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Groundwater Resources Assessment: Gagil-Tomil, Yap State, Federated States of Micronesia

Aminisitai Loco, Andreas Antoniou, Anesh Kumar, Nicholas Metherall, Peter Sinclair

North Pacific Readiness for El Niño (RENI) project

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Contents

List of acronyms

CTD	conductivity, temperature and depth loggers
EPA	Yap State Environmental Protection Authority
ERT	electrical resistivity tomography
EU	European Union
FMI	Fisheries and Marine Institute
GEM	Geoscience, Energy and Maritime Division of the Pacific Community
GTWA	Gagil-Tomil Water Authority
NFS	Yap State National Fire Service
RENI	European Union-funded Readiness to El Niño Impacts project
SPC	Pacific Community
WHO	World Health Organization
YSPSC	Yap State Public Service Corporation
YSSC	Yap State Sports Complex

Abbreviations of units of measurement

cm/d	centimetres per day
Fe	Iron
gal	gallons
gpd	gallons per day
gpm	gallons per minute
in	Inches
L/day	litres per day
L/s	litres per seconds
in	Inches
mg/L	milligrams per litre
Mg	Magnesium
Mn	Manganese
m	Metres
mm	Millimetre
mmol/L	millimoles per litre
Ohm.m	Ohm metre
gal/p/day	gallons per person per day

Conversion factors - imperial to metric units

feet to metres	0.3048
metres to feet	3.2808
inches to millimetres	25.4
millimetres to inches	0.03937
miles to kilometres	1.6093
US gallons to litres	3.7854
US gallons per day per foot to meter squared per day	0.01242

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- Yap Environmental Protection Agency
- Yap State Public Service Corporation
- Gagil-Tomil Water Authority
- Yap Weather Service Office – National Oceanic and Atmospheric Administration
- Division of Public Safety – Yap Fire Service
- Department of Planning and Budget
- the Pacific Community's RENI Project team staff

We would also like to thank the communities of Gagil and Tomil who accommodated the disruptions to their water supply during the time of the investigations.

Executive summary

A groundwater investigation conducted in the Gagil-Tomil area in Yap State, Federated States of Micronesia between 20 September and 12 October 2019, forms part of the European Union – North Pacific Readiness for El Niño (RENI) project. The aim of the RENI project is communities working to secure food and water resources ahead of future droughts.

The groundwater investigation, undertaken by the Pacific Community at the request of the Yap State Government, focused on assessing the impact of abstraction from the existing water supply production bores on the aquifer of Central Tomil. The objective was to provide technical guidance to government and water supply operators on the operation and future development of the Gagil-Tomil aquifer, for improved water security.

Production bores located in the Monguch and Eyeb valleys abstract groundwater from the Gagil-Tomil aquifer system. Abstraction occurs from production bores constructed in two separately administered wellfields, the Gagil-Tomil Water Authority (GTWA) wellfield of Monguch Valley, and the Yap State Public Service Corporation (YSPSC) wellfield of Eyeb Valley.

Concerns were raised by both GTWA and YSPSC on the potential impact of abstraction between wellfields when both are operational, and the impact on the aquifer, especially during extended dry periods and drought.

The basement rocks of Yap Proper are largely metamorphic, dominated by greenschist and amphibolites, referred to as the Yap Formation. The younger Tomil Volcanics unit includes deeply weathered andesitic tuffs and volcanic breccias and is the main water-bearing unit with both structurally controlled primary porosity of fractures, and secondary porosity in the weathered tuffs and breccias.

Assessment of potential abstraction impact

Two pumping test programmes were designed with GTWA and YSPSC to determine the impact of abstraction:

- from the YSPSC wellfield on the Gagil-Tomil aquifer, and potential impact on GTWA wellfield; and
- on the Gagil-Tomil aquifer when both GTWA and YSPSC wellfields are abstracting groundwater.

Both pumping tests abstracted groundwater from existing production bores at a constant rate over predefined time periods to measure the subsequent stress on the aquifer. The first pumping test involved pumping all production bores in the YSPSC wellfield for a continuous 48-hour period using the current pumping rates, while groundwater level response was recorded in all available pumping wells and monitoring bores to assess the potential impact of pumping by the YSPSC wellfield on the GTWA wellfield. The second pumping test, over a 72-hour period, examined the impact on the aquifer from the combined continuous abstraction from production bores, in both the YSPSC wellfield and the GTWA wellfield.

The subsequent analysis of the pumping test data indicates that:

1. The weathered and fractured aquifer in Eyeb and Monguch valleys has the capacity to provide usable and appreciable high-quality groundwater for water supply purposes.
2. The production bores for both GTWA and YSPSC abstract groundwater from a connected aquifer system.

3. No discernible impact was observed on the GTWA wellfield from the YSPSC wellfield during the continuous 48-hour pumping test from production bores at the current abstraction rate.
4. Monitoring bores (M4 and M5) close to the YSPSC production wells demonstrate an impact from YSPSC abstraction.

Groundwater chemistry

To further assist the understanding of the groundwater system and confirm the connectivity between wellfields, groundwater chemistry sampling and the analysis of major cations and anions was conducted from selected production bores in the two wellfields. Eight groundwater samples were collected from all pumping wells (five samples from Eyeb Valley and three samples from Monguch Valley) and compared with the results of historical sampling undertaken in streams and pumping bores.

While there is some variability within the groundwater analysis in response to water and rock interactions, the groundwaters are predominantly Ca-Mg-HCO_3, consistent with the geology expected to be found in the Tomil Volcanics. Increased magnesium (Mg) enrichment was observed in samples that were influenced by the underlying Yap Formation. Sampling and analysis of the production wells indicate similar geochemistry, which further supports the connectivity of the groundwater being from the same aquifer for both the GTWA and YSPSC wellfields.

The stream sample analysis from Shade et al. (1992) shows that groundwater from both the Tomil Volcanics and the Yap Greenschist Formation contribute to the surface water chemistry, suggesting the important contribution of groundwater to surface water flows.

Long-term monitoring

Pressure transducer-type loggers were installed in each of the five monitoring bores to record the changes in water level at these locations over time. The data from these loggers provided a valuable insight into the long-term impacts of climate variability and, potentially, the long-term groundwater abstraction from production bores on the Gagil-Tomil aquifer of the Monguch and Eyeb valleys. The available data from the period October 2019 to April 2020 (six months) indicate the following:

1. A steady and gradual decline of the groundwater level in all monitoring bores during the six-month period in response to reduced rainfall and meteorological drought conditions, indicates the Gagil-Tomil aquifer behaves as a leaky aquifer system.
2. Groundwater levels indicate a rapid response to recharge (1–2 days), followed by a decline in water levels over the following 7–10 days to a state and/or level that is considered in natural equilibrium with the local environment, indicating rapid discharge response to groundwater-fed springs and streams in the Monguch and Eyeb valleys following high rainfall events.
3. Long-term monitoring of the available monitoring bores with loggers is important in order to assist in determining the long-term sustainability of the aquifer, and for future operational management.

Future water resource potential

Electrical resistivity geophysics indicated the potential for future development of the aquifer. The survey locations, selected in consultation with GTWA and Environmental Protection Authority (EPA) staff, considered current and forecasted water demands, accessibility of sites and existing infrastructure.

The geophysical surveys identified two potential groundwater drilling sites near the Yap State Sports Complex. Confirmation of groundwater potential will require drilling at target locations to depths of 40 m, followed by pumping tests to determine the long-term abstraction rate.

- Site 1 was located within the Yap State Sports Complex, identified as a subvertical zone of low resistivity, suggesting a groundwater-bearing fractured system within the Tomil Volcanics.
- Site 2 was identified as a zone of moderate to highly fractured volcanics, opposite the sports complex.

Water resource management improvement options

During periods of extended dry conditions and drought there is potential for introducing water conservation through rationing water to specific distribution sectors on a rotating basis. Consideration should be given to assessing the feasibility of shutting down certain sections of pipeline to limit flow to a specific distribution sector, for a scheduled period, while maintaining flow to other areas. The total volume of water abstracted from the wellfield would be reduced while pressure in the pipeline would be maintained. This is likely to also require investigation into leakage of existing distribution pipelines and some remedial work to be effective.

There is also potential to abstract a larger volume of groundwater in the days after a significant rainfall event, when discharge from groundwater to streams is high. Initial analysis suggests that groundwater discharges for a period of up to 10 days after a significant rainfall event. Consideration could be given to investigate the cost-effectiveness and feasibility of capturing a portion of the discharging groundwater following a large rain event. This action would require additional storage, the identification of trigger levels from rainfall and water level responses, and additional production bores to optimise abstraction during this period.

Establishing a formalised committee to address water resource management and water supply issues will improve coordination, access to resources, and the sharing of relevant information among stakeholders. Such a forum would promote the understanding of the water resources system behaviour under different climatic and anthropogenic conditions, and improve the management and operation of the groundwater system, which is heavily relied upon.

Recommendations

- Monitoring
  - Production bores from YSPSC and GTWA
    - weekly pumping records of production wells,
    - operation of pumps,
    - pumping rates and volumes abstracted,
    - water levels and salinity measurements.
  - Monitoring bores YSPSC, GTWA and EPA
    - monthly manual readings of all monitoring bores, water levels and salinity.
- Establish a committee with scheduled meetings to review and assess the available data and to provide advice to water authorities, government and the community on the operation, management and protection of the wellfields.
- Establish a new automatic rain gauge station at GTWA site.
- Leakage detection program for the GTWA and YSPSC distribution system and replacement of ageing pipeline infrastructure.

- Consider drought response and water conservation actions, including reduced abstraction from the wellfields where monitoring indicates sustained drawdown. This may include rationing abstracted water through scheduled, rotating and short-term section shutdowns within the distribution network during droughts.

Sampling of all GTWA and YSPSC production bores during a drought and analyse samples for dissolved iron (Fe) and manganese (Mn) to identify potential impacts on water quality during droughts.

1. Introduction

As part of the European Union – North Pacific Readiness for El Niño (RENI) project, the Pacific Community (SPC) investigated the potential impact between wellfields on the Gagil-Tomil aquifer in Yap State, Federated States of Micronesia (FSM). Groundwater pumping tests, installation of water level loggers in monitoring bores, and electrical resistivity were employed to better understand the impacts of groundwater abstraction occurring in the Tomil Volcanics, and to identify additional groundwater sources in the Gagil-Tomil areas. The investigations focused on two adjacent valleys, Monguch and Eyeb valleys, where groundwater abstraction is currently undertaken for public and municipal water supply by two separately operated water authorities, the Gagil-Tomil Water Authority (GTWA) in Monguch Valley and the Yap State Public Service Corporation (YSPSC) in Eyeb Valley.

1.1 Project background

The 2015–2016 El Niño-driven drought caused major disruptions to food and water security across the northern Pacific region, and triggered declarations of emergency by a number of northern Pacific countries, including the Republic of Marshall Islands, FSM and the Republic of Palau. The European Union responded with a "Pro-Resilient Special Measure" to assist affected populations. The RENI project, with a total funding of EUR 4.5 million, currently implemented by SPC, was a component of this special measure to assist affected populations in those three countries by strengthening food and water resources to withstand upcoming drought events. Key project outputs include:

1. Uptake of key individuals and community behaviours that support resilience to El Niño climate phenomena.
2. Local area structural measures implemented to support El Niño resilience-building in water and food security, with special consideration for the rights of women and vulnerable groups in outer islands.
3. National measures – institutional, planning and technical – implemented to support readiness to future El Niño events.

1.2 Investigation objectives

The groundwater investigation of the Gagil-Tomil wellfields links to output 3 of the RENI project, by providing technical assistance to government and water operators alike to support readiness to future El Niño events, as well as Yap State's aspiration to secure its water resources ahead of future drought events. The investigations focused on the highly productive Gagil-Tomil aquifer with the following objectives:

1. Assess the impact of abstraction from the existing water supply production bores on the aquifer, and provide guidance on the current and future operations and development, for improved water security, especially during droughts.
2. Investigate new and additional groundwater sources within the Tomil Volcanics to either provide supplementary water sources around the GTWA, or act as an emergency water supply during natural disasters.

2. Background of Tomil and Gagil area

2.1 Geography and land use

Yap is one of FSM's four states. It is located between 7° and 10° N latitude and between 137° and 148° E longitude in the northwestern Pacific Ocean. The four FSM states from west to east include Yap, Chuuk, Pohnpei and Kosrae (Fig. 1).

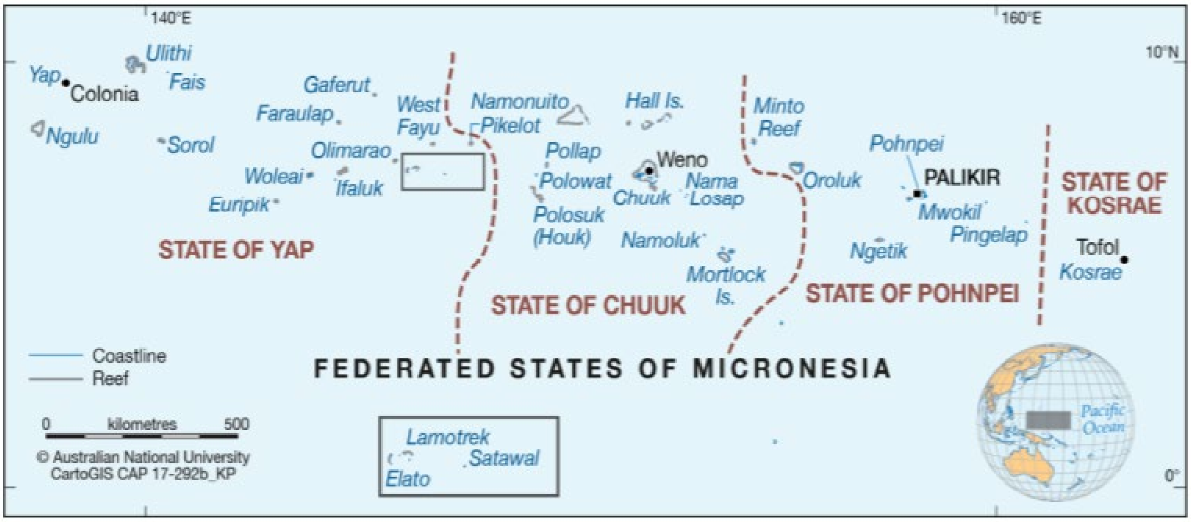

Figure 1. Location of Yap State at the western end of the Federated States of Micronesia, with Yap Island located in the northwest. Source: https://www.adb.org/sites/default/files/project-documents/49450/49450-023-iee-en.pdf

Yap State consists of 134 islands and atolls, with a total land area of 102 km^2, 22 of the islands being populated. Yap's four large islands Yap, Maap, Tomil and Rumung – make up what is widely known as "Yap Proper" (Fig. 2). These main islands, except Rumung, are connected by a road network.

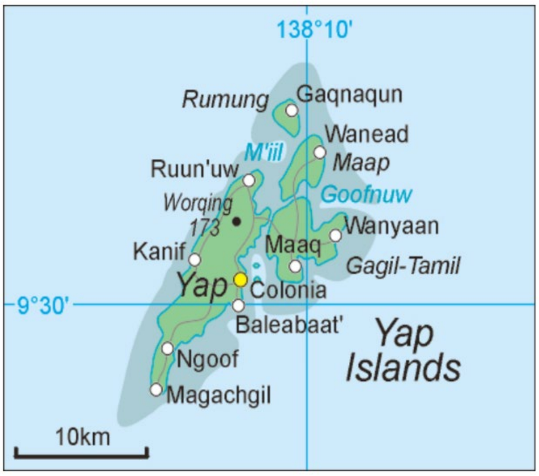

Figure 2. Map of Yap Island showing the major areas in Yap Proper. Source: FSM 2016

Yap Proper's landscape is characterised by gently sloping uplands surrounded by swampy lowlands (FSM 1997). Land use change has seen large areas of natural forest cover converted into agroforestry and secondary vegetation (FSM 1997). Frequent wildfires in the dry season as seen in 1997/1998 have prevented regrowth of primary forest leading to extensive human-induced grasslands in the highland areas (FSM 2016). In the lowland and swampy areas, overharvesting of mangrove forest have also occurred in some localities in Yap (FSM drought report 1997). Yap's main business centre is Colonia, which is also the state capital. Colonia is part of the Weloy in the central–eastern part of Yap Island, and located between the state airport in Rull and Tomil. This mission, however, focuses on the area around Gagil-Tomil.

2.2 Climate and rainfall analysis

Because of its position in the northwestern Pacific, FSM's climate is largely influenced by the occasional northward shift of the Intertropical Convergence Zone, the periodic contribution from the western monsoon and interannual rainfall variations driven by El Niño-South Oscillation conditions, be it El Niño or La Niña (Fig. 3) (Australia's Bureau of Meteorology and CSIRO 2011). Fletcher and Richmond (2010) documented that the wet season in FSM occurs from May to September when the Intertropical Convergence Zone is strongest and farthest north, and where additional rain is also brought by the West Pacific Monsoon affecting FSM's western states. Very high rainfall periods are always experienced during La Niña periods, which usually result in flooding and storm surges around low-lying areas. The dry months are between November and April, with an increasing trend in temperature observed in western areas.

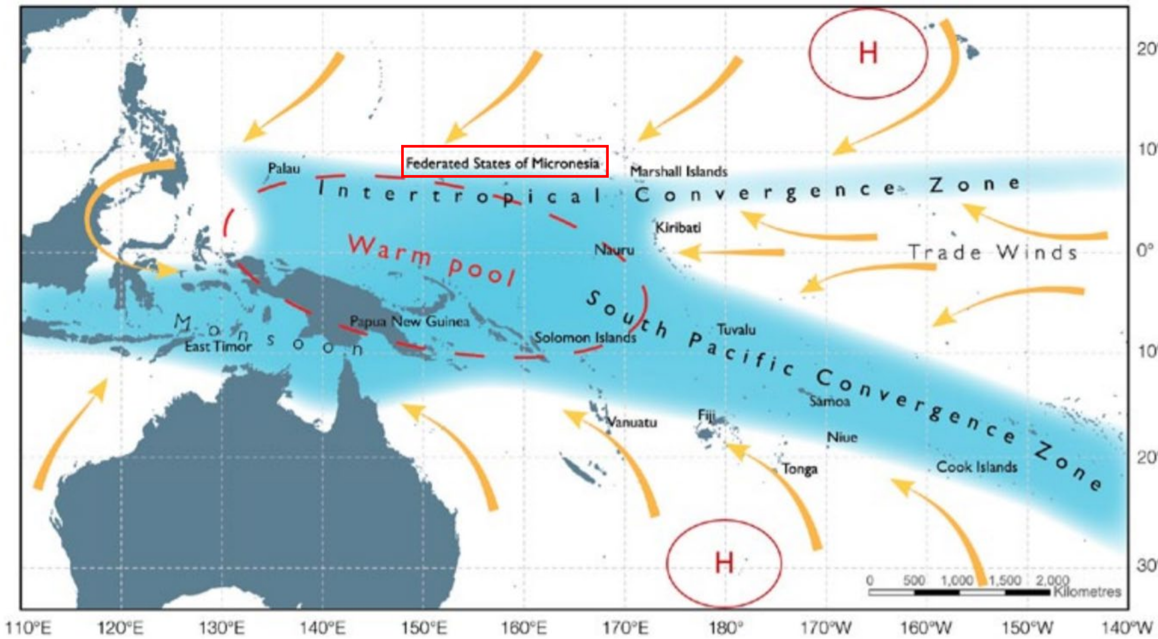

Figure 3. Features that influence the climate in the Federated States of Micronesia climate. Source: BOM and CSIRO 2011

2.2.1 Rainfall analysis

Rainfall data for the period 1949–2019 show a mean monthly and annual rainfall of 10.12 in (257 mm) and 121.73 in (3092 mm), respectively (Yap Weather Service Office 2020). In terms of seasonal rainfall variability, the dry months from November to April receive an average monthly rainfall of 7.44 in (189 mm), while the wet season receives a monthly average of 12.75 in (324 mm), suggesting that more than 60% of the annual rainfall is recorded between May and October (Yap Weather Service Office 2020).

Table 2 shows a significant contrast in seasonal and monthly variabilities of rainfall. This variability is expressed by the coefficient of variation (CV), where dry months show high variability compared with wetter months. Interestingly, the estimated CV for the month of May, although known to be a wet month, is high, suggesting that the effect of the preceding dry months or low rainfall periods may extend into May and, hence, the start of the rainy season is likely to be delayed. Nance (1979) reported that in extremely dry years, drought periods may be extended by one or two months either before, after, or before and after, which suggests the variability of dry periods and supports the high CV recorded in May.

The long-term climate and rainfall records have also recorded rainfall fluctuations, including a number of years of very low rainfall such as the 1997/1998 and the 2015/2016 drought events. In terms of spatial climate variability, Yap – the westernmost FSM state – is likely to be affected earlier and more extensively than FSM's eastern states (FSM 1997).

Table 1. Rainfall station metadata for Yap Proper. Source: https://xmacis.rcc-acis.org

Rainfall station name	Latitude/Longitude*	Elevation (m)	Record start date	Record end date	Data coverage
Tamil	9.55°, 138.15°	21.3	1/6/1991	current	86%
Maap	9.60528°, 138.17861°	14.9	1/6/1991	30/4/2012	97%
Rumung	9.62444°, 138.15917°	19.8	1/10/1993	current	92%
North Fanif	9.57417°, 138.11083°	3.0	1/11/1993	current	91%
Dugor	9.53667°, 138.12111°	20.1	1/8/2000	current	89%
Yap WSO –	9.48333°, 138.08333°	13.4	3/11/1941	current	88%
Gilman	9.45083°, 138.06194°	15.2	1/11/1997	current	90%
Luweech	9.48333°, 138.08333°	10.1	1/6/1987	current	

*Coordinate location may not be accurate; WSO = Weather Service Office

Table 2. Monthly rainfall statistics for Yap Island from 1949 to May 2019. Source: Yap State Weather Service Office

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average monthly rainfall (mm)	200.8	146.6	150.7	153.7	230.5	308.5	365.3	377.0	353.9	318.5	239.7	245.0	3092.4
Maximum (mm)	586.2	487.4	418.1	461.0	562.4	813.1	881.6	747.8	640.1	569.7	524.8	683.0	4171.7
Minimum (mm)	31.8	6.9	13.7	5.3	37.3	86.4	126.7	130.3	135.1	65.8	49.8	56.4	2256.5
Standard deviation (mm)	119.4	98.0	90.2	95.4	121.2	121.8	123.8	135.8	106.0	121.1	97.4	108.3	456.4
Coefficient of variation[1]	0.59	0.67	0.60	0.62	0.53	0.39	0.34	0.36	0.30	0.38	0.41	0.44	0.1

[1]Standard deviation / mean rainfall

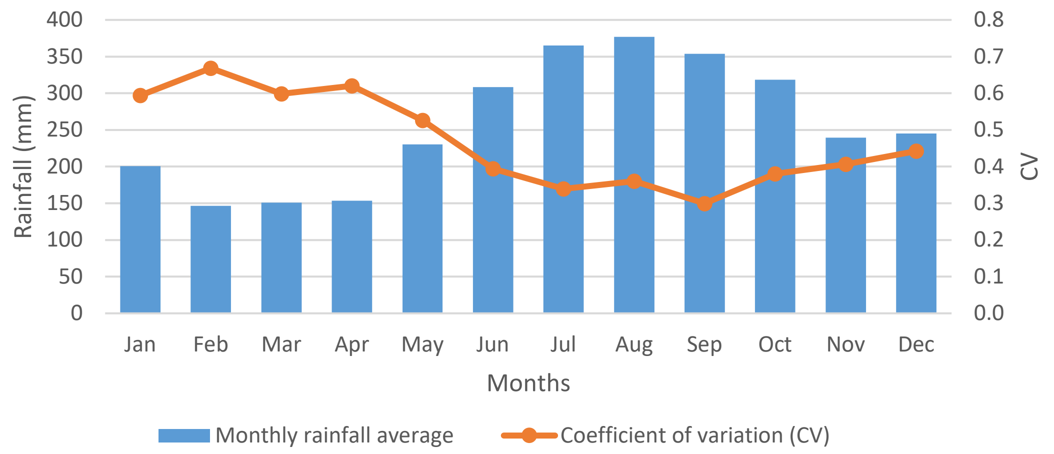

Figure 4. Mean monthly rainfall and coefficient of variation (CV) for Yap State from January 1949 to May 2019, Yap Weather Service Office – Airport.

2.2.2 Drought analysis

Rainfall data collected from Yap's Weather Service Office at the airport were reviewed using the Seasonal Outlook of Pacific Island Countries (SCOPIC) computer software. SCOPIC is a hindcast statistical analysis of rainfall. In this case, the decile approach to drought determination was used with a six-month drought index as likely to be representative of the residence time and behaviour of groundwater in the Tomil-Gagil aquifer. Table 3 indicates that neutral and El Niño ENSO conditions drive and/or influence most of the severe historical drought events in Yap.

Table 3. Summary of historical drought events in Yap using the Seasonal Outlook of Pacific Island Countries (SCOPIC) software and the six-month drought index (28 May 2020).

	All events	El Niño	La Niña	Neutral
Number of droughts	21	9	2	10
Drought length (months)	4–15	4–15	4–8	4–14
Average drought length (months)	8.3	9.6	6.0	7.6

SCOPIC identified drought events when rainfall was below the 10th percentile (i.e. within the driest 10% of all previous such six-month rainfall totals). The ranking of all historical drought events has identified the current October 2019 drought as currently the 8th worst drought on record for the six-month drought index. Table 4 summarises the historical drought records from January 1949 through April 2020 for the six-month drought index.

Table 4. Summary of the 10 worst droughts, Yap Weather Service Office – Airport, January 1949 through April 2020 (after SCOPIC accessed June 2019).

Rank	Drought period	Drought length (months)	Drought ENSO state	Rainfall during drought (mm)
1	Oct 1972 through Dec 1973	15	El Niño	2899.7
2	Nov 2015 through Nov 2016	13	El Niño	2478.3
3	Aug 1968 through Jun 1969	11	Neutral	1819.1
4	Dec 1957 through Jan 1959	14	Neutral	2893.8
5	Jan 1983 through Oct 1983	10	El Niño	1775.5
6	Dec 1997 through Sep 1998	10	El Niño	1905.0
7	Jan 1988 through Sep 1988	9	Neutral	1664.2
8	Oct 2019 through Apr 2020	8	El Niño	991.9
9	Apr 1992 through Feb 1993	11	El Niño	2396.0
10	May 1966 through Feb 1967	10	El Niño	2540.3

2.3 Population and governance

The 2010 census for FSM recorded 102,843 people in all four states. Yap's population, shown in Table 5, is recorded to be 11,043 (11% of FSM's total population), 7371 of whom live in Yap Proper while the rest reside in the outer islands. Population growth in Yap State since 1980 is 9%, while growth in Yap Proper, Gagil and Tomil are 10%, 9% and 14%, respectively, within the same period. This variability in population growth has implications for water demand and use.

Table 5. Yap State's population between 1980 and 2010. Source: FSM 2010

Year	1980	1987	1994	2000	2010
YAP STATE TOTAL	8100	10139	11178	11241	11377
Yap Proper	*5196*	*6650*	*6919*	*7391*	*7371*
Rumung	130	102	143	126	58
Maap	319	520	*547*	592	621
Gagil	616	711	716	734	863
Tomil	713	843	897	1023	1231
Fanif	392	460	462	547	509
Weloy	926	1444	1188	1197	1,031
Dalipebinaw	1436	1852	1973	2019	2095
Rull	211	262	544	645	397
Kanifay	225	276	245	275	314
Gilman	228	180	204	233	252
YAP OUTER ISLANDS	*2904*	*3489*	*4259*	*3850*	*4,006*
Ngulu	21	26	38	26	6
Sorol	7				
Ulithi	710	847	1016	773	847
Fais	207	253	301	215	294
Eauripik	121	99	118	113	114
Woleai	638	794	844	975	1039
Ifalik	389	475	653	561	578
Faraulep	132	182	223	221	193
Elato	51	70	121	96	105
Lamotrek	242	278	385	339	329
Satawal	386	465	560	531	501

Governance in Yap, and FSM in general, has four levels: national, state, municipality and community. The 10 municipalities of Yap State are shown in Table 5, and the study area is governed by the Gagil and Tomil municipalities where community leaders and representatives run and manage the development activities within the area. The drinking water use and demands for each of these municipalities was also recorded by the FSM census in 2010. It is worth noting that the population of the Gagil and Tomil are currently served by the GTWA production bores located in Monguch Valley.

2.4 Water supply systems

FSM's 2010 census recorded the main water sources for Yap municipalities. The data show that both Gagil and Tomil rely primarily on community water supplies. The GTWA wellfield is believed to pump, on average, 57,000 GPD (215,768 L/d) (Edmund Wogthuth, GTWA manager, pers. comm.). A water improvement and optimisation study in Yap State (EGIS 2016), indicated that the average amount of water pumped by GTWA is 71,000 gpd (269,646 L/day). EGIS (2016) estimated that usage per person for YSPSC distributed water is 283 L/person/day, while water usage per person for GTWA distributed water is 132 L/person/day.

Table 6. Sources of drinking water for Yap Proper households (FSM 2010).

Drinking water source	Total	Public utility water supply	Community water supply	Household tank	Water truck	Well – protected	Well unprotected	Bottled water	Spring, river, lake	Other
Yap Proper	1680	290	655	476	-	10	1	207	8	33
Rumung	20	-	13	7	-	-	-	-	-	-
Maap	140	-	62	60	-	3	-	15	-	-
Gagil	192	36	131	20	-	2	1	-	1	1
Tomil	269	62	171	29	-	-	-	1	1	5
Fanif	116	75	6	24	-	5	-	2	3	1
Weeloey	245	71	12	92	-	-	-	66	2	2
Dalipebinaw	93	8	14	51	-	-	-	16	-	4
Ruul	467	38	117	191	-	-	-	104	1	16
Kanifay	75	-	68	2	-	-	-	1	-	4
Gilman	63	-	61	-	-	-	-	2	-	-

Major water resources on Yap Island include both surface water and groundwater, which are managed and operated either by YSPSC or municipal water authorities, such as GTWA and the Maap Water Authority in the northeast, and Southern Yap Water Authority in the southwest.

Over 80% of households in Yap Proper rely on piped water from one of the four water authorities; most of this piped water is sourced from groundwater.

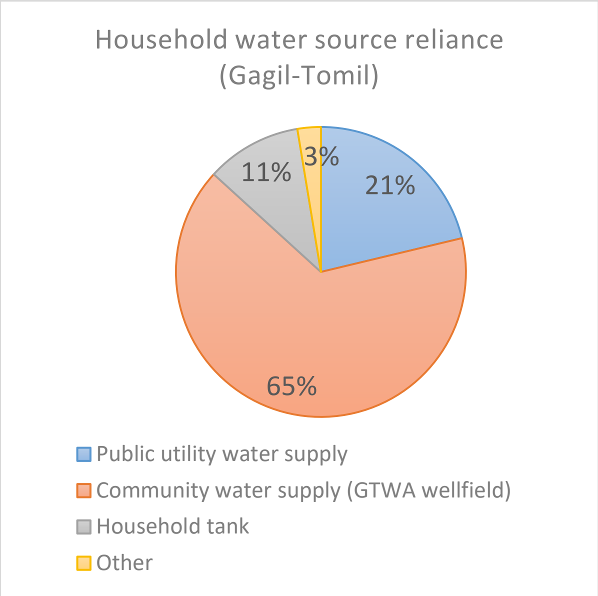

Figure 6. Household water source reliance in the Gagil-Tomil area

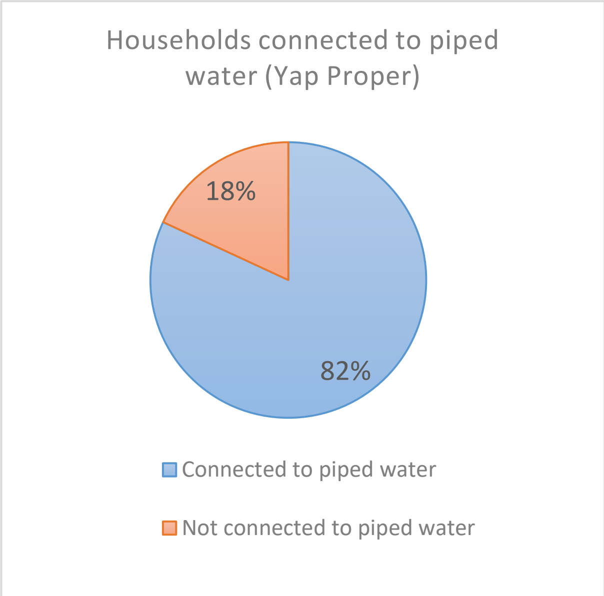

Figure 5. Household drinking water supply reliance for Yap Proper

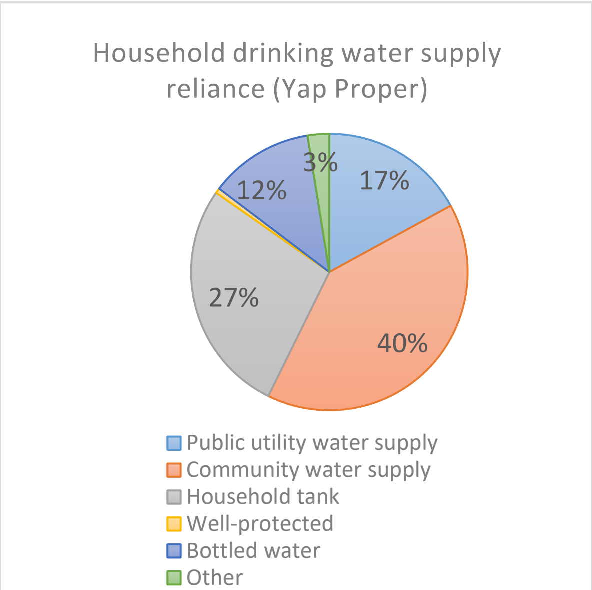

Figure 7. Household connected to piped water in Yap Proper

The GTWA wellfield relies on four wells that are pumped overnight for 6–12 hours per day. This water is distributed in pipelines 2.4 km to the east of the pumping stations, and feeds the 100,000-gal (378,500-L) tank in Gagil (GTWA Tank 1, Fig. 5) before feeding the 50,000-gal (189,250-L) Tomil tank (GTWA Tank 2, Fig. 5) located 1.2 km northwest of the pumps. The current abstraction rate suggests that 57,000 gal (215,784 L) of groundwater is produced per day. During the pumping test, the GTWA water manager mentioned that the storage tank in Gagil (GTWA Tank 1) was draining quickly, which suggests losses greater than those expected in the pipeline feeding from the wellfield to the Gagil 100,000-gal tank.

Eyeb Valley has five operating production bores managed by YSPSC, with a combined abstraction rate of 131 gpm, aggregating to a daily abstraction of 188,000 gal (711,580 L). Production bores 4 and 7 are currently offline due to high turbidity and an electrical fault, respectively. The Eyeb wellfield pumps water to the YSPSC Daobich tank before being distributed to the communities of Fanif and Weloy. Around 245,000 gpd (927,300 L/day) of groundwater are estimated to be pumped from the two wellfields to the communities. Other major users include the Yap State Sports Complex and the Fisheries and Marine Institute.

Table 7. Summary of historical wells drilled in Monguch (Nance 1982).

Original well name	Primary water-bearing formation	Elev. at mean sea level ft (m)	Diam. in (mm)	Total depth ft (m)	Depth of pump below top of casing ft (m)	Design pumping rate GPM (L/s)	Current status
Monguch 1	Tomil Volcanics	19.5 (5.94)	12 ½ (317.5)	100 (30.48)	40 (12.19)	30 (1.9)	Replacement bore drilled in 2012 outside the GTWA office with the new total depth of 150 ft (45.72 m) and site elevation of 34.12 ft (10.4 m) above mean sea level.
Monguch 2	Tomil Volcanics	24.8 (7.56)	12 ½ (317.5)	95 (28.96)	70 (21.34)	30 (1.9)	Replacement bores drilled in 2012 – still serving as production well.
Thilung 1	Tomil Volcanics	26.7 (8.14)	12 ½ (317.5)	116 (35.4)	90 (27.43)	30 (1.9)	Replacement bores drilled in 2012 – still serving as production well.
Thilung 2	Tomil Volcanics	33.3 (10.15)	12 ½ (317.5)	103 (31.4)	75 (22.86)	30 (1.9)	Production well - not working due to pump malfunction.
Dorfay 4”	Tomil Volcanics	27.6 (8.41)	4 (101.6)	95 (28.96)		15 (0.8)	Current observation bore
Dorfay 6”	Tomil Volcanics	29.3 (8.93)	6 (152.4)	170 (51.8)			Test hole now abandoned
Mukong	Soft coral	23.8 (7.19)	12 ½ (317.5)	118 (35.9)	85 (25.91)	30 (1.9)	Test hole now abandoned
Monguch test hole	Tomil Volcanics	39.7 (12.1)	3 (76.2)	96 (29.26)			Test hole now abandoned
Test hole 1	Tomil Volcanics	50 (15.24)	8 (203.2)	48 (14.63)			Test hole now abandoned
Test hole 2	Tomil Volcanics	30 (9.14)	8 (203.2)	80 (24.38)			Test hole now abandoned
Test hole 3	Tomil Volcanics	20 (6.1)	12 (304.8)	90 (27.43)			Test hole now abandoned
Test hole 4	Tomil Volcanics	25 (7.62)	8(203.2)	70 (21.34)			Test hole now abandoned

Table 8. Summary of GTWA production bores (2012 Asian Development Bank-funded water supply expansion and rehabilitation project).

