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Predicting the Hardness of Turf Surfaces from a Soil Moisture Sensor Using IoT Technologies

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Predicting the Hardness of Turf Surfaces from a Soil Moisture Sensor Using IoT Technologies

By

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Abstract

In horseracing, “the going” is a term to describe the racetrack ground conditions. In Ireland presently, a groundskeeper or course clerk walks the racecourse poking it with a blackthorn stick, assesses conditions, and declares the going – it is a subjective measurement.

This thesis will propose using remote low-cost soil moisture sensors to gather high frequency data about the soil water content in the ground and to enable informed decisions to be made. This will remove the subjective element from the ground hardness, and look at the data in an objective way.

The soil moisture sensor will systematically collect high frequency data from the ground and store the data in a remote database using Internet of Things (IoT) technologies such as Message Queuing Telemetry Transport (MQTT), InfluxDB and Node-RED. The database will hold soil moisture readings, their timestamp and GPS location. From this data and data from an industry-standard Clegg hammer, the soil sensor will be automatically calibrated for the soil that it is sitting in regardless of the soil make-up, the sensor model, and the drainage of the soil.

The going of the soil will also be deduced. The primary soil saturation data is fused with secondary open source weather data. Weather forecast information is gathered spanning out 3 hours, 24 hours and 5 days, and estimates can be made regarding how the ground will behave. These estimates are automatically update every 3 hours. The data will also allow decisions to be made for irrigation planning.

Finally, the data will be visually displayed in real-time enabling a clear view of the soil moisture, current ground hardness, the going, rainfall and their forecasts. The system will propose how conditions will change if irrigation is applied.

Declaration

I certify that this thesis which I now submit for the examination for the award of Masters of Engineering in Internet of Things Technologies, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for the graduate study by research of Technological University Dublin and has not been submitted in whole or in part for another award in any other third level institution.

The work reported on in this thesis conforms to the principles and requirements of TU Dublin's guidelines for ethics in research.

TU Dublin has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of this thesis be duly acknowledged.

Signature____

Date____

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List of Symbols, Acronyms & Abbreviations

°C	Degrees Celcius, temperature unit
ACL	Anterior Cruciate Ligament
ADC	Analog to Digital Converter
API	Application Programming Interface
BHA	British Horseracing Authority
Cb	centibar, unit of pressure
CIST	Clegg Impact Soil Test
CIV	Clegg Impact Value
CoE	Centre of Excellence
COSMO-CLM	Consortium for Small-scale Modelling and the Climate Limited-area Modelling Community
CSV	Comma Separated Values
DNS	Domain Name System
EPA	Environmental Protection Agency
ET	Evapotranspiration
ETa	Evapotranspiration (actual)
ETc	Evapotranspiration (crop)
FAO	Food and Agriculture Organization of the United Nations

FIFA	Fédération Internationale de Football Association or in English, International Federation of Association Football
GAA	Gaelic Athletic Association
GPS	Global Positioning System
hPa	hectopascal, an SI unit of pressure and stress equal to 10^2 pascals
HRI	Horse Racing Ireland
HTML	HyperText Markup Language
HTTP	HyperText Transfer Protocol
ICHEC	Irish Centre for High-End Computing
IDE	Integrated Development Environment
IoT	Internet of Things
IRFU	Irish Rugby Football Union
JSON	JavaScript Object Notation
kN	kiloNewtons or Newton x 10^3, unit of force.
LIS	Land Information System
LPWAN	Low Powered Wide Area Network
MAC	Media Access Control
MAD	Management Allowable Depletion
MCU	Microcontroller Unit

MÉRA	Met Éireann Re-Analysis
MQTT	Message Queuing Telemetry Transport
mm	Millimetres
mm^2	Millimetres squared – area
mmd^{-1}	Millimetres per day
ms^{-1}	Millimetres per second
npm	Node Package Manager
r^2	Correlation coefficient
SMD	Soil Moisture Deficit
SQL	Structured Query Language
SSH	Secure Shell
STRI	Sports Turf Research Institute
TCP/IP	Transmission Control Protocol/Internet Protocol
USB	Universal Serial Bus
UTC	Coordinated Universal Time
URL	Uniform Resource Locator
V	Volts
VWC	Volumetric Water Content

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1 Introduction

1.1 Why are Turf Conditions Important in Sports?

In January 2018, a Gaelic football league match was called off after the scheduled throw-in time. An estimated 2,000 people had travelled to McHale Park in Castlebar, Co. Mayo before the game was postponed due to a frozen pitch (Croke, R., 2018). This is not an isolated incident; however, this particular game made the news because of the delay making the decision.

Juvenile and youth volunteer coaches across multiple field sports across the country make decisions about the playability of pitches based on weather and weather forecasts without seeing the pitches and before travelling to the match location.

In horseracing, the “going” is determined by a groundskeeper or independent clerk walking and poking the course with a blackthorn stick.

