Soil Moisture Monitoring in the Auckland Region – Programme Establishment

Emma Chibnall
Fiona Curran-Cournane

June 2018 Technical Report 2018/012

Auckland Council
Te Kaunihera o Tāmaki Makaurau

Soil moisture monitoring in the Auckland region – Programme establishment

June 2018 Technical Report 2018/012

Emma Chibnall
Fiona Curran-Cournane
Research and Evaluation Unit, RIMU

Auckland Council
Technical Report 2018/012

ISSN 2230-4525 (Print)
ISSN 2230-4533 (Online)

ISBN 978-1-98-856450-0 (Print)
ISBN 978-1-98-856451-7 (PDF)

This report has been peer reviewed by the Peer Review Panel.
Review completed on 20 June 2018 Reviewed by Justin Wyatt, Waikato Regional Council and Dr Channa Rajanayaka, NIWA
Approved for Auckland Council publication by: Name: Eva McLaren Position: Acting Manager, Research and Evaluation (RIMU)
Name: Jacqueline Anthony Position: Manager, Environmental Monitoring, Research and Evaluation (RIMU)
Date: 20 June 2018

Recommended citation

Chibnall, E and Curran-Cournane, F (2018). Soil moisture monitoring in the Auckland region – programme establishment. Auckland Council technical report, TR2018/012

Executive summary

Soil moisture is a fundamental part of the hydrological cycle, linking hydrological, biological and biochemical processes. Information on soil moisture status is of interest to farmers because soil water balances are important for irrigation, effluent application, drainage, livestock grazing management, seed sowing and agronomy. The information is also important to climate scientists and hydrologists for climate projections as well as flood warning and drought modelling and monitoring.

A soil moisture monitoring network was established by Auckland Council in 2014. The purpose of this network was to assist with agricultural farm management and for drought information purposes. Ten soil moisture AQUAFLEX sensors were installed across the Auckland region between 2014 and 2016 and in accordance with the *National Environmental Monitoring Standard. Soil water. Measuring, Processing and Archiving of Soil Water Content Data* (NEMS, 2013, 2016a).

The 10 soil moisture sites were spread across north, south and central Auckland and were selected to predominantly represent local soil types and climates. All sites have grass cover, either mown or grazed. Seven of the 10 sensors at the soil moisture sites have been operational for three or more years and have been field calibrated using a neutron probe sensor. Soil moistures across these seven sites were variable, which is likely to be a product of differences in local climate and soil physical characteristics, as well as site management and landscape position.

This report provides an overview of the soil moisture monitoring network, including site selection, installation methodology, calibration and initial results.

Recommendations for future monitoring and research include undertaking additional laboratory analysis to determine field capacity (at -10kPa) and permanent wilting point (at -1500kPa) measurements that better reflect the soil depths monitored by the soil moisture sensors at each of the sites. This additional sampling will also contribute towards gravimetric measurements of soil water contents across the sensor soil depths for additional calibration purposes that will provide validation or necessary adjustment to the current neutron probe calibration.

The ongoing monitoring and calibration of the soil moisture sites are recommended in order to contribute towards establishing longer-term datasets that will aid scientific understanding of how Auckland's diverse soils store and release water.

Table of contents

1.0 Introduction

New Zealand has a national network of soil moisture sensors but different monitoring approaches and the current extent may not always be representative or necessarily adhere to the *National Environmental Monitoring Standard. Soil water. Measuring, Processing and Archiving of Soil Water Content Data* (NEMS 2013, 2016b; shortened to *NEMS for measuring soil moisture* in this report). For example, in the mid-1990s the National Institute of Water and Atmospheric Research (NIWA) established a national network of soil moisture monitoring sites for collecting climate related data. The core climate network uses AQUAFLEX sensors to measure soil moisture, but some sites have additional monitoring equipment that serves different purposes, e.g., multi-depth soil moisture monitoring. Between 1999 and 2016, four of these sites were established across the Auckland region in Warkworth, Kumeu, central Auckland and Pukekohe. However, these AQUAFLEX operated sites in Auckland remain uncalibrated in accordance with the *NEMS for measuring soil moisture* but adopt the manufacturer guidelines for converting the raw data to volumetric soil moisture for two soil textures types that are grouped as 1) sand, silt and sandy and silty loams and 2) clay and clay loams.

While this type of monitoring and calibration using manufacturer surrogate equations for soil textures has served climatic soil moisture monitoring purposes, it is also important to consider how the diverse range of soil types in Auckland influences soil-water dynamics that are specific to each site and microclimate. Developing such a regional soil moisture monitoring network helps us better understand the influence of local soil type, climate and management decisions on soil moisture. This enables us to better predict and prepare for rainfall and drought, and their impacts, and to better manage agriculturally productive areas.

Understanding soil water budgets are a key component of a well-managed productive farm. Farmers and land managers rely on accurate soil moisture information to estimate required irrigation depth, and appropriately time fertiliser application and the planting of crops. They also rely on soil moisture information for stock management, such as grazing rotations, potential for disease spread, the need for forage supplement and estimating stock market prices. Direct measurements of soil moisture are the preferred method for good farm management as they account for the complex relationship between climate, landscape properties and soil type influences on soil moisture. Direct measurements eliminate the need for soil moisture budget calculations, where soil physical characteristics, evaporation and evapotranspiration are often not measured or known.

Additionally, in conjunction with improved climate modelling of drought occurrence, continuous soil moisture measurements quantify the effects of drought on the soil and the severity of the drought (Wright et al., 2009). New Zealand will continue to experience droughts, and with climate change, the frequency and severity of droughts is likely to increase (NIWA, 2011). Drought in Auckland is projected to become more common and severe due to changing rainfall patterns and temperature increases (Pearce et al., 2018).

A soil moisture monitoring network was established by Auckland Council in 2014 in order to provide soil moisture information to aid agricultural and horticultural farm management and drought monitoring, and to inform modelling efforts. The network was established in accordance with the *NEMS for measuring soil moisture* (NEMS, 2013, 2016a). This report provides an overview of the soil moisture monitoring network that includes information on site selection, sensor installation and calibration, as well as reporting initial soil moisture results.

2.0 Materials and Methods

The proceeding section outlines the approach followed for the establishment of the soil moisture monitoring network in the Auckland region. Where possible the *NEMS for measuring soil moisture* (NEMS 2013, 2016a) was adhered to which prescribes technical standards, methods and other requirements associated with soil moisture monitoring.

2.1 Site selection

In 2014,10 soil moisture monitoring sites were selected according to predominant soil types and microclimates across the Auckland region (Figures 1 and 2, Table 1). Soil type description was assessed at each site by a local soil scientist with over 30 years of soil knowledge in the Auckland region (Appendix A).

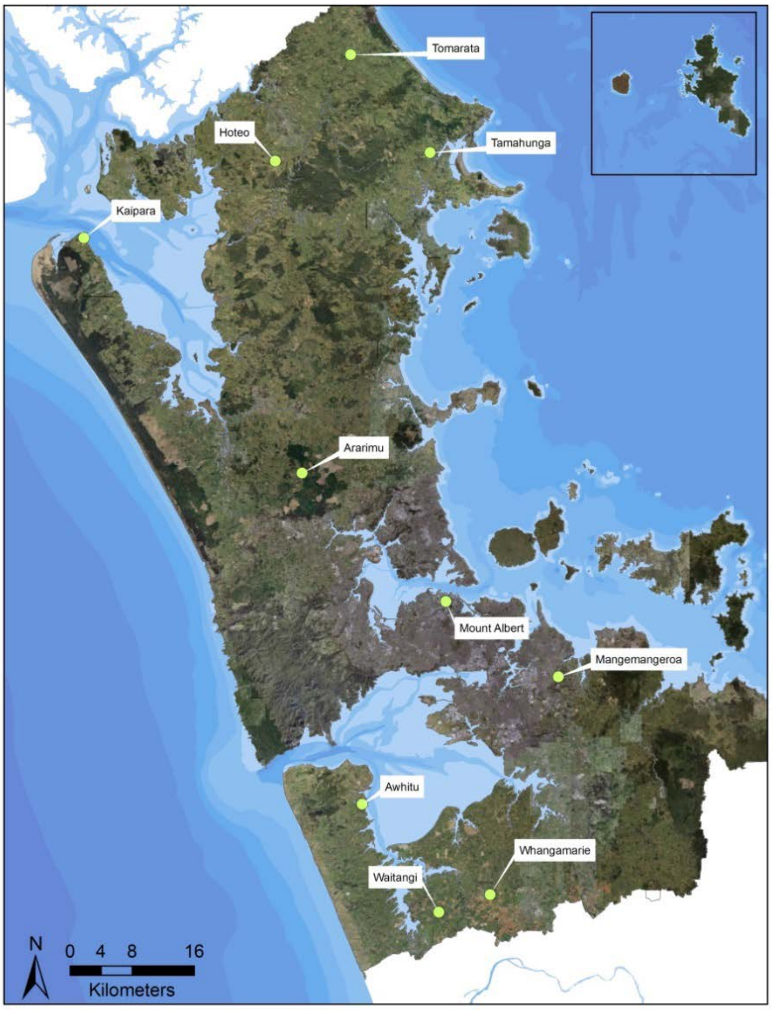


Figure 1. Distribution of soil moisture monitoring sites across the Auckland region as of 2016.

Additionally, site location was narrowed to specific locations based on the location of about 80 pre-existing Auckland Council-operated telemetered rain gauges, which all meet the NEMS for rainfall recording and achieve a maximum quality code of QC500 or better (QC500 is regarded as data of ‘fair quality’ and is one step below the highest regarded QC600 quality code which is considered ‘good quality’) (NEMS, 2017). Quality codes range from QC100-QC600.

The rain gauge locations offered good regional spread and representation to assist with the location criteria for sites, including health and safety, site access, agreeable landowner, and avoidance of large nearby obstacles such as trees and buildings or compounding fencelines that might have posed an issue.

All soil moisture sensors were within 5m of rain gauges except for the Tomarata site whereby a rainfall gauge is yet to be installed on site. Until a rain gauge is installed, rainfall data can be obtained from either the Hoteo or Tamahunga rain gauge sites. Utilising already established telemetered rainfall sites allows real time rainfall data to be collected at or close to soil moisture sites, complimenting soil moisture data collection.

All soil moisture sites were located on pastoral land, which is the predominant vegetative cover in the Auckland region, and therefore will not be disturbed by tree roots or man-made disturbance associated with various forms of cropping and cultivation practices. The land was used for various types of pastoral management including dairy, drystock and lifestyle block living purposes (Appendix A). Only the Waitangi site was exposed to irrigation application and therefore the remaining sites could be considered to act as ambient soil moisture conditions. The Tomarata site was the only site fenced off because the soil type is very susceptible to pugging damage. However, stock still had access to graze over the location of the sensor given the design of the fenced-off area. Detailed site metadata was recorded at each site and is presented in Appendix A.

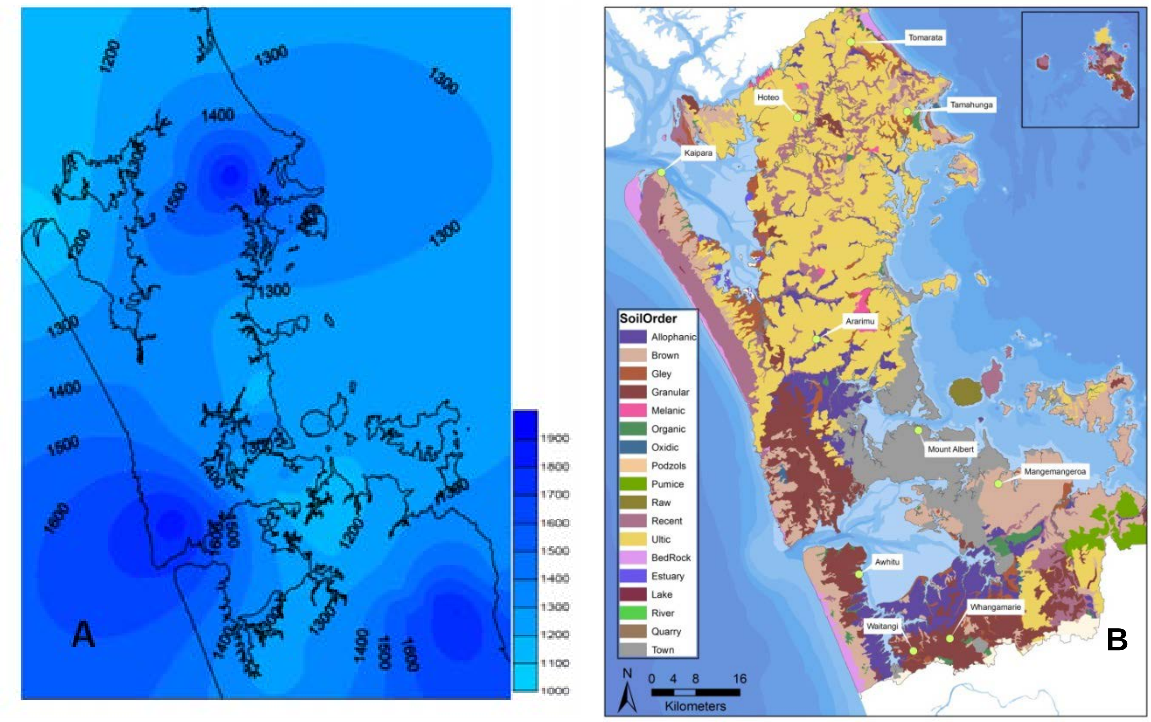


Figure 2. Regional distribution of A) mean annual rainfall (mm)[1] (taken from Curran-Cournane et al., 2013) and B) soil orders across Auckland[2].

[1] Data generated from over 60 rainfall sites using the Research and Evaluation Unit, Auckland Council, automatic rain gauge network, Metservice and Watercare Laboratory Services datasets with rainfall records ranging from around the 1970s to 2012. There will be some degree of overlap between these 60 rainfall sites and the previously referred to 80 sites above.

[2] Taken from the New Zealand Land Resource Inventory Fundamental Soils Layer https://lris.scinfo.org.nz/layer/48079-fsl-new-zealand-soil-classification/ .

Table 1. Brief summary of site information.

Site name	Year installed	Location	Soil order[3]	Mean annual rainfall (mm) (record length)	Pastoral land use
Kaipara	2014	North Auckland	Brown	1054 (1999-2018)	Drystock
Tamahunga	2014	North Auckland	Ultic	1561 (1992-2018)	Drystock
Ararimu	2014	North Auckland	Allophanic	1352 (1978-2018)	Drystock
Hoteo	2015	North Auckland	Ultic	1347 (1978-2018)	Lifestyle block
Tomarata[1]	2015	North Auckland	Ultic	1172 (2009-2017)	Dairy
Awhitu	2014	South Auckland	Granular	1372 (1989-2017)	Regional Park
Mangemangeroa	2014	South Auckland	Ultic	1198 (2001-2018)	Lifestyle block
Waitangi	2014	South Auckland	Granular	1280 (1993-2017)	Dairy
Whangamarie	2014	South Auckland	Allophanic	1329 (1992-2017)	Lifestyle block
Mount Albert[2] (previously New Lynn)	2015	Central Auckland	Ultic	1242 (1991-2017)	Mixed dairy and drystock

[1]The soil moisture sensor at the Tomarata site was initially installed in 2014 but was relocated to a different location on site in 2016 because of problematic site location.

[2]The soil moisture sensor at the New Lynn site was initially installed in 2014 but was relocated to a new site in Mount Albert in 2015 because of problematic site location.

[3] Soil Order as per soil site field inspection which may differ from the Fundamental Soils Layer Classification as per Figure 2b

2.2 Equipment

The AQUAFLEX[3] SI.99 sensor (a 3m long flexible tape measure) was used to measure water content and soil temperature (not reported here). The AQUAFLEX SI.99 was connected to an IRS350fX datalogger over a 4-20 mA output. Soil moisture measurements are recorded and telemetered every 15 minutes. The mA signal was converted to soil moisture and temperature data using the AQUAFLEX SI.99 Manual AF079-06 (AQUAFLEX, 2010).

2.3 Installation

Eight soil moisture sensors were installed across the Auckland region between 26 and 28 May 2014, a ninth one in July 2014 and a tenth one in October 2015 (Table 1 and Appendix A). However, two soil moisture sensors at the New Lynn and Tomarata sites were relocated in 2015 and 2016 as a result of problematic site locations. For example, the New Lynn site was not considered representative of the soil type because it was on a slope that was “fed” by runoff and lateral sub-surface drainage from footpaths and drainage was restricted by a drain downslope. The original Tomarata site was relocated because of pugging damage to the vulnerable soil type and potential hoof damage to the soil moisture sensor. It was not practical to fence-off the site from such grazing activity at the original location (Table 1 and Appendix A).

At each site a single AQUAFLEX was installed in the A-horizon of the soil profile. The A-horizon varied in maximum depth from 20cm to 35cm across sites (Appendix A). At each site three neutron probe access tubes were installed as shown in Figure 3 (later explained in the ‘calibration’ section).