Well name	Elev. at mean sea level ft (m)	Well diam. in (mm)	Total well depth ft (m)	[1]Static water level ft (m) Sept 2019	Length of blank casing ft (m)	Length of perforated screen ft (m)	Depth of pump below top of casing ft (m)	Design pumping rate GPM (L/s)	Current status
GTWA B1	35.3 (10.75)	6 (152.4)	111.56 (34.0)	7.28 (2.21)	81.56 (24.86)	30 (9.14)	40 (12.19)	94 – combined (5.9)	B1 not operational
GTWA B2	28.7 (8.75)	6 (152.4)	116.98 (35.66)	3.35 (1.02)	96.98 (29.56)	20 (6.1)	70 (21.34)		Operational
GTWA B3	27.1 (8.26)	6 (152.4)	96.5 (29.41)	3.1 (0.94)	76.5 (23.31)	20 (6.1)	90 (27.43)	57 (3.6)	Operational
GTWA B4	34.12 (10.4)	6 (152.4)	150 (45.72)	8.94 (2.725)	60 (18.29)	80 (24.38)	75 (22.86)	60 (3.8)	Operational

[1]SWL – all depths relative to ground level; SWL @ 29 September 2019

Table 9. Summary of YSPSC production bores.

Well name (drilled circa 2000)	[1]Approx. elev at mean sea level ft (m)	Well diam. in (mm)	Total well depth ft (m)	[2]Static water level Sept 2019 ft (m)	Pump setting depth ft (m)	Design pumping rate GPM (L/s)	Current pumping rate GPM Sept 2019 (L/s)	Draw-down level - 8 April 2019 ft (m)	Available water above pump intake April 2020 ft (m)
YSPSC P1	NA	6 (152)	157 (47.8)	NA	108 (32.9)	13 (0.8)	13 (0.8)	NA	NA
YSPSC P2	27.2 (8.3)	6 (152)	124 (37.8)	7.4* (2.26)	107 (31.1)	85–100 (5.4–6.3)	66 (4.2)	78.75 (24.00)	28.25 (7.1)
YSPSC P3	35.8 (10.9)	6 (152)	110 (33.5)	7.2* (2.19)	96 (29.3)	20–25 (1.3–1.6)	16 (1.0)	53.25 (16.23)	42.75 (13.07)
YSPSC P4	Production bores was decommissioned due to water quality issue and is now inaccessible								
YSPSC P5	55.1 (16.8)	6 (152)	96 (29.3)	4.2* (1.27)	81 (24.7)	20-25 (1.3–1.6)	19 (1.2)	74.46 (22.70)	6.54 (2.0)
YSPSC P6	55.4 (16.9)	6 (152)	82 (25)	16.4* (5.0)	79 (24.1)	20-25 (1.3–1.6)	14 (0.9)	76.04 (23.18)	2.96 (0.92)
YSPSC P7	49.9 (15.2)	6 (152)	85 (25.9)	5.09 (1.55)	79 (24.1)	20-25(1.3-1.6)	NA	NA	NA

[1]Approximate elevation based on GPS data referenced to known elevation point (+/- 2 m).
[2]SWL – all depths relative to ground level; *Max recovery test 24 hours @29 September 2019

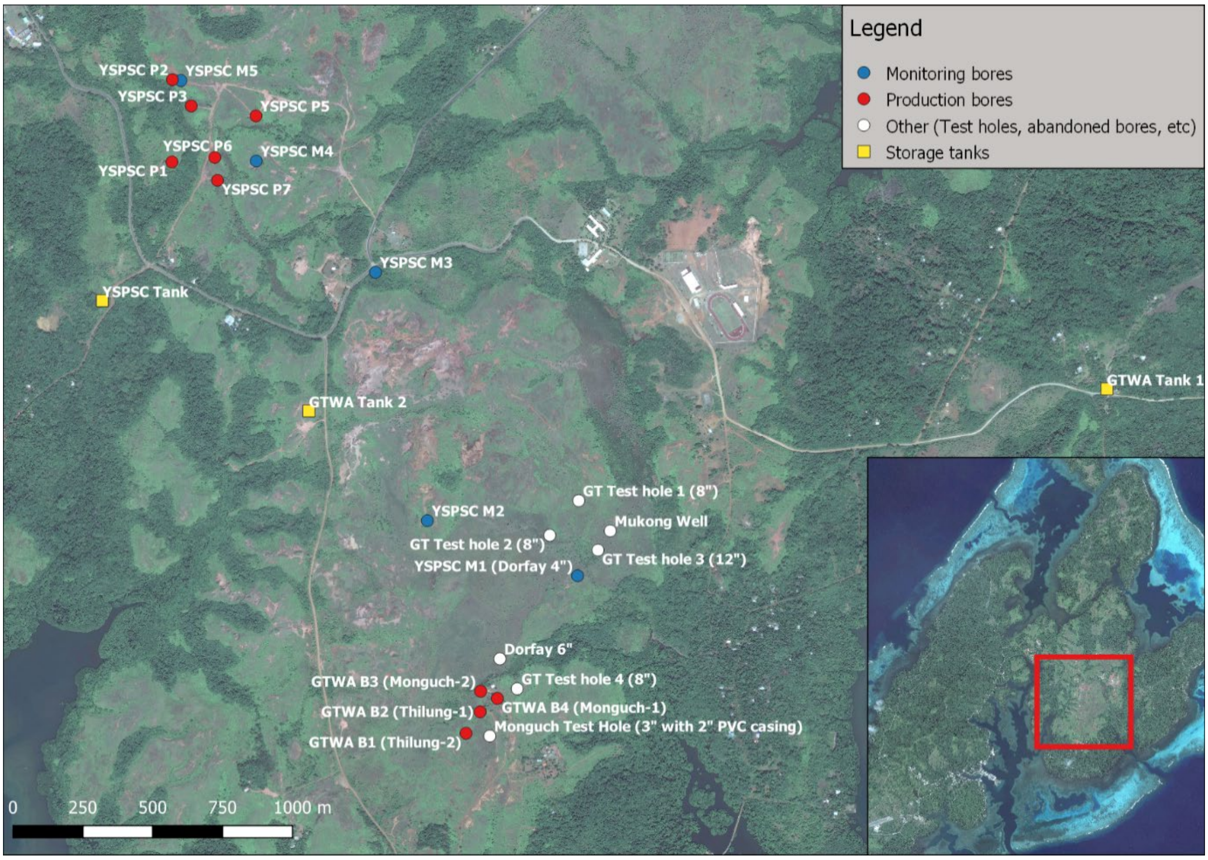

Figure 8. Location of groundwater bores, monitoring wells and tanks within the Gagil-Tomil aquifer area. Source: Bing maps

2.5 Geology and hydrogeology

- Yap Island is composed of five major geological units: Yap Formation, Maap Formation, Tomil Volcanics, alluvium and mangrove swamp deposits (Shade 1992; Munetomo et al. 2001). The composition of these geological formations is described below. The basement Yap Formation is dominated by greenschist comprising pre-Miocene metamorphosed mafic-ultramafic and calc-alkaline volcanic rocks having clinopyroxene, associated with olivine, orthopyroxene, plagioclase and magnetite and amphibolite. In the study area, green schist and amphibolite are exposed around the hills, east and west of the Tomil Volcanics.
- The Maap Formation is composed of fragmental rock of tectonic and sedimentary origin, including breccia, conglomerate and interbedded sandstone and siltstone.
- The Tomil Volcanic formation covers a wide portion of the study area, with an estimated thickness of over 30 m around the central part of the Gagil-Tomil area and considerably thinner where the hilltops of the Yap and Maap formations protrude the landscape. The formation is composed of andesitic tuffs, volcanic breccias and lava flows, and is characterised by rolling and undulating hills capped by clay materials.
- The alluvial deposits are a mixture of stream-alluvium deposits and are observed around the south and northwest of Yap Island, and the eastern side of Gagil-Tomil.
- Mangrove swamps cover the coastal areas.

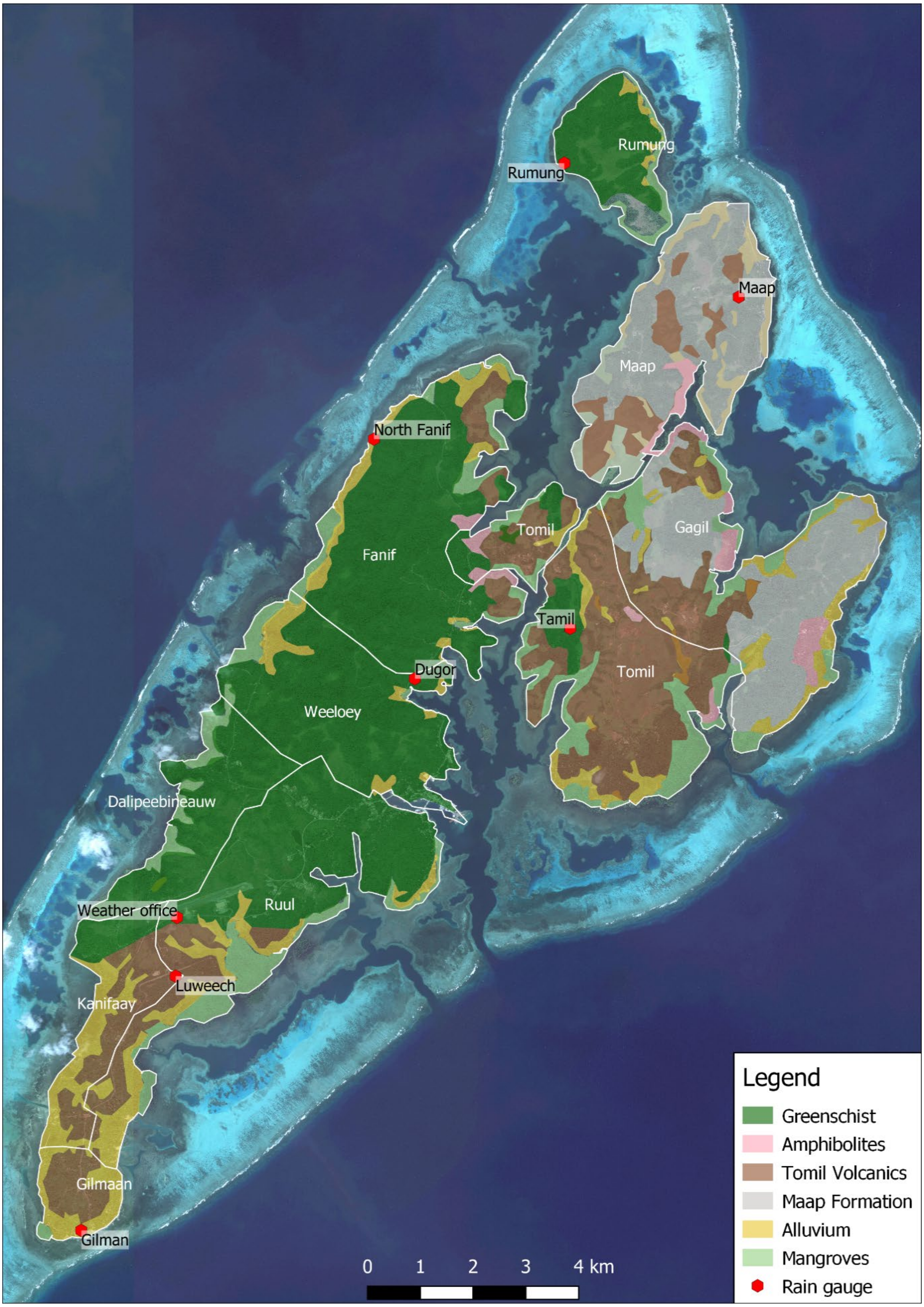

Figure 9. Geological map of Yap Proper, including municipality boundaries and Yap Weather Service Office rain gauge locations. Source: Bing maps

2.6 Historical groundwater investigations

Groundwater exploratory drilling and development within the Tomil Volcanics commenced in the 1970s. Between 1979 and 1982, 15 exploratory and 13 production wells were sited and drilled under the supervision of Tom Nance of Lyon Associates (Nance 1979, 1982). Several exploratory drill holes were installed in Monguch Valley, located south of the mapped volcanic body and through which a number of perennial streams and swampy areas exist. The groundwater potential of the Tomil Volcanics aquifer or water-bearing unit was explored by drilling and test pumping six production wells (Nance 1982), to determine whether they might be a useful water supply source. The Tomil Volcanics have been relied on since then and further developed.

In 1982, four production wells were drilled and constructed in the GTWA wellfield, two in Thilung, the swampy area at the head of the perennial Monguch stream, and two beside the Monguch stream (Fig. 8). These had an estimated transmissivity of 7000 to 8000 gpd/ft (807–920 m^2/d) and an estimated storage coefficient of 0.00010 to 0.00018 (Nance 1982). Two bores were drilled beside the Dorfay stream, one of which is currently used for periodical monitoring while a production well was drilled around the eastern side of the valley near the perennial Mukong stream. In 2012, the production bores of GTWA were replaced as part of an Asian Development Bank-funded water supply expansion and rehabilitation project.

Groundwater investigations in Eyeb Valley commenced in 1989 with the drilling of a test hole (Eyeb Stream 1). This test hole indicated a potential yield of 40 gpm (2.5 L/s) intercepting a porous aquifer consisting of breccia and conglomerate interbedded with sandstone between 60 and 120 ft (18 and 35 m), interpreted as the Maap Formation. The drilling continued into the top of the underlying Yap formation at depths of 120–160 ft (35–48 m) (Zheng 1997). The weathered Tomil Volcanics were identified as a relatively thin layer (60 ft, 18 m) overlying the Maap Formation at this location (near current YSPSC P1). A number of production holes were subsequently drilled in 2000, closer to the valley floor where the thickness of the Tomil Volcanics is considered greater, and are still used to this day as production bores. Details from the original drilling and construction reports could not be sourced.

During the drilling and construction of the YSPSC production bores (circa 2000), five monitoring bores were drilled and constructed and are used today for monitoring purposes. As with the YSPSC drilling and construction reports, copies of these reports were unavailable at the time of this report. Efforts should be made to secure these reports as they can provide valuable information for future analysis.

Table 10. Summary of YSPSC monitoring bores.

Monitoring bores (drilled circa 2000)	Lat/Long	[1]Approximate elevation at mean sea level ft (m)	Total well depth ft (m)	Measuring reference point above ground ft (m)	[2]Static water level Sept 2019 ft (m)	Estimated screen depth ft (m)
YSPSC M1	138.1615028/ 9.5375991	12.1 (3.7)	91.7 (27.95)	2 (0.61)	1.94 (0.59)	85.1–88.4 (25.95–26.95)
YSPSC M2	138.1566744/ 9.539345	46.9 (14.3)	56.6 (17.25)	1.44 (0.44)	4.66 (1.42)	50–53.3 (15.25–16.25)
YSPSC M3	138.1550083/ 9.5472125	106 (32.3)	132.8 (40.48)	3.2 (0.98)	5.33 (1.625)	126.2–129.5 (38.48–39.48)
YSPSC M4	138.151175/ 9.5507356	74.1 (22.6)	117.6 (35.85)	2.79 (0.85)	22.5 (6.85)	111.1–114.3 (33.85–34.85)
YSPSC M5	138.1487506/ 9.5532872	32.8 (10)	129.6 (39.5)	3.3 (1.0)	3.94 (1.2)	123–126.3 (37.5–38.5)

[1]Approximate elevation based on GPS data referenced to known elevation point (+/- 2m).
[2]SWL – all depths relative to ground level; *Max recovery test 24 hours @29/9/2019.

3. Groundwater investigations

During the field investigation (September through October 2019), a number of different techniques were used to help assess the impact of abstraction on the wellfields of GTWA and YSPSC in the Monguch and Eyeb valleys, respectively. Pumping tests were designed and undertaken to determine the potential impact from pumping between the wellfields from the current groundwater abstraction. Water level recorders were installed to assist with understanding the long-term behaviour of the aquifer in response to climate and abstraction stresses. Groundwater chemistry analyses provided insights into the connectivity of the aquifers underlying the two wellfields and provided baseline data for assessing potential water quality changes over time. Geophysical surveys using electrical resistivity tomography (ERT), provided insights into the underlying geology and the identification of groundwater targets for future development.

3.1 Pumping tests

Pumping tests can help identify the potential impact between the GTWA and YSPSC wellfields, and provide an improved understanding of the aquifer's characteristics. Details of the pumping tests can be found in Annex 3.

A pumping test is designed to determine the aquifer's behaviour based on groundwater level measurements in response to groundwater abstraction. An analysis of the pumping test data can provide valuable insights into an aquifer response's to pumping and assist in determining sustainable abstraction rates.

Figure 10. Measuring drawdown and conductivity at YSPSC pump 6 using a digital water level meter.

3.1.1 Pumping test methodology

The pumping test was designed to use existing infrastructure, at the maximum available pumping rate for each production bore. Two scenarios were considered. The first one assessed the impact on the GTWA wellfield and all monitoring bores when all operational production bores at YSPSC wellfield were pumping at their maximum capacity for a period of 48 hours (pumping test 1). The second scenario assessed the impact on all monitoring bores and the interference, if any, between the two wellfields over a 72-hour period (pumping test 2). Three teams consisting of staff from the Pacific Community, Yap Environmental Protection Agency, GTWA and YSPSC measured the groundwater level responses in all the production bores and monitoring bores. The pumping test schedule is outlined in Annex 2.

The pumping test was undertaken at the end of a wet period, suggesting that the aquifer system was "full". It should also be noted that heavy rain occurred during the pumping test period, which acted as an external input to the system, with the measured water level response in the monitoring bores illustrating a groundwater recharge and recovery event during the pumping test period.

Figure 11. Piezometer water level and conductivity readings taken at YSPSC monitoring bore 4 (M4) prior to the pumping test.

Groundwater level measurements were taken using manual water level meters for all production bores during the pumping test period at prescribed measurement intervals (Annex 3). Pressure transducer-type water level recorders were installed in each of the five monitoring bores, recording at 30-second intervals during the pumping test period, with manual water level readings taken at a scheduled period to assist with calibration and data confidence.

A significant rainfall event was experienced in the catchment area in the early hours of 30 September 2019 (21:00–04:00) recorded at the Tamil rain station to be 1.3 inches (51.2 mm) of rain. Heavy showers were also experienced on 26 September 2019 for 1 hour 12:25–13:30, recording 0.13 in (5.1 mm) at the Tamil rain station. These rain events acted as external inputs into the system adding some complexity to the data analysis.

Arrangements were made with GTWA to minimise disruption to water users during the pumping test, including informing users of potential disruptions and to store water. However, during the pumping test, when pumps at GTWA were to be switched off over a period of 48 hours, it became evident that there were greater losses in the GTWA system than previously expected, requiring the water manager to resume pumping to ensure sufficient water supply to the community. The operation of these pumps during the period they were to be switched off added another layer of complexity to the analysis.

During the 72-hour pumping test (pumping test 2), production bores for both GTWA and YSPSC were pumped continuously. After completion of this test, GTWA production bores were then switched off, although due to water demand, the production bores in the YSPSC wellfield remained operating and the abstraction of groundwater continued for the remainder, with no shutdown period.

3.1.2 Pumping test results

The results of the pumping test analysis are summarised below. Full datasets can be found in Annex 3. Individual wells showed variability in flow capacities, which demonstrates the degree of localised heterogeneity of aquifer properties controlling the vertical and horizontal flow through the aquifer materials and into the wells.

Pumping test results were undertaken by Nance (1982) on the original Monguch-Thilung wells (Monguch 1, Monguch 2, Thilung 1, Thilung 2). The hydraulic conductivity (K) obtained by Nance and by the current testing were similar for the GTWA bores, albeit Nance's K values were slightly higher, 13–18 m/day than those of the current analysis at 11–14 m/day. It is worth noting that the K estimates for the YSPSC production bores obtained during the current pumping test were considerably lower than the ones determined for the GTWA bores, with K-value estimates of 1–4 m/day, suggesting that the permeability in Eyeb Valley is lower than in Monguch Valley. Possible explanations for this include:

1. The permeability of the aquifer unit is reduced, possibly with the presence of increased clay content within the lithology, or less open fractures, resulting in lower permeabilities in Eyeb Valley.
2. The abstraction occurring from YSPSC production bores in Eyeb Valley is accessing groundwater from the less permeable Maap Formation, rather than the assumed Tomil Volcanics.

If indeed the geological formation from which abstraction occurs in the Eyeb Valley is different from the one in Monguch Valley (weathered Tomil Volcanics), this could account for the differences in observed hydraulic conductivities. Drilling logs are unavailable for the YSPSC bores, so it is difficult to provide any certainty for the above explanation. Nevertheless, the aquifers in both valleys demonstrate similar hydraulic characteristics, with similar groundwater chemistry (see Section 3.3) and water level response, albeit they seem to be separated by a groundwater divide located along the highest elevation and crossing monitoring bore M3 (see Fig. 13).

3.2 Groundwater monitoring

Groundwater monitoring included the installation of automatic pressure transducer (water level) loggers in all the monitoring wells, and during the pumping tests in selected pumping wells in both the Eyeb and Monguch valleys. The continuous water level data provided by the loggers in the monitoring bores provided invaluable insight into the aquifer's behaviour from abstraction during the pumping test, and over the following months from longer term climate and abstraction impacts.

After the pumping test of October 2019, which was undertaken after a period of sustained rainfall, Yap Proper went into a sustained dry period and drought (October 2019–June 2020) that is expected to continue at least until July 2020 (NIWA 2020). The record of water level changes in the monitoring bores during this period proved to be extremely useful in order to demonstrate:

- the natural impact from reduced recharge into the groundwater system; and
- the impact on the groundwater system due to intensive pumping from the YSPSC bore field operating continually from October 2019 to June 2020.

3.2.1 Pumping test

Water level recorders were installed in all monitoring bores, and some production bores during the pumping tests to record continuous water level response data. Figure 12 shows the groundwater table decline (drawdown) recorded in monitoring wells M1, M2, M3, M4 and M5 in response to the pumping of the YSPSC and GTWA wells. Monitoring bores M4 and M5 are clearly influenced by the pumping of YSPSC wells, whereas monitoring bores M2 and M3 illustrate a gradual decline in groundwater level, which reflects the natural background groundwater discharge, and are not discernibly impacted by the groundwater pumping during this period. Monitoring bore M1 was slightly influenced by the pumping of the GTWA wells.

The loggers installed in the GTWA bores did not indicate any impact from the pumping of the YSPSC bores. The drawdown effects observed in the GTWA wells is the result of the GTWA pumps being switched on by the GTWA water manager for 6 hours each night during the YSPSC 48-hour pumping test to ensure minimal water disruption to the Gagil-Tomil communities (Annex 3).

The logger data also reflect the impact of rainfall on the pumping test, whereby a significant rainfall event of 1.3 in (33 mm) of rain was experienced overnight and in the early morning of the 30 September 2019, for an estimated total of six hours. During this period, all bores showed a rapid and connected response to rainfall, with water level responses reaching their maximum generally within an average of six hours from the commencement of rainfall, which is similar to the period of rainfall. This closely connected behaviour of rainfall and water level response was observed in all bores, except for M4 which demonstrated continued recharge for another 16 hours, or a total of over 23 hours, for the same 6-hour rainfall event. The average groundwater level increase due to this rainfall event in M2, M3, M4 and M5 was 0.23 m, with M4 showing a water level response of 0.36 m over approximately 23 hours.

The behaviour observed in M4 suggests that groundwater in this area receives prolonged recharge from groundwater flow higher in the catchment, resulting in a larger and more sustained water level response to recharge than observed in other monitoring bores. Similarly, the decline in water level in M4, representing discharge, over the following approximately 10 days after a rainfall event is also larger and more sustained than observed in other bores. This water level behaviour observed in the monitoring bores is a strongly connected response to rainfall, and indicates a rapid groundwater system that is most likely to be fracture controlled.

Table 11. Pumping test results.

						Drawdown analysis		Recovery analysis		Aquifer hydraulic conductivity (K)	
Well	Static water level ft (m)	Max drawdown ft (m)	Discharge (GPM)	Discharge (m^3/day)	Aquifer thickness ft (m)	ΔS per log-cycle (m)	Transmissivity (m^2/day)	ΔS per log-cycle (m)	Transmissivity (m^2/day)	K based on drawdown data (m/day)	K based on recovery data (m/day)
GTWA B2	3.2 (0.98)	24.3 (7.4)	49	267.07	20 (6)	1.6	61.13	1.3	75.24	10.19	12.54
GTWA B3	3.1 (0.95)	14.8 (4.5)	48	261.62	20 (6)	0.9	106.46	1.4	68.44	17.74	11.41
GTWA B4	9.8 (3)	15.1 (4.6)	64	348.83	42 (13)	0.95	134.48	0.7	182.51	10.34	14.04
YSPSC P2	7.2 (2.18)	62.3 (19)	66	359.73	32 (10)	3.2	41.17	8.2	16.07	4.12	1.61
YSPSC P3	9.6 (2.93)	20.3 (6.2)	16	87.21	20 (6)	1.2	26.62	2.5	12.78	4.44	2.13
YSPSC P5	5.7 (1.75)	64 (19.5)	18	98.11	20 (6)	2	17.97	10.3	3.49	2.99	0.58
YSPSC P6	16.6 (5.05)	61.3 (18.7)	14	76.31	32 (10)	NA		5.4	5.18		0.52

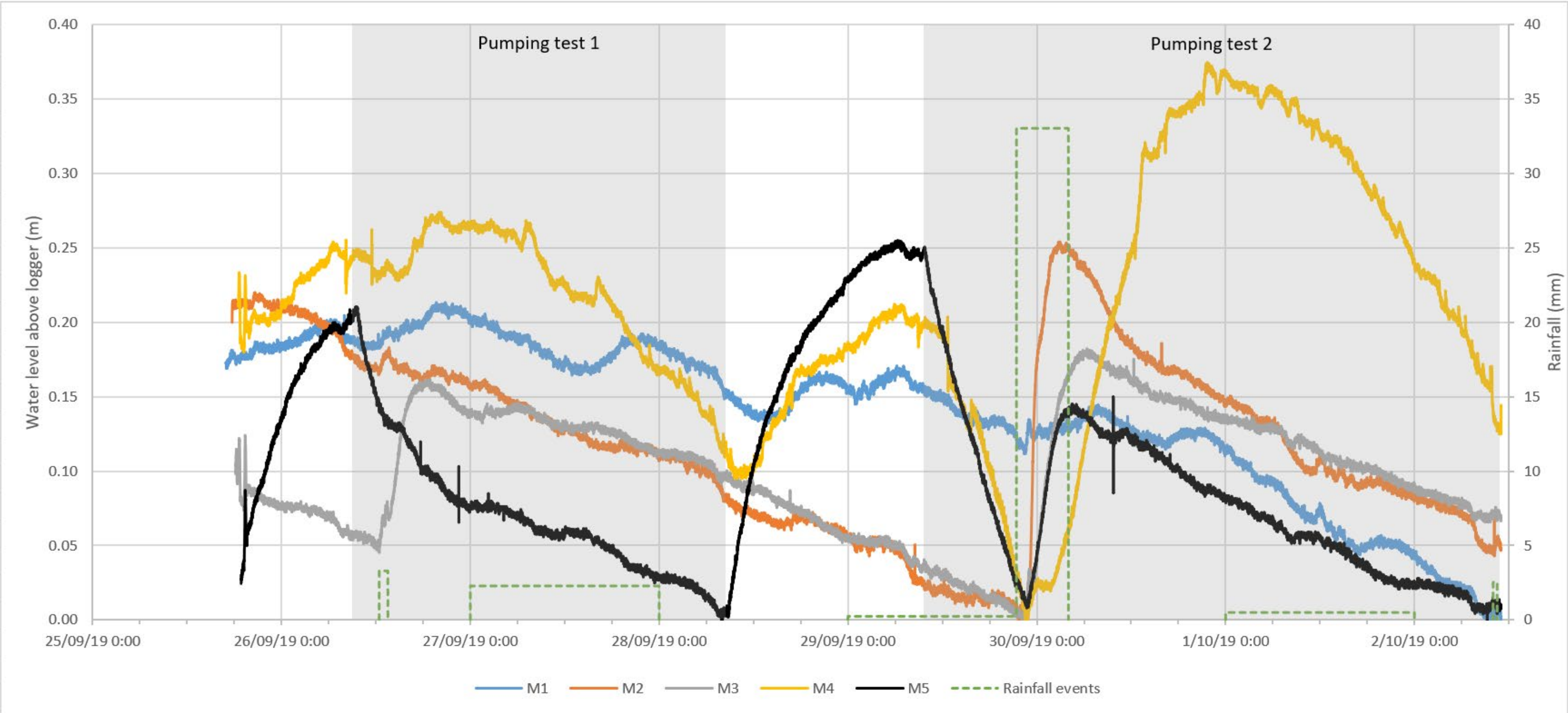

Figure 12. Groundwater level response in the monitoring bores during the two pumping tests (rainfall presented as rainfall events).

3.2.2 Long-term monitoring

Upon completion of the pumping test programme, automatic loggers were installed in all monitoring bores as part of a long-term data acquisition programme to collect water-level measurements every six minutes. These loggers were installed in all the bores in October 2019, at depths expected to match the screen depths. Data from these loggers were downloaded in February 2020 and again in April 2020 by Yap EPA. The loggers were installed at the end of the wet period and captured the gradual water-level decline in response to reduced recharge and abstraction from pumping wells over a seven-month period of extended dry conditions. This monitoring data have proven to be very useful to further the understanding of the aquifer system under natural low recharge conditions and with long-term pumping impacts, as well as responses to rainfall events.

Figure 13 illustrates the calculated hydraulic head contours, as approximated by groundwater level measurements in the monitoring bores in September 2019, governing the general groundwater flow direction. The groundwater appears to flow from the topographically higher areas towards the streams and associated estuaries. Analysis of the Mukong stream flow data (16 September 1980 to 21 March 1984, elevation 20’) operated by the United States Geological Service (https://waterdata.usgs.gov/nwis/inventory/?site_no=16893200) indicates that the groundwater supports the perennial streams, except during dry periods when the streams run dry, where it is expected that discharge is out towards the ocean through the underlying rocks of greenschist (Annex 4, Fig. 41). The potentiometric contours in Figure 13 represent the measured depth to groundwater for recovered static water levels under a “full” groundwater system (as measured on 29 September 2019). Figure 13 indicates that groundwater flow is towards the streams from higher in the catchment. A groundwater divide is observed between the two catchments, broadly mimicking the catchment topography, with discharge towards the base of the catchment.

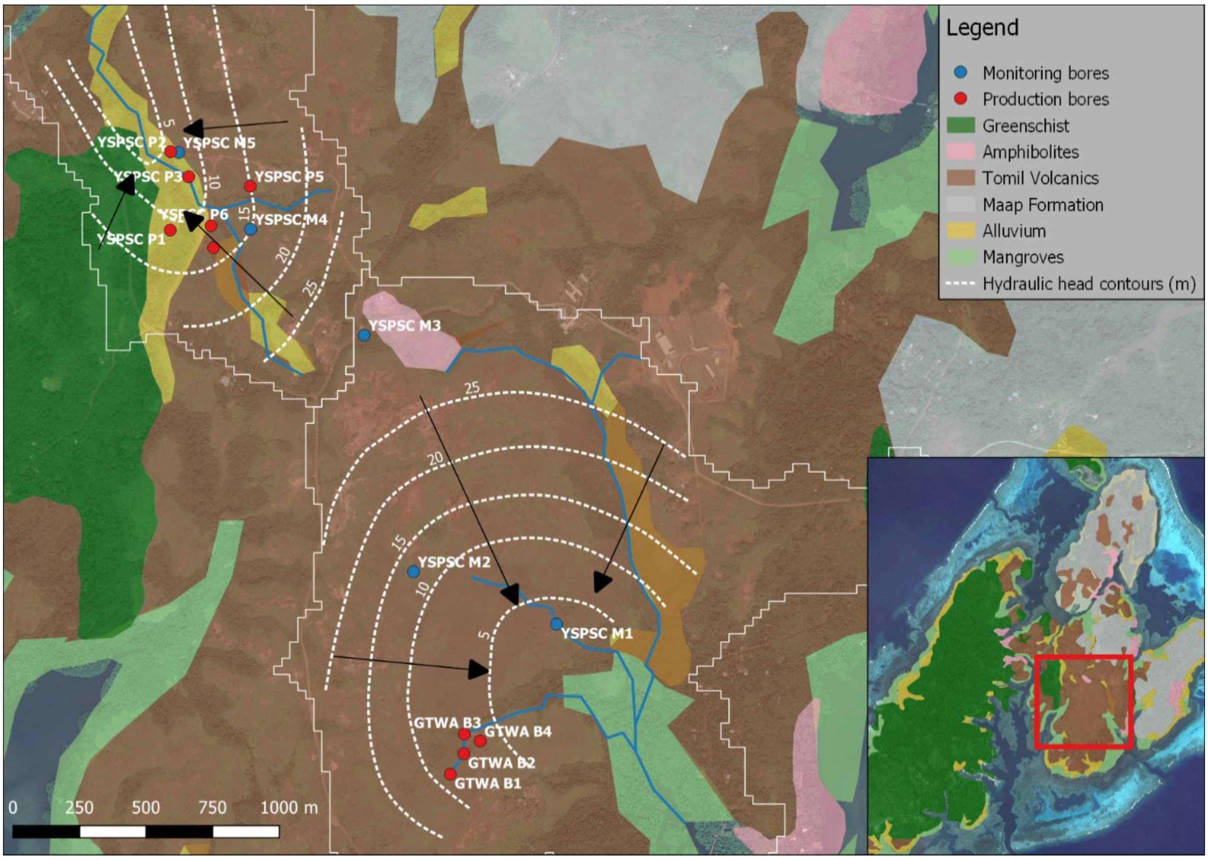

Figure 13. Groundwater head contour map under natural conditions, not pumping induced (September 2019). Black arrows indicate the flow direction of groundwater (perpendicular to the hydraulic head contours.

An analysis of the water-level data collected by the loggers from September 2019 until May 2020 (Fig. 14) provides insight into the aquifer's behaviour over an extended seven-month dry period, with continuous pumping from the YSPSC bores in Eyeb Valley. The GTWA pumping schedule during this period is unknown, and assumed to be 8–12 hours nightly, as per normal scheduling during this period. Notable features observed in the groundwater and rainfall data collected include the following:

- The aquifer demonstrates a strong and rapid response to rainfall. All monitoring bores indicate a rise in the water-level head immediately after a significant rainfall event, suggesting a dynamic system that is responsive to rainfall.
- Declining water levels over time, during reduced recharge periods, indicate continuous discharge, initially to streams within the catchment, and then to underlying geology and presumable discharge to the ocean.
- Monitoring bores M4 and M5 are impacted by YSPSC pumping bores as demonstrated by the steeper decline in water level in response to their proximity to the production wells.
- M4's rapid and larger water level response to rainfall, followed by a rapid and large decline, is likely a result of its location and the geology it intercepts. It is suggested that M4 receives prolonged recharge in response to the connectivity to fractures higher in the catchment, which is observed by the duration of the water level response to rainfall. Equally, it is observed that the water level decline indicates prolonged discharge over a 10-day period following a significant rainfall event (Fig. 12 and Fig. 14).
- A sudden groundwater level decline was recorded on 27 January 2020 until 4 February 2020 (dashed circle in Fig. 14). Two explanations for this observed phenomenon are:
    - Increased rate of pumping in a nearby production well for a period of seven days.

- Abstraction impacts from the production wells have resulted in the flow to the monitoring bore being temporarily interrupted, possibly where the flow within the assumed fracture-dominated system is exhausted, or a boundary is reached. This may have resulted in the release of groundwater from within the aquifer matrix, indicating a secondary porosity effect. The system's recovery is in response to the recharge from a rainfall event, albeit the water level response observed in M4 is more subdued than what would be expected from similar rainfall events observed in a less stressed system. This subdued response to rainfall recharge is likely due to the need for the "wetting up" of the unsaturated zone before recharge can begin.

The value of maintaining automatic water level loggers in monitoring bores to determine the trends in aquifer systems in response to abstraction and climate is clearly showcased. These data, when coupled with the rainfall and pumping schedule and abstraction volumes, will further the understanding of the dynamics of the aquifer system, thereby providing increased confidence for future management and operational decisions. To improve the understanding of rainfall recharge into the groundwater system, installing an automatic rainfall station in Monguch Valley, preferably near the GTWA office, is recommended to generate site-specific rainfall information.

The rate of decline in water levels, in response to reduced recharge, was calculated from the monitoring bores M1, M2 and M3, where the water levels of a "full" groundwater system were compared against the water level at the end of a sustained 4.5-month dry period with a total of 16.2 inches (412 mm) of rainfall. The average of the water level data for each monitoring bore at the end of a "wet" period over a seven-day period (20 December 2019–27 December 2019) was compared to the seven-day averaged water level for each monitoring bore at the end of a "dry" period (23 April 2020–30 April 2020). The decline in head over the period was then determined and compared between monitoring bores to indicate the decline in water level over a sustained dry period under natural discharge conditions and under the same conditions with the impacts of abstraction. While the data for M5 during December 2019 were not available at the time of analysis, the water level starting point was estimated from earlier data during a similarly "full" groundwater system. The data from the monitoring bores indicate that over 132 days (20 December 2019–30 April 2020) the decline in water level due to natural groundwater discharge during an extended dry period was, on average, 5.1 ft (1.54 m). Monitoring bores M4 and M5 in Eyeb Valley demonstrate the influence of abstraction from the YSPSC pumping wells, and exhibited a groundwater level decline of 2.7 m and 12.3 m, respectively. These groundwater declines translate into a natural groundwater decline rate of 1.15 cm/day during an extended dry period, and an abstraction-influenced groundwater decline rate of 2–9 cm/day for Eyeb Valley.