With 43% of the population regularly participating in sport (Ipsos MRBI, 2018), there is often very little overview into the field conditions that are played on. The exception to this is at an elite level (Hunt, 2016).

The hardness of natural turf ground applies to many sports, and has many repercussions:

- Player safety and welfare in field sports and jockeys in horseracing
- Safety and welfare of horses in racing
- Planning the viability of matches and meetings - frozen or water-logged ground causes the cancellation of matches or meetings.

1.1.1 The Physical Impact

The correlation between anterior cruciate ligament (ACL) injuries and ground/weather conditions across six international footballing codes was investigated (Orchard, 2002).

Orchard looked at association football[1], rugby union, rugby league, American football, Australian football and Gaelic football. American, Australian and Gaelic football are quite specific to their individual countries. Rugby union and rugby league are played in Australasia & the British Isles predominately - union is also played, in a limited capacity, in more global locations. Association football is probably the most international sport in the world. Orchard used medical records as data and concluded that increased surface hardness, and increased shoe-surface traction, may be risk factors for non-contact lower limb injuries in football.

Gabbett et al. (2007) investigated the injury rates in training and matches, and their correlation with daily temperature, humidity and rainfall recordings over two years. They found in rugby league, ground conditions do not influence training injuries; however, both harder ground conditions and less rainfall are associated with a greater number of match injuries. A specific pilot study was conducted on elite Gaelic footballers (Cromwell et al., 2000) concluded that only 35% of injuries occurred in training, with the remaining in match situations. Also common between various studies, is that for contact football (all football excluding association football), most of the injuries are in the lower limbs. It should be noted that the study on Gaelic players was retrospective; therefore, it may not be as accurate as other research data.

In the majority of these researches, the harder and drier conditions are referring to warm weather. The hard ground could be leading higher injuries because of "greater peak reaction forces when a player either lands of applies a force to it than occurs on softer ground" and "hard grounds enable faster game speeds potentially increasing the risk of a higher collision impact" (Twomey et al., 2012). There is less research done into frozen pitches. Lee and Garraway (2000) did extensive research sampling on rugby union players in the Borders District in the south of Scotland – where the climate is

[1] Association football commonly known as soccer in Ireland.

similar to Ireland and the sport is played from August to April. They categorised the weather, state of pitch, air temperature, wind and wind-chill temperature for their analysis. They concluded that “the month of the season and the weather may influence the occurrence of rugby injuries, but that the state of the pitch does not”. However, the “state of the pitch” is inextricably linked to the weather.

Association football has very clear guidelines on the quality of the turf used on a playing pitch. Both climatic and ground conditions vary widely across the playing pitches of the world’s most popular sport. Fédération Internationale de Football Association, FIFA, has published comprehensive guidelines on the quality of a pitch (FIFA, 2015a).

The physical impact on horses is well documented. Serious fractures in horses can leads to the animal being put down. Williams et al. (2001) investigated 222,993 races over three-year period and reported 2,358 (1.057 %) post-race clinical conditions, including injuries and fatalities. Jump racing has a higher risk injury to flat racing. Wood et al. (2000), showed that the equine fatality rates in the UK for flat racing were 0.1 per 100 starts, 0.52 per 100 starts for hurdling, with steeplechase racing having 0.71 fatalities per 100 starts.

1.1.2 The Social Impact

45.2% of people in Ireland are involved in a social form of sports participation – attending events, club membership or volunteering (Ipsos-MRBI, 2018). Gaelic games have the highest attendance, followed by horseracing.

There are two type of horse racing in Ireland – Jump and Flat.

Jump racing includes obstacles for the horse to negotiate and it includes National Hunt, Hurdles and Steeplechase (hri.ie, 2019). The jump season is usually between mid-

October and mid-March, that is, typically the wetter and colder months, and on wetter and softer ground.

Flat racing has no jumps, operates from the end of the jump season, through the summer, and finishes up in mid-October. Flat racing is faster and run on firmer ground.

Ireland has 26 licenced racecourses across 17 counties. There were 2,606 races with an average field size (i.e. number of runners) of 11.5 in 357 fixtures in Ireland in 2017. These fixtures are a combination of festivals and one-off meeting (Deloitte, 2018).

From *Figure 1: HRI Map of Ireland* horseracing is a national sport despite being weighted towards the bottom half of the country.