[3] It should be noted that this monitoring programme is not an endorsement of the use of the AQUAFLEX sensor tape and that other instruments can be used that also accord to the *NEMS for measuring soil moisture*.

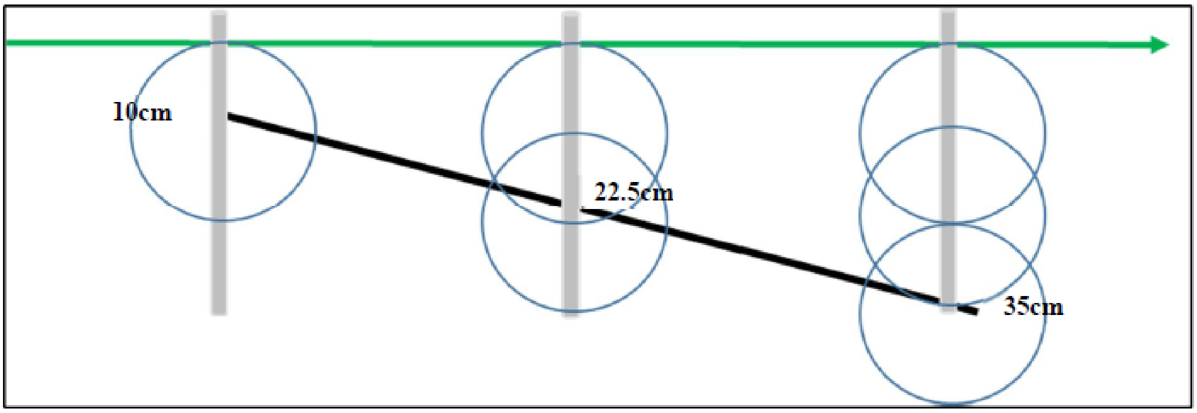


Figure 3. Schematic illustration of site installation; where ▬ = AQUAFLEX (3m in length), ▮ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.

At each site, the sensor was installed by excavating a trench and laying the sensor against one wall of the trench. Installation depth varied from site to site due to soil horizon depth variations (Appendix A). Soil was removed from the trench and laid on a plastic sheet in the order of removal. Care was taken to ensure the soil excavated from the trench was returned in the order it was removed. Once the sensor was installed soils were packed back into the trench in the reverse order of removal to ensure as little disturbance to the soil profile as possible. For site specific installation photos refer to Appendix A.

2.4 Calibration

While the AQUAFLEX user manual contains manufacturer formulas for calibrating raw sensor data for two combination soil textures, 1) sand, silt and sandy and silty loams and 2) clay and clay loams sand, neutron probe sensors were used to calibrate the raw sensor data as part of this monitoring network. This approach is generally considered best practice by the *NEMS for monitoring soil moisture*, and for volcanic soils at least, research has shown the importance of developing soil specific calibrations (Stenger et al., 2007). Additionally, calibrations using the neutron probe provide confidence when comparing soil moisture between sites and sensors.

For field calibration purposes, three aluminium neutron probe access tubes were installed adjacent to the sensor at the start, middle and end (Figure 3). The access tubes were installed by auguring a hole 10mm smaller than the 80mm diameter access tube. The tapered end of the access tube was then placed in the hole and the tube was pushed in using a hammer. Caps were used to seal the top of the access tubes to prevent them filling with water and sediment and were flush with the ground surface.

Soil moisture calibration measurements using a neutron probe were carried out by HydroServices Ltd. several times over the course of twelve months across a range of soil moisture contents for all seven sites that have remained installed since May 2014. Additional calibrations were also carried out after the first year of installation (Appendix B). Volumetric soil moistures (% v/v) with a neutron probe were taken at various soil depths at each site in each of the three access tubes (Appendix B). For each calibration, the neutron probe readings were averaged across the relevant soil depths per site (i.e., highlighted cells in Appendix B) and used as the volumetric soil moisture for that date. The volumetric soil moisture value used for each neutron probe recording, therefore, corresponds to the depth of the adjacent soil moisture sensor (Appendix B). Volumetric soil moisture equations were then established between these neutron probe averages and AQUAFLEX recordings, which were then used to calibrate the raw sensor data (Appendix B).

The intention is to continue to carry out additional soil moisture calibration measurements using a neutron probe at least once a year in subsequent years where possible (or more frequently for remaining network sites, e.g., Hoteo, Tomarata, Mount Albert) in order to continually check and calibrate the data over time. For any new or relocated sites, this practice will also be implemented (Appendix B).

The accuracy of neutron probe measurements closer to the soil-air interface may be low due to the fact that the sphere of influence (radius) of the neutron probe instrument extends into the air above the soil surface[4]. Further, the sphere of influence of the neutron probe is a strong function of moisture content, decreasing as volumetric water content increases (Chanasyk and Naeth, 1996). Extensive testing of the neutron probe to determine the most precise first measurement depth has been carried out by those conducting these calibrations. It has been observed that the shallowest depth is 16cm at which the sphere of influence will extend from just below the soil surface to a depth of 26-32cm. A soil depth shallower than 16cm results in neutron loss at the surface[5]. Notwithstanding the latter, it was considered important to attain soil moisture monitoring across a range of soil depths (10-35cm) in order to get representative data for the soil A-horizon across all sites.

Additionally, many sites outside of this monitoring network have been destructively sampled by HydroServices for gravimetric analysis to determine and compare

[4] Dr Channa Rajanayaka, NIWA, pers. comm. March 2018

[5] Dr Anthony Davoren, HydroServices, pers. comm. May 2018

volumetric soil moisture content with neutron probe readings. Stable reference drums are also used biannually by these practitioners to check every neutron probe to ensure every neutron probe has no drift or measurement error[5].

In October 2015, physical properties of the topsoil were analysed by Landcare Research, Hamilton (Appendix C) at 1, 2, and 3m distances along the soil moisture sensor, and approximately 5m away. A surface soil stainless steel ring was used that was 7.5cm deep and 10cm in diameter[6] which was then subsampled using a small steel ring (5.5cm diameter and 3cm depth). The subsampling of the larger ring is to correct for any sampling error or bias between field staff and to ensure the measurement of a fully intact soil core. The smaller cores were saturated and equilibrated at both -5 and -10kPa on a ceramic tension plate to determine macroporosity. Macroporosity (% v/v) at -10kPa, or air-filled porosity, which will be referred to in a later section in relation to soil compaction, is the volumetric percentage of pores > 30 microns. Dry bulk density and total porosity were calculated from oven (105^{o}C) dry weights. Field capacity (FC; vol water content 10kPa % v/v[7]) and wilting point, often referred to as permanent wilting point, (PWP; vol WC 1500kPa % v/v[8]) were measured at tensions of -10kPa and -1500kPa, respectively (Appendix C). Total available water (TAW) was calculated as the difference between FC and PWP and readily available water (RAW) was the difference between FC and a tension of -100kPa (Appendix C).

[6] Note the sampling at the 0-7.5cm soil surface depth. In hindsight this should have corresponded with the soil depth increments specific to the location of the AQUAFLEX sensor for each site. This will be discussed further, including in the recommendations section.

[7] Field capacity is equivalent to the water content held in soil after gravitational drainage from a saturated condition falling to a rate that is insignificant (i.e., drainage rate ≤ 1 mm/day) (NEMS 2016b).

[8] Permanent wilting point is the soil water content at which plants can no longer extract water from the soil and the plant is permanently wilted. In New Zealand it is nominally estimated in the laboratory by measuring the soil water content at −1500kPa soil water potential (NEMS 2016b).

3.0 Results and Discussion

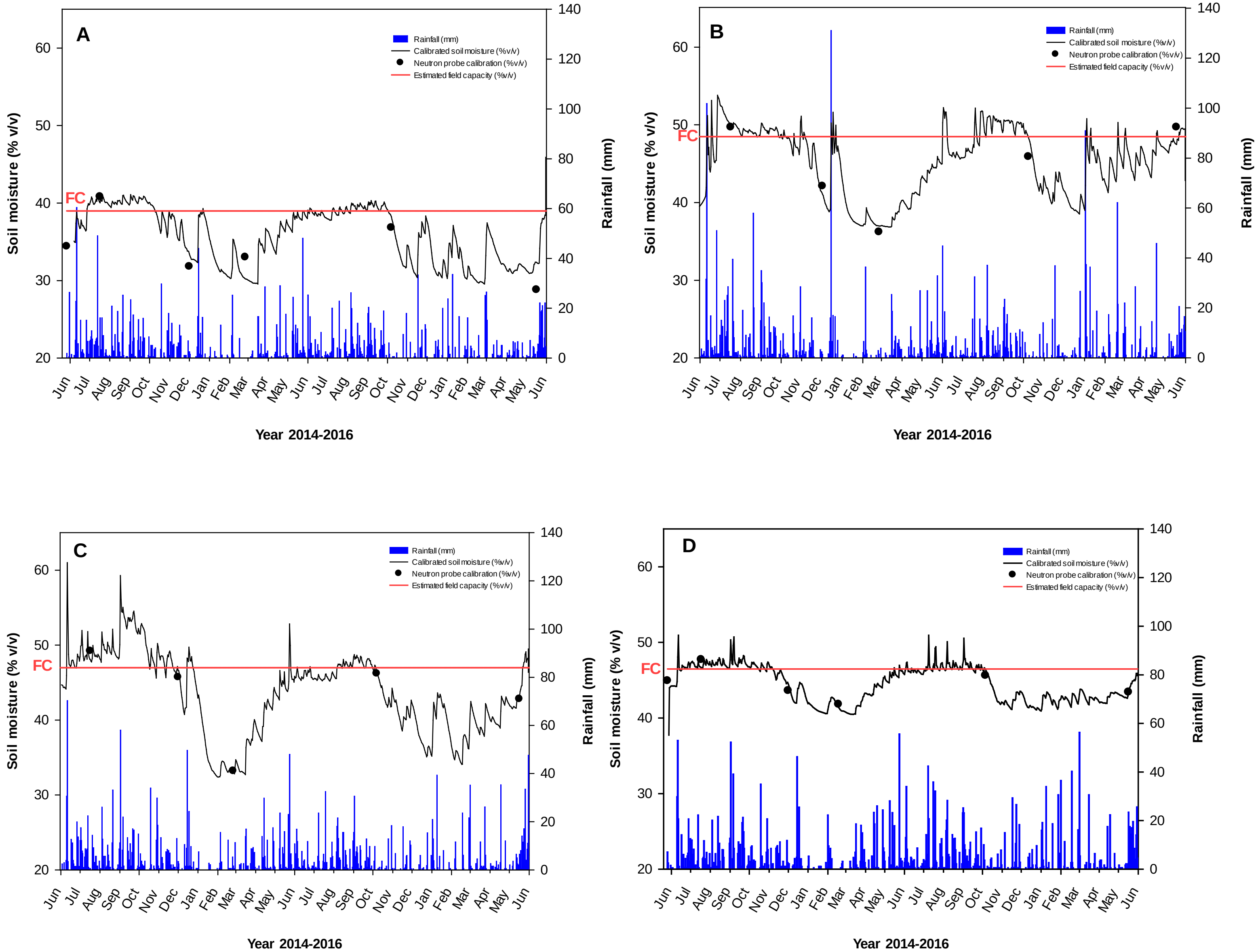
Soil moisture is constantly changing and is not homogenous across the Auckland region. Rainfall differs spatially across Auckland and is a key driver of day to day differences in soil moisture. Long-term annual rainfall ranges from 1000 to 1900mm across the region (Figure 2a) and from 1056 to 1561mm at the soil moisture sites (Table 1). Geographical variations in soil physical characteristics (texture, structure, organic matter, soil depth, profile layering, stone content), expressed by soil orders (Hewitt, 2010) also influence soil moisture as do crop/pasture types, farm management, landscape position, slope and aspect all of which are site specific. For example, with its characteristically deep rooting systems, kikuyu grass which is a prominent pasture species in Auckland that originated from South Africa is one of the more drought resilient pastures in the region.

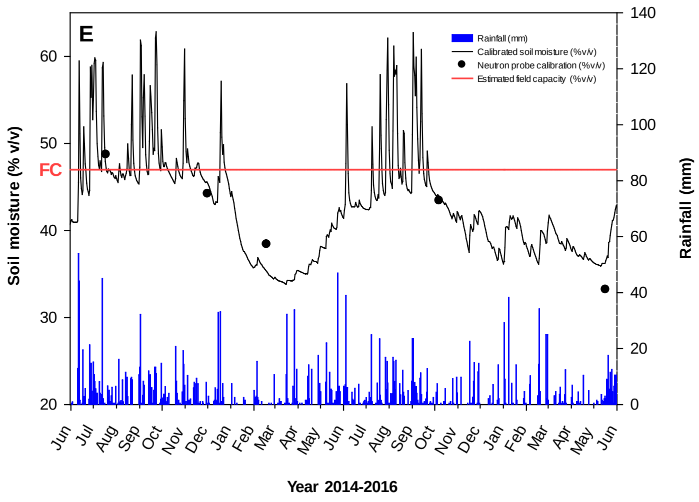
Seven of the 10 soil moisture monitoring sites have been operational since May 2014 (Table 1), and have been field calibrated using a neutron probe. The results and discussion will therefore focus largely on these seven sites.

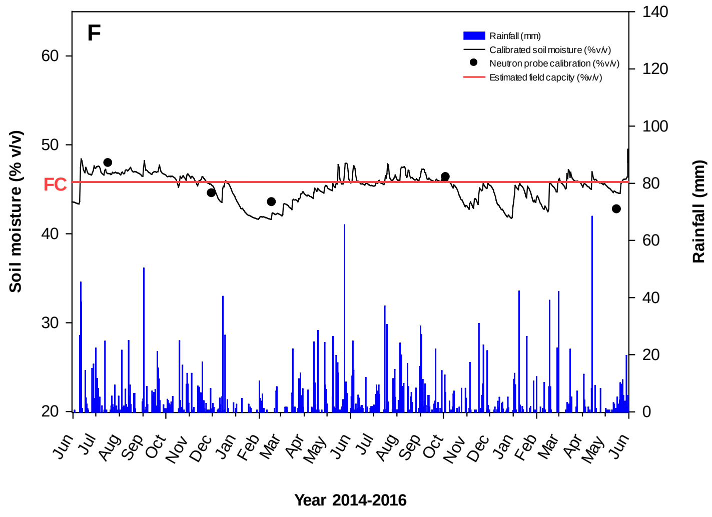
3.1 Volumetric soil moisture calibration

A summary of neutron probe calibrated volumetric soil moisture and rainfall data for seven sites collected between June 2014 and June 2016 are presented in Figure 4. Rainfall is plotted as daily total rainfall and soil moisture as daily mean percentage. Using neutron probe calibrated sensor data, estimates of field capacity (FC) were determined from analyses of these data and are displayed for each site on each graph as the upper red line on colour printed versions. This was typically determined by assessing the calibrated volumetric soil moisture data about 48-72 hours after the ceasing of heavy rainfall in the wet season, particularly over months July-September. When determining field capacity for each site, less weight was directed towards calibrated volumetric soil moisture data in the first 12 months because it can take time for the soil to settle after being disturbed. This would also stand when reporting on calibrated volumetric soil moisture data across sites.

Specific neutron probe (% v/v) recordings at the time they were taken are shown in Figure 4 as black dots. A linear relationship between the averaged neutron probe readings and the AQUAFLEX soil moisture recordings was created with the r^2 values ranging from 0.62-0.97 for those seven sites that have remained installed since May 2014 (Appendix B).


A
B
C
D
Rainfall (mm)
Calibrated soil moisture (%v/v)
Neutron probe calibration (%v/v)
Estimated field capacity (%v/v)
FC
Soil moisture (% v/v)
Rainfall (mm)
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun
Year 2014-2016





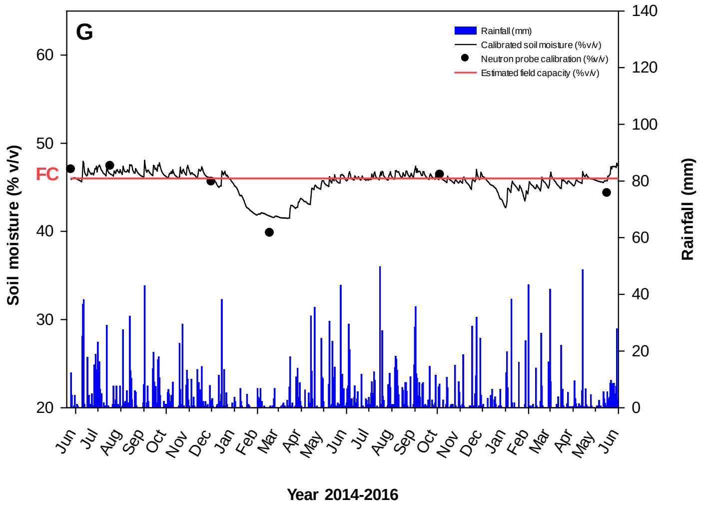


Figure 4. Neutron probe calibrated soil moisture sensor data (black line) for A) Kaipara, B) Tamahunga, C) Ararimu, D) Awhitu, E) Mangemangeroa, F) Waitangi and G) Whangamarie sites with neutron probe calibration recordings (black dots), estimated field capacity (red line) and daily total rainfall (blue bars).