The extended dry period for Yap (October 2019 to June 2020) resulted in the YSPSC wellfield pumping continuously during the entire period (Charles Falmeyog, YSPSC Water Manager, pers. comm.). Automatic monitoring of water levels in monitoring bores M3, M4 and M5 allowed an assessment of the impact on the aquifer from this continuous abstraction. A groundwater level decline contour map, showing the impact of pumping on the aquifer and production bores, is based on drawdown water levels in production bores and monitoring bores, over a seven-month period from October 2019 to May 2020. Figure 15 identifies the drawdown impact on the aquifer in Eyeb as the difference between the static water level as recorded on 28 September 2019 (after a 24-hour no-pumping period) and the water level recorded on 8 April 2020 after continuous pumping. Maximum drawdowns of > 20 m were recorded close to the production bores, with the drawdown impact decreasing to 3.5–10.7 m in the monitoring bores. This level of drawdown is expected to result in reduced yields in the YSPSC production wells. Additionally, the available water above the pump inlet in YSPSC P5 and P6 is reaching critical levels, with only 6.54 ft (2 m), and 2.96 ft (0.92 m), respectively, of water above the pump inlet. This has potential operational implications, such as pumps "tripping" thus requiring reset, and possible damage to pumps.

Figure 16 illustrates a conceptual cross section of Eyeb Valley, demonstrating the impact of pumping on groundwater levels. This conceptual section indicates that drawdown levels are below mean sea level, suggesting that there is potential for sea water to be induced towards the Eyeb production bores. While this impact to water quality was not observed in any of the production or monitoring bores, or for just short periods, may be an acceptable abstraction and management strategy to meet water demands. Given the existing high manganese (Mn) and iron (Fe) within the groundwater, and where the reduced recharge is likely to result in increased reliance of groundwater within storage, there could be the potential for Fe and Mn concentrations to increase. The following, therefore, are recommended:

- Continue monitoring the salinity in all production bores (weekly) and monitoring bores (monthly) to determine if there are any significant increases in salinity that may indicate impacts of saline intrusion induced through pumping.
- During the extended dry period and current abstraction, sample all production bores in GTWA and YSPSC and analysing for Fe and Mn for comparison against baseline water quality. This will be useful to indicate changes in water quality.
- During the extended dry period and for a period of six months after emerging from meteorological drought conditions, conduct weekly monitoring of drawdown levels, abstraction rates and volumes abstracted for all production bores in YSPSC and GTWA. Monthly monitoring and downloading of logger data in monitoring bores is also recommended.
- Review and analyse all available data emerging from this drought to develop guidance notes for future management and operation to minimise long-term impacts and look for potential induced salinisation.

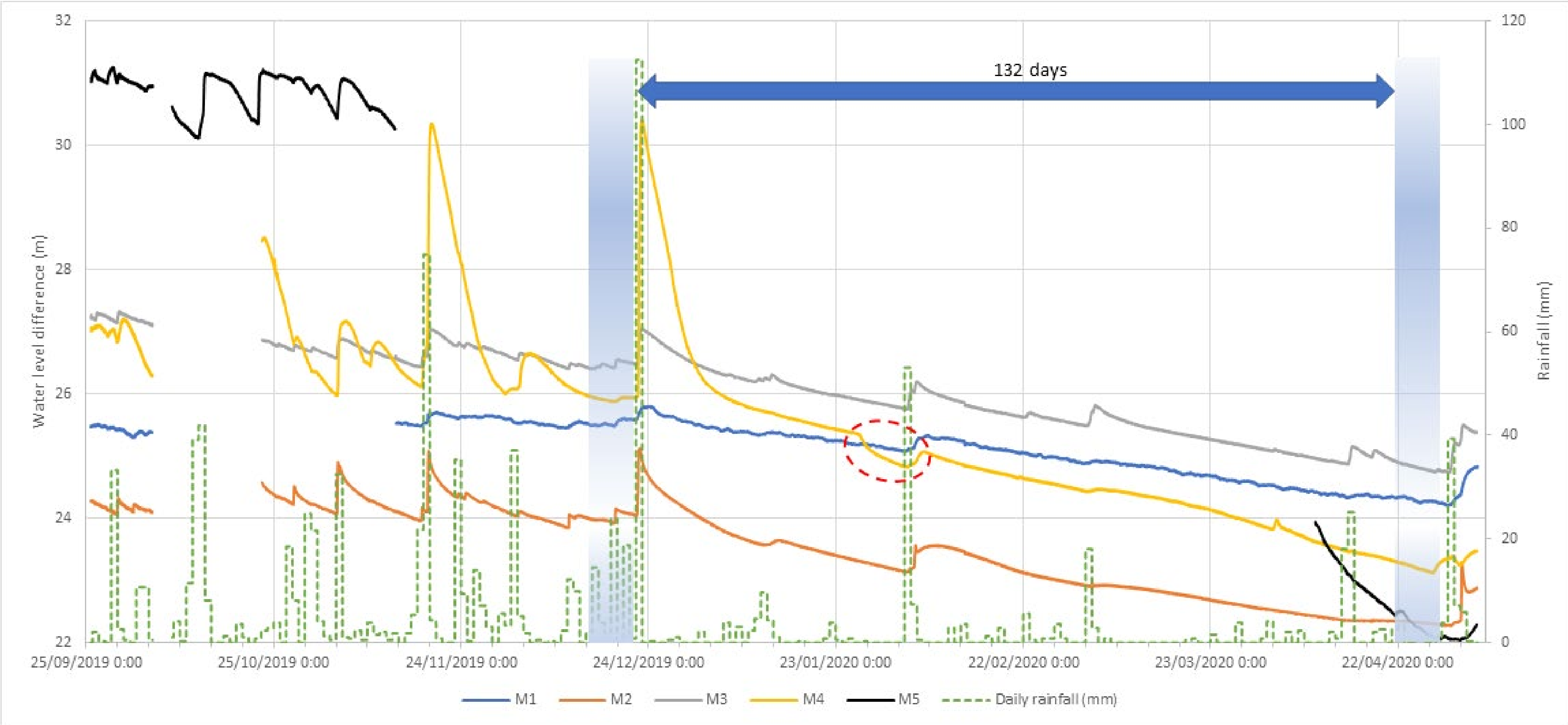

Figure 14. Estimation of rate of decline in water levels over 4.5 months, in response to drought and pumping impacts. Tamil station rainfall included. The dashed red circle for M4 indicates a sudden decline in water level response due to additional stress from increased pumping, or more likely the effect from a boundary impact.

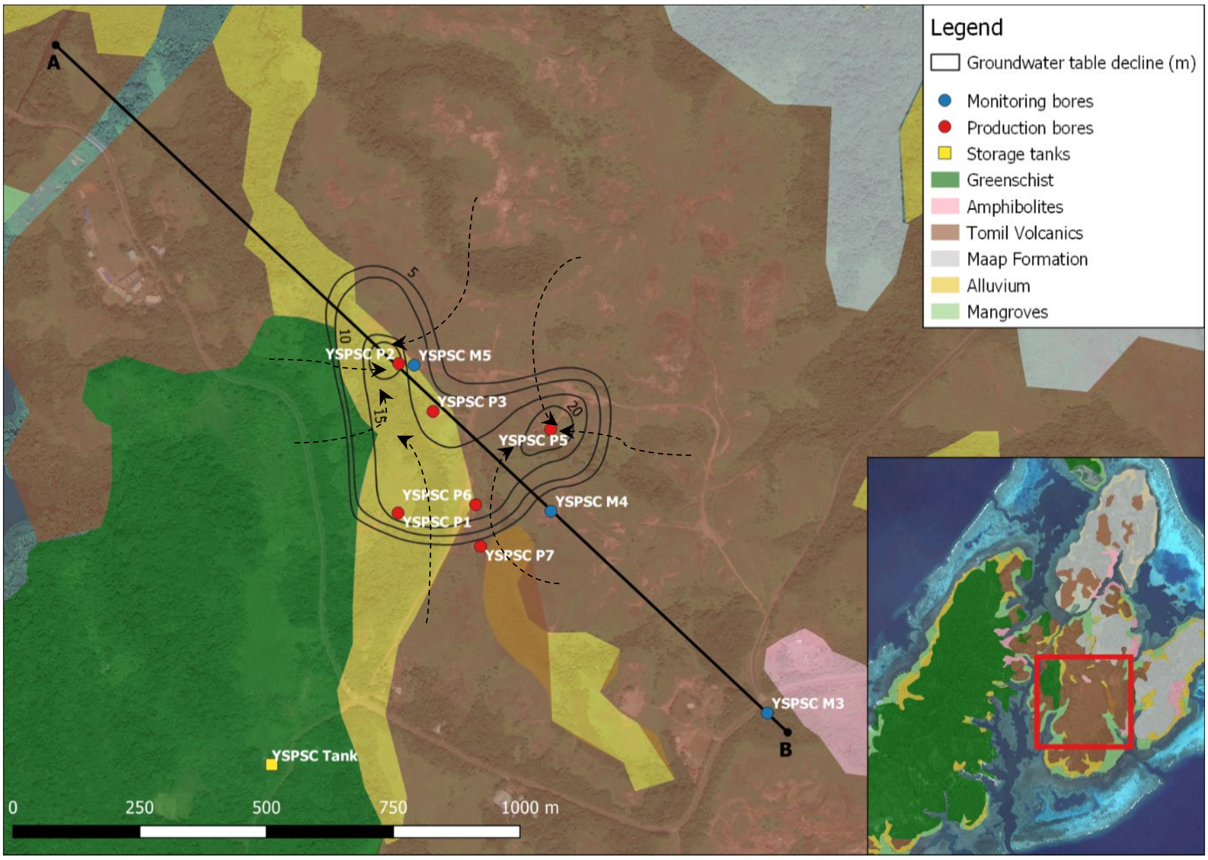

Figure 15. Geological map of Eyeb Valley (YSPSC wellfield), illustrating the groundwater drawdown decline between September 2019 and April 2020. Arrows represent groundwater flow during extended pumping.

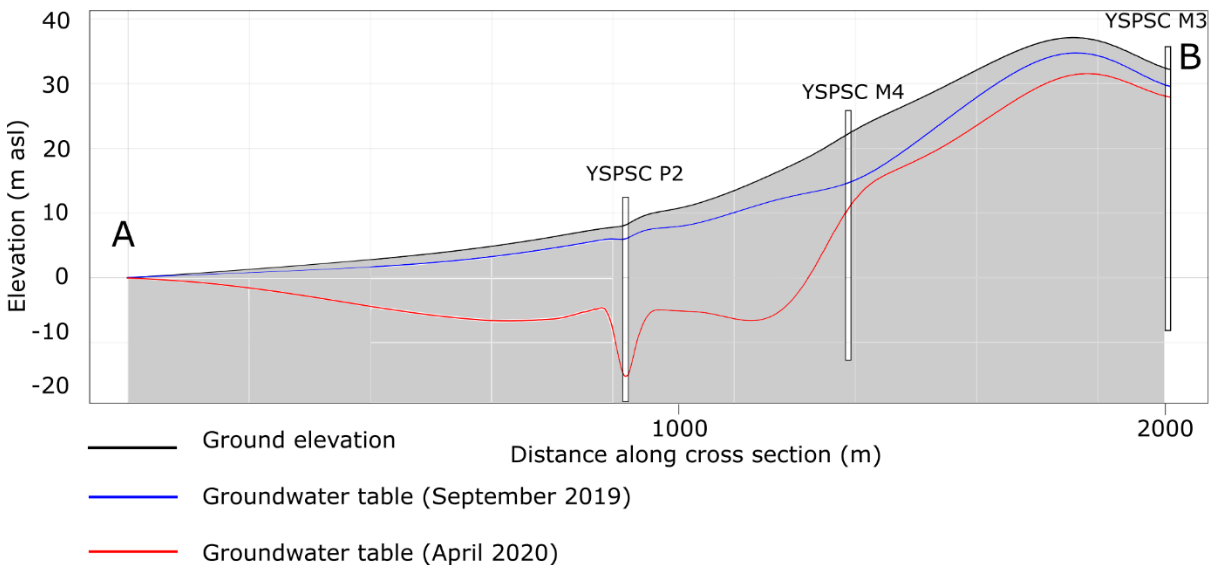

Figure 16. Cross section illustrating groundwater drawdown decline in Eyeb Valley between September 2019 and April 2020 in response to an extended dry period and abstraction. Note: "m asl" refers to meters above sea level.

3.3 Groundwater chemistry

Groundwater chemistry provides insight on the origin of groundwater and can be used to help characterise the groundwater. Groundwaters that exhibits similar concentrations in dissolved constituents suggests that they originate from aquifers with similar geochemical conditions, usually indicating hydraulic connectivity between aquifers. Groundwater samples were collected from production wells YSPSC P1, P2, P3, P5 and P6, and GTWA B2, B3 and B4. Groundwater chemistry results were analysed using piper plots to allow the identification of hydrochemical facies of the Gagil-Tomil groundwater.

Figure 17. Groundwater chemistry sample collected at GTWA pumping well B3, following purging.

A previous hydrochemical analysis of stream water and groundwater – conducted by Shade et al. (1992) – revealed that groundwater from Gagil-Tomil is high in silica (Si), sodium (Na) and total dissolved solids (TDS) (Table 12). They attributed these high concentrations to water–rock interaction and groundwater residence time within the Tomil Volcanics, where plagioclase feldspar in the andesitic unit has weathered into kaolinite clay, and in the process, releases more Na cations and dissolved Si into the groundwater.

Table 12. Hydrochemistry of groundwater samples, including samples obtained in Gagil-Tomil by Shade et al. 1992.

Sample Source	GTWA B2	GTWA B3	GTWA B4	YSPSC P1	YSPSC P2	YSPSC P3	YSPSC P5	YSPSC P6	GT groundwater (1992)	GT streams (1992)
TDS	100	106	99	121	114	69	72	66	98	41
Chloride (mg/L)	7	8	8	7.5	6.5	6	7	7	6.7	6.2
Calcium (mg/L)	4.04	7.53	4.02	17.4	9.61	3.71	4.66	4.58	3.7	3
Iron (mg/L)	0.077	1.72	1.42	<0.019	0.19	1.38	0.584	0.034	0.015	0.52
Magnesium (mg/L)	3.52	6.04	4.52	9.88	8.55	5.16	4.11	2.78	3.2	2.3
Manganese (mg/L)	<0.006	<0.006	0.01	<0.006	<0.006	3.53	0.099	0.011	0.002	0.11
Potassium (mg/L)	1.27	1.75	2.05	0.292	1.74	0.626	0.911	0.603	1.6	0.2
Sodium (mg/L)	7.02	7.51	9.04	8.22	11.9	6.88	8.38	8.97	7.3	4.4
Sulphate (mg/L)	1.5	1.91	1.62	2.35	6.43	6.55	2.41	1.76	1.7	3.1
Bicarbonate (mg/L)	34	58	43	100	77	43	41	37	29.3	17.9
Carbonate (mg/L)	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7	-	-
Silica (mg/L)	-	-	-	-	-	-	-	-	63.3	8.4

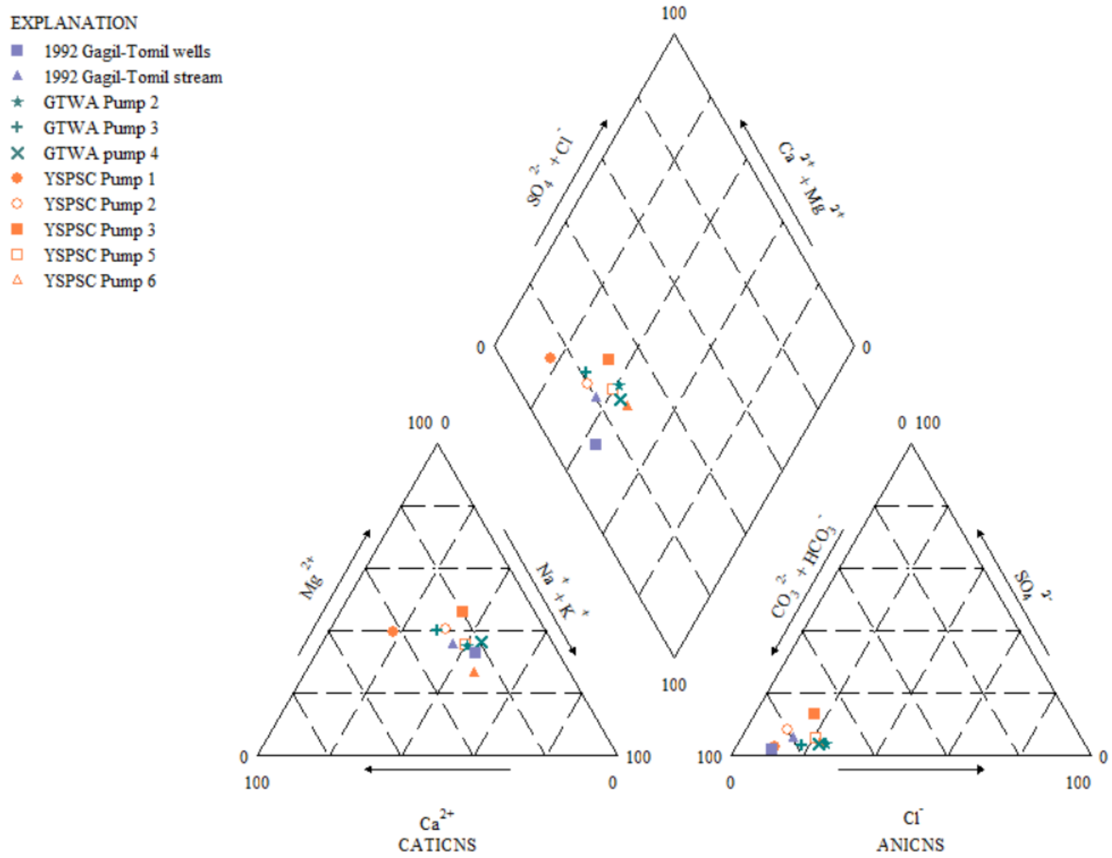

Figure 18. Characterisation of sampled groundwaters from Monguch and Eyeb valleys.

Plotting the groundwater samples on a Piper diagram revealed the dominant presence of Ca-Mg-HCO_3 type groundwater. Dissolved calcium (Ca) and magnesium (Mg) concentrations, in conjunction with high bicarbonate (HCO_3) concentrations suggests the dissolution of Ca and possibly of Ca-Mg-carbonates (i.e. dolomite) present in the Yap greenschist that underlies the Tomil Volcanics. In fact, as observed in Figure 19, the HCO_3 production observed in all wells generally matches the expected stoichiometric production of Ca + Mg concentrations following CO_2-driven Ca-Mg-carbonate dissolution (equation 2, Table 13). This CO_2 production is possibly the result of oxidation of sedimentary organic matter (equation 1) and of other mineral phases that may be present in the Yap formation (e.g. Fe-carbonate, Mn-carbonate). Whether these Fe and Mn carbonates exist as individual phases (i.e. siderite, rhodochrosite) or whether they are incorporated in the Ca-Mg-carbonates (i.e. ankerite) is unknown. Nevertheless, increased Fe and Mn concentrations were recorded in some of the groundwater samples, indicating the possible release of these heavy metals during carbonate dissolution. Groundwater from YSPSC well B1 shows some additional Ca + Mg production, which might be derived from carbonate dissolution (equation 3) triggered by protons produced during minor oxidation reactions, such as the oxidation of trace amounts of pyrite. Other possible sources of Fe is the dissolution of amphiboles and the ferruginous clay observed within the Yap Formation, and derived from the weathering of intruded serpentine dikes and sills (Shade et al. 1992). The silicate minerals (amphibole, olivine) that compose the rocks of the Yap Formation may also be the source of elevated dissolved Mg concentrations in the groundwater.

Table 13. Hydrogeochemical reactions potentially taking place in the aquifer and determining groundwater quality.

Oxidation of sedimentary organic matter	$\boldsymbol{O_2 + CH_2O \rightarrow CO_2 + H_2O}$	**1**
Ca-Mg-carbonate dissolution (CO_2-driven)	$CO_2 + (Ca, Mg)CO_3 + H_2O \rightarrow (Ca, Mg)^{2+} + 2HCO_3^-$	2
Ca-Mg-carbonate dissolution (proton-driven)	$CaMg(CO_3)_2 + 4H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2H_2O + 2CO_2$	3

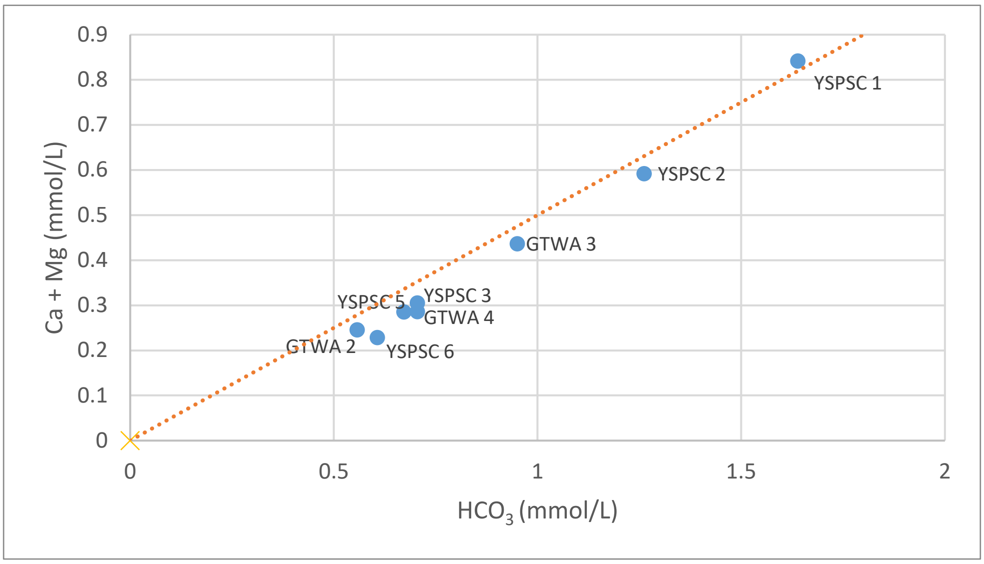

Figure 19. Ca^{2+} + Mg^{2+} versus HCO_3^- concentrations in groundwater samples obtained from the pumping wells. The dashed line represents Ca-Mg-carbonate equilibrium for increasing CO_2 pressure.

Although the chemistry of groundwater samples exhibited some small variability due to the fractured and weathered nature of the Tomil Volcanics and the Yap Formation, it is safe to conclude that groundwater sampled from the two wellfields originates from the same aquifer system. This supports the conclusion of the two wellfields tapping into the same aquifer unit located at the base of the weathered Tomil Volcanics. It was also observed that the Fe and Mn levels in some of the YSPSC wells breached the World Health Organization guideline values of 0.3 mg/L and 0.05 mg/L (WHO 2003, 2011, 2017), respectively, suggesting that periodic monitoring of these elements should continue.

3.4 Geophysical assessment

Electrical resistivity geophysics were used to assess, visualise and identify the spatial variability in electrical resistivity responses within the underlying geological framework. The main objective of undertaking the geophysical survey was to identify potential sites for groundwater drilling to expand the existing water supply in the future. Additional groundwater abstraction points could be useful, particularly around the Gagil area where the Yap State Sports Complex (YSSC) and Fisheries and Marine Institute (FMI) are located, both of which have been identified as important stakeholders with considerable water demands. A successful production bore located near YSSC could prove to be a useful asset as an emergency supply bore that could reduce the stress on the existing distribution system and provide a water security option during droughts.

Three exploratory survey lines were completed around the eastern end of the study area, where the YSSC and FMI are located. These include a 500-m line that trends from southeast to northwest (ERT-1) and two west to east lines (ERT-2 and ERT-3) from the swampy land near the Mukong stream catchment through the YSSC. The objective of these survey lines was to determine: a) the possible extent of the Tomil Volcanics aquifer to the east, and b) the depth of the Yap Formation basement.

The interpretation of the electrical resistivity surveys revealed the presence of three major hydrogeological zones:

1. a highly resistive 5–10 m thick zone on top, indicating low permeability laterite soil;
2. a thick zone of low to medium resistivity interpreted as fractured and/or weathered volcanic breccia, and expected to yield groundwater; and
3. a medium resistivity (40–80 Ohm.m) zone at depth, suggesting the presence of less weathered volcanics or of the low permeability Yap Formation (i.e. the greenschist basement).

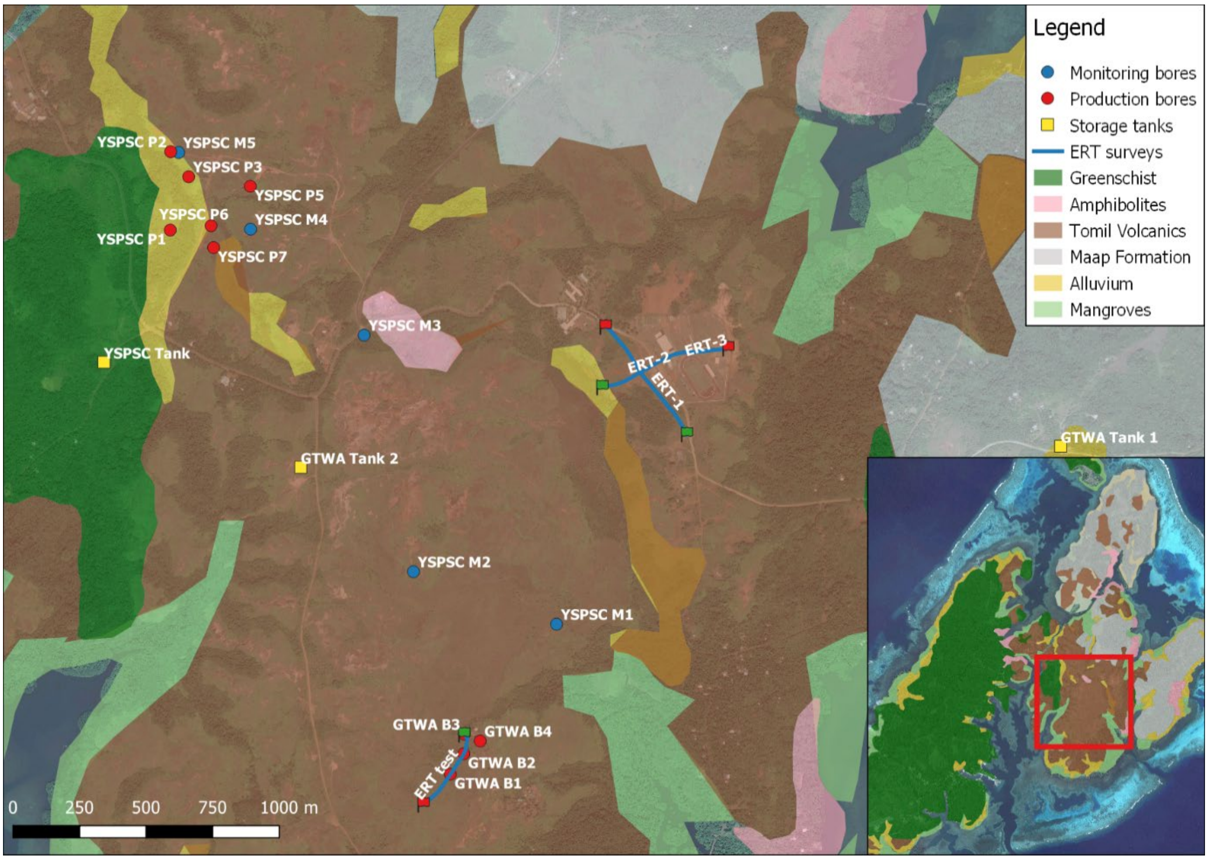

Figure 20. Location of the groundwater infrastructures and the electrical resistivity tomography survey lines superimposed onto the geological framework. Red box indicates the location of the study area.

Survey line 1 (Fig. 21), a southeast–northwest trending line of 500 m, commenced 80 m from the southeast end of the YSSC. The resistivity profile exhibited a three-layered system, comprising a highly resistive unit (> 80 Ohm.m) on top, interpreted as the weathered lateritic clay, which is likely to act as a partially confining layer into the volcanic groundwater-bearing zone. A second zone underlying the lateritic clay was interpreted as moderate to highly weathered volcanic deposits, exhibiting a resistivity range of 10–40 Ohm.m, with varying degrees of groundwater saturation. Underlying this unit is a zone of increasing resistivity, which may indicate less weathered volcanic deposits with decreasing groundwater content. An interesting feature located at 60–100 m distance along the survey line, is an old quarry where the Tomil Volcanics was extracted for road sealing. The resistivity profile suggests moderate weathering and saturation starting from where the quarry is located, which may suggest that the site acts as a recharge area into the volcanic framework. In terms of groundwater potential, the zone of low resistivity observed between 20 and 40 m depth and around 380 m profile distance, may represent a promising drill target into the volcanic aquifer.

Similarly, survey lines 2 and 3 (Fig. 22) revealed a highly resistive zone interpreted as laterite soil overlying a low to medium resistivity zone, and is interpreted as being moderately weathered volcanic deposits with moderate groundwater development potential. An interesting low-resistivity vertical feature was identified at 90–115 m distance along survey line 3, possibly suggesting the presence of a highly fractured zone in the volcanic deposits that is likely to be saturated with groundwater. This feature was interpreted as another potential drill target for groundwater development.

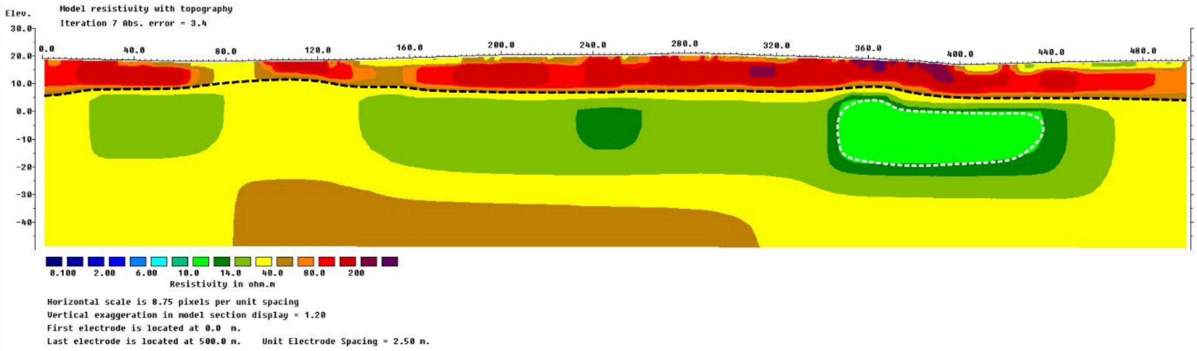

Figure 21. Electrical resistivity tomography survey line 1, illustrating the depth to the top of the Tomil Volcanics (black dashed line) and a potential drilling site for groundwater development (white dashed line).

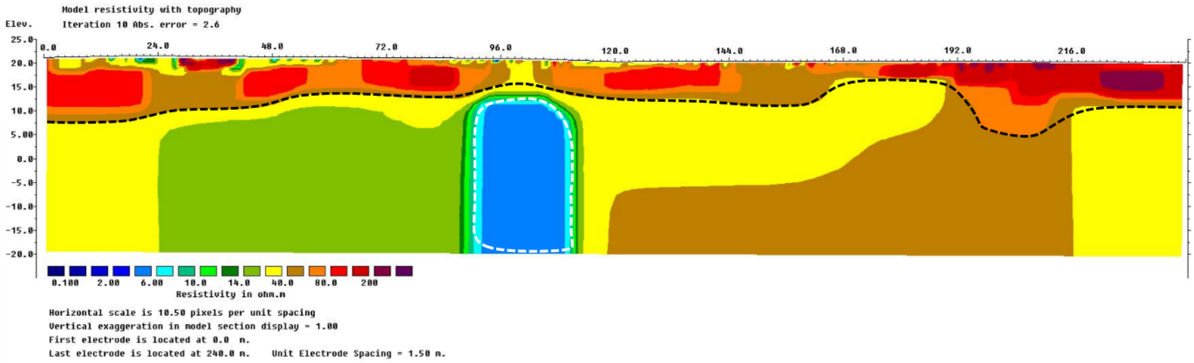

Figure 22. Electrical resistivity tomography survey line 3, illustrating the depth to the top of the Tomil Volcanics (black dashed line) and a potential drilling site for groundwater development (white dashed line).

4. Discussion and recommendations

The study provides a useful insight into the hydraulics, operations, and climatic responses to the YSPSC and GTWA wellfields of Eyeb and Monguch valleys, to help guide the operation and management of the groundwater system. Pumping test data and groundwater quality results indicate connectivity between the groundwater systems, although under current abstraction, impacts between YSPSC and GTWA wellfields are not observed. Under the current abstraction scheduling, the observed impacts on the groundwater from the operation of the two wellfields would indicate they ostensibly operate independently and are not impacting on each other.

It is observed that the groundwater system is quite dynamic, and that during periods of rain, recharge response is rapid, and equally, post-rain there is rapid discharge towards the streams indicating the close connectivity between groundwater and streams. It is suggested from the observed rapid water level response to rainfall, and high-quality water, that groundwater flow is primarily through open fractures within the existing geological framework. It was also observed using historical stream flow data that during extended drought periods these streams will often cease to flow, while groundwater continues to discharge to the underlying geology, albeit at a much slower rate.

The longer-term water level data from the monitoring bores suggest that the current abstraction within the YSPSC wellfield in Eyeb has caused localised drawdown with a resulting impact on some of the production wells including reduced yields and reduced head of water above the pump inlet. If this drawdown, which is below mean sea level, is sustained over a long period of time, it will pose a potential risk of inducing flow from the ocean towards the wells, resulting in salinisation. Weekly monitoring of the production wells – including salinity, drawdown water level, and production rate – during this sustained drawdown, is recommended.

The use of resistivity identified two potential groundwater drilling targets in the fractured Tomil Volcanics near YSSC and FMI. These targets are located in areas that are quite accessible, and which could be used to provide additional water for use at the YSSC or FMI or as a standalone emergency water supply well.

Preliminary findings from the investigation were communicated prior to departure from Yap in October 2019. Follow-up meetings were held in March 2020 and then again in April 2020 to present the findings from the study, the analysis of the monitoring data in response to drought conditions, the impact from sustained abstraction on the wells, and to discuss options for operational supply management and water resource management. Stakeholders present in the meetings included Yap EPA staff, YSPSC water operators, GTWA water operators, and Yap Weather Service officers.

During the meetings, discussions included:

- The need to maintain monitoring to capture relevant information during the drought period on:
    - Daily rainfall data in Eyeb and Monguch valleys (in the absence of a dedicated rainfall station, the Tamil rainfall station would be the closest available reliable rainfall record).
    - Monthly outlooks on forecast rainfall, suitable for drought response planning.
    - Continued monitoring of all monitoring bores, including monthly download of the water level loggers, coupled with monthly manual records of water level and salinity. During non-drought times quarterly (every three months) manual readings and downloading of loggers is recommended.
    - Weekly monitoring of drawdown water levels, salinity readings, pump operation, abstraction rates, and total volume pumped records for all production bores in both Eyeb and Monguch valley wellfields.

- Data from this monitoring should be shared on a monthly basis (during drought periods) among relevant stakeholders, in both analysed and raw data format.
- During extended dry periods and droughts, consider hosting monthly meetings of all stakeholders to present on collected monitoring data and any identified impacts on the water source, and options for water supply and water source management.

Specific management options for drought response to be considered include:

Figure 23. Discussion with key stakeholders and government authorities.

- Investigate the potential for introducing water conservation through water rationing to specific distribution sectors. That is, to consider the feasibility of shutting down certain sections of pipeline to limit flow to a specific distribution sector, for a scheduled period, while maintaining flow to other areas. Then, to replicate the approach of scheduled rationing throughout the distribution network to reduce the total volume of water abstracted and delivered. YSPSC raised concerns about the practicalities of this due to the age of the existing pipeline, potential leakages, and the need for flushing the pipes after being shut down. This constraint is acknowledged and would mean an investigation into the refurbishment needs of the YSPSC and GTWA pipelines, with the objectives of reducing leakage, minimising flushing needs, and providing capacity to isolate different sections of the distribution network as needed, to assist with future drought management.
- Investigate the cost effectiveness and feasibility of abstracting additional groundwater for a period of up to 10 days after a significant rainfall event to capture the high volume of discharged groundwater following the event. This action would require additional storage, the identification of trigger levels for rainfall and water level responses, and additional production bores to optimise abstraction during this period. Additional technical investigations and a cost–benefit analysis would be useful to determine the efficacy of this approach.
- Install an automatic rain gauge to provide site-specific and event-based rainfall data. It is recommended that a new rainfall station be installed at the GTWA workshop in Monguch Valley. The establishment of this rainfall station, which could be operated by GTWA and EPA under the guidance of the Yap State WSO and with the data archived by Yap WSO, will strengthen the understanding of rainfall-driven groundwater recharge and impacts during prolonged dry periods.
- The GTWA manager during the pumping test advised that the pipeline from the GTWA wellfield to GTWA Tank 1 was leaking at a rate greater than expected, due to rapidly declining storage levels during the 48-hour YSPSC pumping test, which necessitated GTWA pumps to be switched on. It is recommended that a leak detection programme be considered within the GTWA distribution system to determine the leakage percentage and determine the necessary repair and/or replacement work within the distribution systems to ensure optimal water use and management.

It is recommended that a leak detection programme be instituted for both for both GTWA and YSPSC water authority distribution networks and upgrade to minimise leaks and improve water distribution management is recommended.