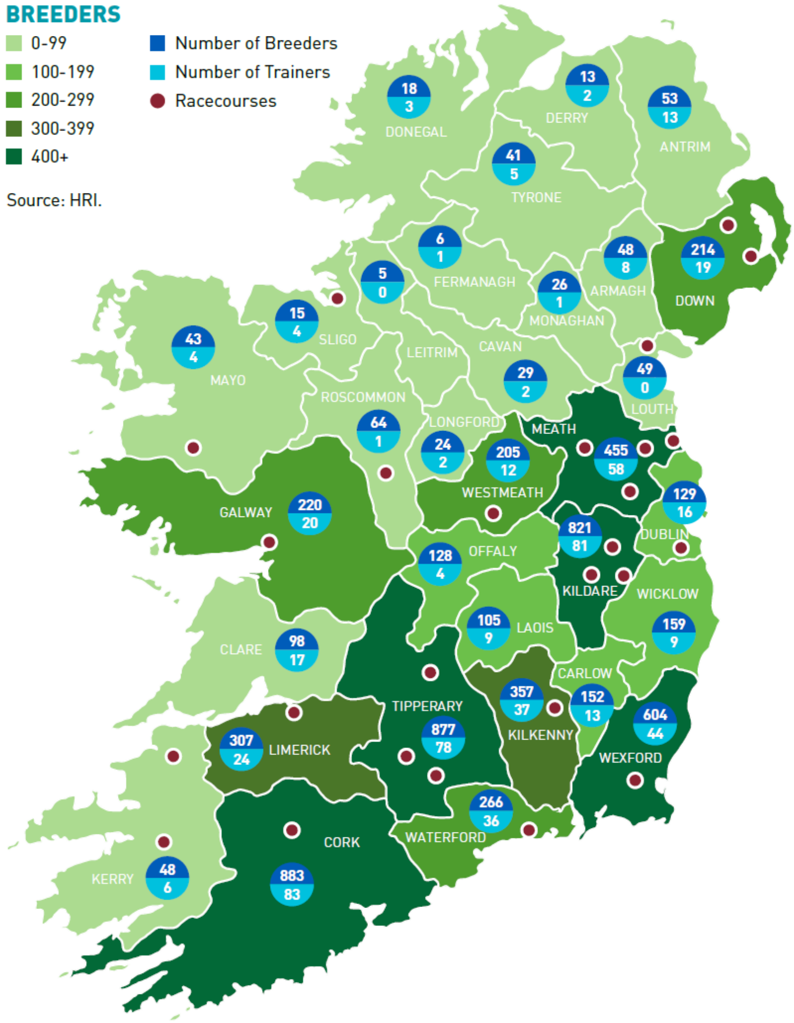


Figure 1: HRI Map of Ireland (Deloitte, 2018)

Horseracing is a year-round sport with some of the big festivals dotted throughout the year such as:

- the Fairyhouse Irish Grand National at Easter
- Punchestown Irish National Hunt Festival on the May bank holiday
- the Galway Races and the Curragh Irish Derby Festivals in the Summer
- Listowel Festival and Leopardstown Champions Weekend in September
- Leopardstown Christmas racing at Christmas.

1.1.3 The Financial Impact

Deloitte's Economic Impact Study into the Irish Breeding and Racing industry for Horse Racing Ireland (HRI) outlined the extent of the importance of the equine industry in Ireland, both Northern Ireland and the Republic of Ireland. In 2017 alone, the industry contributed

- €1.84 billion to total direct and simulated expenditure,
- 28,900 direct, indirect and secondary employments
- 1.3 million attended Irish races, making racing the second most attended sport in Ireland after Gaelic Athletic Association (GAA) (Deloitte, 2018)

The racegoers spent €45 million, of which the racecourses retained €21 million. The quality of a racecourse is a key driver in attracting top trainers and jockeys to meetings (Deloitte, 2018).

Racecourse clerk, Paddy Graffin (2018) cites "*honesty to the racing customers*" as being a key consideration in the honesty of the going estimation. The consumers of this sport are the people to attend and bet on the horses. Betting on racing is a core part of the popularity of the sport. Per capita betting turnover on racing in Ireland is amongst the highest in the world and plays a key role in supporting a large Irish betting industry

(Deloitte, 2018). Due to the betting patterns moving online, it is difficult to quantify the extent of betting on Irish horse racing.

Irish racing is attractive to the betting audience, due to more variable conditions, higher field sizes, and the popularity of both flat and jump racing.

DATE	COURSE / CLASS / TYPE / PRIZE	DIST.	GNG.	WGT / HDGR	POS. FINISH DIST / WINNER OR RUNNER-UP / WGT
06Apr19	Aintree grand national C1HcChG3 500K	4m2½f	GS	10-11 p	2/40 btn 2¾L Tiger Roll 11-5
12Mar19	Cheltenham old C1HcChG3 62K	3m1f	Sft	11-8 p	7/24 btn 11L Beware The Bear 11-8
23Feb19	Fairyhouse ChG3 24K	3m1f	Gd/Y	10-10 p	UR/6 Rathvinden 11-8
25Jan19	Huntingdon C1ChL 43K	2m4f	GS	11-4 p	2/7 btn 1L Happy Diva 11-0
19Jan19	Ascot C1HG2 29K	2m7½f	GS	11-0 p	1/6 by 3¼L Jester Jet 11-4
19Dec18	Newbury C1ChL 16K	2m7½f	Sft	11-2 p	1/5 by 14L Drinks Interval 10-12
25Nov18	Navan HcCh 53K	3m	Gd	10-10 p	3/25 btn 11L Tout Est Permis 10-12
					212 days break
27Apr18	Punchestown HcCh 40K	2m5f	Sft	10-10 p[1]	1/15 by 1½L Goodthynemilan 9-10
17Apr18	Fairyhouse ChG3 21K	2m4f	Sft/Hy	10-11	4/5 btn 15½L Youcantcallherthat 11-5
					54 days break
22Feb18	Thurles NvCh 12K	3m	Sft	11-4	2/7 btn 6L Youcantcallherthat 11-7

Figure 2: Form Record of Magic of Light (Racing Post, 2019)

The betting public require as much information as possible to make an informed decision about their bet. The form record of a horse, as shown above, includes what the going was in the previous races that the horse ran in.