Laboratory measurements for field capacity varied considerably from estimated field capacities using neutron probe calibrated sensor data (Table 2). This is because calibrated soil moisture sensor estimates for FC were averaged between 10-35cm soil depths, whereas laboratory FC measurements were from soil cores collected at 0-7.5cm soil depths. Field capacity measurements from shallow topsoil depths do not take into account changes in soil texture and structure along the soil profile or the depth measured by the soil moisture tape, ignoring the effects of the profile on water drainage and storage (McLaren and Cameron 1996), and thus do not relate well to the deeper sensor data. It is therefore recommended that estimates of FC using calibrated neutron probe soil moisture sensor data be used to determine FC.

While estimated FC can therefore be easily determined via analyses of daily total rainfall and calibrated neutron probe soil moisture sensor data, permanent wilting points (PWP) cannot. PWP is the lowest soil moisture plants can tolerate before wilting, which is plant specific. Without observing and measuring plants, the best estimate of PWP is the water content of the soil at -1500kPa. PWP is therefore measured in the laboratory at -1500kPa using the surface soil moisture samples (at 0-7.5cm soil depths). The results should therefore be treated with caution as the depth of measurement does not reflect the depth of the soil moisture sensor (Table 2).

Table 2. Comparison of estimated and laboratory field capacity (FC) and permanent wilting point (PWP) across soil moisture sites and depths.

Site	**Estimated FC** (10-35cm soil depths)	**Laboratory FC** (volume water content 10kPa 0-7.5cm soil depth)	**Laboratory PWP** (volume water content 1500Pa 0-7.5cm soil depth)
Kaipara	39% v/v	47.6% v/v	29% v/v
Tamahunga	48.5% v/v	55.4% v/v	21% v/v
Ararimu	47% v/v	54.5% v/v	22.5% v/v
Awhitu	46.5% v/v	44.8% v/v	29% v/v
Mangemangeroa	47% v/v	55.2% v/v	25.5% v/v
Waitangi	45.8 % v/v	54% v/v	30.2% v/v
Whangemarie	46% v/v	54.3% v/v	30.4% v/v

Due to the disparity between FC (-10kPa) and PWP (-1500kPa) values from the laboratory analyses that reflect 0 to 7.5cm soil depths versus estimated FCs using calibrated soil moisture sensor data that are recorded between 10 to 35cm soil depths, it is recommended that additional soil samples be collected in the field for FC (at -10kPa) and PWP (at -1500kPa) analyses that represent the depth measured by the AQUAFLEX soil moisture sensors for each site. It should be noted, however, that true FC may not necessarily be at the nominally measured -10kPa soil water potential; direct field measurements show that it can vary between −2kPa and −30kPa, depending on soil texture (NEMS, 2013, 2016b, McLaren and Cameron, 1996). Field capacity can also be estimated in the field by measuring the soil water content two to three days after heavy rainfall (NEMS, 2016b), as per current determination of estimated FC using calibrated soil moisture sensor data (Figure 4 and Table 2).

Volumetric soil moisture samples (i.e. initial water content ((% w/w) * dry bulk density: Appendix C) collected in October 2015 at the 0 to 7.5cm soil depths across all sites are listed in Table 3, along with calibrated volumetric neutron probe soil moistures at the 0 to 20cm soil depths (extracted from Appendix B). Volumetric soil moisture differences range between -7% - +42% (mean 17%) and the disparity can be largely explained by the differences in soil depths measured. Similar to the above recommendations that additional soil sampling and laboratory analysis for FC and PWP determination be carried out, analyses should also include the gravimetric measurement of soil water content across the AQUAFLEX sensor soil depths for additional calibration purposes that will provide validation or necessary adjustment to the current neutron probe calibration.

Table 3. Comparison of volumetric soil moistures using laboratory and neutron probe values for sampling carried out in October 2015.

Site name	Laboratory water content % v/v	Neutron probe % v/v
	Depth 0-7.5 cm	**Depth 0-20 cm**
Kaipara	38.9	36.5
Tamahunga	60.3	45.9
Ararimu	52.0	45.7
Hoteo	46.9	36.7
Tomarata[1]	66.0	38.5
Awhitu	42.5	45.6
Mangemangeroa	53.2	43.5
Waitangi	52.5	46.3
Whangamarie	52.9	45.5
Mt Albert	54.4	39.6

[1] Relocated Tomarata site

3.2 Overview of volumetric soil moisture data across sites

Data from 2014 to 2016 (Figures 4a - 4g) are insufficient to carry out a long-term analysis of soil moisture regimes at Auckland Council's soil moisture monitoring sites. As previously mentioned, the first twelve months of calibrated volumetric soil moisture data should be interpreted with caution because it can take time for the soil to settle after being disturbed during sensor installation. Nevertheless monitoring to date demonstrate that the measurement technique selected (neutron probe calibrated AQUAFLEX sensors) have produced records that relate well to each site's rainfall. They also show different responses to rainfall on the various soils. Therefore, the relative change in soil moisture can be utilised to understand the soil-water dynamics at each site.

Comparisons of soil moistures across northern, southern and inactive sites are plotted in Figures 5a, 5b and 5c, respectively, and seasonal rainfall is displayed in Table 4. All 10 sites display a similar annual pattern with isolated differences. Soil moisture rises with increased precipitation at the start of May, peaks around July/August and remains high until late October. Numerous narrow spikes in soil moisture appear on all plots, except for the New Lynn site in Figure 5c, and are correlated with the seasonal rise in soil water recharge by winter and spring rainfall which occurs regularly region wide (Table 4).

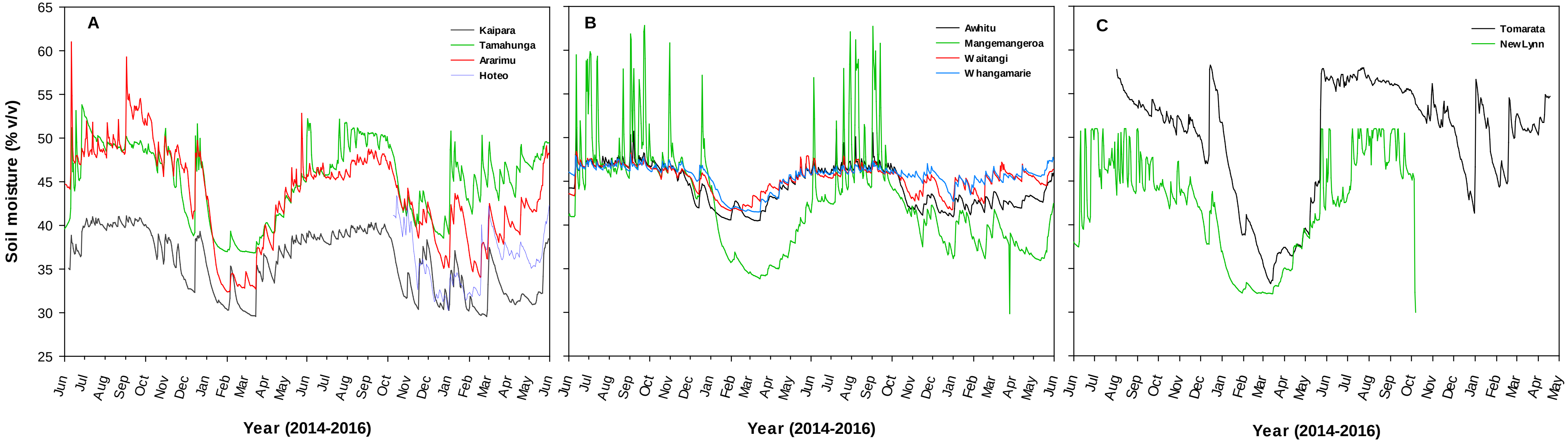


Figure 5. Volumetric soil moisture comparison plots for A) northern sites (Kaipara, Tamahunga, Ararimu, Hoteo), B) southern sites (Awhitu, Mangemangeroa, Waitangi and Whangamarie) and C) removed sites (original Tomarata and New Lynn).

Table 4. Seasonal total rainfall from 2013-2016 for all soil moisture sites.

Soil moisture monitoring site	Seasonal total rainfall (mm)											
	Summer *December-February*			**Autumn** *March-May*			**Winter** *June-August*			**Spring** *September-November*		
	Year			**Year**			**Year**			**Year**		
	2013-2014	**2014-2015**	**2015-2016**	**2013-2014**	**2014-2015**	**2015-2016**	**2013-2014**	**2014-2015**	**2015-2016**	**2013-2014**	**2014-2015**	**2015-2016**
Kaipara	97	159	230	160	330	246	461	290	321	313	256	309
Tamahunga	301	271	432	175	330	282	648	322	658	315	251	432
Ararimu	227	185	232	227	292	294	502	359	493	405	248	407
Hoteo	242	211	430	299	227	227	591	337	536	365	254	424
Tomarata	No data currently available on-site (rainfall gauge to be installed at soil moisture location in near future)											
Awhitu	211	166	335	209	372	297	414	492	427	416	274	409
Mangemangeroa	222	156	281	207	317	186	448	347	394	315	232	372
Waitangi	197	154	294	262	387	226	398	436	454	342	299	400
Whangamarie	204	143	306	261	389	272	440	445	506	373	291	386
Mt Albert	166	169	266	205	343	226	389	432	455	411	263	348

From late October until early February at all sites, volumetric soil moisture fell to a trough, which persisted from February to April 2015 (with low spikes corresponding to occasional summer rain) and from February to mid-May 2016 (Figure 5) (with four spikes that corresponded to substantial summer rain events that were particularly pronounced for the four northern sites Figure 5a). The dip in soil moisture in the summer and early autumn may be due to evaporation and plant soil moisture uptake exceeding precipitation, as well as ongoing soil water drainage which would most likely only tend to occur after significant rainfall events. Tropical cyclones are a feature of the climate in Auckland’s summer to autumn months (Chappell, 2013) and can be responsible for the large rainfall events and spikes in summer soil moisture.

3.3 Northern sites

Monthly and seasonal patterns of soil moisture were similar across the northern sites (Figure 5a) with a consistent pattern of summer drying and winter wetting and short-term response to rainfall. While only collected at the 0 to 7.5cm soil depths, topsoil physical characteristics that create slow to imperfect drainage for some of the sites can help explain the short-term and seasonal soil moisture patterns (Appendix C). However, in other cases it doesn’t explain the hydrological behaviour of all soil sites, particularly those that are not exposed to intensive grazing management, which is more likely controlled by subsoil structure. The range of physical characteristics from some 0 to 7.5cm topsoil samples from northern sites are presented below:

- bulk density: 0.83 - 1.31 t/m^3
- total porosity: 51 - 67% v/v
- macroporosity: 2 - 12% v/v at -10kPa (average 5% v/v)
- total available water: 18 - 35% v/v
- readily available water: 6 - 10% v/v

Intensive grazing causing topsoil compaction by stock treading, shown by macroporosity -10kPa measurements less than the 10% v/v recommended guideline range (Sparling et al., 2003) may have caused a reduction in the readily available water at some sites (i.e., the difference between FC and a tension of -100kpa). Soil compaction was apparent in the upper 0 to 7.5cm at three of the five northern sites (Hoteo, Ararimu and Kaipara), which can impact the water holding capacity of soils by reducing the volumetric percentage of pores > 30 microns in the soils. A reduction in soil macropores through compaction is an issue in Auckland soils (Curran-Cournane et al., 2013, Curran-Cournane, 2015), which can affect a soil’s drainage capacity, infiltration rate, agronomic and environmental performance. Land management is essential to maintaining good soil physical quality.

The Kaipara and Ararimu sites showed differences in soil moisture patterns (Figure 5a). The Kaipara site consistently recorded the lowest soil moisture of the four northern sites. The Ararimu site recorded low soil moisture troughs in summer and autumn. Laboratory analyses (Appendix C) indicated the Kaipara site's topsoil had the highest bulk density of any site, as well as lower total porosity and macroporosity than most. These soil physical properties are atypical of Red Hill sandy loam topsoil, which was the soil type recorded at the Kaipara site, and therefore indicates a degree of soil compaction in the topsoil.

The Ararimu site is a Waitemata silt loam, classed within the typic orthic sub-order of Allophanic soils. Laboratory analyses (Appendix C) indicated the topsoil bulk density and total porosity were similar to the sites with Ultic soil (i.e., Tamahunga and Hoteo sites in the north), except for its macroporosity which was lower than the site with sandy loam Brown soil (i.e., the Kaipara site). However, this low soil macroporosity does not appear to impact the site's RAW which is relatively high, suggesting the topsoil (0 to 7.5 cm) physical characteristics at this site are not reflective of soil moisture dynamics at the 10 to 24cm soil depths where the sensor is located. Furthermore, although classed by Landcare Research as Allophanic, the Waitematā soil occurs on alluvium with a variable content of re-deposited ash, so it is not a typical Allophanic soil. A phosphate retention test would confirm this Allophanic soil order classification for this and the Whangamarie site in the south.

3.4 Southern sites

The southern sites (Figure 5b) that occupy Granular (Awhitu and Waitangi), Allophanic (Whangamarie) and Ultic (Mangemangeroa) soils show a peaked short-term rainfall response. Apart from the Mangemangeroa site, seasonal wetting (winter-spring) and drying (summer-autumn) is not as pronounced as the northern sites. The range of some 0 to 7.5cm topsoil physical characteristics for southern sites are presented below (summarised from Appendix C):

- bulk density: 0.83 - 1.12 t/m^3
- total porosity: 56 - 66% v/v
- macroporosity: 2 - 15% v/v at -10kPa (average 9% v/v)
- total available water: 16 - 30% v/v
- readily available water: 7 - 9% v/v

Similarly to three of the northern sites, topsoil compaction by stock treading may have caused low soil macroporosity and RAW at the Waitangi and Whangamarie sites.

The Mangemangeroa site was the driest of the four southern sites for both summers and wettest during both rainy seasons. The soil at this site is Brookby clay loam, a typic yellow Ultic soil which is similar to the yellow Ultic soils at two northern sites (Hoteo and Tamahunga). Laboratory soil physical measurements for the Brookby soil at Mangemangeroa, particularly its low bulk density of 0.83 g/cm^3, high macroporosity 11% v/v (-10kPa) and its high porosity of 66% v/v, are consistent with undisturbed topsoils of better sub-orders of Ultic soils (yellow or sandy) (Curran-Cournane et al., 2013).

3.5 Inactive sites

The two inactive sites (Figure 5c) show short-term responses to rainfall in late autumn and again in late spring. At the Tomarata site, 0 to 7.5cm topsoil physical properties are provided below noting that the collection of soil samples commenced after the New Lynn site monitoring had ceased:

- bulk density: 0.83 t/m3
- high total porosity: 66% v/v
- moderate macroporosity: 10 at -10kPa
- high total available water: 38% v/v
- high readily available water: 10% v/v

The topsoil properties do not explain the hydrological behaviour of the soil at the Tomarata site likely because the fenced-off site is protected from compaction and pugging damage. Therefore, the soil moisture dynamics are more likely controlled by the subsoil structure at the 10 to 35cm soil moisture sensor location depths. Key features of these perch-gley ultic and densipan ultic sub-orders at the Tomarata and New Lynn sites are either a perch-gley layer in the topsoil (above a naturally compact subsoil which cracks in summer permitting rapid soil drainage, but swells and seals in winter impeding drainage); or a structureless eluvial layer in the lower topsoil that forms a near-impermeable densipan (uncemented pan) when wet. These soils, widespread in Auckland's landscape, are naturally prone to ponding in winter-spring, resulting in pugging of pasture, and surface runoff of animal waste and other pollutants towards drains and waterways.

While the soil moisture sensor data provided a reasonable record of the perch-gley and densipan Ultic soils' moisture regime, which is needed for land management, these sites were impacted either by issues associated with slope or grazing damage of vulnerable soils when wet, and therefore potential hoof damage to the soil moisture sensor necessitated their subsequent relocation.

3.6 NEMS Quality Codes – Soil water content recording

Volumetric soil moisture data for the seven sites that have remained installed and monitored since May 2014 have been assigned tentative QC400 codes at a minimum. This has been calculated using estimated FCs (Figure 4 and Table 2) and preliminary laboratory values for PWP (Table 2) as outlined in NEMS (2013, 2016b). Until additional soil sampling and laboratory analyses for PWP, and to a lesser degree FC, that better reflect the soil depths monitored by the soil moisture sensors, such QC codes are tentative for now. Performance objectives for site selection, installation and calibration stability are satisfactory, so future efforts should be directed towards a satisfactory calibration range by targeting neutron probe calibrations at the upper and lower range of volumetric soil moistures.

3.7 Limitations

While some studies have shown that neutron probe monitoring data is not always accurate and advise caution when using the AQUAFLEX data with the neutron probe calibration (Gaze et al., 2002), under the current monitoring and reporting circumstances the neutron probe data has been rigorously "field" calibrated to the best of our understanding.