- Consider establishing a formalised group of relevant stakeholders to improve the coordination and collaboration between the Yap Government and water authorities to improve awareness, strengthen coordination, optimise resource mobilisation, and develop shared outcomes. Identified stakeholders include:
    - water authorities: Southern Yap, YSPSC, GTWA and Maap,
    - National Oceanic and Atmospheric Administration – Yap Weather Service Office,
    - Department of Resources and Development,
    - Disaster Coordination Office within the Office of Planning and Budget
    - Public health under the Department of Health Services
    - Fire Section of the Division of Public Safety,
    - Yap EPA, and
    - civil society.
- Consider the use of triggers to initiate drought response actions, such as rainfall analysis and forecasts, water level declines or water quality changes. Trigger thresholds should be determined based on observed data and agreed on by stakeholders, including the EPA and water authorities. Linked to the trigger levels should be clear and agreed water resource responses or conservation actions.
- Develop a communication strategy, explaining and advising government stakeholders and communities on the drought response and justification for the response. This will be critical for ensuring the efficacy and success of the action.
- Conduct an analysis of the water from the production bores in YSPSC and GTWA during the current drought for Mn and Fe to determine if there are any significant changes in water quality under reduced recharge conditions.

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List of Annexes

Annex 1 – Yap State monthly rainfall

Table 1. Yap State monthly rainfall provided by the Weather Service Office.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1949	209.30	101.35	106.43	131.57	168.15	290.58	126.75	193.55	497.08	390.91	154.69	191.26
1950	175.77	27.43	418.08	107.95	146.05	314.20	226.57	267.97	377.19	307.59	395.99	286.51
1951	148.84	275.34	87.88	100.84	202.69	86.36	275.59	418.34	319.53	261.62	168.91	316.23
1952	106.93	83.06	37.85	173.23	291.85	527.05	324.61	401.57	398.02	451.36	198.12	189.48
1953	102.36	238.00	199.90	208.79	167.89	514.86	165.35	747.78	174.75	360.68	372.11	311.66
1954	75.44	49.02	60.20	51.05	328.42	251.71	186.18	223.77	247.40	357.12	332.49	433.07
1955	586.23	123.44	56.39	202.69	312.17	283.97	329.95	508.25	373.89	389.89	252.73	312.93
1956	197.61	92.20	222.00	461.01	309.12	290.83	496.82	289.81	308.10	362.20	304.04	362.46
1957	383.54	119.38	216.66	133.86	156.46	291.59	351.03	299.72	447.04	236.98	49.78	92.71
1958	347.98	37.08	35.05	74.17	118.87	259.33	402.34	154.18	325.12	247.40	470.66	132.08
1959	196.85	202.95	230.38	111.25	293.12	119.13	481.33	294.89	283.97	294.89	262.64	283.46
1960	197.61	158.24	107.19	160.02	322.58	240.28	290.83	303.78	270.00	458.98	524.76	206.50
1961	295.91	143.76	283.21	120.65	459.23	313.18	322.58	438.15	383.54	537.46	112.27	286.26
1962	216.66	339.34	198.63	405.13	366.52	202.18	493.78	439.93	310.64	245.11	188.21	381.25
1963	286.00	309.88	282.70	106.68	181.36	222.76	342.65	716.28	260.35	423.42	189.74	258.32
1964	60.20	164.34	101.85	193.29	463.04	171.20	239.78	424.69	318.77	296.93	157.23	278.89
1965	84.33	152.40	193.80	107.95	206.25	276.35	672.34	314.71	450.34	213.87	305.31	93.73
1966	126.49	32.77	58.67	47.24	170.43	318.01	456.69	229.11	243.59	180.59	224.54	253.24
1967	305.31	158.75	136.40	298.70	406.40	424.43	359.16	417.83	297.69	325.12	265.18	189.99
1968	273.56	204.22	94.49	46.23	100.08	146.30	361.70	276.86	270.76	284.73	91.19	211.84
1969	104.14	31.50	52.83	76.96	195.33	223.01	881.63	294.13	432.56	291.59	247.90	211.33
1970	117.86	156.72	118.62	77.22	247.90	222.50	223.52	646.43	280.42	312.67	242.82	207.01
1971	264.67	256.79	342.39	311.15	326.14	354.08	358.65	308.61	352.30	384.81	260.60	246.63
1972	153.16	264.67	360.93	227.84	135.38	258.57	233.68	240.03	447.04	143.26	237.49	130.56
1973	54.36	25.40	39.12	142.75	151.89	313.69	256.79	130.30	448.06	378.97	268.48	178.56
1974	300.74	108.46	253.75	255.78	248.16	363.22	365.76	313.18	240.79	485.39	478.79	337.82
1975	494.79	30.48	79.25	272.54	230.89	271.02	212.85	302.26	285.75	321.82	172.47	277.62
1976	186.94	81.03	222.50	171.96	318.01	337.82	290.32	413.77	341.38	65.79	225.55	253.24
1977	100.08	55.37	61.47	23.11	263.14	190.25	437.13	355.35	475.74	146.30	240.54	295.66
1978	107.19	133.35	51.82	136.65	123.70	327.41	220.22	470.41	486.92	459.74	281.69	228.09
1979	98.55	80.26	179.32	101.09	224.03	535.18	366.78	497.08	243.59	309.37	186.44	340.36
1980	58.93	116.84	163.07	196.09	268.48	343.41	453.14	241.81	322.83	340.61	182.88	368.81
1981	327.66	203.20	73.41	27.94	128.27	273.56	470.92	345.69	483.36	361.19	257.05	279.65
1982	185.42	319.53	190.50	66.55	266.45	813.05	331.22	362.20	353.82	237.24	125.73	178.05
1983	31.75	6.86	70.10	34.54	91.19	177.29	409.96	421.39	319.79	212.60	344.42	136.65
1984	135.38	243.59	99.06	56.13	44.96	314.45	243.59	389.38	162.81	439.17	305.56	138.18
1985	367.28	83.06	170.18	224.28	172.97	473.71	292.61	393.45	440.44	261.87	147.07	363.73
1986	191.26	269.49	276.86	176.28	243.59	332.23	390.14	285.75	312.67	193.55	357.38	149.35
1987	151.38	124.71	49.78	121.92	100.58	280.42	383.54	707.90	135.13	170.18	164.34	69.60
1988	93.47	92.20	71.12	99.82	184.15	266.45	350.27	135.89	370.84	561.85	229.11	227.08
1989	256.29	311.15	181.86	118.36	270.76	344.42	344.17	450.85	297.69	341.63	181.36	220.98
1990	157.73	59.18	80.77	148.08	318.01	583.18	312.17	578.10	369.82	192.02	239.78	56.39
1991	214.88	53.09	62.48	92.71	124.97	340.87	437.13	342.65	392.43	440.18	172.21	94.74
1992	106.68	38.10	75.44	33.27	37.59	192.79	329.69	411.73	262.13	569.72	70.36	157.99
1993	161.04	169.67	292.86	148.08	37.34	292.86	398.53	363.22	306.83	260.86	239.52	346.46
1994	205.99	96.52	78.74	284.23	260.35	370.59	378.21	291.85	392.68	85.34	71.12	246.63
1995	200.15	248.67	82.04	45.21	256.03	157.23	166.37	318.26	331.72	437.64	230.89	406.40
1996	499.11	326.64	141.48	172.47	375.41	188.72	499.11	196.60	537.46	337.57	214.12	683.01
1997	341.38	249.68	116.33	68.33	61.47	403.61	384.30	336.55	275.59	265.68	158.50	150.62
1998	112.78	34.04	13.72	5.33	61.21	456.44	304.80	305.56	460.50	409.19	201.93	194.31
1999	152.15	138.94	231.90	379.98	389.13	406.15	329.18	501.40	223.01	125.73	328.93	316.74

2000	114.05	117.86	248.16	187.71	559.05	256.54	518.92	391.16	232.16	457.45	253.49	312.17
2001	127.51	173.74	151.89	58.42	279.65	384.30	478.28	534.92	189.23	186.18	192.02	304.55
2002	121.16	170.94	150.37	137.67	109.22	612.14	497.33	658.37	446.53	350.77	165.35	137.67
2003	151.89	42.93	193.80	166.12	562.36	297.18	620.27	343.15	467.36	429.51	391.41	345.44
2004	163.58	138.94	279.65	262.38	286.77	382.02	328.42	569.98	305.05	210.06	451.36	101.09
2005	176.28	51.82	151.64	326.14	136.40	349.25	431.04	424.18	284.48	84.58	295.66	250.70
2006	114.05	84.58	115.32	86.36	214.63	232.16	353.31	461.01	470.66	187.20	124.46	505.97
2007	181.10	117.35	159.51	176.78	414.53	276.86	382.27	339.34	456.18	442.72	324.10	221.74
2008	168.40	163.83	68.07	171.20	246.13	133.10	195.58	269.75	525.27	359.16	198.63	211.33
2009	218.44	370.84	80.26	299.21	163.32	215.39	446.53	197.10	421.89	280.92	265.68	95.50
2010	134.37	53.85	109.73	180.59	75.18	251.21	450.34	456.18	255.78	440.18	219.46	164.59
2011	299.72	170.43	261.11	183.39	383.54	344.42	529.34	486.66	534.16	312.93	251.97	247.90
2012	53.59	154.69	214.12	127.00	282.96	297.18	323.60	505.21	640.08	433.83	271.02	220.47
2013	145.29	150.88	130.56	71.37	137.41	410.46	203.20	322.33	619.51	447.04	166.62	141.22
2014	552.20	119.89	177.55	323.09	77.98	252.73	417.07	243.33	428.75	237.24	142.24	425.96
2015	148.84	116.84	107.19	198.12	467.36	281.18	314.71	558.55	233.93	134.37	84.07	125.22
2016	56.64	44.96	17.78	88.14	226.06	164.08	254.76	332.74	225.81	508.00	350.01	218.19
2017	321.82	487.43	237.49	157.23	137.16	207.26	464.06	208.28	319.79	482.35	238.76	286.26
2018	295.66	214.38	312.17	96.52	188.21	296.42	401.57	375.41	372.36	141.22	305.56	271.27
2019	403.86	39.88	123.95	74.17	181.61	333.76	311.15	294.13	224.03	216.92	236.22	251.21
2020	37.08	83.31	28.96	108.97	204.22							

Table 2. Tamil area monthly rainfall.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	M	M	M	M	M	353.82	433.07	348.74	465.84	403.10	185.93	126.24
1992	125.22	53.09	62.48	31.50	41.66	256.54	318.77	344.68	253.49	670.81	76.20	M
1993	134.62	131.06	275.08	123.44	29.46	415.54	347.98	496.82	240.28	221.74	268.99	389.38
1994	155.45	161.29	93.98	112.01	162.31	405.89	505.21	269.24	480.06	57.91	102.11	255.52
1995	176.28	278.64	124.97	30.73	205.74	145.54	128.52	312.17	270.76	271.78	210.31	303.78
1996	361.70	250.70	44.20	163.32	389.64	239.27	580.64	320.80	421.13	295.40	290.58	457.96
1997	227.84	228.09	78.49	88.14	35.56	385.57	401.07	214.12	230.63	273.56	159.00	84.07
1998	117.35	24.64	10.41	9.14	45.72	290.32	252.48	343.41	381.00	447.55	169.42	187.45
1999	193.04	146.81	253.24	357.89	384.30	319.53	254.25	331.98	239.78	196.34	321.56	320.29
2000	132.08	115.82	245.62	194.31	566.67	159.26	492.51	275.84	215.90	254.51	330.45	362.20
2001	152.15	118.87	106.43	30.99	158.50	205.49	589.28	575.31	138.68	90.68	187.45	172.47
2002	164.85	216.92	102.87	141.73	137.92	172.21	321.56	608.84	407.16	204.47	180.85	69.09
2003	128.78	28.19	165.35	189.99	313.44	229.62	492.00	400.05	M	375.16	325.12	258.32
2004	123.19	127.51	247.65	M	M	M	M	M	M	M	149.86	122.94
2005	202.95	36.07	113.79	M	M	374.90	388.62	448.56	279.65	130.30	247.40	340.87
2006	187.71	159.00	158.50	75.95	201.93	254.00	453.64	378.97	365.76	216.66	121.41	414.53
2007	123.44	74.42	81.53	292.35	394.46	288.04	275.59	297.94	587.76	348.49	391.92	342.65
2008	151.13	71.37	111.76	182.37	258.83	138.43	239.27	271.78	397.51	267.46	M	185.67
2009	220.22	368.30	109.47	105.16	144.02	277.37	381.00	206.50	520.70	249.43	354.33	86.11
2010	104.65	M	128.78	189.74	93.73	270.76	314.20	289.05	220.47	320.04	171.70	191.01
2011	367.03	225.55	230.63	354.08	422.66	357.89	511.81	390.91	503.17	438.66	340.36	250.19
2012	39.88	201.93	209.04	96.01	M	M	M	M	M	M	M	M
2013	M	M	M	M	M	M	M	338.07	M	419.35	153.67	133.86
2014	614.93	143.00	200.15	265.68	84.84	136.65	258.83	435.10	475.49	214.12	185.67	402.08
2015	189.99	127.51	103.63	225.30	424.43	314.45	396.24	476.76	376.94	66.04	M	138.68
2016	50.04	49.78	21.34	71.63	205.49	M	160.02	413.51	287.02	494.28	379.22	239.01
2017	378.46	635.51	294.39	125.22	167.89	238.76	M	244.09	440.18	473.46	227.84	348.49
2018	287.53	185.42	342.14	115.32	212.60	375.41	M	509.27	346.46	243.84	310.90	226.57
2019	323.09	M	146.56	77.47	164.59	542.80	316.23	335.79	305.31	262.89	322.83	270.51

Annex 2 – Pumping test schedule and list of participants

Table 3. Summary of the pumping test program with all the schedules and logistics.

Date	Time	YSPSC wells	GTWA wells	Monitoring wells	Water disruption support
25/09/2019	8.00 am	Pumping of all bores (1, 2, 3, 5 and 6) and filling of YSPSC tanks	Pumping of all bores (2, 3 and 4) to fill up both the Gagil and Tomil tanks with enough water for at least 24 hours	NA	Discussion and agreement with National Fire Service on water cartage schedules in relation to the pumping test schedule 2. Radio communication on potential water disruption undertaken to adequately inform affected customers
	2.00 pm	Measured static water level and well depth prior to installing CTD divers in pump 2, 5	Measured static water level and well depth prior to installing CTD divers	Measure groundwater levels and well depth and install CTD divers	
	4.00 pm	All pumping stations were shut down to allow groundwater recovery prior to the 48 hours test the following day	All pumping stations were shut down to allow groundwater recovery prior to the 48-hr test from the YSPSC well stations the following day		National Fire Service stood by for water carting support when required
26/09/2019	8.00 am	Groundwater levels in pumping wells measured prior to pumping test commencement	Groundwater levels in pumping wells measured prior to pumping test commencement	Groundwater levels in monitoring wells measured prior to pumping test commencement	
	9.00 am	Pumping of wells 1, 2, 3, 5, 6 with periodical pumping rates and decreasing groundwater level or groundwater drawdown measurements taken	instantaneous groundwater drawdown measurements taken	instantaneous groundwater drawdown measurements taken	
	8.30 pm		Pumps were turned on for 5 hours due to rapid decline in tank water level, indicating potential leakage in the distribution system		
28/09/2019	9.00 am	Pumping stopped - instantaneous increase in groundwater level or groundwater recovery measurements taken	instantaneous groundwater recovery measurements taken	instantaneous groundwater recovery measurements taken	GTWA managers required to monitor the tanks levels until critical level is reached and when water carting support is done by the NFS to cart water from the YSPSC tanks and/or from nearby and accessible Fire outlet into the GTWA tanks.
29/09/2019	9.00 am	72-hr pumping test with pumping of wells 1, 2, 3, 5, 6. Decreasing	72-hr pumping test of wells 2, 3, 4 with periodical pumping rates and decreasing groundwater level or	instantaneous drawdown measurements taken	NA

		groundwater level or groundwater drawdown measurements taken	groundwater drawdown measurements taken		
2/10/2019	11.00 am	YSPSC continued pumping and abstraction after the 72-hr pumping test to meet water supply demand due to tank rehabilitation works	Pumping stopped - instantaneous increase in groundwater level or groundwater recovery measurements taken	instantaneous groundwater recovery measurements taken	
3/10/2019	9.00 am	All recovery measurements stopped			

Table 4. List of participants during the stakeholders engagement meeting held on Monday, 7 October 2019.

Name	**Position**	**Organisation**
Joe Tun	Treasurer	Gagil-Tomil Water Authority (GTWA)
Charles Falmeyog	Water Division Manager	Yap State Public Service Cooperation (YSPSC)
John Guswel	Manager	Southern Yap Water Authority (SYWA)
Noel Yagisemal	Adaptation Project-Yap State Coordinator	FSM Adaptation Project
Anastasia Perogolo	Water Quality Officer	Yap Environmental Protection Authority (EPA)
Francis Itimai	Director	Office of Planning and Budget (OPB)
Linda Phamau	Member	DYCA
William Bamoon	Technician	GTWA
Edmund Wogthuth	Manager	GTWA
Ezekiel Kenfathlee	Watershed Project Coordinator	Tamil Resources Conservation Trust (TRCT)
Jonathan Fathal	Chief of Planning	OPB
Victor Bamog	Disaster Coordinating Officer	OPB
Jesse Gadjusek	Grant Writer	OPB
Jesse Salalu	Lieutenant Governor	Yap State Governor's Office
Gidion Moofal	Customer Service Manager	YSPSC
Christina Fillmed	Director	Yap EPA
Dominic Brug	Board member	GTWA
Tom Fetan	Chairman	Tamil Municipal Council

Annex 3 – Pumping test data

Pumping test introduction

A pumping test, also known as drawdown test, involves the pumping or dewatering of either a single or a group of groundwater wells for a pre-determined period and at a fixed (and known) abstraction rate. Since the start of pumping, measurements on the instantaneous decline in groundwater level (or drawdown) in the pumping wells, and the surrounding monitoring wells were taken to determine how the groundwater-bearing formation responds to a unit head drop (Kruseman et al. 1970).

Pumping test methodology

In preparation for the test, measurements of groundwater level and total well depth were taken and recorded for the pumping and monitoring wells within the two valleys. *Solinst* water level meters Model 101 equipped with conductivity and depth sensors, were used to measure groundwater and salinity levels.

Table 5 illustrates the time intervals where groundwater levels were taken from the start and from the termination of pumping for the drawdown and recovery tests, respectively. Efforts were made to ensure that all pumps started around the same time. Other data elements required to better understand and estimate the groundwater movement and hydraulic conditions in the underlying aquifer are presented in Table 6.

Table 5. Measurement intervals for groundwater level since start of pumping test.

Time since start/termination of pumping (minutes)	Measurement interval
0–10	30 seconds
10–15	1 minute
15–60	5 minutes
60–360	30 minutes
360–1440	1 hour
1440–2880	5 hours
2880–pump shutdown	12 hours

Table 6. Critical data elements to be collected from pumping and monitoring wells to confidently estimate the aquifer's hydraulic properties

Data source	Pumping wells	Monitoring bores
Initial groundwater condition	Measured groundwater level prior to pumping test start	Measured groundwater level prior to pumping test and monitoring started
Pumping time	Note start time of pumping in minutes	Note start time of pumping at the nearest well in minutes
Water level changes	Measured drawdown in meters or feet since pumping starts	Measured drawdown in metres or feet since pumping starts
Salinity or electrical conductivity	Measured electrical conductivity	Measured electrical conductivity
Influence of pumping	Note distance of nearby pumping well to see possible interference	Note distance from the pumping well(s) in line with water level changes
Pumping or abstraction rate	Pump rate at pumping wells in gpm or L/s	Pump rate or combined pumping rate at nearest pumping well(s)
Hydraulic Parameters	transmissivity and hydraulic conductivity	transmissivity, hydraulic conductivity and storativity

The drawdown test was followed by the recovery test or residual drawdown when pumping ceases and the groundwater levels in the wells and the piezometers start to rise – rapidly in the first hour, but more slowly afterwards. If the pumping rate during the drawdown test are not kept constant, recovery test data are more reliable than the drawdown data because the water table recovers at a constant rate, which is usually the average of the pumping rate. The data from a recovery test can also be used to check the calculations made based on the drawdown data (Kruseman et al. 1990).

Data analysis

The analysis of the pumping test (drawdown) and recovery (residual drawdown) data measured in both the pumping and monitoring wells results in the estimation of aquifer parameter such as hydraulic conductivity (K in m/d), transmissivity (T in m^2/d) and specific storage or storativity (dimensionless). The analysis was conducted in Microsoft Excel, where drawdown and residual drawdown data were plotted against pumping test times on either a log-log or semi-log plot, depending on the scale at which noticeable trends can be best presented.

The compilation and analysis of pumping test and recovery data was done in line with tested groundwater pumping test models and conditions and coupled with some assumptions. The conceptual model applied was that of a fractured volcanic breccia system that is partially confined by overlying clayey formations. The pumping test data were treated as a confined aquifer having unsteady flow and with the following assumptions, as suggested by Kruseman et al. (1990):

1. The aquifer has a seemingly infinite areal extent; the aquifer is homogeneous and of uniform thickness over the area influenced by the test.
2. Prior to pumping, the piezometric surface is horizontal over the area that will be influenced by the test.
3. The aquifer is pumped at a constant rate.
4. The wells penetrate the entire thickness of the aquifer and, thus, received water by horizontal flows.
5. The water removed from aquifer storage is discharged instantaneously with decline in head.
6. The diameter of the well is small, thus the storage in the well can be neglected.

The Jacob straight line analytical method was used for assessing confined aquifers with unsteady flow state. This method works on a semi-log analysis similar to the one documented by Nance (1982). The reader is invited to look into the "Analysis and evaluation of pump test data" (Kruseman et al. 1990) for more information.

In summary, the **Jacob straight method** is such that:

1. **$T = 2.3*Q/2*\pi*\Delta s$** where T is the transmissivity and expressed as m^2/day, Q is the abstraction rate and expressed as L/day and Δs is derived from the linear semi-log drawdown and recovery data.
2. **$S = 4Tt_0/r^2$** where S is the dimensionless storativity, T is the transmissivity, t_0 is the match point time, and r is the distance from the pumping well; this means storativity can only be estimated from observation or monitoring wells.
3. **K = T/D** where K is the hydraulic conductivity expressed as m/day, T is the transmissivity (m^2/day) calculated in 1 above and D is the estimated aquifer thickness based on available drill logs in the two well fields.

These methods are ideally used in single pumping wells with one or more monitoring wells nearby and measuring different drawdown responses as the cone of depression expands over time. This is not the case here – the pumping test programme involved multiple pumping wells in the two valleys, whereby the monitoring wells were responding to a combined abstraction effect rather than a single abstraction point. Thus, two nominated points were generated through the centroid in-built function in QGIS to generate an averaged location of all the wells, one for the YSPSC wellfield (Eyeb) and one for the GTWA wellfield (Monguch). This was used to simulate a single pumping well scenario in both valleys where the total abstraction can be assigned. Thus, in the analysis of the drawdown and recovery data discussed later, aquifer properties were estimated using responses from each of the pumping wells when reliable data were obtained as well as from a number of monitoring bores when reliable water level trends could be established. These monitoring bores included M1, M4, M5 and GTWA B1.

Logistics

This pumping test was undertaken on a network of pumping wells used for public and municipal water supply systems which posed a series of challenges. There was a need to balance the requirements of a pumping test to ensure meaningful results while trying to keep water disruption to a minimum. This required the coordination of major authorities and stakeholders.

Pumping test schedule:

1. A 48-hour pumping test on YSPSC wells followed by the 24-hour recovery period from 26 to 29 September – during this time groundwater level changes were taken on all the pumping wells and monitoring wells. GTWA production bores were shut down with no to minimal abstraction.
2. A 72-hour pumping test of both YSPSC and GTWA wells at optimum abstraction followed by a 24-hour recovery test.

Key to the success of this exercise was the timely and meaningful communication and coordination between SPC, YSPSC, GTWA and the National Fire Service (NFS). This information exchange included a clear understanding and agreement amongst the water manager of the pumping schedules, the need to closely monitor the tank levels to determine when and how much water cartage is required, have a clear communication line and simultaneously manage and respond to customers during the entire exercise.

Limitations and challenges

Several limitations were encountered during the tests.

1. Over the seven days of pumping and recovery period, several periods of heavy rain were encountered, and 1.52 in (49 mm) of rain was recorded (Source: Yap Weather Service, acis-compare.rcc-acis.org). These rainfall events resulted in sudden increases in groundwater levels observed in the wells during the dewatering process. The rainfall events were regarded as an external input to the greater system that may complicate the analysis of aquifer drawdown (Kruseman et al. 1990).

2. During the first 48 hours of pumping the YSPSC wells, all the GTWA wells were supposed to not operate for that entire period in order to allow the impacts of YSPSC pumping only to be assessed in both the valleys. The GTWA manager, who closely monitored the tank water levels in Gagil and Tomil, determined that GTWA pumping was required during the 48-hour period to ensure sufficient water supply to communities. GTWA manager identified that the Gagil tank water level was drawing down faster than expected, and suggested there was a possible leakage in the distribution line. A leakage detection programme is recommended to identify leakage and ensure optimum groundwater use and management.

3. Variations in pumping rates (Q) were observed in all the wells and in most cases pumps were observed to be decreasing in yield, which does not satisfy the assumption of a constant rate of pumping. This is probably attributed to the discharge from the pumping wells into the distribution pipe network and to storages, rather than to outflow unrestricted from the pump. Discharge (Q) was observed to be the highest during the early pumping stages, when the distribution line and the storage tanks were empty and pressure was low, allowing the pumps to operate at near maximum yield with relatively free water flow. As pumping continues and all wells contribute water into the piping network, pressure builds up in the pipes, resulting in reduced flow and forcing the pump impellers to adjust to the new pressure condition.

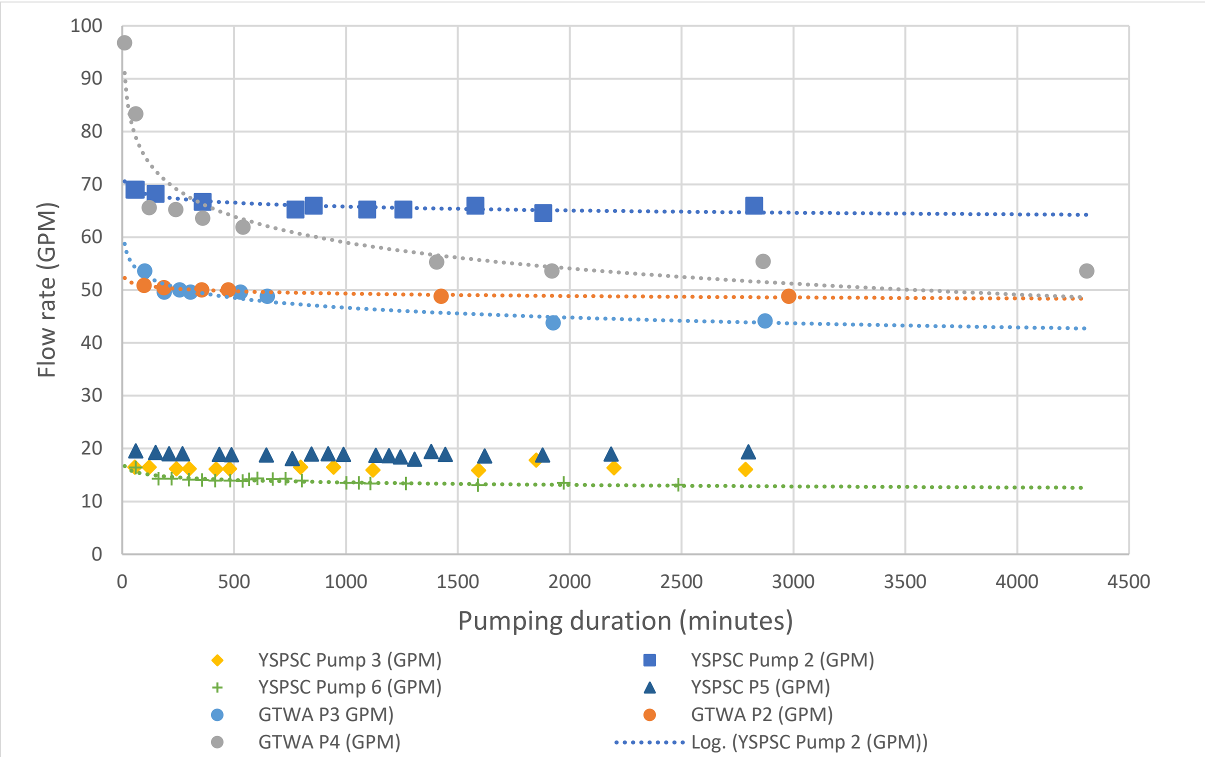

Figure 24. Variability in discharge rates (Q) recorded in pumping wells.

The GTWA wells displayed the highest variations – this is possibly related to how the distribution system works where water is pumped to the Gagil tank first (2.4 km to the east) before feeding the Tomil reservoir (1.2 km to the northwest). The delayed discharge associated with this distribution plan will only reduce Q further as observed in this case. The YSPSC wells, on the other hand, are only required to fill up one tank located around 1 km from the well field and with its outlet open for the nearby communities. This would suggest that pressure buildup is regulated and minimised by the constant flow of water through the tank outlet.

4. Faulty water level meters were identified in YSPSC wells 6 and 7 due to the sensitivity of the instrument not being sufficient to indicate the water level. This resulted in erroneous data due to difficulties in discerning drawdown levels. This rendered the drawdown data from these wells invalid.

Pumping test data

Table 7. YSPSC pumping well P2 drawdown data.

Actual Time	Time (min)	DTW (ft)	DTW (m)	Drawdown (m)
26/09/2019 9.27am	0.5	22.80	6.95	3.25
	1	33.00	10.07	6.36
	1.5	37.00	11.29	7.58
	2	39.40	12.02	8.31
	2.5	41.20	12.57	8.86
	3	42.40	12.93	9.23
	3.5	43.40	13.24	9.53
	4	44.70	13.63	9.93
	4.5	45.90	14.00	10.29
	5	47.20	14.40	10.69
	5.5	47.60	14.52	10.81
	6	48.40	14.76	11.06
	6.5	49.20	15.01	11.30
	7	49.70	15.16	11.45
	7.5	50.30	15.34	11.64
	8	50.80	15.49	11.79
	8.5	51.10	15.59	11.88
	9	51.60	15.74	12.03
	9.5	51.90	15.83	12.12
	10	52.40	15.98	12.28
	11	53.00	16.17	12.46
	12	53.60	16.35	12.64
	13	54.10	16.50	12.79
	14	54.40	16.59	12.89
	15	54.70	16.68	12.98
	20	56.10	17.11	13.40
	25	57.20	17.45	13.74
	30	58.10	17.72	14.01
	35	58.70	17.90	14.20
	40	59.40	18.12	14.41
	45	59.90	18.27	14.56
	50	60.40	18.42	14.72
	55	60.70	18.51	14.81
	60	61.10	18.64	14.93
10.57 am	90	62.80	19.15	15.45
11.27 am	120	64.20	19.58	15.88
11.57 am	150	65.10	19.86	16.15
12.27 pm	180	65.90	20.10	16.39
12.57 pm	210	66.70	20.34	16.64
1.27 pm	240	67.35	20.54	16.84
1.57 pm	270	67.95	20.72	17.02
2.27 pm	300	68.40	20.86	17.16
3.27 pm	360	69.35	21.15	17.45
4.37 pm	430	70.20	21.41	17.71
5.28 pm	481	70.60	21.53	17.83
7.03 pm	576	70.75	21.58	17.87
8.18 pm	651	71.15	21.70	18.00
9.25 pm	718	71.50	21.81	18.10
10.22 pm	775	71.69	21.87	18.16
11.43 pm	856	71.90	21.93	18.22
27/09/2019 00.55 am	928	72.05	21.98	18.27
2.15 am	1008	72.05	21.98	18.27
3.42 am	1095	72.15	22.01	18.30
5.42 am	1215	72.30	22.05	18.35
6.23 am	1256	72.35	22.07	18.36
7.35 am	1328	72.50	22.11	18.41
8.45 am	1398	72.50	22.11	18.41
9.34 am	1447	72.50	22.11	18.41
11.46 am	1579	72.75	22.19	18.48
4.49 pm	1882	72.95	22.25	18.54
9.57 pm	2190	73.75	22.49	18.79
28/09/2019 8.00 am	2793	74.00	22.57	18.86
8.32 am	2825	74.55	22.74	19.03

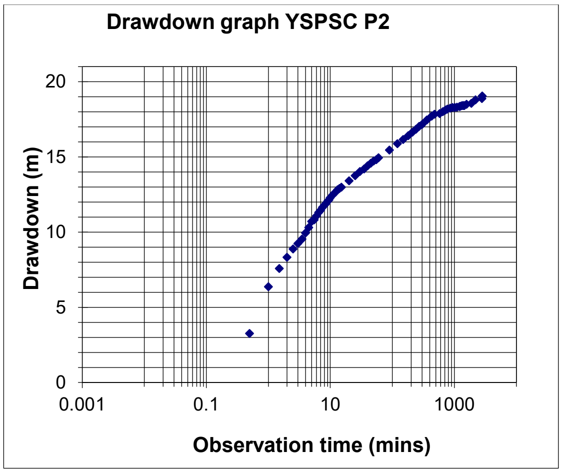

Figure 2. YSPSC well P2 semi-log drawdown graph.

Table 8. YSPSC pumping well P2 recovery data.

Date/Clock Time	Time (mins)	DTW (m)	Recovery (m)	t/t"
28/09/2019 8.34 am	0.5	22.052	18.803	5650.00
	1	19.612	16.363	2825.00
	1.5	17.538	14.289	1883.33
	2	16.531	13.283	1412.50
	2.5	15.830	12.581	1130.00
	3	15.128	11.880	941.67
	3.5	14.518	11.270	807.14
	4	14.106	10.858	706.25
	4.5	13.695	10.446	627.78
	5	13.298	10.050	565.00
	5.5	13.069	9.821	513.64
	6	12.871	9.623	470.83
	6.5	12.688	9.440	434.62
	7	12.444	9.196	403.57
	7.5	12.215	8.967	376.67
	8	12.002	8.754	353.13
	8.5	11.819	8.571	332.35
	9	11.651	8.403	313.89
	9.5	11.483	8.235	297.37
	10	11.331	8.083	282.50
	11	11.072	7.823	256.82
	12	10.523	7.274	235.42
	13	10.401	7.152	217.31
	14	10.172	6.924	201.79
	15	9.989	6.741	188.33
	20	9.425	6.176	141.25
	25	9.074	5.826	113.00
	30	8.738	5.490	94.17
	35	8.546	5.298	80.71
	40	8.418	5.170	70.63
	45	8.220	4.972	62.78
	50	8.083	4.834	56.50
	55	7.808	4.560	51.36
9.34 am	60	7.747	4.499	47.08
	90	7.198	3.950	31.39
10.34 am	120	6.771	3.523	23.54
11.10 am	156	6.390	3.142	18.11
11.40 am	186	6.085	2.837	15.19
12.11 pm	217	5.856	2.608	13.02
12.41 pm	247	5.749	2.501	11.44
1.11 pm	278	5.475	2.227	10.16
1.41 pm	308	5.322	2.074	9.17
2.41 pm	368	5.048	1.800	7.68
3.41 pm	428	4.819	1.571	6.60
4.41 pm	487	4.621	1.373	5.80
5.41 pm	547	4.438	1.190	5.16
6.41 pm	607	4.301	1.052	4.65
29/09/2019 8.49 am	1455	3.279	0.031	1.94
9.36 am	1502	3.248	0.000	1.88

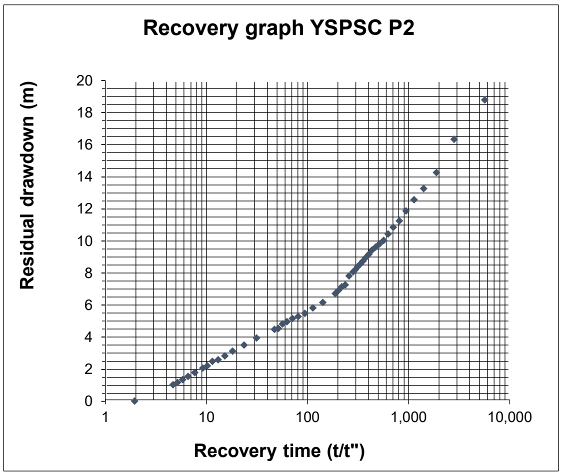

Figure 3. YSPSC pumping well P2 semi-log recovery graph.

Table 9. YSPSC pumping well P3 drawdown data.