The hardness of the surface can also be hugely important in cricket. The hardness of the strip on a cricket pitch directly impacts the bounce of the ball. This will have a large bearing on how customers bet on a match.

All field sports can be affected by cancellation of meeting or games, which has a financial impact. The relative hardness of a playing pitch does not have much financial impact other than cancellations.

1.2 Scope of Project

While this project was borne out of arranging juvenile GAA matches, the historical data of how, when and why matches get cancelled is generally not recorded in the GAA at club level, except perhaps at a county and senior standard level. Other field sports (rugby and soccer) are similar, there is not much data on ground conditions or match cancellations unless it is at the senior club level. As a result, the focus of this project moved to another turf sport, horseracing. All meeting fixtures have recorded ground conditions and these records are kept by HRI and other parties with vested interests like the Racing Post and betting companies.

In horse racing the ground conditions are recorded as the going. This can be a general classification for the whole course, or slightly more specific - a general classification with variants usually on the bends. *1.3 The Current Situation* explains how the going is declared.

This project will show that the hardness of the ground can be predicted from primary source remote soil moisture sensors and secondary source weather conditions and drainage, regardless of soil type.

This project can apply to all turf sports and agriculture. The main focus of this project is on horseracing because horseracing records the ground conditions.

1.2.1 Time

The biggest restriction in the project is time. The time limitations of a masters' project do not include a full season a horse racing. Although historical data on the ground conditions are available through the HRI, no historical soil saturation levels were recorded in conjunction with them. A combination of the data being recorded and the historic data collated by the HRI would produce a useful tool to align prediction models.

Data was gathered every minute, but processing was run hourly, around the clock for over 90 days, during the course of this project.

The time period for data collection did not allow for seasonal weather patterns to be included. Much further analysis could be done in this area.

1.2.2 Weather

Ideally the weather during this test period would be quite varied and include acute weather events. The weather leading up to initial data collections was very dry. Soon after the data collection started, the weather got extremely wet and for a prolonged period of three weeks. The mix of wet and dry weather was recorded in the data.

While the data was recorded through the summer, the summer of 2019 temperatures, were not as high as the more extreme conditions of Summer 2018.

The weather data does not include cold and frosty conditions normally associated with winter. These are usually the main cause of cancellations in outdoor sports.

There was no race meeting cancelled in Ireland during this data collection phase.

1.2.3 Soil Type & Soil Moisture Sensor

In *2.2 What makes a good surface for racing?, 2.5 Soil Moisture Measurement* and *3.2.1 Soil Moisture Sensor*, the research methodology, soil types and the selection of soil moisture sensor are discussed. This project will show that regardless of the soil type or the soil moisture sensor, the soil sensor can be calibrated to show standard results.

A Clegg Impact Soil Tester (CIST), commonly called the Clegg hammer, is used as the industry standard that will calibrate the soil moisture sensor to indicate the hardness of the ground.

1.3 The Current Situation

The going is managed and regularly assessed by the course groundskeepers and the course manager. Racecourses are keen to get ideal conditions and attract as many horses, jockeys, trainers and owners as possible to their meeting. Famous horses and their trainers can attract more customers to race meetings.

The seasonality of the racing is primarily linked the climate of the country. However, with the prevalence of course maintenance through drainage and watering, conditions are somewhat more controlled. "*An ideal horse racing track will have an elastic and resilient surface, which will provide adequate cushioning and then return to its original state*" (Adams & Gibbs, 1994). Jump racing requires softer ground to allow the horses to land safely after the jumps.

Horse trainers and owners submit horses for particular races based on multiple criteria (for example, age, sex, jump or flat, success of the horse) and conditions (for example: track layout, direction of the race and speed of the track). The condition of the track has a direct impact on the speed of the track: the harder the surface, and faster the track.

While the horse-racing calendar is set at the beginning of each year, the weather does not always behave with the expectations of warm dry summers and cold wet winters. The flat and jump racing calendars were originally set around the expectations of weather behaviour. Now, with modern drainage systems and watering methods the groundkeepers can manage their courses to their highest potential.

The going on any course is submitted to HRI five days before the scheduled meeting. HRI opens the race card to all trainers to submit horses to particular races, with trainers requesting what the conditions are on the track. The going and soil conditions of a racetrack suit different horses. Trainer Thomas Gibney (2018) explains that trainers build a relationship with the course manager to understand their definition of ground conditions. Trainers choose and submit horses to the particular races in a meeting, based on the criteria for the race and if the conditions suit them. The going is reassessed every day leading up to and including the day of the meeting.

