted mean} \\ C_n &= \text{Ionic concentration (mg/L)} \\ H_n &= \text{Rainfall depth (mm)} \end{aligned}$$

Table 2 – Precipitation volume-weighted chemical composition for Skukuza and Louis-Trichardt

Ions	Skukuza			Louis-Trichardt
	Dry Season	Wet Season	Annual Mean	Annual Mean
pH	4,44	4,76	4,72	4,91
H ⁺	35,6	17,3	18,9	12,2
Na ⁺	10,9	8,7	8,9	9,3
NH ₄ ⁺	10,9	8,8	9,0	9,7
K ⁺	6,9	5,3	5,9	3,8
Ca ²⁺	6,5	5,6	5,6	12,0
Mg ²⁺	3,6	2,9	3,0	4,1
NO ₃ ⁻	12,0	7,7	8,1	8,0
Cl ⁻	12,6	12,0	12,1	10,0
SO ₄ ²⁻	33,9	14,5	16,3	14,5
HCOO	3,5 (3,0 ^a)	2,3 (1,7 ^a)	3,5 (2,9 ^a)	12,9 (11,5 ^a)
CHCOO	4,1 (1,8 ^a)	3,7 (0,9 ^a)	4,1 (1,8 ^a)	8,2 (4,3 ^a)
Average rainfall (mm)	119,96	629,86	749,82	462,48

2.4.10 Groundwater Quality

Groundwater sources in South Africa tend to be influenced by various different aspects ranging from geology (Adams *et al.*, 2001), geothermal sources (Olivier *et al.*, 2008), mining activities (Tutu *et al.*, 2008), vegetation (Humphries *et al.*, 2011), and pesticides used on agricultural crops (Arias-Estévez *et al.*, 2008). All of these aspects mentioned influence the chemistry of groundwater and upon analysis of the groundwater, the origin of these constituents may be traced. In the Limpopo Province, all of these resulting constituents affect the chemistry of the groundwater, and thus by analysing groundwater chemistry in comparison with rainwater chemistry, recharge events will be evident.

Groundwater is one the most important resources in rural communities as it is the essence of life, and with little to no municipal water supply in rural areas, and surface water absent in many areas, groundwater extraction is a vital manner in which to obtain water. In a study done by Adams *et al.* (2001) on an aquifer near Sutherland in the Western Cape, it was determined that geology may have an adverse effect on groundwater depending on the topography of the extraction point, and the underlying geology. Adams *et al.* (2001) further found that biogenic rain, precipitation that is charged with CO₂, dissolves minerals and solubles in the unsaturated zone, as well as the saturated zone to a lesser extent, which then enter into the groundwater. When the groundwater with a high salinity is extracted and consumed by human it has a very foul salty taste. When groundwater has a relatively low mineral content, it indicates that

recharge recently took place which may have either diluted the dissolved mineral content in the existing storage, or the water entering into the subsurface did not have enough time to allow mineralisation thereof to occur (Chimphamba *et al.*, 2009). In a study done by Adams *et al.* (2009) an assumption was made that groundwater that has a chemical composition that does not substantially deviate from that of rainwater chemistry can be as a result of direct recharge of rainwater into aquifer. This assumption can especially be applied to groundwater recharge in areas with fractured hydrogeological characteristics as fractured igneous geologic formations, as found in the Limpopo Province, allow surface recharge to quickly flow into the underlying aquifers.

Thermal springs are abundant in the Limpopo Province due to groundwater flowing deep in fractures through areas of rock that have been heated by a magmatic source through conduction after which the heated water moves to the surface and vents at the surface (Healy & Hochstein, 1973). Recent plutonic activity also allows rock to contain enough heat to warm up any surrounding water (Olivier *et al.*, 2008). Kent (1949) stated that the higher the temperature of the thermal spring is, the higher the flow rate of the water within the system will be. This higher flow rate allows mineralization to be accelerated as well due to that water with a higher temperature will be flowing over rocks at a faster rate than usual, thus allowing rocks to be dissolved more quickly than water with a lower temperature flowing at a slower rate (Olivier *et al.*, 2008). Due to that thermal water originates from deep below the surface, the chemistry of these waters does not resemble any of the geologic formations found at the surface of the spring (Kent, 1949). Groundwater venting at springs that originates from geothermal processes is highly mineralised, and contains greater concentrations of the highly soluble minerals found in the rocks below (Olivier *et al.*, 2008). In a study done by Olivier *et al.* (2008) in the Limpopo Province, various thermal springs were chemically analysed to see which minerals are more abundant than that found in non-thermal groundwater. The results of this study illustrated how certain minerals are far more susceptible to dissolution than others and that many springs that vent thermal groundwater are not suitable for human consumption according to the South African Guidelines for Domestic Water Quality (DWAF, 1996). Table ii shows the chemical composition of the water sampled at various springs in the Waterberg area, and an evident result of this analysis is that these thermal waters have a relatively low ionic concentration in comparison to water sampled in areas where sedimentary rocks dominate. As thermal waters do not resemble surface rock's chemistry, these deep waters have a higher salinity and lead the dissolution of rocks with a higher Cl^- (Gascoyne & Kamineni, 1994).

In wetlands, surface water and groundwater temporarily interact when cycles of wetting and drying occur within the wetland due to that the evapotranspiration may exceed the precipitation, or the precipitation may exceed the evapotranspiration (Humphries *et al.*, 2011).

Evapotranspiration often leads to salinization of either the remaining surface water or salt accumulation on the surface, and due to the groundwater-surface water interaction the shallow groundwater becomes salinized (McCarthy *et al.*, 1991). Groundwater and surface salt accumulation are normal natural processes within ecosystems, but are also seen as environmental problems due that these salts threaten the productivity of ecosystems and agricultural practises, and as with almost all environmental issues, the threat of salinization is exacerbated by human activity (Ghassemi *et al.*, 1995). In a study done by Runyan and D'Odorico (2010), a coupling between the salinity and surrounding vegetation was seen to lead to a strong influence by the vegetation on the water table movements. High salt concentrations in vegetation leads to osmotic stress within the plants which ultimately leads to the accumulation of toxic ions such as Cl^- and Na^+ (Hasegawa *et al.*, 2000).

Mining activities across South Africa are a common feature on the landscape and the affect these mines have on the subsurface water is enormous. The Limpopo Province has rich deposits of platinum-group metals, iron ore, chromium, coal, diamonds, antimony, phosphate and copper along with other mineral deposits which include gold, emeralds, magnetite, vermiculite, silicon and mica across the province (NAFCOC, 2014). Water draining from areas that contain coal- or any heavy metal -deposits which are being mined and oxidised by weathering, frequently contain sulfuric acid and high concentrations of heavy metals that subsequently enter into the subsoil and contaminate groundwater (Ochieng *et al.*, 2010). In South Africa, one of the greatest threats to groundwater quality is acid mine drainage (AMD) as it forms from chemical reactions between water and rocks containing sulphur-bearing minerals (Jarvis & Younger, 2001). AMD is usually formed where ore or coal mining activities have exposed Pyrite (FeS_2) to weathering (Jarvis & Younger, 2001). The chemical reaction of the FeS_2 and water leads to the creation of other constituents such as sulphuric acid (SO_4^{2-}) and ferric iron (Fe^{3+}) which is a serious pollutant in any water body (Ochieng *et al.*, 2010). These constituents formed by AMD are evident in any analysis of groundwater contaminated thereby, thus a change in water chemistry can clearly be observed. In a study done by Tutu *et al* (2008) a series of groundwater samples were analysed in the Witwatersrand Basin and clearly show how evident SO_4^{2-} contamination is within the groundwater

Pesticides are used to mitigate either pests or weeds and are mostly used in commercial agricultural practises. A study done by Pimentel and Levitan (1986) it is estimated that less than 0.1% of the pesticide applied to the crop reaches the targeted pest, of which the rest of the pesticide affects either the air, water, soil, or organisms that were not supposed to be affected by the application of the pesticide. Pesticides can exist in water sources for long periods as in the case of organochlorine insecticides, where chemical remnants thereof were found in surface water 20 years after it was banned (Larson *et al.*, 1997). A study done by the U.S. Geological

Survey in the United States discovered that more than 95% of samples collected from streams and rivers contained at least one pesticide, whereas almost 50% of samples from wells also contained one pesticide (Robert *et al.*, 1999). Chemicals in pesticides contaminate the groundwater through leaching from the soil or by direct infiltration of surface water into the saturated zone below (Arias-Estévez *et al.*, 2008). These chemicals alter the composition of the groundwater and thus upon analysis of the water, distinct variations can be seen that differ from uncontaminated groundwater samples.

2.5 Cyclones

Tropical cyclones (TCs) are created by low pressure systems over the ocean and move from the east to west. In the South-West Indian Ocean (SWIO) TCs often move in a south-western direction as well. TCs usually occur between 5° and 30° north and south of the equator during the warmest months of the year when the lowest pressure systems exist (Mavume *et al.*, 2009). Sea surface temperatures exceeding 26° to 27°C are required for the formation of a TC, along with large values of low level relative vorticity, low levels of vertical and horizontal wind shear, restrictive volatility throughout the deep atmospheric layer, high humidity in the lower and middle troposphere, and a deep oceanic mixed layer (Henderson-Sellers *et al.*, 1998; Mavume *et al.*, 2009).

Studies done by Gray (1968; 1979) also states that other factors required for cyclogenesis include an atmospheric environment that cools quickly with increasing elevation to such an extent that it is potentially unstable to moisture convection, layers with reasonable amounts of moisture must exist near the mid-troposphere about 5km above mean sea level, a preceding near-surface disturbance coupled with adequate vorticity and convergence, and cyclogenesis can only occur any at least 500 km from the equator to allow the vital Coriolis force to take effect providing near gradient wind balance and maintaining the low pressure disturbance.

In the southern hemisphere, the months between November and April provide the highest sea-surface temperatures thus creating the most ideal conditions for a TC to form in the SWIO. TCs rarely make landfall, nonetheless the effects of the low pressure system that lead to the genesis of the TC are evident inland (Vitart *et al.*, 2003). Only 5% of TCs make landfall on the eastern coast of Southern Africa, with the effects of the TC's that don't make landfall also evident for hundreds of kilometres inland due to the entire storm system generating large amounts of rainfall over a vast area (Reason & Keibel, 2004). On average, only 9 TCs develop in SWIO each year of which only 0.45 thereof make landfall along the African coast, which is a fair amount less than the average 3.7 extreme TCs that make landfall over the Guangdong province in China (Elsner & Liu, 2003; Reason, 2007). Even though less TCs make landfall over the African continent, the effects of these TC's are exacerbated by the lack of properly developed

disaster management strategies and handling initiatives along with reasonably inadequate disaster warning systems (Ash & Matyas, 2012).

The areas that may be affected by cyclonic storms in South Africa include Limpopo-, Mpumalanga-, and the Kwa-Zulu Natal provinces as any areas more inland and south are rarely impacted by the effects of cyclones due to the friction caused by the land surface on the storm (Dyson & Van Heerden, 2001). South Africa's coast is fortunately well-guarded against south-west moving cyclones by Mozambique and Madagascar as these landmasses absorb the ferocity of a TC, and by the time it makes landfall in South Africa, the intensity thereof has dissipated (Vitart *et al.*, 2003). Once these storm systems make landfall the intensity is vastly decreased due to the lack of moisture and heat that was provided by the ocean (India Meteorological Department, 2015). Ho *et al.* (2006) has found that TC frequency increases during El Niño years in the SWIO. Cyclones more frequently make landfall during La Niña years as zonal mean flows of between 200 hPa and 850 hPa and below are common during La Niña years (Vitart *et al.*, 2003). As a TC ideally develops between the 26° and 27°C isotherm, the 0.3 °C increase in the mean sea surface temperature in the SWIO since 1960 is causing TC's to develop further away from the equator, and thus changing the cyclonic prediction patterns (Gouretski *et al.*, 2012).

TCs may bring large amounts of widespread rainfall to the interior of South Africa, and specifically to the Limpopo province. When TCs move along a southwestern or southern path and then make landfall, they often displace into a south-eastern path, especially when they reach below 25° south of the equator (Dyson, 2012). TCs that make landfall, move a western path inland, and TCs that do not make landfall are either displaced to the north or south. Rainfall associated with TCs may have varying impacts inland depending on the movement of the tropical system such as when a TC moves in a southern or south-eastern direction along the eastern coastline of Africa, rainfall can be expected along the coastline up the escarpment of South Africa (Dyson, 2012). The position where a TC makes landfall is an important component in determining the amount of rainfall to the interior of South Africa as TC Demoina (Jury *et al.*, 1993) and TC Dando (Chikoore *et al.*, 2015) both made landfall close to Maputo, and in both cases the majority of the rainfall as a direct result of the TC was experienced on the eastern escarpment of South Africa. TC Eline made landfall north of Beira which allowed the system to move inland through Mozambique, Zimbabwe, Botswana, and into Namibia, and as a result of this TC making landfall north of the escarpment it was able to move into the interior of the southern African landmass causing widespread floods and destruction along its path (Reason & Keibel, 2004; Dyson, 2012). Between 1948 and 2008, 48 TCs and tropical lows, which are less intense than TCs, made landfall and were responsible for widespread flooding across the

Limpopo river basin, which also acts as a border between South Africa and Zimbabwe (Malherbe *et al.*, 2012).

TC intensities are predicted by calculating the equilibrium between energy generation by surface fluctuations and dissipation, of which mostly occurs in the atmospheric boundary layer, and are difficult to predict beyond a 24-hour period (Bister & Emanuel, 1998; Emanuel, 2000). TC in the SWIO are monitored by Regional Specialized Meteorological Centre (RSMC) La Réunion as designated by the World Meteorological Organization (WMO) in 1993. Each tropical storm monitoring centre across the globe is responsible for the classification of the storm involved, and is measured by different standards to provide information for the different nations involved at a specific monitoring centre (Meteo France, 2016).

The RSMC La Réunion has classified the tropical systems in the SWIO in order of succession as presented in Table 3 (Meteo France, 2016).

Table 3 - Summary of tropical system's descriptions

Name of Tropical System	Description	Wind Speed
Zone of disturbed weather	Non-frontal synoptic low-pressure area originating in the tropics or sub-tropics with intensified convection	Light surface winds
Tropical disturbance	Non-frontal synoptic low-pressure area originating over tropical or sub-tropical waters with structured convection and defined cyclonic surface wind circulation	Wind speeds not exceeding 50km/h (27 knots)
Tropical depression	Tropical disturbance with higher maximum average wind speeds	wind speed ranging from 51 to 62 km/h (28 to 33 knots)
Moderate tropical storm	Tropical system with such wind speeds that the system is usually named	wind speed ranging from 63 to 87 km/h (34 to 47 knots), gale or strong gale force winds
Severe tropical storm	Tropical storm's convection is focused closer to the storm's centre along with rainfall unifying in distinctive outer bands coupled with high average wind speeds	wind speed ranging from 88 to 117 km/h (48 to 63 knots), storm or violent storm force winds
Tropical cyclone	Tropical disturbance with higher maximum average wind speeds than a severe tropical storm	wind speed ranging from 118 to 165 km/h (64 to 89 knots), hurricane force winds
Intense tropical cyclone	Tropical disturbance with higher maximum average wind speeds than a tropical storm	wind speed ranging from 166 to 212 km/h (90 to 115 knots), hurricane force winds
Very intense tropical cyclone	Tropical disturbance with higher maximum average wind speeds than an intense tropical storm	wind speeds exceeding 212 km/h (115 knots), hurricane force winds
Extra-tropical depression	Synoptic low-pressure area outside of the tropics, or former tropical disturbance having lost its tropical characteristics	Undefined
Subtropical depression	Synoptic low-pressure area coupled with characteristics which could belong to tropical and extra-tropical depressions	Undefined

Nelson (2014) mentioned that the intensity, when either measured by wind speed or central pressure, of a cyclone is not necessarily related to its size. Winds have the highest velocity within the eye's wall from which the cyclonic zone extends outwards up to 1100km from the eye as measured with Typhoon Tip in the northwest Pacific Ocean in 1979 (Nelson, 2014). According to (Meteo France, 2016) a tropical cyclone has wind speeds ranging from 118 km/h

to 165 km/h and does not define the average size of the tropical cyclone, with Nelson (2014) stating that Hurricane force winds exceed 119 km/h with an average storm radius of 240km around the eye. Various tropical storms have shown various different sizes in relation to each storm's wind speed and central pressure (Nelson, 2014). Kaplan and DeMaria (1995) and DeMaria *et al.* (2006) found that the moment when a cyclone makes landfalls is defined as when the strongest winds of the storm, thus the winds surrounding the eye, make landfall. Upon landfall, a cyclone's wind speed will decrease due to friction from the land surface and with a lack of sufficient moisture inland, a tropical cyclone's movement speed will decrease until the storm system dies completely (DeMaria *et al.*, 2006; Nelson, 2014).

3 CYCLONIC ACTIVITY OVER THE SOUTH-WEST INDIAN OCEAN

This chapter discusses the historic cyclonic events that occurred in the SWIO. The cyclones are categorised as those making landfall and those moving within 100km of Mozambique's and South Africa's coastline.

3.1 Cyclones making landfall over Mozambique and South Africa

The cyclones are grouped in periods of nine years, with the exception of the last time period from 2010 to 2016. A brief discussion is given on the cyclones that occurred during each time period.

3.1.1 Period 1960 to 1969

The cyclones making landfall along Africa's south-eastern coast during the period 1970 to 1979 is shown Figure 2.

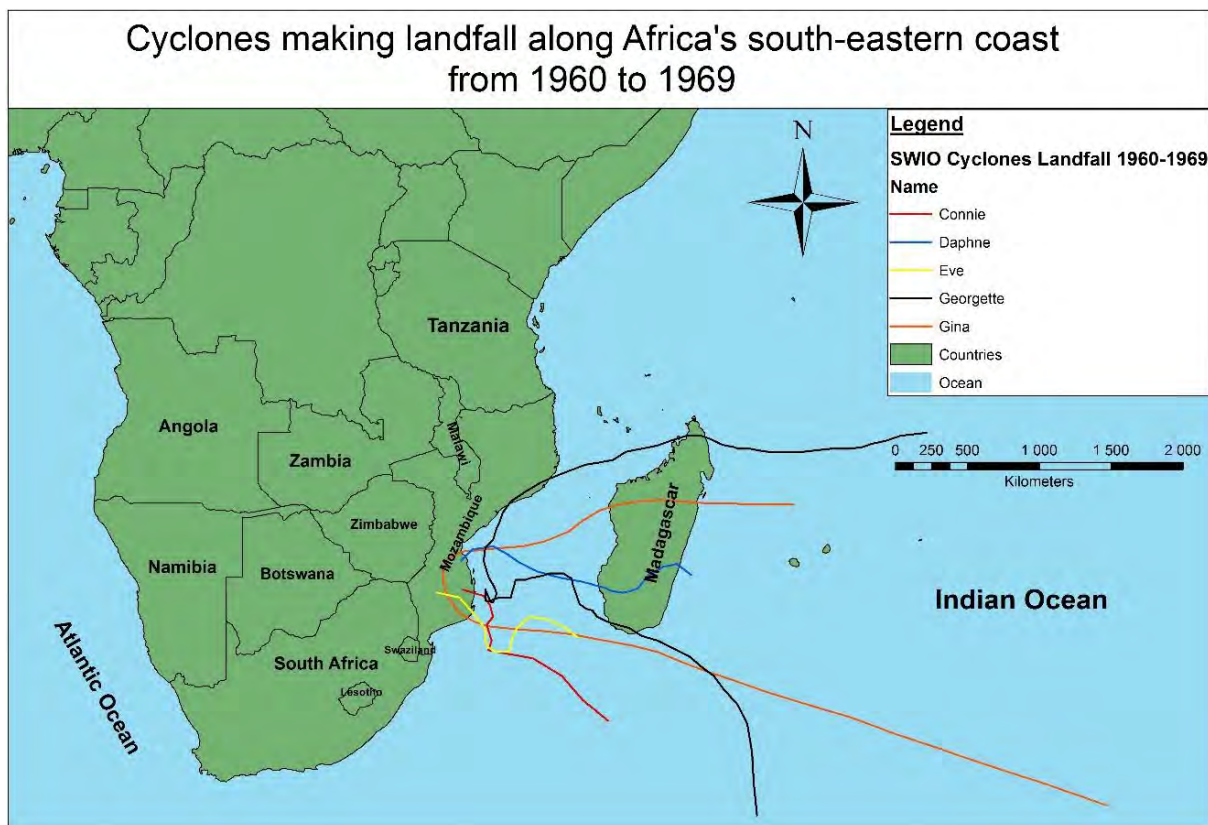


Figure 2 - Cyclones making landfall from 1960 to 1969

Tropical depression (TD) Gina originated on the 8th of February 1962 about 650km off the east coast of Madagascar, generating wind speeds of about 55 km/h which decreased within a day of cyclogenesis to 47 km/h after the wind speeds then increased steadily over the next couple of days to a maximum wind speed of 63 km/h but did not sustain these winds long enough for it to be classified as a moderate tropical storm (MTS). The TD moved in a

westerly direction, briefly moving in a south-westerly direction, before continuing west. The TD made landfall 100km south of Beira in Mozambique when the surface-friction significantly decreased the wind speed of the system after which it travelled south and then moved in a south-easterly direction leaving land and moving back over the ocean 100km north of Xai-Xai in Mozambique. The system made landfall on the 12th of February and left land again on the 14th of February eventually dissipated on the 18th of February 1962, 3500km south-east of the coast of Madagascar.

MTS Connie originated on the 17th of December 1964 about 1350km southeast off the coast of Mozambique, generating wind speeds of about 55km/h before only reaching MTS wind speeds of 65km/h more than a day after it originated. The MTS moved in a north-westerly direction making landfall 250km north of Inhambane in Mozambique on the 19th of December. The system dissipated 200km inland when the required amount of air-moisture was no longer available. The MTS's wind speed reached a maximum of 80km/h a few hours before the system made landfall.

Severe tropical storm (STS) Daphne originated on the 23rd of December 1966 about 250km off the coast of Madagascar, generating wind speeds of about 64km/h which steadily increased to about 128 km/h within 48 hours from cyclogenesis. This wind speed was only briefly sustained as the intensity of the system soon started to dissipate before it made landfall on the 27th of December with a final wind speed of only 35km/h. The STS made landfall 150km south of Beira in Mozambique and totally dissipated within 3 hours of making landfall.

Intense tropical cyclone (ITC) Georgette originated on the 10th of January 1968 about 1550km off the east coast of Madagascar, generating wind speeds of about 45 km/h upon cyclogenesis which increased to 60km/h within a day after which the wind speeds very gradually increased to 76 km/h on the 16th of January. The system moved in a westerly direction until it made landfall on the 18th of January with wind speeds in excess of 92 km/h. The system was at the stage briefly before landfall categorised as a STS, after which some energy of the system dissipated upon landfall. Upon landfall the Georgette moved in a south-westerly direction and then in a southerly direction as soon as the system moved over the ocean again on the 19th of January with a wind speed of 74km/h. The storm soon gained intensity over the ocean and within 72 hours of moving over the ocean again the wind speed had increased to 185km/h which it sustained for 24 hours. During these wind speeds of 185 km/h the ITC made a small loop in the Mozambican Channel before starting to move in an easterly direction on the 23rd of January after which the ITC continued in a south-easterly direction and then south until its ultimate dissipation on the 1st of February. The wind speeds

decreased to 70 km/h within 72 hours of the system starting to move in an easterly direction with the final wind speeds measuring only 47 km/h before the system's dissipation.

TD Eve originated on the 29th of January 1969 about 300km off the south-west coast of Madagascar, generating wind speeds of about 38km/h, classifying it as a zone of disturbed weather, after which the wind speed increased within 12 hours to 55 km/h, leading to its classification as a TD. The TD moved in the north-westerly direction for the first 24 hours after cyclogenesis after which the system made a drastic shift in direction south within the next 12 hours. Upon moving south, the TD started to change direction west and then north again to complete a U-turn of the system of which the wind speed maintained a consistent velocity of 55 km/h. Eve made landfall on the 1st of February causing the wind to drop to 43 km/h within 12 hours ultimately leading to the system dissipation 6 hours later on the 2nd of February.

3.1.2 Period 1970 to 1979

The cyclones making landfall along Africa's south-eastern coast during the period 1970 to 1979 is shown Figure 3.

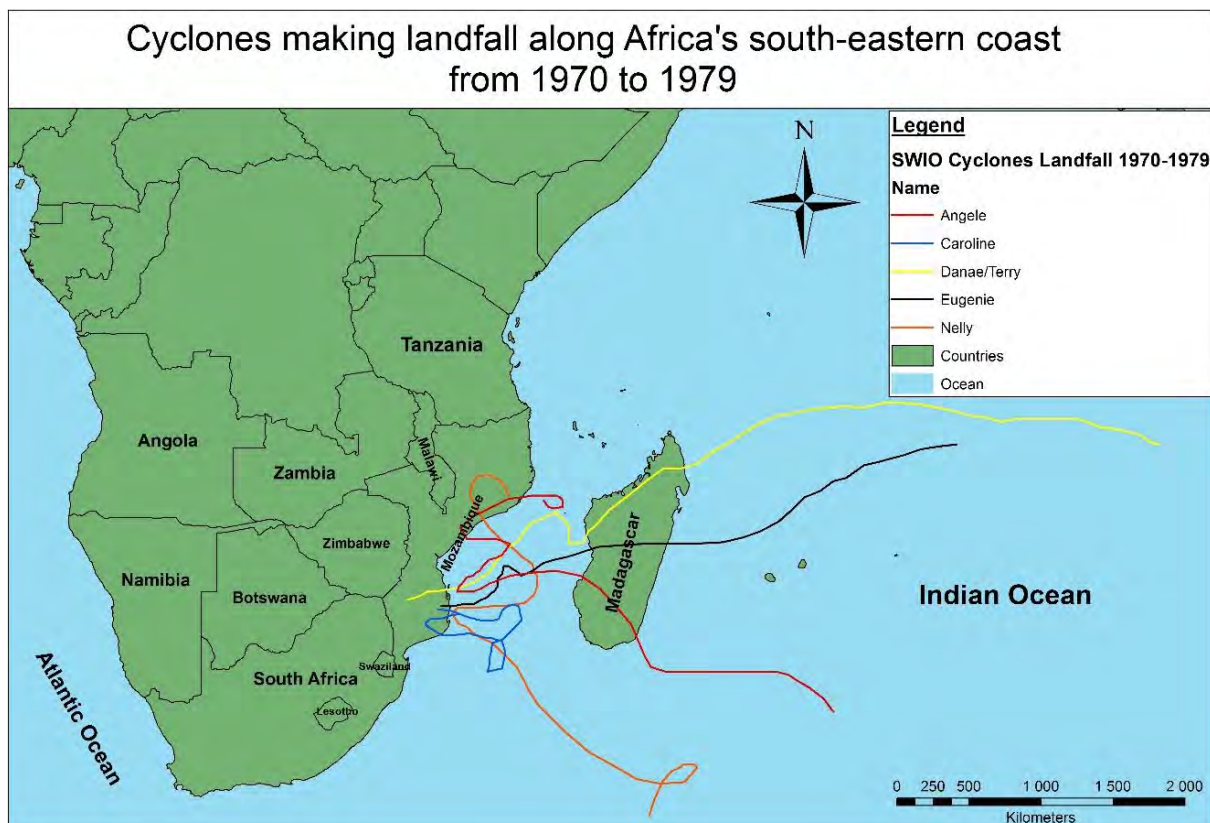


Figure 3 - Cyclones making from 1970 to 1979

STS Nelly undergone cyclogenesis on the 12th of March 1971 over land 100km south of Nampula in Mozambique, starting with wind speeds of 63 km/h and moving in a north-

westerly direction for 12 hours before the system started moving west, then south-west, and eventually south-east. 48 hours after cyclogenesis STS Nelly moved over the Mozambican Channel allowing the intensity of the storm to increase with wind speeds also increasing to 115km/h by the 18th of March, which for a brief 6 hours increased to 135 km/h. This brief increase in wind speed did not cause reason for the system to be classified as a TC, but rather as a STS. By the 19th of March the STS started moving in a south-easterly direction with the wind speed decreasing to 76 km/h, 48 hours reaching its maximum wind speed, and ultimately dissipated 26th of March after making a loop in a north-easterly direction 23rd of March, with final wind speeds of less than 63 km/h.

TD Caroline originated on the 3rd of February 1972 120km north-east of Inhambane with wind speeds of 37 km/h and made landfall within 6 hours 100km north of Inhambane while moving in a westerly direction. 24 hours after cyclogenesis, TD Caroline made a 180° turn in easterly direction moving back over the ocean with wind speeds maintained at 60 km/h. On the 7th of February the system made a loop in a southerly direction before continuing in a north-easterly direction up the Mozambican Channel for approximately 400km. By the 11th of March, TD Caroline started moving west and then south-west for 24 hours, increasing the wind speed to 62 km/h for 48 hours, before remaining on a westerly path until it made landfall again on the 13th of February after which the system dissipated only 6 hours later on the 14th of February with a final wind speed of 52 km/h.

TC Eugenie originated on the 10th of February 1972 1800km off the east coast of Madagascar, with wind speeds of only 47 km/h upon cyclogenesis while moving in a west-south-westerly direction for the first 96 hours until the TC first made landfall on the 14th of February 150km west of Antananarivo in Madagascar. Upon the first landfall on Madagascar the wind speeds had already increased to 115 km/h which increased to 132 km/h as the system moved over the Madagascan landmass in a westerly direction. TC Eugenie moved the Mozambican Channel on the 15th of February with wind speeds of 120 km/h still being maintained, which decreased to 89 km/h by the 16th of February also causing the storm system to move in a north westerly direction for 48 hours before it started moving in a south-westerly and then westerly direction for the remainder of the system's path while the wind speed was rapidly increasing over the next 48 hours to 143 km/h on the 20th of February. The TC made landfall on the 21st of February and dissipated only 3 hours after making landfall with a final wind speed of 92 km/h.

ITC Danae/Terry underwent cyclogenesis on the 14th of January 1976, 3300km off the east coast of Madagascar, generating wind speeds 147 km/h which decreased to 90 km/h only 24 hours after originating while moving in a westerly direction. On the 15th of January the wind speeds started to increased again to more than 185km/h over the following 132 hours after

which the ITC started to move in a south-westerly direction with the wind speed decreasing to 137 km/h. ITC Danae/Terry made landfall 70km north-east of Andapa in Madagascar on the 22nd of January with the wind speeds decreasing significantly over the Madagascan landmass to 75 km/h by the time the system moved over the Mozambican Channel on the 23rd of January. The system moved north and made a gradual 180° manoeuvre to move south and then south-west with the wind speed decreasing to 47 km/h by the 25th of January but regained some intensity when the system started moving south-west again increasing the wind speed to 80km/h by the 26th of January. The ITC made landfall on the 27th of January and dissipated by the 29th of January 200km east of the South African border with Zimbabwe and Mozambique with a final speed of less than 37 km/h.

ITC Angele originated on the 16th of December 1978 in the Mozambican Channel 200km south-east of Nacala in Mozambique, starting as a STS with wind speeds of 95 km/h moving in an easterly direction for 24 hours which then translated into anti-clockwise 180° turn over the next 24 hours which increased the wind speed to 147 km/h by the time the system was heading west towards the Mozambican coastline. After travelling in a westerly direction for less than 24 hours, ITC Angele made landfall 130km south-east of Nampula on the 18th of December with maximum wind speeds before landfall briefly reaching 170 km/h but could not be sustained for a long enough period for the system to be classified as a ITC. The ITC continued in a west-south-westerly direction for another 24 hours over land while wind speeds drastically decreased to 69 km/h before starting to head south after which the system moved back over the Mozambican Channel on the 20th of December. 12 hours after moving east over the ocean again, the ITC made another 180° turn moving briefly west and then south-west which increased to wind speed to 140 km/h by the 22nd of January. Angele continued heading in a south-easterly direction for the next 60 hours while the wind speed progressively increased to 165 km/h by the 24th of January and then briefly increased 12 hours later to 201 km/h before the system maintained a wind speed of 178 km/h for the next 48 while moving east. ITC Angele made landfall 100km south of Morondava in Madagascar on the 26th of January with the wind speed decreasing over the Madagascan landmass to 118km/h while moving in a south-easterly direction. On the 27th of January the ITC started moving in a westerly- and then south-westerly direction until its dissipation on the 31st of December with a final wind speed of 57km/h ending the system's life cycle as an Extra-tropical depression (ETD).

3.1.3 Period 1980 to 1989

The cyclones making landfall along Africa's south-eastern coast during the period 1980 to 1989 is shown in Figure 4.

STS Demoina undergone cyclogenesis on the 16th of January 1984, 2000km off the North-eastern coast of Madagascar, generating wind speeds of 60km/h while moving in a westerly direction and then a south-westerly direction with the wind speeds increasing to 99 km/h by the time the system made landfall 150km east of Antananarivo on the 21st of January. The STS's wind speed decreased over the Madagascan landmass to 44km/h heading in westerly- and the north-westerly direction for the next 36 hours until the system moved over the Mozambican Channel on the 23rd of January and continued moving south for the next 24 hours before making a 90° turn west with wind speeds measured at 69km/h. Over the following 96 hours the STS headed in a west-south-westerly direction gaining wind speed until it reached 107 km/h just before the system made landfall again at Inhambane on the 28th of January. Upon landfall Demoina was classified as a ETD and moved in a south-westerly direction for the next 36 hours while the wind speed decreased to 48km/h after which the ETD moved south until its dissipation on the 2nd of February.

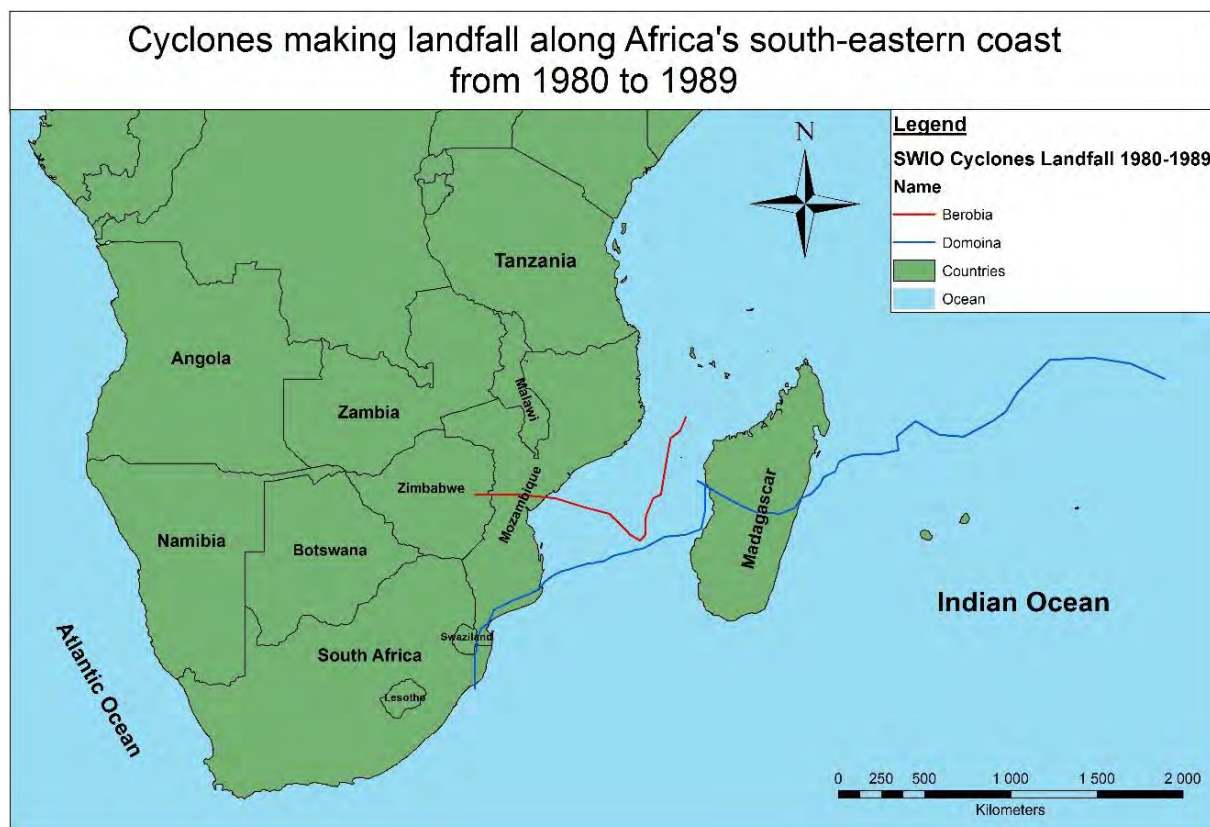


Figure 4 - Cyclones making landfall from 1980 to 1989

Moderate tropical storm (MTS) Berobia originated on the 5th of January 1986, 300km from Nacala in the Mozambican Channel, generating wind speeds of below 35km/h while moving in a south-west-southerly direction for the following 72 hours reaching wind speeds of 66km/h. On the 8th of January the system started heading in a north-westerly- and then westerly direction until it made landfall 36 hours later with maximum wind speeds before

landfall briefly reaching 98 km/h before the MTS's dissipation 6 hours later 200km south-east-south of Harare in Zimbabwe on the 10th of January.

3.1.4 Period 1990 to 1999

The cyclones making landfall along Africa's south-eastern coast during the period 1990 to 1999 is shown in Figure 5.

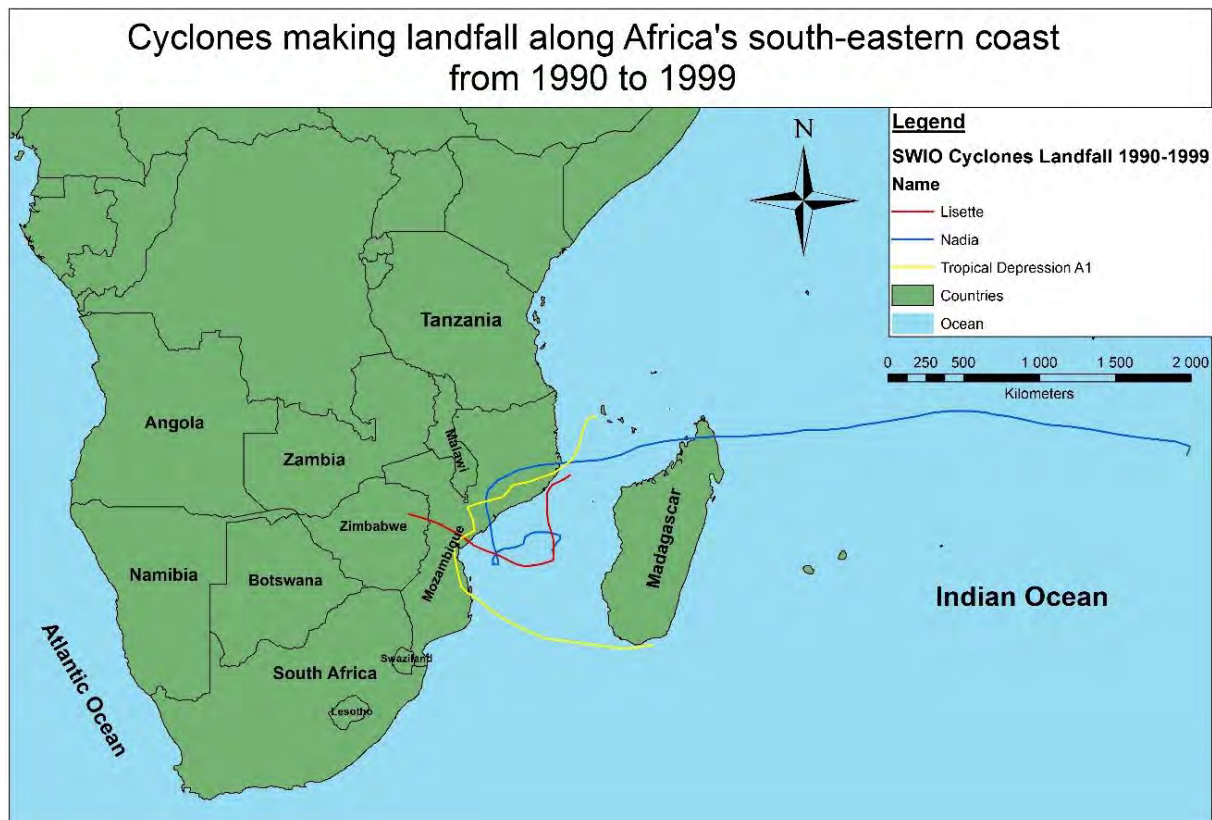


Figure 5 - Cyclones making landfall from 1990 to 1999

ITC Nadia originated on the 16th of March 1994, 3100km off the north-east coast of Madagascar, generating wind speeds of only 37 km/h while moving in a westerly direction until the system made landfall 120km north of Andapa on the 22nd of March with a wind speed of 185 km/h. 12 hours prior to the ITC making landfall over Madagascar the system reached wind speeds exceeding 232km/h while still continuing in a westerly direction over the Mozambican Channel until Nadia made landfall again at Nacala on the 24th of March with wind speeds of 152km/h. Upon landfall ITC Nadia headed in a westerly and then south-westerly direction for the next 24 hours with the wind speed decreasing to 38km/h and within the following 24 hours the system's wind speed had decreased to a mere 25km/h after which it moved over the ocean again into the Mozambican Channel on the 26th of March. ITC Nadia moved in a southerly direction and made a clockwise loop and continued east gaining intensity until a wind speed of 95 km/h was measured on the 29th of March which as

sustained for 24 hours before the system starting dissipating and ultimately died down on the 1st of April with a final wind speed of 55 km/h.