Notwithstanding the above, it is recommended that the soil moisture data be used to identify the relative change over time due to different climate stresses (e.g., rainfall and evapotranspiration) rather than as absolute measurements to inform specific actions or policies, such as specific crop irrigation requirements. The regional network is to act as a tool to assist with sustainable agricultural land use management for representative soil types and microclimates across the region and for climatic informing purposes.

4.0 Conclusion

Auckland Council's soil moisture monitoring network provides soil moisture measurements for the region, which are potentially useful to farmers for irrigation and drainage, cultivation and timing of crop planting, fertiliser application, land disposal of effluent and sustaining good management practices. In addition, soil moisture measurements could be used for climate modelling and predictions in the future.

AQUAFLEX soil moisture sensors, field calibrated utilising a neutron probe, have shown that volumetric soil moisture is correlated with rainfall patterns at each site. Data from the first two years confirm that the sites display a consistent annual pattern of soil moisture variation in response to the Auckland region's climate. Calibrated volumetric soil moisture also varies from site to site, showing a differing response to rainfall across the various soils.

Seasonal differences in soil moisture were also evident at all of the sites, with troughs in soil moisture through summer-autumn and peaks in winter-spring. There were also short-term differences in the magnitude and duration of soil moisture spikes caused by individual rainfall events. The seasonal and short-term differences were related to soil texture and structure (the main physical factors affecting soil water movement through soils) and soil pore size and distribution, which are affected by bulk density and macroporosity. All these factors play a part in the storage and drainage of soil water, and thus the availability of water to plants.

Soil compaction was also apparent at several of the soil moisture sites with six out of 10 sites having topsoils with macroporosities below the recommended guidelines for agricultural soils (Sparling et al., 2003). Compaction is a persistent issue in Auckland’s agricultural soils that causes structural breakdown, which can reduce storage, impede drainage, increase surface runoff, and transport contaminants into waterways (McDowell et al., 2008; Curran-Cournane et al., 2011).

Based on the initial review of the data and programme to date, it can be concluded that ongoing soil moisture measurements will create longer-term datasets that will facilitate scientific understanding of how Auckland's diverse soils store and release water. It is recommended that:

- Additional laboratory analyses are carried out to determine field capacity (at -10kPa) and permanent wilting point (at -1500kPa) measurements that better reflect the soil depths monitored by the soil moisture sensors at each of the sites in the future. Such sampling and laboratory analysis should also include the gravimetric measurement of soil water contents across the AQUAFLEX sensor soil depths to provide validation or necessary adjustment to the current neutron probe calibration.

- Soil moisture data be made available in real time to aid farm management practices, increase understanding of seasonal soil moisture deficits, and facilitate climate and runoff modelling efforts to predict droughts and floods.
- Consideration be given to expanding the soil moisture sensor network onto several soils that are poorly represented (the Brown and Allophanic soils) or unrepresented (the Recent soils).
- Continuous monitoring and calibration of the soil moisture sites so relative change due to different climate stresses can be assessed over time.

5.0 Acknowledgements

The authors thank all the landowners for allowing access to sites and for providing valuable information.

Clive Coleman, Hamish Allen, Nicholas Holwerda and other members of the Environmental Monitoring and Reporting (EMR) Team of Auckland Council are thanked for their technical knowledge and assisting with installation and calibration sample collection. Melanie Vaughan from the EMR team is thanked for assistance with the map work. Dr Edda Kalbus (United Arab Emirates University, previously EMR) is thanked for early soil moisture reporting discussions.

Melanie Smith and Dr Anthony Davoren from HydroServices Ltd. are thanked for assistance with setting up the soil moisture monitoring programme and neutron probe calibrations as well as assisting with technical advice.

Andrew Harper and Dr MS Srinivasan from NIWA are thanked for discussions related to different approaches to soil moisture monitoring.

Dr Douglas Hicks is sincerely thanked for early peer review comments for which the authors are very grateful for as well as carrying out soil type descriptions at all the soil moisture sites.

Justin Wyatt (Waikato Regional Council) and Dr Channa Rajanayaka (NIWA) are thanked for their incredibly valuable peer review comments which have immensely improved the quality of this report.

The Auckland Council Peer Review Panel, particularly Dr Melissa Foley, are thanked for their involvement and assistance with the publication of this report.

6.0 References

AQUAFLEX (2010). AQUAFLEX soil moisture sensor X SI.99 User Manual AF079-06 (Revision Date 24 August 2010), Irrigation Management Made Easy. Streat Instruments Limited. Christchurch.

Chanasyk, D. S. and Naeth, M. A. (1996). Field measurement of soil moisture using neutron probes. *Canadian Journal of Soil Science*, 76, 317-323.

Chappell P.R. (2013). The climate and weather of Auckland, second edition, NIWA Science and Technology Series, no 60. NIWA, Wellington https://www.niwa.co.nz/static/web/Auckland_Climate_NIWA.pdf

Chibnall, E., Curran-Cournane, F. (2016). Soil quality for drystock and lifestyle-converted sites in the Auckland region in 2015 and changes after 20 years. Auckland Council technical report, TR2016/045.

Curran-Cournane, F., McDowell, R. W., Littlejohn, R. P. and Condron, L. M. (2011). Effects of cattle, sheep and deer grazing on soil physical quality and phosphorus and suspended sediment losses in surface runoff. *Agriculture Ecosystems & Environment*, 140, 264-272.

Curran-Cournane, F. (2015). Soil quality state and trends in New Zealand's largest city after 15 years. *International Journal of Environmental, Ecological, Geological and Geophysical Engineering*, 9, 227-234 http://waset.org/publications/10001081/soil-quality-state-and-trends-in-new-zealand-s-largest-city-after-15-years

Curran-Cournane, F., Fraser, S., Hicks, D. L., Houlbrooke, D. J., and Cox, N. (2013). Changes in soil quality and land use in grazed pasture within rural Auckland. *New Zealand Journal of Agricultural Research*, 56, 102-116.

Curran-Cournane, F., Holwerda, N., Mitchell, F. (2013). Quantifying catchment sediment yields in Auckland. Auckland Council technical report, TR2013/042

Gaze, S. R., Stalham, M. A. and Allen, E. J. (2002). Accuracy of the neutron probe for measuring changes in soil water storage under potatoes. *Journal of Agricultural Science,* 138**,** 135-152.

Hewitt A.E. (2010). New Zealand Soil Classification 3rd edition, Landcare Research Manaaki Whenua, Palmerston North.

McDowell, R. W., Houlbrooke, D. J., Muirhead, R. W., Muller, K., Shepperd, M., Cuttle, S. P. (2008). *Grazed pasture and surface water quality*. Nova Science Publishers, Inc., New York.

McLaren R.G., Cameron K.C. (1996). *Soil Science*, Oxford University Press, Auckland.

National Environmental Monitoring Standard (NEMS) (2013). Soil Water. Measurement, Processing and Archiving of Soil Water Content Data, Version 1.0. http://www.nems.org.nz/assets/Documents/NEMS-18/Soil-Water-Measurement-v1.0.pdf

National Environmental Monitoring Standard (NEMS) (2016a). Soil Water. Measurement, Processing and Archiving of Soil Water Content Data, Version 1.2. http://www.nems.org.nz/assets/Documents/NEMS-18/Soil-Water-Measurement-v1.2.pdf

National Environmental Monitoring Standard (NEMS) (2016b). Glossary Terms, Definitions and Symbols Version: 1.0 Date of Issue: July 2016. https://www.lawa.org.nz/media/2982084/NEMS-Glossary.pdf

National Environmental Monitoring Standard (NEMS) (2017). Rainfall Recording (August 2017). http://www.nems.org.nz/assets/Documents/NEMS-16/Rainfall-Recording-v21.pdf

NIWA (2011). National Scenarios of Regional Drought under Climate Change, National Institute of Atmosphere and Water (NIWA), Wellington.

Pearce, P., Bell, R., Bostock, H., Carey-Smith, T., Collins, D., Fedaeff, N., Kachhara, A., Macara, G., Mullan, B., Paulik, R., Somervell, E., Sood, A., Tait, A., Wadhwa, S., Wooley, J-M. (2018). Auckland region climate change projections and impacts. Revised January 2018. Prepared by the National Institute of Water and Atmospheric Research, NIWA, for Auckland Council. Auckland Council technical report, TR2017/030-02. http://www.knowledgeauckland.org.nz/assets/publications/TR2017-030-Auckland-region-climate-change-projections-and-impacts.pdf

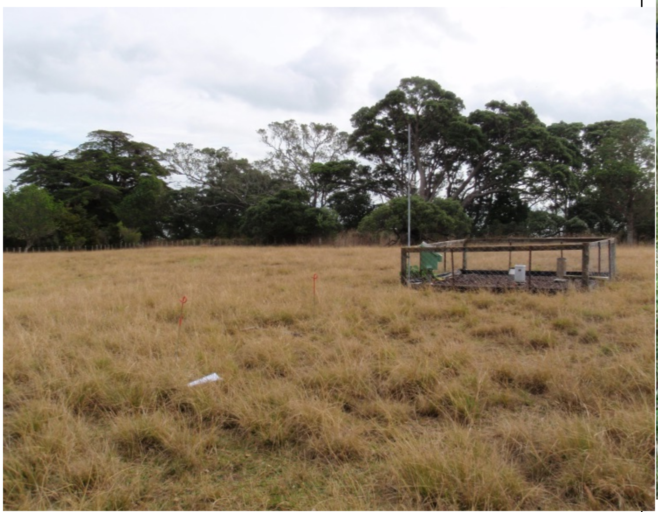
Sparling, G. P., Lilburne, L. and Vojvodic-Vukovic, M. (2003). Provisional targets for soil quality indicators in New Zealand. Landcare Research. Palmerston North, New Zealand.

Stenger, R., Wohling, T., Barkle, G, F., Wall, A. (2007). Relationship between dielectric permittivity and water content for vadose zone materials of volcanic origin. *Australian Journal of Soil Research* 45: 299-309.

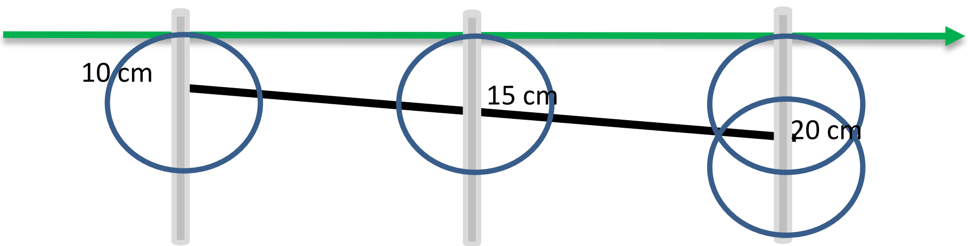
Wright, K., Baldi, M., Lindsay, J, Van Dissen, R., Salinger, J., Dellow, G., Page, M., Power, W., King, D. (2009). Natural hazards and their impacts: Auckland Region. Prepared for Auckland Regional Council. Auckland Regional Council technical report, TR2009/010.

Appendix A Site specific summaries and metadata

Name of site	Awhitu (South Auckland)
Site number	741611
Location	Awhitu
Co-ordinates NZTM	E 1746752 N 5894063
Date of installation	26/05/2014
Land position	Terrace
Slope	0-3^{o}
Soil Series	Matakawau clay loam
NZSC Subgroup	Typic Orthic Granular
Soil profile description	**0-10cm** brown sandy loam, powdery structure **10-20cm** brown sandy clay loam nutty to crumbly structure **20-30+cm** orange-brown sandy clay, crumbly structure
Land use	Regional farm park- drystock grazing by sheep
Typical regional land use	Under intensive uses (orchards, market gardens) and dairy and drystock grazing
Ground cover	Semi-improved pasture (kikuyu dominant in summer with some fescue and browntop, a little ryegrass and clover)
Additional notes	Unfenced and no compounding obstructions

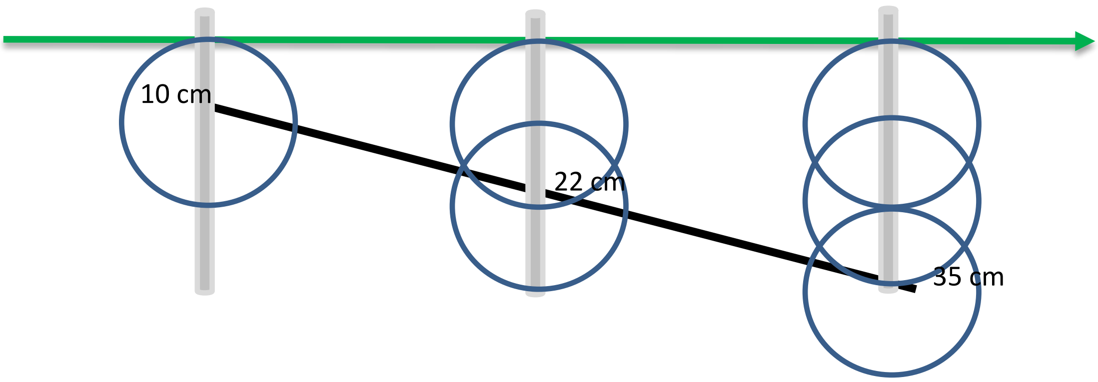


Schematic of site installation; where ▬ = AQUAFLEX, ▌ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



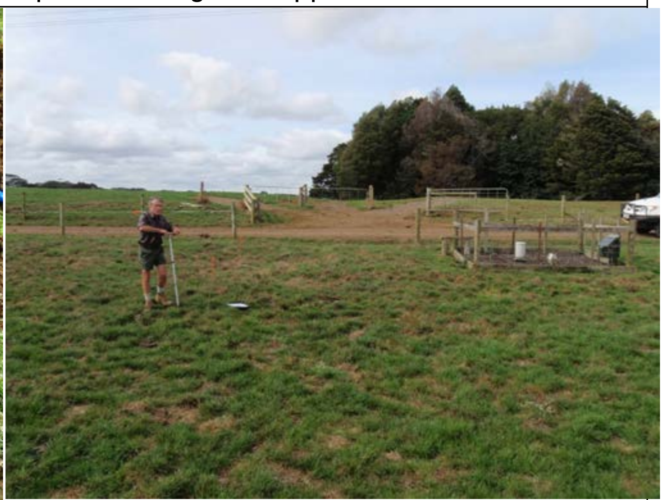
Name of site	Whangamarie (South Auckland)
Site number	741813
Location	Whangamaire
Co-ordinates NZTM	E 176XX74 N 588XX81[9]
Date of installation	26/05/2014
Land position	Terrace edge
Slope	0-3^{o}
Soil Series	Mauku silt loam
NZ soil classification	Typic Orthic Allophanic (subject to P retention soil test)
Soil profile description	**0-15cm** brown sandy loam, powdery structure friable consistence(when dry) **15-30cm** Pale brown silt loam containing a little sand, powdery structure, friable consistence. **30+cm** orange brown clay loam, crumbly structure, firm consistence (slightly moist)
Land use	Small lifestyle block lightly grazed by goats, pigs and fowl
Typical regional land use	Market gardening and dairying
Ground cover	Improved pasture (ryegrass clover dominant)
Additional notes	Unfenced and no compounding obstructions

Schematic of site installation; where — = AQUAFLEX, = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.

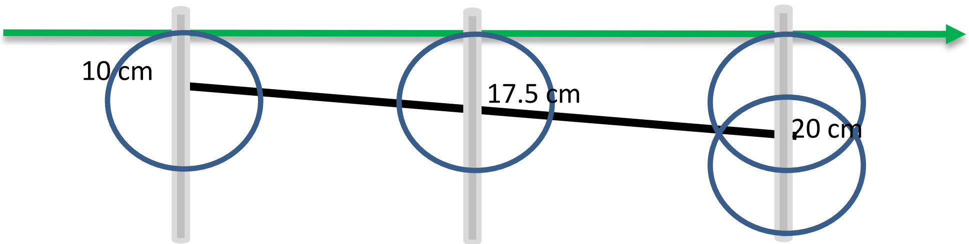


[9] Currently awaiting consent from landowners to release GPS coordinates where XXXs appear

Name of site	Waitangi (South Auckland)
Site number	742736
Location	Waiuku
Co-ordinates NZTM	E175XX67 N588XX10
Date of installation	26/05/2014
Land position	Flat terrace edge above scarp
Slope	0^{o}
Soil Series	Patumahoe clay loam
NZ soil classification	Typic Orthic Granular
Soil profile description	**0-15**cm brown sandy loam, powdery structure, loose consistence (when dry) **15-30+cm** orange-brown clay loam crumbly structure, firm consistence (slightly moist)
Land use	Dairy farm
Typical regional land use	Market gardening and dairying
Ground cover	Improved pasture (ryegrass- clover pasture)
Additional notes	Unfenced and no compounding obstructions but exposed to irrigation application.