Any updates on the going is communicated through the HRI, the individual racecourse, or via media channels, such as *Figure 3: Fairyhouse Racecourse publish the going*.

Figure 3: Fairyhouse Racecourse publish the going in Twitter

The day before and the day of the meeting, a course clerk independently assesses a racecourse. The course clerks have three main concerns when measuring the going:

1. safety and welfare of the jockey
2. safety and welfare of the horse
3. honesty to the racing customers to call the conditions true (Graffin, 2018).

Despite the horse racing industry being worth over a billion euro per annum in Ireland, the method of measuring the going is surprisingly low-tech. For most racecourse managers and course clerks, a wooden stick, usually blackthorn[2], is used for its hardness, lightness and durability (Kilkelly, 2007).

[2] Blackthorn Scientific name: Prunus spinosa

Field sports do not choose to play based on the condition of the ground, and the term going does not exist outside of horseracing. However, due to the volume and frequency of rain in Ireland, pitches can get water-logged and may be deemed unplayable. It is a regular occurrence that games get cancelled due to adverse weather conditions.

Gaelic games are fast becoming a year-round sport, and the wet winter of 2017/18 and snow in March 2018 put a lot of pressure on pitch availability right across the country. The cancellation of the Gaelic Athletic Association (GAA) games due to the snow highlighted that there was only one spare weekend in the GAA calendar to reschedule matches! It is little wonder that many GAA clubs are now laying artificial/3G/4G pitches.

Most GAA and Irish Rugby Football Union (IRFU) clubs require the groundskeeper or a member of the coaching staff to walk the pitch and send texts from the club to ascertain the viability of the pitch. Communication of these decisions sometimes gets more complicated if there is a team travelling for a match.

1.4 The Technology Gap

Cranfield University and TurfTrax Ltd. developed the GoingStick, a technological solution to determine the going. In January 2009, the use of the GoingStick was mandatory on British racecourses (Wood, G., 2008). Gowran Park racecourse in Kilkenny are leading the way in Ireland introducing TurfTrax technology into grounds keeping on their racecourse. Navan racecourse are currently trialling the GoingStick. The HRI do not (re)publish any GoingStick data that comes from Gowran Park. The GoingStick has not gained the support of the HRI in Ireland.

The GoingStick is explained in more detail in *2.3.5 GoingStick*.

In this project, the data collected from the soil moisture sensor will have:

- global positioning system, GPS co-ordinates of the sensor
- timestamps – to ensure the person reading the data can verify the date and time of the reading
- remote data collection and decision making

Rather than a racecourse issuing one going report per day, the going can be automatically updated and published every three hours, even during a race meeting.

Multiple sensors that could be placed around the track could also pick up the nuances of the course. While a long straight section of track may have a uniform behaviour, dips in the ground or high intensity areas such as bends, may show variations in the soil moisture levels.

1.5 Research Questions

With all of this information that has already been discussed, the aim of the project presents itself.

1. Can frequent, low-quality, low-cost data from an Internet of Things (IoT) soil moisture sensor be supplemented with a high-quality, infrequent, scientific readings to determine the hardness of the ground?
2. Can this data determine the characteristics of the drainage of the surrounding soil?
3. Can the automatically collected data, along with the weather forecast, predict the future soil hardness?

This information can also allow decisions to be made on irrigation, event management, and even travel plans.

1.5.1 Research Objectives

The soil moisture sensors will systematically collect data from the ground and store the data in a remote database using IoT technologies such as Message Queuing Telemetry Transport (MQTT), InfluxDB and Node-RED. The database will hold the readings, their timestamp and location. With this data, the soil sensor will be calibrated against the known scientific quantity of a Clegg hammer, regardless of the soil make-up or the soil moisture sensor type.

The going of the ground will be deduced from the soil moisture levels. The data will allow decisions to be made in regards to irrigation plans for the soil. Finally, the data will be visually displayed to enable a clear view of the soil moisture trends.

There are various tasks that need to be addressed during the course of the project:

- Quantify the range of the soil sensor.
- Transmit the data from the soil moisture sensor to a database with timestamps and GPS location. The database need to be secure and password-protected.
- Physically record the hardness of the ground with a Clegg hammer - a widely used instrument in turf sports management. The data gathered for the ground hardness also needs to be stored in a database for analysis.
- Run regression tests to understand the relationships between variables.
- Calibrate the low-cost high-frequency soil moisture sensor against the low-frequency, accurate industrial standard.
- Store and retrieve the data in the database in a structure that can be easily interpreted.
- Gather weather data from a weather station and weather forecast data from an open source resource.
- Analyse the data, and run regression test and algorithms to convert the raw data to predicted ground hardness.

- Present the findings graphically and readable format.
- Make irrigation decisions as a result of the analysis.