TC Lisette originated on the 24th of February 1997 120km south-east of Nacala in the Mozambican Channel, generating wind speeds of less than 35km/h upon cyclogenesis which was sustained for the next 24 hours while the system moved south-west. The TC headed in a southerly direction for the next 48 hours gaining wind speed that was measured at 114 km/h upon the system's shift in westerly direction on the 28th of February. Lisette continued to move west and then in a north-westerly direction generating wind speeds in excess of 140 km/h until the system made landfall 50km north-east of Beira on the 2nd of March after the TC dissipated 18 hours later with a final wind speed of 53 km/h on the 3rd of March.

TD A1 undergone cyclogenesis on the 15th of January 1998 20km south-west of the Comores, generating wind speeds of 46 km/h which remained constant for the next 36 hours while briefly moving west and then in a southerly direction until the system made landfall on the 17th of January. Upon making landfall the TD stated heading in a south-westerly direction while the wind speed increased to 60km/h after which the system continued in a southerly and then south-westerly direction and ultimately headed in a south-easterly direction while maintaining a wind speed of 52 km/h before moving over the Mozambican Channel on the 20th of January. TD A1 continued in a south-easterly direction for the next 36 hours subsequently moving east for the remainder of the TD's duration until the system dissipated on the 23rd of January with a final wind speed of 48 km/h.

3.1.5 Period 2000 to 2009

The cyclones making landfall along Africa's south-eastern coast during the period 2000 to 2009 is shown in Figure 6.

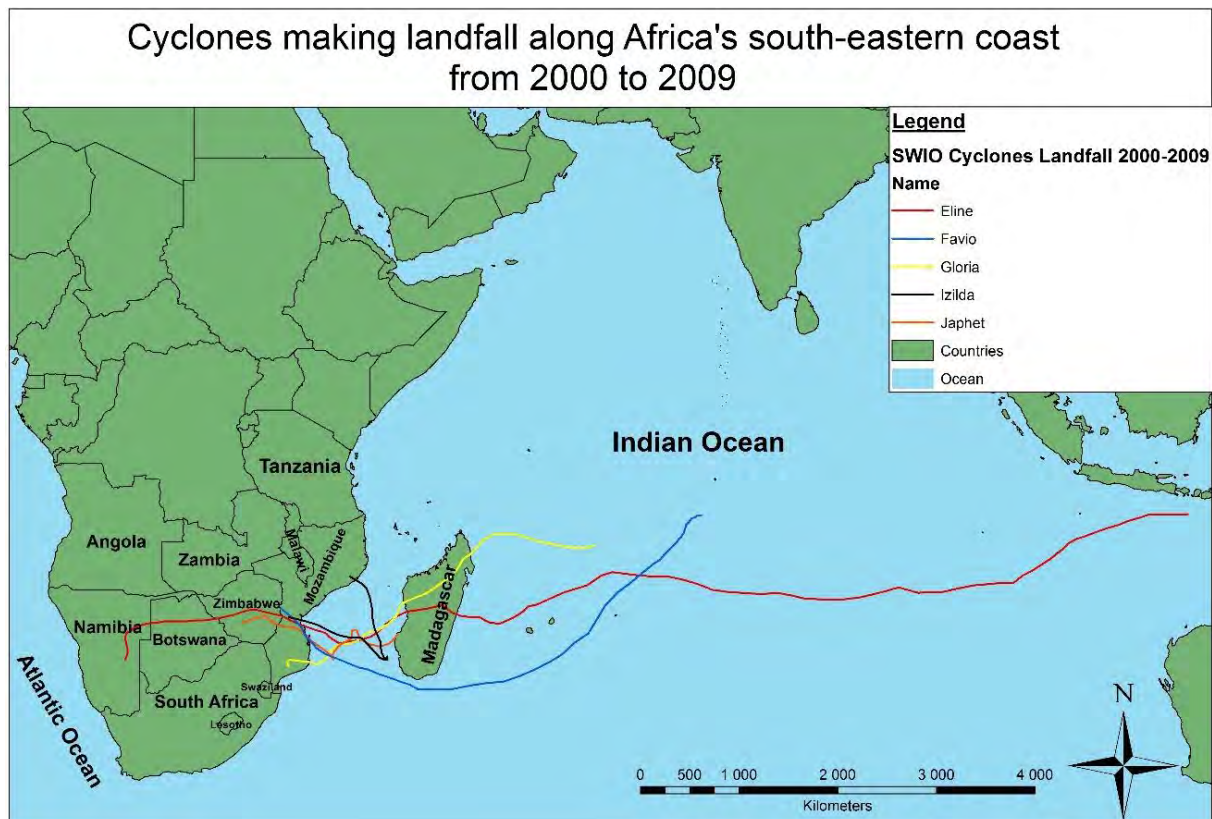


Figure 6 - Cyclones making landfall from 2000 to 2009

ITC Eline originated on the 1st of February 2000, 250 km south of Bali province in Indonesia, but was originally classified by Australian Bureau of Meteorology as TC Leon as it undergone cyclogenesis in the Western Australian basin. The ITC originated with wind speeds less than 74 km/h and headed in a westerly direction over the Indian Ocean for the following 17 days upon making landfall 200km south-east of Antananarivo with a measured wind speed of 146 km/h before making landfall. Eline tracked over Madagascar for the next 24 hours in a north-westerly and then westerly direction with the wind speed decreasing to 55 km/h by the time the system reached the Mozambican Channel on the 18th of February. The ITC headed in a south-westerly direction for the following 24 hours while the wind speeds increased to 66km/h during this period after which the storm moved in a westerly and then a west-north-westerly direction until ITC Eline made landfall on the 22nd of February 80km south of Beira with wind speeds exceeding 205 km/h. 6 hours later inland the wind speed briefly increased to beyond 215km/h after which it continued in a westerly direction with the wind speed decreasing to 45km/h 36 hours later. The system kept on tracking west over central Zimbabwe, northern Botswana, and crossed the Namibian border on the 26th of February after which it headed in a south-westerly direction for 24 hours upon changing direction south until the system's dissipation on the 29th of February.

STS Gloria originated on the 27th of February 2000, 1300km off the north-east coast of Madagascar, generating wind speeds of 38km/h while tracking in a westerly direction for the first 60 hours since cyclogenesis occurred with the wind speeds increasing to 82 km/h. The STS started moving in a south-westerly direction for the following 12 hours while the wind speed increased to 95 km/h before making landfall on the 1st of March 80km north-east of Andapa. Gloria moved south-west the Madagascan landmass for the next 48 hours with the wind speed decreasing to 45km/h after which it headed out over the Mozambican Channel on the 4th of March. The system continued tracking in a south-westerly direction for the following 96 hours while maintaining an almost constant wind speed of 50 km/h before making landfall at Inhambane on the 9th of March. The system dissipated on the 10th of March with final wind speeds of below 35km/h after tracking westwards over the landmass.

ITC Japhet originated on the 25th of February 2003, 150km north of Toliara on the Madagascan coast, generating wind speeds of 40km/h and tracked in a westerly and then north-westerly direction with wind speeds increasing to 85 km/h 48 hours after cyclogenesis. On the 27th of February the ITC tracked south and then south-west when the system suddenly made a 90° turn in a north-westerly direction with the wind speed increasing to 212 km/h 24 hours before the system made landfall at Vilanculos in Mozambique on the 2nd of March with the wind speed upon landfall measured at 170 km/h. Japhet continued moving in a north-westerly direction for the following 72 hours and eventually dissipated 40km south-east of Bulawayo in Zimbabwe on the 5th of March with a final wind speed of below 90km/h.

ITC Favio undergone cyclogenesis on the 11th of February 2007, 2400km off the northern most tip of Madagascar, generating wind speeds of below 36 km/h upon cyclogenesis while tracking in a south-westerly direction for the next 6 days with wind speed increasing to 75 km/h. On the 17th of February the system started moving in a westerly direction and continued west for the next 48 hours while the wind speed increased to 121 km/h and then tracked in a west-north-westerly direction over the ocean below the Madagascan landmass reaching the maximum wind speed of 226km/h 48 hours after the change in the system's direction occurred. With the wind speed decreasing while the ITC was travelling north-west 400km off the Mozambican coast the system made landfall 30km north of Vilanculos with the wind still maintaining a speed of 182 km/h. Favio travelled north-west for the next 24 hours with the wind speed decreasing to 80km/h when the system dissipated on the border between Zimbabwe and Mozambique.

STS Izilda originated on the 22nd of March 2009, 200km south of Nampula inland, generating wind speeds of 38 km/h while moving in a south-easterly direction and reached the Mozambican Channel within 6 hours of cyclogenesis. The STS headed south-east and then south over the following 72 hours down the Mozambican Channel with the wind speed

increasing to 93 km/h before the system complete an anti-clockwise rotation and then moved headed in a north-westerly direction until STS Izilda made landfall 70km south of Beira on the 29th of March while the maximum wind speed was recorded directly after the storm completed the loop with a measurement of 114 km/h. The system dissipated 6 hours later with a final wind speed of 35 km/h being measured on the 29th of March.

3.1.6 Period 2010 to 2014

The cyclones making landfall along Africa's south-eastern coast during the period 2010 to 2014 is shown in Figure 7.

Subtropical depression (SD) Dando originated on 10th of January 2012, 130km south-east off the coast from Manakara in Madagascar, generating wind speeds of below 55 km/h while moving in an east-south-easterly direction for the following 60 hours after which the system made a U-turn west which increased the wind speed to 73 km/h by the 12th of January. 48 hours later the system neared the Madagascan south-east coast before heading in a south-westerly direction below the Madagascan landmass with speeds maintaining about 57 km/h for this period until the 14th of January when the intensity of the system starting increasing again. SD Dando continued along a west-south-westerly direction and then west after which it ultimately started heading in a north-westerly direction with wind speeds reaching 82 km/h upon landfall 40km north-east of Xai-Xai on the 16th of January. The SD continued in a north-westerly and the westerly direction while losing intensity before dissipating 70km north-east of Lephalale in South Africa on the 18th of January with final wind speeds of below 45 km/h.

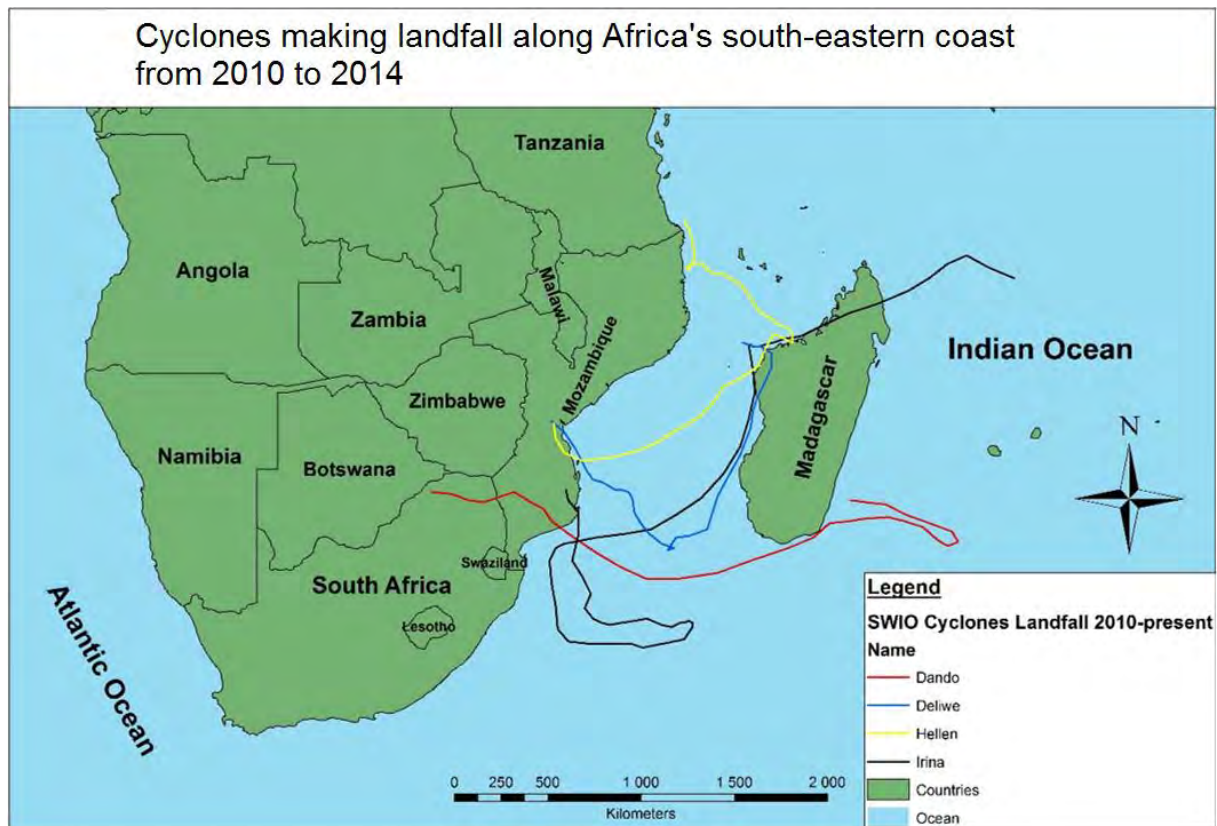


Figure 7 - Cyclones making landfall from 2010 to 2014

STS Irina originated on the 25th of February 2012, 700km off the north-east coast of Madagascar, generating wind speeds of about 40 km/h while first heading in a north-westerly direction and then in a south-westerly direction with the wind speed increasing to 55 km/h only 36 hours after cyclogenesis. The STS made landfall on the 26th of February 70km north-east of Andapa while still tracking in a south-westerly direction for the following 18hours and entered the Mozambican Channel on the 27th of February with wind speeds measured at 37 km/h before the system moved over open water again at Mahajanga in Mozambique. Over the following 48 hours Irina continued in a west-south-westerly direction and then in a westerly direction while gradually gaining wind speed which were measured at 65 km/h on the 29th of February. The STS made an abrupt 90° turn south and reached a maximum wind speed of 95 km/h on the 1st of March when the system started heading in a south-westerly and the westerly direction with the wind speeds being maintained at between 85 km/h and 90 km/h until the 3rd of March. STS Irina started heading south on the 4th of March after which the system turned 90° east and then made an 180° anti-clockwise rotation on the 7th on March, allowing wind speeds to increase to 92 km/h during this movement of the system. The storm maintained its intensity while moving west and upon a change in direction of the system towards north the wind speeds had decreased to 47 km/h by the 10th of March. The STS continued north and made landfall 20km south of Inhambane on the 11th of March after which the system dissipated a mere 12 hours later on the 12th of March.

MTS Deliwe undergone cyclogenesis on the 14th of January 2014, 300km west off the coast of Mahajanga in the Mozambican Channel, generating wind speeds of 35 km/h while moving in a south-easterly direction and made landfall within 12 hours 250km south-east of Mahajanga with the wind speeds decreasing to a mere 20 km/h over land by the 15th of January while the MTS headed south. The system moved over the Mozambican Channel again by the 16th of January and continued in a south-west-southerly direction for the following 36hours while gaining wind speed which were measured at 84 km/h on the 17th of January. Deliwe started then moving west and made an anti-clockwise loop on the 18th of January after which it continued north-west with the wind speed gradually decreasing until the MTS made landfall 50km south of Beira on the 22nd of January and dissipated on the same day with final wind speeds of below 28 km/h.

Very intense tropical cyclone (VITC) Hellen originated on the 26th of March 2014, 50km east off the coast of Mtwara in Tanzania, generating wind speeds of 30km/h upon cyclogenesis while moving in a southerly direction for the following 24 hours before making a clockwise loop and heading off in a easterly direction with the wind speeds measured at 37 km/h by the 28th of March. The system then started heading in a south-easterly direction which gained immense intensity over the following 72 hours with wins speeds reaching in excess of 230 km/h by the 30th of March before the system made landfall the following day 50km west of Mahajanga with wind speeds of 75 km/h upon landfall. VITC Hellen moved over the open water again as soon as the system made landfall and briefly headed in a north-westerly before moving south-west fleetingly making landfall again 170km west of Mahajanga of the 1st of April with wind speeds measured at 47 km/h. Hellen continued moving in a south-westerly direction and then in westerly direction with constant wind speeds of 37 km/h until the system made landfall 80km north of Vilanculos with wind speeds measured at 30 km/h after which the system dissipated 12hours later on the 5th of April with wind speeds of 25 km/h.

3.2 Cyclones moving within 100km of Mozambique's and South Africa's coastline

The cyclones moving within 100km of Mozambique's and South Africa's coastline is categorised as Tropical Storms (TS100) and Tropical Depressions (TD100).

3.2.1 TS100 from 1960 to 2014

During the period between 1960 and 2014, five cyclonic systems moved within 100km of Mozambique's and South Africa's coastline that were classified as tropical storms (Figure 8).

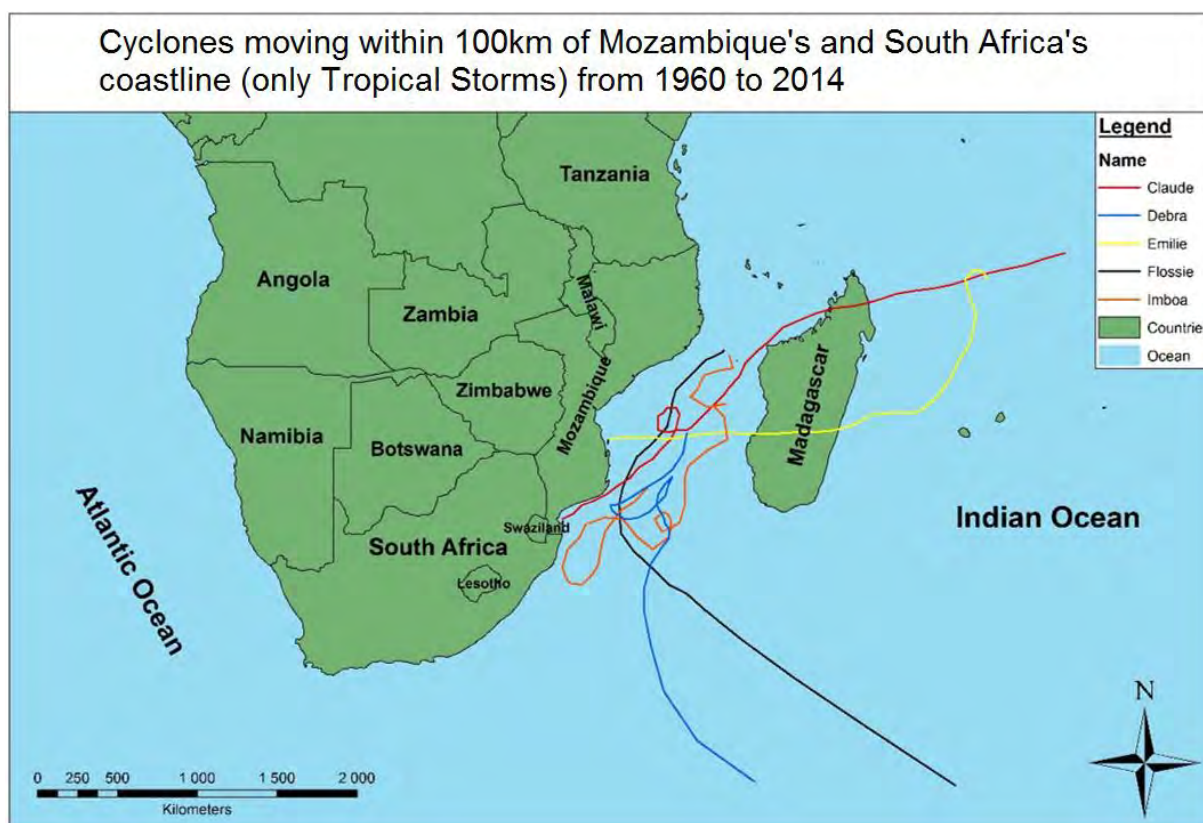


Figure 8 - Tropical storms moving within 100km from Africa's coastline between 1960 and 2014

A summary of these aforementioned systems is presented in Table 4.

Table 4 - Summary of tropical storms within 100km of Mozambique's and South Africa's coastline

Name of storm	Name of tropical system	Date of cyclogenesis	Date of dissipation	Position of cyclogenesis	Position of dissipation	Maximum sustained wind speed
Claude	MTS	1965-12-24	1966-01-05	1300km off the north-east coast of Madagascar	In the Maputo Bay	87km/h
Flossie	STS	1968-01-07	1968-01-14	250km south-east of Nacala	2100km off the south coast of Madagascar	115km/h
Emilie	STS	1977-01-28	1977-02-05	750km off the north-east coast of Madagascar	40km north-east of Vilanculos	114km/h
Imboa	STS	1984-02-10	1984-02-21	300km south-east of Nacala	260km east of Inhambane	95km/h
Debra	STS	1991-02-22	1991-03-03	550km east of Vilanculos	1750km off the south coast of Madagascar	115km/h

3.2.2 TD100 from 1960 to 2014

During the period between 1960 and 2014, four cyclonic systems moved within 100km of Mozambique's and South Africa's coastline that were classified as tropical depressions (Figure 9).

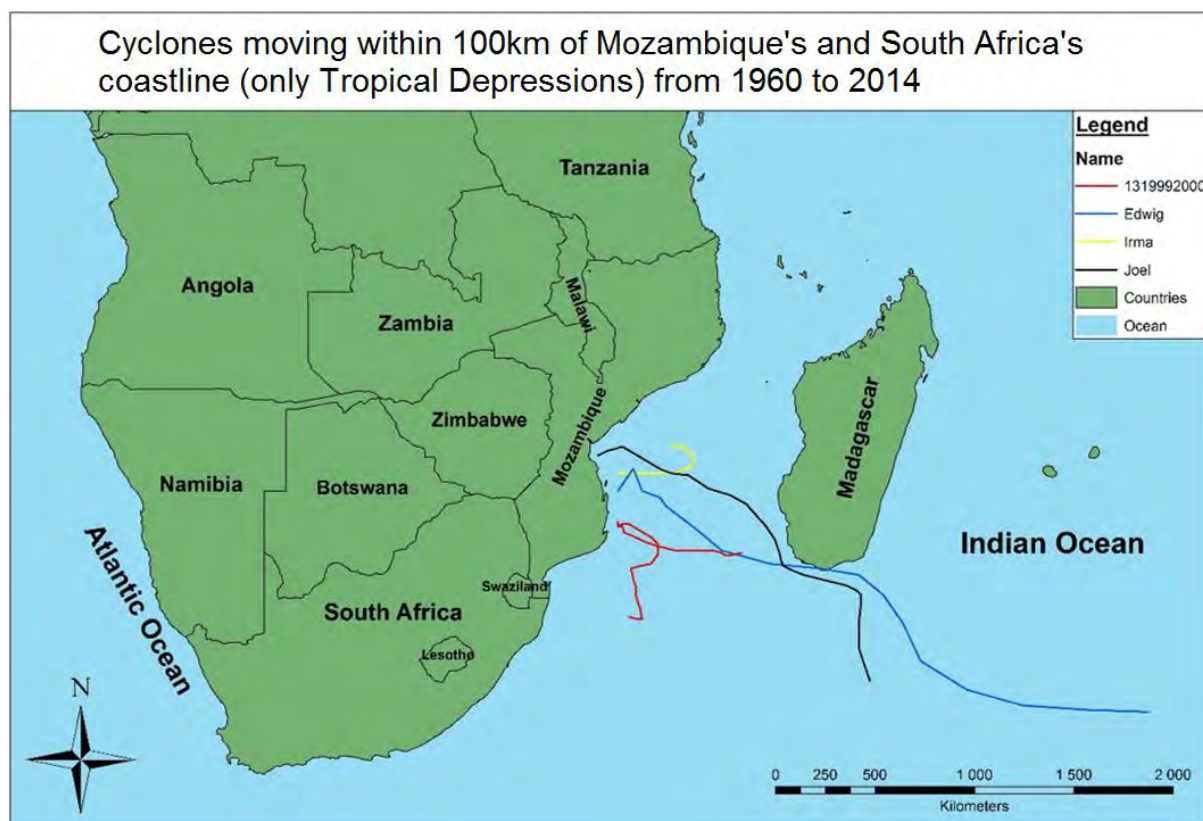


Figure 9 - Tropical depressions moving within 100km from Africa's coastline between 1960 and 2014

A summary of these aforementioned systems is presented in Table 5.

Table 5 - Summary of tropical depressions within 100km of Mozambique's and South Africa's coastline

Name of storm	Name of tropical system	Date of cyclogenesis	Date of dissipation	Position of cyclogenesis	Position of dissipation	Maximum sustained wind speed
Irma	TD	1967-02-21	1967-02-24	400km east of Beira	250km north-east of Vilanculos	51km/h
Edwig	TD	1980-12-28	1981-01-01	90km east of Vilanculos	1650km south-east off the south coast of Madagascar	62km/h
1319992000	SD	2000-04-07	2000-04-15	430km east of St. Lucia in South Africa	300km sou-west of Toliara	92km/h
Joel	SD	2010-05-22	2010-05-29	70km south of Beira	620km off the south coast of Madagascar	110km/h

4 STUDY AREA

4.1 Location

The Limpopo Province is the northern most province in South Africa as shown in Figure 10. The province shares borders with Mozambique, Zimbabwe and Botswana. The Limpopo River forms the northern boundary of the province. Limpopo is known for its game parks including the bigger part of the Kruger National Park (Limpopo Provincial Government, 2017).

Limpopo's capital city is Polokwane is located adjacent to the N1 highway approximately halfway between Pretoria and the Zimbabwean border. It is known as a commercial and agricultural centre.

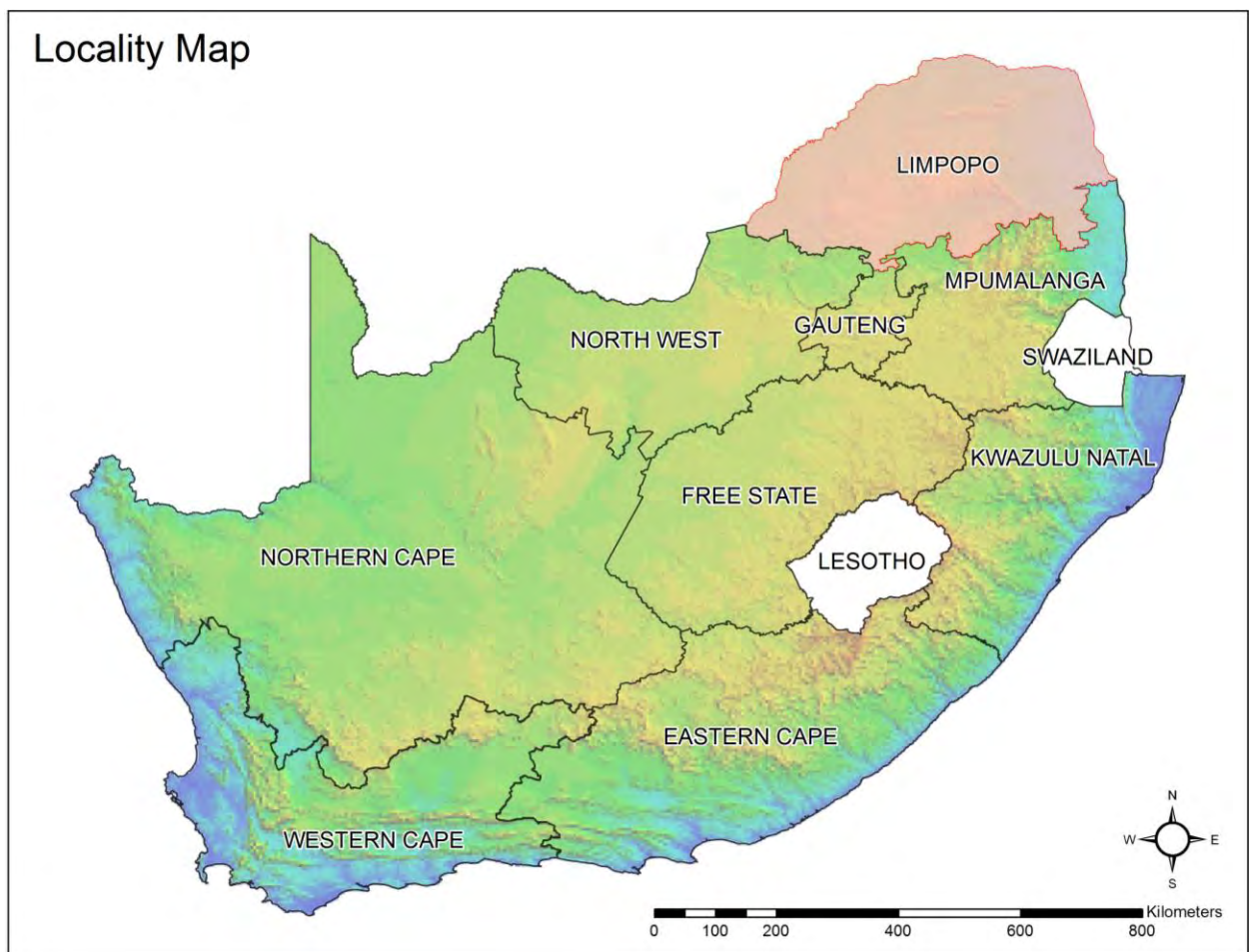


Figure 10 - Location of study area

4.2 Climate and Rainfall

Limpopo's climate varies greatly from sub-tropical to semi-arid. The western parts have a dry, hot semi-arid climate, becoming cool along the escarpment. Large variations occur in seasonal temperatures, while the eastern parts of experience cooler temperatures compared to the north-

eastern parts. Maximum temperatures are experienced in January and minimum temperatures occur on average in July (Table 6).

Table 6 - Temperature variations (adapted from Holland, 2011)

Town	Summer		Winter		Annual	
	Min (°C)	Max (°C)	Min (°C)	Max (°C)	Min (°C)	Max (°C)
Polokwane	16	27	8	22	25	12
Mara	17	29	8	25	27	12
Tzaneen	18	27	14	24	25	16
Modjadji	14	26	11	23	25	13
Levubu	18	28	12	25	27	15
Thoyandou	18	29	12	26	27	15
Giyani	19	31	11	27	29	15

The average annual rainfall varies accordingly from 1000 mm in the central parts to only 300 mm in the west and 400 mm in the east (Holland, 2011). Orographic rainfall occurs along the Great Escarpment. The mean annual precipitation (MAP) ranges from below 370 mm in the western arid area of the province to almost 700 mm in the central-eastern area of the province according to the selected rainfall stations across the province. The 1:20 drought and flood conditions also vary significantly based on the rainfall data available. The rainfall distribution and statistics are shown in Table 7 and Figure 11.

Table 7 - Rainfall per area (SAWS)

Town	MAP (mm)	5 th (1:20 Drought)	95 th (1:20 Flood)
Letaba	477	216	837
Mara	434	189	688
Ohrigstad	539	309	728
Phalaborwa	429	194	646
Thohoyandou	697	105	1300
Bela Bela	587	360	848
Shingwedzi	462	218	835
Polokwane	428	242	660
Tolwe	367	181	599

The average annual evaporation ranges from 1600 mm in the central mountainous region to over 2000 mm in the western and eastern areas (Holland, 2011).

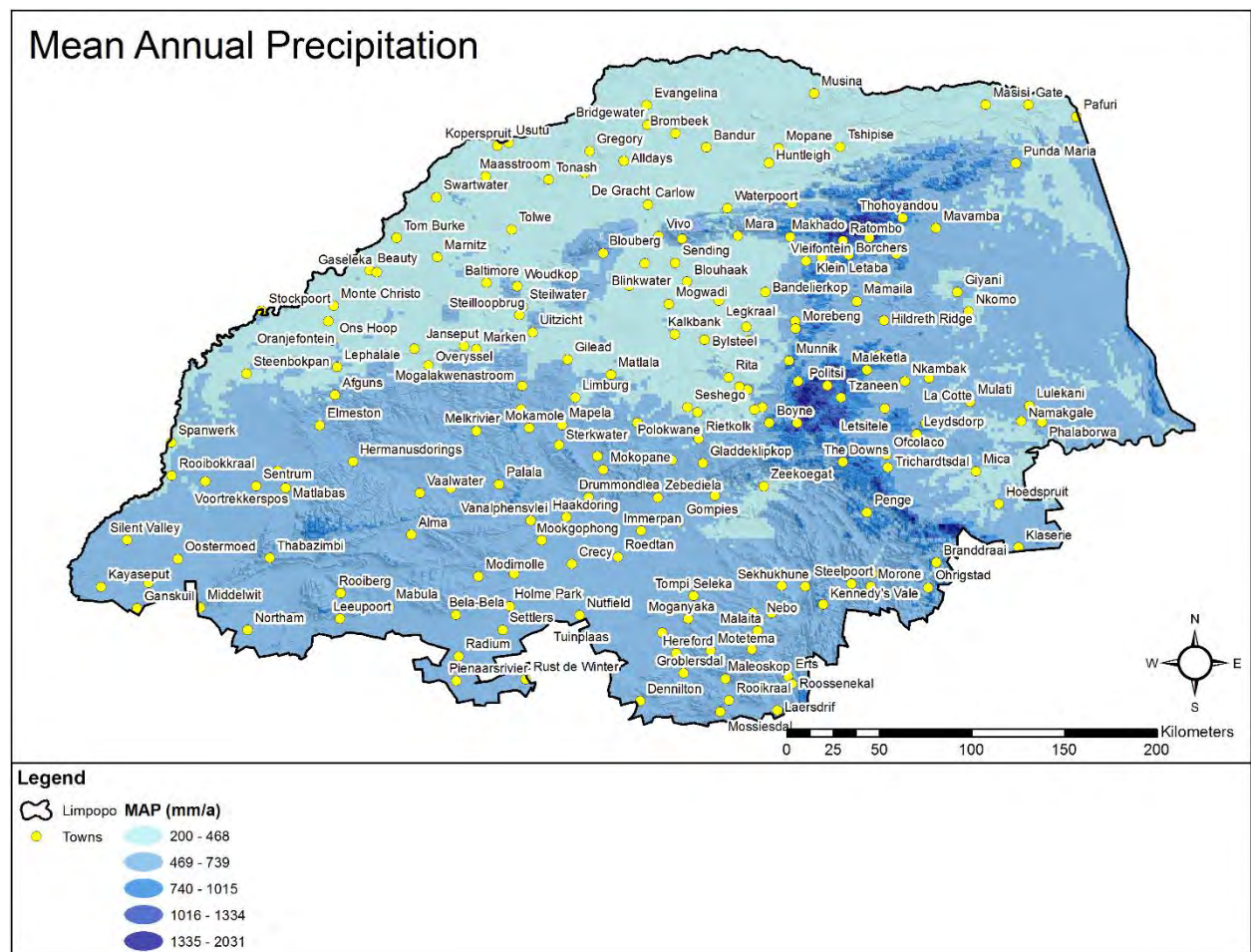
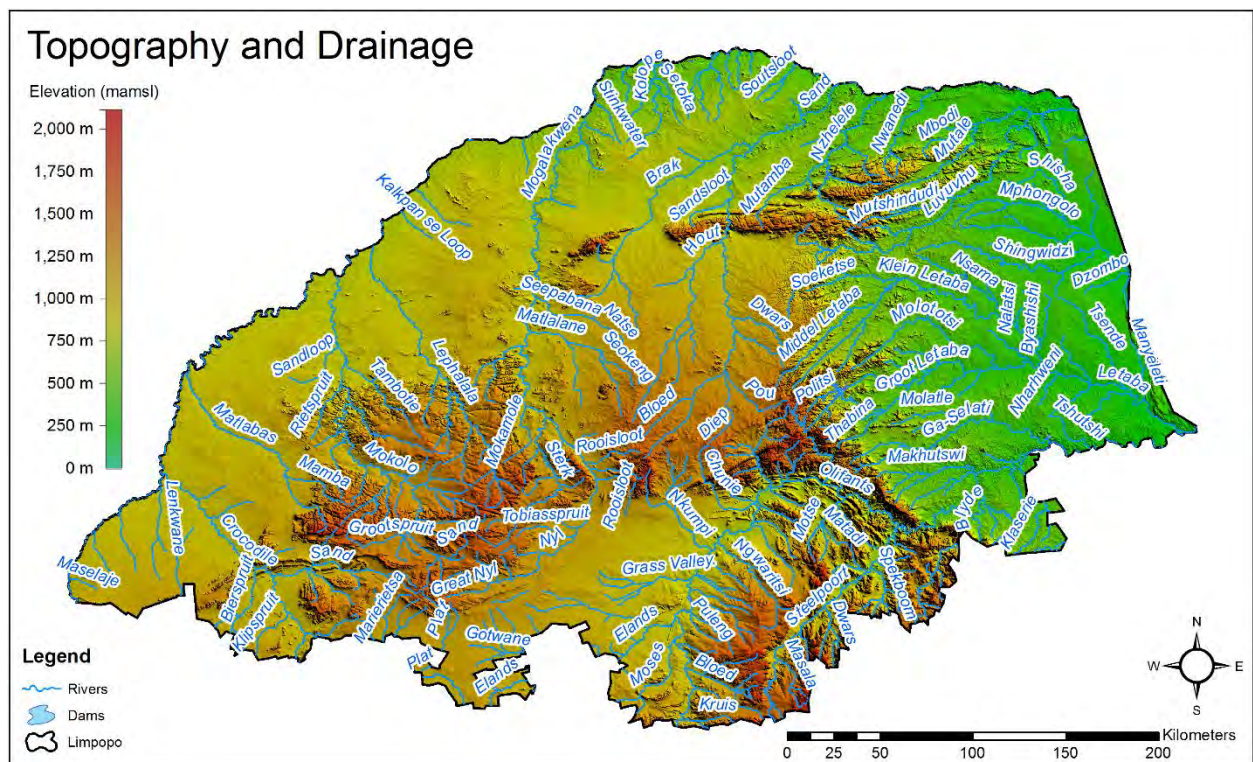


Figure 11 - Average rainfall distribution of Limpopo province

4.3 Topography and Drainage

The topography (Figure 12) of the area varies from mountainous zones in the west through to foothills in the central areas and plains in the east. The average elevation in the central part of the study area is 400 to 800 mamsl, and is 1200 to 1600 mamsl in the Blouberg and areas. The Great Escarpment to the east and south east is deeply incised by the major tributaries draining towards the east (Holland, 2011).

The main rivers within the study area the Sand, Hout and Brak Rivers. These are relatively slow flowing rivers and have extensive alluvial deposits. All these rivers flow towards the Limpopo River which in turn flows into the Indian Ocean in Mozambique. Right throughout the study area runoff is seasonal, with intermittent flow in the tributaries (Holland, 2011). Only a small amount of the rivers is classified as perennial rivers (e.g. the Great Letaba River and the Little Letaba River).



4.4 Geohydrology

4.4.1 Recharge

Recharge is defined as the process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation. Two recharge maps have been generated for South Africa, the first being Vegter's 1995 recharge map and the second being the Groundwater Resource Assessment II (GRAII) (Department of Water Affairs and Forestry, 2006). These maps for the study area are included in Figure 13 and Figure 14. The GRA II dataset is based on the chloride recharge method but also takes into account groundwater levels, slope, land cover and variations in precipitation. Recharge is lower in the northern regions of the study area and higher in the mountainous areas and to the south-east of the area.