Actual Time	Time (min)	DTW (m)	Drawdown (m)
26/09/2019 9.20 am	0.5	3.580	0.975
	1	3.990	1.385
	1.5	4.470	1.865
	2	4.730	2.125
	2.5	3.980	1.375
	3		
	3.5	5.340	2.735
	4	5.490	2.885
	4.5	5.610	3.005
	5	5.730	3.125
	5.5	5.860	3.255
	6	5.920	3.315
	6.5	5.990	3.385
	7	6.040	3.435
	7.5	6.060	3.455
	8	6.110	3.505
	8.5	6.060	3.455
	9	6.080	3.475
	9.5	6.120	3.515
	10	6.140	3.535
	11	6.170	3.565
	12	6.200	3.595
	13	6.240	3.635
	14	6.270	3.665
	15	6.320	3.715
	20	6.420	3.815
	25	6.540	3.935
	30	6.610	4.005
	35	6.700	4.095
	40	6.780	4.175
	45	6.820	4.215
	50	6.840	4.235
	56	6.870	4.265
10.20 am	60	6.890	4.285
	90	7.080	4.475
11.20 am	120	7.090	4.485
	150	7.175	4.570
12.20 am	180		
	210		
1.23 pm	243	7.360	4.755
	270	7.430	4.825
2.20 pm	300	7.550	4.945
3.31 pm	371	7.610	5.005
4.20 pm	420	7.590	4.985
5.20 pm	480	7.670	5.065
7.29 pm	609	7.865	5.260
8.37 pm	677	7.960	5.355
9.34 pm	734	8.150	5.545
10.38 pm	798	8.750	6.145
11.52 pm	872	8.850	6.245
27/09/2019 1.05 am	945	8.115	5.510
2.38 am	1038	8.115	5.510
4.01 am	1121	8.080	5.475
4.54 am	1174	8.060	5.455
5.50 am	1230	8.045	5.440
7.12 am	1312	8.050	5.445
7.53 am	1353	8.050	5.445
8.53 am	1413	8.050	5.445
11.53 am	1593	8.110	5.505
4.17 pm	1850	8.120	5.515
10.05 pm	2198	8.425	5.820
28/09/2019 7.53 am	2786	8.525	5.920
8.25 am	2818	8.831	6.226
8.35 am	2828	8.625	6.020

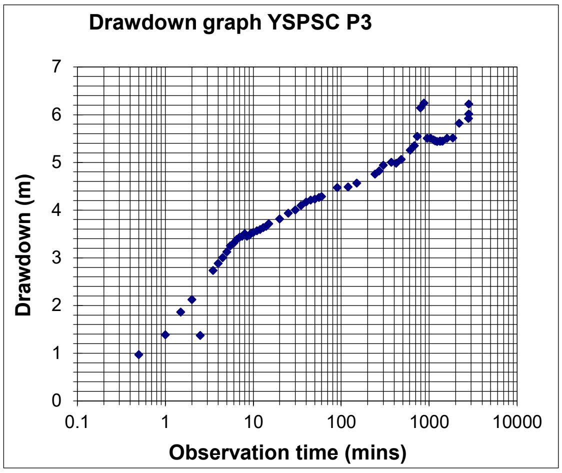

Figure 4. YSPSC pumping well P3 semi-log drawdown graph.

Table 10. YSPSC pumping well P3 recovery data.

Date/Clock Time	Time (minutes)	DTW (m)	Recovery (m)
28/09/2019 8.35 am	0.5	8.140	5.750
	1	7.800	5.410
	1.5	7.880	5.490
	2	6.940	4.550
	2.5	6.685	4.295
	3	6.300	3.910
	3.5	6.105	
	4	5.905	3.515
	4.5	5.700	3.310
	5	5.530	3.140
	5.5	5.390	3.000
	6	5.335	2.945
	6.5		
	7	5.170	2.780
	7.5		
	8	5.040	2.650
	8.5	5.005	2.615
	9	4.970	2.580
	9.5	4.920	2.530
	10	4.900	2.510
	11	4.820	2.430
	12	4.780	2.390
	13	4.720	2.330
	14	4.675	2.285
	15	4.650	2.260
	20	4.480	2.090
	25	4.330	1.940
	30	4.240	1.850
	35	4.145	1.755
	40	4.075	1.685
	45	4.020	1.630
	50	3.980	1.590
	55	3.925	1.535
9.35 am	60	3.875	1.485
	90	3.675	1.285
10.35 am	120	3.555	1.165
	150	3.450	1.060
11.35 am	180	3.375	0.985
	210	3.315	0.925
12.35 pm	240	3.255	0.865
	270	3.180	0.790
1.35 pm	300	3.115	0.725
2.35 pm	360	3.065	0.675
3.35 pm	420	2.960	0.570
4.35 pm	480	2.900	0.510
5.35 pm	540	2.840	0.450
6.35 pm	600	2.785	0.395
29/09/2019 8.42 am	1447	2.420	0.030
9.51 am	1516	2.390	0.000

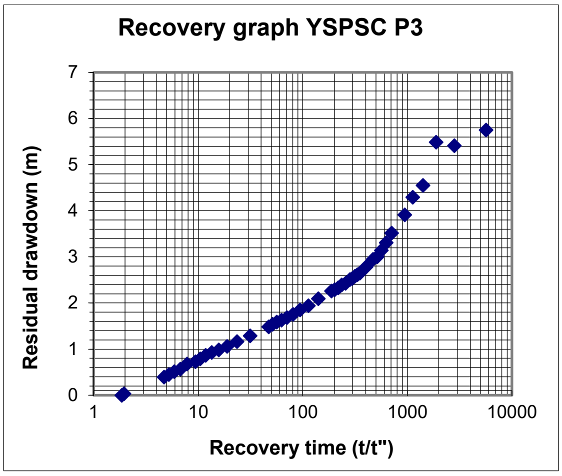

Figure 5. Semi-log recovery graph for YSPSC pumping well P3.

Table 11. YSPSC pump P5 drawdown or pumping test record.

Actual Time	Time (min)	DTW (m)	Drawdown (m)
26/09/2019 9.43 am	15	2.013	1.495
	20	2.013	1.495
	25	2.013	1.495
	30	2.013	1.495
	35	2.013	1.495
	40	2.013	1.495
	45	2.013	1.495
	50	2.013	1.495
	55	2.028	1.510
	60	2.044	1.525
10.58 am	90	2.059	1.540
11.28 am	120	2.044	1.525
11.58 am	150	2.059	1.540
12.28 pm	180	2.074	1.556
12.58 pm	210	2.074	1.556
1.28 pm	240	2.089	1.571
1.58 pm	270	2.089	1.571
2.28 pm	300	2.089	1.571
3.28 pm	360	2.089	1.571
4.53 pm	445	2.089	1.571
5.33 pm	485	2.135	1.617
7.07 pm	579	2.120	1.601
8.20 pm	652	2.135	1.617
9.27 pm	719	2.135	1.617
10.33 pm	785	2.150	1.632
11.33 pm	845	2.150	1.632
27/09/2019 1.00 am	932	2.147	1.629
2.00 am	992	2.144	1.626
3.27 am	1079	2.150	1.632
4.14 am	1126	2.135	1.617
5.25 am	1197	2.150	1.632
6.27 am	1259	2.150	1.632
7.37 am	1329	2.135	1.617
8.47 am	1399	2.166	1.647
9.36 am	1448	2.150	1.632
11.49 am	1581	2.166	1.647
4.45 pm	1877	2.173	1.655
10.00 pm	2192	2.196	1.678
28/09/2019 8.00 am	2792	2.211	1.693

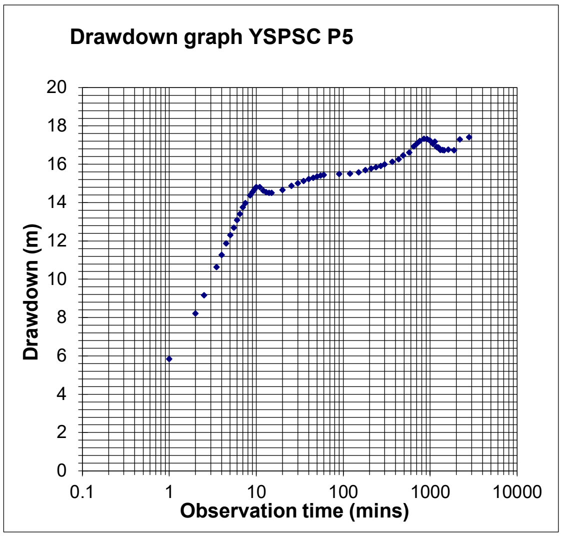

Figure 6. YSPSC pump 5 semi-log drawdown graph.

Table 12. GTWA pump P5 recovery data.

Date/Clock Time	Time (minutes)	DTW (m)	Recovery (m)
28/09/2019 8:31 am	0	19.470	17.720
	0.5	17.740	15.990
	1	16.250	14.500
	1.5	15.210	13.460
	2	14.220	12.470
	2.5	13.045	11.295
	3	12.065	10.315
	4.2	10.405	8.655
	4.5	9.715	7.965
	5	9.065	7.315
	5.5	8.555	6.805
	6	8.025	6.275
	6.5	7.535	5.785
	7.5	6.700	4.950
	8	6.345	4.595
	8.5	6.095	4.345
	9	5.865	4.115
	9.5	5.685	3.935
	10	5.525	3.775
	11	5.280	3.530
	12.2	5.065	3.315
	13	4.890	3.140
	14	4.725	2.975
	15	4.595	2.845
8:51:00 am	20	4.230	2.480
8:54:00 am	23	4.045	2.295
9:01:00 am	30	3.895	2.145
9:04:00 am	33	3.780	2.030
9:11:00 am	40	3.685	1.935
9:16:00 am	45	3.585	1.835
9:21:00 am	50	3.515	1.765
9:24:00 am	53	3.465	1.715
9:31:00 am	60	3.400	1.650
10:01:00 am	90	3.145	1.395
10:31:00 am	120	2.980	1.230
11:01:00 am	150	2.845	1.095
11:31:00 am	180	2.730	0.980
12:01:00 pm	210	2.665	0.915
12:31:00 pm	240	2.600	0.850
1:01:00 pm	270	2.530	0.780
1:31:00 pm	300	2.480	0.730
2:19:00 pm	348	2.410	0.660
3:31:00 pm	420	2.340	0.590
4:31:00 pm	480	2.250	0.500
5:29:00 pm	538	2.195	0.445
6:31:00 pm	600	2.140	0.390
8:35:00 am	1444	1.755	0.005
10:00:00 am	1529	1.750	0.000

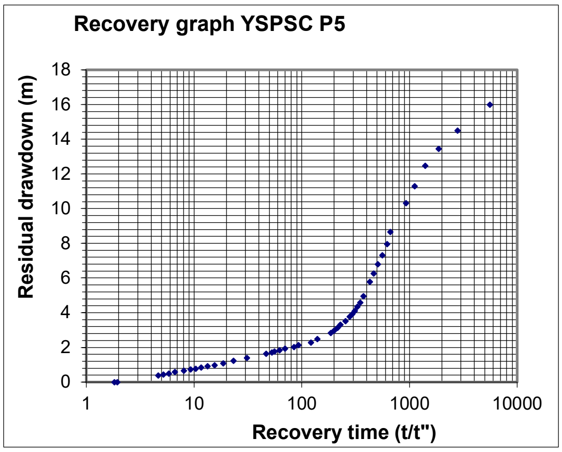

Figure 7. YSPSC pump 5 semi-log recovery graph.

Table 13. YSPSC pump P6 drawdown or pumping test data.

Actual Time	Time (min)	DTW (m)	Drawdown (m)
26/09/2019 9:05	0	5.120	0.000
	0.5		
	1		
	1.5		
	2		
	2.5		
	3		
	3.5		
	4		
	4.5		
	5.01		
	5.5		
	6		
	6.5		
	7		
	7.5		
	8		
	8.5	23.890	18.770
	9		
	9.5	23.960	18.840
	10		
	11		
	12		
	13		
	14	23.900	18.780
	15	23.890	18.770
9:25:00 am	20	23.885	18.765
9:30:00 am	25	23.880	18.760
9:35:00 am	30	23.870	18.750
9:40:00 am	35	23.875	18.755
9:45:00 am	40	23.870	18.750
	45	23.875	18.755
	50	23.870	18.750
10:03:00 am	55	23.880	18.760
10:05:00 am	60	23.870	18.750
10:36:00 am	91	23.875	18.755
11:05:00 am	120	23.875	18.755
11:47:00 am	162	23.875	18.755
12:09:00 pm	184	23.880	18.760
12:46:00 pm	221	23.885	18.765
12:59:00 pm	234	23.880	18.760
1:39:00 pm	274	23.880	18.760
2:03:00 PM	298	23.885	18.765
3:02:00 PM	357	23.880	18.760
4:01:00 PM	416	23.875	18.755
5:08:00 PM	483	23.885	18.765
6:03:00 PM	538	23.885	18.765
7:38:00 PM	633	23.890	18.770
8:47:00 PM	702	23.920	18.800
9:43:00 PM	689	23.900	18.780
10:53:00 PM	759	23.900	18.780
12:06:00 AM	832	23.900	18.780
1:31:00 AM	917	23.910	18.790
2:49:00 AM	985	23.900	18.780
3:35:00 AM	1031	23.890	18.770
4:31:00 AM	1087	23.895	18.775
5:22:00 AM	1138	23.895	18.775
6:48:00 AM	1224	23.890	18.770
8:01:00 AM	1297	23.870	18.750
9:08:00 AM	1364	23.890	18.770
12:41:00 PM	1577	23.930	18.810
4:00:00 PM	1619	23.895	18.775
10:23:00 PM	2002	23.885	18.765
7:55:00 AM	2514	23.890	18.770

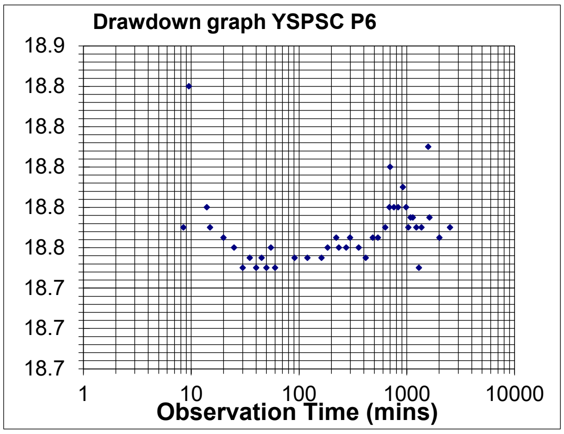

Figure 8. YSPSC pump P6 semi-log drawdown graph.

Table 14. YSPSC pump P6 recovery data.

Date/Clock Time	Time (minutes)	DTW (m)	Recovery (m)
28/09/2019 8:16	0	23.890	18.840
	0.5	22.310	17.260
	1	21.320	16.270
	1.5		
	2	20.090	15.040
	2.66	18.820	13.770
	3	18.580	13.530
	3.75	17.160	12.110
	4	17.120	12.070
	4.5	17.170	12.120
	5.5	16.880	11.830
	6.25	16.400	11.350
	6.5	16.280	11.230
	7	16.330	11.280
	7.5	16.100	11.050
	8	16.100	11.050
	50	6.775	1.725
	74	6.450	1.400
	82	6.400	1.350
	90	6.310	1.260
	120	6.140	1.090
	150	6.000	0.950
	180	5.895	0.845
	210	5.795	0.745
	240	5.740	0.690
12:43:00 pm	270	5.685	0.635
1:14:00 pm	301	5.630	0.580
2:25:00 pm	372	5.525	0.475
3:20:00 pm	427	5.465	0.415
4:20:00 pm	487	5.400	0.350
5:20:00 pm	547	5.370	0.320
6:19:00 pm	606	5.335	0.285
9:16:00 am	1509	5.500	0.450
10:20:00 am	1573	5.050	0.000

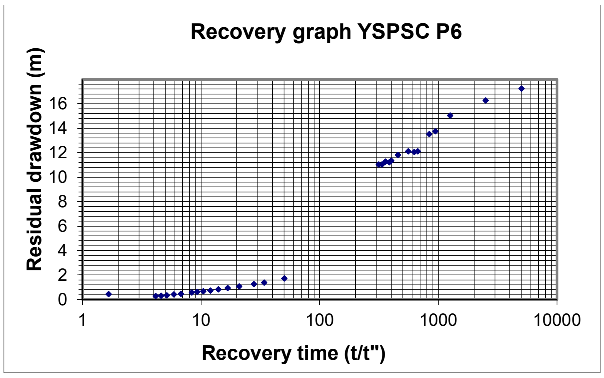

Figure 9. YSPSC pump P6 semi-log recovery graph.

Table 15. YSPSC pump P7 drawdown. Note this was used as a monitoring bores as the pump was not working due electrical fault.

Actual Time	Time (min)	DTW (m)	Drawdown (m)
26/9/19 9.05 am	1	1.775	0.0000
9:57:00 am	52	1.775	0.0000
10:33:00 am	88	1.775	0.0000
11:11:00 am	126	1.775	0.0000
11:52:00 am	167	1.780	0.0050
1:09:00 pm	234	1.785	0.0100
1:44:00 pm	269	1.780	0.0050
2:12:00 pm	297	1.760	-0.0150
3:09:00 pm	354	1.760	-0.0150
4:08:00 pm	413	1.765	-0.0100
5:17:00 pm	482	1.775	0.0000
6:05:00 pm	530	1.775	0.0000
7:42:00 pm	627	1.775	0.0000
8:51:00 pm	696	1.780	0.0050
9:47:00 pm	752	1.790	0.0150
11:10:00 pm	835	1.820	0.0450
12:18:00 am	903	1.805	0.0300
1:25:00 am	970	1.790	0.0150
2:57:00 am	1062	1.800	0.0250
3:40:00 am	1105	1.800	0.0250
4:35:00 am	1160	1.800	0.0250
5:34:00 am	1219	1.810	0.0350
6:51:00 am	1296	1.805	0.0300
8:04:00 am	1369	1.815	0.0400
9:11:00 am	1436	1.815	0.0400
12:47:00 pm	1652	1.820	0.0450
3:50:00 pm	1835	1.820	0.0450
10:20:00 pm	2225	1.840	0.0650
7:58:00 am	2803	1.850	0.0750

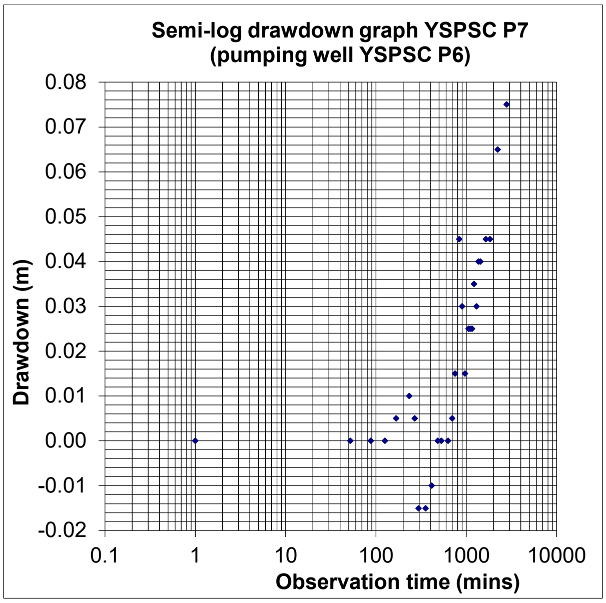

Figure 10. YSPSC pump 7 semi-log drawdown graph, which was used as an additional monitoring bores due to non-operation but data was erroneous.

Table 16. GTWA pump B1 72-hour drawdown or pumping test data.

Actual Time	Time (min)	DTW (m)	Drawdown (m)
29/09/2019 9.26 am			
11.47 am	141	3.530	0.980
1.05 pm	219	3.750	1.200
2.45 pm	319	3.995	1.445
3.41 pm	375	4.110	1.560
4.49 pm	443	4.190	1.640
5.39 pm	503	4.250	1.700
6.40 pm	564	4.420	1.870
30/09/2019 9.23 am	1437	4.845	2.295
5.41 pm	1935	5.095	2.545
01/10/2019 9.25 am	2879	5.185	2.635

Table 17. Drawdown records measured at GTWA B2 pumping well.

Actual Time	Time (min)	DTW (m)	Drawdown (m)
29/09/2019 9.26 am			
11.14 am	98	7.425	6.000
12.43 pm	187	7.680	6.255
2.34 pm	298	7.910	6.485
3.32 pm	356	8.030	6.605
4.43 pm	427	8.100	6.675
5.30 pm	474	8.185	6.760
6.33 pm	537	8.255	6.830
30/09/2019 9.12 am	1426	8.570	7.145
5.40 pm	1934	8.785	7.360
01/10/2019 9.25 am	2979	8.860	7.435

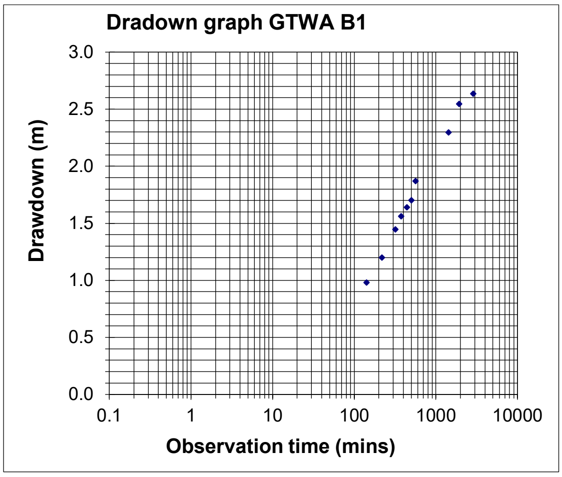

Figure 11. GTWA B1 semi-log drawdown graph.

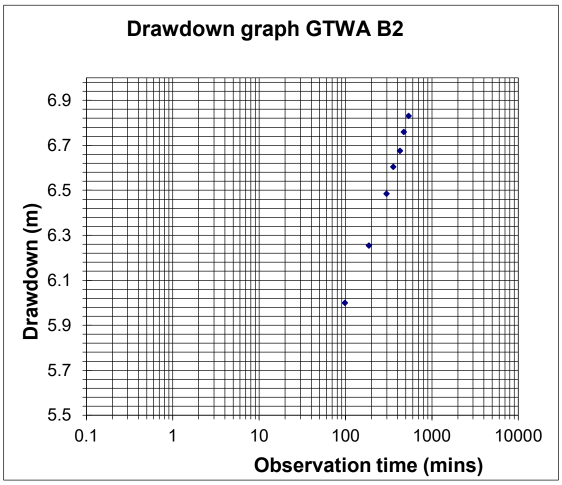

Figure 13. GTWA B2 semi-log graph.

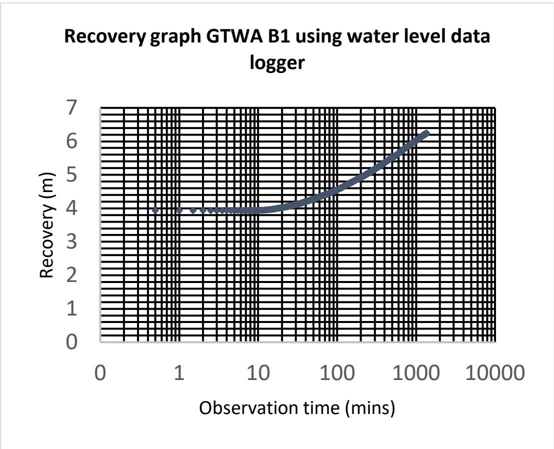

Figure 12. GTWA B1 semi-log recovery graph based on water level logger readings.

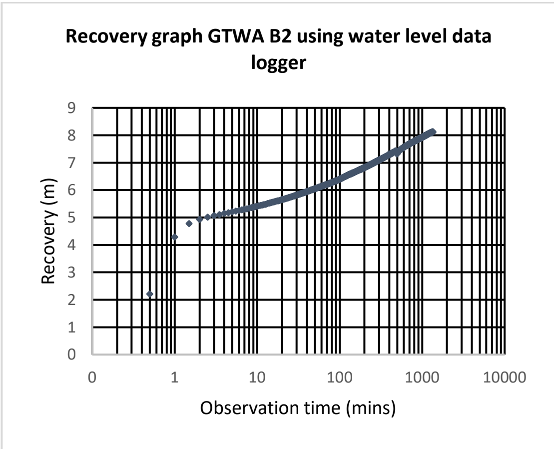

Figure 14. GTWA B2 semi-log recovery graph using water level data loggers.

Table 18. GTWA pump 3 drawdown or pumping test.

Actual Time	Time (min)	DTW (m)	Drawdown
29/09/2019 9.26 am			
11.14 am	98	7.425	6.000
12.43 pm	187	7.680	6.255
2.34 pm	298	7.910	6.485
3.32 pm	356	8.030	6.605
4.43 pm	427	8.100	6.675
5.30 pm	474	8.185	6.760
6.33 pm	537	8.255	6.830
30/09/2019 9.12 am	1426	8.570	7.145
5.40 pm	1934	8.785	7.360
01/10/2019 9.25am	2979	8.860	7.435

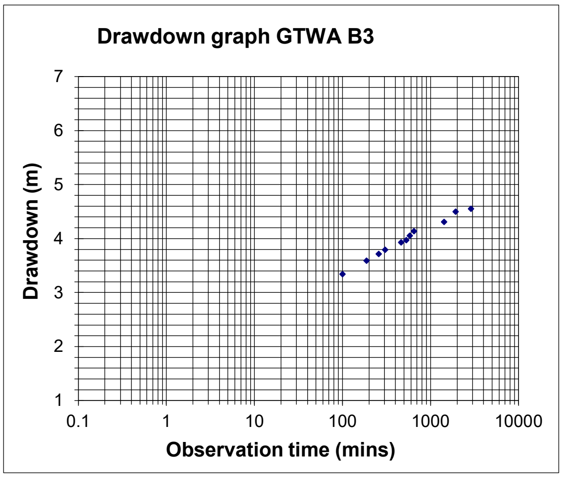

Figure 15. GTWA B2 semi-log drawdown graph.

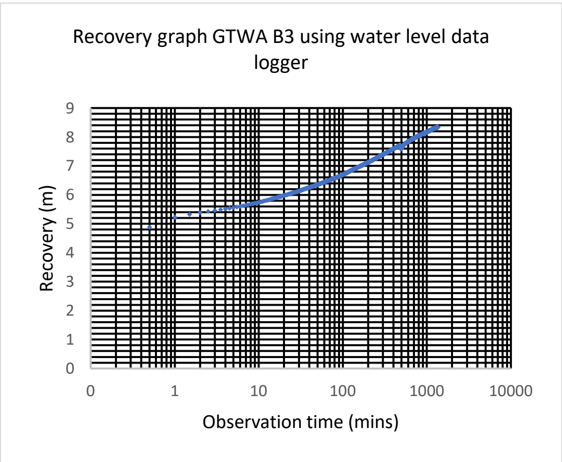

Figure 16. GTWA B3 semi-log recovery graph using water level data loggers.

Table 19. GTWA pump B4 72-hours drawdown or pumping test record.

Actual Time	Time (min)	DTW (m)	Drawdowm (m)
29/09/2019 9.24 am	0.5	5.640	2.225
	1	5.900	2.485
	1.5	5.980	2.565
	2	6.050	2.635
	2.5	6.120	2.705
	3	6.155	2.740
	3.5	6.190	2.775
	4	6.230	2.815
	4.5	6.260	2.845
	5	6.260	2.845
	5.5	6.315	2.900
	6	6.335	2.920
	6.5	6.365	2.950
	7	6.385	2.970
	7.5	6.405	2.990
	8	6.415	3.000
	8.5	6.430	3.015
	9	6.440	3.025
	9.5	6.455	3.040
	10	6.470	3.055
	11	6.500	3.085
	12	6.510	3.095
	13	6.535	3.120
	14	6.560	3.145
	15	6.585	3.170
	20	6.665	3.250
	25	6.750	3.335
	30	6.850	3.435
	35	6.960	3.545
	40	7.015	3.600
	45	7.085	3.670
	50	7.095	3.680
	55	7.150	3.735
10.24 am	60	7.100	3.685
	90	7.135	3.720
11.24 am	120	6.755	3.340
	150	6.855	3.440
12.24 pm	180	6.865	3.450
	210	6.990	3.575
1.24 pm	240	7.050	3.635
	270	7.100	3.685
2.23 pm	299	7.160	3.745
3.24 pm	360	7.270	3.855
4.24 pm	420	7.360	3.945
5.24 pm	480	7.430	4.015
6.24 pm	540	7.500	4.085
7.24 pm	600	7.555	4.140
30/09/2019 8.50 am	1406	7.615	4.200
5.24 pm	1920	7.825	4.410
01/10/2019 9.08 am	2864	7.895	4.480
5.24 pm	3360	8.050	4.635
02/10/2019 9.15 am	4311	8.025	4.610

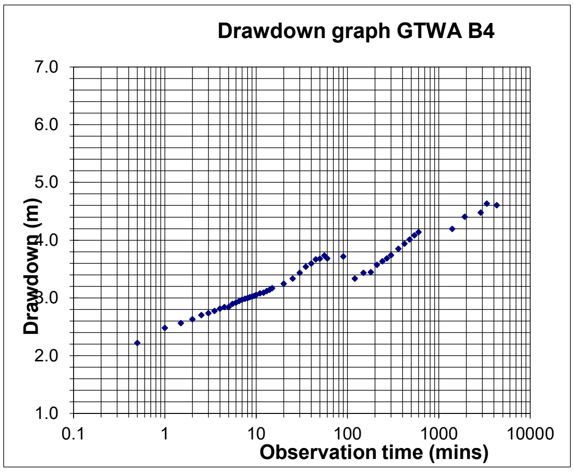

Figure 17. GTWA B4 semi-log drawdown curve.

Table 20. GTWA pump 4 recovery data.

Date/Clock Time	Time (minutes)	DTW (m)	Recovery (m)
02/10/2019 11.06 am	0.5	8.080	4.665
	1	7.090	3.675
	1.5	6.995	3.580
	2	6.890	3.475
	2.5	6.850	3.435
	3	6.830	3.415
	3.5	6.750	3.335
	4		
	4.5	6.730	3.315
	5	6.715	3.300
	5.5	6.695	3.280
	6	6.675	3.260
	6.5	6.655	3.240
	7	6.635	3.220
	7.5	7.620	4.205
	8	6.605	3.190
	8.5	6.585	3.170
	9	6.570	3.155
	9.5	6.555	3.140
	10	6.540	3.125
	11	6.500	3.085
	12	6.475	3.060
	13	6.455	3.040
	14	6.435	3.020
	15	6.410	2.995
	20	6.310	2.895
	25	6.220	2.805
	30	6.145	2.730
	35	6.080	2.665
	40	6.015	2.600
	45	5.960	2.545
	50	5.915	2.500
	55	8.870	5.455
12.06 pm	60	5.820	2.405
	90	5.595	2.180
1.06 pm	120	5.435	2.020
	150	5.275	1.860
2.06 pm	180	5.165	1.750
	210	5.050	1.635
3.06 pm	240	4.955	1.540
	270	4.875	1.460
4.06 pm	300	4.795	1.380
5.06 pm	360	4.660	1.245
6.06 pm	420	4.560	1.145
7.06 pm	480	4.460	1.045

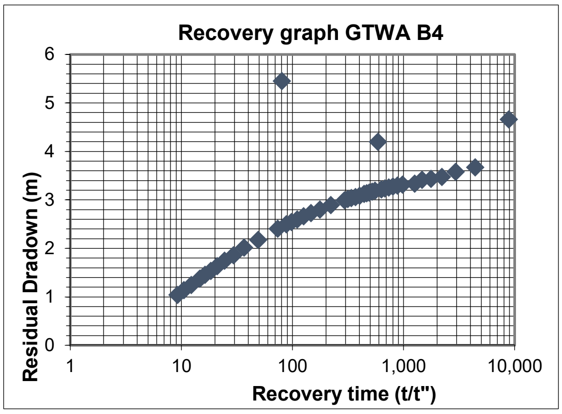

Figure 18. GTWA B4 semi-log recovery graph.

Annex 4 – Groundwater monitoring data from CTD data loggers

Pressure transducer-type loggers measure water pressure in cm of water above the instrument, which is then converted into a water level; the loggers also measure electrical conductivity (EC) and temperature. The loggers are suspended on stainless steel wire to an adequate depth to ensure they are always submerged below the water. A barometric logger concurrently measures atmospheric pressure at the surface to compensate for any changes in atmospheric pressure.

Table 21. Well characteristics and logger installation depths.

Well name	Measuring point ft (m)	Total depth ft (m)	Static water level Sept 2019 ft (m)	Logger depth ft (m)
GTWA B1	1.08 (0.33)	111.65 (34.03)	7.28 (2.22)	29.72 (9.06)
GTWA B2	1.03 (0.32)	116.99 (35.66)	3.35 (1.02)	31.20 (9.51)
GTWA B3	1.33 (0.41)	96.49 (29.41)	3.10 (0.95)	30.97 (9.44)
YSPSC P2	3.48 (1.06)	124.02 (37.80)	7.41 (2.26)	88.58 (27.00)
YSPSC P7	0.72 (0.22)	84.97 (25.90)	5.09 (1.55)	45.93 (14.00)
YSPSC M1	2.00 (0.61)	91.70 (27.95)	1.94 (0.59)	87.60 (26.70)
YSPSC M2	1.44 (0.44)	56.59 (17.25)	4.66 (1.42)	52.66 (16.05)
YSPSC M3	3.20 (0.98)	132.81 (40.48)	5.31 (1.62)	130.71 (39.84)
YSPSC M4	2.79 (0.85)	117.62 (35.85)	22.47 (6.85)	113.68 (34.65)
YSPSC M5	3.28 (1.00)	129.59 (39.50)	3.94 (1.20)	125.59 (38.28)

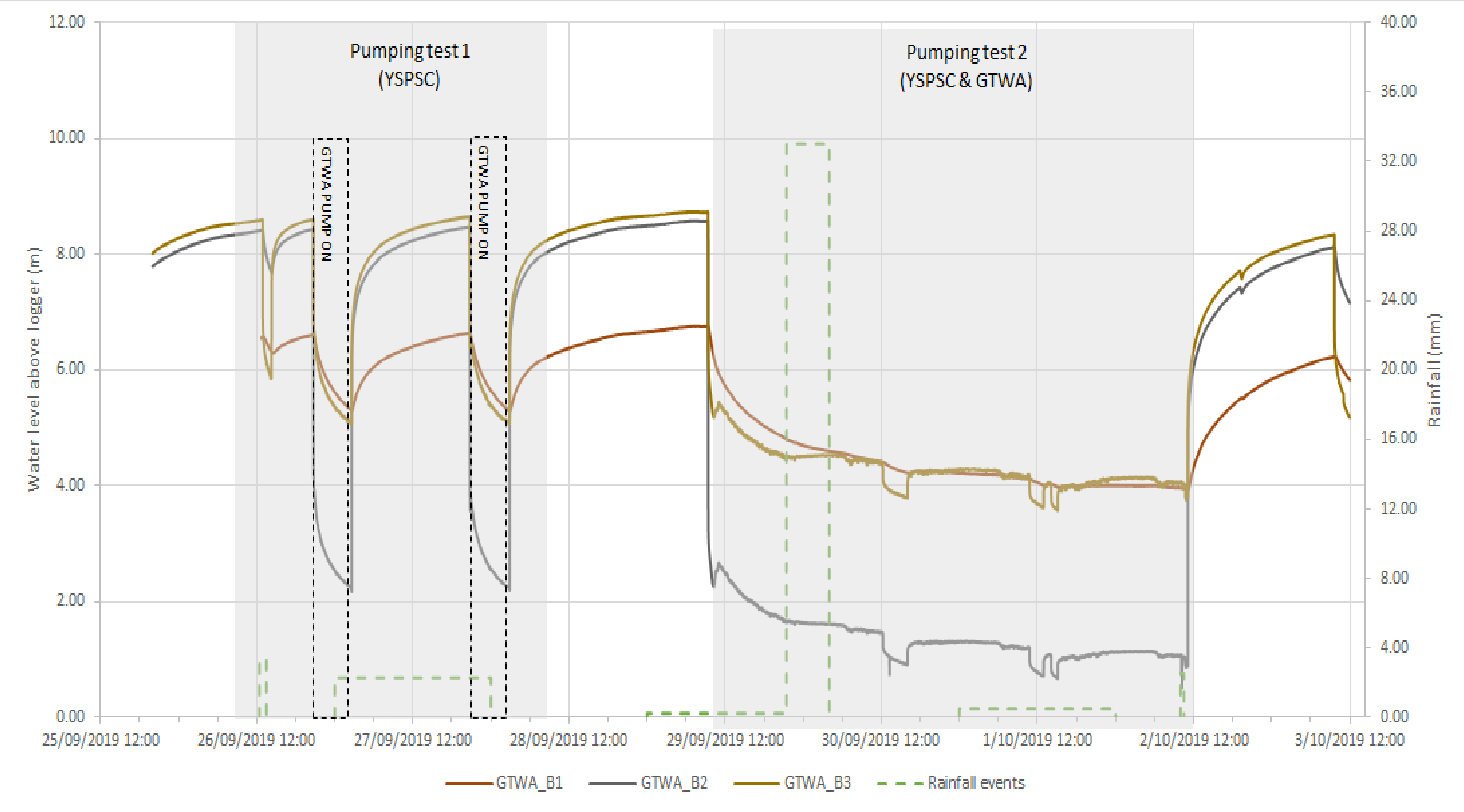

Figure 19. Logger data in GTWA production bores B1, B2, B3, during pumping tests. Note B1 is non-operational, B2, and B3 were pumped for 6 hours per night during the YSPSC 48-hour pumping test.