1.6 Research Hypothesis

Can a low-cost, high-frequency soil moisture IoT sensor be automatically calibrated by a high quality infrequent manual soil hardness instrument? And as a result, can the IoT sensor accurately determine the soil hardness?

Can the soil moisture IoT sensor determine the drainage characteristics of the soil?

Can the addition of weather forecast data help determine the ground hardness over a forecasted time?

1.7 Document Outline

This thesis will propose using a remote IoT soil moisture sensor to capture data about the water content in the ground and store this data to a time series database with its timestamp and location. Simultaneously, high quality ground hardness values are manually captured and saved to the database. Linear regression of these data points allows a transformation from raw soil moisture values to a hardness values. The document will show the high correlation between the values and how this regression is reassessed daily. This will remove the subjective element from the ground hardness, and look at the data in an objective way.

The analysis continues with exploring the drainage characteristics of the ground. The future hardness can be estimated once weather forecast information or irrigation plans are available.

Chapter 2 - Literature Review, will deal with the impact of ground hardness in various sports and how some of the sports measure this. This will help explain the use of the Clegg Hammer in the project. It will also explain some of the mechanical behaviours of soil and the various different characteristics that are required for the analysis. The literature review will also discuss other factors that have an influence on ground hardness, like weather, evapotranspiration and drainage. The various mathematical models that are used are explained and justified.

Chapter 3 Research Methodology, will discuss how data on each variable that has an influence on the ground hardness can be gathered. It explains how these variables interact with each other, and what is happening with the data at each stage and the format that it is in.

Chapter 4 Results & Analysis looks at the data that has been gathered and how it has been used. This chapter shows the calculations applied and what results were gathered.

Chapter 5 Discussion explains the aspects of the project that worked well and not so well – along with suggesting improvements. There is also discussion on whether the results were as expected and why.

Chapter 6 Conclusion covers the strengths and weaknesses of the research methodology; and where this project could potentially lead on too.

2 Literature Review

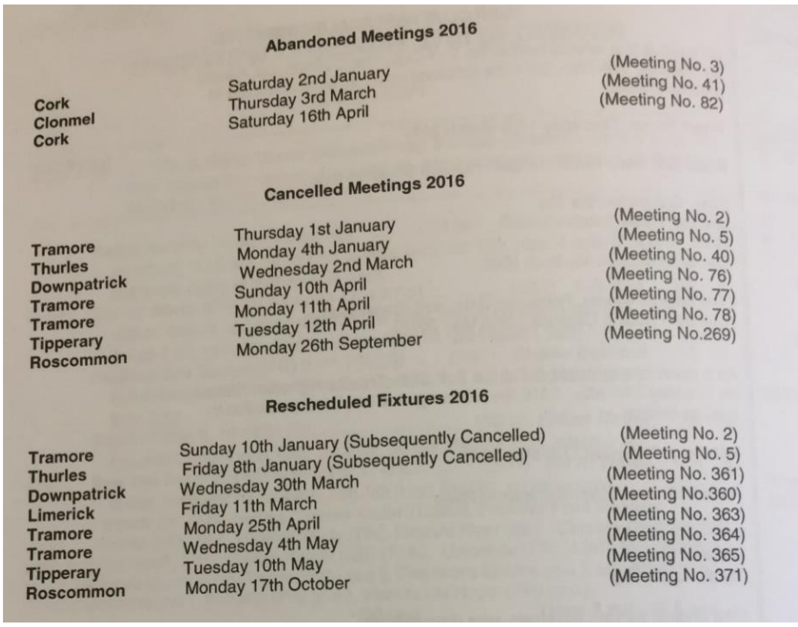
2.1 How Ground Firmness Impact Various Sports

Frozen pitches are an issue with all field games. If a player falls, the injuries can be more serious (particular care is taken regarding knocks to the head). Due to the high volume of rain in Ireland, pitches can also get water-logged and deemed unplayable. It is a regular occurrence that outdoor games and horse racing meetings get cancelled due to adverse weather conditions.

In a healthy soil, there are large and small pore spaces that contain the air, water and room for plant roots and soil organisms to breathe, grow and reproduce successfully (PitchCare, 2019). If the pore spaces get consistently filled with water, it can lead to damaging effects on the soil and crop roots.

2.1.1 Horse Racing

After a particularly high amount of rain in the winter of 2015/16, a number of meetings (Tramore, Cork and Thurles) were either abandoned cancelled due to waterlogging (Horse Racing Ireland, 2017).