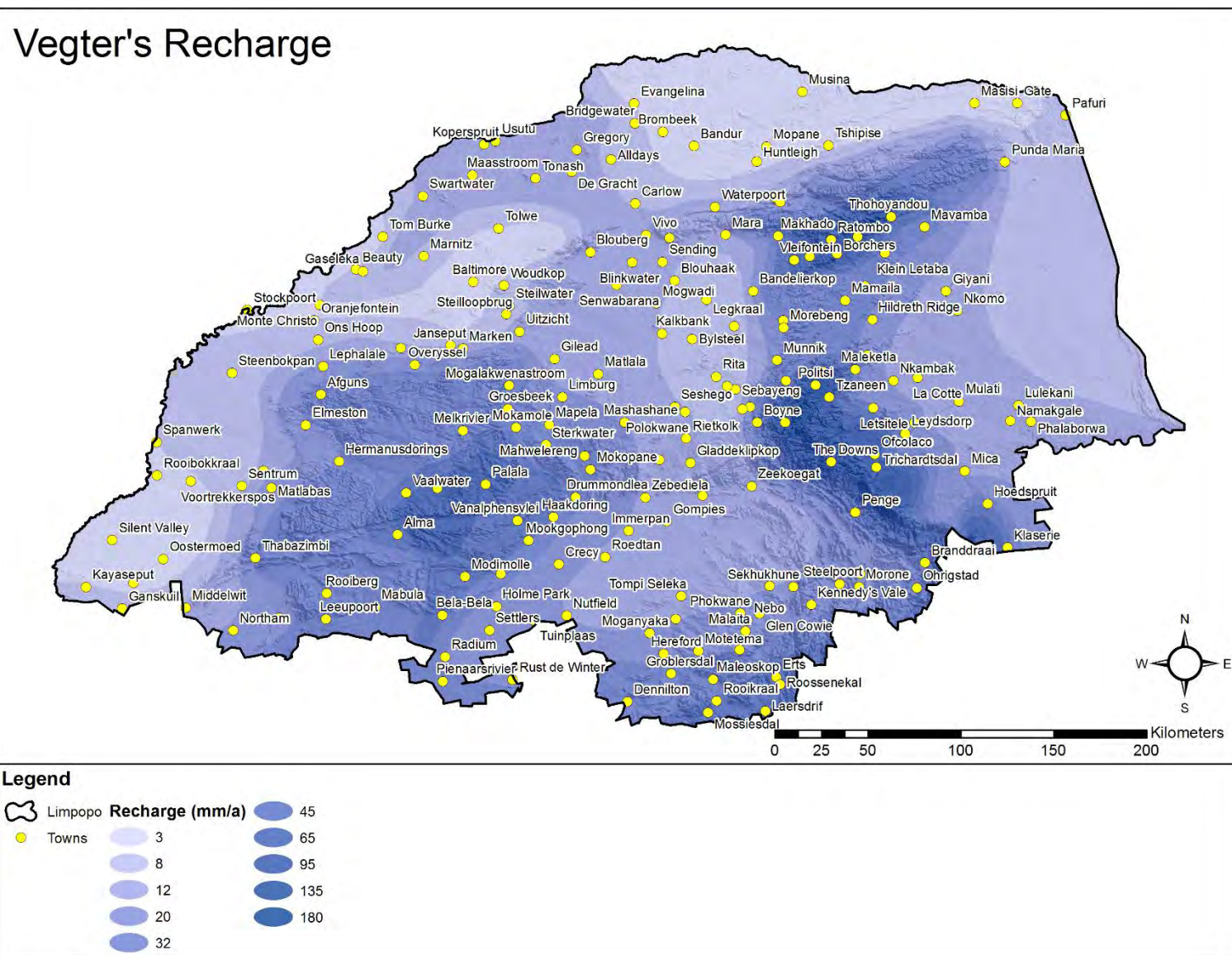


Figure 13 - Vegter's recharge map for Limpopo province

GRAII Recharge

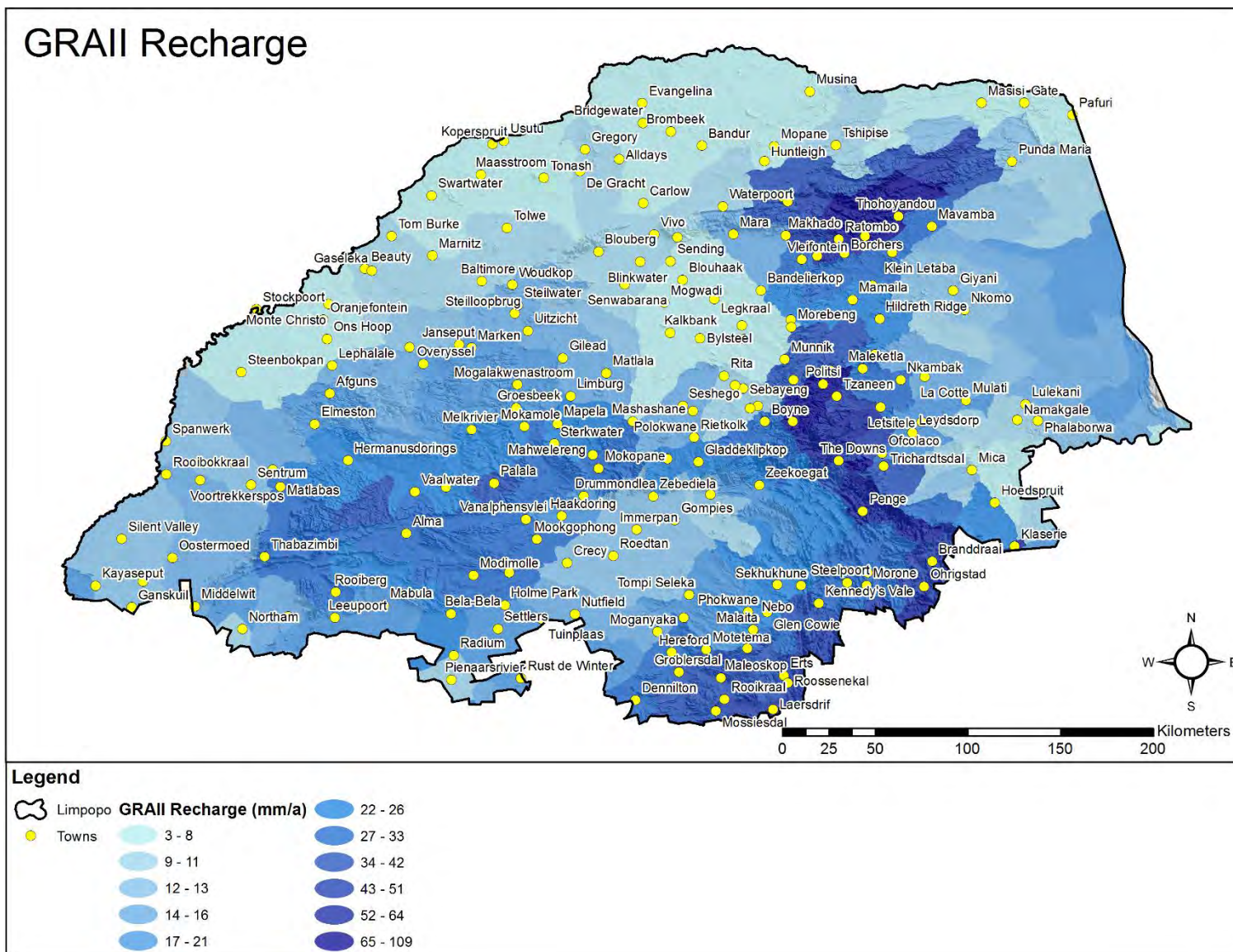


Figure 14 - GRAII recharge map for Limpopo province

4.4.2 Groundwater Yields

Sustainability implies groundwater use that does not cause long-term deterioration of the overall resource. Before any abstraction takes place, aquifers are in a state of equilibrium. However, when pumping starts this equilibrium can be disturbed. The only way to maintain this equilibrium is by balancing groundwater abstractions by increasing recharge or by reducing the discharge from the aquifer. Some aquifers have high storage, therefore allowing abstractions to exceed recharge at times. However, in the long term, the balance must be maintained. For example, aquifers can recharge after unusually high rainfall events every few years. Groundwater yields based on lithology are shown in Figure 15. The groundwater yields vary from 0.1 l/s to greater than 5 l/s.

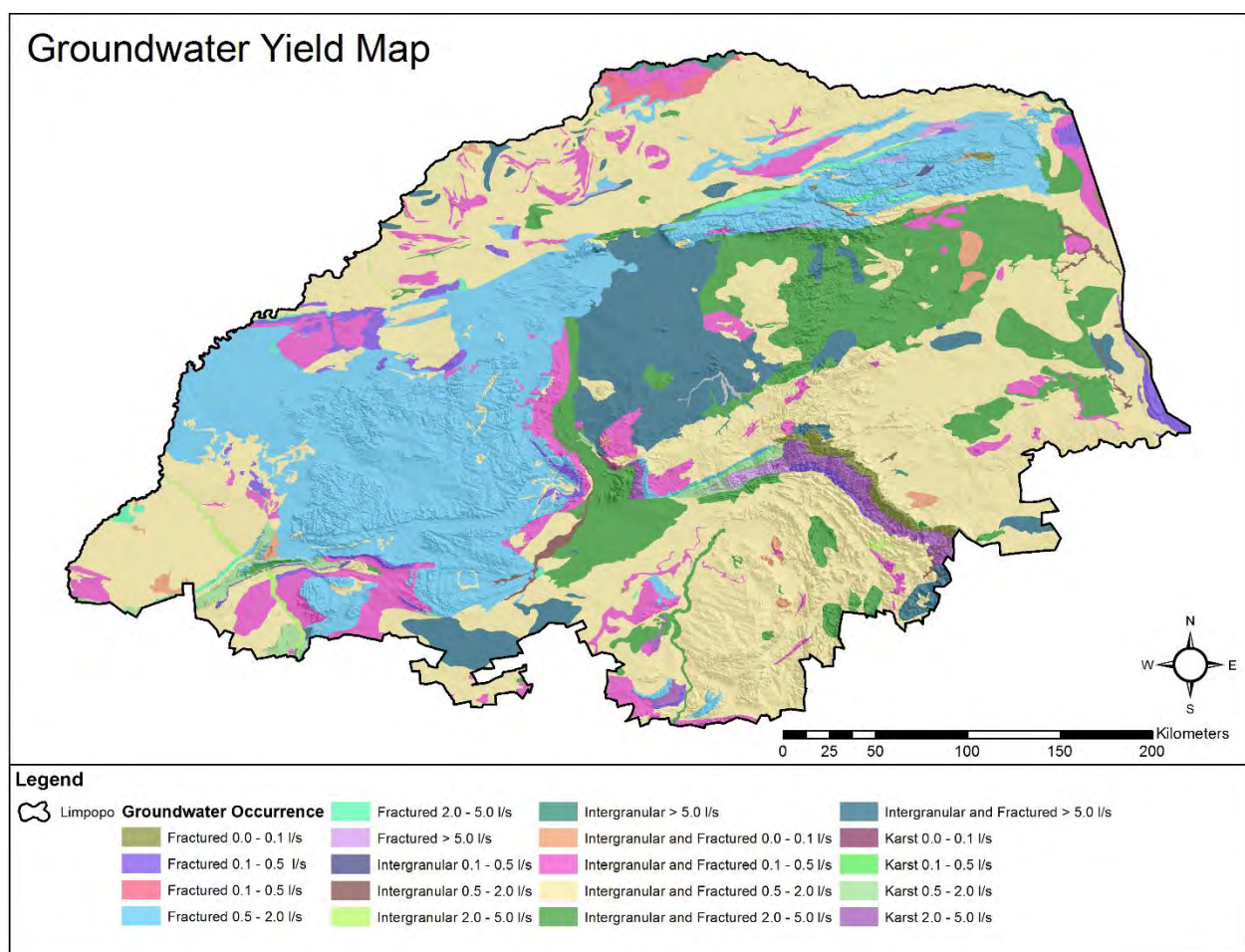


Figure 15 - Groundwater yields of Limpopo province

4.4.3 Aquifer Vulnerability

Aquifer vulnerability refers to the tendency or likelihood for contamination to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer. The DRASTIC aquifer vulnerability method makes use of seven factors to calculate the vulnerability index value (Aller *et al.* 1987):

- (D) Depth to groundwater – determines the maximum distance contaminants travel before reaching the aquifer;
- (R) Net recharge – the amount of water that is able to travel from ground surface to the water table;
- (A) Aquifer – the composition of the aquifer material;
- (S) Soil media– the uppermost portion of the unsaturated zone;
- (T) Topography– the slope of the ground surface;
- (I) Impact of vadose zone– the type of material present between the bottom of the soil zone and water table; and
- (C) Hydraulic conductivity of the aquifer– indicates the aquifer's ability to allow for the flow of water to occur.

This vulnerability index is used to determine the aquifer's vulnerability to pollution and the index range from 0 to 200, where 200 represents the theoretical maximum aquifer vulnerability. The results of this assessment are shown in Figure 16. It is clear from the aquifer vulnerability map that a large portion of the study area has a low to medium vulnerability (58 - 176).

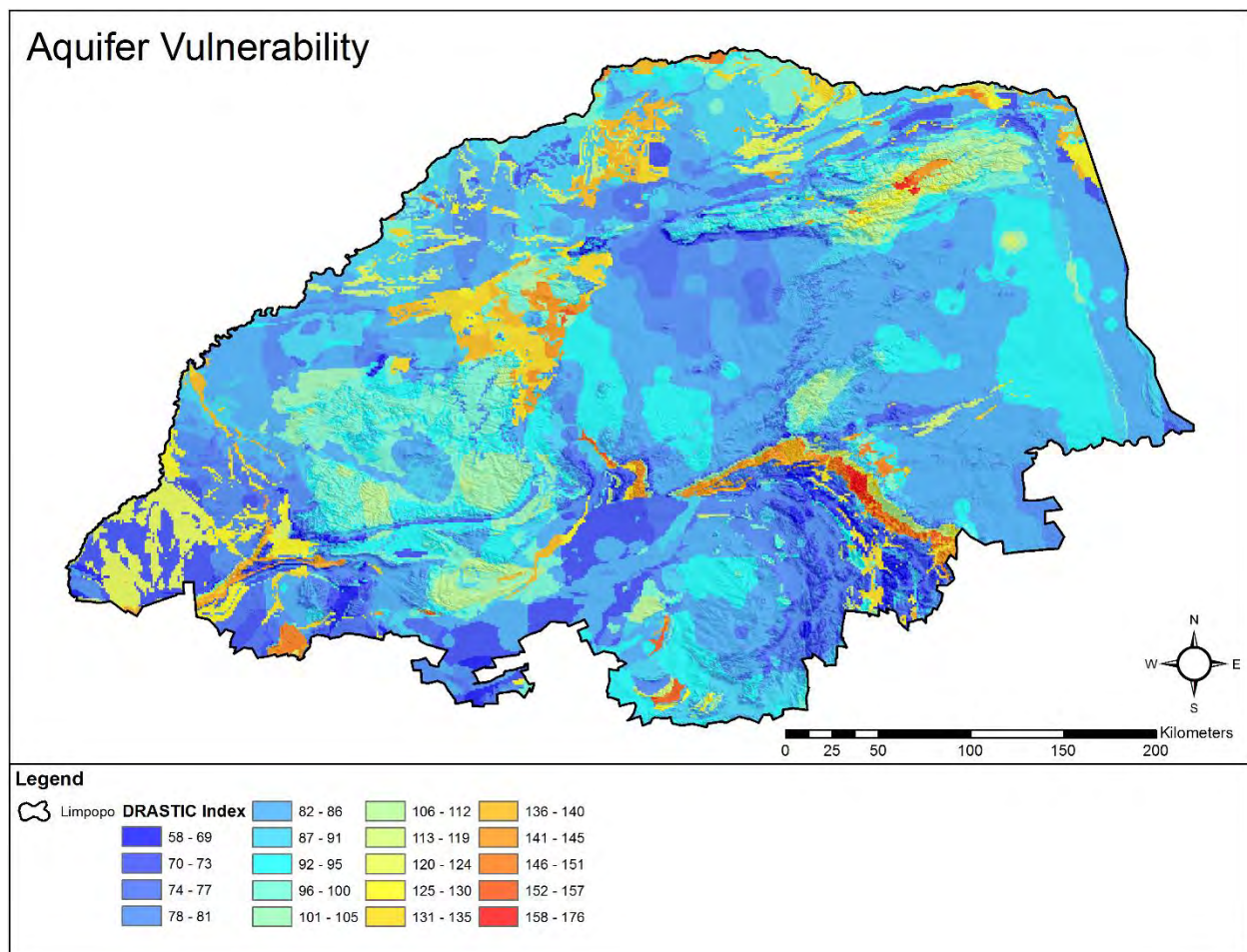


Figure 16 - Aquifer vulnerability map of Limpopo province

4.5 Geology

The study area covers the area between the granite-greenstone terrain of the north-eastern part of the Kaapvaal Craton and the metamorphic rocks of the Southern Marginal zone of the Limpopo Mobile Belt. The Mobile Belt consists of:

- The Northern Marginal Zone
- the Central Zone and
- the Southern Marginal Zone

The above-mentioned zones lie parallel to one another. The Hout River Shear Zone is the boundary between the metamorphism granitoid-greenstone terrane to the south and the higher-grade metamorphism rocks of the Southern Marginal Zone to the north. The Hout River Shear Zone is over 250 km from west to east across and acts as a complex thrust system (Holland, 2011).

The geology is dominated by Archaean basement rocks (granite, gneiss and greenstone) which outcrop in an approximately rectangular area bordered (Holland, 2011);

- to the south by younger overlying sedimentary strata,
- to the north by the Soutpansberg Group,
- to the west by the Bushveld Complex, and
- to the east by the Drakensberg basalts

Numerous dyke swarms occur in the area. The north-western and south-western domains are predominantly characterized by the gneissic rocks of the Goudplaats-Hout River Group with a smaller number of dykes and lineaments when compared to the Letaba northeastern and south-eastern domains. The two eastern structural domains are characterized by the highest dyke intensity. Dyke trends in the NE domain are cut obliquely across the greenstone belts. Dykes in the SE domain are almost parallel to a batholith. The Hout River Shear Zone can be regarded as the split between the northern and southern domains (Holland, 2011).

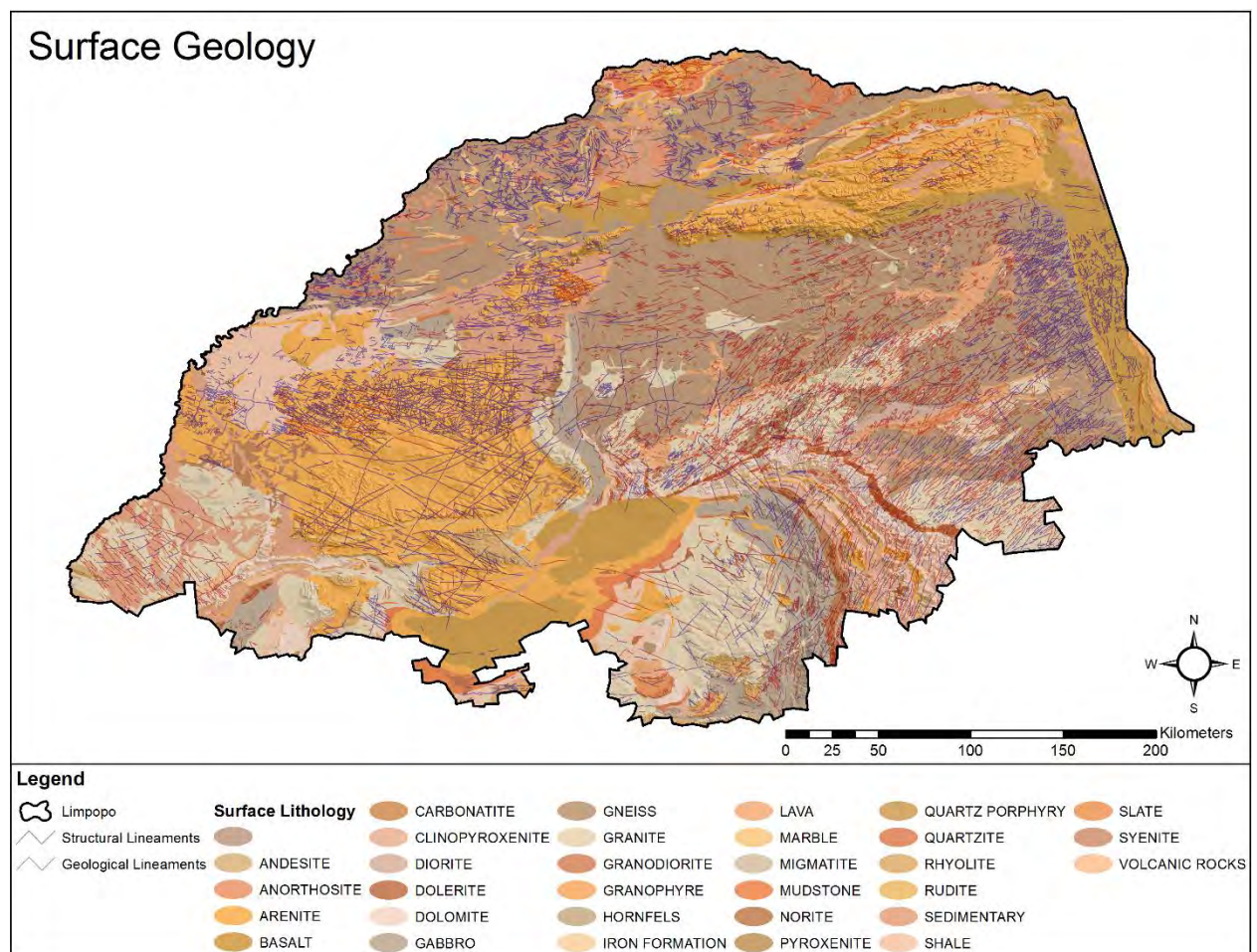


Figure 17 - Geology map of study area

5 METHODOLOGY

It is clear from Chapter 2 that modelling episodic recharge would require detail datasets for each site and in addition, complex interactions between the relevant components would be challenging to model across a study area the size of the Limpopo province. Therefore, instead of modelling episodic recharge as a function of various parameters, the episodic recharge response is mathematically described as a function of water level change for identification purposes in this study.

5.1 Episodic Recharge Identification

In a general groundwater balance, the change in water level can be related to a change in storage as shown in Equation 1.

$$\Delta H_j = \frac{R_j}{S_y} \quad (1)$$

where,

$$\begin{aligned} \Delta H_j &= \text{Water level change in time step } j \\ R_j &= \text{Recharge in time step } j \\ S_y &= \text{Specific Yield} \\ j &= \text{The } j^{\text{th}} \text{ time step} \end{aligned}$$

Equation 2 actually express the derivative of H with respect to time, because it represents the change in head with the change in time, dH/dt .

$$\frac{dH}{dt} = \frac{R_j}{S_y} \quad (2)$$

where,

$$\begin{aligned} dH &= \text{Water level change} \\ dt &= \text{Change in time step} \\ R_j &= \text{Recharge in time step } j \\ S_y &= \text{Specific Yield} \\ j &= \text{The } j^{\text{th}} \text{ time step} \end{aligned}$$

The use of derivatives of pressure head is in use for many years in the oil field to evaluate flow regime characteristics (Bourdet et al, 1984; Horne, 1997). Use of the derivative of pressure head versus time is mathematically satisfying because the derivative is directly represented in one of the diffusivity equations, which is the governing equation for all the models of transient pressure behaviour. The derivative response is much more sensitive to small phenomena, which implies that erratic or noisy data will generate huge derivative responses, which is not of interest, but rather the underlying response represented by a smoothed version of the noisy data. Due to this a least square fit of the derivative calculation is implemented as shown in Equation 3.

$$\frac{dH}{dt} = \frac{N \sum t_i H_i - \sum t_i \sum H_i}{N \sum t_i^2 - (\sum t_i)^2} \quad (3)$$

where,

- N = Number of data points considered in calculation
- i = Index (1 to N)
- t_j = Time at index i
- H_i = Water level at index i

A sudden increase in water level will result in a positive response of the derivative as described by Equation 3 and the converse will happen when a drop, in water level occurs from one time step to another. By applying Equation 3 to the long-term water level data of a borehole, recharge events can be identified.

For the purpose of this study only episodic recharge events are of interest and since these events cannot be modelled, a mathematical definition is assigned to define these recharge events. Two types of episodic recharge are formulated based on Equation 3 and is discussed in the following sections.

5.1.1 Type I - Episodic Recharge

Since the water level response in a borehole will be mainly governed by the associated aquifer parameters e.g. specific yield (Equation 2), it is difficult to compare the responses of different boreholes in different geologies. For the purpose of this study a normalised derivative response is calculated for each borehole based on the maximum derivative calculated and only positive derivatives associated with recharge events are considered.

The Type I episodic recharge is then defined by a threshold value that must be exceeded in the normalised derivate for the event to be classified as a Type I episodic recharge event.

5.1.2 Type II – Episodic Recharge

The Type II episodic recharge is formulated on the basis of the Type I event, but with the additional restriction that water level recovery, based on the maximum historic recorded level, should take place. It is clear from this definition that fewer Type II episodic events will occur compared to the Type I episodic events on the same dataset.

5.2 Correlation

Episodic recharge events (Type I and Type II) are identified by applying their mathematical definition to historic groundwater levels. A database of cyclonic events is available to construct a time line of these cyclonic events. The correlation between the episodic recharge and cyclonic events is then calculated making use of Equation 4.

$$r = \frac{N \sum x_i y_i - (\sum x_i)(\sum y_i)}{\sqrt{(N \sum x_i^2 - (\sum x_i)^2)(N \sum y_i^2 - (\sum y_i)^2)}} \quad (4)$$

where,

r	=	<i>Correlation coefficient</i>
N	=	<i>Number of data points</i>
i	=	<i>Index 1 to N</i>
x_i	=	<i>Data set x at index i</i>
y_i	=	<i>Data set y at index i</i>

The correlation coefficient is a measure of the extent to which two measurement variables "vary together." The value of any correlation coefficient must be between -1.0 and 1.0 inclusive, where a correlation coefficient of 1.0 implies the datasets are identical. It is important to note that dataset x and y must have the same number of data points n .

5.3 Water Level Time Lag Response

It is a common occurrence that the water level response associated with a recharge event exhibit a delay, due to the time scale associated with groundwater movement. Cyclonic events are associated with rainfall and therefore the lag between the rainfall and water level response

should be calculated when comparing rainfall events with water level events. This is accomplished by making use of cross-correlation between the two aforementioned datasets.

In signal processing, cross-correlation is a measure of similarity of two series as a function of the displacement of one relative to the other. Cross-correlations are useful for determining the time delay between two signals. After calculating the cross-correlation between the two signals, the maximum (or minimum if the signals are negatively correlated) of the cross-correlation function indicates the point in time where the signals are best aligned. The cross-correlation of two datasets are presented in Equation 5.

$$r(d) = \frac{\sum[(x_i - x_{max})(y_{i-d} - y_{max})]}{\sqrt{(x_i - x_{max})^2} \sqrt{(y_{i-d} - y_{max})^2}} \quad (5)$$

where,

r	=	Cross-correlation coefficient
d	=	Number of time steps to shift
N	=	Total number of data points in each dataset
i	=	Index 1 to N
x_i	=	Data set x at index i
y_i	=	Data set y at index i
x_{max}	=	Maximum value of dataset x
y_{max}	=	Maximum value of dataset y

5.4 Detection Algorithm

The detection algorithm is based on Equation 3 and applied the Type I and Type II episodic recharge definitions. The criteria used to specify the Type I and Type II episodic recharge is determined empirically through visual inspection of the datasets.

Since Equation 3 is sensitive sudden changes in water level some pre-screening of the water level data is performed to remove artefacts from the data. Groundwater level monitoring data is often prone to gaps in the data, which can lead to sudden changes in water level which the detection algorithm will see as episodic recharge based on the applied definition. To avoid the aforementioned scenario the following is done with a water level dataset subjected to the detection algorithm:

- a) Ensure the dataset represent continuous long-term water level data as far as possible. If monitoring data is very sparse and no sections of continuous data is available, rather discard the dataset.

- b) If enough continuous data exist for the detection, ignore all episodic recharge events detected just after time steps where no water level data was present.

Finally, the detection algorithm performs a shift between the episodic recharge events and the cyclonic events, based on the time lag calculated between the rainfall data and water level response. The correlation coefficients are then calculated between the different types of episodic recharge and cyclonic events.

6 DATA ANALYSIS

6.1 Temporal Nature of Cyclones

Making use of the cyclone data presented in Chapter 3, a database was constructed of the different types of cyclones; those that make landfall, tropical depressions and tropical storms 100km from the eastern seaboard. The monthly occurrences of these aforementioned cyclones are shown in Figure 18. It is clear from the graph that the cyclones generally start in December with most occurring in January and February and then taper off towards May. There is also significantly more cyclones that makes landfall in comparison to the tropical storms and depressions that come within a 100km of the eastern seaboard.

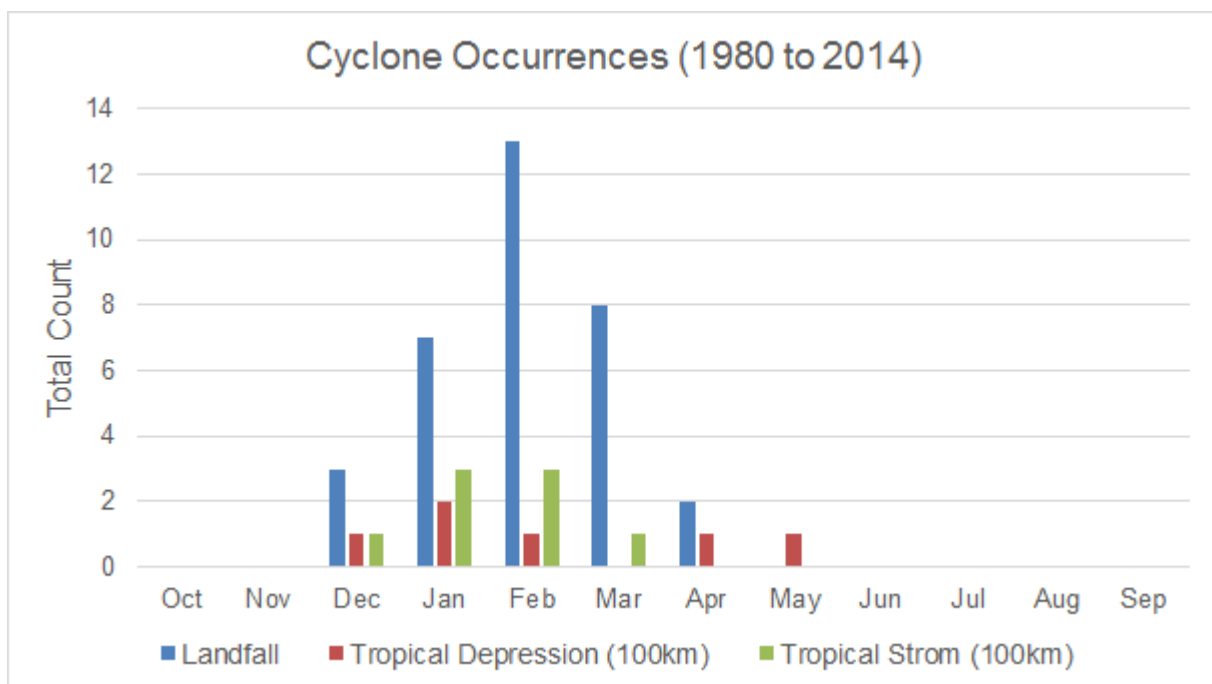


Figure 18 - Cyclone occurrences between 1980 and 2014

6.2 Borehole Selection

To determine the correlation between cyclonic events and episodic recharge, monitoring boreholes with long-term historic water levels are required. The cyclone database considered has data from 1980 to 2014 and hence boreholes with water levels over the same time period is required.

The National Groundwater Archive (NGA) and Groundwater Resources Information Project (GRIP) databases were consulted to identify boreholes with long-term water levels. In addition to the aforementioned databases, the monitoring data of the Groundwater Monitoring and Assessment Programme for Limpopo and the monitoring boreholes of the Kruger National Park

was also used. The borehole distribution of the aforementioned data sources is shown in Figure 19. It is important to note that some boreholes reside on more than one database.

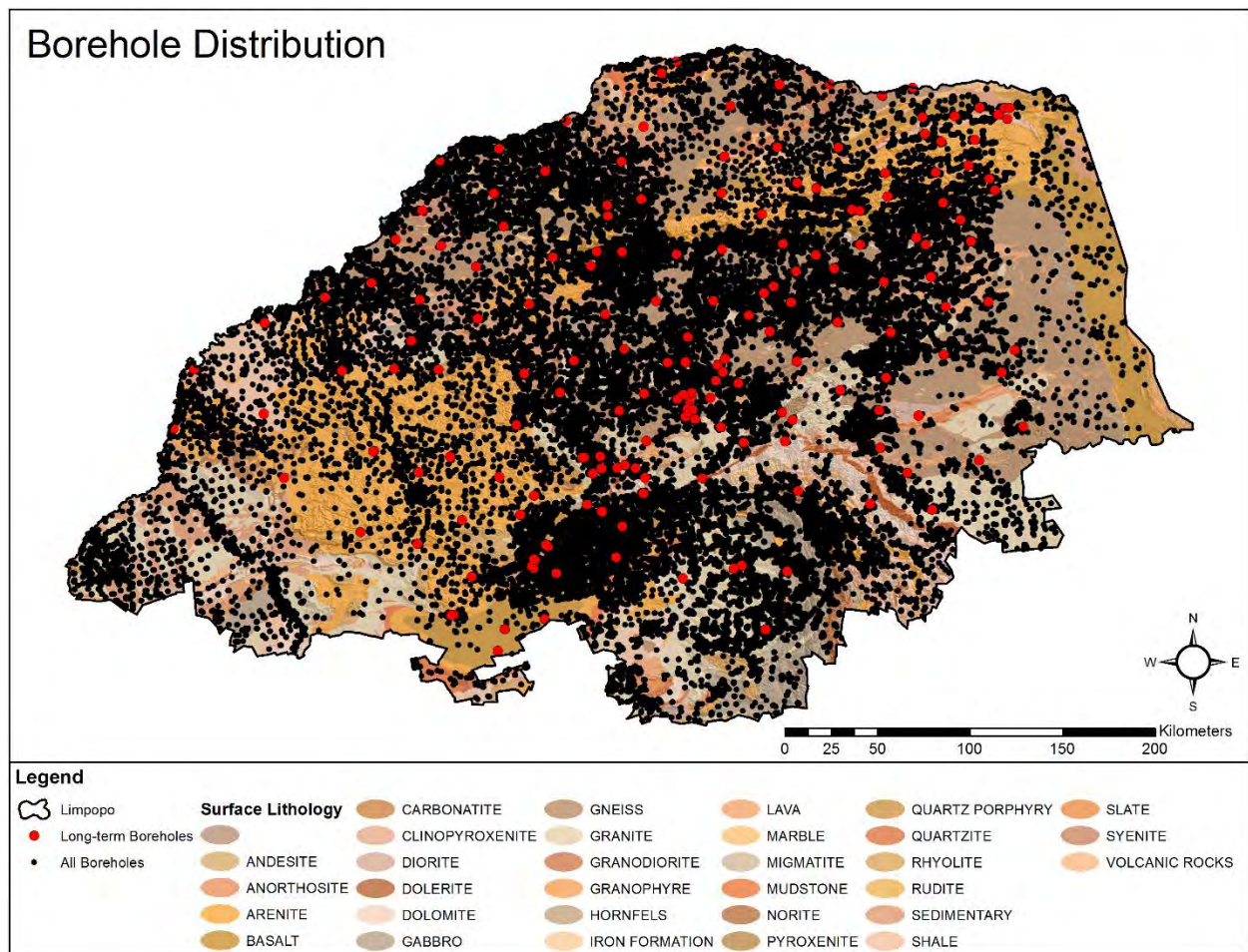


Figure 19 - Limpopo borehole distribution

A time series analysis was conducted on the water levels and only boreholes with long-term water levels during the period 1980 to 2014 was selected. The borehole distribution of these boreholes is also shown in Figure 19.

To refine the borehole selection all DWS meteorological were chosen and a 10km buffer was applied to determine which boreholes are encompassed by the respective buffer zones. The DWS meteorological sites with a 10km buffer and boreholes with long-term water level data is presented in Figure 20.

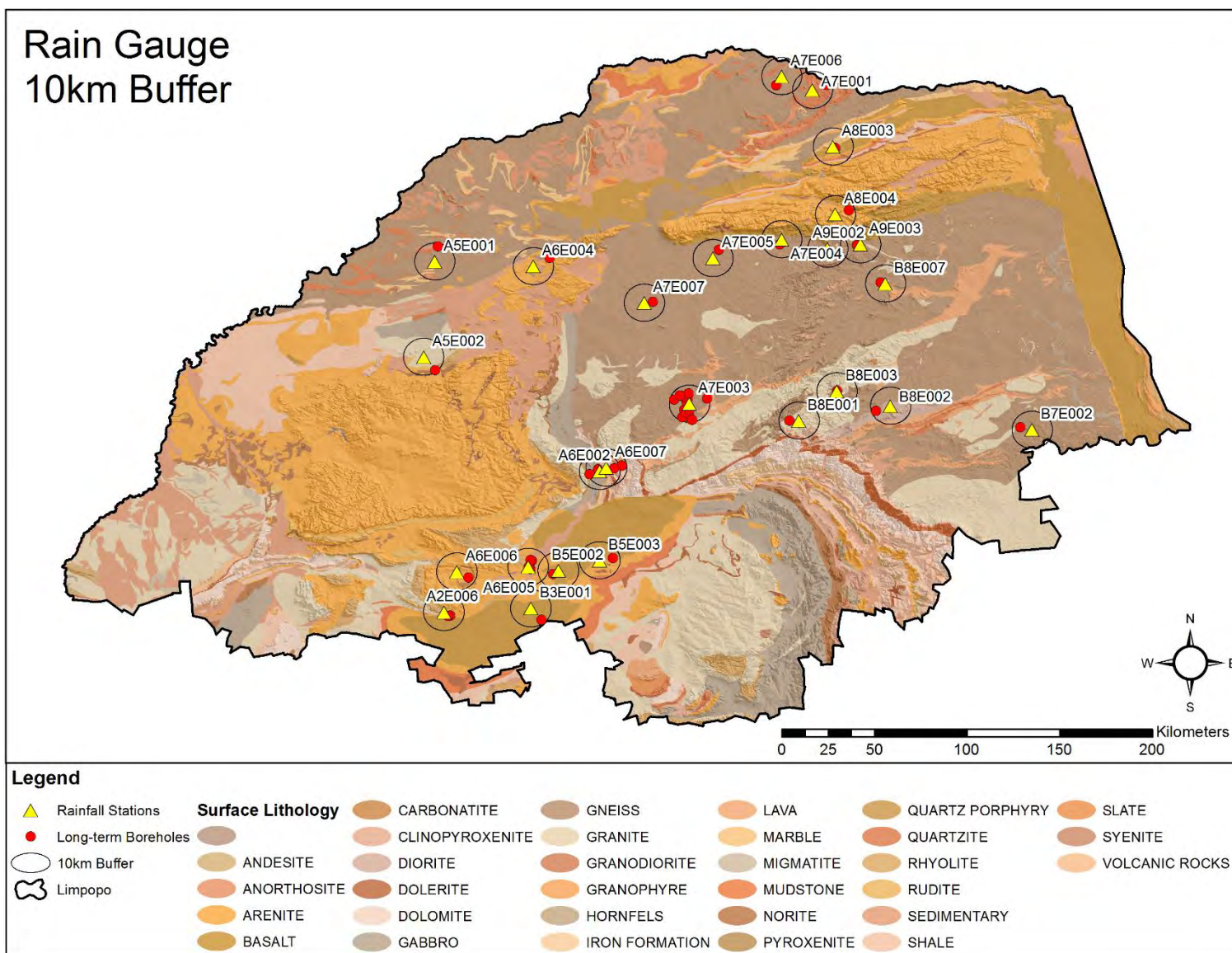


Figure 20 - DWS meteorological sites with 10km radius buffer zone

The final borehole selection was then determined by comparing the temporal data of the meteorological site and the boreholes encompassed by the buffer zone. Only boreholes and meteorological sites were selected where a window of overlap existed between the precipitation data and water level data. In addition to the overlap, good continuous data was also used as selection criteria. The spatial distribution of this final dataset is shown in Figure 21 and the borehole and rain gauge positions are presented in Table 8 and Table 9 respectively.

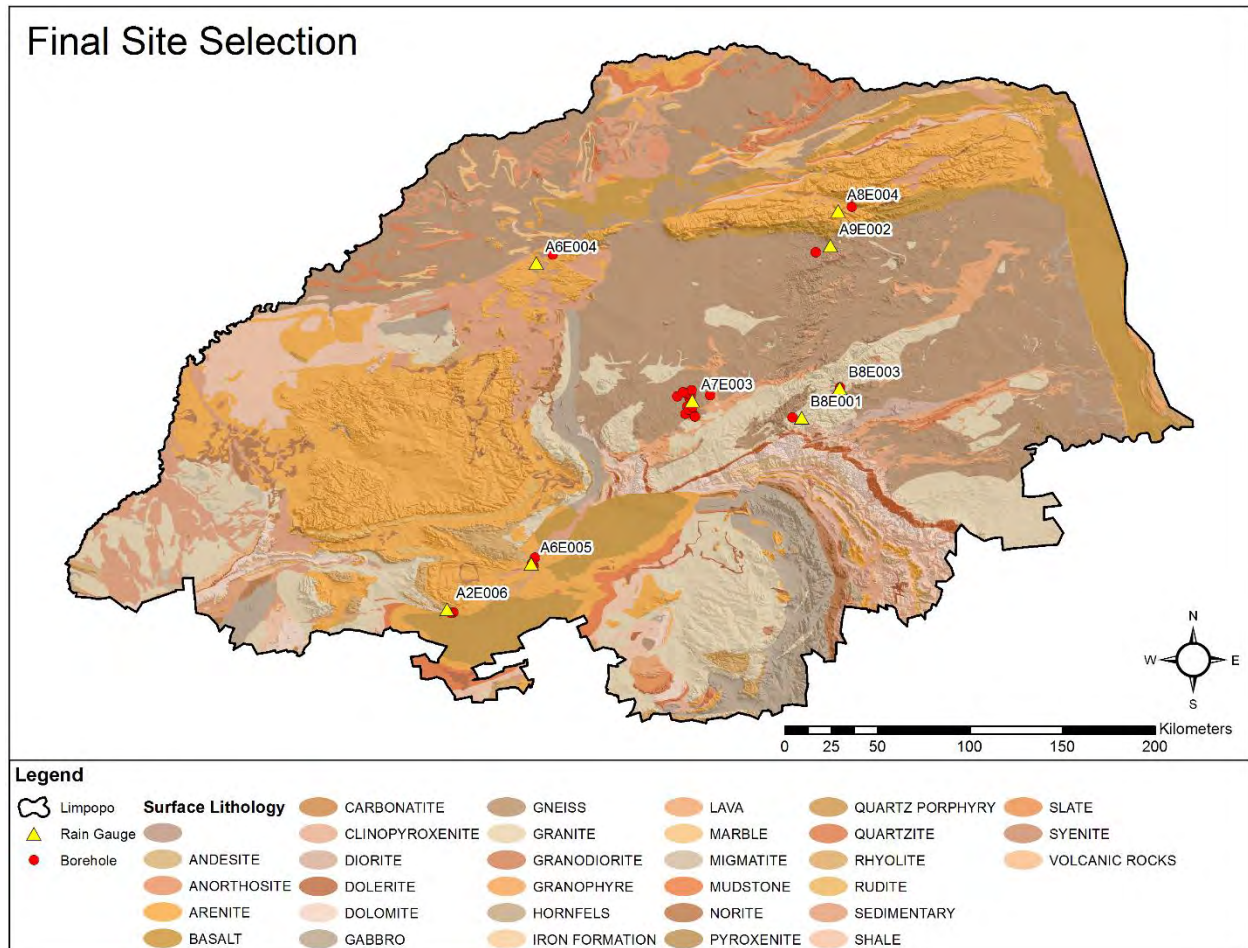


Figure 21 - Final meteorological and borehole sites used in assessment

Table 8 - Geographical borehole locations

Borehole	Description	Longitude	Latitude	Elevation (mamsl)	Gauge
A2N0116	A2HetbadDorp	-24.885500	28.291280	1130.0	A2E006
A2N0199	A2HetbadSkool	-24.887670	28.280440	1132.5	A2E006
A6N0544	A6Nyilsvley2	-24.659300	28.678540	1095.8	A6E005
A6N0545	A6Nyilsvley7	-24.620500	28.687330	1092.0	A6E005
A6N0546	A6Nyilsvley3	-24.659300	28.678540	1095.8	A6E005
A6N0547	A6Nyilsvley4	-24.659300	28.678540	1095.8	A6E005
A6N0550	A6Nyilsvley1	-24.649300	28.671780	1106.5	A6E005
A6N0582	A6Sekhung	-23.149530	28.773870	901.0	A6E004
A7N0029	A7Doornkraal	-23.847300	29.438370	1208.8	A7E003
A7N0525	A7Tweefontein	-23.832400	29.539410	1260.0	A7E003
A7N0538	A7Sterkloop Pump	-23.887900	29.427890	1226.5	A7E003
A7N0539	A7Waterland	-23.922800	29.453440	1270.4	A7E003
A7N0549	A7Sterkloop Farm	-23.922900	29.417390	1244.8	A7E003
A7N0561	A7Westernburg	-23.901200	29.435030	1240.6	A7E003
A7N0586	A7Doornkraal 2	-23.833000	29.444120	1202.6	A7E003
A7N0636	A7Uniepark	-23.935440	29.465450	1285.5	A7E003
A7N0637	A7Seshego	-23.838920	29.378780	1237.6	A7E003
A7N0642	A7Pelgrimshoop 2	-23.820300	29.418610	1209.0	A7E003
A7N0646	A7Doornbult 2	-23.807990	29.448120	1190.8	A7E003
A7N0647	A7Boordepot	-23.889200	29.451570	1265.0	A7E003
A7N0655	A7Palmietgat	-23.817910	29.407710	1220.5	A7E003
A8N0508	A8Mandala	-22.918800	30.225700	815.1	A8E004
A9N0007	A9Elim	-23.139070	30.051420	818.6	A9E002
B8N0502	B8Haenertsburg	-23.940550	29.939230	1396.2	B8E001
B8N0514	B8Tzaneen	-23.794830	30.170930	750.5	B8E003

Table 9 - Geographical rain gauge locations

Gauge	Longitude	Latitude
A2E006	-24.868470	28.260530
A6E005	-24.649230	28.669880
A6E004	-23.189910	28.695420
A7E003	-23.857650	29.451670
A8E004	-22.938050	30.160960
A9E002	-23.104650	30.123690
B8E001	-23.939500	29.984350
B8E003	-23.797070	30.168250

6.3 Borehole Geology

The surface geology associated with the selected boreholes is summarised in Table 10. Not all of the boreholes have geological log data, but those that exist are indicated in Table 10 and the detail logs are presented in Appendix A.