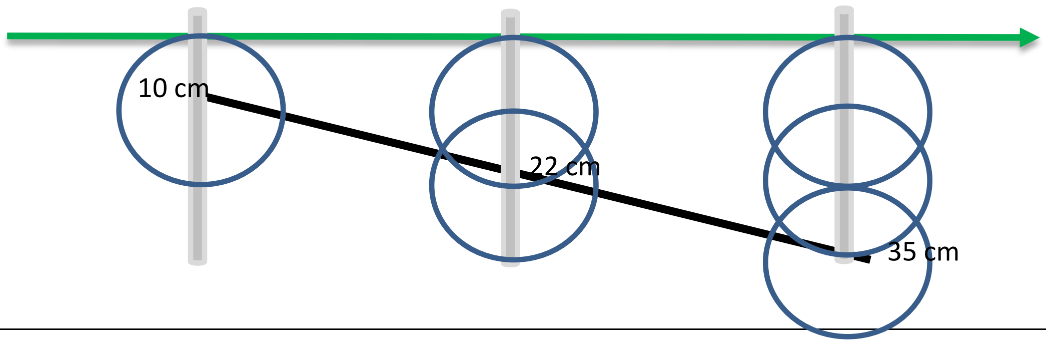


Schematic of site installation; where ▬ = AQUAFLEX, ▮ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



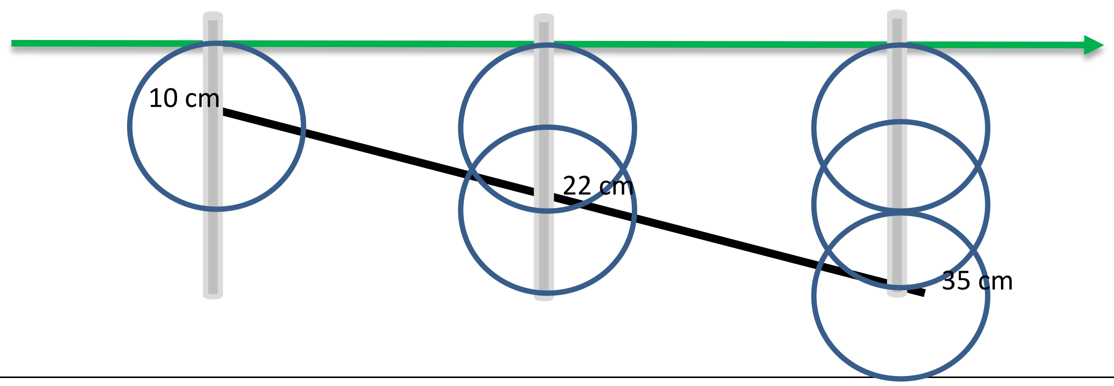
Name of site	Mangemangeroa (South Auckland)
Site number	649937
Location	Howick/Whitford
Co-ordinates NZTM	E1772101 N5910526
Date of installation	26/05/2014
Land position	Spur
Slope	4-7 ^{o}
Soil Series	Brookby clay loam
NZ soil classification	Typic Yellow Ultic
Soil profile description	**0-20**cm dark grey clay loam, nutty structure (when dry) **20-25**cm dark grey clay loam mixing with **25-30+cm** yellow-brown silty clay, powdery structure (when dry) blocky (if moist), massive (if wet).
Land use	Small lifestyle block- grazed by sheep
Typical regional land use	Dairy and drystock grazing
Ground cover	Semi- improved pasture (kikuyu grass)
Additional notes	Unfenced and no compounding obstructions
	

Schematic of site installation; where ▬ = AQUAFLEX, ▯ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



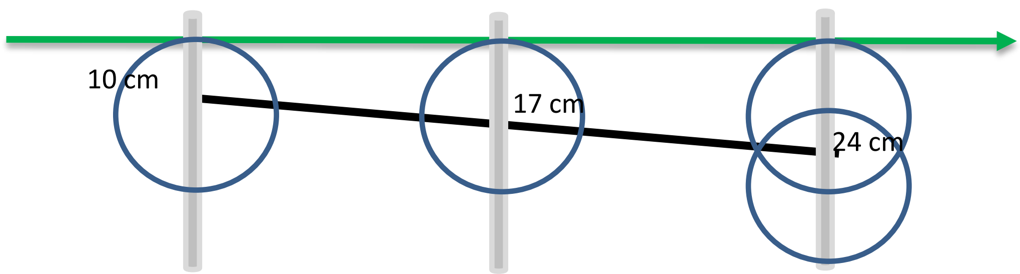
Name of site	Tomarata (North Auckland)
Site number	64068001
Location	Tomarata
Co-ordinates NZTM	E174XX56 N599XX58
Date of installation	17/07/2014 (**removed and relocated to other location on property 18/05/2016**)
Land position	Footslope
Slope	$0\text{-}3^{o}$
Soil Series	Kara sandy loam
NZ soil classification	Perch Gley or Densipan Ultic
Soil profile description	**0-15cm** dark grey clay loam (contains some sand grains) **15-30cm** silty sand; structure massive when dry, single-grain when wet **30-50 cm+** pale grey sandy clay subsoil
Land use	Dairy farm
Typical regional land use	Dairy and drystock grazing
Ground cover	Improved pasture (rye grass clover)
Additional information	Relocated site is fenced-off
	

Schematic of site installation; where — = AQUAFLEX, = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



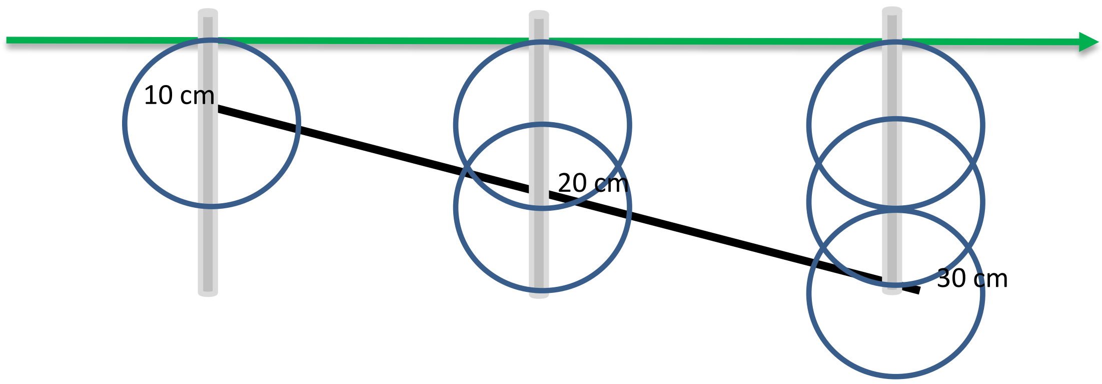
Name of site	Ararimu (North Auckland)
Site number	647510
Location	Waimauku
Co-ordinates NZTM	E173XX84 N593XX76
Date of installation	27/05/2014
Land position	Terrace
Slope	0-3 degrees
Soil Series	Waitemata silt loam
NZ soil classification	Typic Orthic Allophanic
Soil profile description	**0-20cm** dark brown loam, powdery to crumbly structure (when dry) **20-30+cm** yellow-brown silt loam, powdery to crumbly structure (when dry)
Land use	Drystock farm
Typical regional land use	Intensive use (orchards, vineyards, berry crops) and dairy and drystock grazing
Ground cover	Improved pasture (cultivated and re-sown)
Additional notes	Unfenced and no compounding obstructions
	

Schematic of site installation; where ▬ = AQUAFLEX, ▮ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



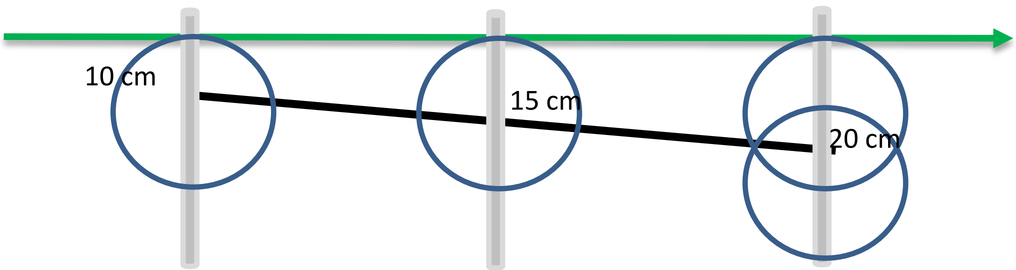
Name of site	Kaipara (North Auckland)
Site number	644211
Location	Kaipara Heads
Co-ordinates NZTM	E 1710814 N 5967291
Date of installation	27/05/2014
Land position	Hill terrace
Slope	0-3 ^{o}
Soil Series	Red Hill sandy loam
NZ soil classification	Typic Sandy Brown
Soil profile description	**0-10cm** dark grey (almost black) sandy silt loam, structure nutty (when dry), firm consistence, compact **10-15cm** dark grey sandy loam (contains some silt, structure nutty (when dry), somewhat firm, less compact **15-50cm** dark brown sandy loam (contains some silt), structure single grain (when dry), loose consistence
Land use	Drystock farm
Typical regional land use	Dairy and drystock grazing
Ground cover	Rye grass-clover pasture
Additional notes	Unfenced and no compounding obstructions

Schematic of site installation; where ▬ = AQUAFLEX, ▮ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



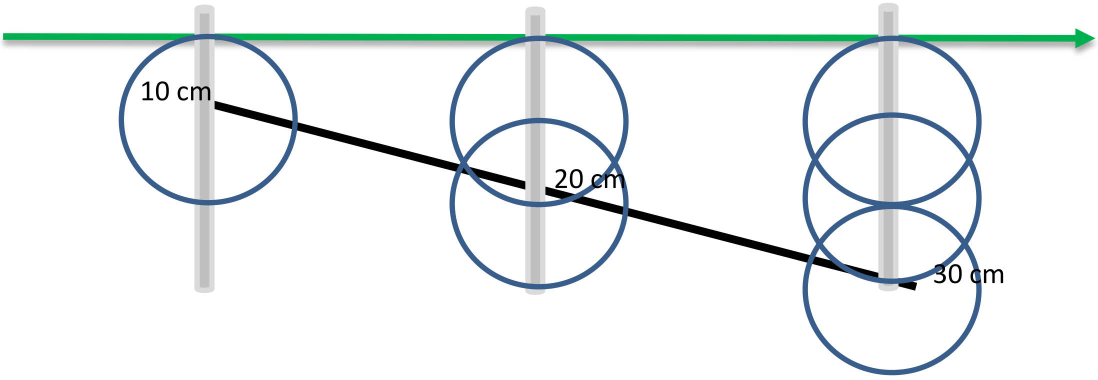
Name of site	Tamahunga (North Auckland)
Site number	643713
Location	Tamahunga
Co-ordinates NZTM	E 175XX40 N 597XX03
Date of installation	28/05/2014
Land position	Terrace
Slope	**0-3 °**
Soil Series	Whareora sandy clay loam
NZ soil classification	Typic Yellow Ultic
Soil profile description	**0-10cm** dark grey clay loam, structure crumbly (when moist), to nutty (when dry) **10-20cm** dark grey clay loam, mixing with yellow-brown sandy clay **20-30cm** yellow-brown sandy clay , structure granular (when moist) to nutty (when dry)
Land use	Small farm grazed by beef cattle
Typical regional land use	Cropping, dairying and drystock farming
Ground cover	Kikuyu- ryegrass pasture
Additional notes	Unfenced and no compounding obstructions

Schematic of site installation; where ▬ = AQUAFLEX, ▮ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



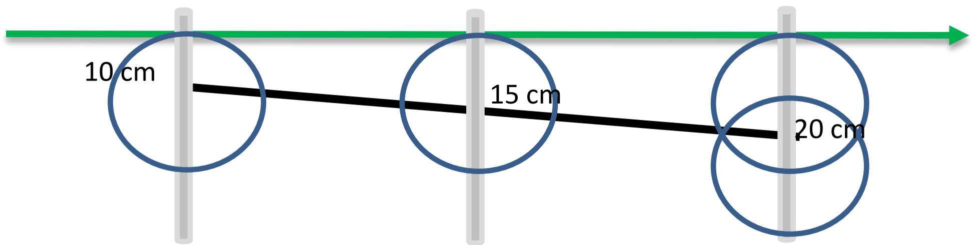
Name of site	Mount Albert (Central Auckland)
Site number	648717
Location	Mount Albert
Co-ordinates NZTM	E: 1757591 N5920276
Date of installation	7/10/2015
Land position	Flat ridge
Slope	0-3 ^{o}
Soil Series	Whangaripo clay loam
NZ soil classification	Mottled Yellow Ultic
Soil profile description	**0-10cm** dark grey sandy clay loam, structure crumbly when wet, likely to be granular when dry **10-15**cm dark grey sandy clay loam, mixing with yellow brown sandy clay **15-40** yellow brown sandy clay with grey mottles, structure massive with sticky consistence when wet, likely to be nutty of blocky when dry
Land use	Small mixed dairy and sheep farm
Typical regional land use	Dairying and drystock grazing on outskirts of Auckland. Suburban housing, parks and reserves within urban boundary.
Ground cover	Ryegrass-clover pasture
Additional notes	Unfenced and in close proximity to fenceline but not considered to pose a significant issue

Schematic of site installation; where ▬ = AQUAFLEX, ▮ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



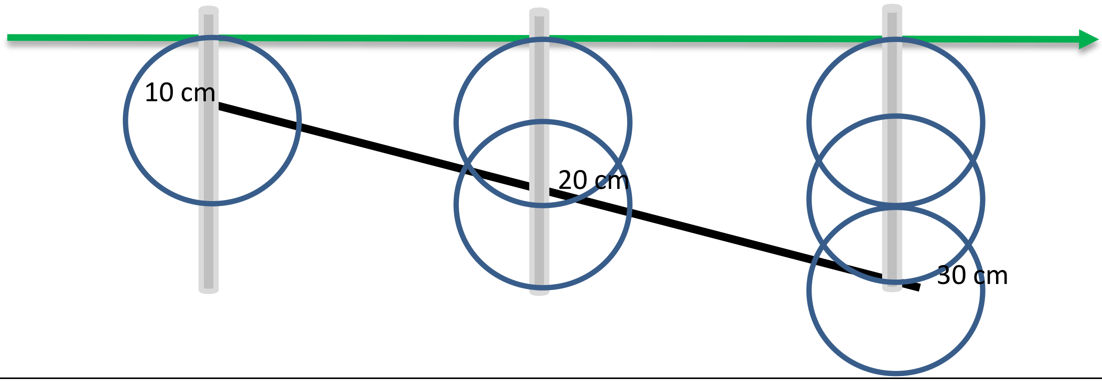
Name of site	Hoteo (North Auckland)
Site number	643510
Location	Hoteo
Co-ordinates NZTM	E173XX47 N597XX17
Date of installation	21/10/2015
Land position	Foot slope
Slope	4-7 °
Soil Series	Aponga clay loam (colluvial variant)
NZ soil classification	Typic Yellow Ultic
Soil profile description	**0-20cm** dark grey sandy loam, nutty structure (when dry) **20-30**cm pale brown silty clay with grey mottles, blocky structure (when dry)
Land use	Large lifestyle block grazed by sheep
Typical regional land use	Dairying and drystock grazing.
Ground cover	Kikuyu- browntop-fescue pasture with scattered rushes
Additional notes	Unfenced and no compounding obstructions

Schematic of site installation; where ▬ = AQUAFLEX, ▮ = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.



Name of site	New Lynn (Central Auckland)
Site number	649637total
Location	New Lynn
Co-ordinates NZTM	E 1749991 N 5912354
Date of installation	27/05/2015 (**removed and relocated to Mount Albert 7/10/2015**)
Aspect	West
Land position	Rolling slope
Slope	8-11^{o}
Soil type	Kara sandy loam (without pan)
NZ soil classification	Perch-Gley or Densipan Ultic
Soil profile description	**0-5cm** dark grey clay loam, nutty structure (when slightly moist) **5-20cm** grey sandy loam, structureless to powdery (when slightly moist) **20-25cm** grey sandy loam grading to grey sandy clay, crumbly structure (when moist) **25-40cm** grey sandy clay, becoming pale below
Land use	Auckland Council urban reserve
Typical regional land use	Dairy and drystock grazing on outskirts of Auckland; suburban housing, parks and reserves within urban boundary.
Ground cover	Mown lawn (kikuyu grass)
	

Schematic of site installation; where — = AQUAFLEX, = neutron probe access tube, O = neutron probe measurement spheres and depths (cm) at start, mid-point and end of the AQUAFLEX.