Abandoned Meetings 2016

Cork	Saturday 2nd January	(Meeting No. 3)
Clonmel	Thursday 3rd March	(Meeting No. 41)
Cork	Saturday 16th April	(Meeting No. 82)

Cancelled Meetings 2016

Tramore	Thursday 1st January	(Meeting No. 2)
Thurles	Monday 4th January	(Meeting No. 5)
Downpatrick	Wednesday 2nd March	(Meeting No. 40)
Tramore	Sunday 10th April	(Meeting No. 76)
Tramore	Monday 11th April	(Meeting No. 77)
Tipperary	Tuesday 12th April	(Meeting No. 78)
Roscommon	Monday 26th September	(Meeting No.269)

Rescheduled Fixtures 2016

Tramore	Sunday 10th January (Subsequently Cancelled)	(Meeting No. 2)
Thurles	Friday 8th January (Subsequently Cancelled)	(Meeting No. 5)
Downpatrick	Wednesday 30th March	(Meeting No. 361)
Limerick	Friday 11th March	(Meeting No.360)
Tramore	Monday 25th April	(Meeting No. 363)
Tramore	Wednesday 4th May	(Meeting No. 364)
Tipperary	Tuesday 10th May	(Meeting No. 365)
Roscommon	Monday 17th October	(Meeting No. 371)

Figure 4: Extract from The Irish Form Book 2016

Where possible, the HRI will try to accommodate the meeting in an alternative venue. Cancelled, abandoned and rescheduled meetings have adverse financial, logistical and social effects.

Some courses have the space and width to alter the course (omit a bend or remove jumps) if the ground deteriorates excessively leading up to or during a meeting. For example, on Sunday January 10^{th} 2016, Fairyhouse went ahead with their meeting with a going of heavy. There were seven races on the card that day. Races 1 & 2 were maiden hurdles, race 3 was a handicap hurdles, races 4, 5, 6 & 7 are steeple chases. Race 7 was always scheduled to be a flat race. After the first three races the course began to deteriorate. Race 4 had the 6^{th} and 3^{rd} last fences omitted. Race 5 had the 5^{th}, 6^{th} & 7^{th} and 3^{rd} last fences omitted. Race 6 had 6^{th}, 7^{th} & 8^{th} and 3^{rd} last fences omitted and race. Race 7 was unaffected as there were no jumps. (HRI, 2017)

The condition of the soil, especially in extreme weathers, like the Winter 2015/16 (excessively wet) and Summer 2018 (excessively dry) has an impact on the length of the racing season. The flat racing season will have poor/slow results if the ground is soft. Likewise, the racecourses required persistent watering during the extended dry period of Summer/Autumn/Winter 2018 to soften the ground for both flat and jump racing. As a result of the long hot summer, the jump season was delayed, thereby affecting the jump horses getting ready for jump racing.

2.1.2 Field Sports

Player safety is a large concern in any field sport. The hardness of the ground conditions has an effect on the viability of a match going ahead. Frozen pitches and waterlogged pitches cannot be played on, and would lead to the cancelling of Gaelic and rugby matches.

2.1.3 Golf

There are two different type of golf courses, links and parkland. Kelley (2019) defines the two types as follows:

Links refer to a specific style of golf course whose hallmarks include being built on sandy soil on coastline; being buffeted by strong winds that require deep bunkers to prevent the sand from blowing away; and being completely or largely treeless. A links course generally has slow greens and firm, fast fairways.

A ***parkland*** course is one that is lushly manicured with verdant fairways and fast greens, with plenty of trees, and typically located inland. So named because of the park-like setting (Kelley, 2019).

While links courses are generally watered by the weather, parkland courses and watered, drained and scientifically managed.

The Sports Turf Research Institute, STRI, commissioned an agronomy report into ideal conditions for golfing greens in the UK (Windows & Bechelet, 2010). The playing qualities of the greens that were assessed were speed, smoothness and firmness. The STRI created a firmness scale to label the ideal firmness of a green, as seen in *Table 1: STRI Firmness Scale (Windows & Bechelet*, 2010).

Table 1: STRI Firmness Scale (Windows & Bechelet, 2010)

STRI Firmness Scale		
Clegg Value	**Description of Firmness**	**Ideal**
Over 130	**Hard and unreceptive.** Ball impacts and continually bounces forward. No control from well-struck shots as hardness increases. Frustrating to all levels of golfer.	
100 – 130	**Very firm.** Ball impacts, bounces on, checks and then rolls out. Well-struck shots need to be positioned correctly. A true test of ball striking and accurate play.	Links
80 – 100	**Firm.** Ball impacts, bounces forward, checks and then quickly stops. Good control of well-struck shots but less control from loose ball striking (especially at the firmer end).	Parkland
70 – 80	**Receptive.** Ball impacts then stops on first bounce or spins backwards. No footprinting. No real premium for ball striking. Such surfaces are flattering to average play.	
60 – 70	**Soft.** Balls stop dead and leave a large pitch mark. Footprinting becomes evident to make putting surface uneven. Not a good surface.	
Below 60	**Very soft.** Unstable and unplayable.	

The Clegg Values in above table will be explained in more detail in *2.3.1 The Clegg Hammer*.

2.2 What makes a good surface for racing?

There is one all-weather race track in Ireland – Dundalk, although, HRI are seeking expressions of interest in building a second track by 2021 (Horse Racing Ireland, 2019). Racing takes place on Dundalk's racecourse every Friday night with a going of 'standard'. Racing at Dundalk takes place on a wax-coated sand, recycled rubber and synthetic fibre surface that is less intensive than turf (RTE, 2019).