Table 10 - Borehole geology

Borehole	Lithology
A2N0116	BASALT
A2N0199	BASALT
A6N0544	SEDIMENTARY
A6N0545	SEDIMENTARY
A6N0546	SEDIMENTARY
A6N0547	SEDIMENTARY
A6N0550	ARENITE
A6N0582	GNEISS
A7N0029	GNEISS
A7N0525	GNEISS
A7N0538	GNEISS
A7N0539	GNEISS
A7N0549	GNEISS
A7N0561	GNEISS
A7N0586	GNEISS
A7N0636	GNEISS
A7N0637	GNEISS
A7N0642	GNEISS
A7N0646	GNEISS
A7N0647	GNEISS
A7N0655	GNEISS
A8N0508	SEDIMENTARY
A9N0007	GNEISS
B8N0502	GRANITE
B8N0514	No Data

6.4 Temporal Water Level Data

The water level depth and elevation data of the selected boreholes are shown in Figure 22 and Figure 23 respectively. Please note A2N0199 was omitted from Figure 22 to provide a better water level resolution for the remaining sites. Three distinct groups were identified:

- Early 1970s to 2014
- Early 1980s to 2014
- 2008 to 2014

Long historic time series values are important as the cyclone database considered has data from the 1960s. Long-term water level data for the entire study area is not available and posed a challenge for this study. Since the main aim of the study is to try and establish a correlation between the historic episodic recharge events in the Limpopo province and the historic cyclonic events, it is essential that long-term water level responses are available.

Due to the limited long-term time series water level data, shorter, more recent (2008 to 2014) datasets were also used in the study. It is expected that these datasets are likely to provide less of a correlation with the cyclonic events, due to the shorter time period considered.

The time series water level dictated the time series used in the associated rainfall stations.

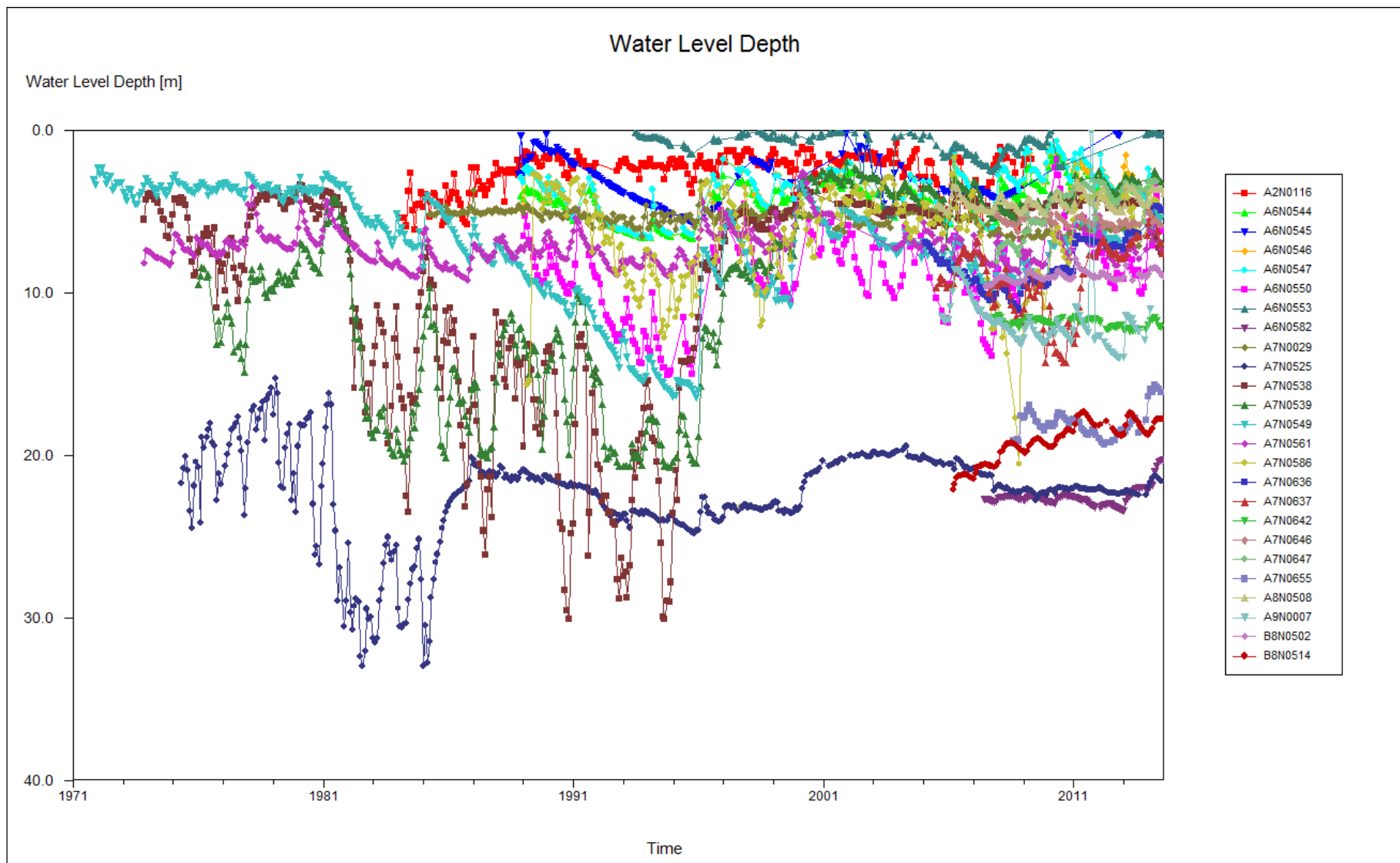


Figure 22 - Water level depth data of selected boreholes

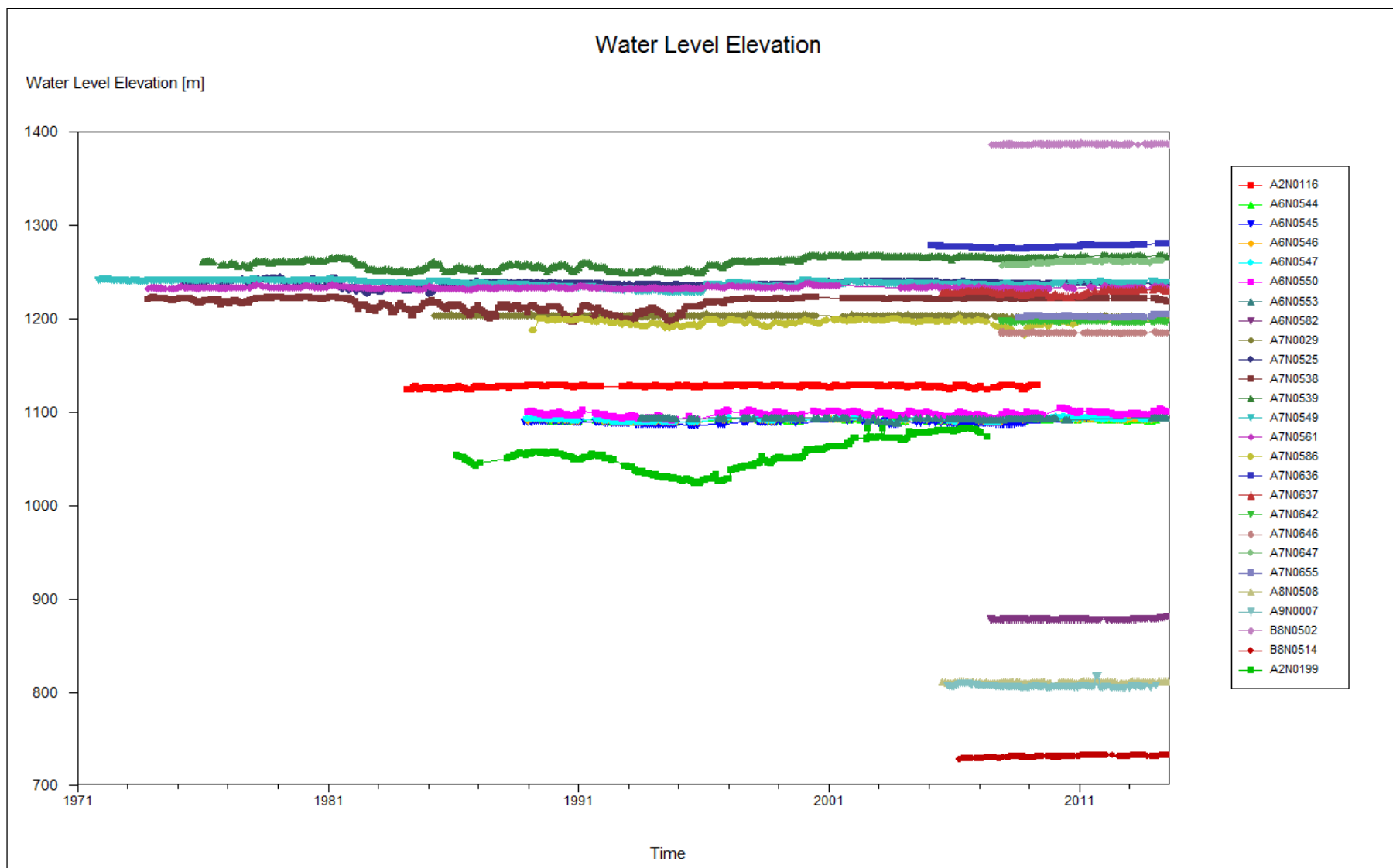


Figure 23 - Water level data of selected boreholes

6.5 Correlation between Water Level and Rainfall

Due to the time scale of groundwater movement, there exists a lag between recharge and water level response. This cross correlation indicates that with each studied borehole there is a delay in groundwater recharge from the time of the rainfall event. This delay varies from site to site as differentiating factors such as permeability, specific storage, etc. play a factor of the time involved with recharge each borehole's associated aquifer. The lag time also varies with many of the rainfall events as the pore pressure between the particles differ as a result of periods of wetness or dryness which will vary the ease at which water can percolate into the subsoil.

An example (A2N0116) of how the lag time between rainfall and water level response is calculated making use of cross correlation is shown in Figure 24. Since the time step of the data being used is on monthly scale, the calculated time lag will be in multiples of months. A summary of the calculated time lags for the boreholes in question is presented in Table 11.

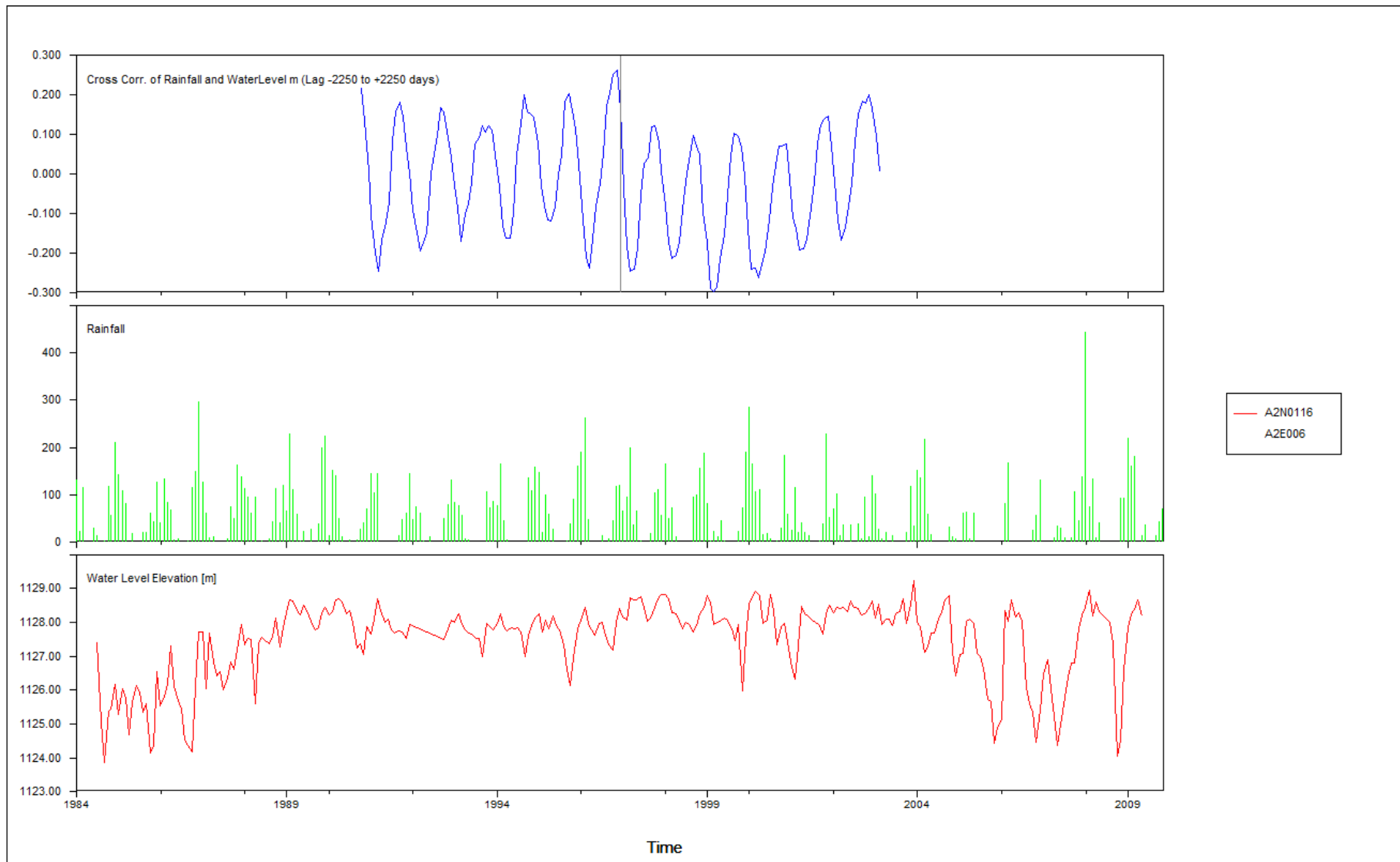


Figure 24 – Example of cross correlation between rainfall and water level response

Table 11 - Rainfall water level time lag summary

Borehole	Estimated Lag Time
A2N0116	±2 months
A6N0544	±1-2 months
A6N0545	±1-2 months
A6N0546	±1-2 months
A6N0547	±2 months
A6N0550	±1 month
A6N0553	< 1 month
A6N0582	±2-3 months
A7N0029	±1-2 months
A7N0525	±2-3 months
A7N0538	±1 month
A7N0539	±1 month
A7N0549	±1 month
A7N0561	< 1 month
A7N0586	< 1 month
A7N0636	±1 month
A7N0637	±1-2 months
A7N0642	±1 month
A7N0646	±1 month
A7N0647	±1-2 months
A7N0655	±1-2 months
A8N0508	±2 months
A9N0007	±1-2 months
B8N0502	±2 months
B8N0514	±1-2 months

6.6 Detection Algorithm Analysis

To increase readability, only one borehole analysis based on the detection algorithm will be presented in this section for illustration purposes. The rest of the borehole analyses is available in Appendix B.

A magnitude of 0.5 for the normalised derivative was used for the Type I episodic recharge definition. Total aquifer recovery was selected as 80% of the maximum water level (mamsl) for the Type II episodic recharge definition. The aforementioned parameters were chosen empirically based on visual inspection of the available datasets.

The results of the episodic recharge detection algorithm together with the monthly rainfall and water level response is shown in Figure 25 and Figure 26 respectively. It is important to note that the time lag between rainfall and water level as determined in Table 11 is applied by the detection algorithm to allow the comparison of a rainfall event to a water level change.

The following cyclone events are indicated on Figure 25 and the magnitude on the graph bears no importance, as a value of 1 was chosen purely for display purposes on the graph:

- All cyclone events that made landfall during the period of the recorded water levels (indicated in green on the graph)
- All tropical depressions that came within 100km from the coastline (TD100, indicated in purple)
- All tropical storms that came within 100km from the coastline (TS100, indicated in light blue)

The Type I and Type II episodic recharge is represented by the red and blue markers respectively. The magnitude of the Type I (red) markers represent the normalised derivative value and the Type II (blue) markers will always have an amplitude of half of the Type I markers for visualisation purposes.

In the example shown (Figure 25) it is clear that the Type II episodic recharge only takes place when the definition of total recovery is met. It is further clear that there exists no correlation with the cyclone events and the episodic recharge as defined.

The detection algorithm was applied to all selected boreholes (Appendix B) and correlation figures were calculated between the cyclone events and the episodic recharge events. These results are discussed in Chapter 7.

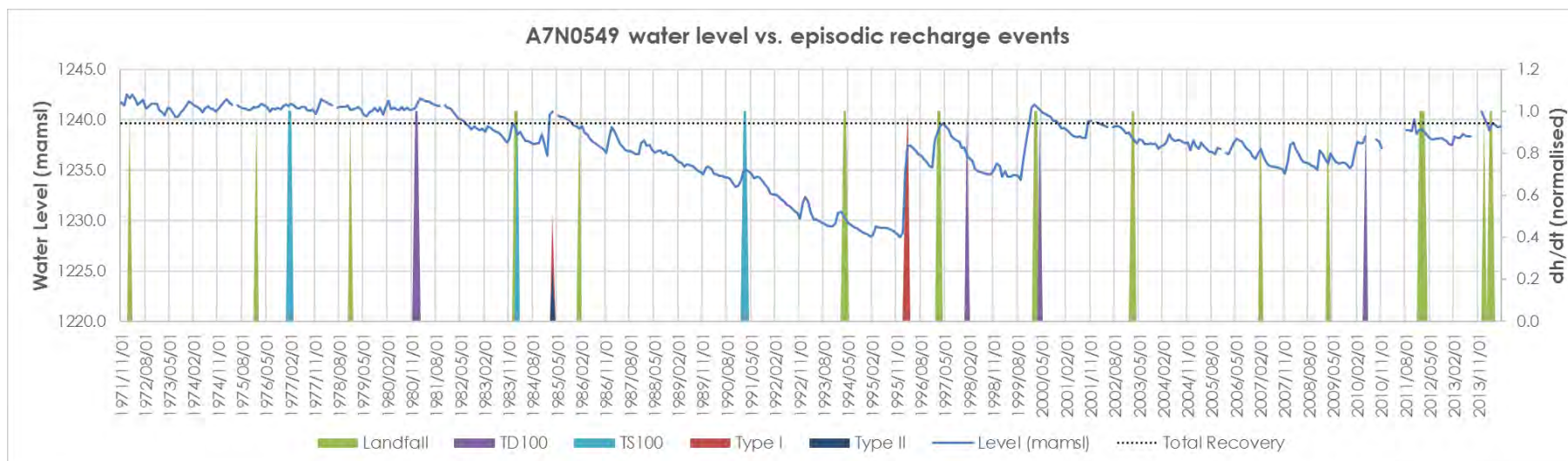


Figure 25 - Episodic recharge detection algorithm analysis

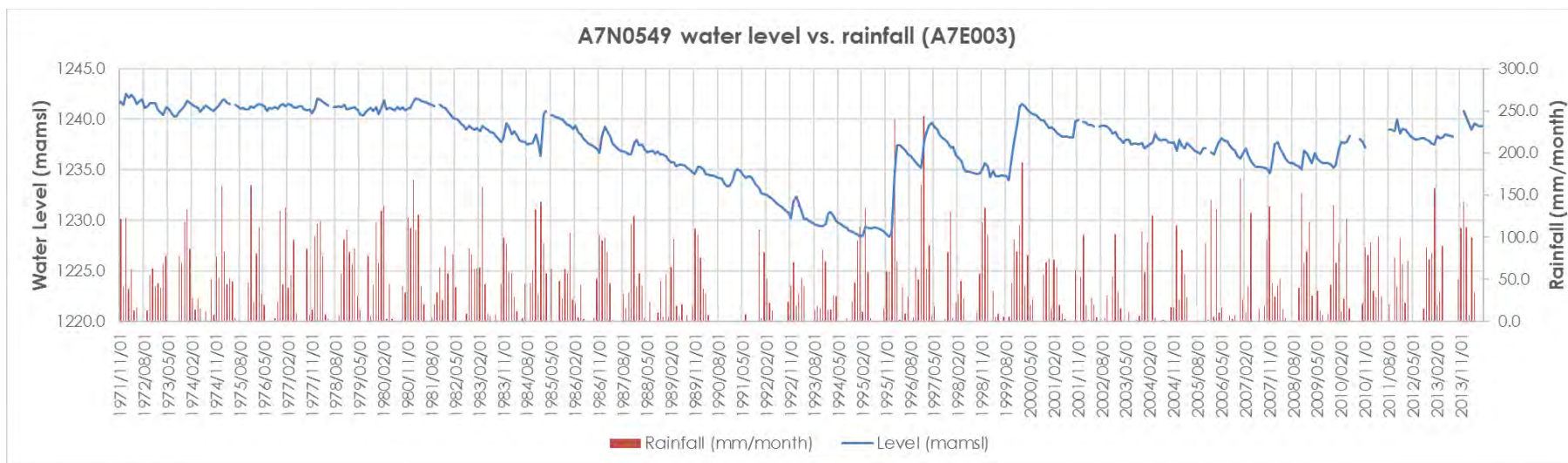


Figure 26 - Monthly water level response versus rainfall data

7 RESULTS AND DISCUSSION

Through the use of the detection algorithm, the correlation between the cyclone events and the episodic recharge events were calculated.

7.1 Episodic Recharge Type I

The calculated correlation figures for the Type I episodic recharge is shown in Figure 27. Correlation figures are generally below 0.5 with the exception with one instance of a single TD100 and TS100 event. The majority of TS100 events have a positive correlation as opposed to the landfall events of which only 50% show a positive correlation.



Figure 27 - Correlation figures for episodic recharge Type I

The positive correlation between the TS100 events and the boreholes can be attributed to the intensity of these cyclonic systems as the rainfall associated with these events can be widespread. Figure 28, Figure 29, and Figure 30 illustrate the correlation between the Type I episodic recharge and the associated rainfall event along with subtropical depression Dando (2012). Of the roughly 50% of the boreholes that showed a positive correlation with landfall events, only one (A2N0199) had a correlation of higher than 0.5 which is located in Bela-Bela. Another borehole located nearby (A2N0116) showed a slightly negative correlation of the same parameter which contradicts the correlation of with landfall events of the other (A2N0199) borehole. This contradiction questions the validity of the correlation based on Type I episodic recharge.

All selected boreholes have instances of Type I episodic recharge present, and it is clear from Figure 27 that some boreholes do not exhibit any correlation between cyclone events and episodic recharge. The spatial distribution of the correlation figures presented in Figure 27 is shown in Figure 28, Figure 29 and Figure 30.

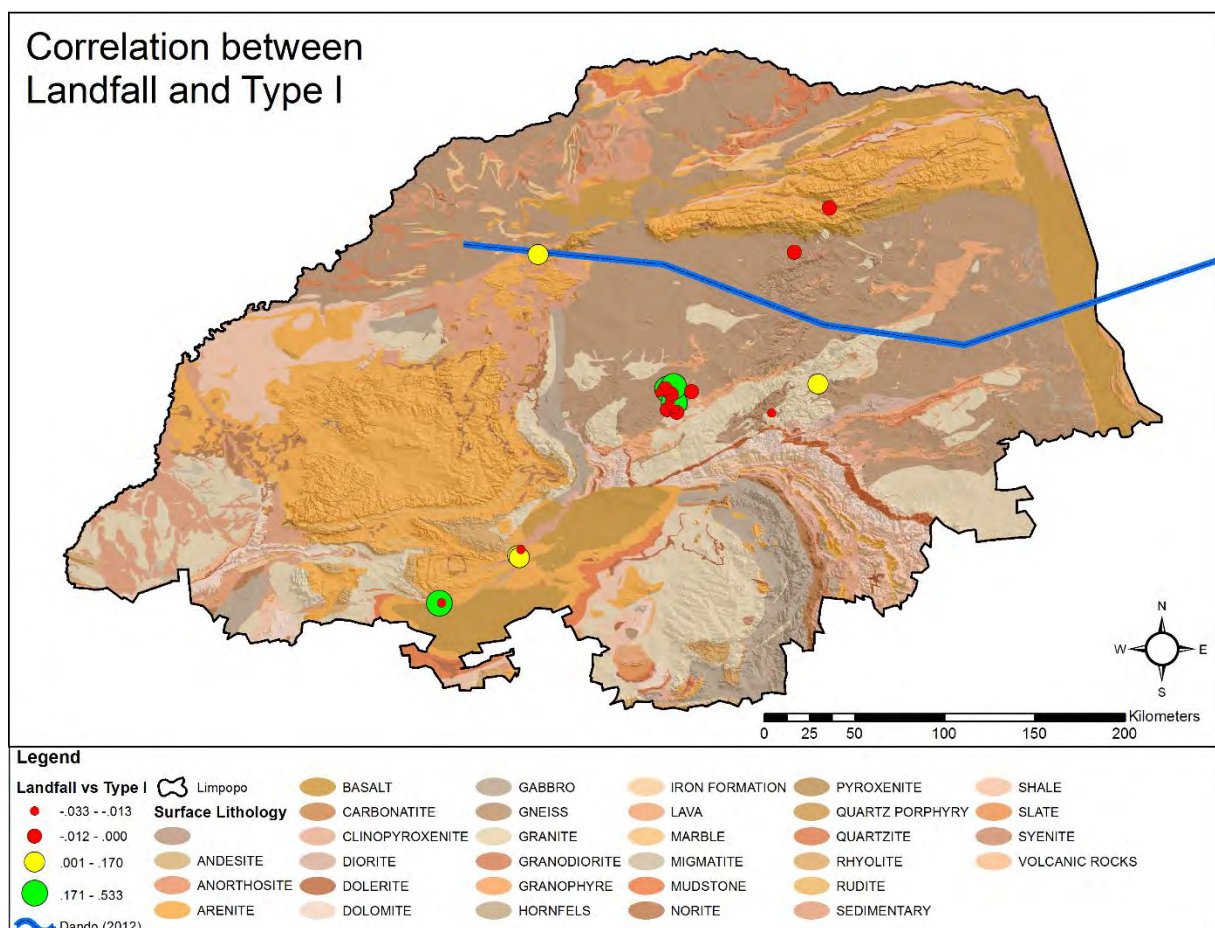


Figure 28 – Landfall correlation with Type I episodic recharge

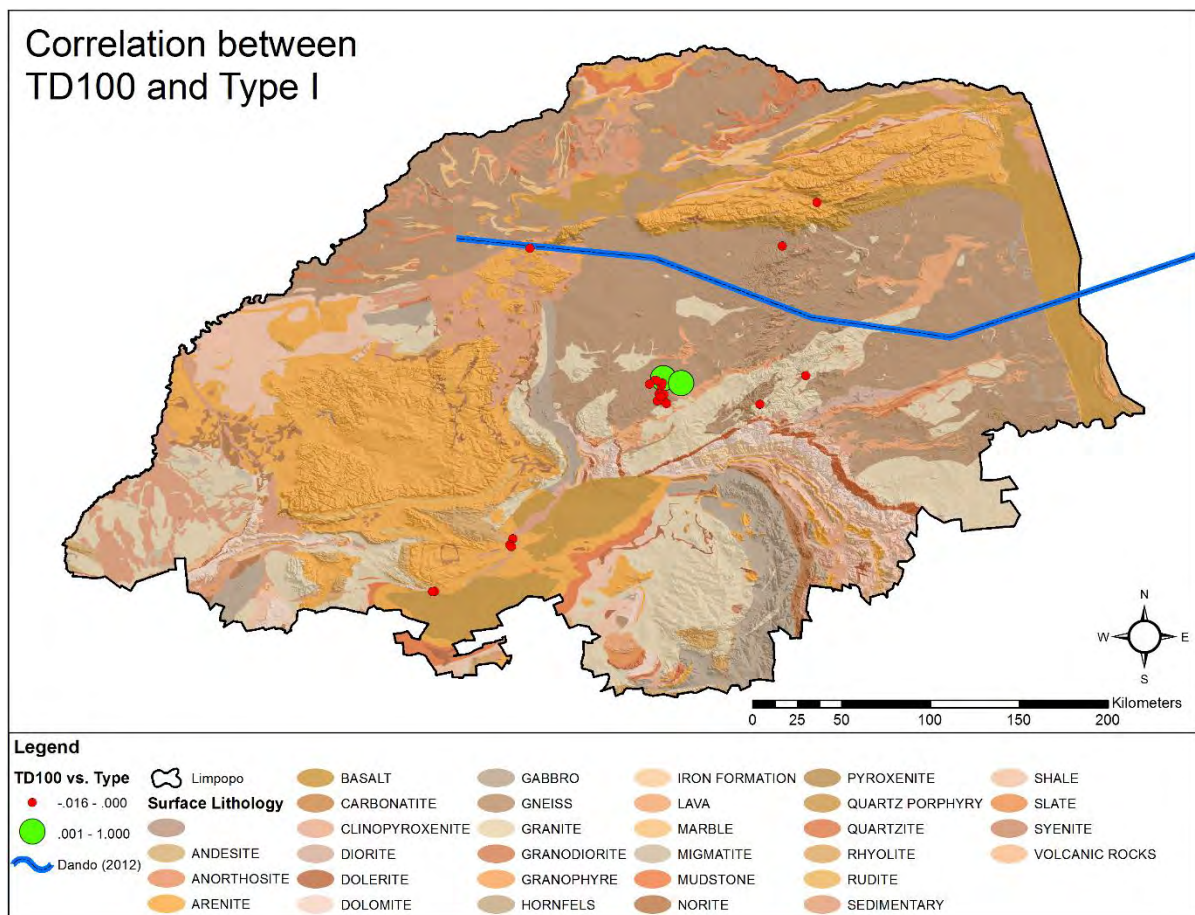


Figure 29 – TD100 correlation with Type I episodic recharge

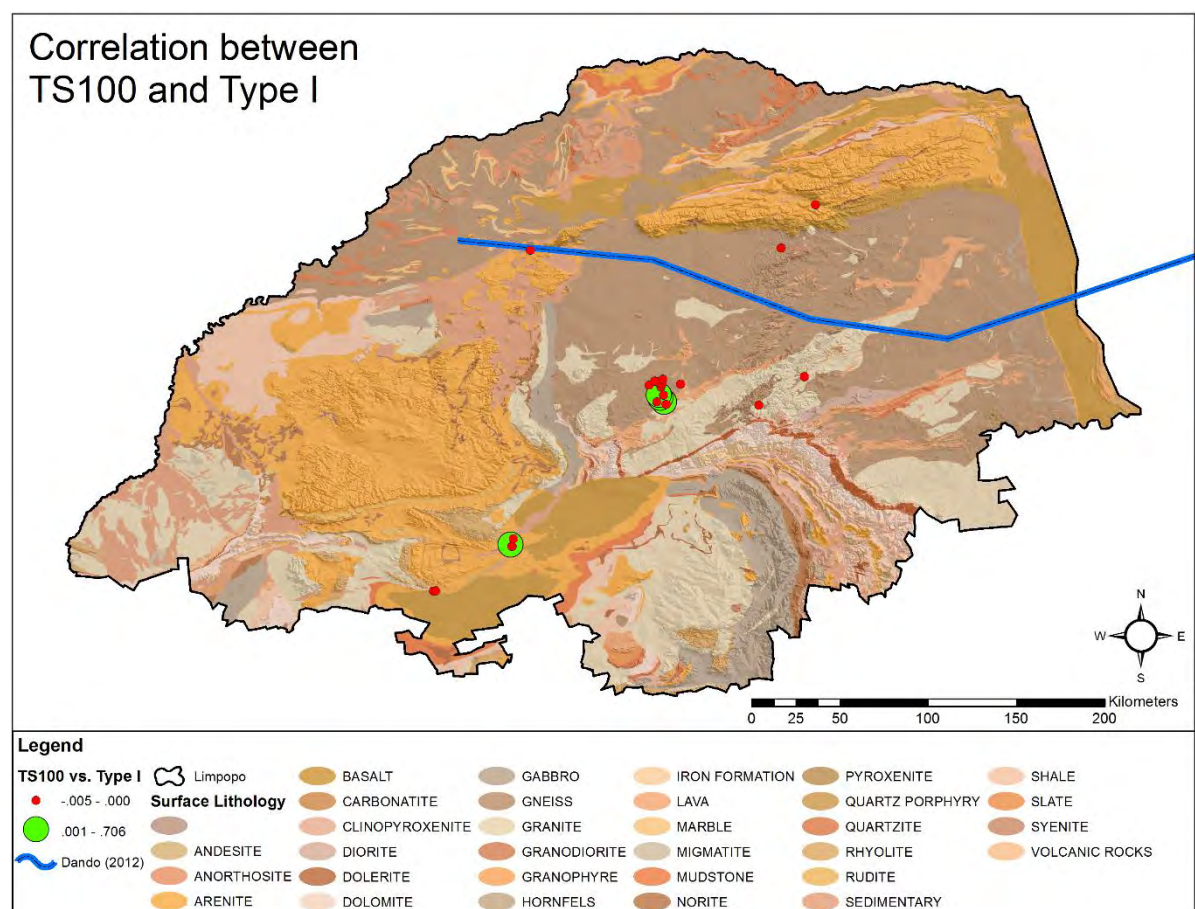


Figure 30 – TS100 correlation with Type I episodic recharge

7.2 Episodic Recharge Type II

The calculated correlation figures for the Type I episodic recharge is shown in Figure 31. With the exception of one TS100 event only the landfall events show a positive correlation at four boreholes.

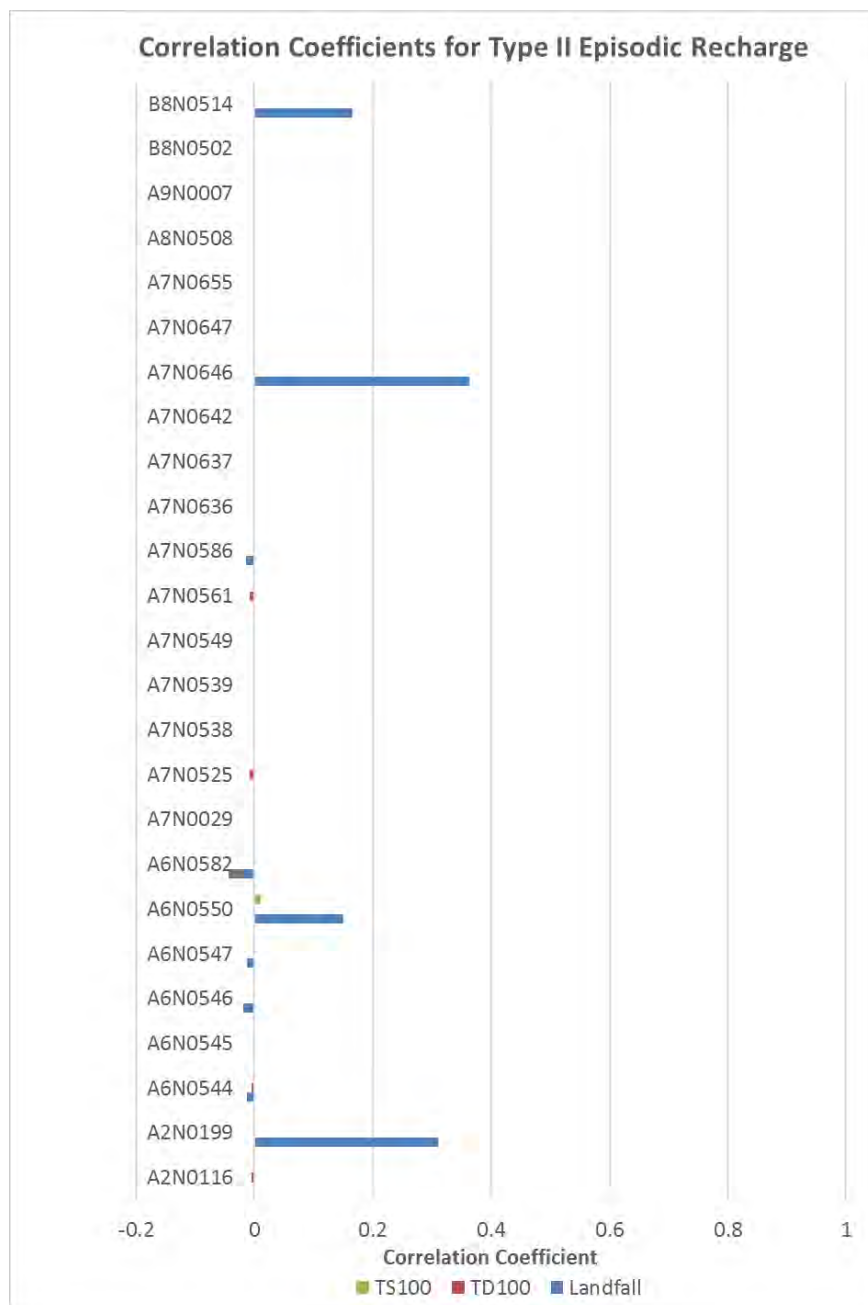


Figure 31 - Correlation figures for episodic recharge Type II

The lack of correlations between any of the parameters and boreholes, to any extent, cause this type of episodic recharge to be less likely to occur than Type I. The negative correlation at many of the boreholes rather illustrates the conflicting of water levels in comparison with rainfall associated with cyclonic events.

The following list of boreholes do not exhibit any episodic recharge Type II events (Appendix B) and therefore no correlation figures are expected at these sites:

- A7N0538
- A7N0539
- A7N0636
- A7N0637
- A7N0642

The reason for the diminished response of the correlation of Type II episodic recharge is due to definition of the Type II episodic recharge which is more stringent than the pure Type I response as shown in Equation 6.

$$\text{Type II} = \text{Type I} + 80\% \text{ recovery} \quad (6)$$

The spatial distribution of the correlation figures presented in Figure 31 is shown in Figure 32, Figure 33 and Figure 34.