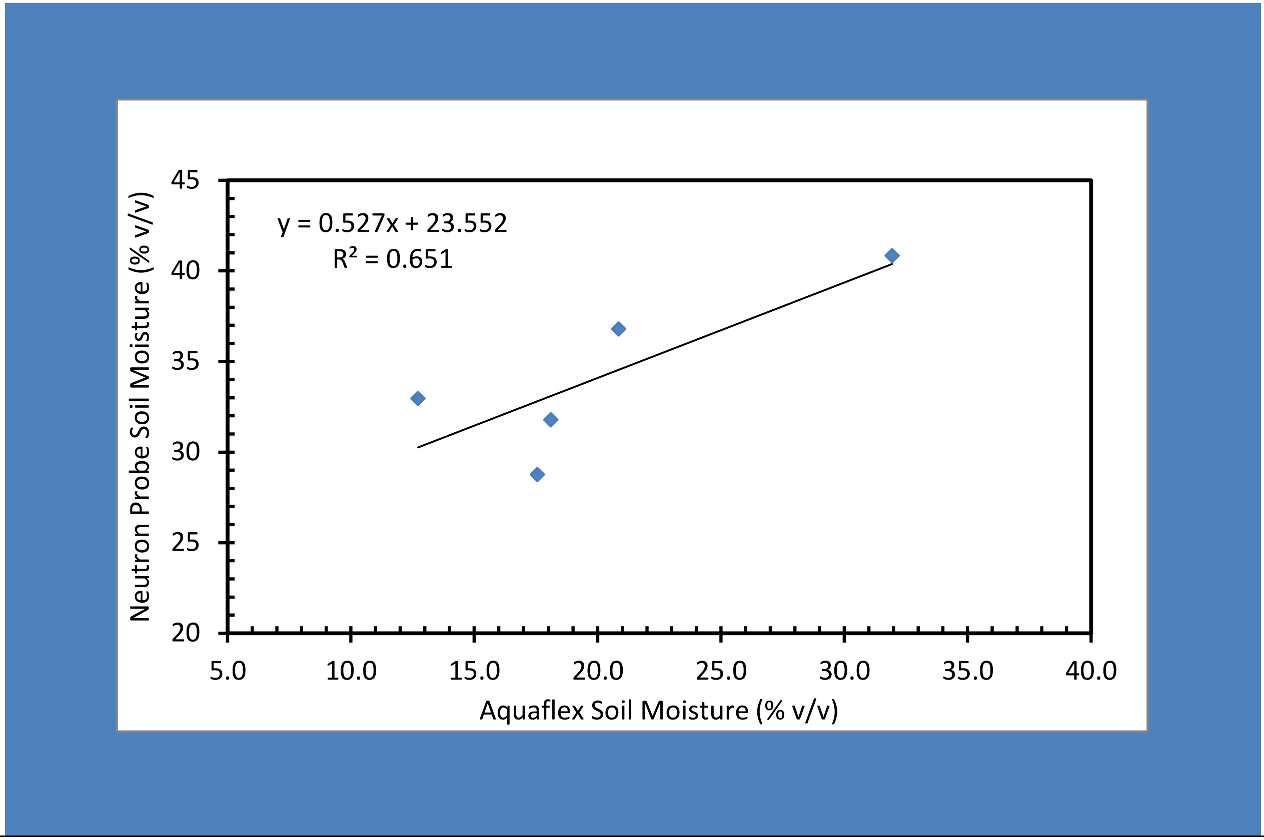


Appendix B Preliminary neutron probe calibrations and relationships

Kaipara

Date	27/05/2014			17/07/2014			1/12/2014			25/02/2015			7/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	34.4	33.1	33.3	39.8	40.1	40	28.3	29.2	30.8	30.7	30.8	29.3	36.7	35.5	36.4	26.9	26.4	27.2
20-30	33.6	35	33.7	40.6	40.7	41.3	29.1	29.2	32.8	33	31	32.6	36.7	37.7	35.9	27.8	26.4	28
30-40	37.9	36.4	36.4	42.8	42.8	42.1	35.7	34.6	36.8	33.9	37.7	37.7	40.1	39.2	39	33.7	32.3	33.7
40-50	40.5	41	39	45.4	44.6	43.7	41.1	39.6	40.3	38.6	43.5	42.1	43	43.2	41.7	38.8	38.6	37.7
50-60	41.2	41.4	39	45.1	47.1	44.6	42.2	41.3	39.8	38.2	46.3	43.3	46.1	44.3	41.4	39	39.4	37.9

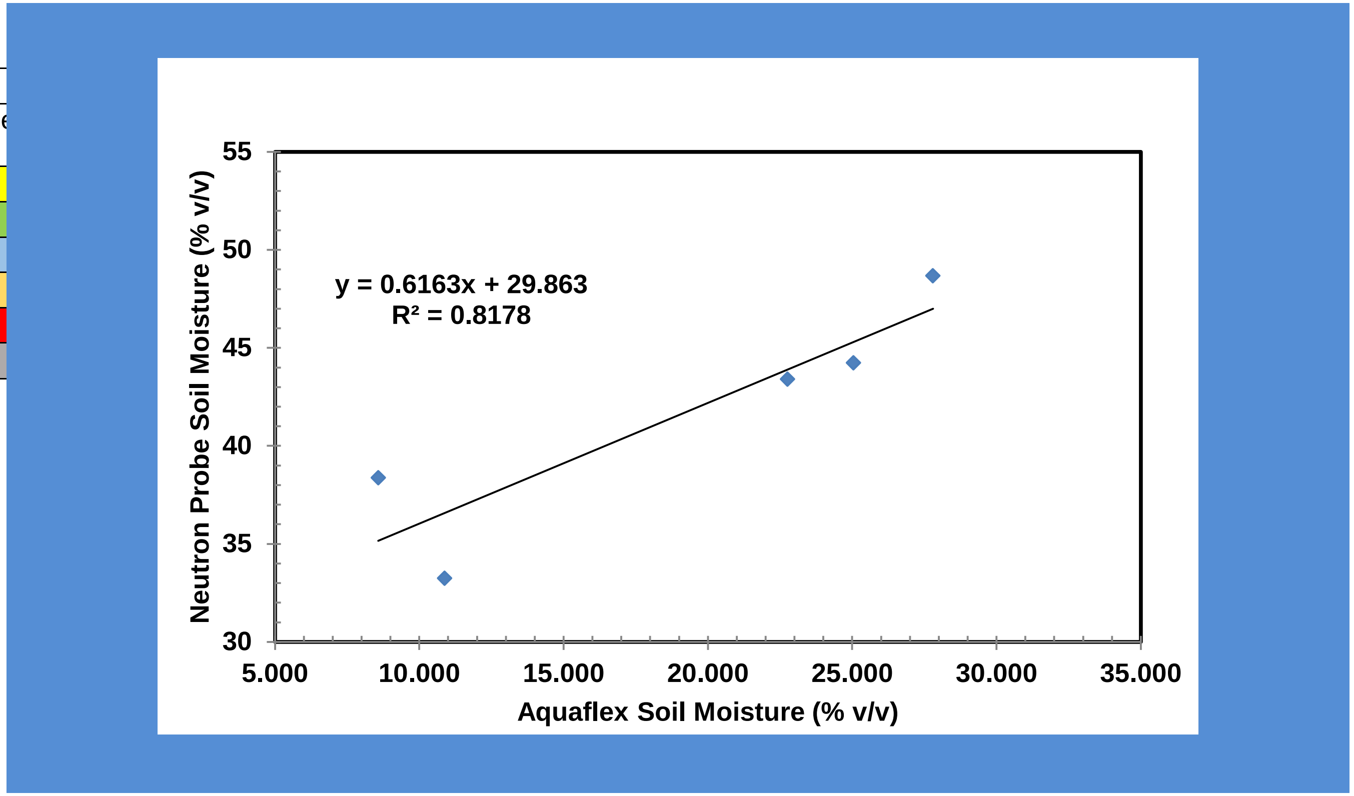
	Average	
Date	AQUAFLEX (% v/v)	Neutron Probe (% v/v)
27/05/2014		34.4
17/07/2014	31.937	40.8
1/12/2014	18.097	31.8
25/02/2015	12.722	33.0
7/10/2015	20.857	36.8
17/05/2016	17.557	28.8



Mangemangeroa

Date	26/05/2014			18/07/2014			1/12/2014			18/02/2015			7/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	42	40.4	42.2	48.7	47	47.8	44.1	42.3	43.1	36.4	33.4	32.6	43.5	43.1	42.1	33.2	29.1	28.6
20-30	41.9	42.4	43	49.7	48.1	48	44.5	44.2	44.7	38.4	37.8	37.1	44.8	43.2	43.2	33.9	31.6	30.5
30-40	43.8	43.2	44	52.3	50.2	49.2	47.2	44.7	44.4	41.2	38.4	40.9	46.2	44.1	43.5	35.5	33.9	34.9
40-50	44.3	44.3	44.5	52	50.3	51.8	47.1	45	46.8	45.2	42.1	44.5	46.6	44.7	46.1	37.5	36.2	38.5
50-60	45.9	45.5	46.3	53.1	52.2	52.5	49.6	47.2	49		43.3	46.8	48.1	46.4	47.6	39.8	37.5	40.6

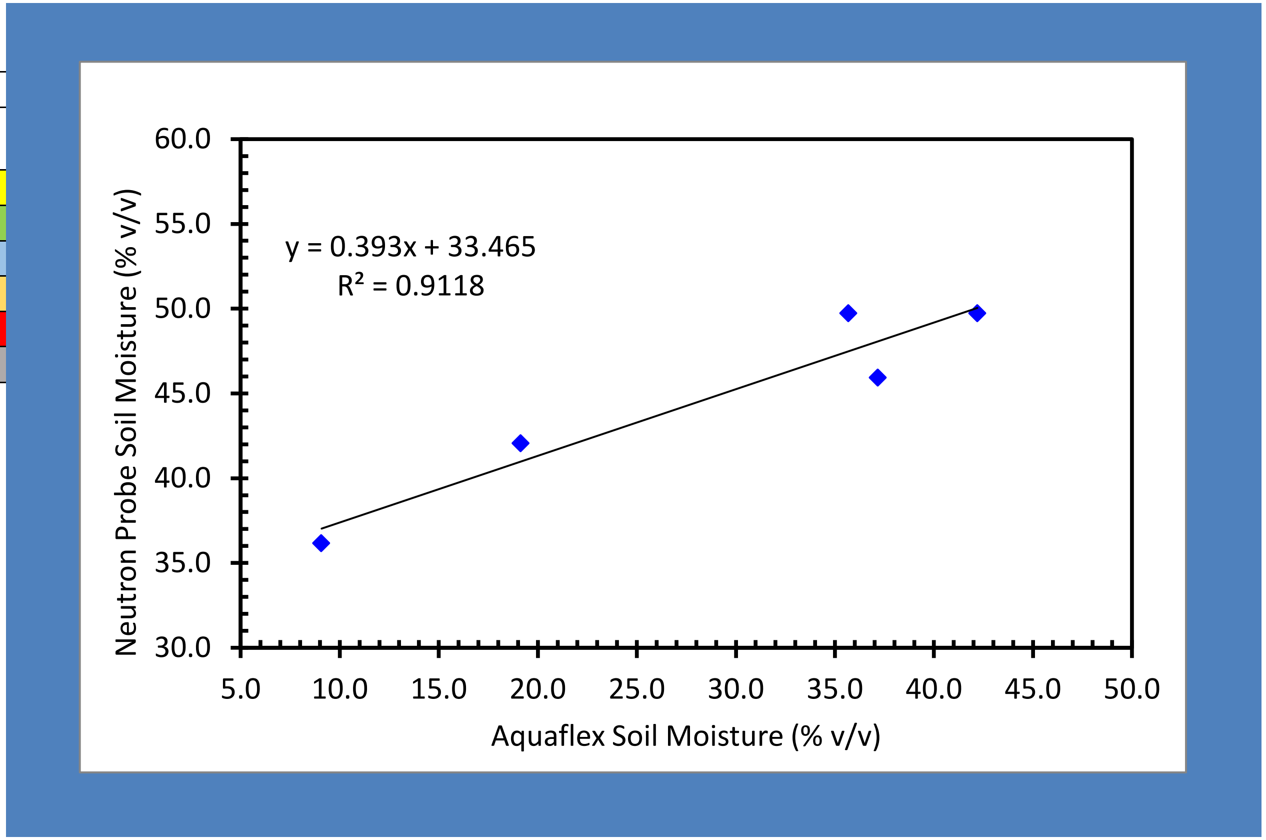
	Average	
Date	AQUAFLEX (% v/v)	Neutron Probe (% v/v)
26/05/2014	16.6	42.8
18/07/2014	27.800	48.7
1/12/2014	25.046	44.2
18/02/2015	8.581	38.4
7/10/2015	22.755	43.4
17/05/2016	10.877	33.2



Tamahunga

Date	28/05/2014			17/07/2014			2/12/2014			25/02/2015			8/10/2015			18/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	43.4	43.4	44.2	50.2	50.2	48.8	42.3	43	40.9	33.8	39.7	35	47.2	46	44.6	45.1	45.4	43.5
20-30	44.6	44.4	45.5	49.8	51.4	50.1	45.7	47.7	44	43.5	43.8	42.4	46.2	47.9	46.6	46.6	47.4	45.2
30-40	45.7	44.9	45.1	50.8	51.9	51.5	49.3	48.5	46.3	46.7	46.9	46.7	48.6	48.3	47.9	48.1	47.6	47
40-50	46.7	46.8	45.6	51.8	52.4	52.6	50.3	49.4	48.7	48.3	49.7	49.8	50.8	50.1	49.8	48.9	47.9	48.3
50-60		47.7	47.7		52.6	52.8		51.9	51.7		50.3	52.1		54.5	51.8		49.6	48.5

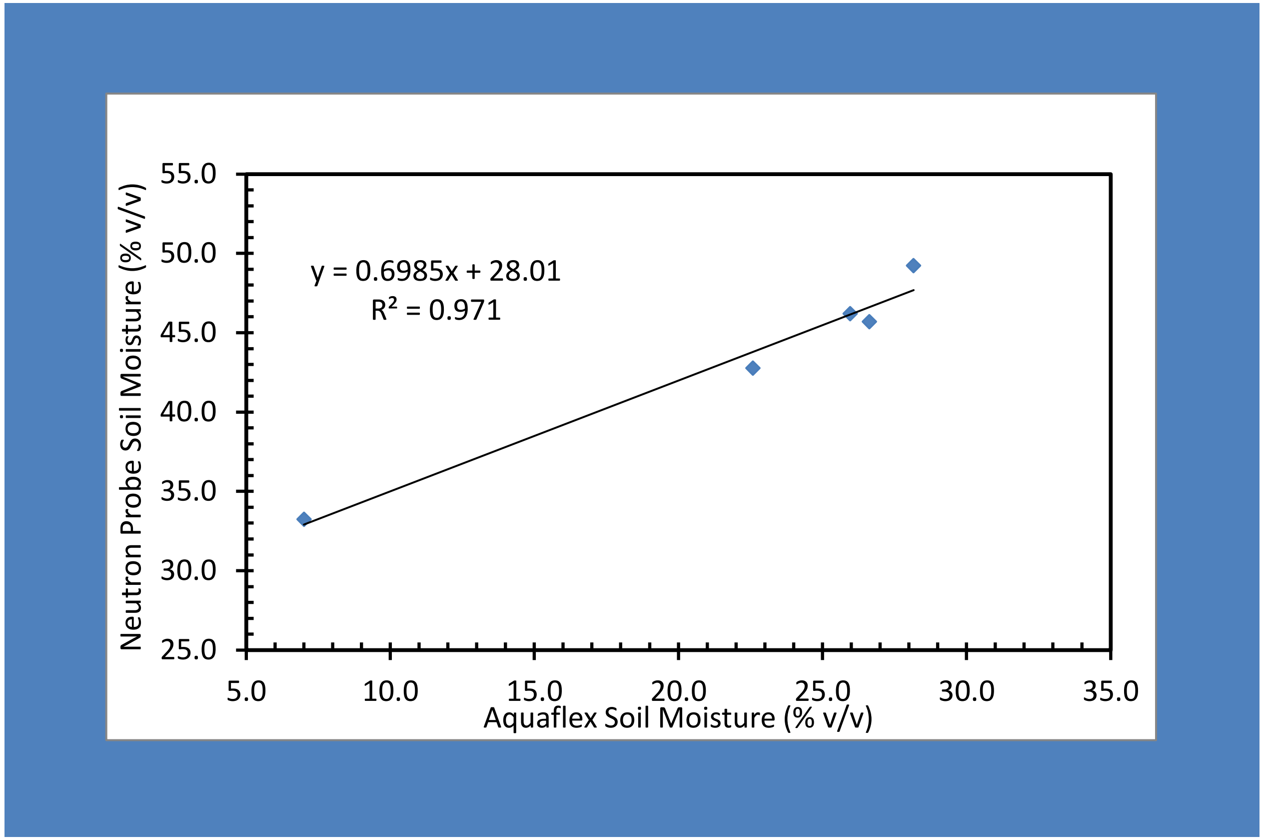
	Average	
Date	AQUAFLEX (% v/v)	Neutron Probe (% v/v)
28/05/2014	14.5	43.7
17/07/2014	42.197	49.7
2/12/2014	19.147	42.1
25/02/2015	9.080	36.2
8/10/2015	37.179	45.9
18/05/2016	35.683	49.7