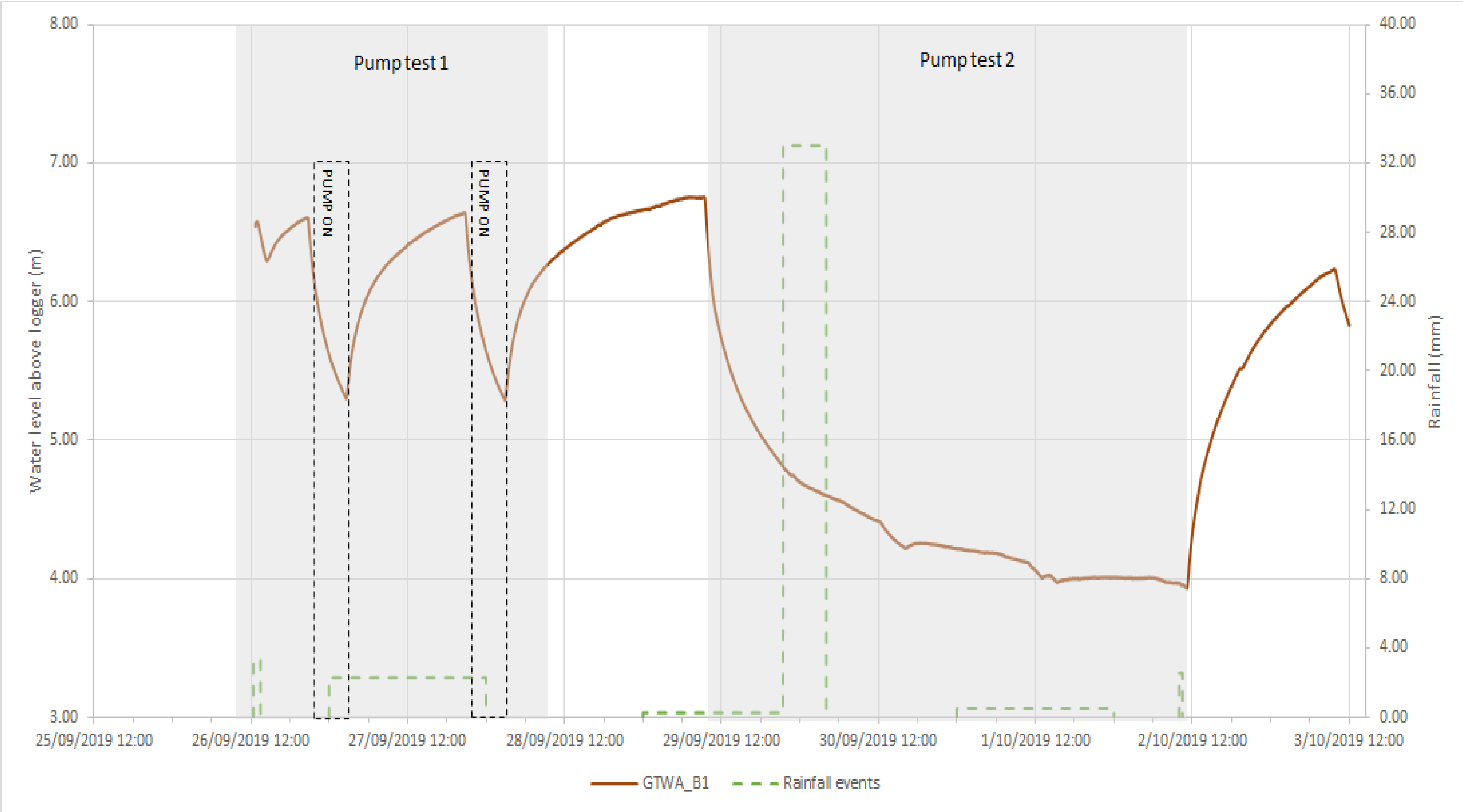

Figure 20. GTWA B1 water level response during pumping tests. B1 is non-operational and responds to pumping from B2 and B3.

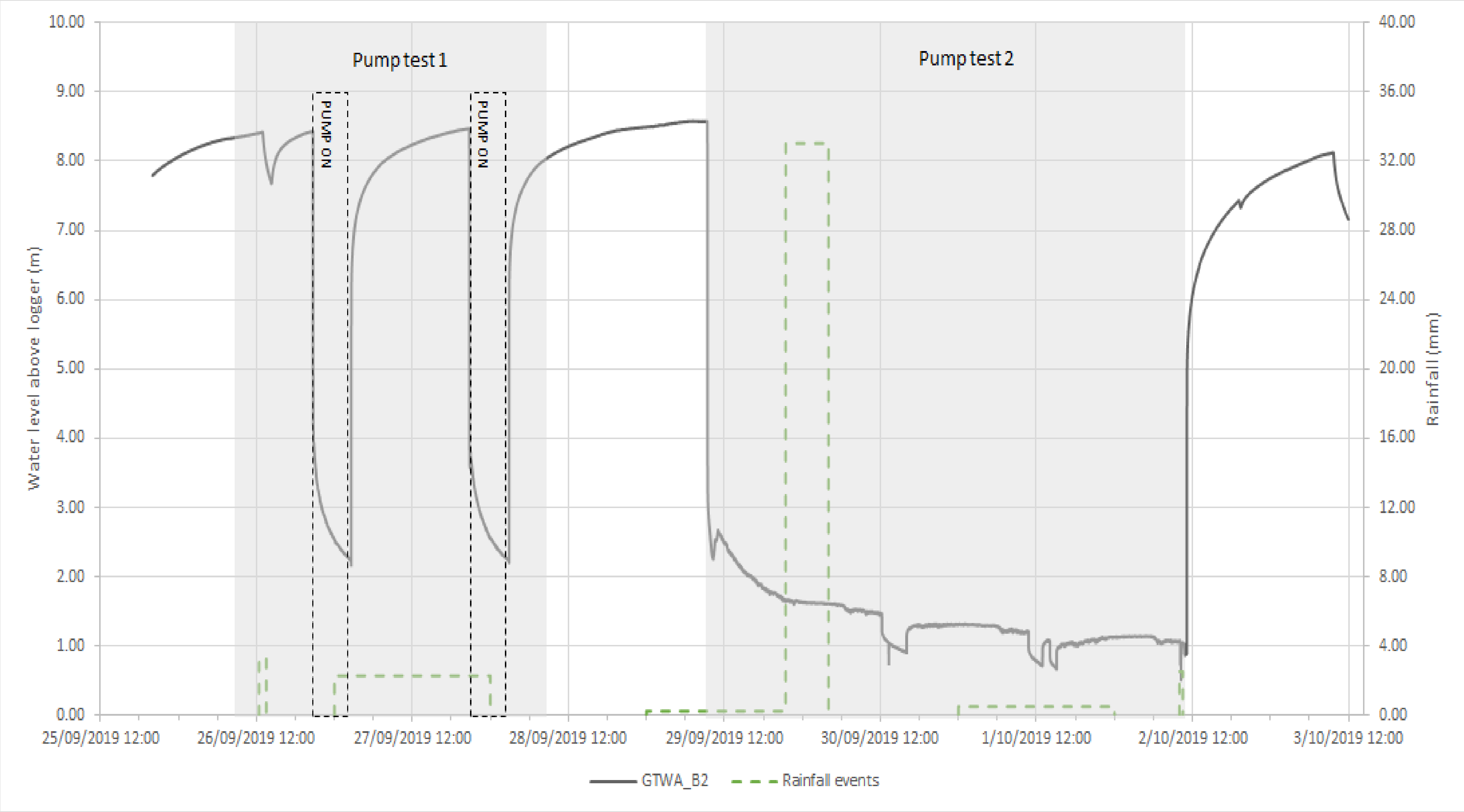

Figure 21. GTWA B2 water level response during pumping tests.

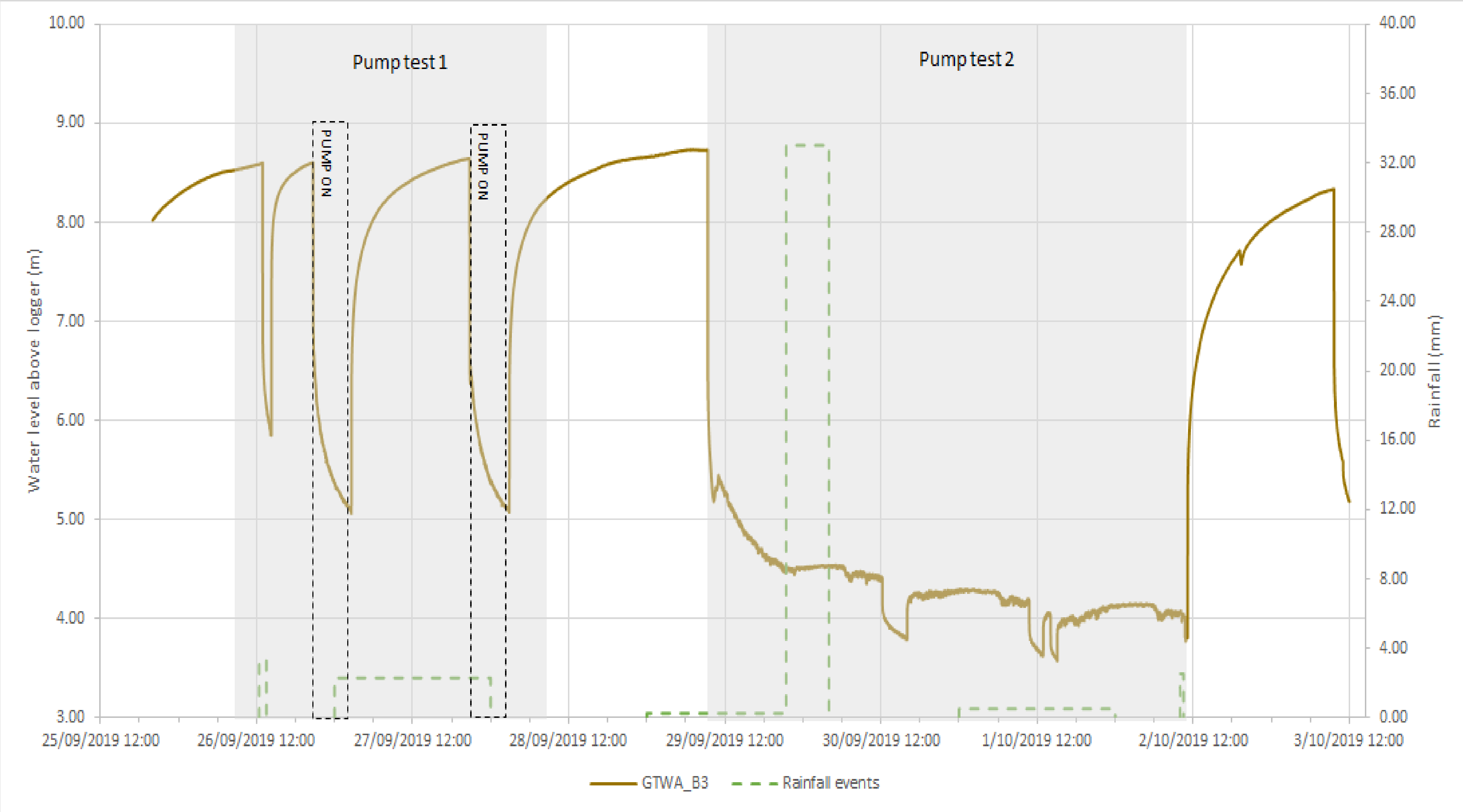

Figure 22. GTWA B3 water level response during pumping tests.

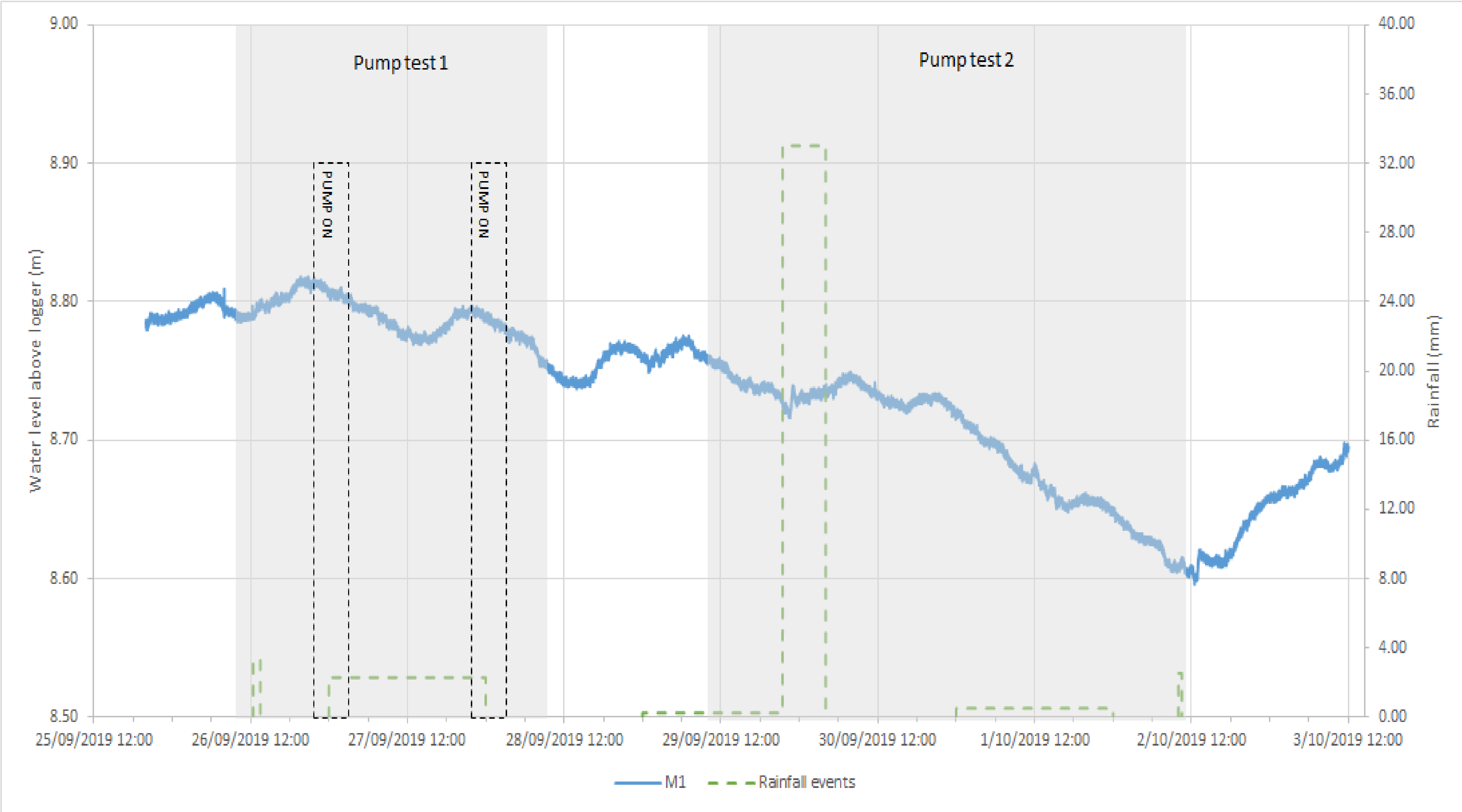

Figure 23. YSPSC M1 water level response during pumping tests.

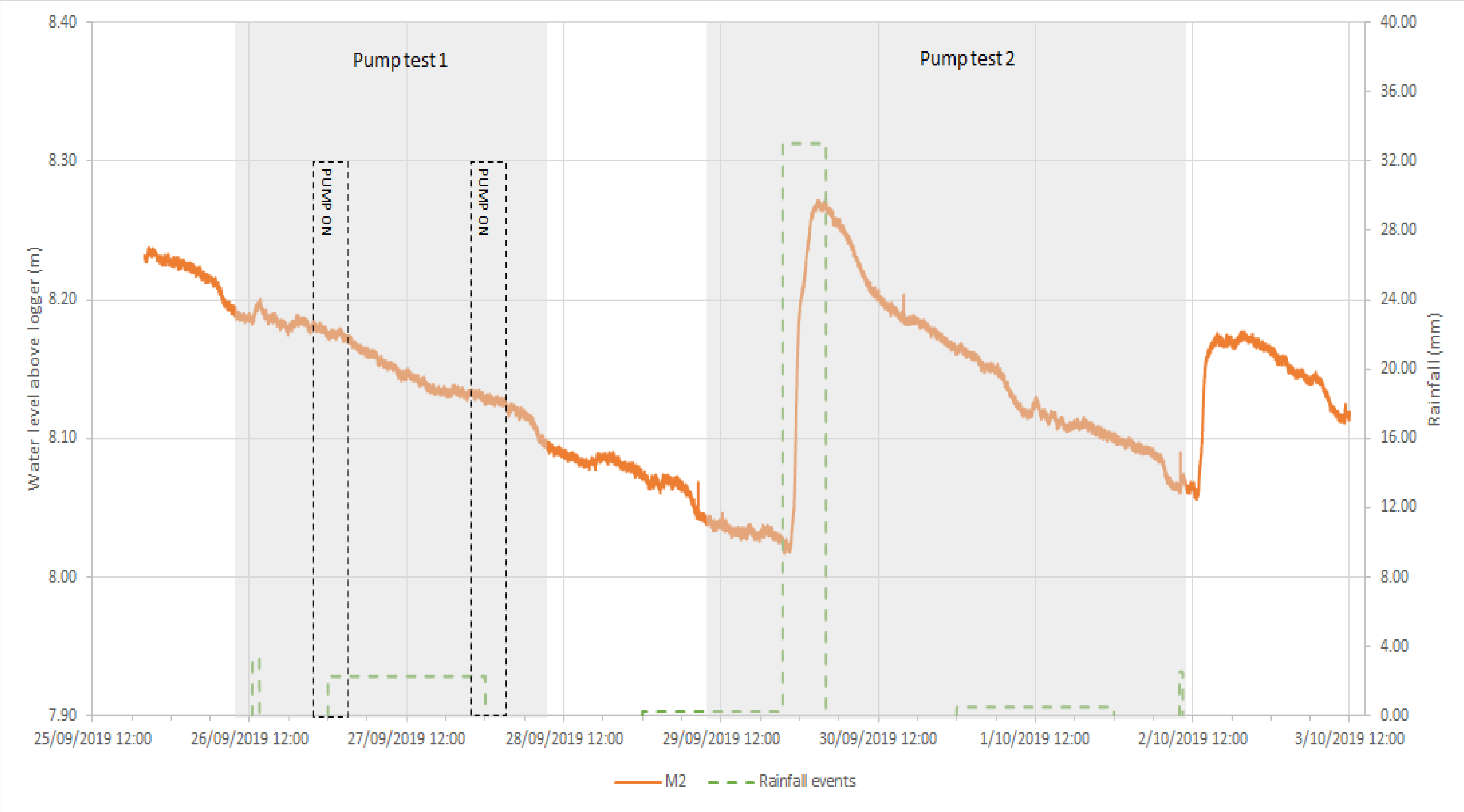

Figure 24. YSPSC M2 water level response during pumping tests.

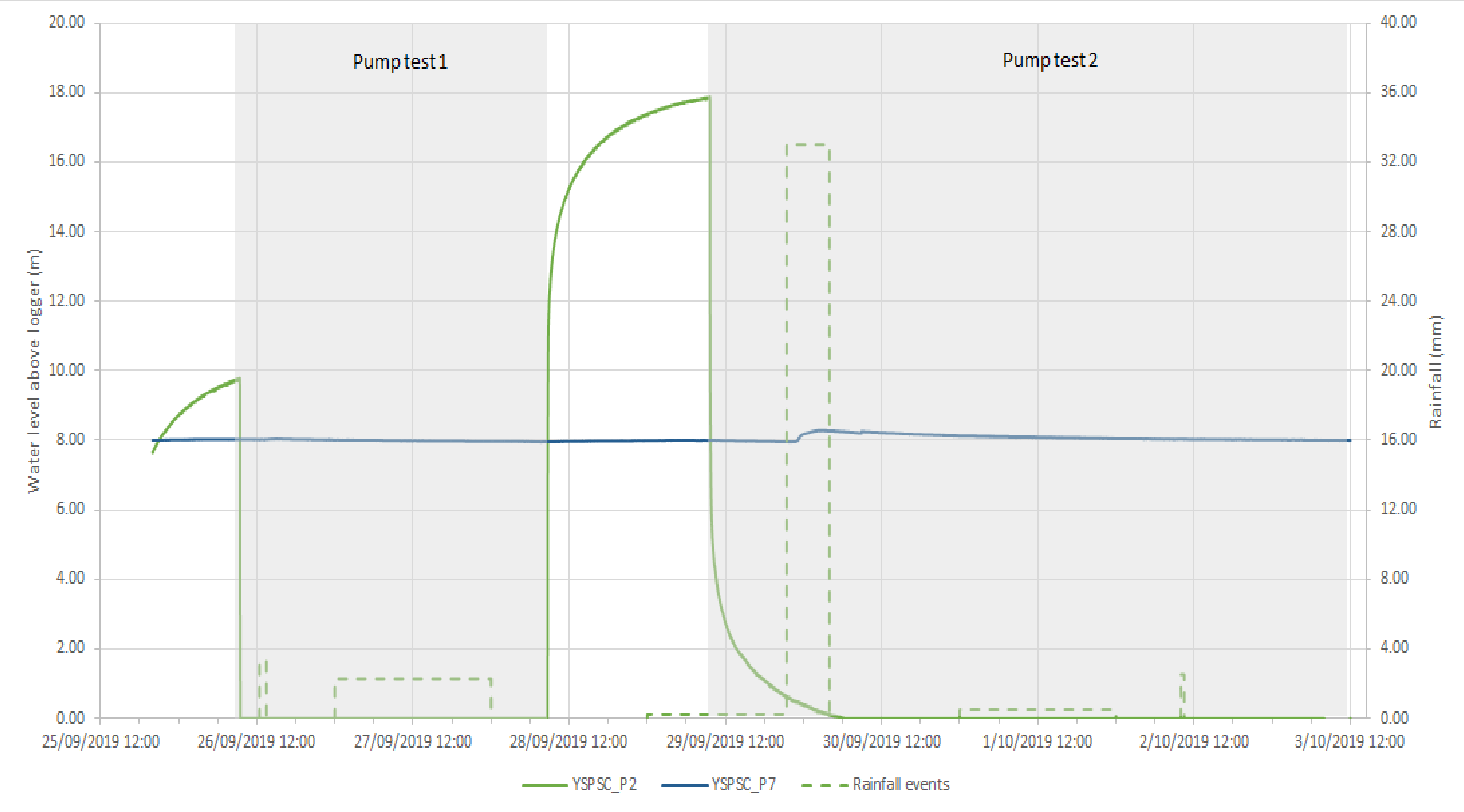

Figure 25. YSPSC P2 and P7 water level response during pumping tests.

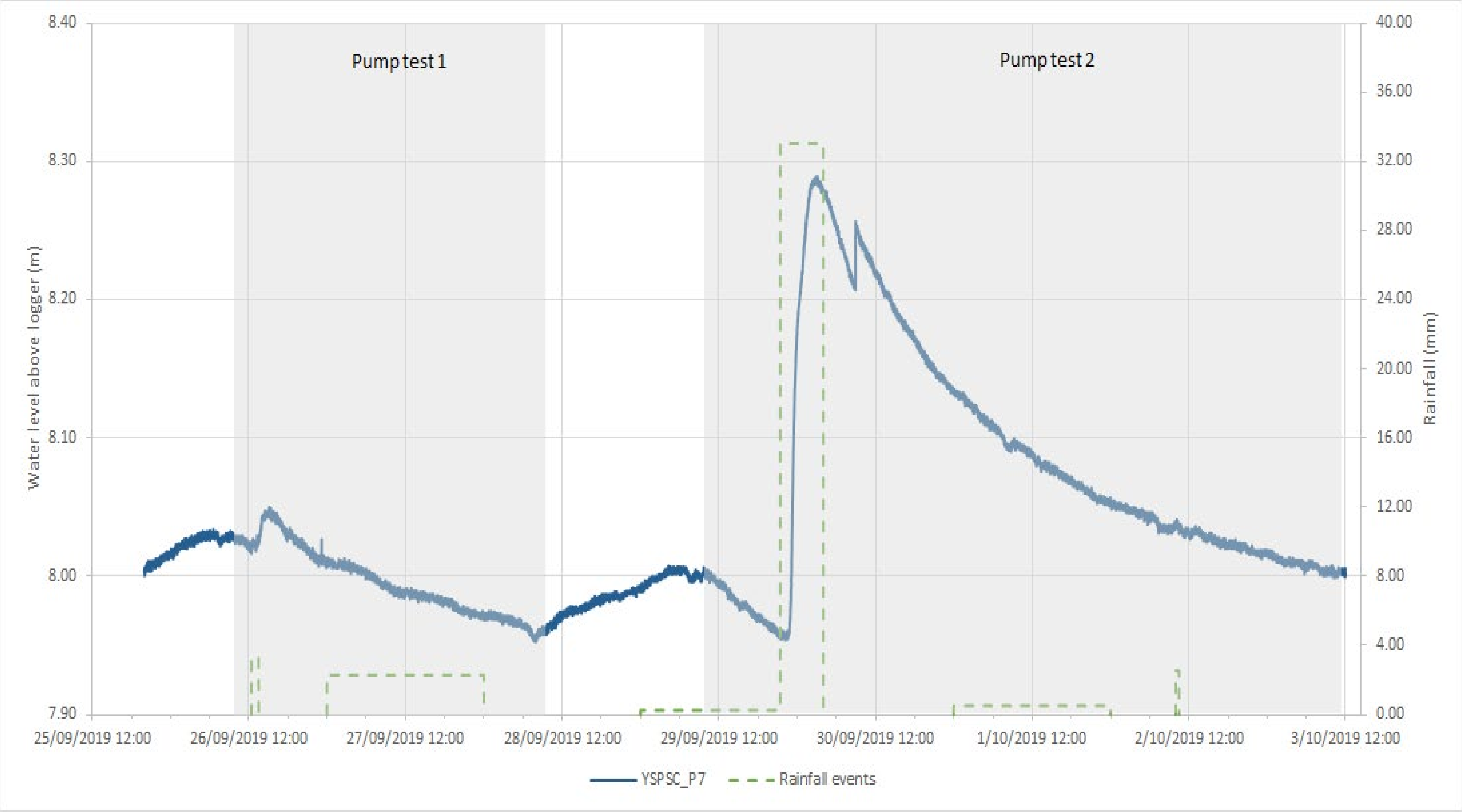

Figure 26. YSPSC P7 water level response during pumping tests.

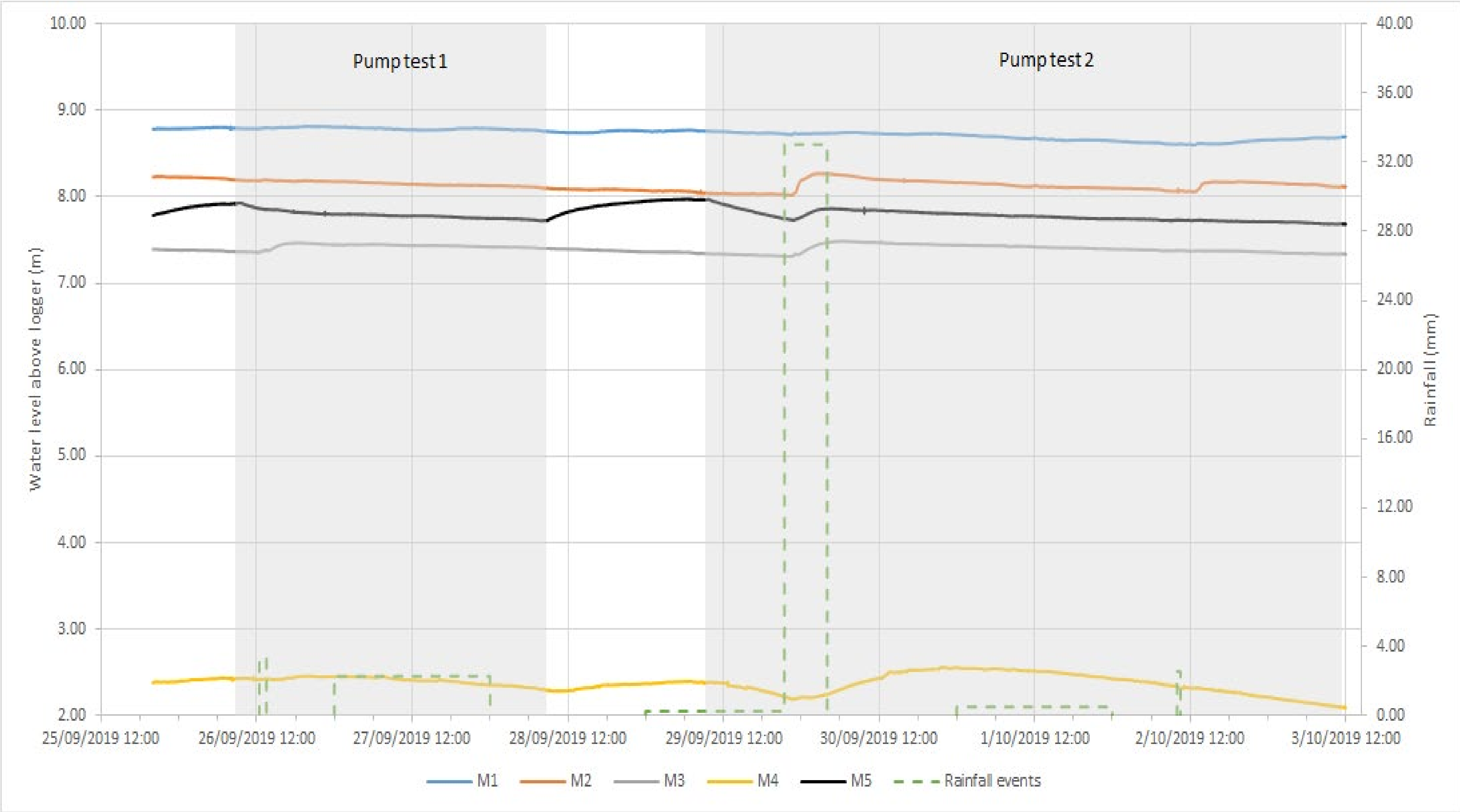

Figure 27. YSPSC monitoring bores M1, M2, M3, M4 and M5 water level response during pumping tests.

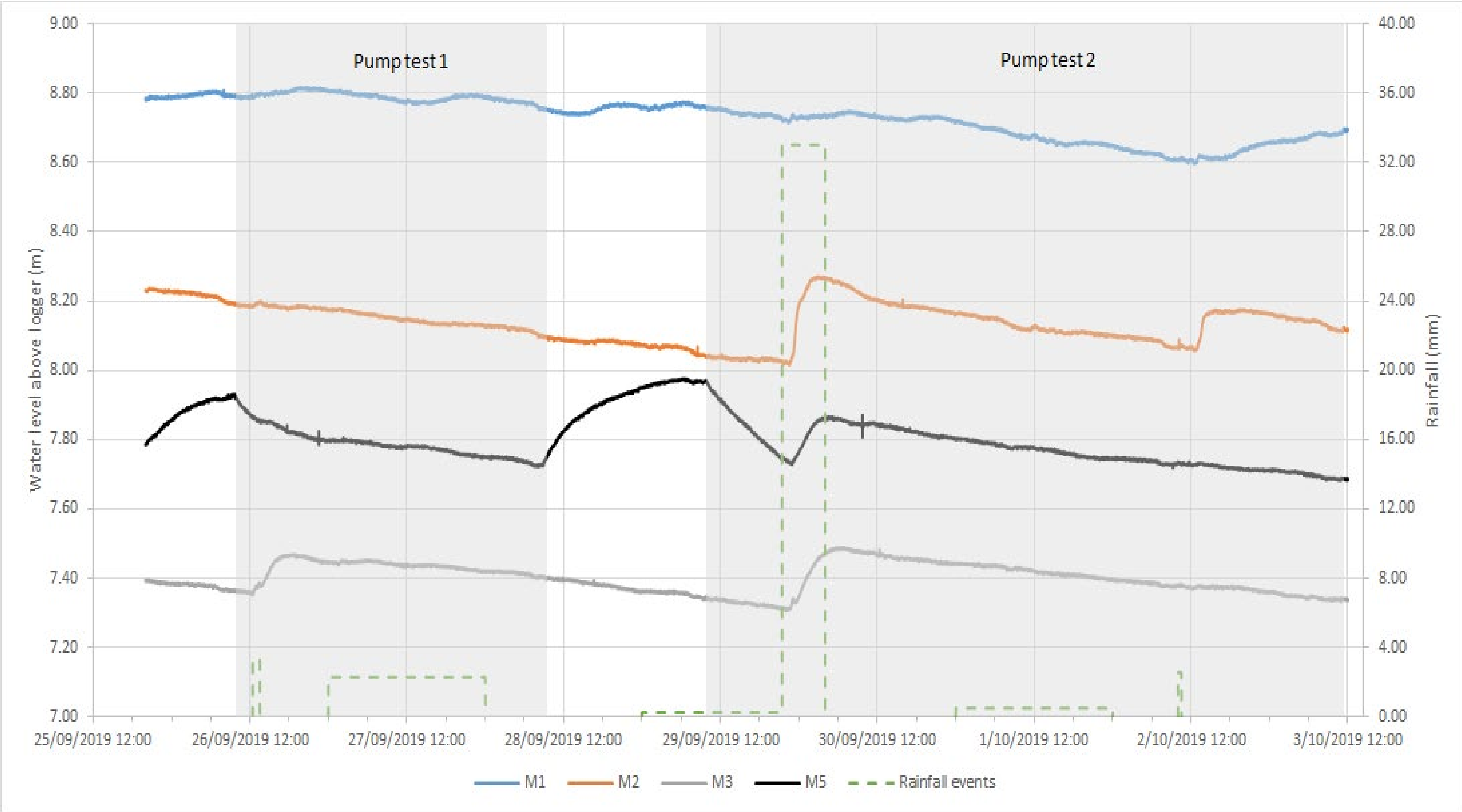

Figure 28. YSPSC monitoring bores M1, M2, M3 and M5 water level response during pumping tests.

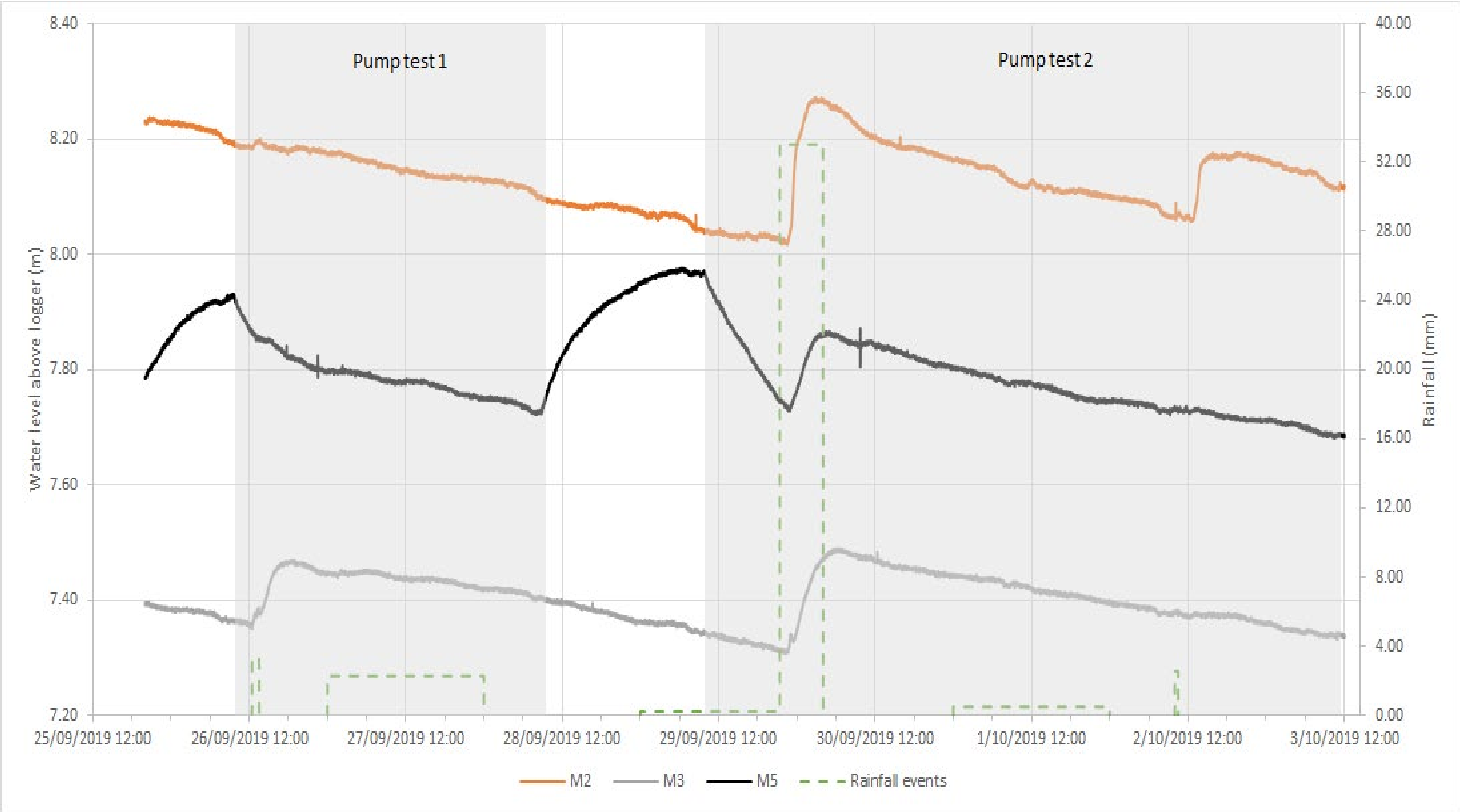

Figure 29. YSPSC monitoring bores M2, M3 and M5 water level response during pumping tests.