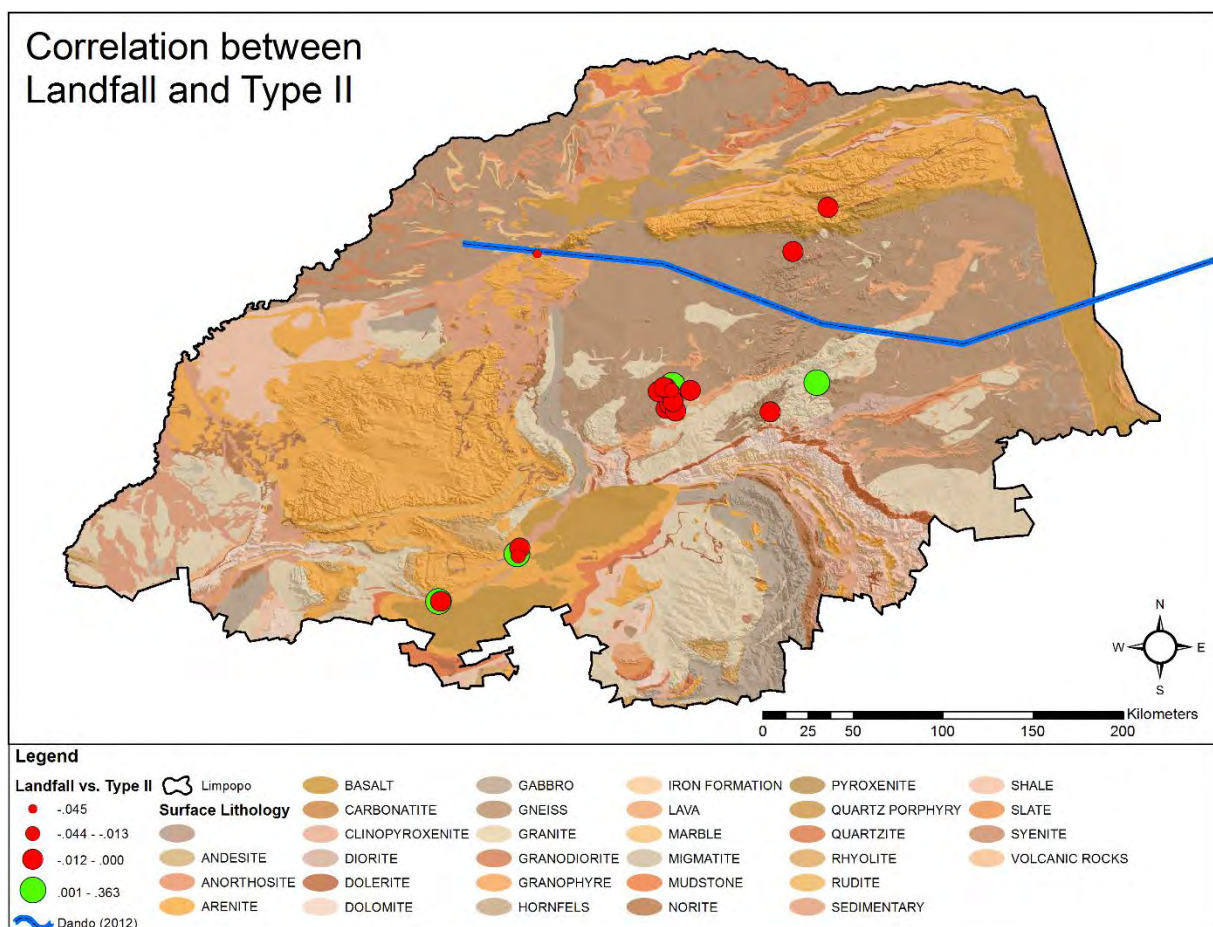


Figure 32 – Landfall correlation with Type II episodic recharge

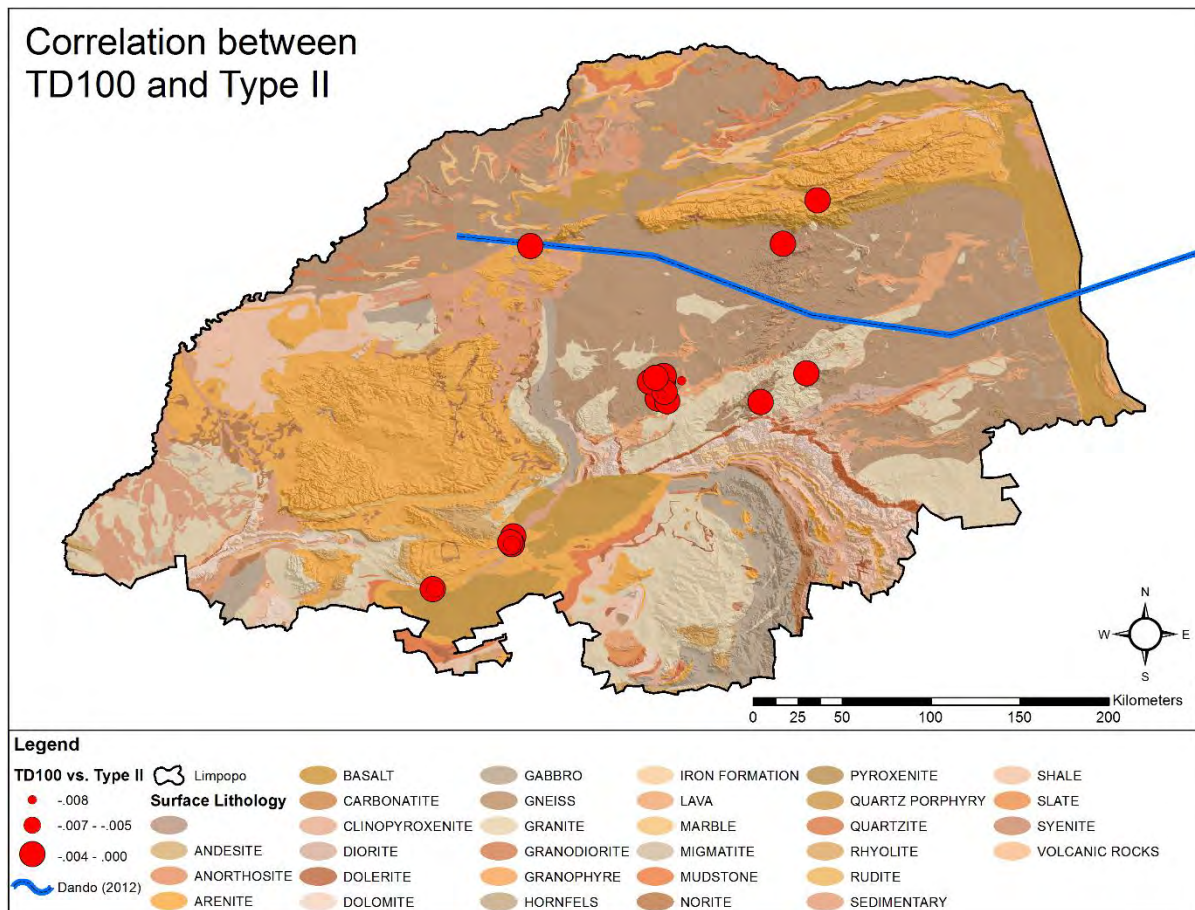


Figure 33 – TD100 correlation with Type II episodic recharge

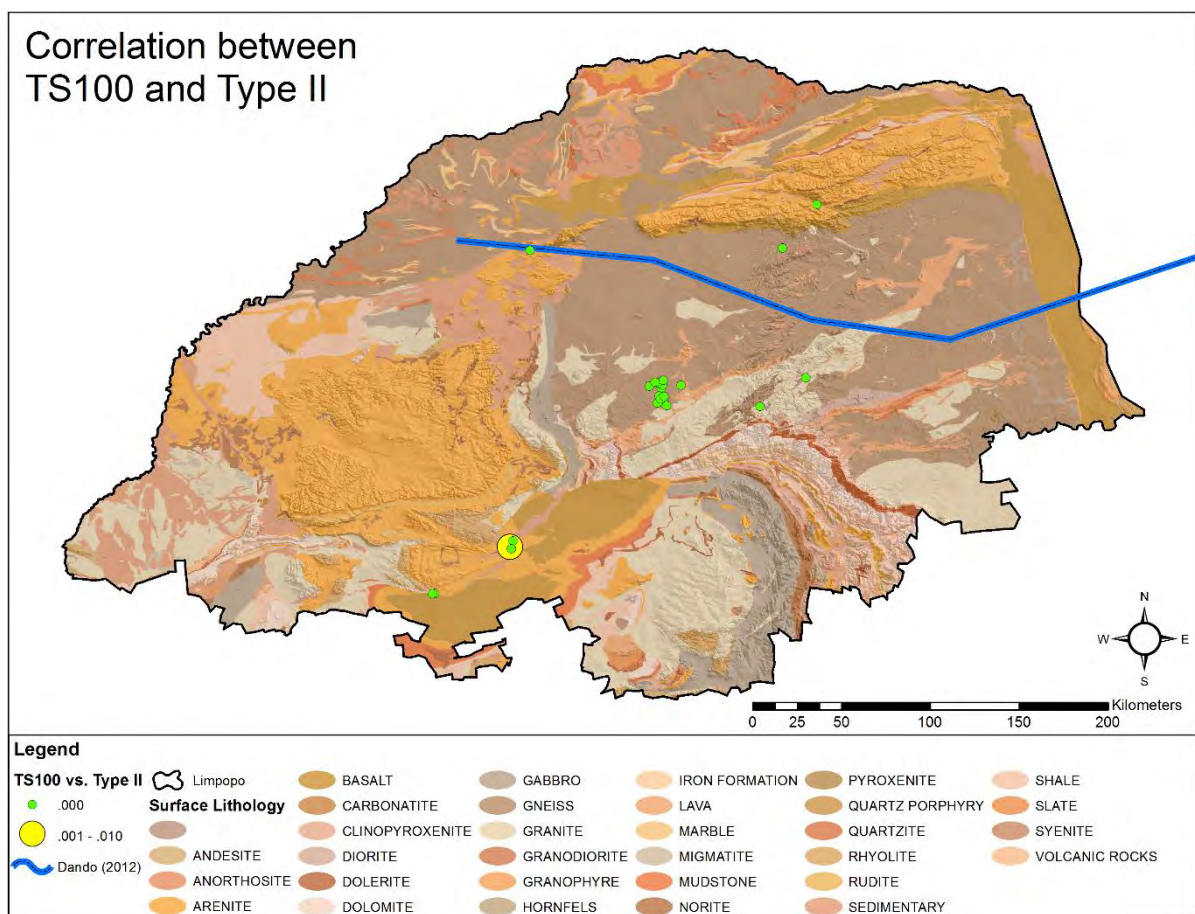


Figure 34 – TS100 correlation with Type II episodic recharge

The lack of spatially representative long-term data across the study area does limit the result as both episodic recharge types' algorithmic results may illustrate a different representation upon spatial demonstration thereof. Taking into account the normalised maximum derivative response to water levels along with the recovery of water levels, Type II episodic recharge is less likely to occur as a result of the latter mentioned limitation. The recovery of the water levels may be limit as a result of various factors such aggregation of top-soils, permeability, pore pressure, or specific storage of the aquifer. Taking into account all of these factors along with the variability of cyclonic rainfall, episodic recharge, regardless of type, may be difficult to determine as each contributing factor may vary with each cyclonic event.

7.3 Maximum Rainfall Events

The maximum rainfall associated with the episodic recharge and cyclonic events are shown in Figure 35. Individual boreholes are associated with different rainfall stations except, where explicitly indicated otherwise. This is due to the locality of each borehole that has long-term water level measurements in relation to a rainfall station.

In general, the rainfall associated with the different cyclonic events seems to represent the rainfall associated with the episodic recharge, with the exception of A6N0545, A8N0508 and A9N0007. The factors contributing to this lesser rainfall may be localised, as the topographical locality of each borehole may influence each boreholes' surrounding area's recharge potential or localised orographic constraints.

The rainfall comparison only confirms that the cyclonic events could be associated with the episodic recharge, but it is evident from the preceding two sections, that cyclones are not solely responsible for episodic recharge.

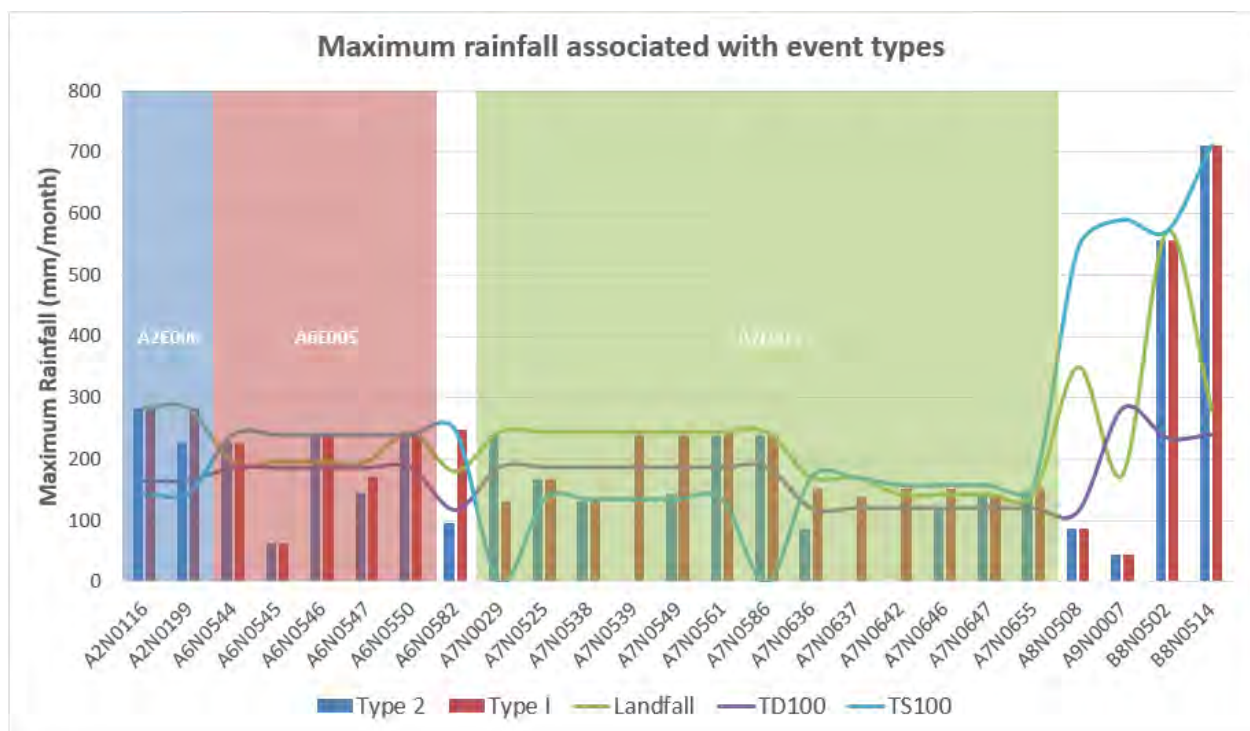


Figure 35 - Maximum rainfall associated with events

A6N0545, A8N0508, and A9N0007 do not illustrate the same recharge patterns as the other boreholes with regards to cyclonic rainfall recharge. A6N0545 is situated in a large seasonal marsh which may influence the specific recharge of the borehole as the underlying aquifer will be saturated for longer periods seasonally. A8N0508 and A9N0007 are both located nearby drainages which may influence the recharge capabilities of the underlying aquifers as the

sediments will alter the infiltration capabilities of the soil. The soils' infiltration factors may limit recharge which will affect the rainfall's effect on the water levels.

These boreholes (A6N0545, A8N0508, and A9N0007) may require larger amounts of rainfall to exhibit an extent of episodic recharge due to the geologic influences. Taking Vegter's recharge as well as the GRA II recharge distribution into account, these areas are indicated to receive high amounts of recharge, but local influences prevent significant episodic recharge events from occurring.

8 CONCLUSIONS

Cyclones are associated with torrential rainfall and although some systems do not make landfall, these systems are associated with high rainfall events and therefore it is necessary to also study these offshore systems. Both tropical storms and tropical depressions that came within a 100 km from Mozambique's coastline as well as the South African coastline were considered.

Episodic recharge is dependent on various factors and is complicated to model from first principals. Detailed historic datasets would be required over the whole of the study area to accomplish this and in the absence of these datasets the aforementioned approach is rendered impractical. The episodic recharge response is more prevalent in arid areas when considering long-term water level information of boreholes, but this does not imply that episodic recharge does not take place in areas with more humid conditions.

In the absence of a model that can model episodic recharge, two episodic recharge definitions (Type I and Type II) were formulated through mathematical expressions:

- Type I – Normalised positive derivative response, where the magnitude is 0.5 or greater
- Type II – Type I episodic recharge, but with the restriction that 80% recovery in water level has occurred as measured from the maximum water level (mamsI)

The normalised derivative magnitude and the percentage recovery was determined empirically through visual inspection of the available datasets. The Type II episodic recharge has less chance of occurrence as compared to the Type I episodic recharge due to the additional water level recovery condition.

By applying the Type I and Type II episodic recharge definitions to long-term water levels and accounting for the possible lag between rainfall and recharge events as reflected in the water level response, a detection algorithm was developed. The detection algorithm allows for the detection of episodic recharge events which in turn can be correlated to cyclonic events.

The calculated correlations between episodic recharge and cyclonic events showed some correlation at selected sites, but it is concluded that the cyclones are not the driving factor in episodic recharge as it relates to the Limpopo province.

The maximum rainfall associated with cyclonic and episodic recharge events seem to correspond in general, but does not serve as proof that cyclones drive episodic recharge. The correlation of the maximum rainfall events is attributed to the fact that high rainfall occurs within the wet season and generally this is also the time that cyclones are present.

The conclusion that cyclones do not drive episodic recharge events in the Limpopo province does not rule out the possibility that cyclones do contribute to episodic recharge.

The effect of the type of geology is also ruled out as a major contributing factor to episodic recharge as a cluster of boreholes within the same geological setting showed different correlations between episodic recharge events and cyclonic events. Even though the boreholes are situated in the same geology, they differ in their associated geological logs, which again highlights the complexity involved in modelling episodic recharge.

Boreholes with long-term water level measurements that have associated data such as, borehole construction, lithology, etc. are a scarcity when it comes to their spatial position across the province. The ideal spatial distribution for this study would involve boreholes situated in each geology type across different rainfall zones within the Limpopo province. The study thus relies on the existing data from which conclusions are drawn based on the analyses performed on the existing dataset. As the monitoring network of boreholes has not been drilled correctly in many parts of the province, results may be thwarted for further similar studies.

Recharge by means of cyclonic rainfall may be influenced by local factors which may prevent episodic recharge. Geological influences locally may explain why some boreholes within the same geology, which are also spatially located nearby each other, do not tend to exhibit similar trends and patterns with regards to the different type of episodic recharge.

Based on the research results the H_1 hypothesis is rejected and the H_0 hypothesis is accepted which state:

No clear correlation exists between episodic recharge and cyclonic events, due to the fact that episodic recharge generally takes place during the wet season, which is also the season when cyclonic events takes place.

9 RECOMMENDATIONS

Although this study did not prove the H_1 hypothesis, it did reveal the complexity involved in modelling episodic recharge. Based on the outcomes of the study wherein limitations were found to complicate the presentation of the results, the following recommendations are made:

1. Borehole localities across the province should be identified which represent the ideal monitoring parameters in order to initiate a collection of the data going forward with the purpose of collecting representative data to complete this study.
2. Additional research should be done to determine the extent to which extent cyclones may influence the Limpopo province's long-term episodic recharge capability.
3. Rainfall chemistry analysis should be done to determine amount of cyclonic rainfall entering the aquifer systems as recharge after a cyclonic event as well as which factors may influence recharge such as bush encroachment, etc.
4. Spatial analysis of recharge of the Limpopo province's aquifers in comparison with rainfall events must be done.
5. Trend analysis of all known factors (rainfall, chemistry, and water levels) must be done to distinguish between different recharge events.

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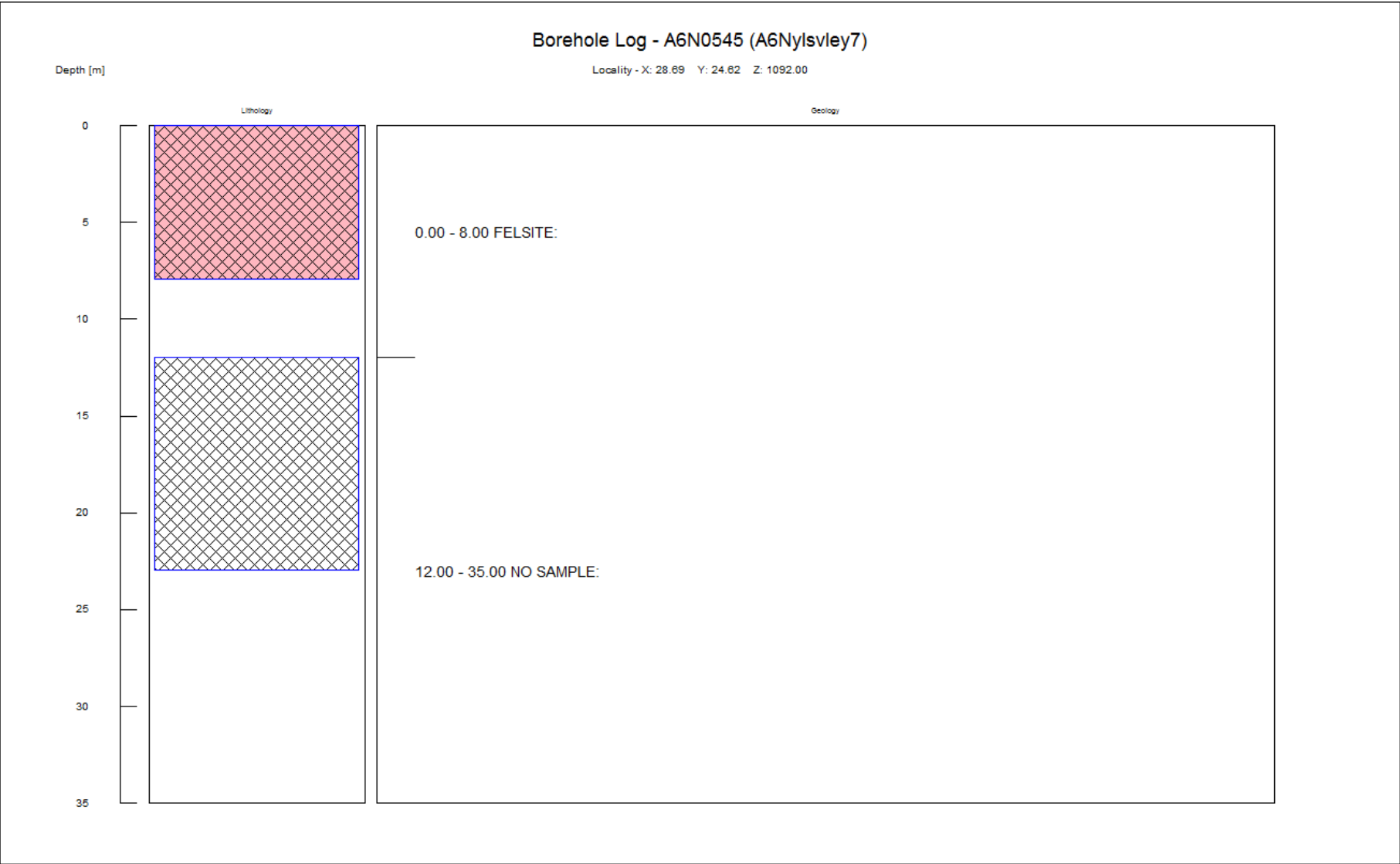
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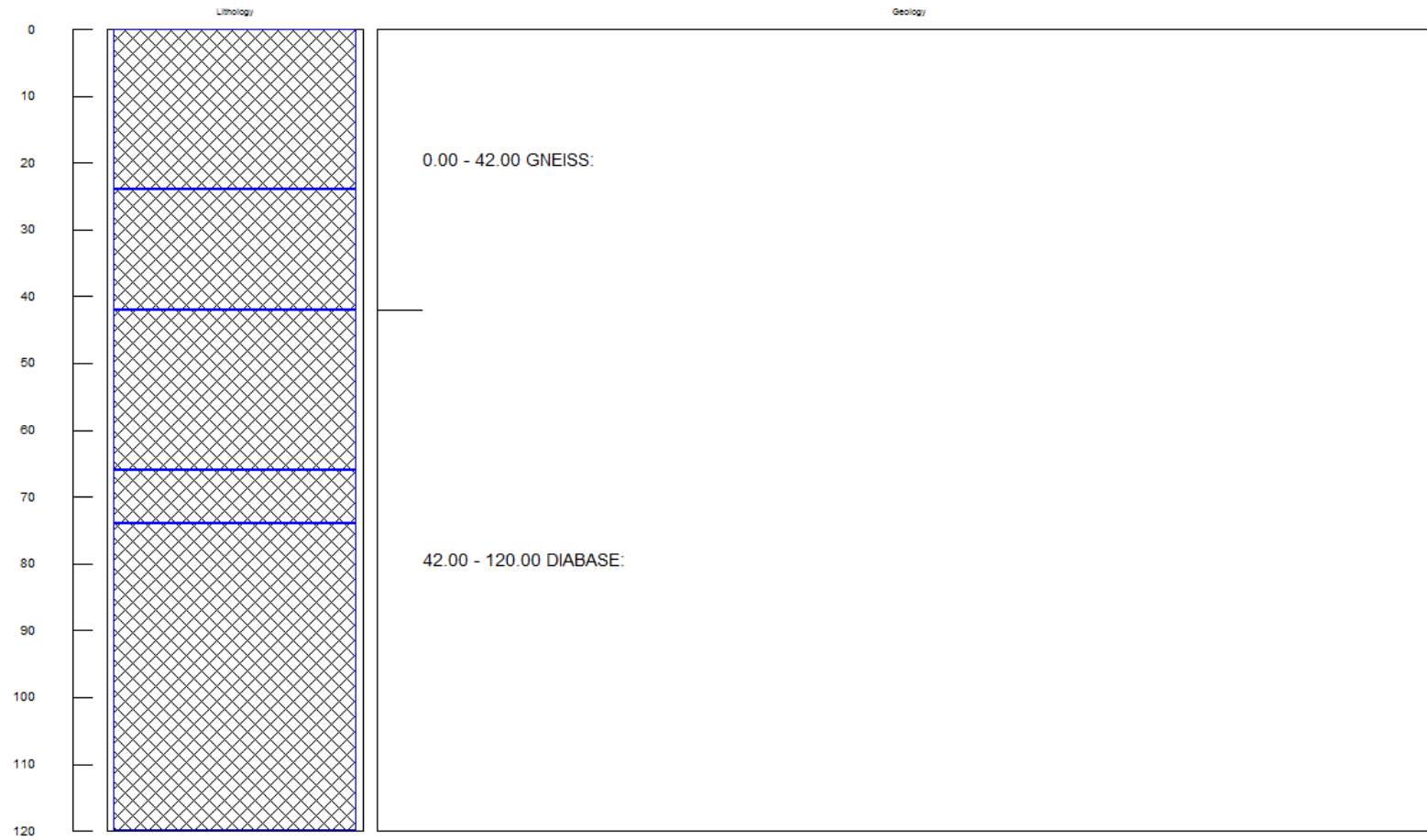
APPENDIX A – BOREHOLE LOGS



Borehole Log - A6N0582 (A6Sekhung)

Locality - X: 28.77 Y: 23.15 Z: 901.00

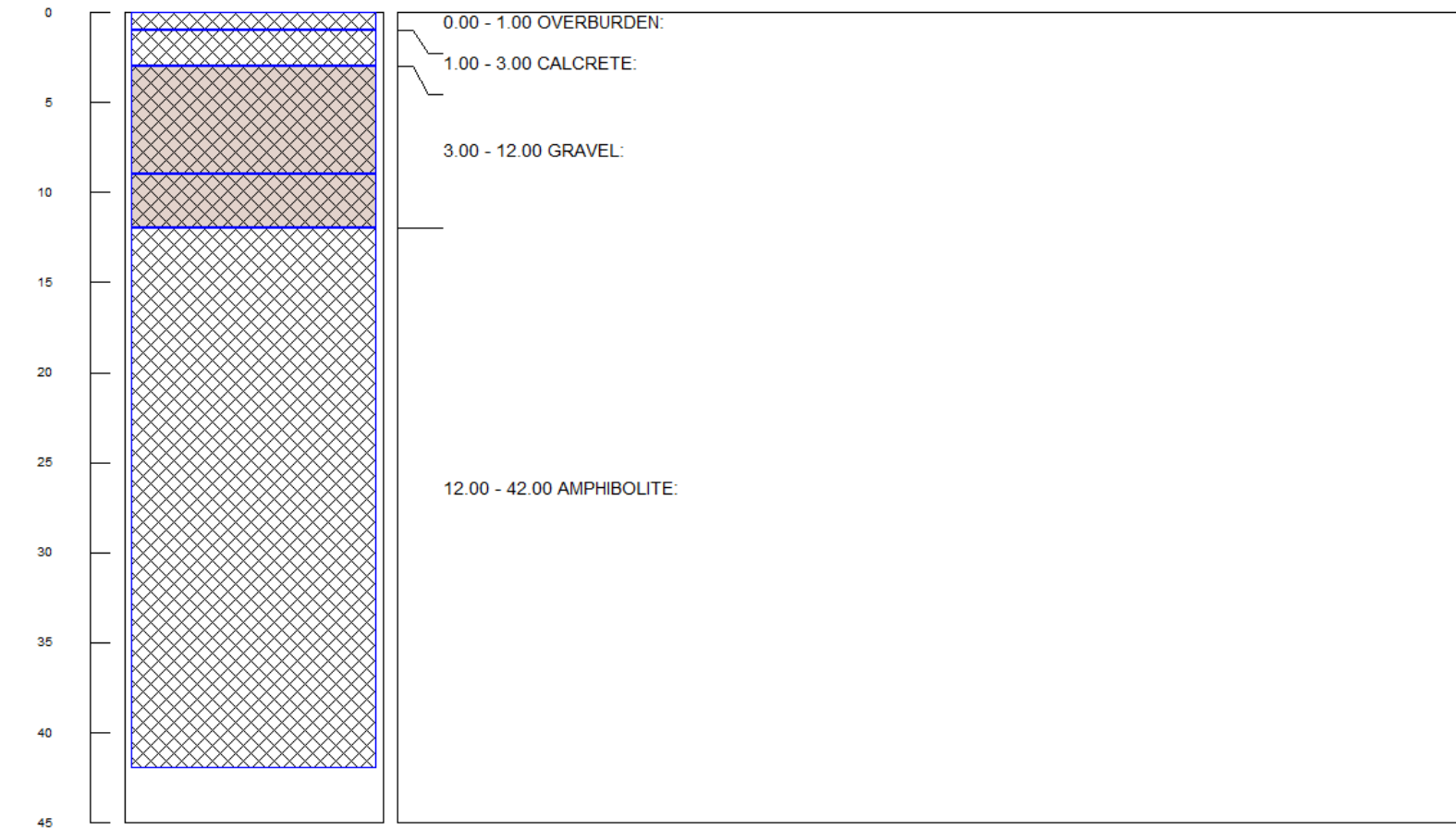
Depth [m]

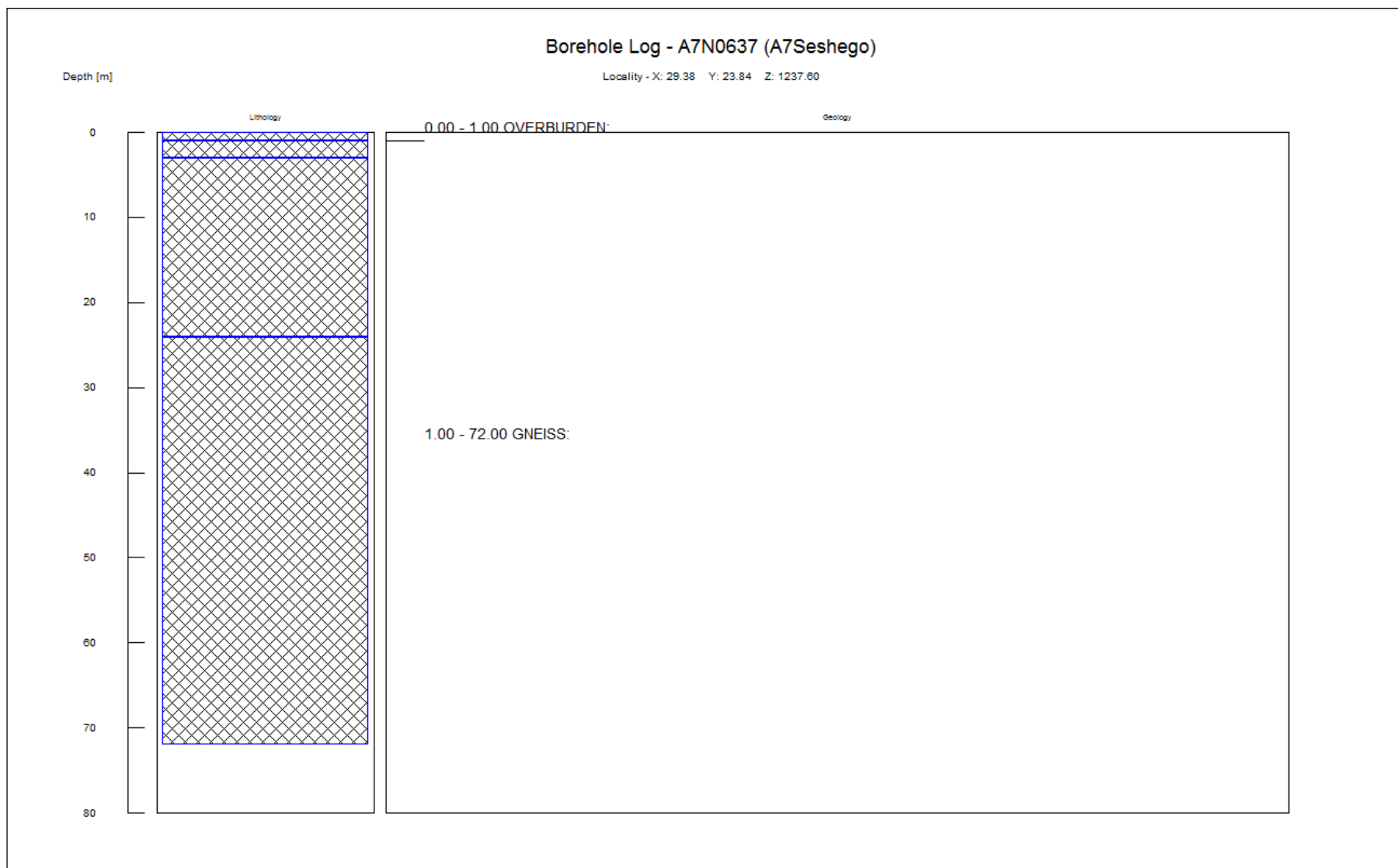


Depth [m]

Lithology

Geology

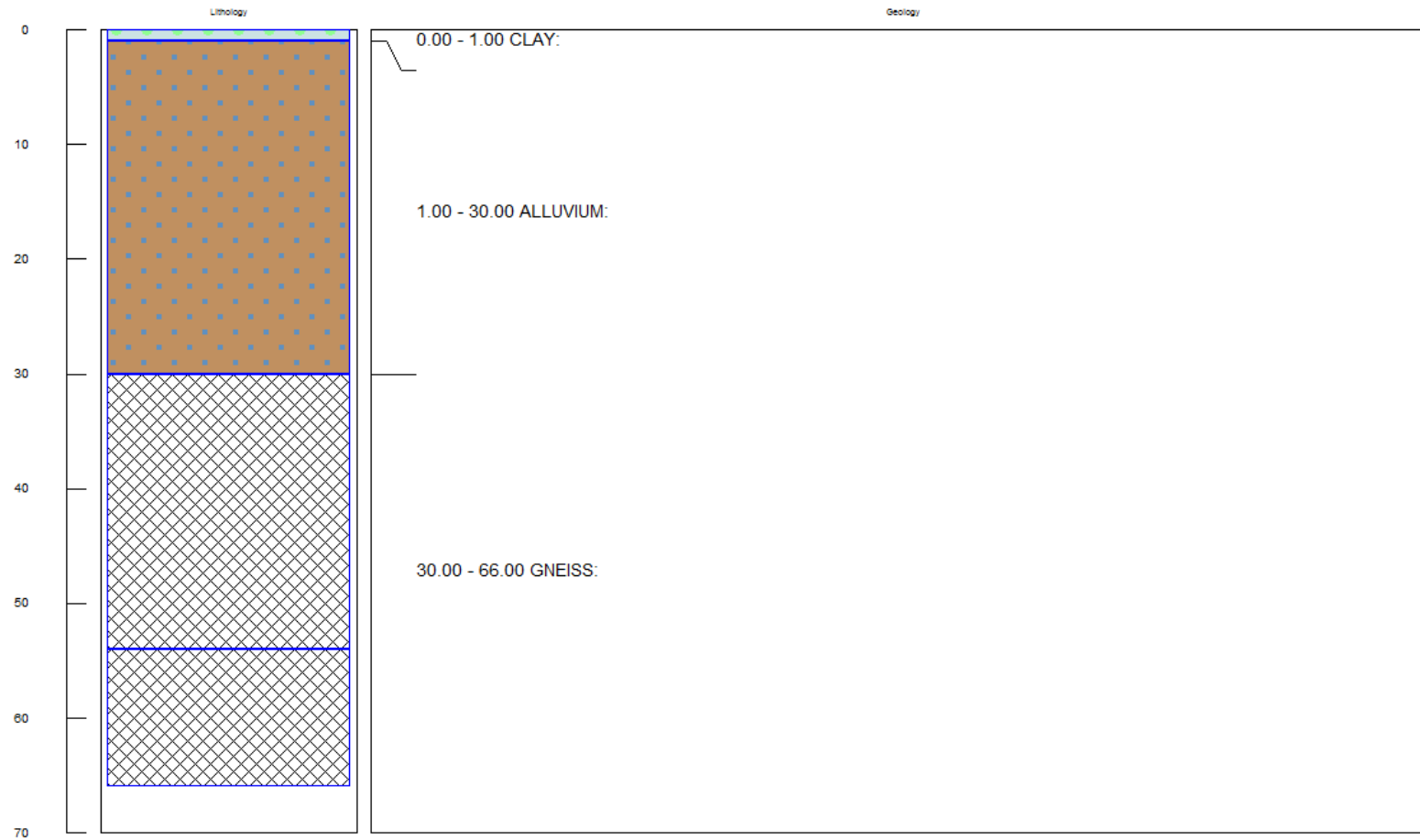


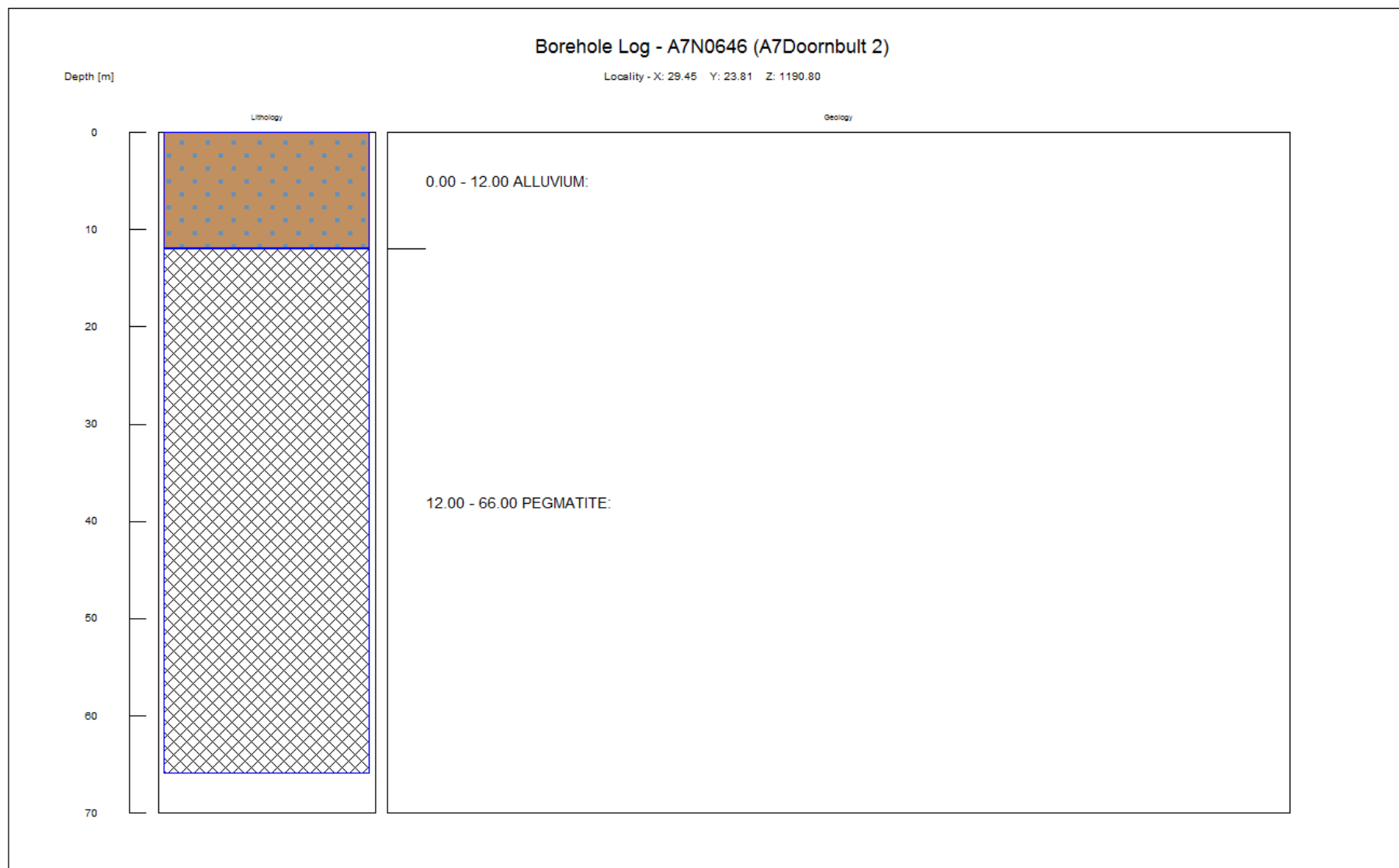


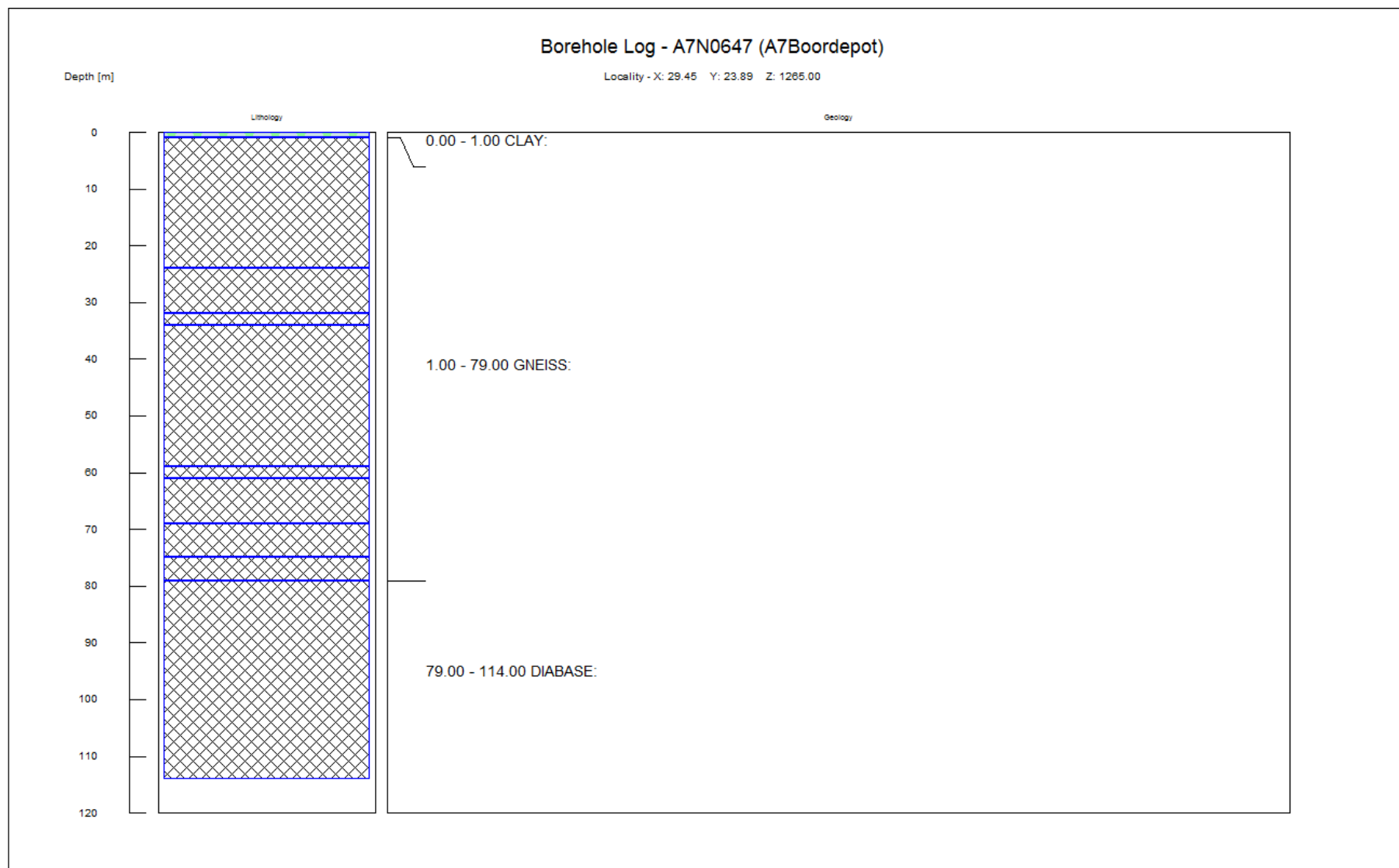
Borehole Log - A7N0642 (A7Pelgrimshoop 2)