Ararimu

Date	27/05/2014			17/07/2014			1/12/2014			25/02/2015			7/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	46.6	47.2	47	48.1	49.3	50.1	44.5	45.9	46	33.9	34.2	30.3	45.9	45.6	46.7	42	42.9	42.2
20-30	49	50.5	49	50.1	50	50.3	46.2	45.7	46.7	40.6	40.4	31.6	47.6	45.8	47.1	44.2	43.4	43.4
30-40	49.2	48.3	47.5	50.3	49.7	48.1	46.2	46	43.3	42.6	43.8	31.5	47.1	46.7	43.8	43.2	44.1	40.1
40-50	47.4	50.1	42.3	48.1	50.9	43.8	44.2	48.8	40.6	41.4	46.7	31.4	43.5	49.3	40.4	40.6	45	35.6
50-60	49	51.8	42.3	48.7	52.5	44.8	47.9	51.7	42.6	46.2	52	37.5	48	52.1	41.9	42.9	48.3	38.8

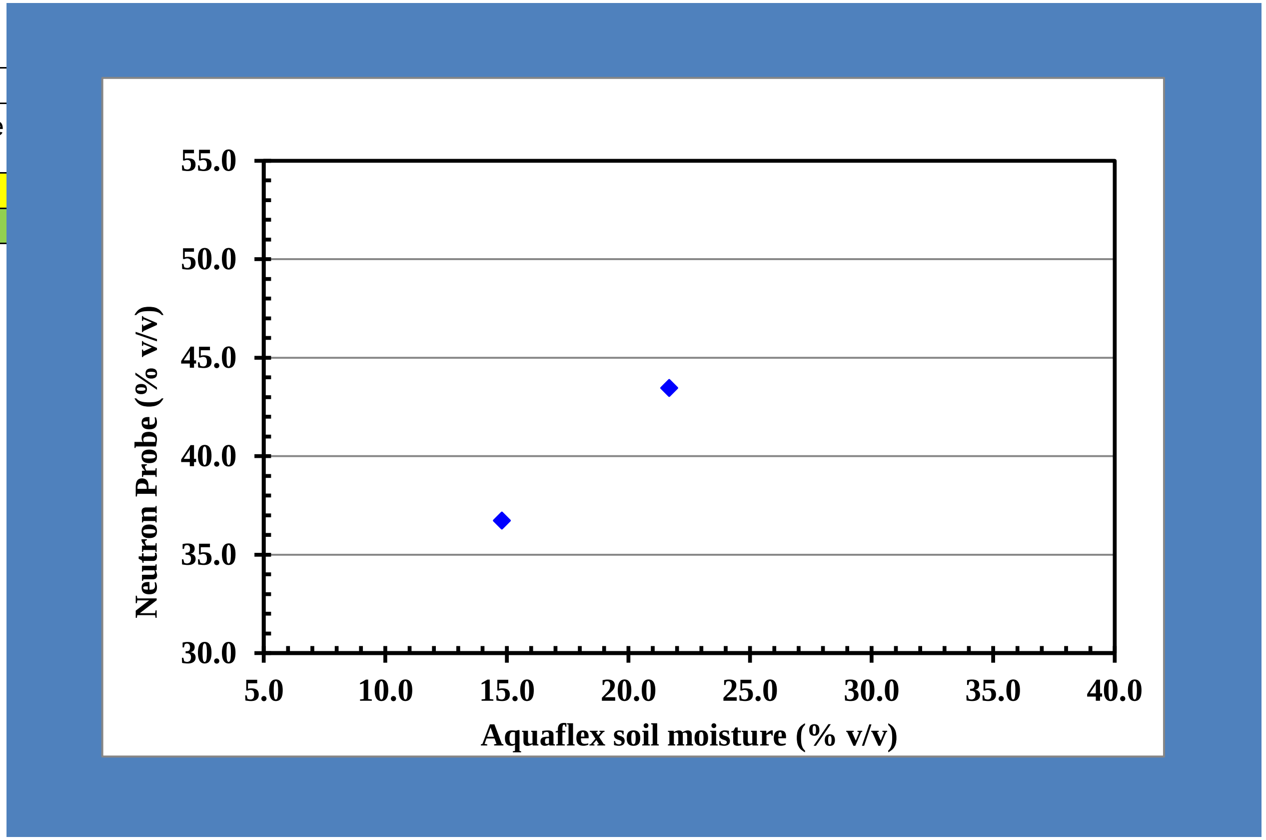
	Average	
Date	AQUAFLEX (v/v)	Neutron Probe (V% v/v)
27/05/2014	22.36	47.6
17/07/2014	28.165	49.2
1/12/2014	26.633	45.7
25/02/2015	7.006	33.2
7/10/2015	25.965	46.2
17/05/2016	22.582	42.8



Hoteo

Date	8/10/2015			18/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	43.8	43.6	43	37.8	37	35.4
20-30	42.8	43.8	43.8	39.8	38.9	37.8
30-40	44.2	43.3	43.5	42.2	41.2	40.5

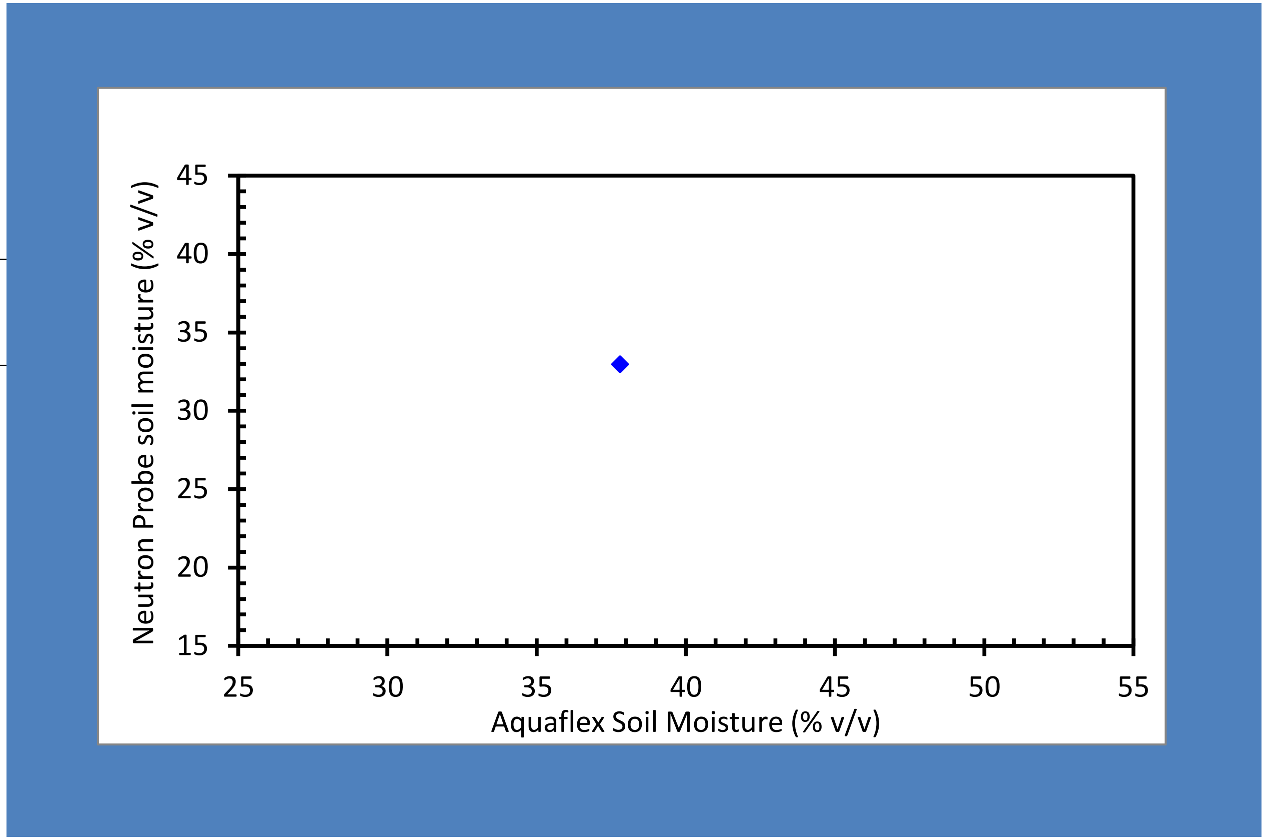
	Average	
Date	AQUAFLEX (% v/v)	Neutron probe (% v/v)
8/10/2015	21.67	43.5
18/05/2016	14.80	36.7



Tomarata

Date	17/07/2014			2/12/2014			25/02/2015			site relocated . 18/5/2016	18/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**		**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**		**V%**	**V%**	**V%**
0-20	50.2	51	49.7	46.1	45	44.6	40.4	34.6	34.6		38.5	39.8	34.6
20-30	51.2	48	50.4	48.2	47.3	47.6	39.6	31.7	37.9		37	39.5	37.8
30-40	52.5	48.4	47.9	49.8	45.6	47	41.5	31.8	37.5		36.9	38.8	36.3
40-50	54.9	47.4	46.5	53.9	44.6	44.8	45.9	32.3	38.8		38.1	37.6	38.9
50-60	52.9	44.8	45.3		42.4	43.2		36.1	38.6			41.3	41.9

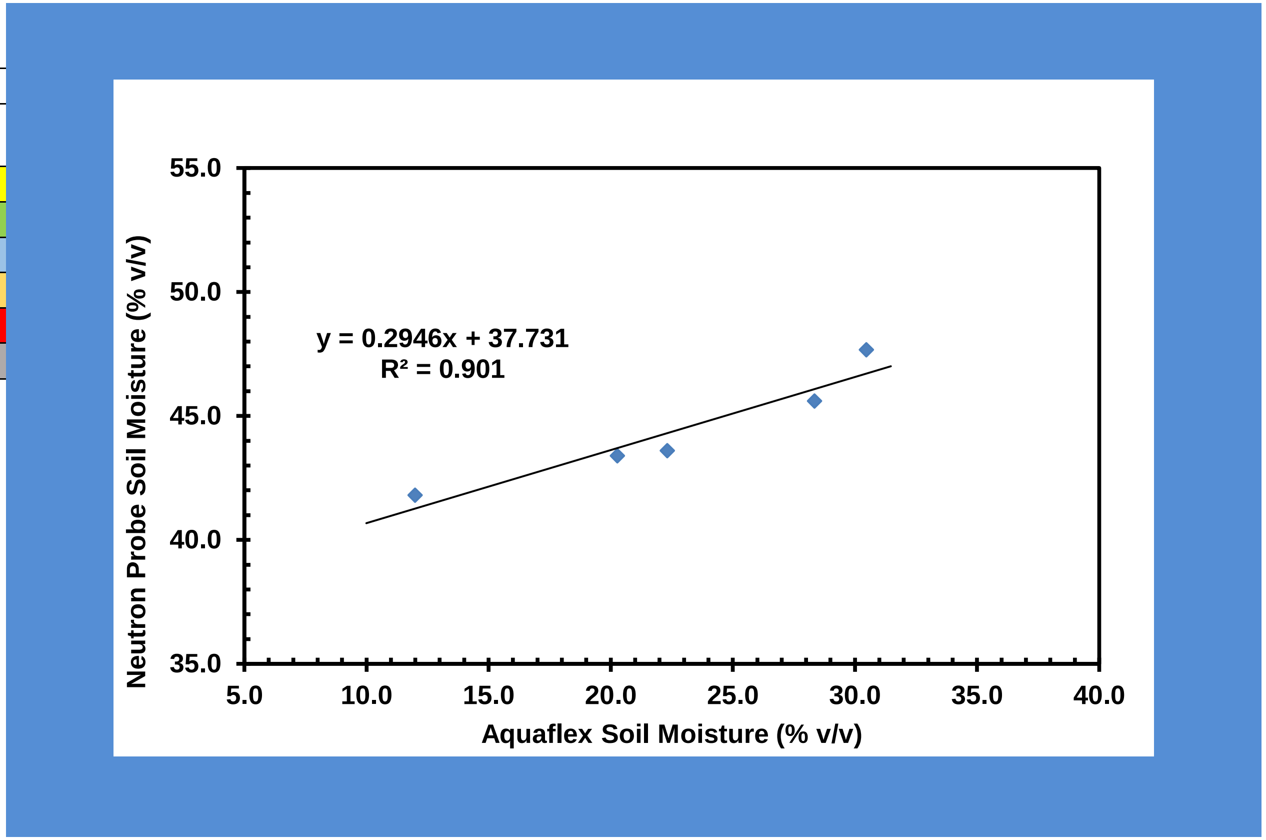
	Average	
Date	AQUAFLEX (% v/v)	Neutron Probe (% v/v)
17/07/2014		48.7
2/12/2014	31.378	46.8
25/02/2015	20.695	36.5
8/10/2015	DECISION MADE TO RELOCATE SITE DUE TO VERY WET LOCATION AND PUGGING DAMAGE IN THE PADDOCK	
18/05/2016	32.96	38.1



Awhitu

Date	26/05/2014			18/07/2014			1/12/2014			18/02/2015			6/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	46.2	43.9	44.6	48.5	48.1	46.4	44.9	44	41.9	43.9	42.4	39.1	46.8	45.7	44.2	46	42.4	41.8
20-30	49	48.2	47.6	52	49.4	48.8	49.1	46.5	45.2	49.3	48.6	45.9	49.6	48.2	45.5	47.9	47	45.7
30-40	50.7	49.1	49.9	53	51.6	51.5	51.7	50.3	48.5	51.8	51.7	48.6	50.6	48.6	49	50	48.5	47.5
40-50	56	52.7	53.3	56.8	56	54.4	56	54.1	52.5	58.7	56.5	53.9	56.4	54.1	52	55.4	52.5	51.1
50-60			56.3			59			58.2			58.7			57			57.1

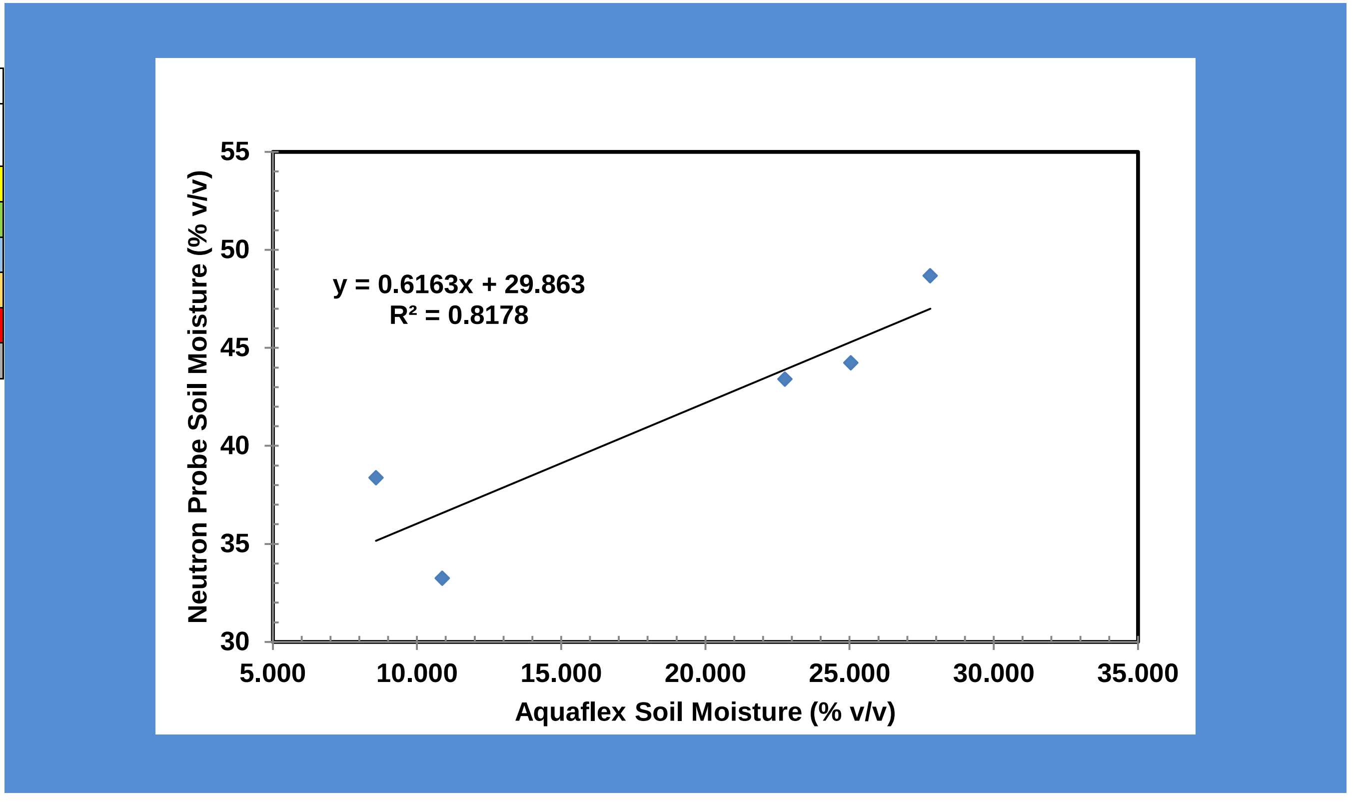
	Average	
Date	AQUAFLEX (% v/v)	Neutron Probe (% v/v)
26/05/2014		44.9
18/07/2014	30.472	47.7
1/12/2014	22.321	43.6
18/02/2015	11.992	41.8
6/10/2015	28.343	45.6
17/05/2016	20.279	43.4