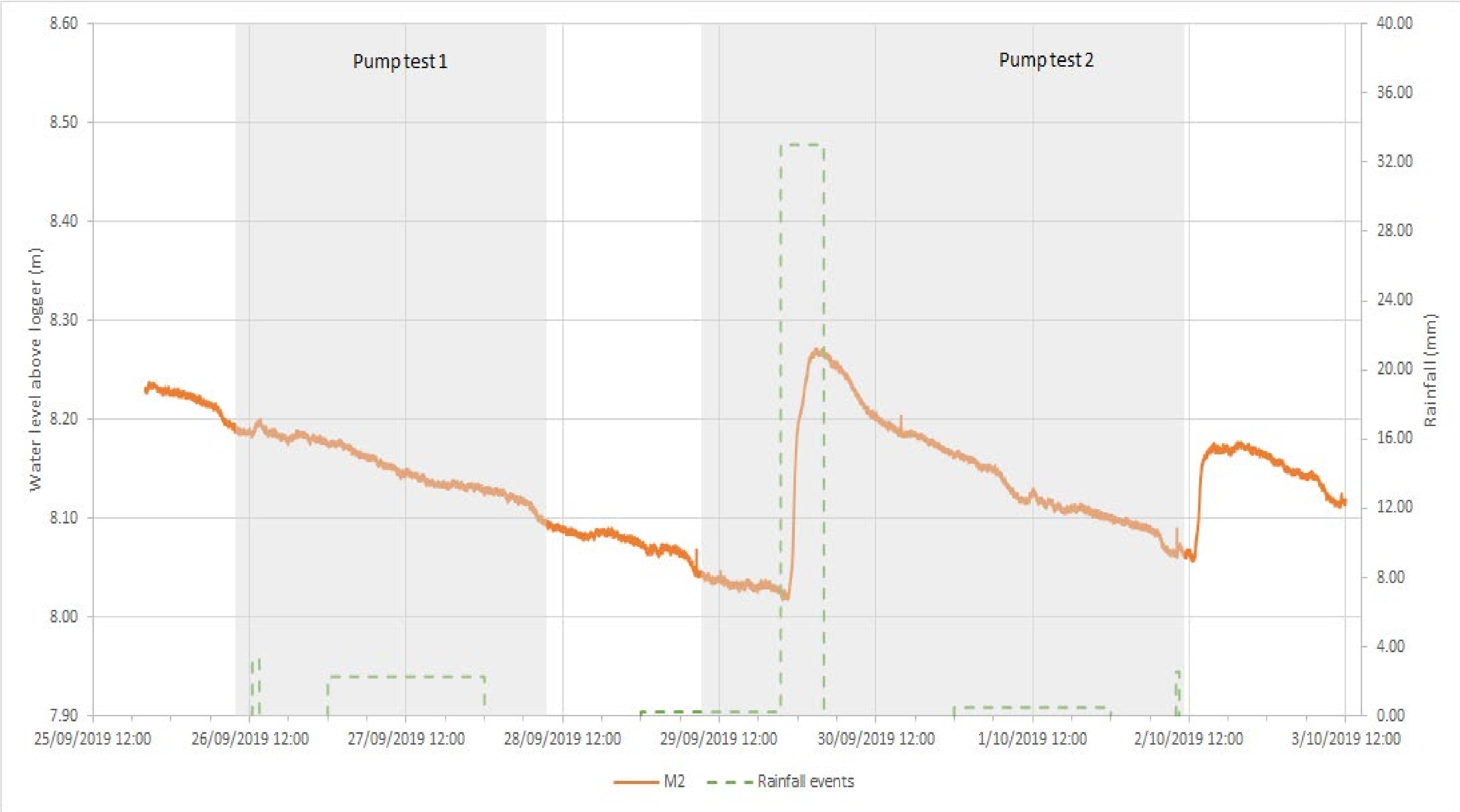

Figure 30. YSPSC monitoring bore M2 water level response during pumping tests.

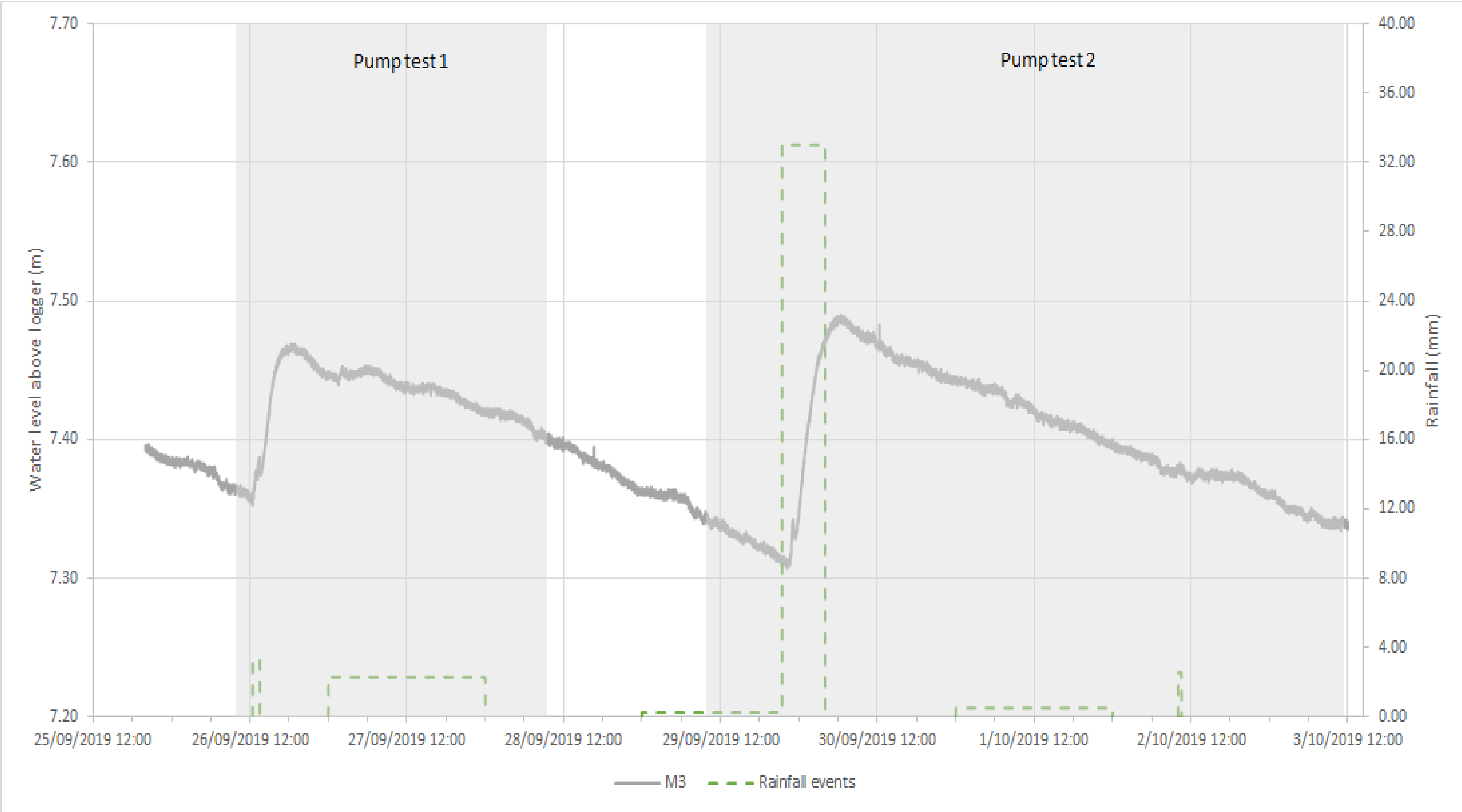

Figure 31. YSPSC monitoring bore M3 water level response during pumping tests.

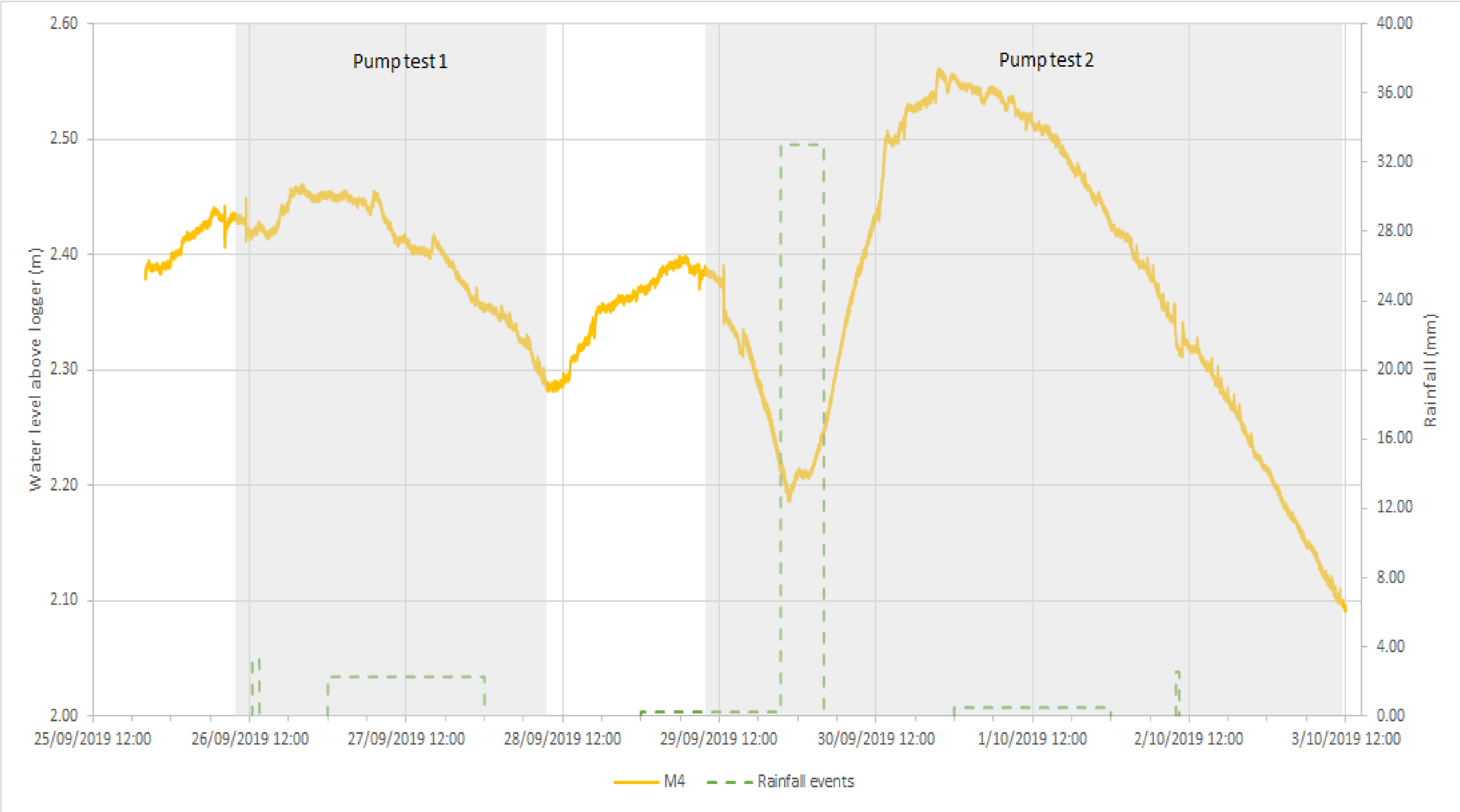

Figure 32. YSPSC monitoring bore M4 water level response during pumping tests.

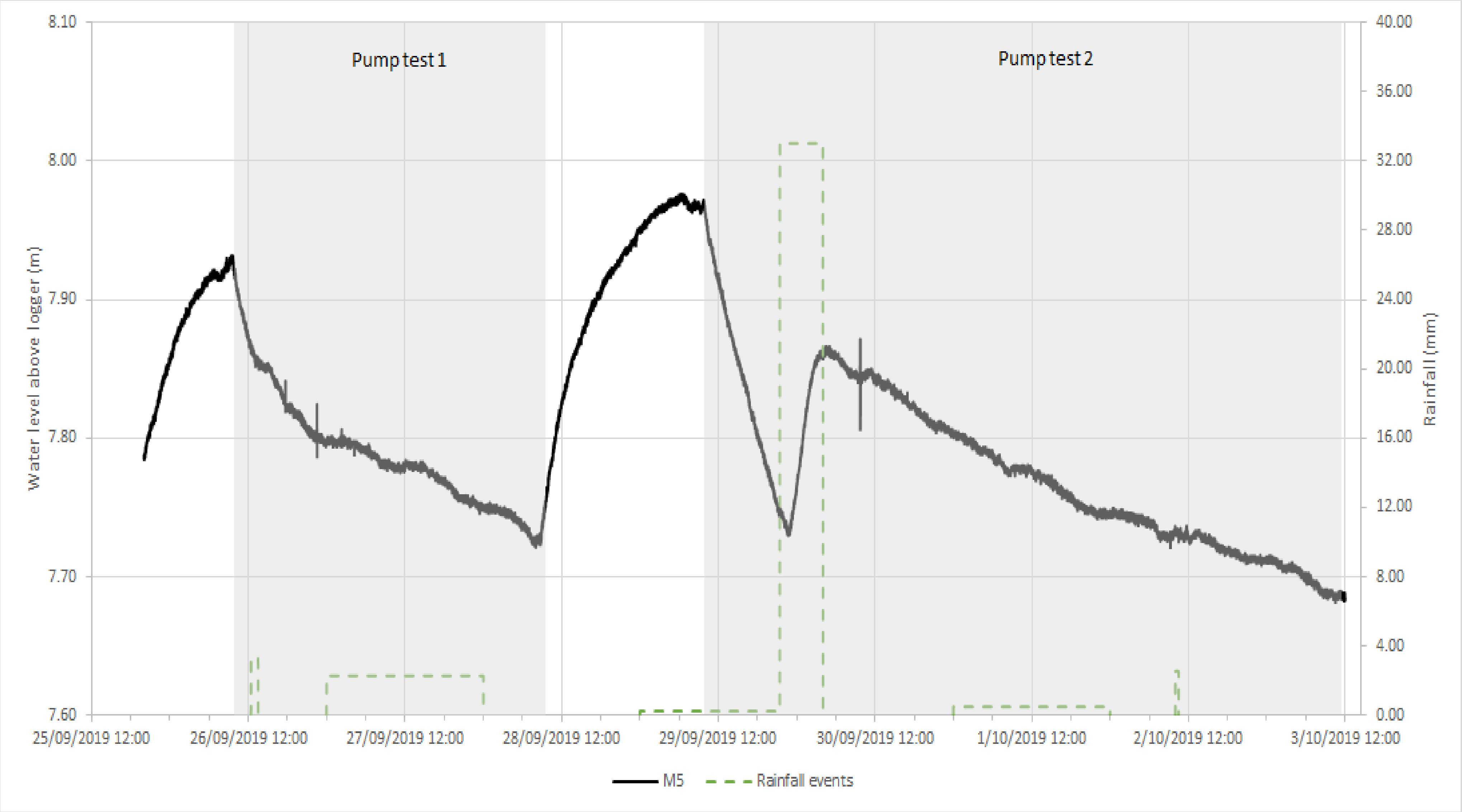

Figure 33. YSPSC monitoring bore M5 water level response during pumping tests.

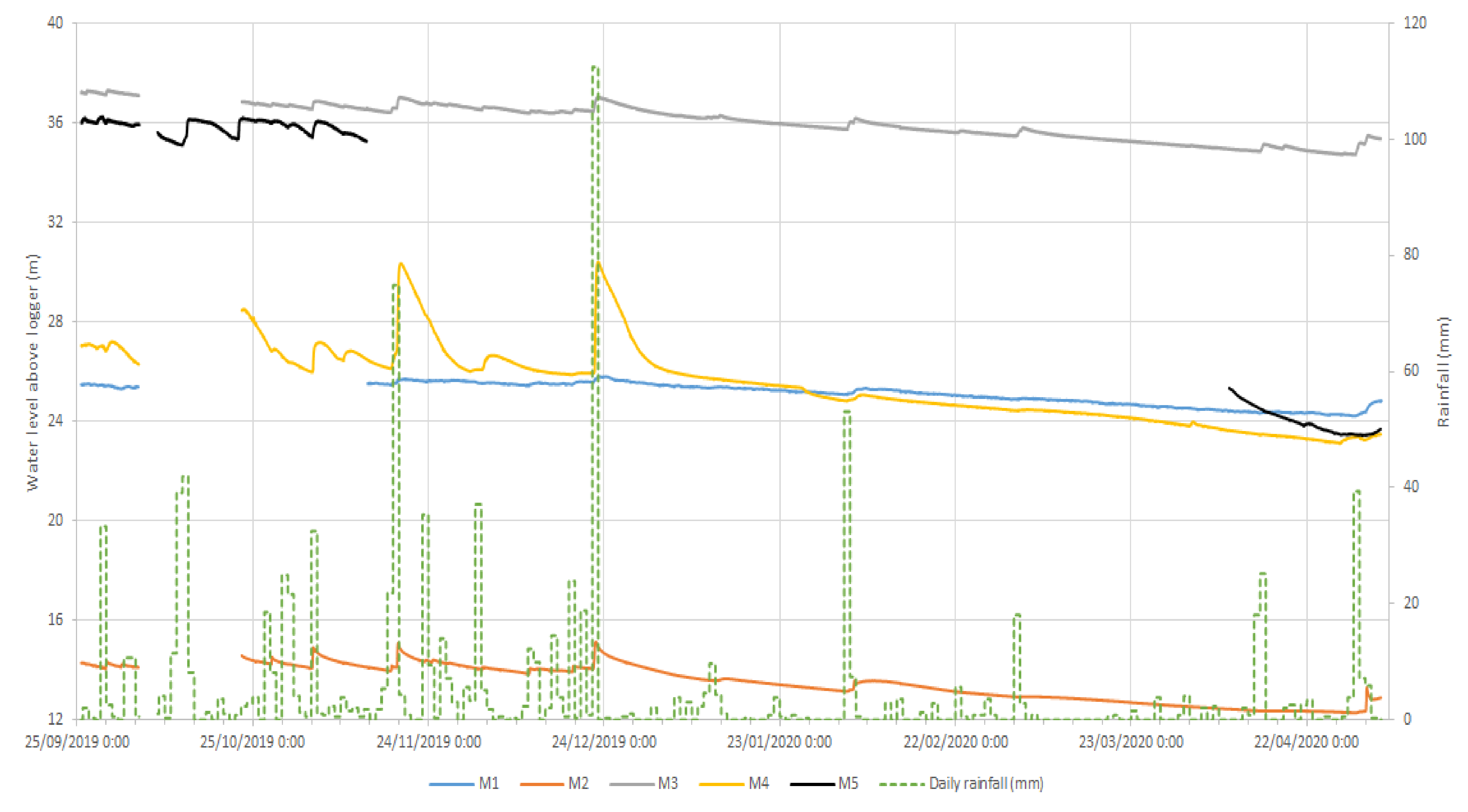

Figure 34. YSPSC monitoring bores M1, M2, M3, M4 and M5 water level response during long-term monitoring period.

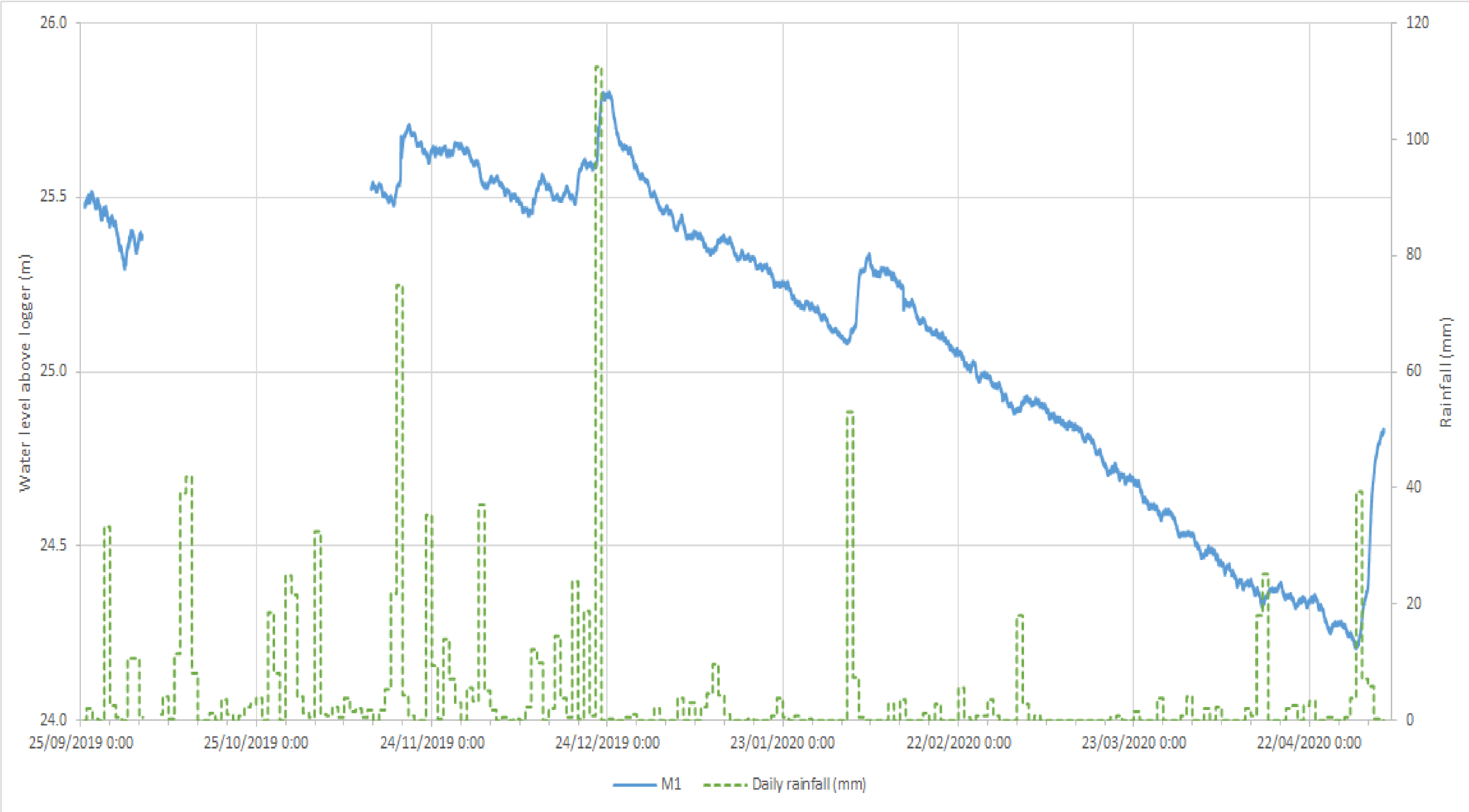

Figure 35. YSPSC monitoring bore M1 water level response during long-term monitoring period.

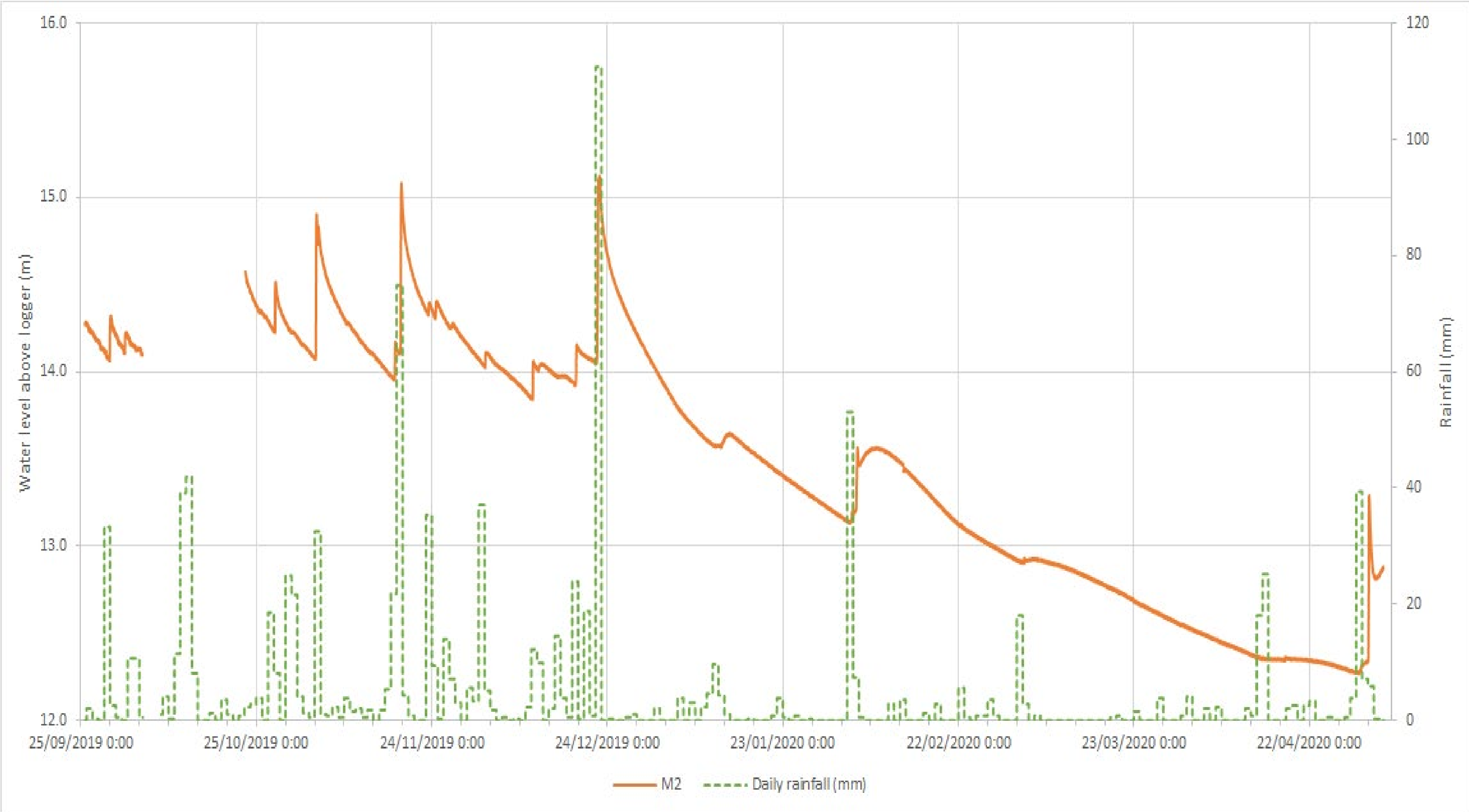

Figure 36. YSPSC monitoring bore M2 water level response during long-term monitoring period.

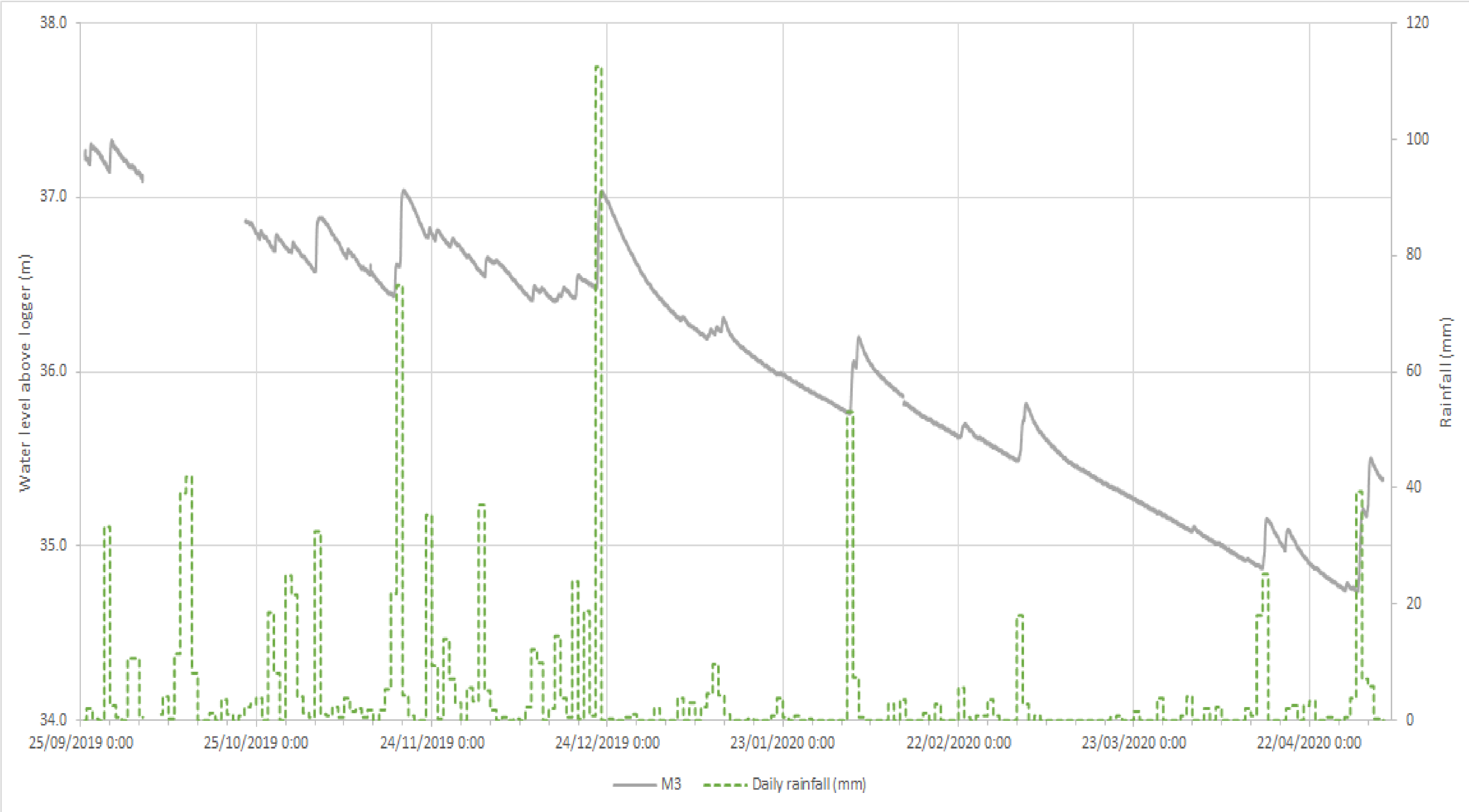

Figure 37. YSPSC monitoring bore M3 water level response during long-term monitoring period.

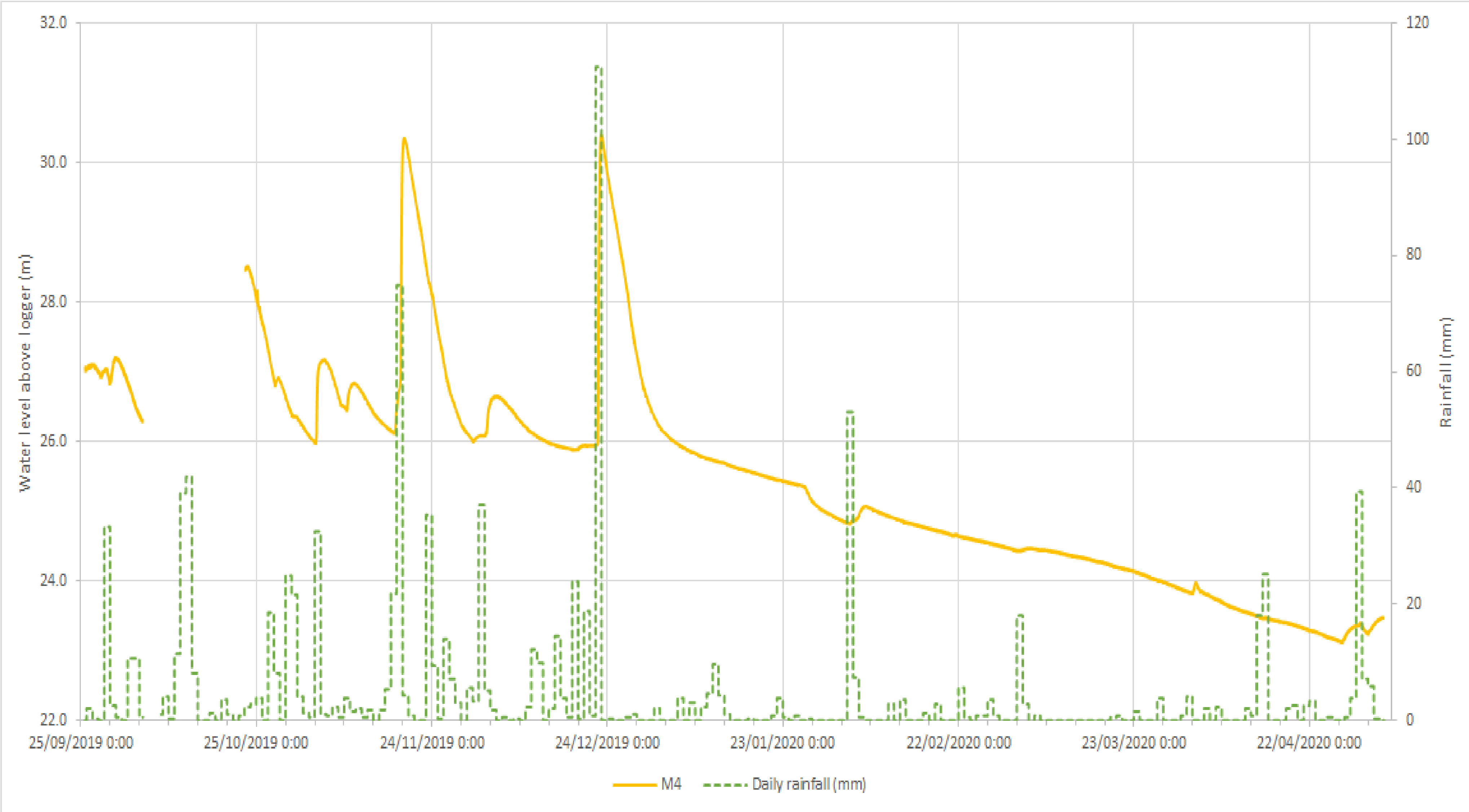

Figure 38. YSPSC monitoring bore M4 water level response during long-term monitoring period.

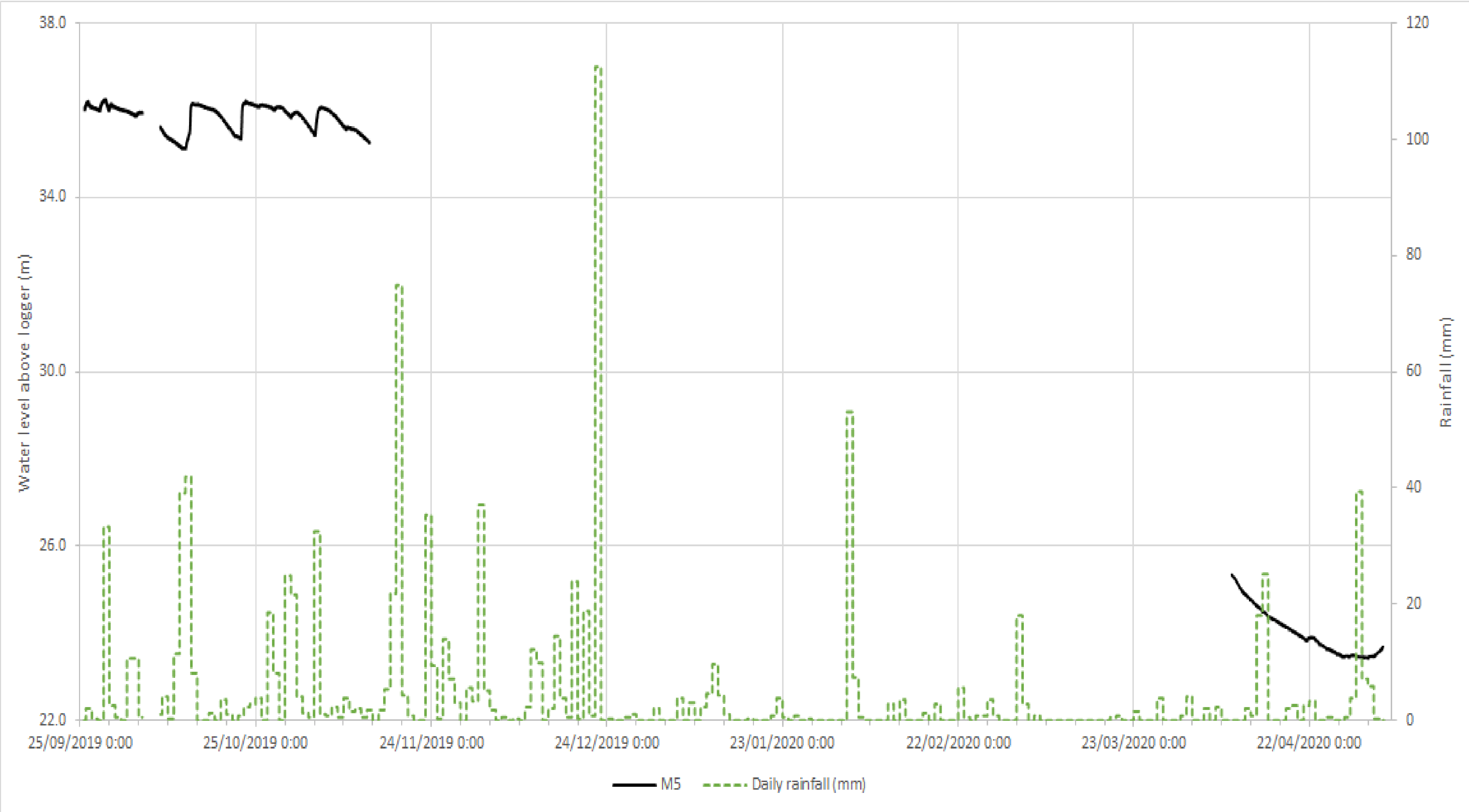

Figure 39. YSPSC monitoring bore M5 water level response during long-term monitoring period.