Locality - X: 29.42 Y: 23.82 Z: 1209.00

Depth [m]



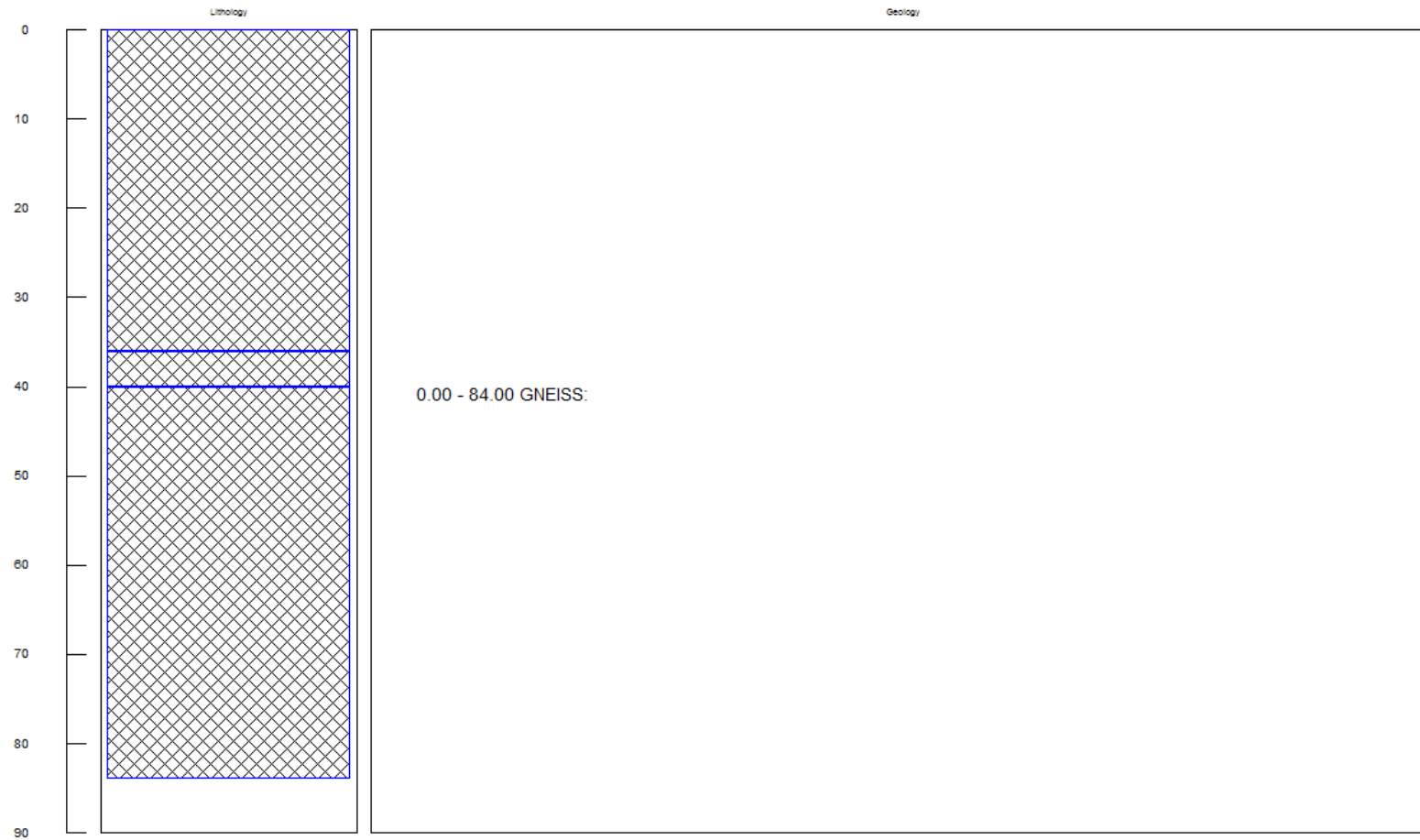




Borehole Log - A7N0655 (A7Palmietgat)

Locality - X: 29.41 Y: 23.82 Z: 1220.50

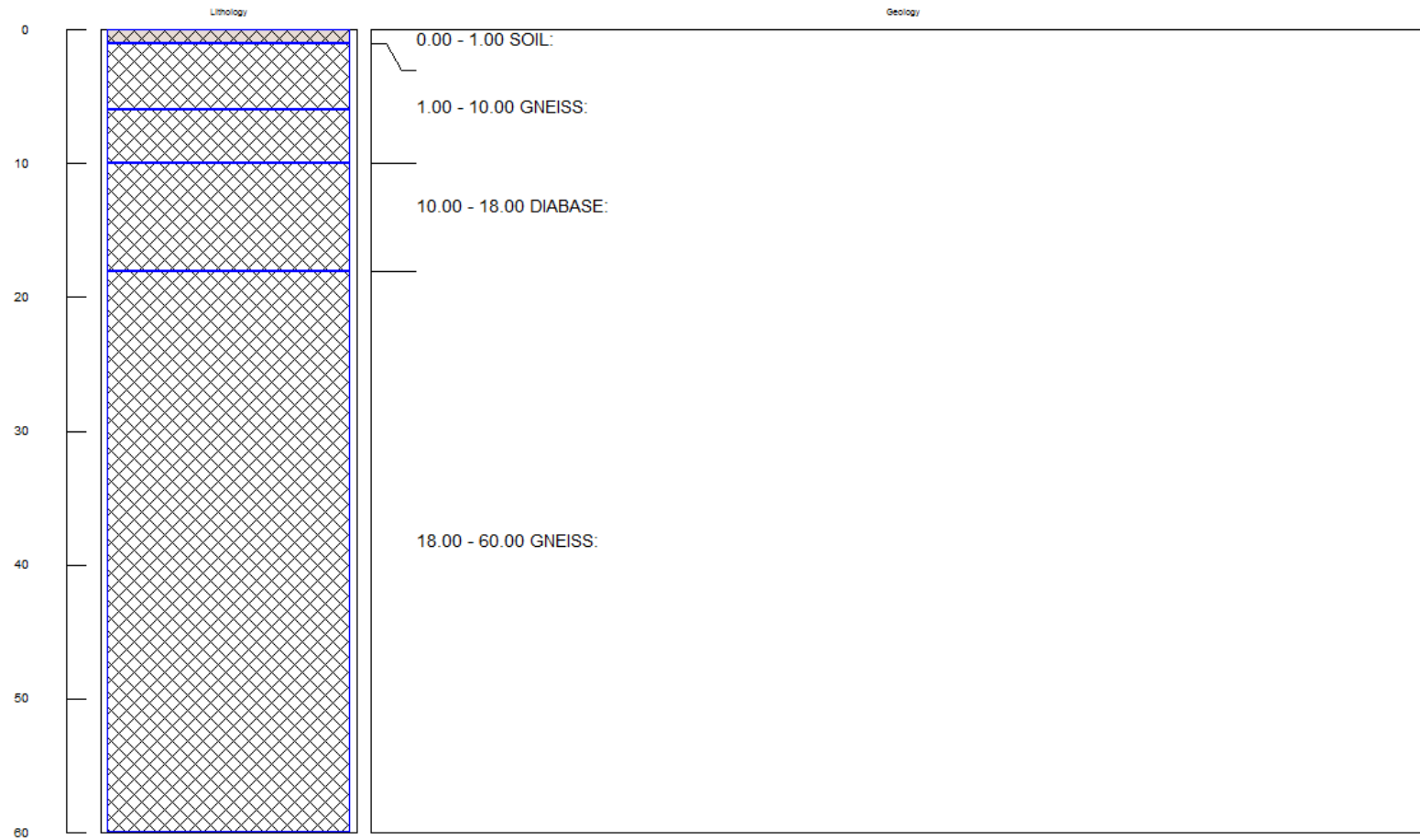
Depth [m]



Borehole Log - A9N0007 (A9Elim)

Locality - X: 30.05 Y: 23.14 Z: 818.60

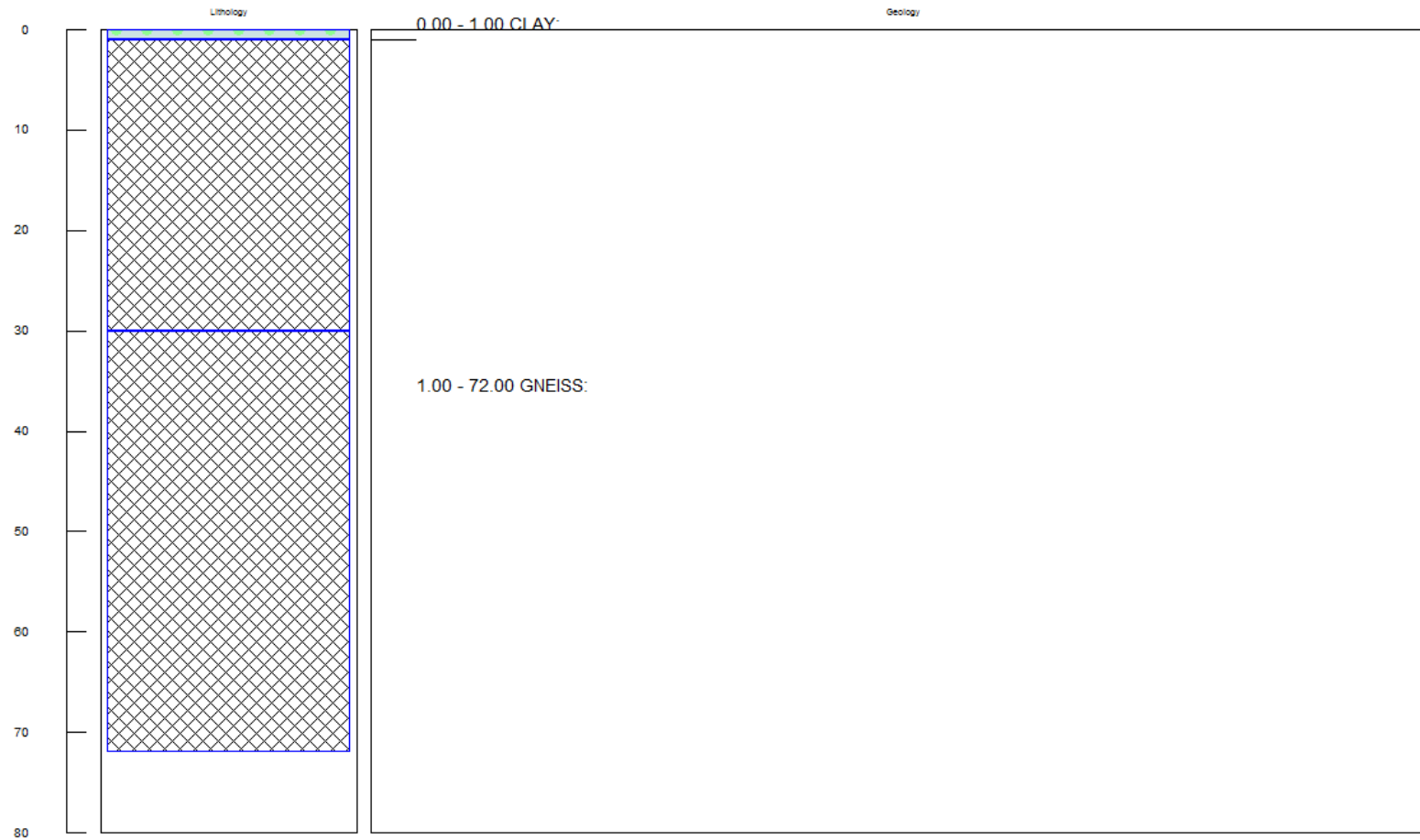
Depth [m]



Borehole Log - B8N0514 (B8Tzaneen)

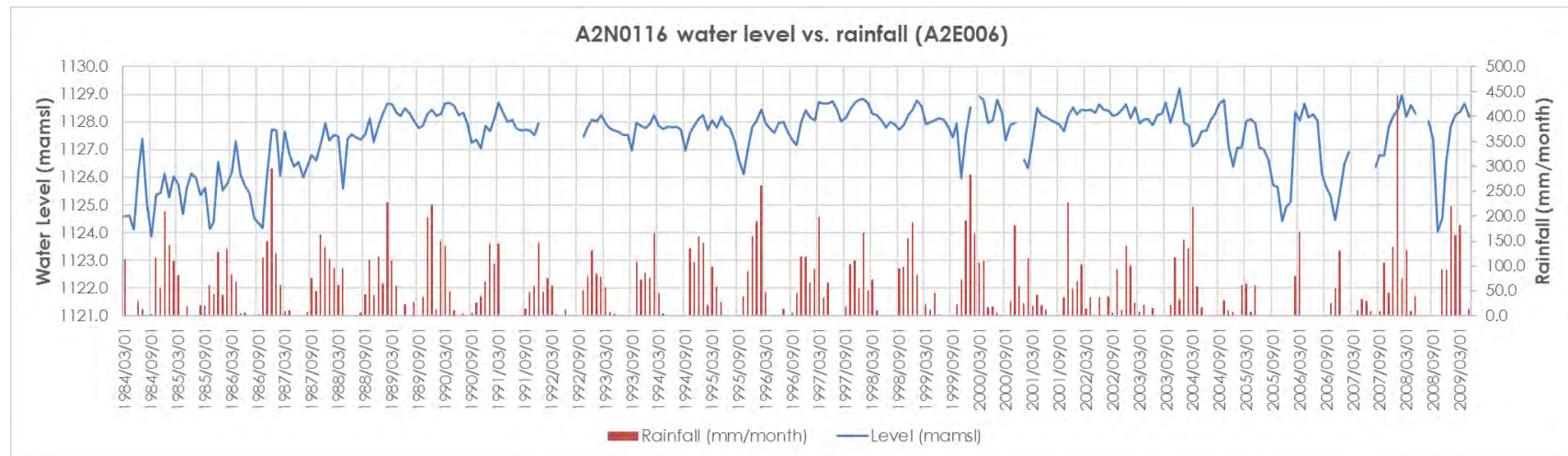
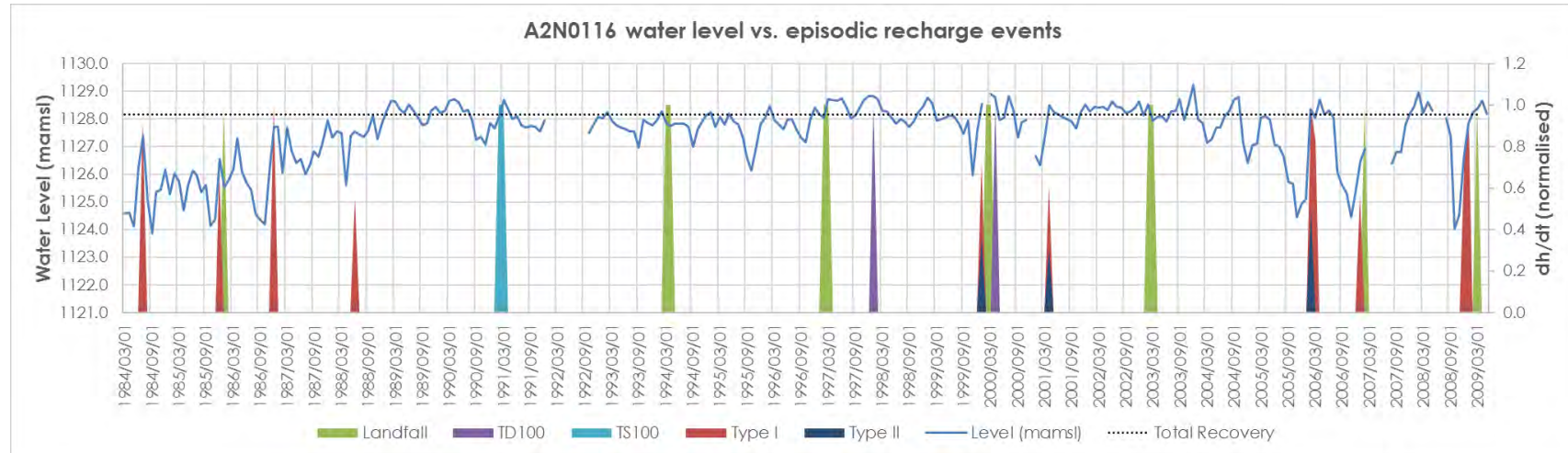
Locality - X: 30.17 Y: 23.79 Z: 750.50

Depth [m]

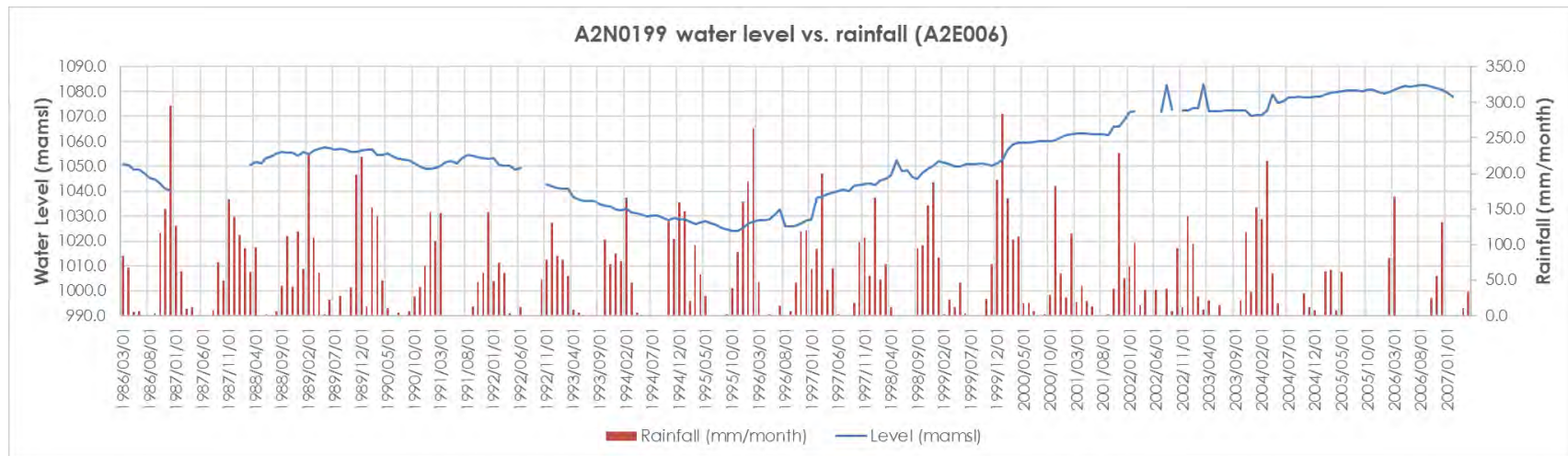
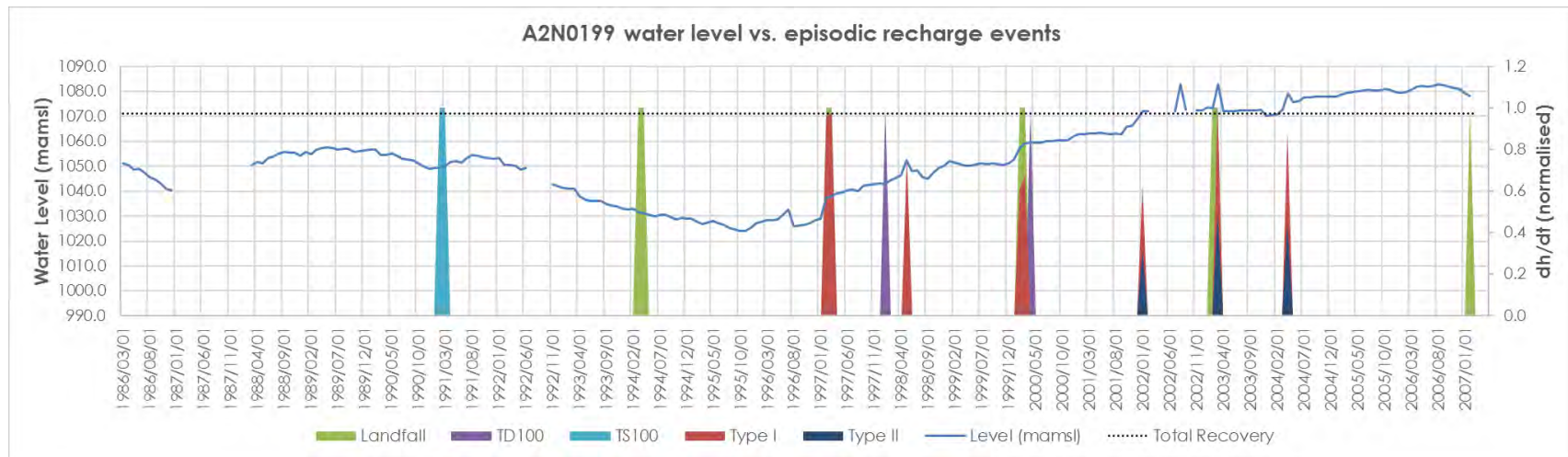


APPENDIX B – DETECTION ALGORITHM RESULTS

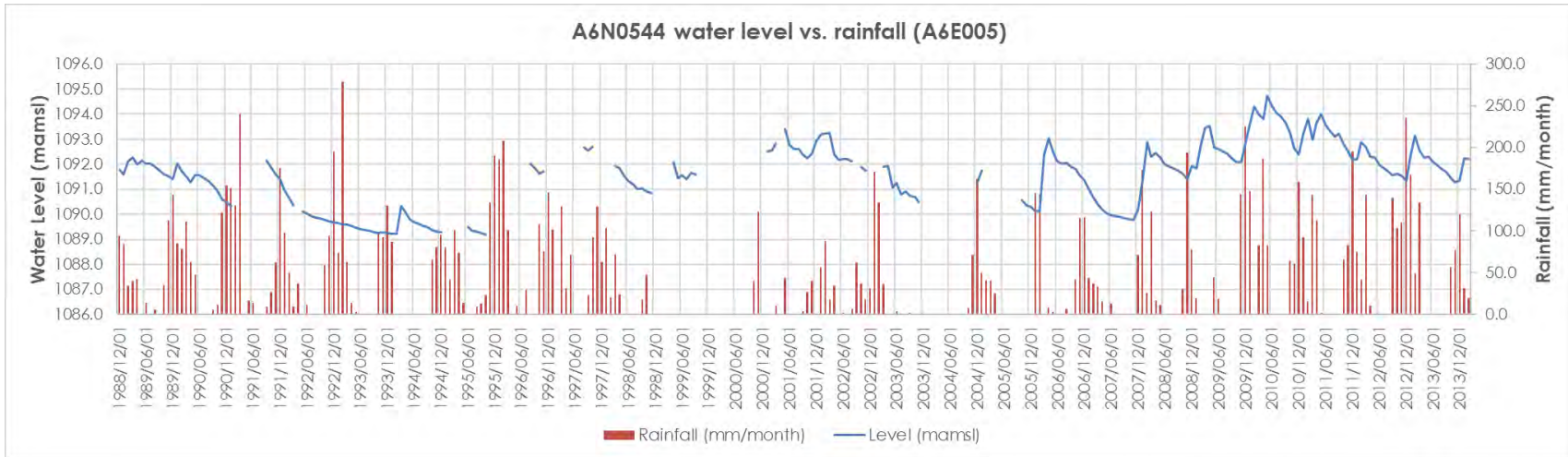
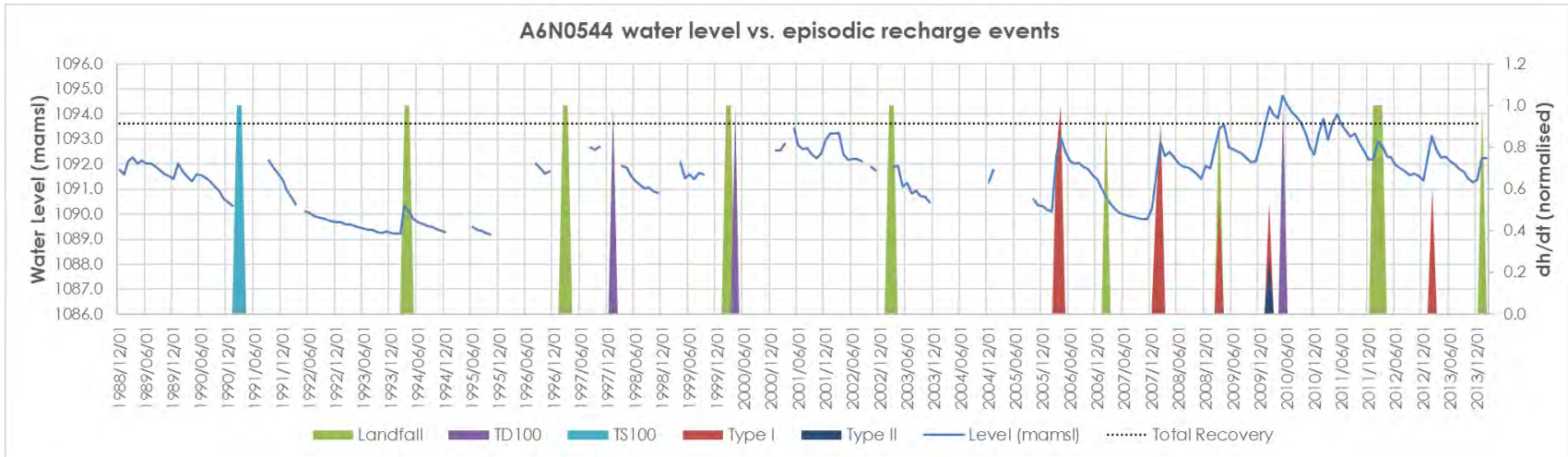
10.1 Borehole A2N0116



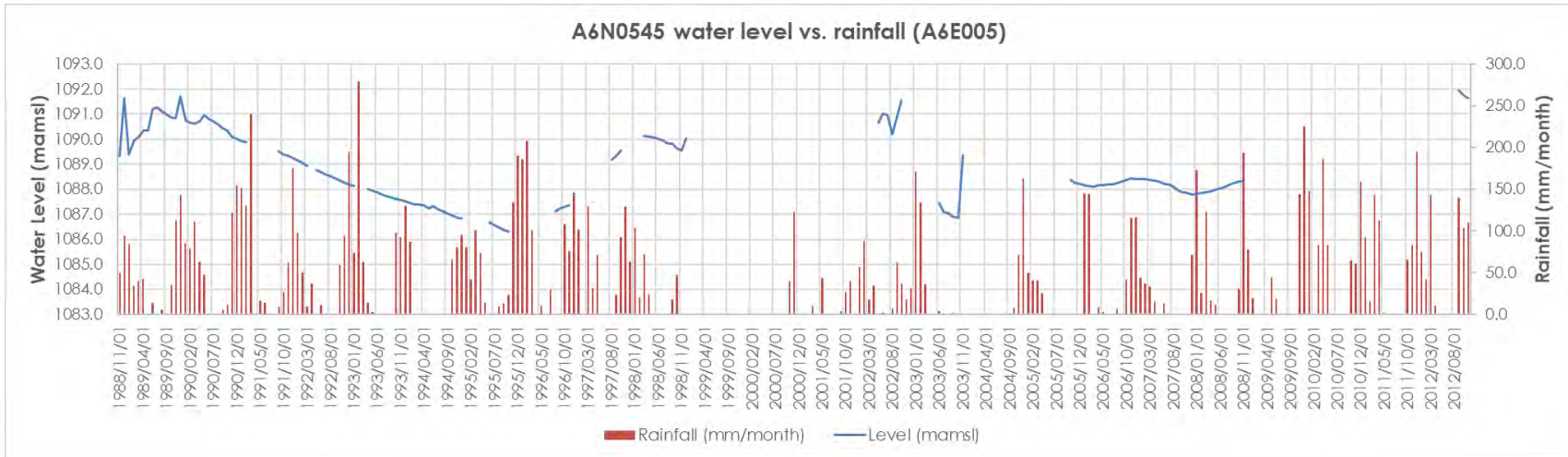
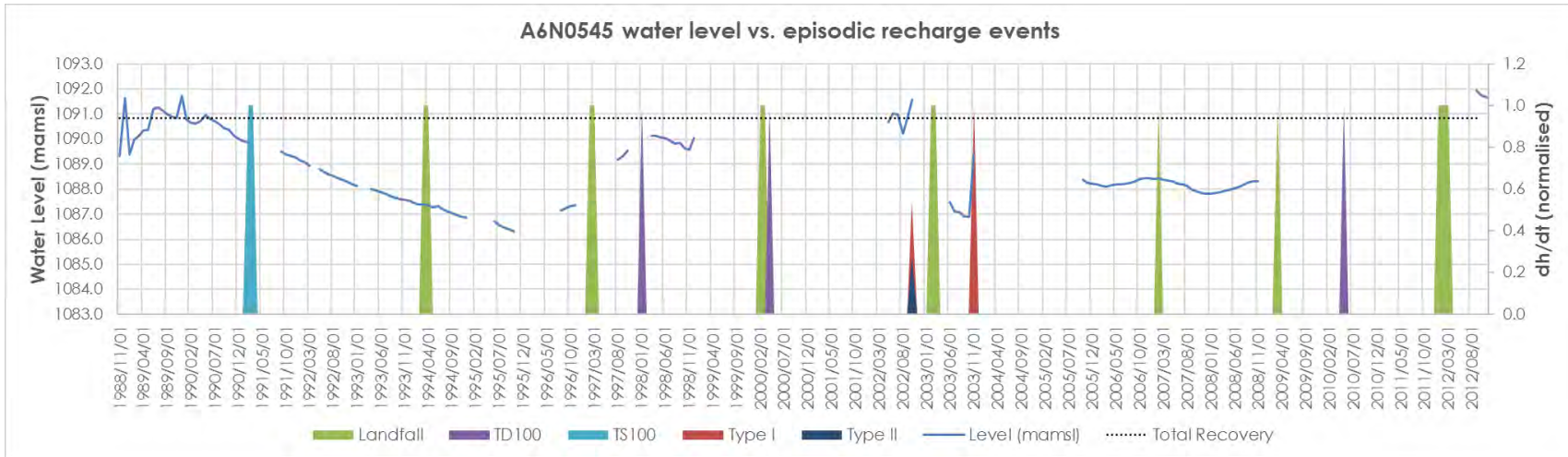
10.2 Borehole A2N0199



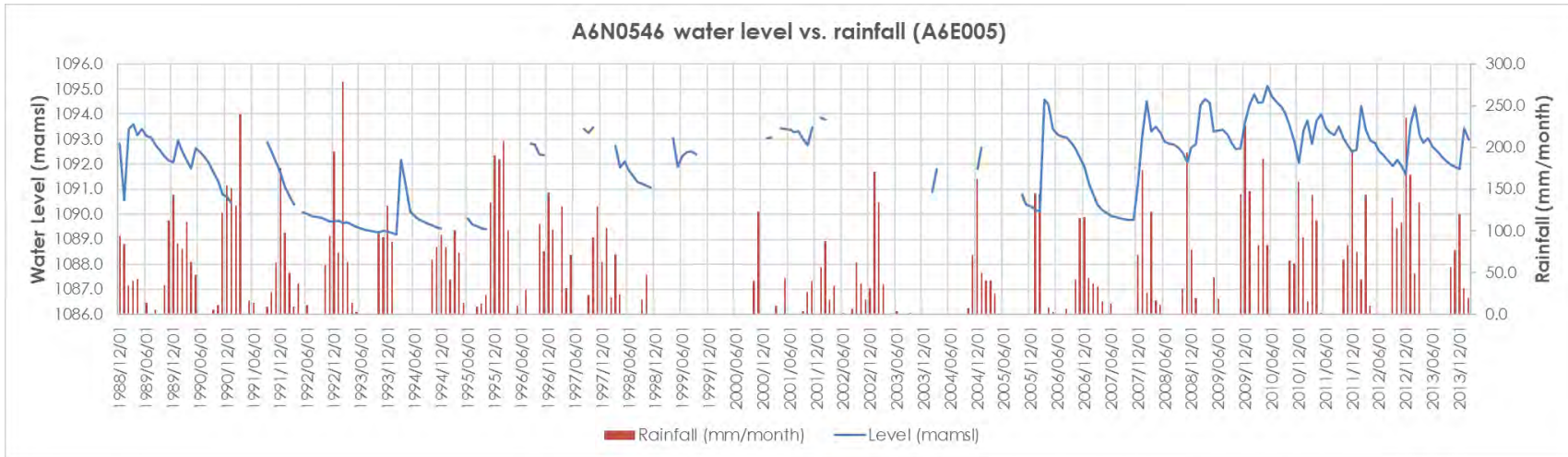
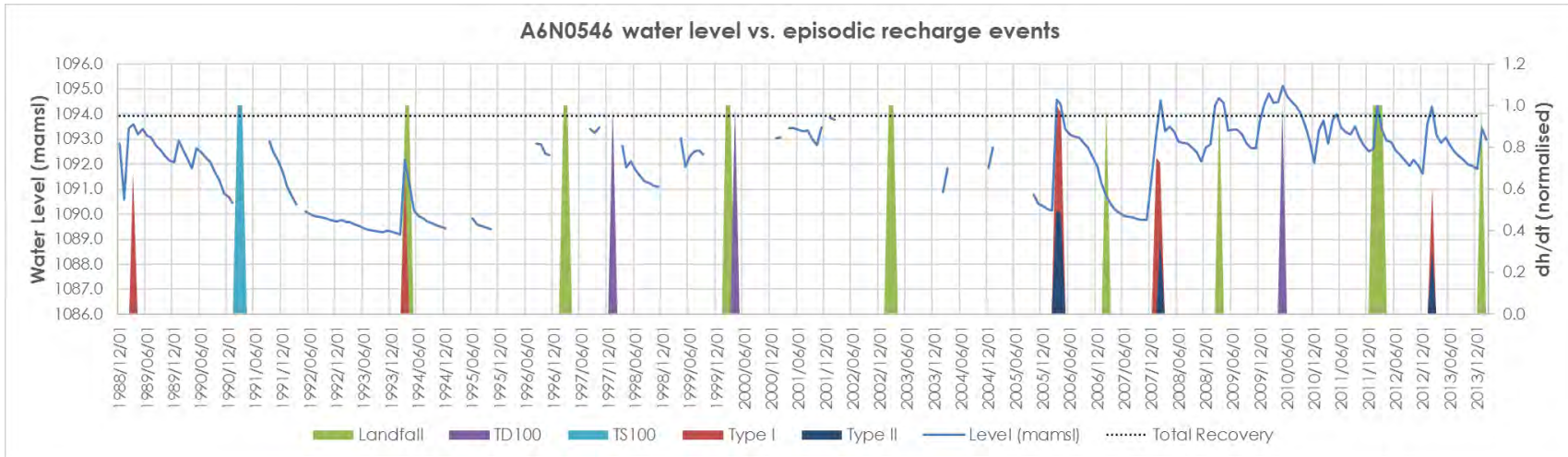
10.3 Borehole A6N0544



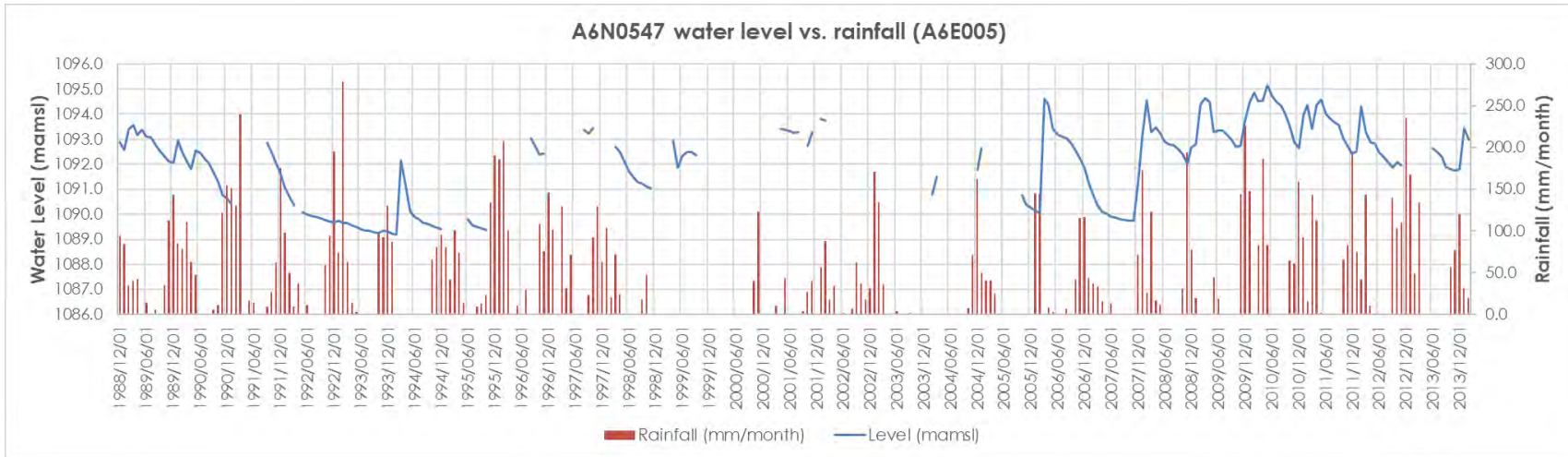
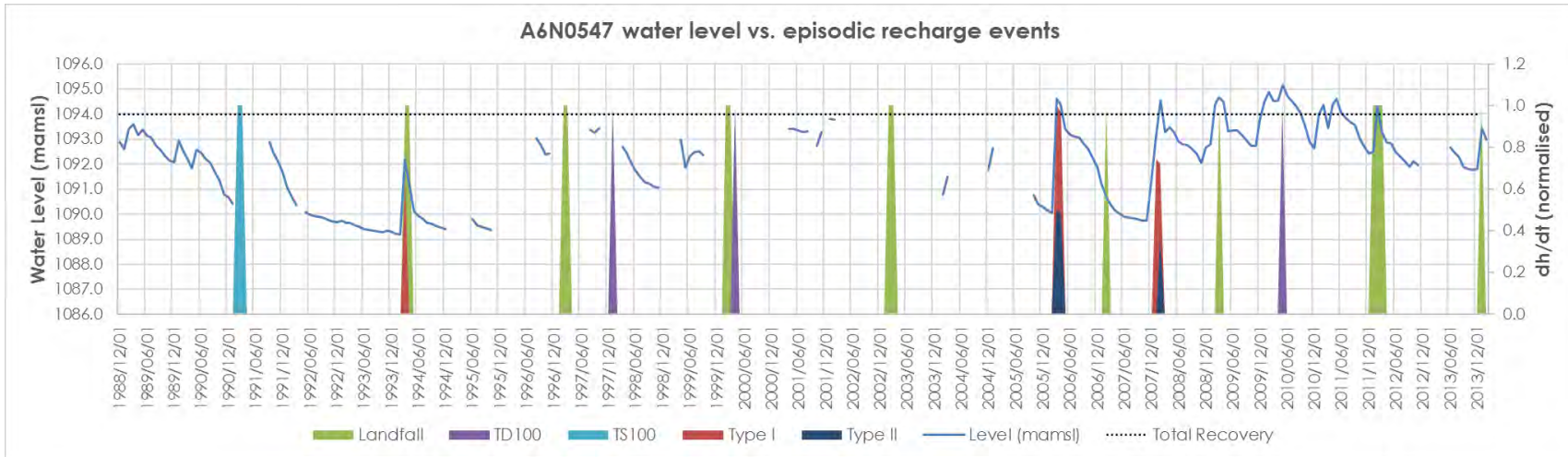
10.4 Borehole A6N0545