Mangemangeroa

Date	26/05/2014			18/07/2014			1/12/2014			18/02/2015			7/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	42	40.4	42.2	48.7	47	47.8	44.1	42.3	43.1	36.4	33.4	32.6	43.5	43.1	42.1	33.2	29.1	28.6
20-30	41.9	42.4	43	49.7	48.1	48	44.5	44.2	44.7	38.4	37.8	37.1	44.8	43.2	43.2	33.9	31.6	30.5
30-40	43.8	43.2	44	52.3	50.2	49.2	47.2	44.7	44.4	41.2	38.4	40.9	46.2	44.1	43.5	35.5	33.9	34.9
40-50	44.3	44.3	44.5	52	50.3	51.8	47.1	45	46.8	45.2	42.1	44.5	46.6	44.7	46.1	37.5	36.2	38.5
50-60	45.9	45.5	46.3	53.1	52.2	52.5	49.6	47.2	49		43.3	46.8	48.1	46.4	47.6	39.8	37.5	40.6

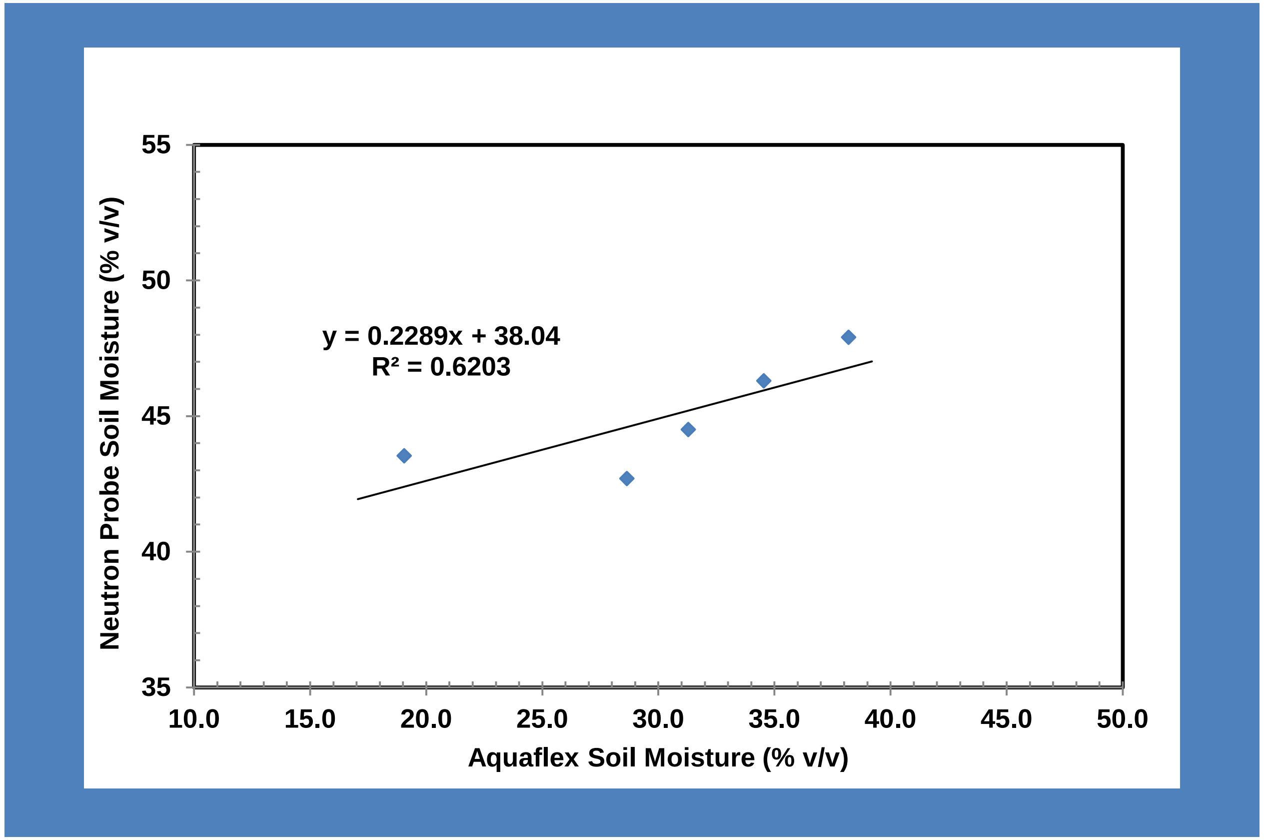
	Average	
Date	AQUAFLEX (V%)	Neutron Probe (V%)
26/05/2014	16.6	42.8
18/07/2014	27.800	48.7
1/12/2014	25.046	44.2
18/02/2015	8.581	38.4
7/10/2015	22.755	43.4
17/05/2016	10.877	33.2



Waitangi

Date	26/05/2014			18/07/2014			1/12/2014			18/02/2015			5/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	46.9	45.2	48.3	47.2	47	49.5	44.6	42.8	46.1	42.4	42.4	45.8	46.3	45.1	47.5	42.3	41.3	44.5
20-30	48.9	46.5	48.9	48.7	46.5	49.6	46.8	44.3	47.2	47.2	44.3	47.5	48.6	46.4	48.6	44.6	42.9	44.7
30-40	51.1	48	48.8	51.3	48.6	49.6	48.1	46.4	46.5	49.6	47.1	47.5	48.8	48.8	47.7	47.2	45.8	45.9
40-50	52.1	50.9	51.3	52.1	51.4	51.5	50.3	49.2	49.7	50.6	49.7	49.8	51.1	51	49.8	48	48.3	47.9
50-60		54	53.8			54.2	54.9	54	51.9	55.8	51.6	53.2	55.2	53.6	52	53.4	52.1	50.8

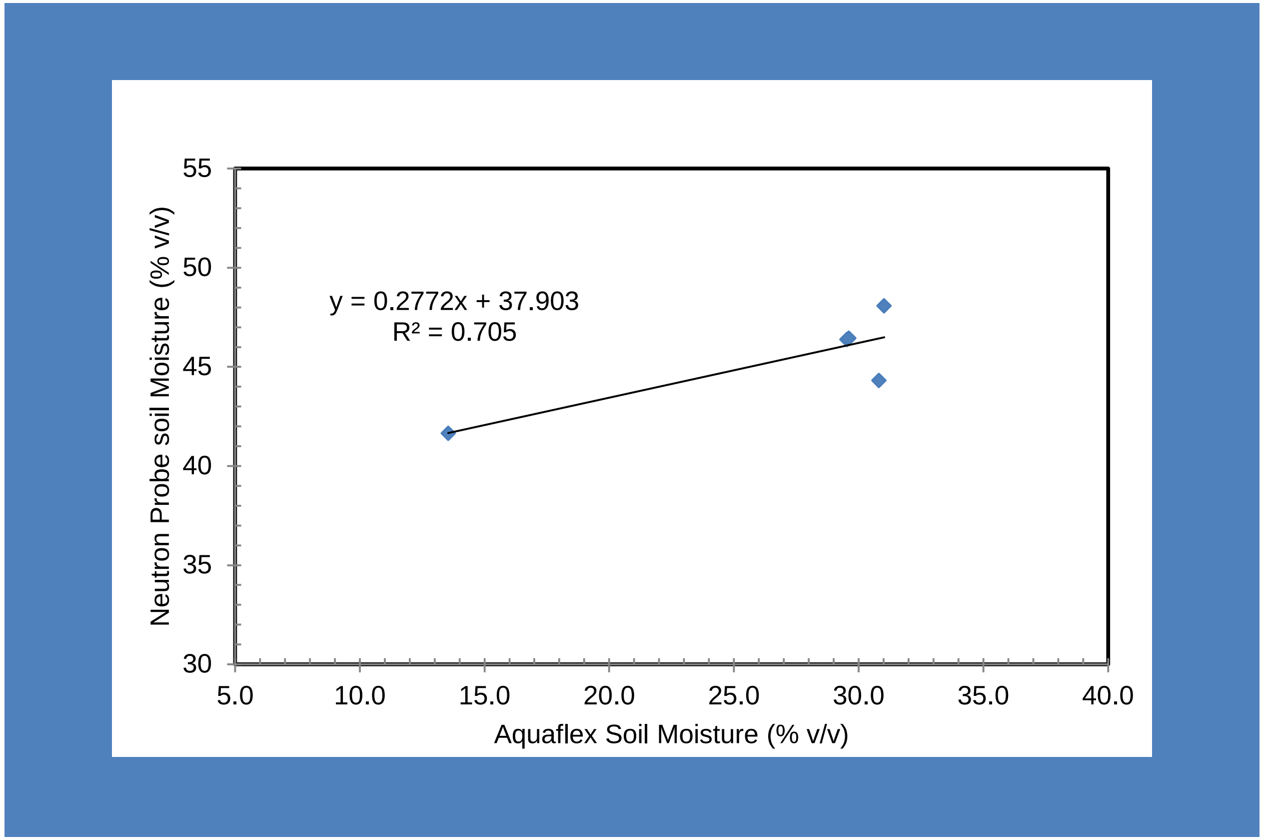
	Average	
Date	AQUAFLEX (% v/v)	Neutron Probe (% v/v)
26/05/2014	19.6	46.8
18/07/2014	38.203	47.9
1/12/2014	31.300	44.5
18/02/2015	19.053	43.5
5/10/2015	34.544	46.3
17/05/2016	28.656	42.7



Whangamarie

Date	26/05/2014			18/07/2014			1/12/2014			18/02/2015			5/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	47.1	45.8	45.9	46.7	46.5	46.2	45.5	44.8	44.1	40.1	36.5	38.6	45.5	45.1	44.9	43.7	43.3	43.6
20-30	51.1	48.4	47.1	51.3	49.1	47.3	48.3	46.7	45.7	47	40.6	38.7	50.4	46.5	46.2	47.3	44.8	42.9
30-40	52.8	51	47.6	53	51	48.4	50.3	48.8	46.9	52.8	46.1	44.2	51.6	49.8	47.3	49.4	46.8	44.4
40-50	54.3	52.6	50.8	53.9	52.2	51.8	52.1	51.1	48.6	56.8	51.1	47.6	52.5	51	48.7	51.7	49	47.2
50-60		54	52.8		54.3	54.4	57.2	52.8	51.8	60.2	55.4	52.7	56.7	53	51	54.8	50.9	49.7

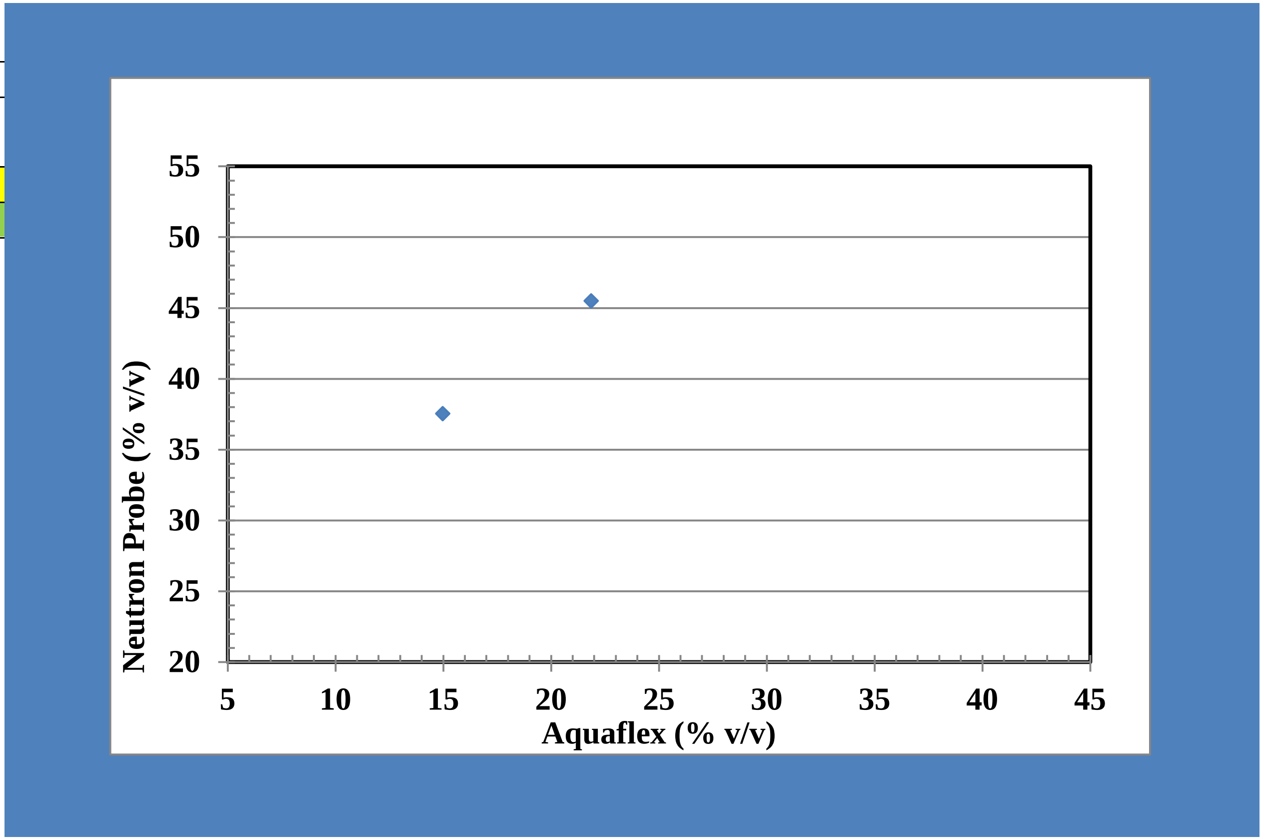
	Average	
Date	AQUAFLEX (% v/v)	Neutron Probe (% v/v)
26/05/2014	22.96	47.7
18/07/2014	31.024	48.1
1/12/2014	29.531	46.4
18/02/2015	13.548	41.6
5/10/2015	29.611	46.4
17/05/2016	30.815	44.3



Mt Albert

Date	7/10/2015			17/05/2016		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**
Depth	**V%**	**V%**	**V%**	**V%**	**V%**	**V%**
0-20	45.6	46.1	46.5	39.6	36.6	36.7
20-30	45.1	45.5	45.9	39	37.2	36.7
30-40	45.5	45.1	44.4	38.1	37	37.3
40-50	47.6	46.4	45.8	38.4	38	37.8

	Average	
Date	AQUAFLEX (% v/v)	Neutron probe (% v/v)
7/10/2015	21.868	45.5
17/05/2016	14.980	37.55



Appendix C Mean laboratory measurements for soil physical properties at 0-7.5cm soil depths

	Initial water Content (%, w/w)	Dry Bulk density (t/m^3)	Particle Density (t/m^3)	Total Porosity (% v/v)	Macro-porosity -5 kPa (% v/v)	Macro-porosity -10 kPa (% v/v)	Vol WC 5 kPa (% v/v)	Vol WC 10 kPa (%, v/v)	Vol. WC 100 kPa (% v/v)	Vol. WC 1500kPa (% v/v)	Readily Available WC (% v/v)	Total Available WC (% v/v)
Kaipara	29.80	1.31	2.68	51.17	2.03	3.53	49.40	47.63	41.27	29.43	6.30	18.17
Tamahunga	72.83	0.83	2.50	66.93	7.30	11.57	59.60	55.37	47.47	20.83	7.93	34.57
Ararimu	48.93	1.06	2.44	56.37	<1	1.87	56.87	54.50	44.20	22.47	10.30	32.03
Hoteo	52.07	0.90	2.44	63.13	3.23	4.50	60.33	58.67	49.80	29.83	8.83	28.80
Tomarata[1]	79.10	0.83	2.48	66.40	6.40	10.27	59.97	56.13	45.70	18.17	10.47	37.97
Awhitu	41.33	1.03	2.56	59.90	12.30	15.10	47.60	44.80	37.67	29.07	7.10	15.73
Mangemangeroa	64.07	0.83	2.48	66.47	8.63	11.27	57.83	55.20	46.30	25.50	8.93	29.77
Waitangi	46.77	1.12	2.56	56.10	<1	2.10	55.80	54.00	46.87	30.20	7.07	23.80
Whangamarie	58.67	0.90	2.48	63.60	6.93	9.17	56.63	54.43	46.60	30.37	7.80	24.07
Mount Albert	58.20	0.93	2.52	63.00	5.20	7.80	57.80	55.20	45.60	24.10	9.57	31.10

[1] Relocated Tomarata site

Find out more: phone 09 301 0101, email rimu@aucklandcouncil.govt.nz or visit aucklandcouncil.govt.nz and knowledgeauckland.org.nz

Auckland Council
Te Kaunihera o Tāmaki Makaurau