Correlation of the monitoring well water level and tidal hourly data was also made on monitoring well YSPSC M1 due to its close proximity to the estuary, although it is located beside the Dorfay stream. Hourly tidal information for Yap, obtained from the University of Hawaii Sea Level Centre, was superimposed onto the groundwater level data to determine if 6-hourly peaks and troughs are repeated throughout the monitoring dataset to suggest tidal influences. Figure 40 illustrates the presence of several peaks in groundwater level that may be tied to tidal processes. No discernible tidal impact was observed, although further analysis may be required to differentiate the tidal influence from other influences.

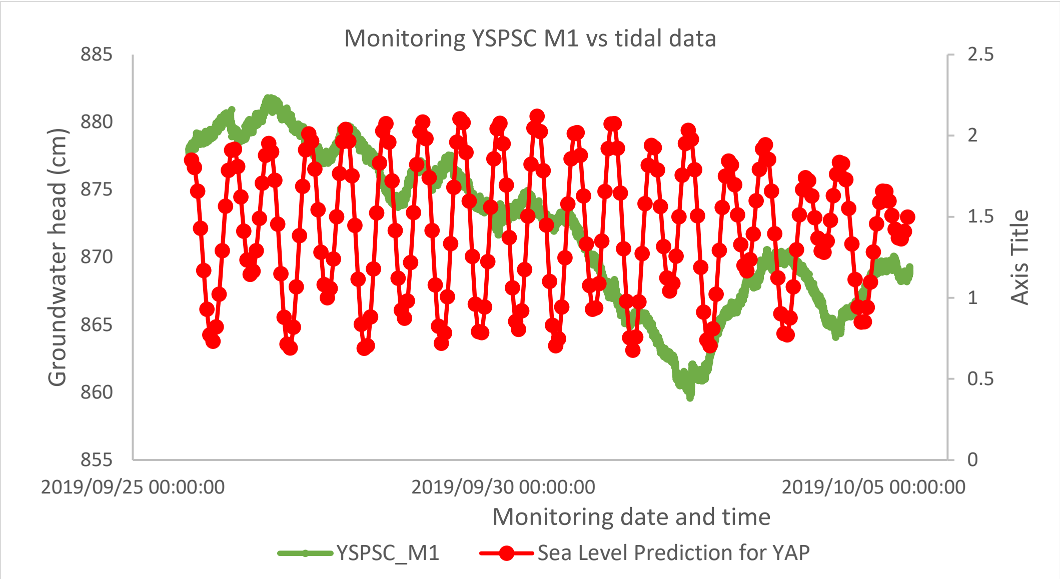

Figure 40. Groundwater level in monitoring well M1 during the GTWA pumping test from 29 September to 2 October against the predicted hourly tidal data for Yap.

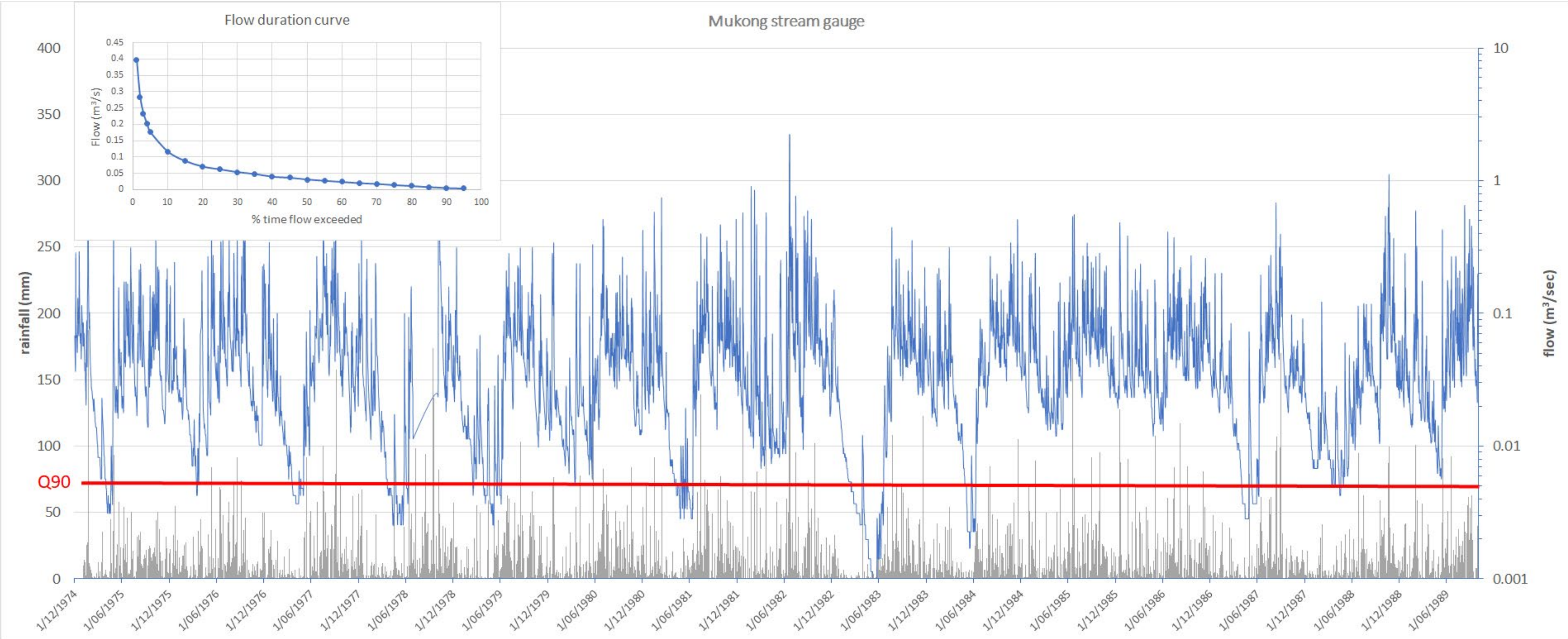

Figure 41. Mukong stream hydrograph for the complete series of records (USGS 16893180, 16/9/1980 – 21/3/1984), including flow duration curve identifying 10% lowest flow levels.

Annex 5 – Electrical resistivity survey results

An electrical resistivity tomography (ERT) survey is used to assess, visualise and identify lateral and vertical variability in electrical resistivity responses within the underlying geological framework. The method works on the principle that different materials conduct electrical current differently, which can be used to differentiate resistive geological materials from non-resistive geological materials and groundwater. The method involves injecting an electrical current into the ground using a pair of electrodes. This current causes a potential voltage difference in the ground, which is measured by a separate pair of electrodes. The measured voltage and electrode spacing can be converted into the apparent resistivity value, used to generate a subsurface resistivity profile to aid in geological and hydrogeological interpretation.

The main objective of undertaking ERT was to identify potential sites for groundwater drilling and water supply expansion in the future. Additional abstraction points could be useful, particularly around the Gagil area where the Yap State Sports Complex (YSSC) and Fisheries and Marine Institute (FMI) are located, as they were identified as important stakeholders, with considerable demand, and where an successful production bore located near the YSSC could prove a useful asset as an emergency supply bore and thereby reducing the stress on the existing distribution system and providing a water security option during droughts.

Table 22. Summary of the ERT survey lines completed in the Gagil Tomil area.

Location	Survey line	Orientation	Length (m)	Array type	Objective
GTWA pumping stations, Monguch Valley	ERT test	N-S	300	Multiple gradient	Field calibration
	ERT test	N-S	300	Wenner	
Near Yap Sports Stadium, Gagil	ERT-1	S-N	500	Wenner	Groundwater exploration
Near Yap Sports Stadium, Gagil	ERT-2	W-E	214	Wenner	Groundwater exploration
Near Yap Sports Stadium, Gagil	ERT-3	W-E	240	Wenner	Groundwater exploration

The ABEM Terrameter LS2 model equipment was used for this survey. Five survey lines were completed, covering a distance of 0.9 km (*Figure 42*). Two field calibration lines were undertaken around the GTWA pumping stations to help determine the resistivity values for known geologies and identify the array protocol that was most appropriate. This exercise resulted into a three-layered, site-specific conceptual model, reflecting the hydrogeological condition and can be used later around Gagil and Tomil. Numerous measurement errors and delays were observed when the multiple gradient was used, although a higher resolution dataset was generated. The Wenner array was trialled with minimal delay and issues. It was realised that the multiple gradient protocol worked well in a geological framework dominated by vertical to subvertical structures, whereas the Wenner protocol is ideal in subhorizontal geological formations. The latter is more relevant in this case as the subsurface formations could be treated as a near horizontal system comprising three units: 1) extensive laterite soils or clays near the surface, 2) fractured or weathered volcanic breccias as a middle zone that is either infilled clay and little groundwater or fully saturated with groundwater, and 3) less weathered basement greenschist of the Yap formation, as identified in Figure 44 and Figure 45.

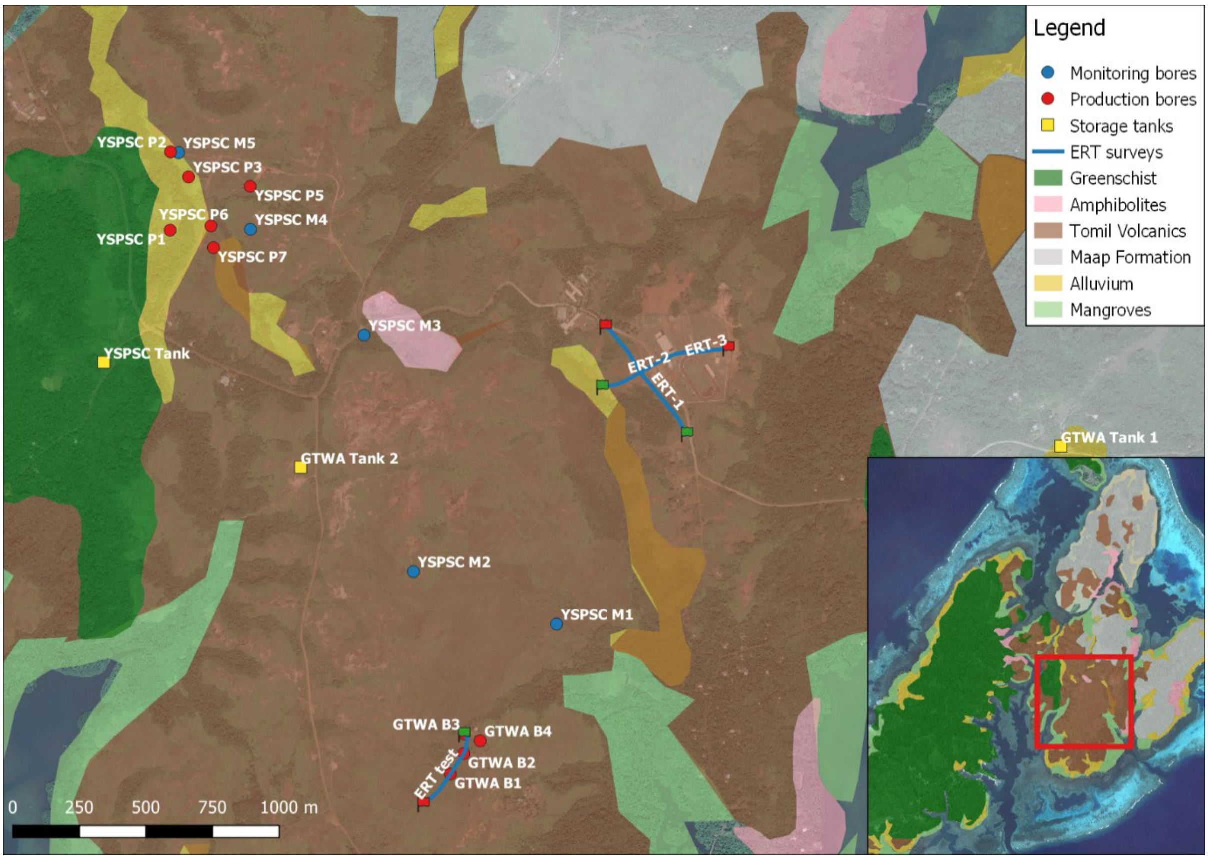

Figure 42. Location of the groundwater infrastructures and the ERT survey lines superimposed onto the geological framework.

Three exploratory survey lines were completed around the eastern end of the study area, near the YSSC and FMI. These include a 500 m south to north trending traverse, and two west to east lines coming from the swampy land near the Mukong stream catchment and going through the YSSC. These lines were targeting the possible continuity of the Tomil Volcanics aquifer to the east, and the depth of the Yap Formation basement.

The above field calibration profiles, coupled with typical resistivity values for volcanic deposits guided the interpretation of all the resistivity lines. It was interpreted that, based on results and the available drill logs, the underlying geological framework has three major hydrogeological major zones including:

- a highly resistive materials (with capping units covering the top 5 to 10 m below the ground which may indicate low permeability laterite soil;
- a thick zone of low to medium resistivity zone that may suggest high fractured and/or weathered volcanic breccia and groundwater yielding zones; and
- a slightly high resistivity zone 40–80 Ohm.m which may indicated a less weathered volcanics or the low permeability Yap Formation basement, greenschist.

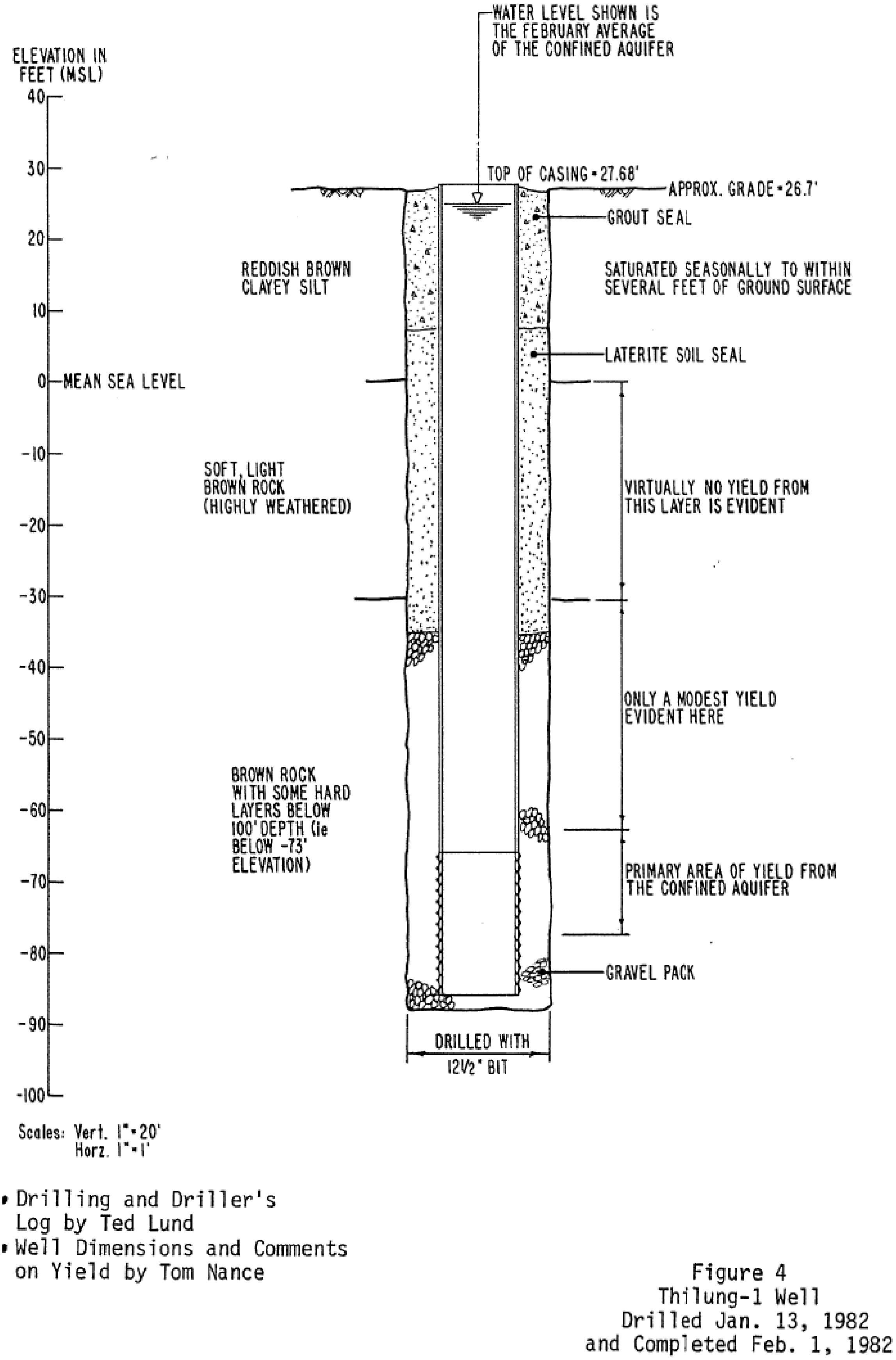

Figure 43. Drill log of Thilung 1 located 60 m along the ERT test (calibration) line. Source: Nance 1982

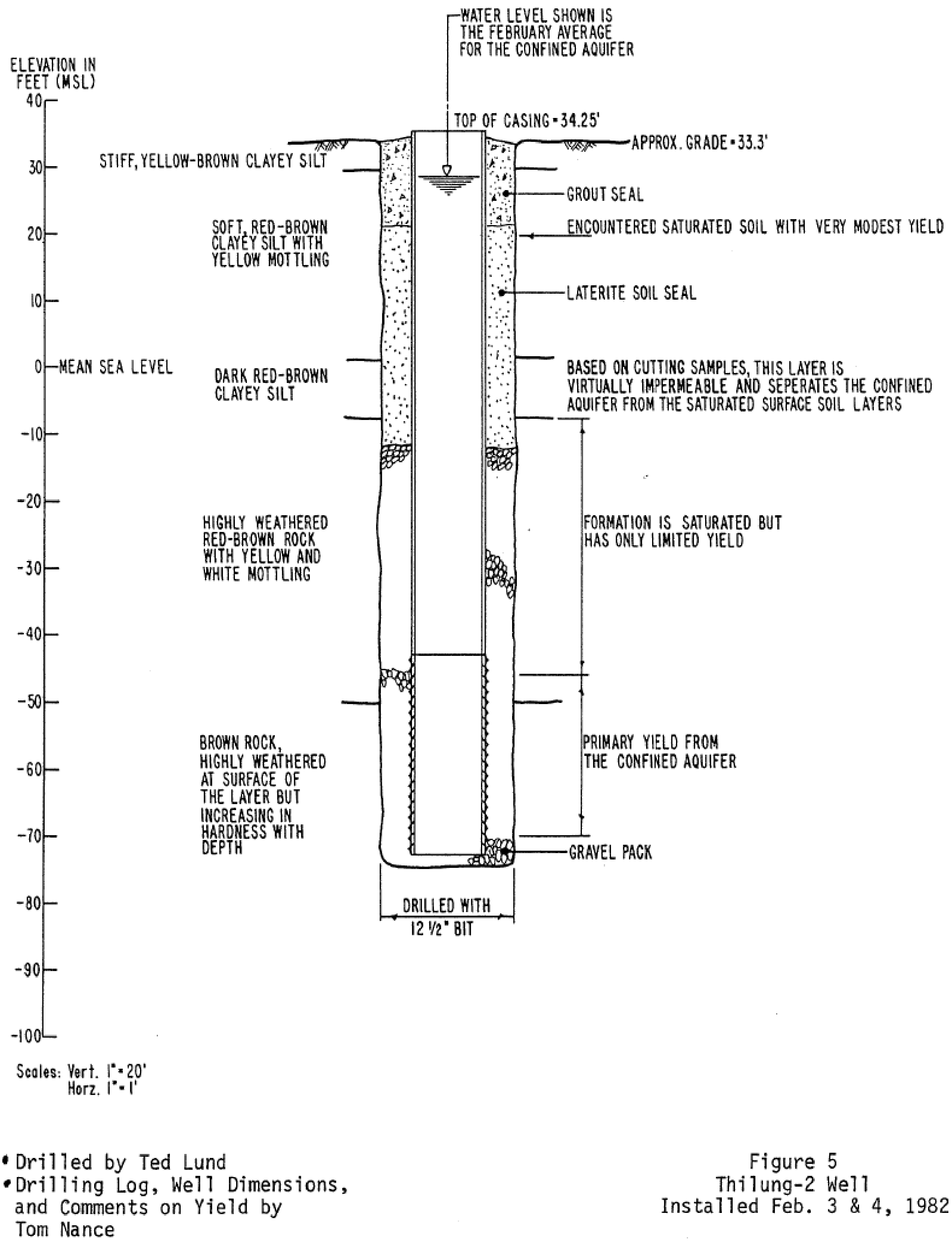

Figure 44. Drill log of Thilung 2 (now called GTWA pump 1) located 150 m along the ERT test line. Source: Nance 1982

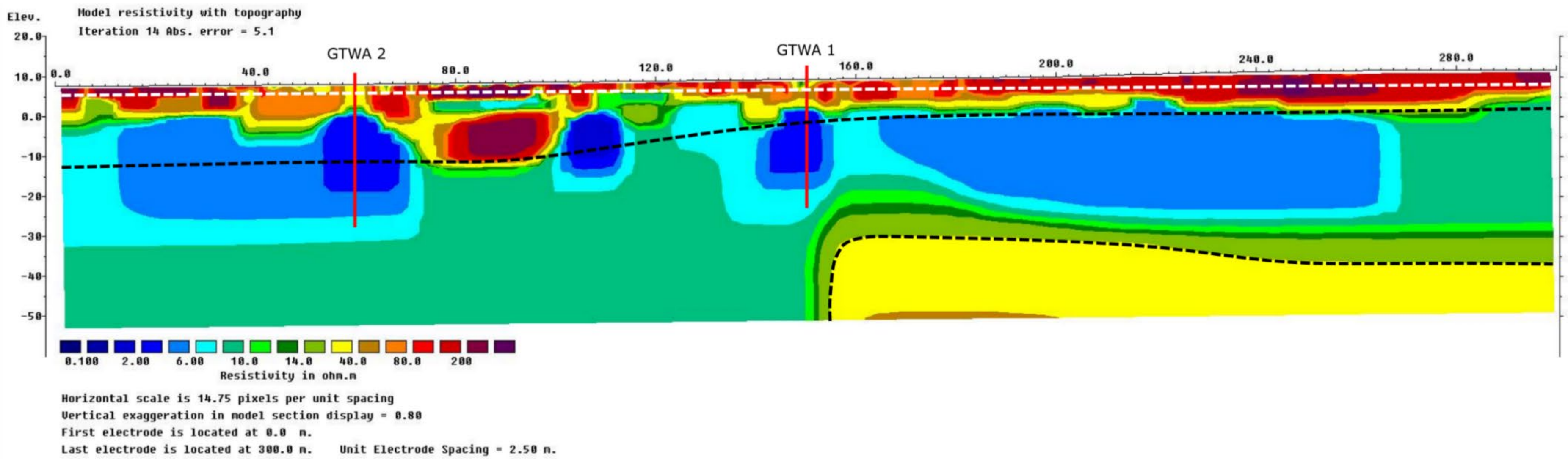

Figure 45. Field calibration line using Multiple Gradient array.

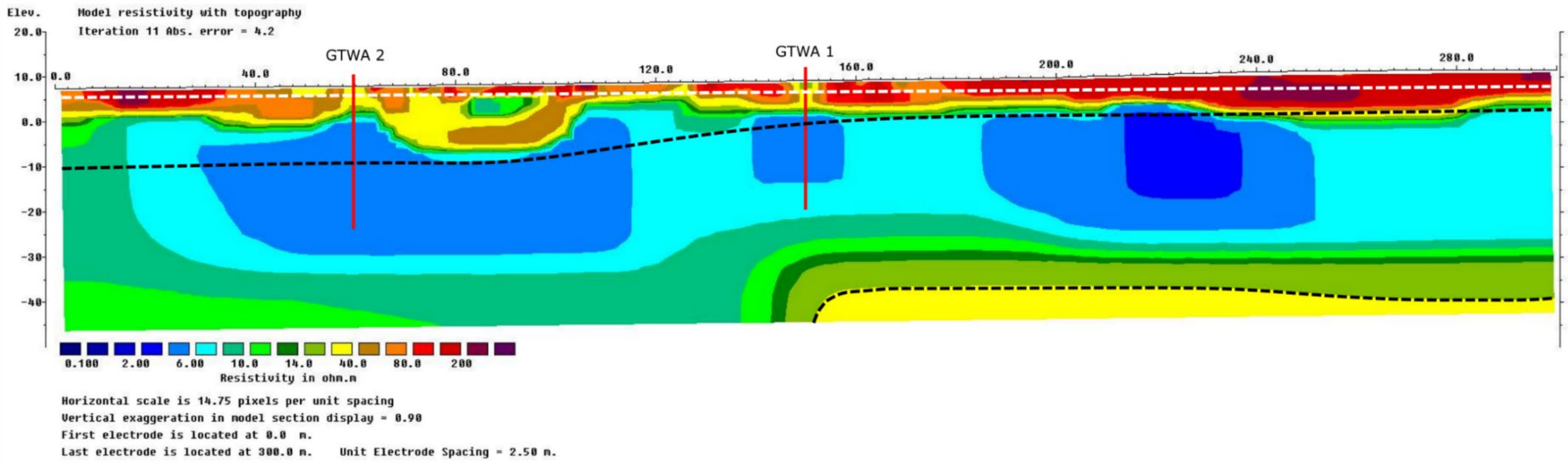

Figure 46. Field calibration line using Wenner array.

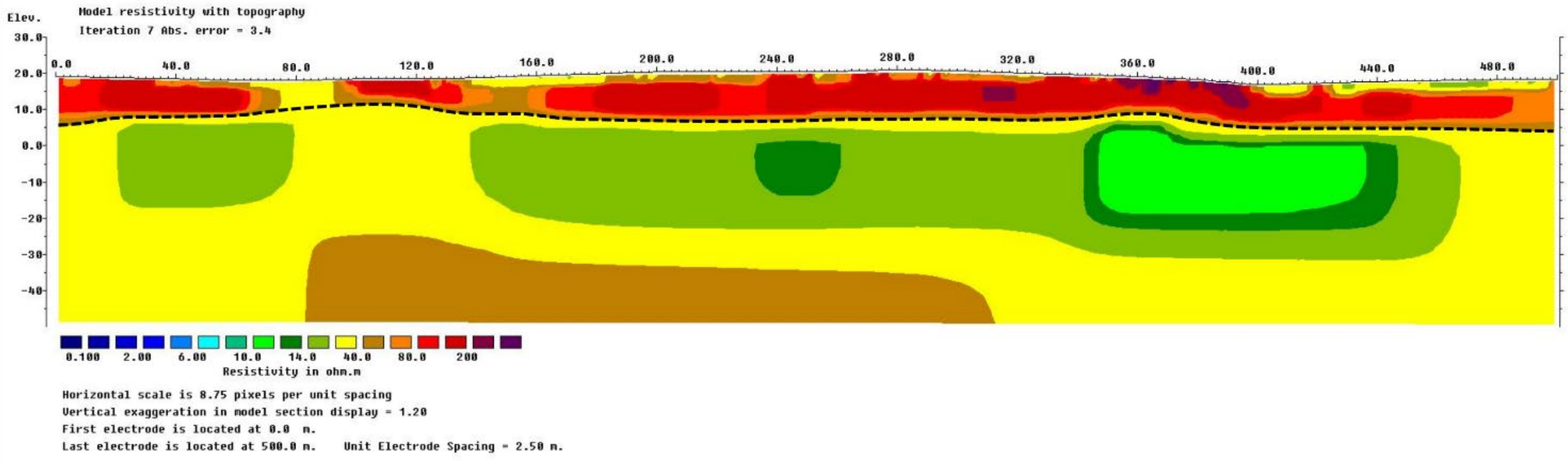

Figure 47. Survey line ERT-1

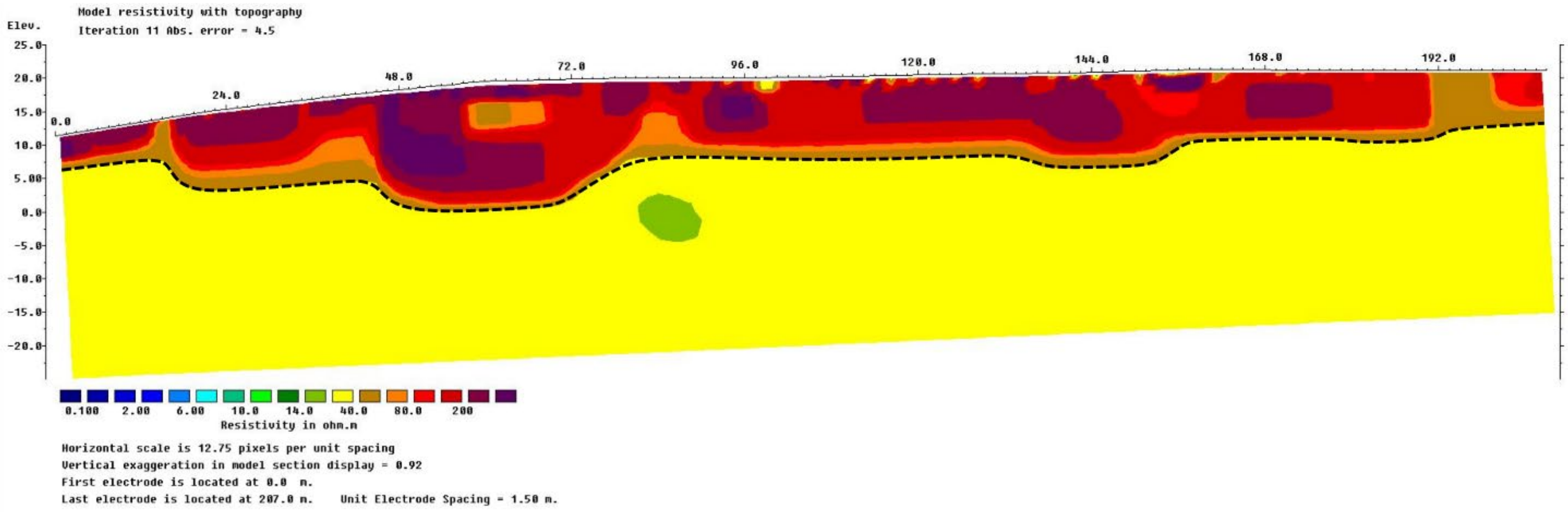

Figure 25. Survey line ERT-2

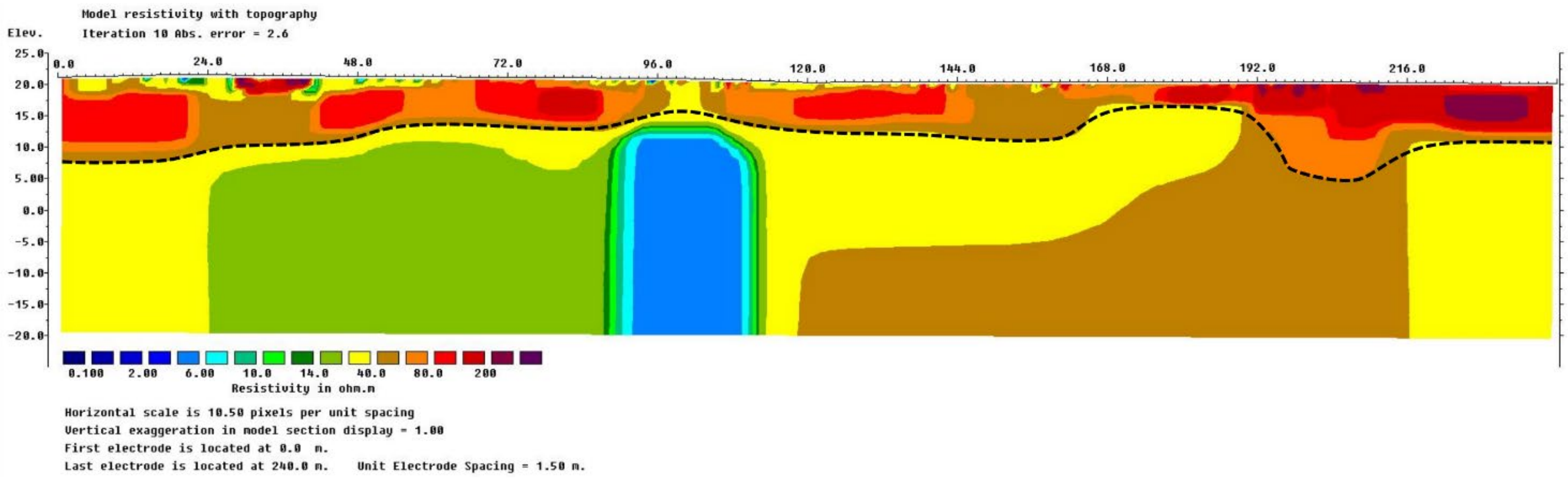

Figure 26. . Survey line ERT-3

Annex 6 – Catchment delineation

Methodology

Delineation of the water catchment and watershed boundaries were generated to provide insights into regional groundwater flow direction as well as surface to groundwater interactions. The digital elevation model (DEM) raster data for Yap was accessed through Google Earth Engine. This was processed using the java programming language and the use of Shuttle Radar Topography Mission (SRTM) to generate a 30-m resolution and georeferenced raster data for Yap proper. Existing hydrology routines in Quantum Geographical Information System (QGIS) were used to fill depressions and preserve downward slope along flow paths by preserving minimum slope gradient between cells. The outputs were used to define and categorise streams to map flow direction, channels and drainage basins. This led to the identification of perennial and ephemeral streams and which in turn were verified using historical studies (Nance 1982; Shade et al. 1992). These streams were later digitised in QGIS and incorporated into the water resources base map of the two study valleys. This geospatial analysis process aided the delineation of catchment and sub-catchment boundaries and the combined use of these hydrological information with measured static groundwater levels below ground level permitted the generation of groundwater head or potentiometric contours.

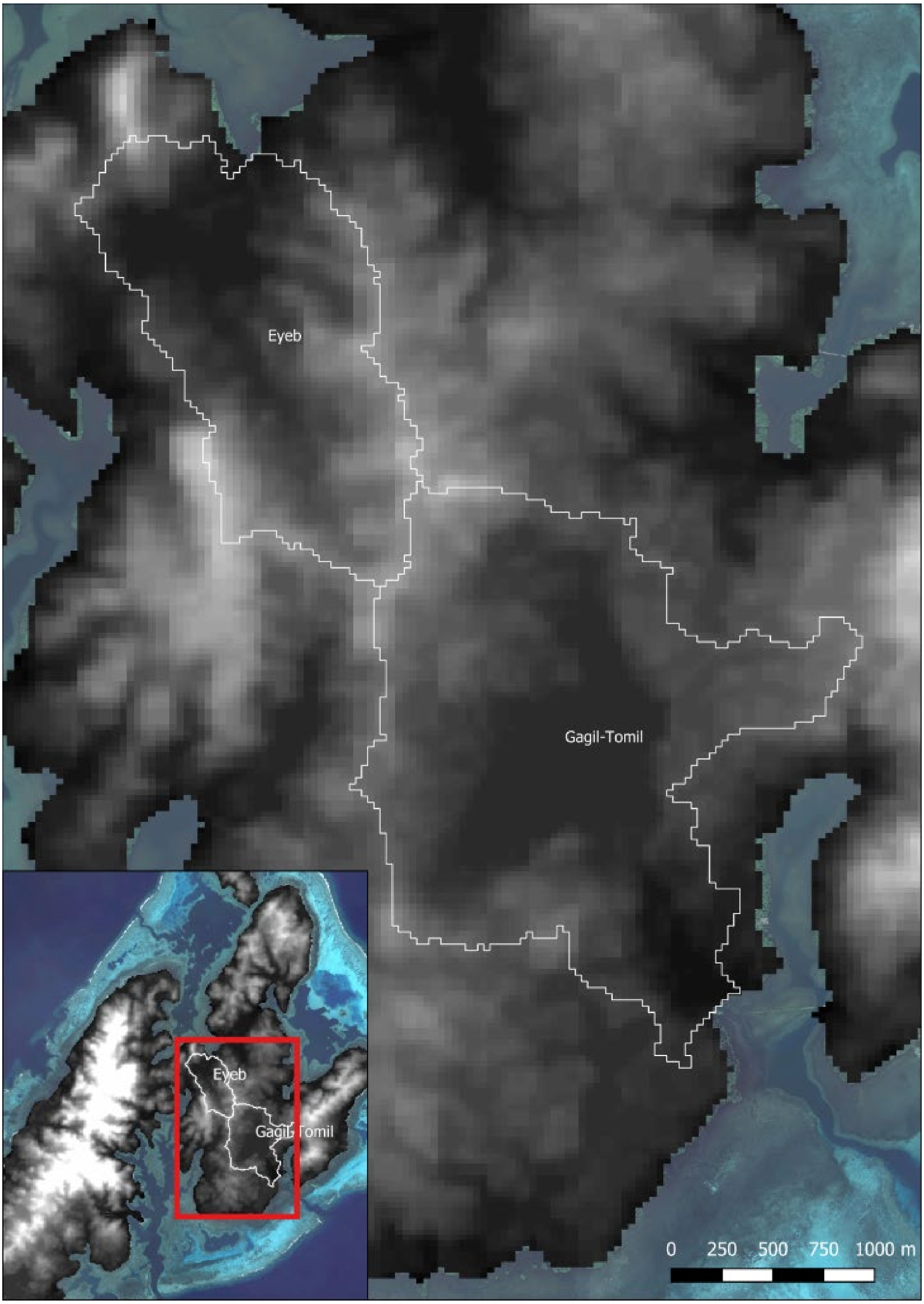

Figure 50. Digital elevation model of Yap used to derive the catchment delineation.

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