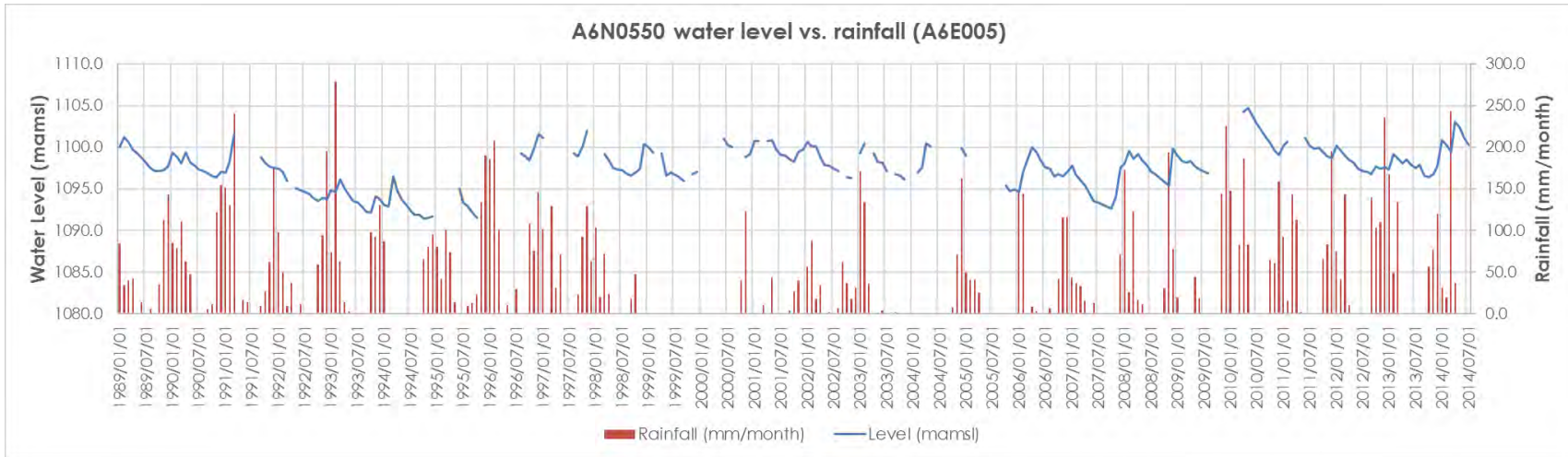
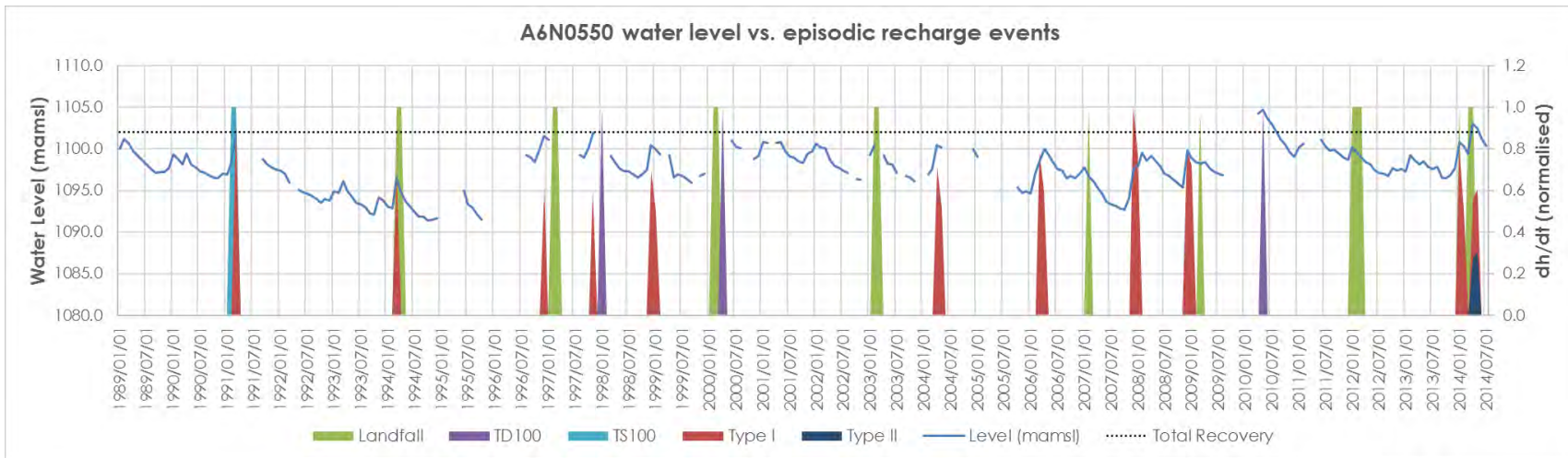
10.5 Borehole A6N0546



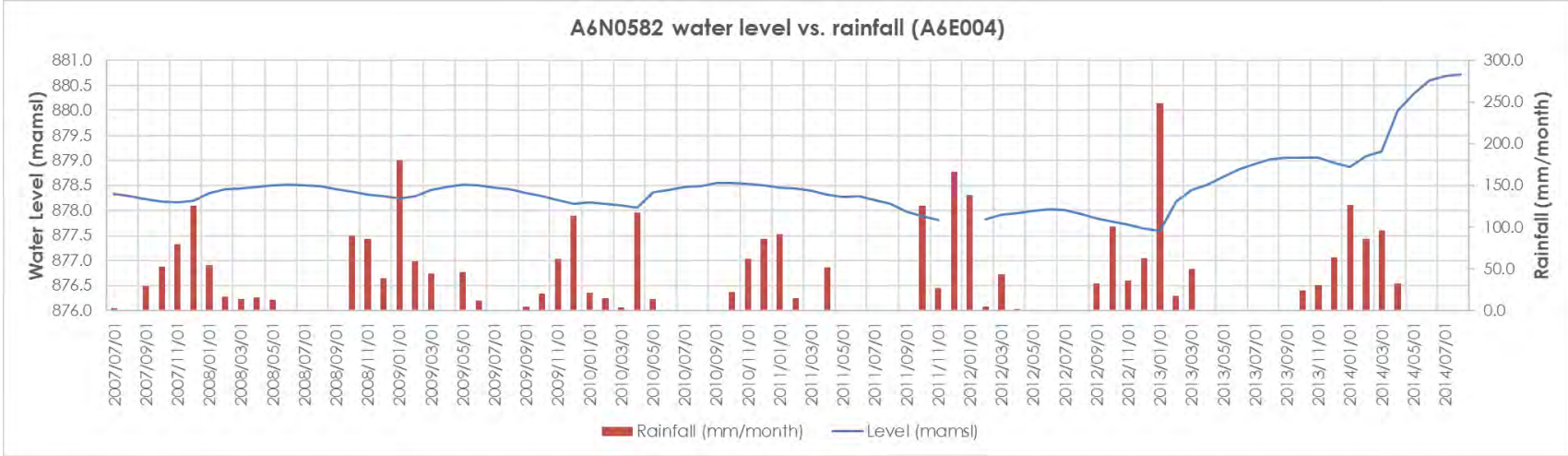
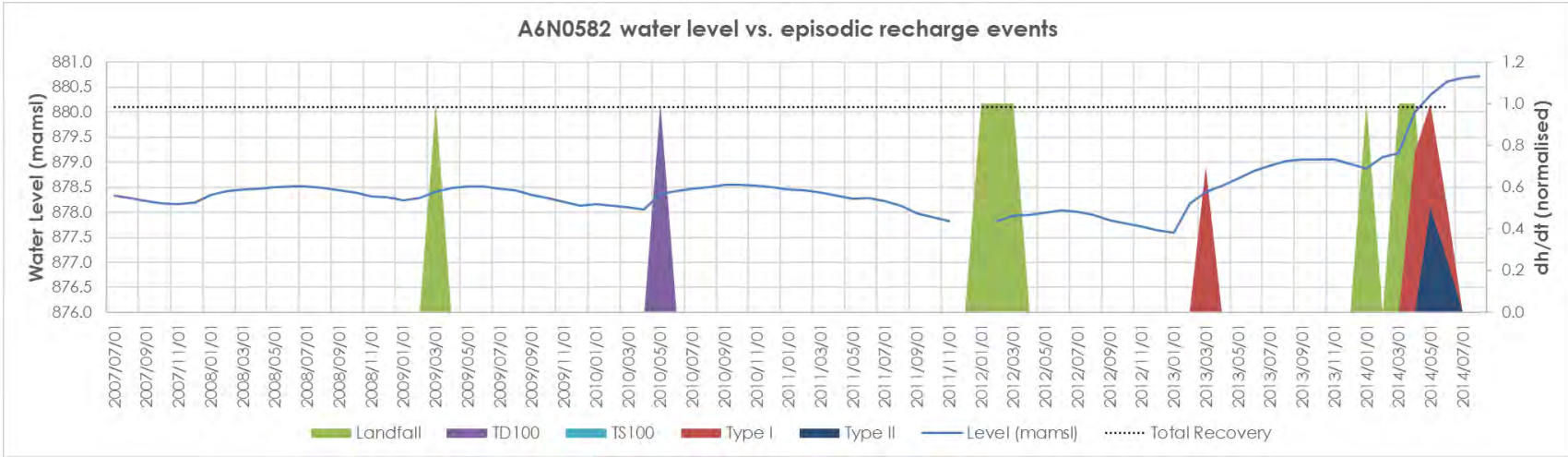
10.6 Borehole A6N0547



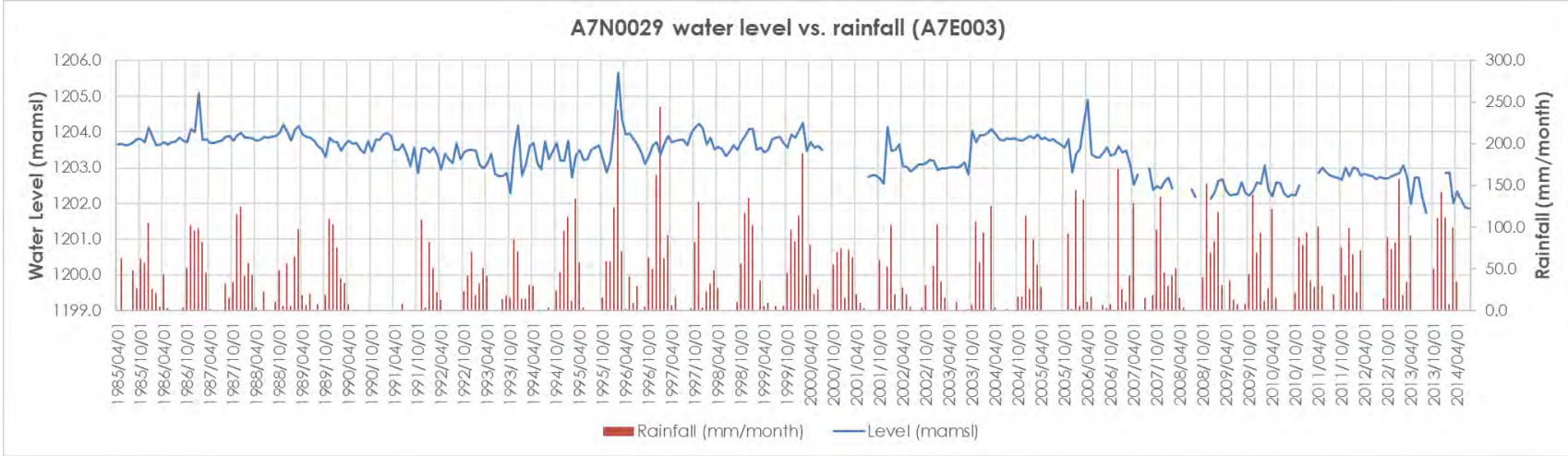
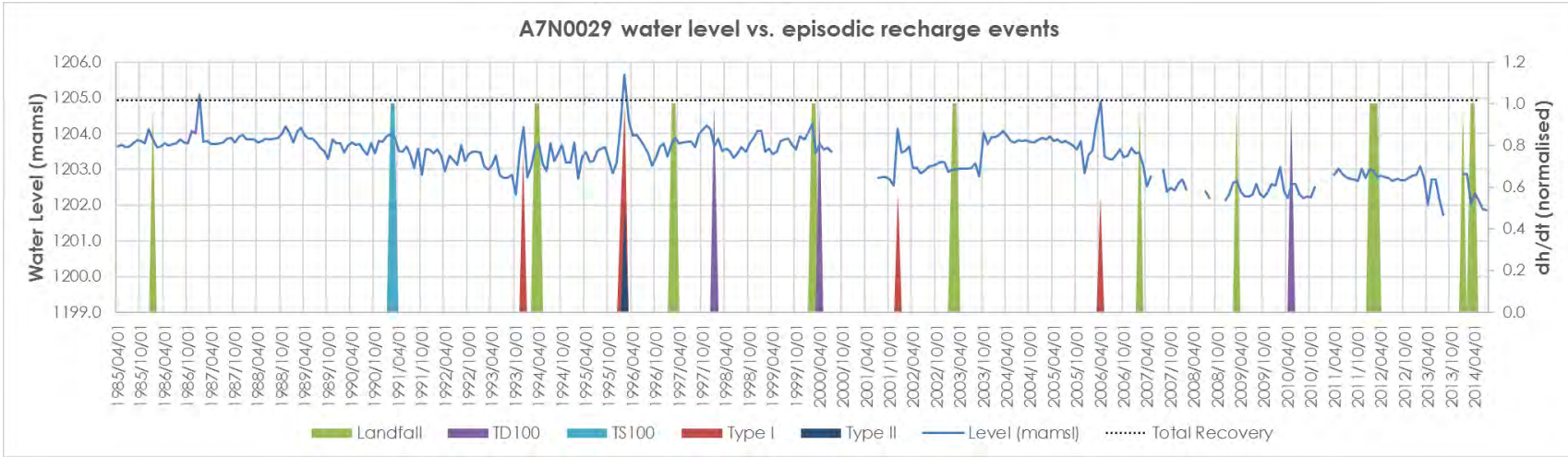
10.7 Borehole A6N0550



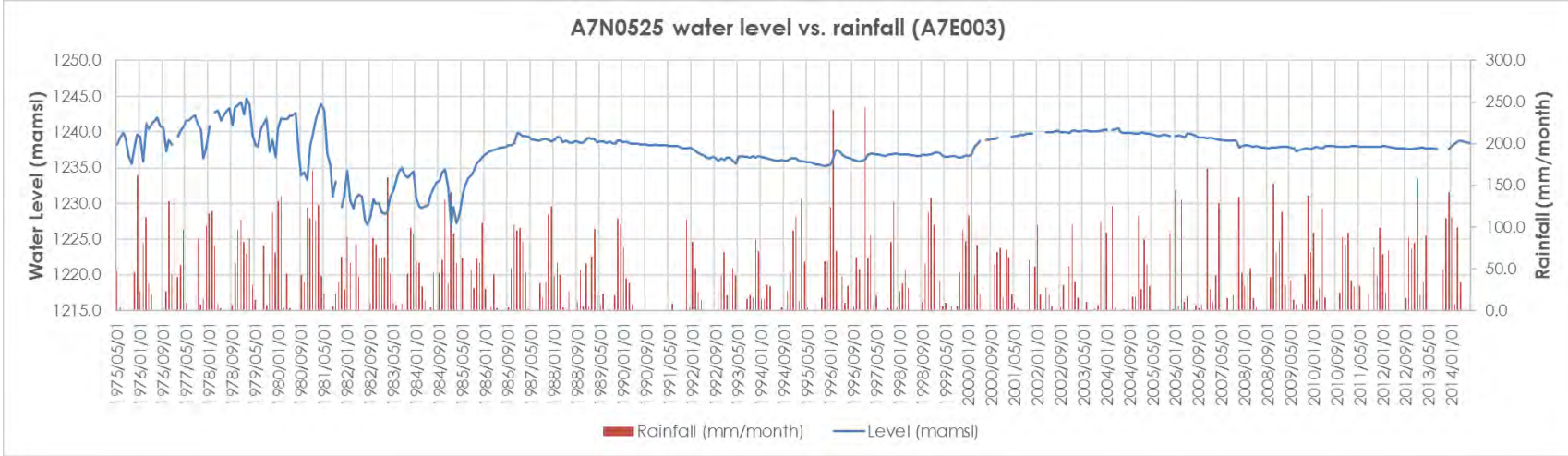
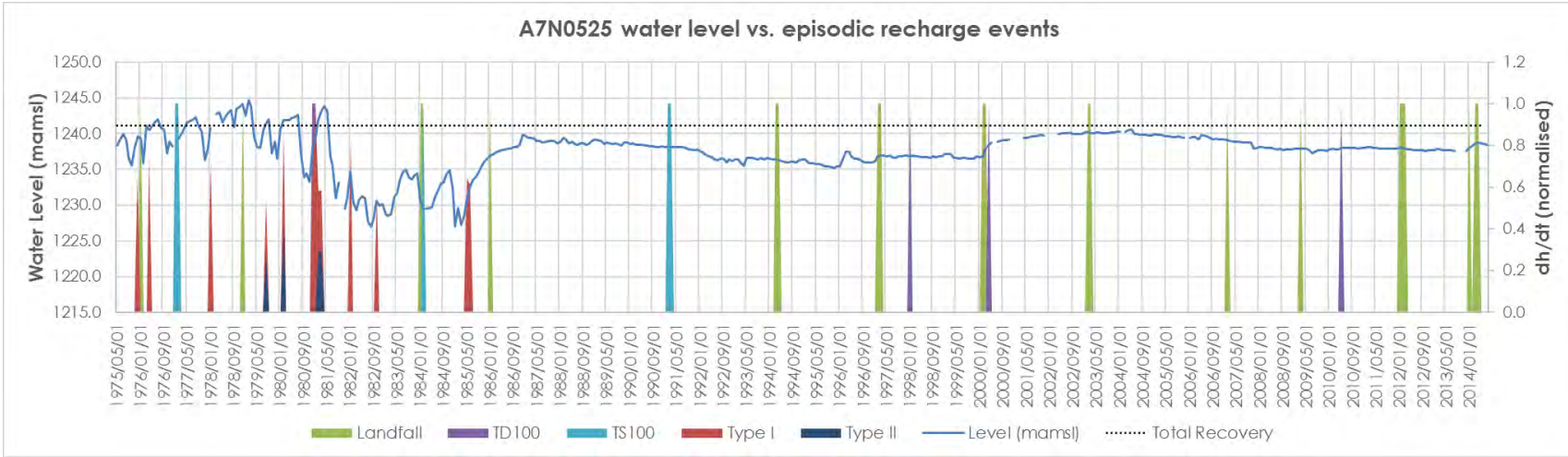
10.8 Borehole A6N0582



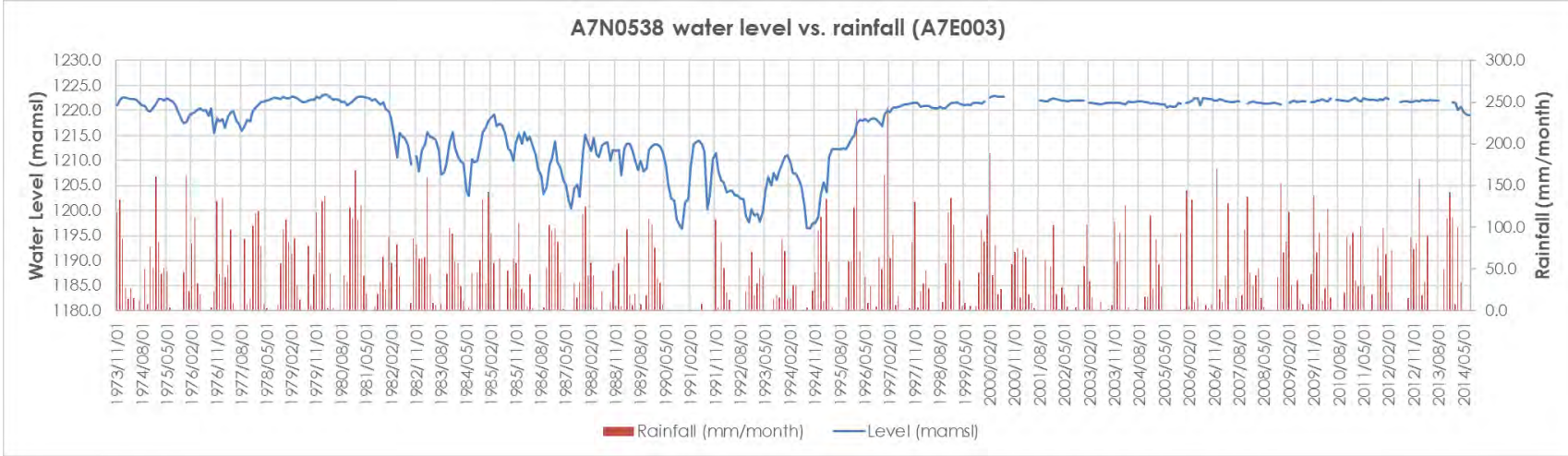
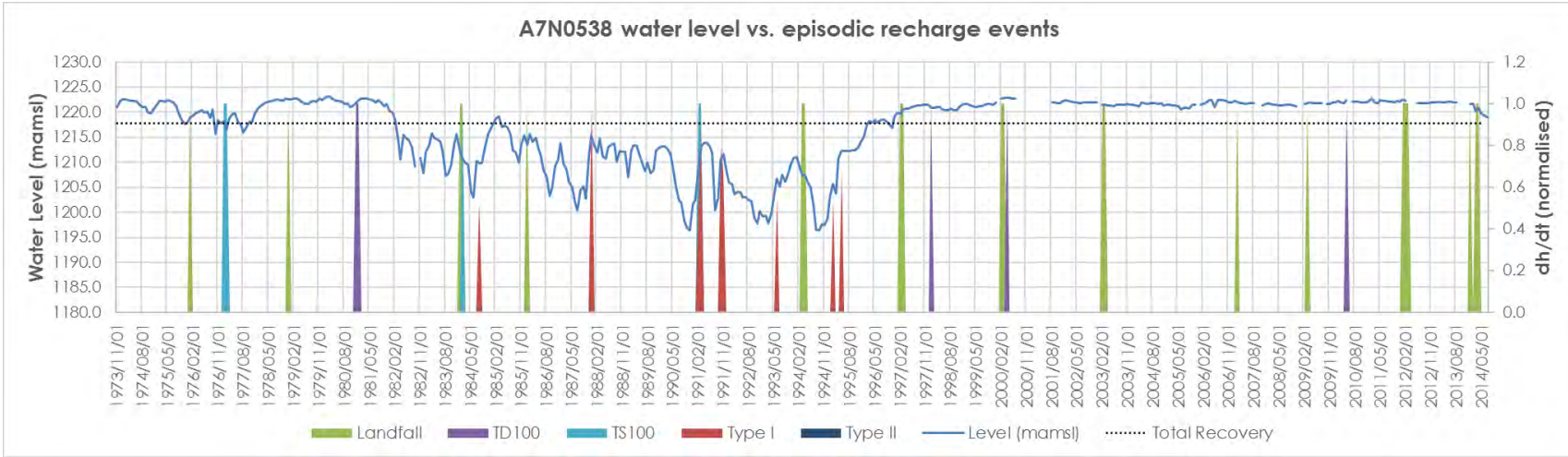
10.9 Borehole A7N0029



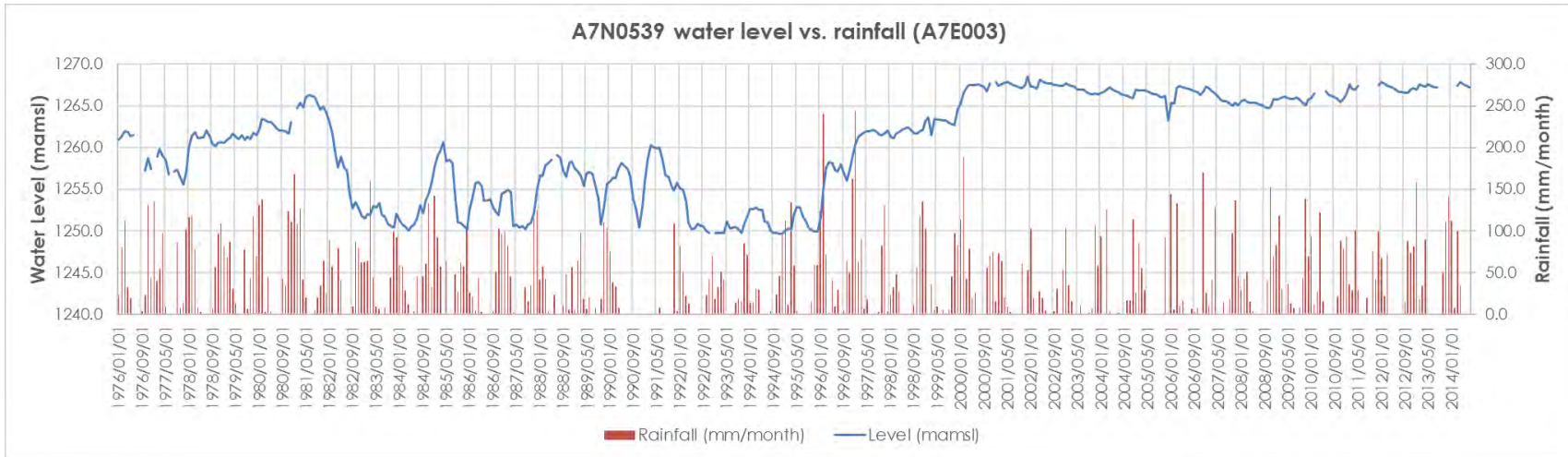
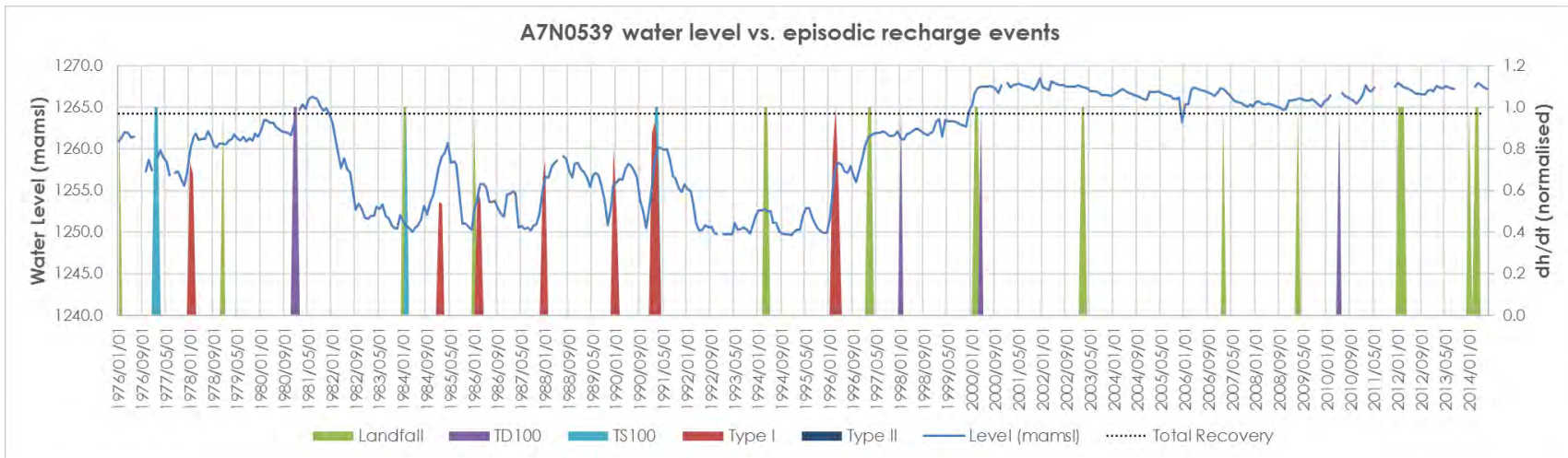
10.10 Borehole A7N0525



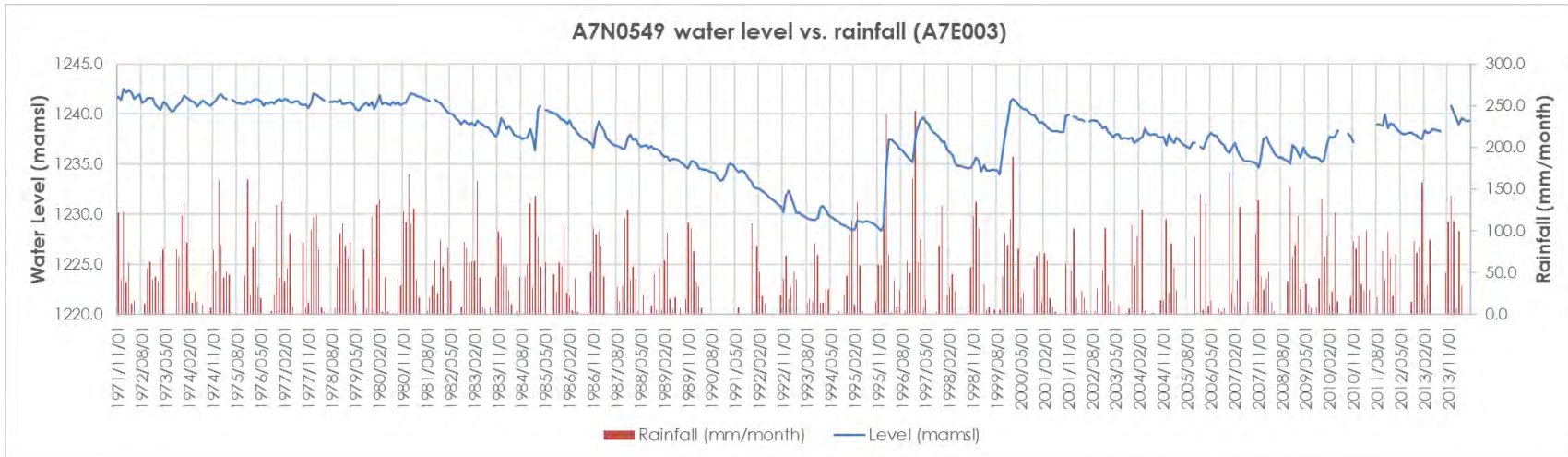
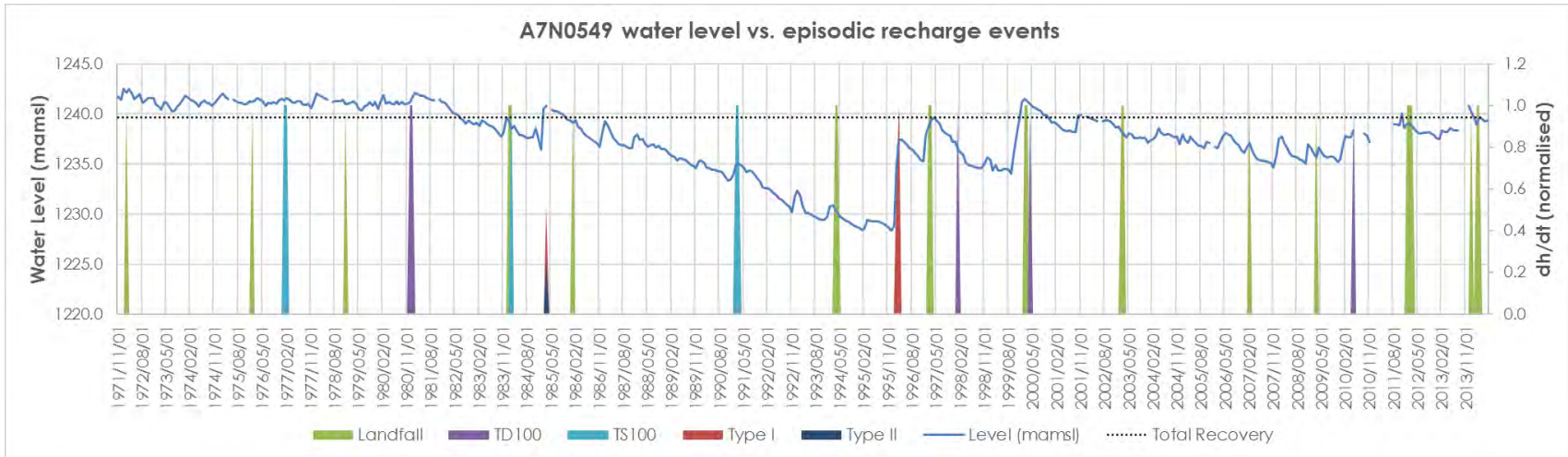
10.11 Borehole A7N0538



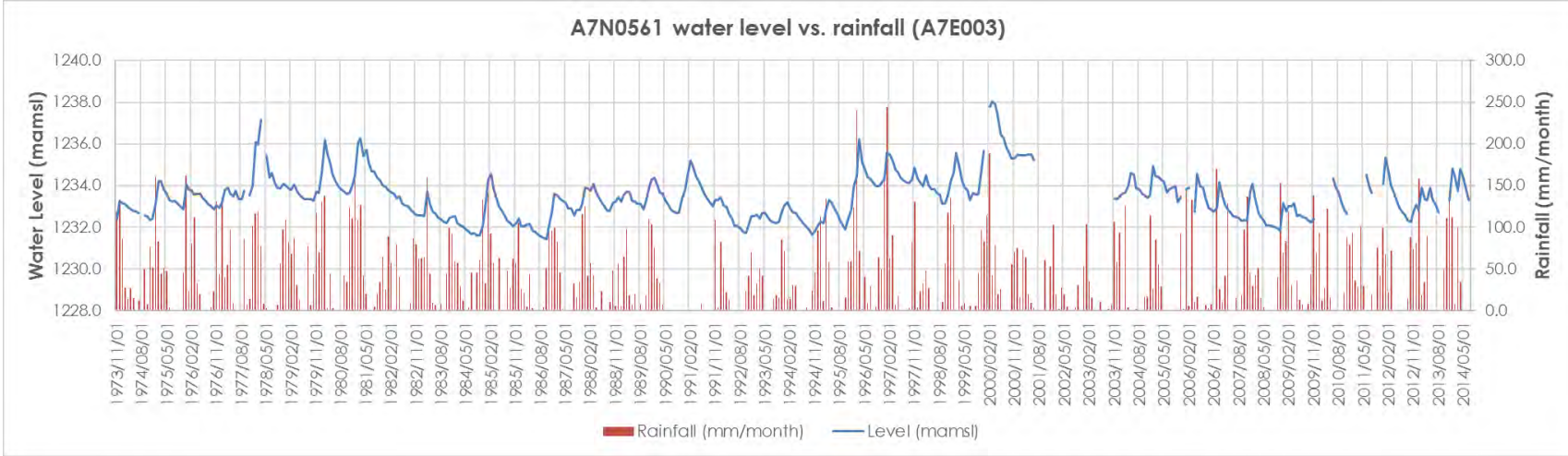
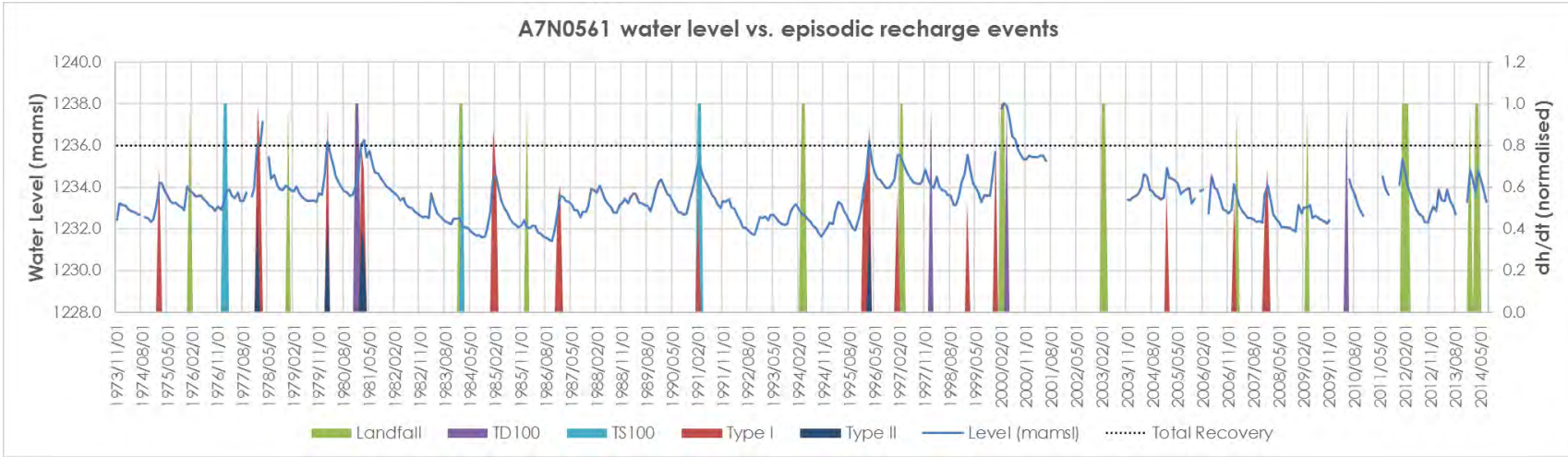
10.12 Borehole A7N0539



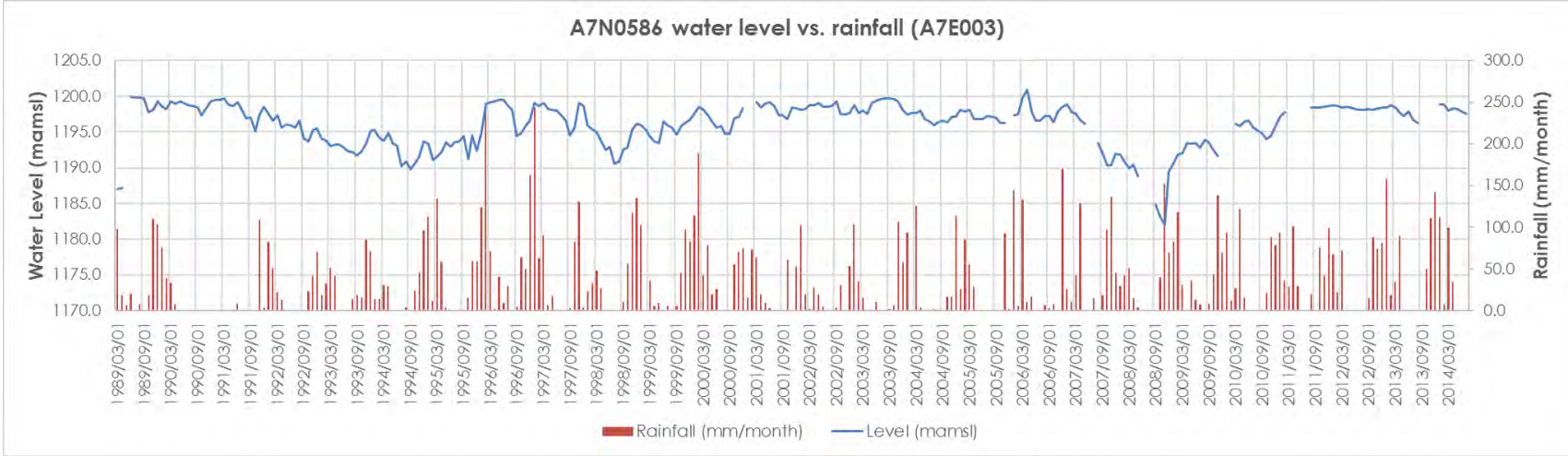
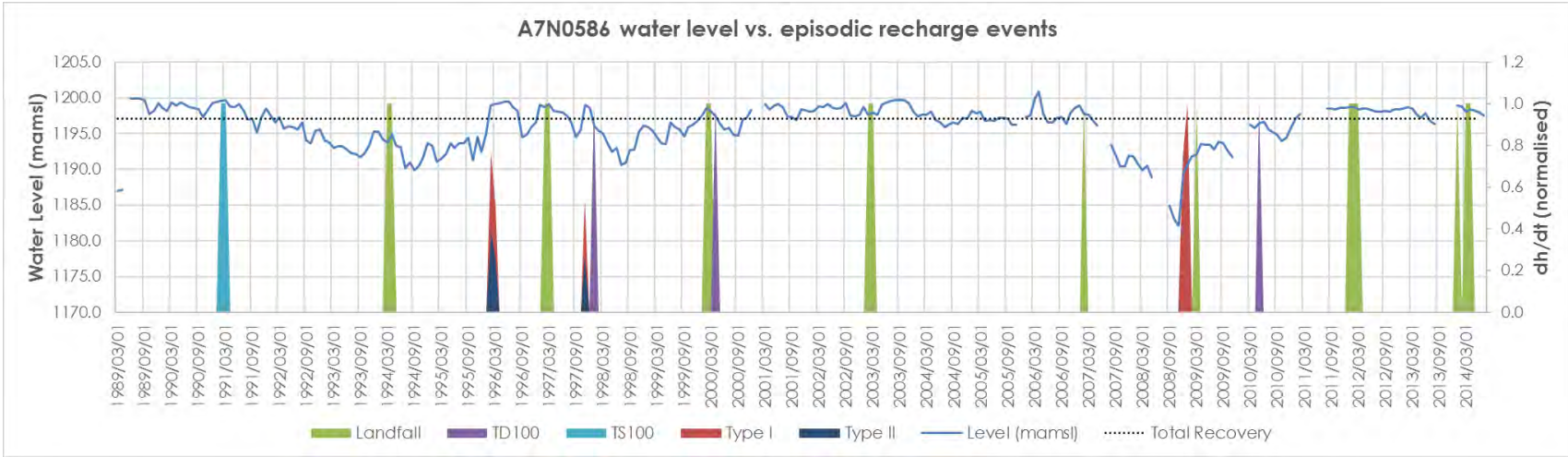
10.13 Borehole A7N0549



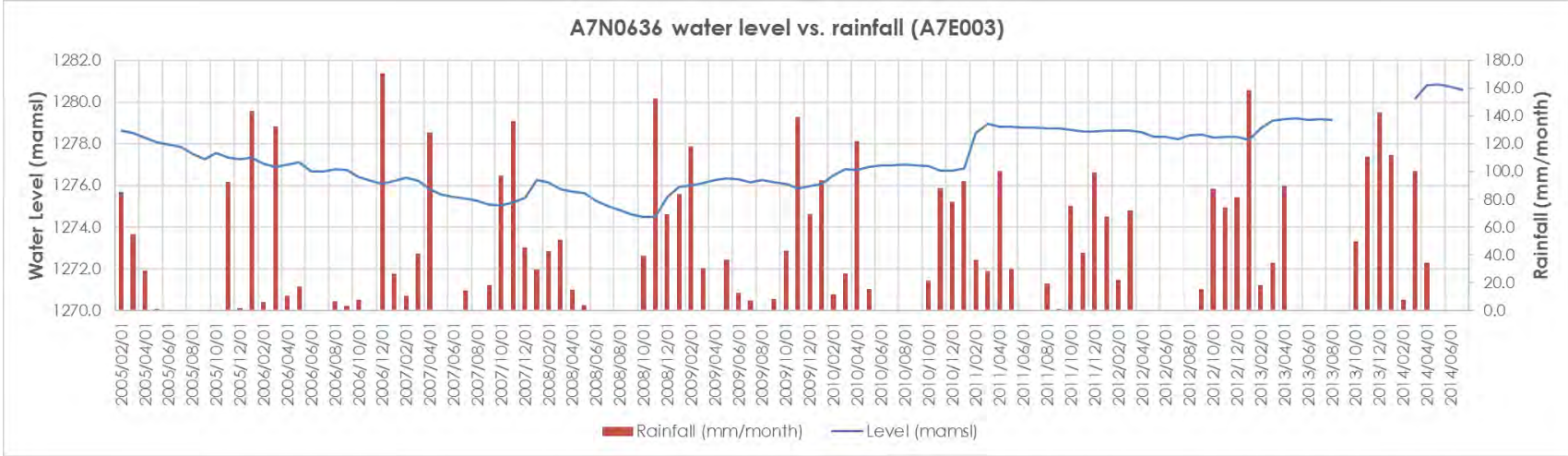
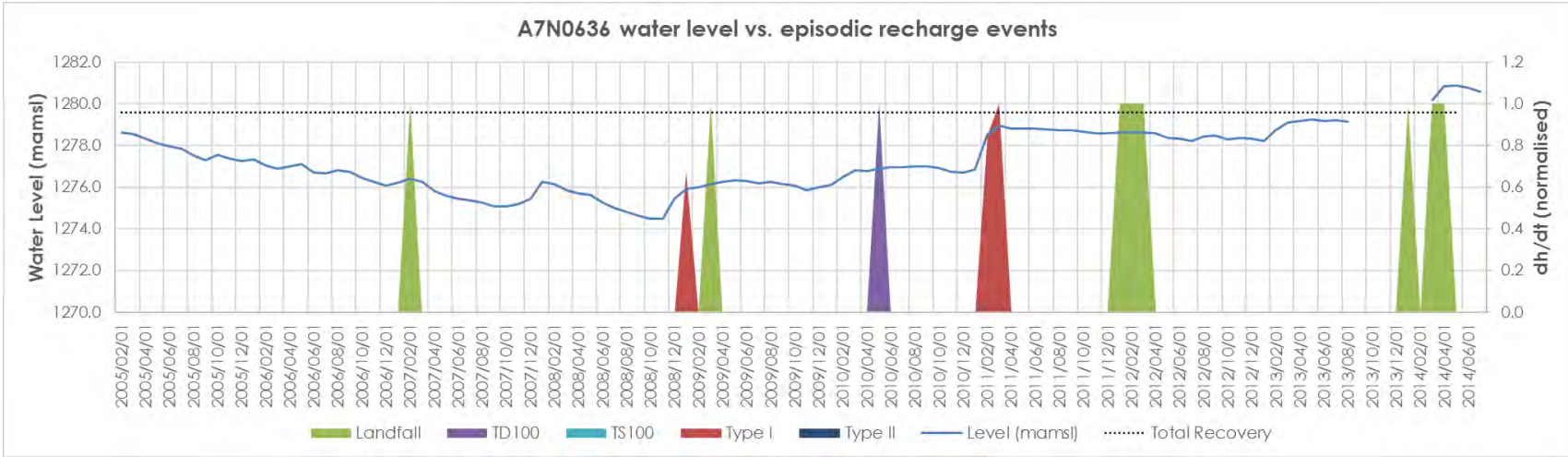
10.14 Borehole A7N0561



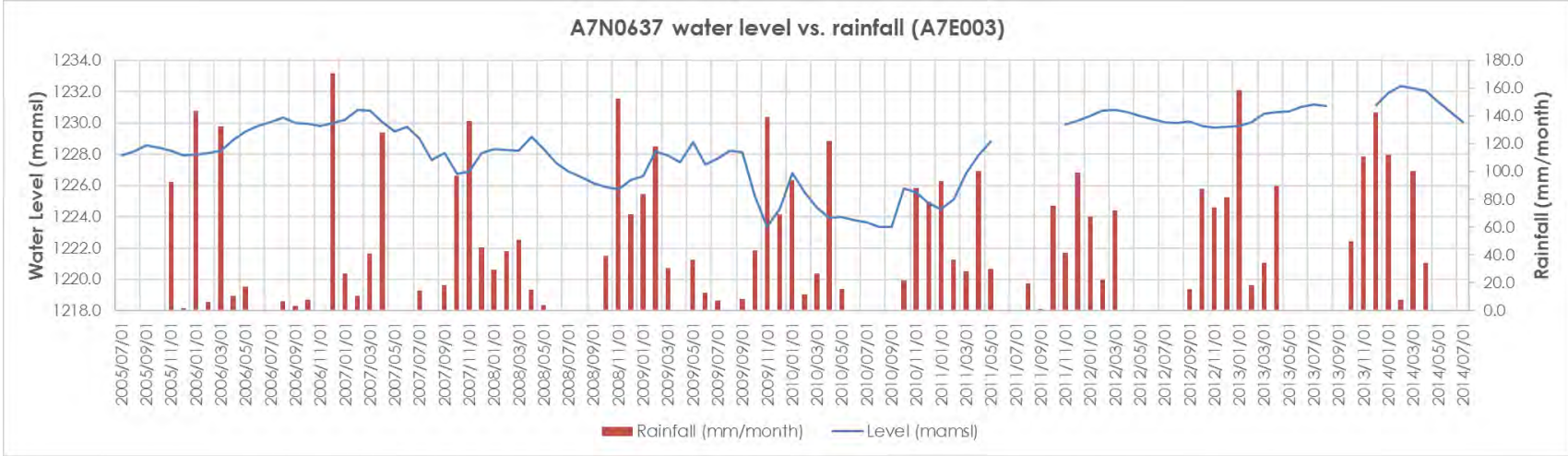
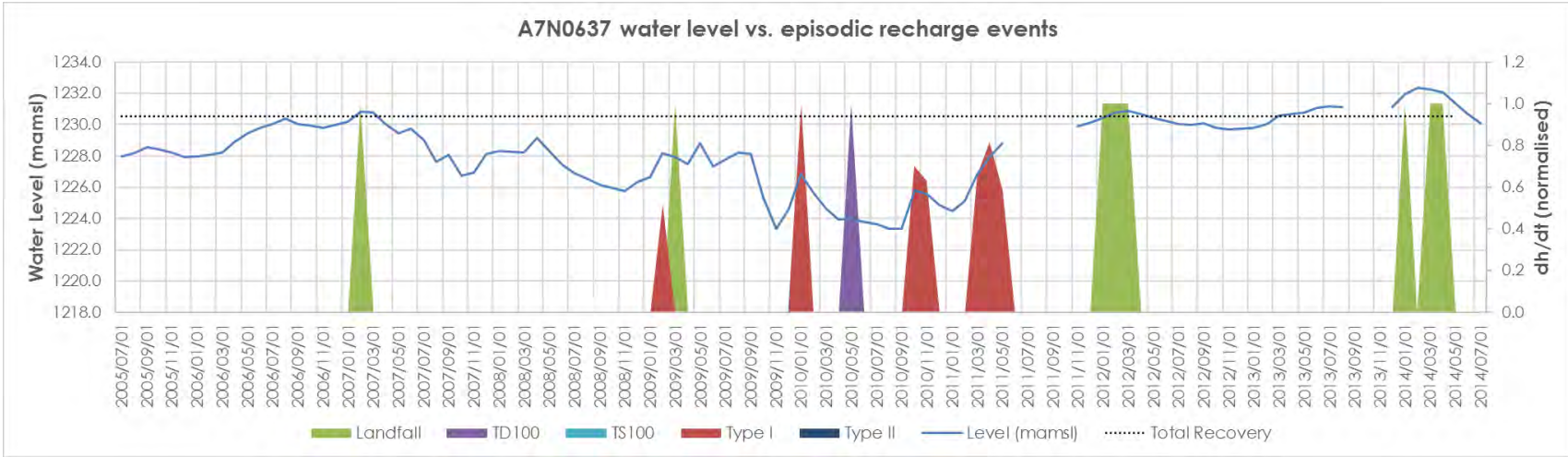
10.15 Borehole A7N0586



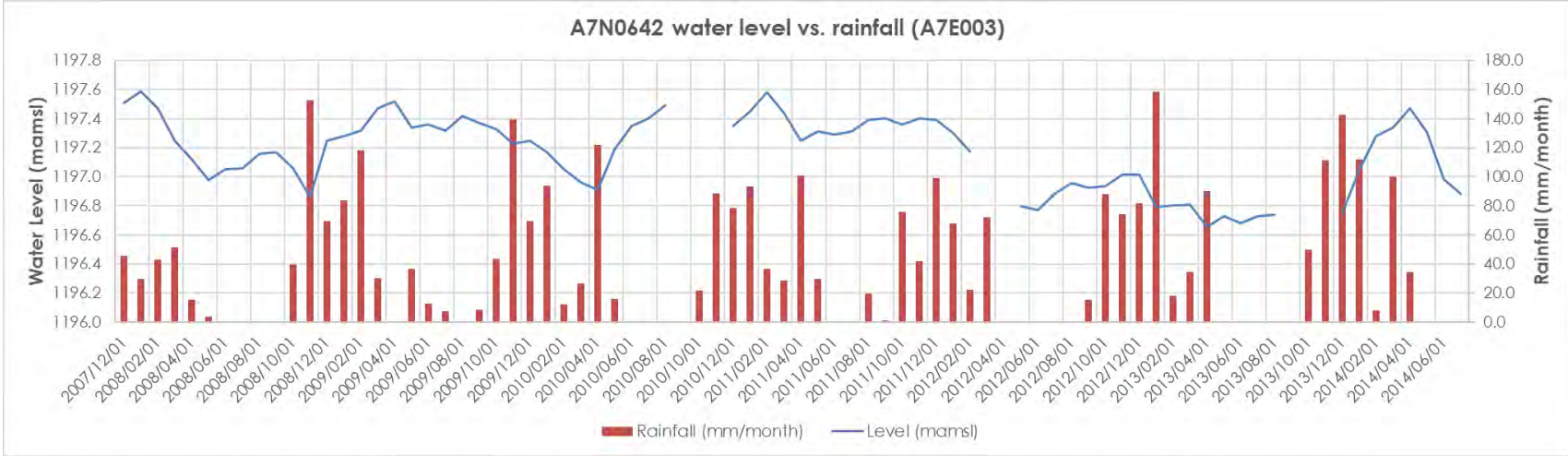
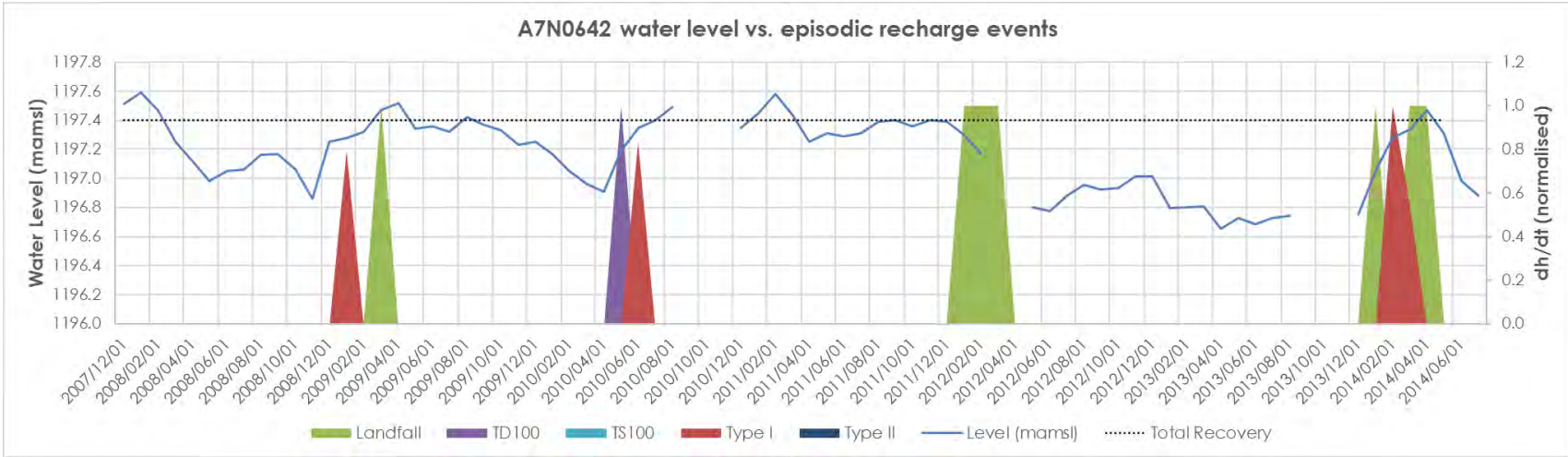
10.16 Borehole A7N0636



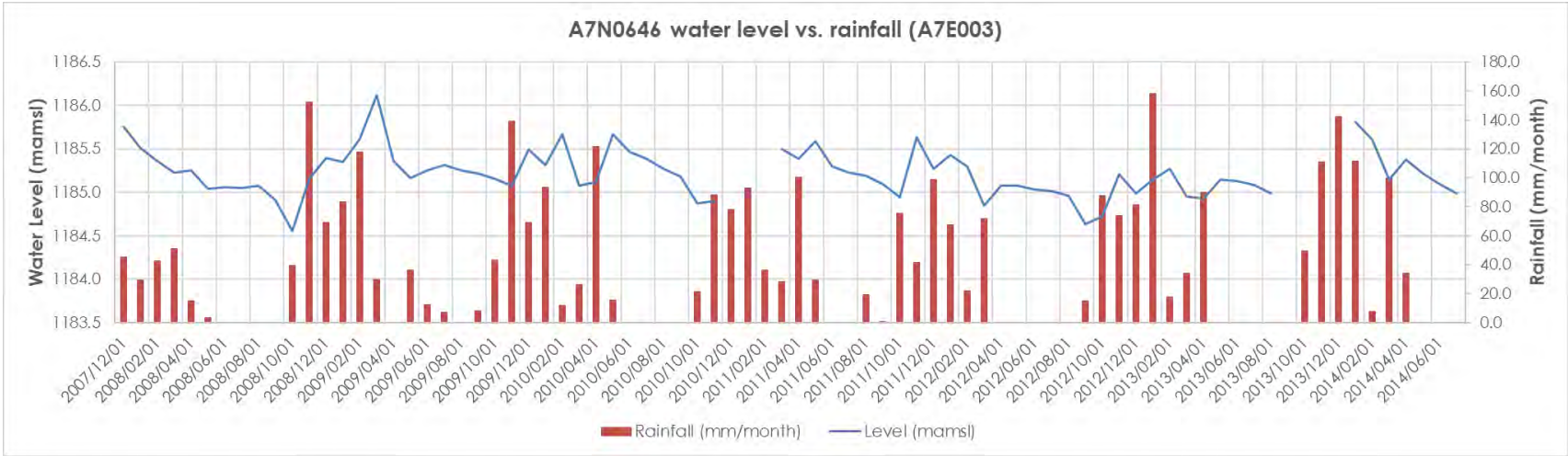
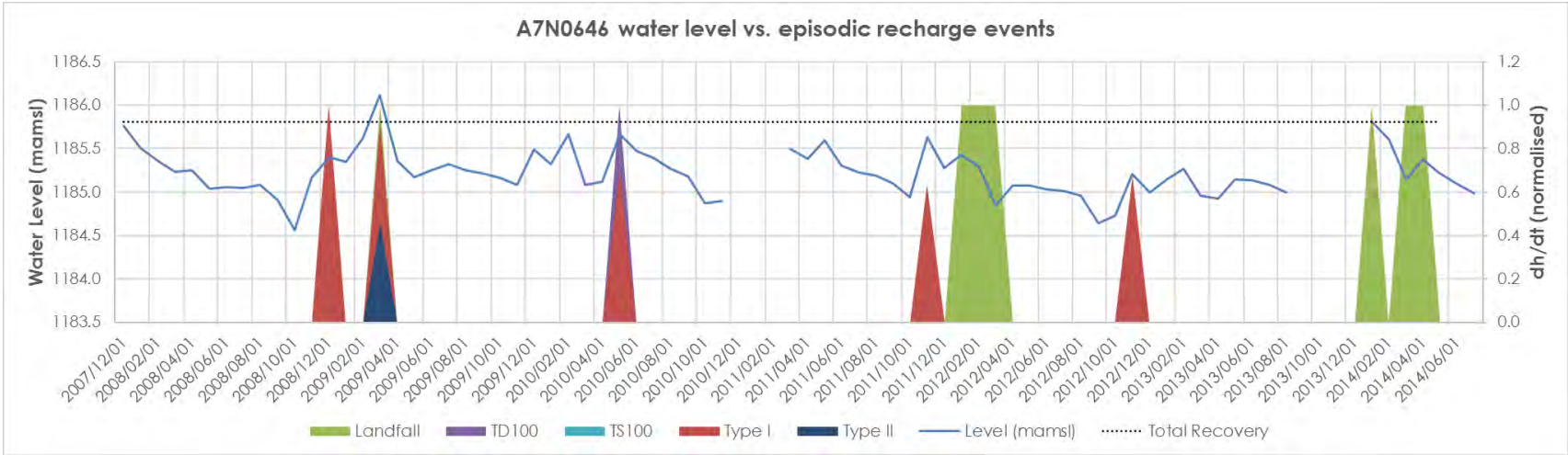
10.17 Borehole A7N0637



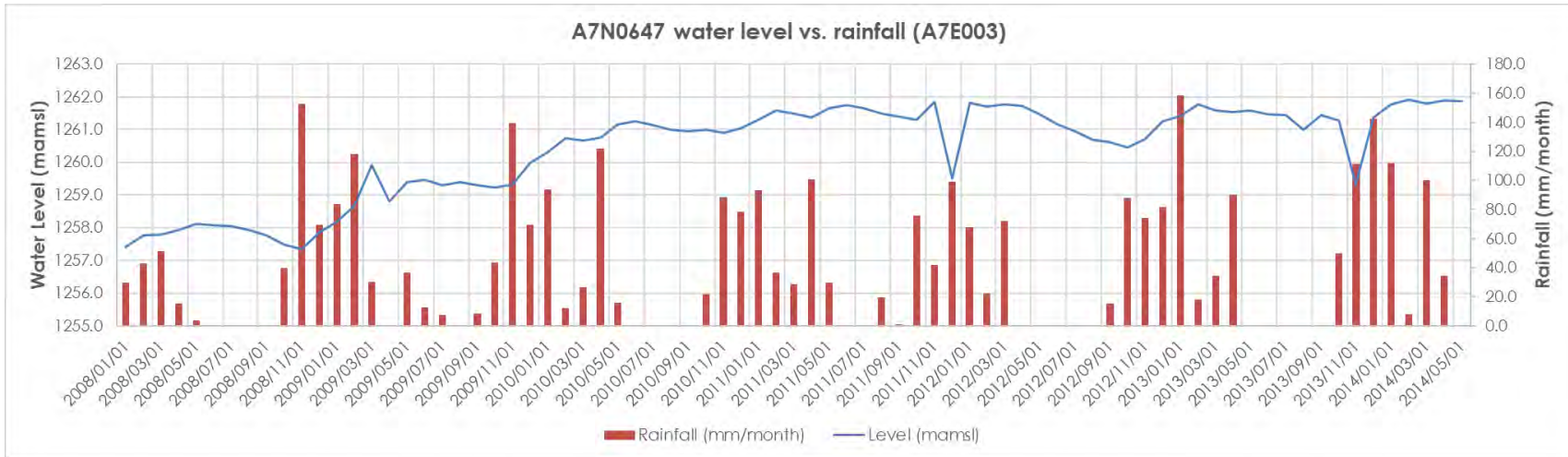
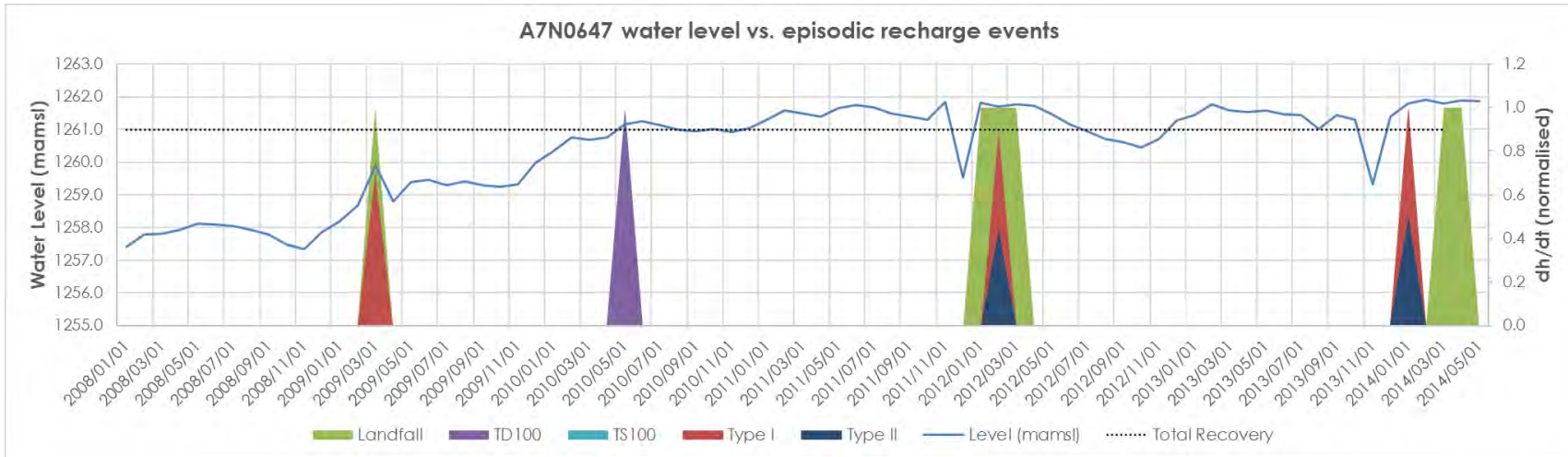
10.18 Borehole A7N0642



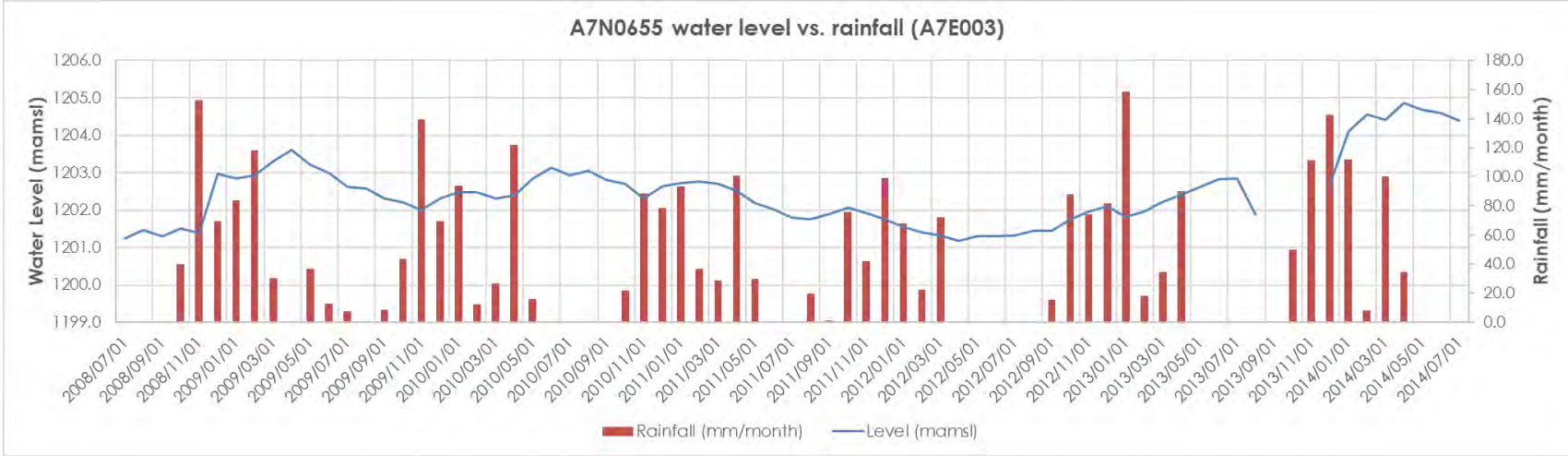
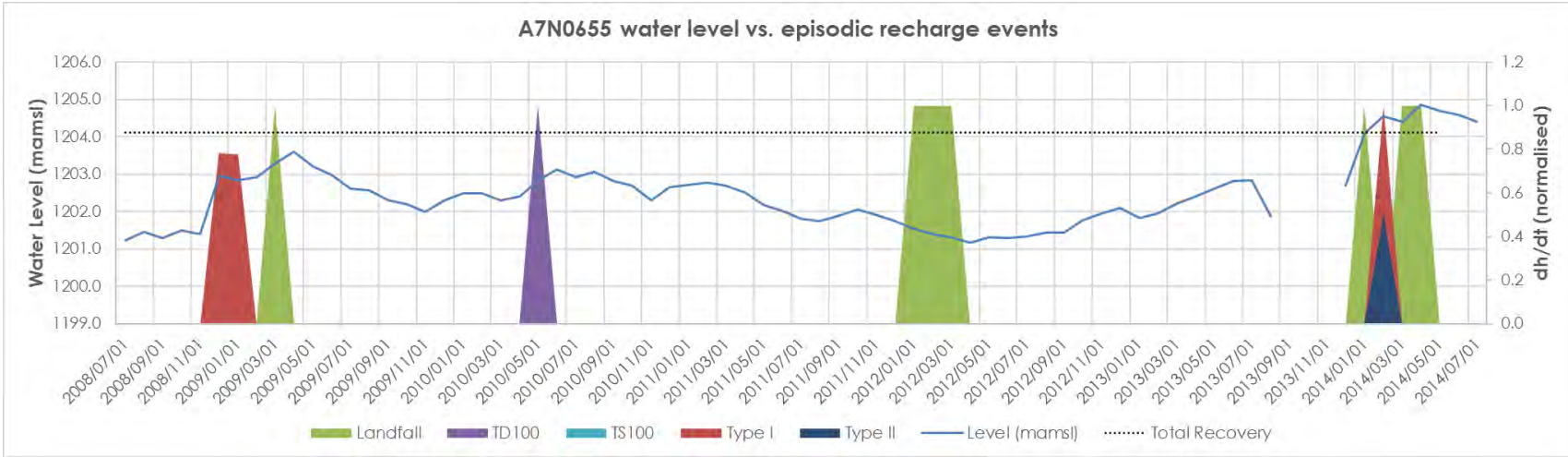
10.19 Borehole A7N0646



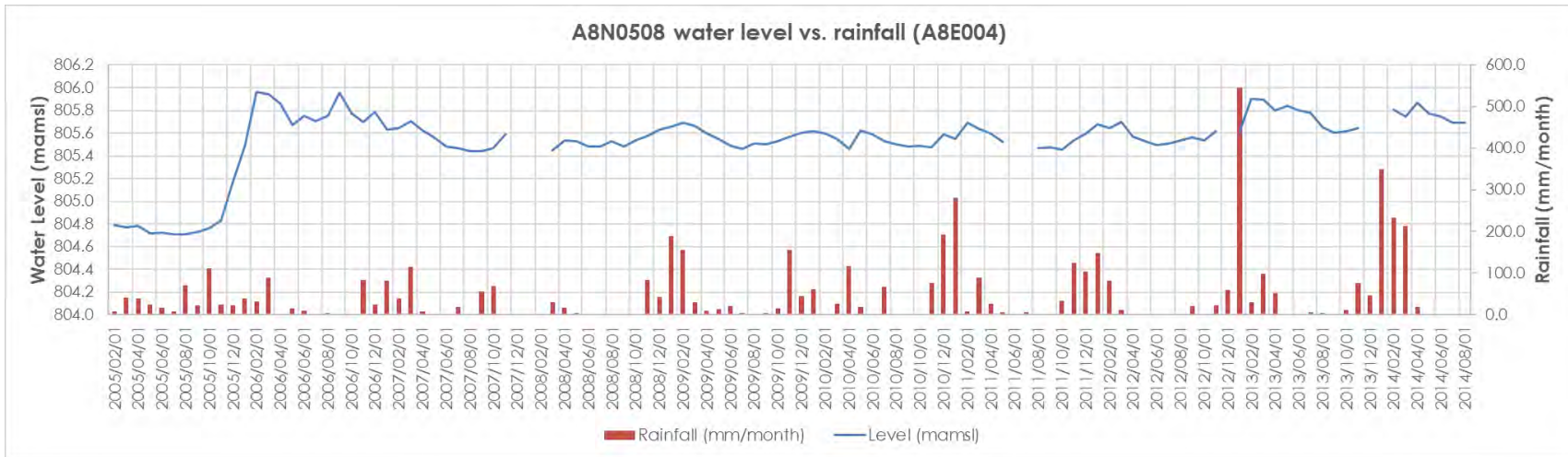
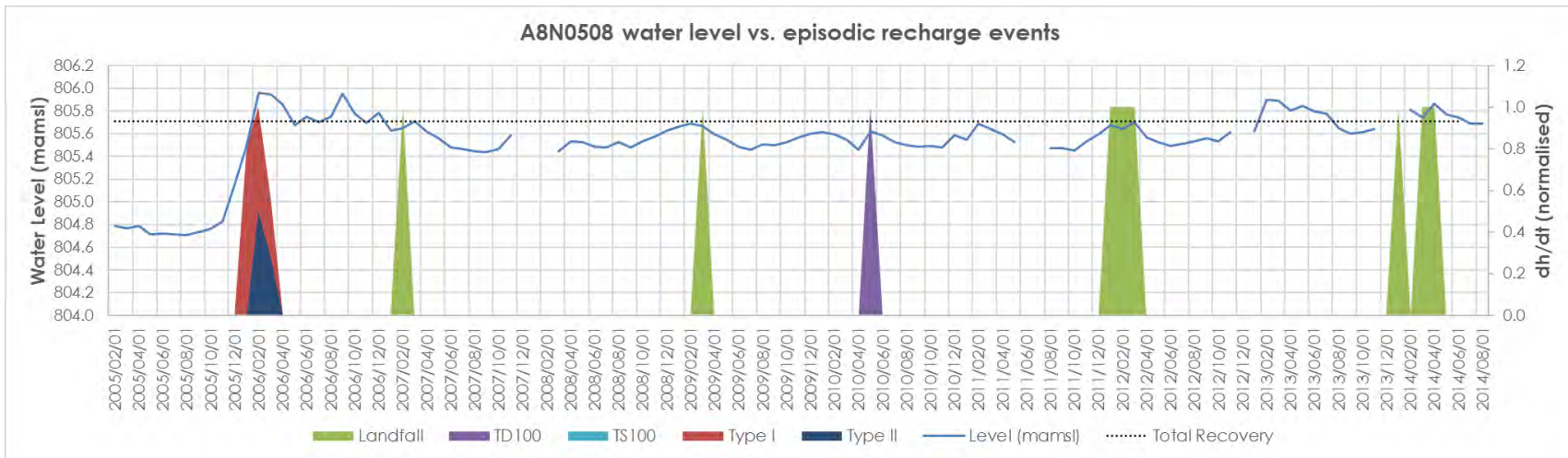
10.20 Borehole A7N0647



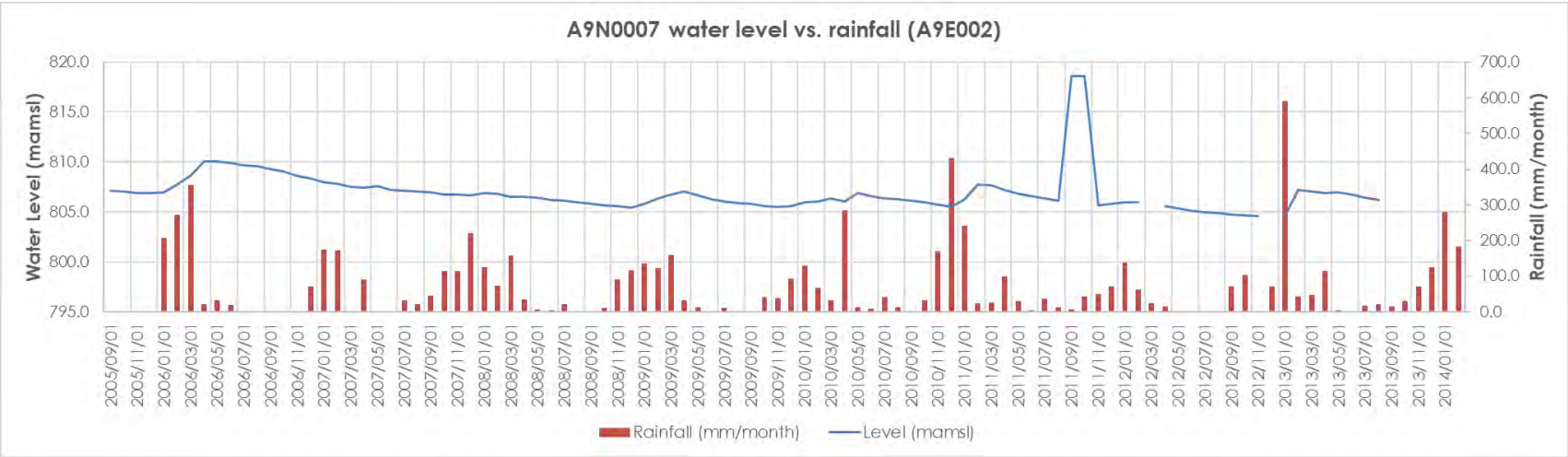
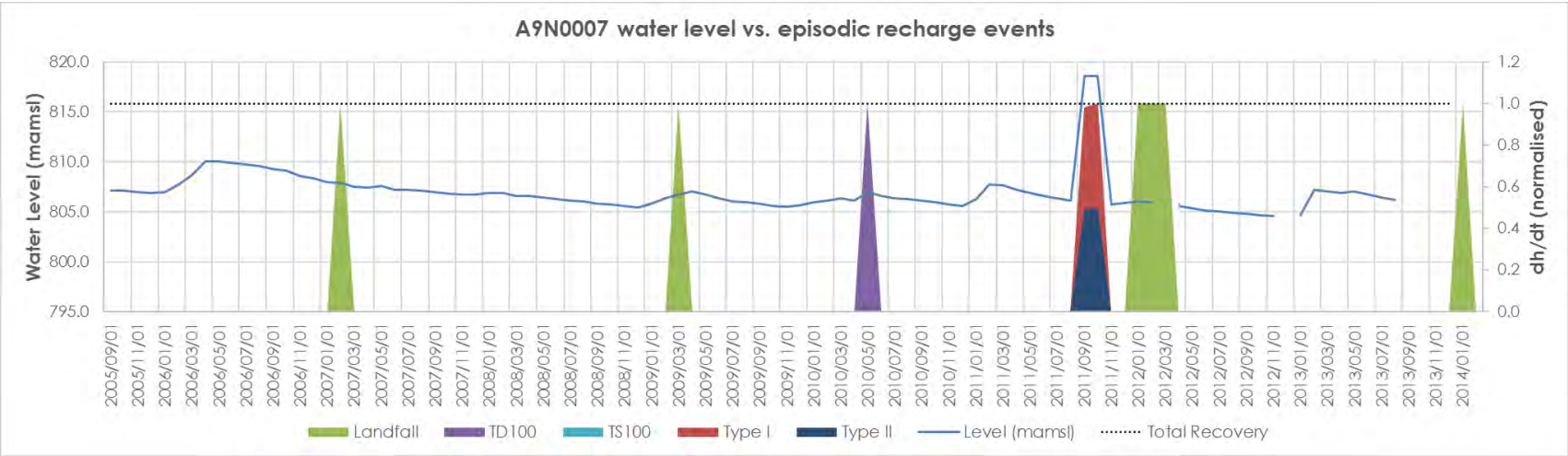
10.21 Borehole A7N0655



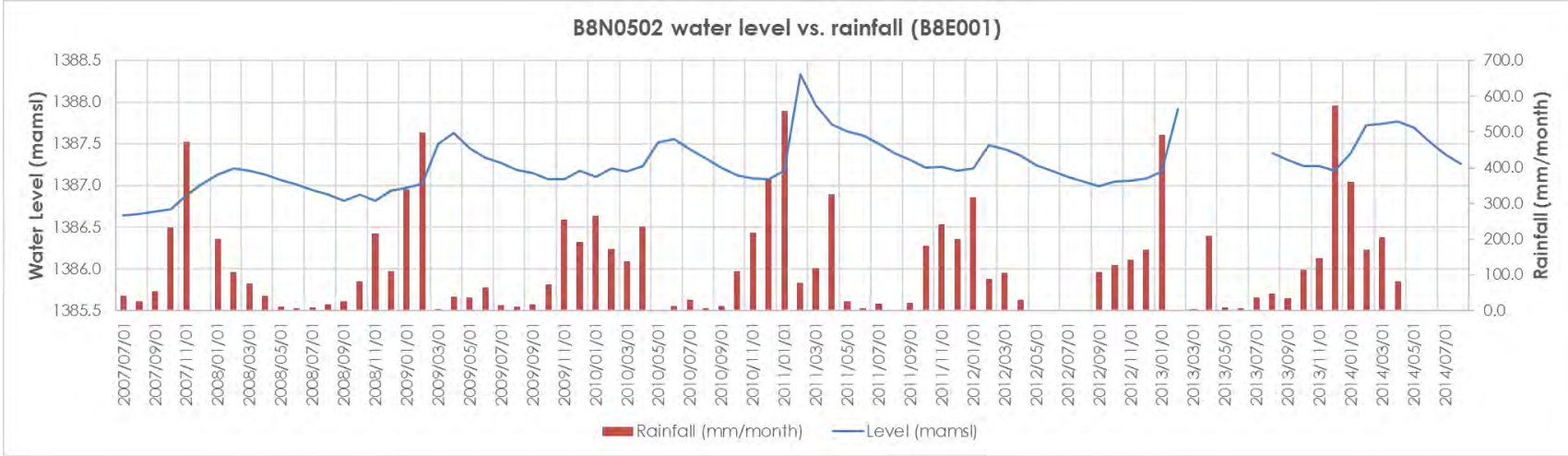
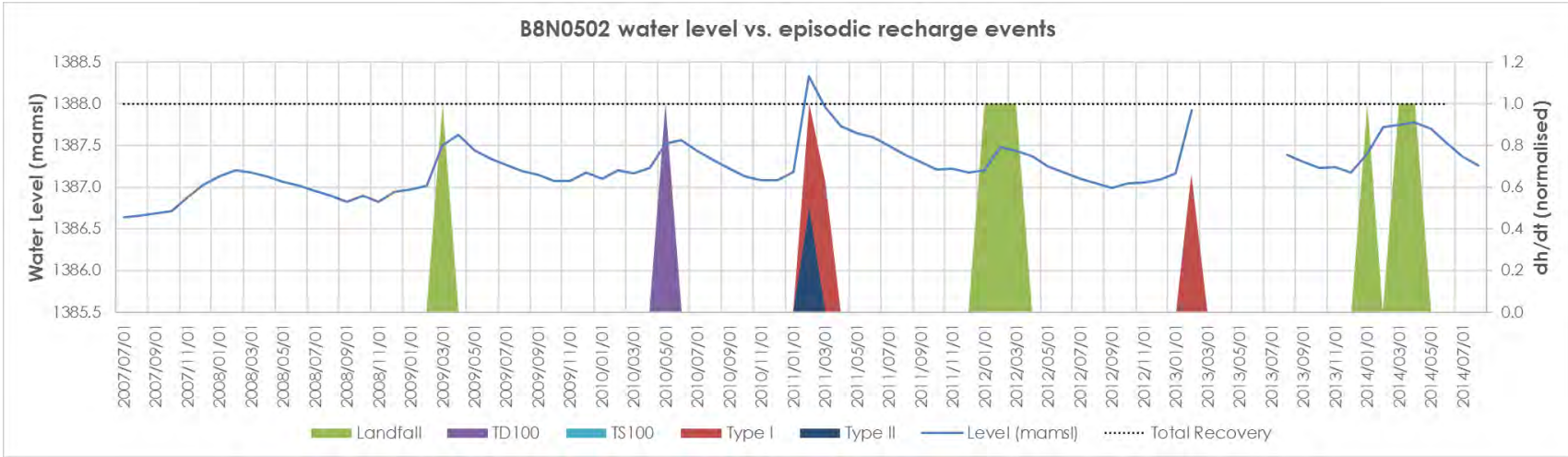
10.22 Borehole A8N0508



10.23 Borehole A9N0007



10.24 Borehole B8N0502



10.25 Borehole B8N0514