There have been multiple studies on mechanical wear on artificial surfaces, albeit more likely on football pitches. Sánchez-Sánchez et al. (2018) investigated the mechanical wear and environmental conditions on pitches. They found temperature did not significantly alter the mechanical behaviour of the pitch, but humidity reduced the absorption capacity of the ground. The Sánchez-Sánchez et al. (2018) study in football confirmed Charalambous et al, (2015), correlating colder and harder surfaces to less range of movement in athletes (multi-discipline). However, athletes adapt their leg stiffness to the conditions of the surface on which they move (Stafilidis & Arampatzis, 2007; Farley et al., 1998).

Environmental factors have a greater impact turf tracks than synthetic tracks. Serious injuries can cause fatalities in horseracing. Oikawa & Kusunose (2005) noted that horseracing times became longer as track conditions became softer. The incidents of fractures decrease as track conditions become softer (Wood et al., 2000; Oikawa & Kusunose, 2005). Chivers (1999) found the serious injury occurs in horses when the ground condition change from hard to soft in one stride length. The energy returned from track to horse at galloping velocities and the impact resistance of the track varies in accordance with the moisture content of the track (Ratzlaff et al., 1997). Chivers (1999) suggested that irrigation could help create more uniform conditions on dry parts of the racecourse by matching the moisture content of the drier and wetter areas of the racecourse.

There are many reasons why tracks are fast or slow. Meta-analysis from Sobczynska (2011) show that there are a number of environmental factors that affect the speed of thoroughbred horses competing in Poland but track conditions can contribute gap of $1.13 ms^{-1}$ between fast and heavy tracks.

"More than 9kN of force is applied during each stride to the contact area of the hoof. The hoof contact area is approximately $9500 mm^2$ and the hoof moves downward at a speed of more than $5 ms^{-1}$ during each stride" (Peterson et al., 2008). Peterson et al. develops a system for the in-situ characterisation of track racing surface with particular emphasis on force and simulation of the hoof rotation on impact and resistance.

Setterbo et al., (2012), compared the in-situ tests with laboratory methods. The instruments used were:

- a test-tracking device to simulate hoof impact similar idea to Peterson et al. (2008),
- a Clegg hammer to assess surface compaction, and
- a custom shear vane tester, again to assess surface horizontal properties.

This study found that shallow or surface Clegg hammer values were more closely correlated with test-tracking device figures with deeper values. They did suggest that a heavier 4.5kg Clegg hammer works better for thoroughbred racetrack surface assessment, that is, fast, firm and flat tracks.

2.2.1 Grass and Soil

Most groundskeepers would keep track of growth days or growth potential days. Growth potential is predominately based on temperature and the type of grass that you are growing. For most grasses, an air temperature of greater than 6°C will be a growth day (Woods, 2013). A site visit in October 2018, to the GAA National Games Development Centre at the National Sports Campus in Abbotstown, demonstrated the level of importance and precision that is attributed to data pertaining to their pitches and environmental conditions. *Table 6: Environmental Data taken from the GAA National Games Development Centre* shows the extent of the data collected and analysed by top groundskeepers.

Soil moisture is also closely aligned optimal grass growth (Pitts, 2016), where too little moisture can lead to yield loss and plant death; and too much water can cause root disease and nutrient loss.

Water resides in the spaces between soil particles. Soil with sand[3], clay[4], loamy[5] or silt[6] contents have various characteristics when it comes to how they absorb, store and move water (Adams and Gibbs, 1994). Each racetrack will have a combination of these soil types. Within a racetrack, the topography of the track will vary to add other characteristics and complexities as to how the soil behaves.

2.2.2 Soil Compaction

Another aspect that is not covered in the scope of this project is the soil compaction. Compacted soil is a large impact of poor racing surfaces. The compaction is caused by both horses and machines. Soil compaction can lead to poor drainage. On excessively soft tracks, horses' hooves can sink as deep as 200 mm into the ground. Compaction at depth as a result of such severe damage can have significant repercussions on winter racing, when good drainage is essential (Mumford, 2007).

2.2.3 Water Content Levels

There are different terms associated with the soil moisture content. Volumetric Water Content (VWC) is a percentage or ratio of water to soil. Four water content terms are important when planning irrigation:

- Saturation
- Field Capacity
- Management Allowable Depletion
- Permanent Wilting Point

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[3] Pure Sand – Large particles, low water holding capacity, high water mobility, poor storage – water quickly drains out of root zone

[4] Pure Clay – Very small particles, high water holding capacity, low mobility, less water available to plants due to low mobility

[5] Loam – Blend of particle size, high water holding capacity, good water mobility, good storage and good availability to plants

[6] Pure Silt – Small particles, low-mid water holding capacity, low-mid mobility, less water available to plants due to low holding capacity and mobility

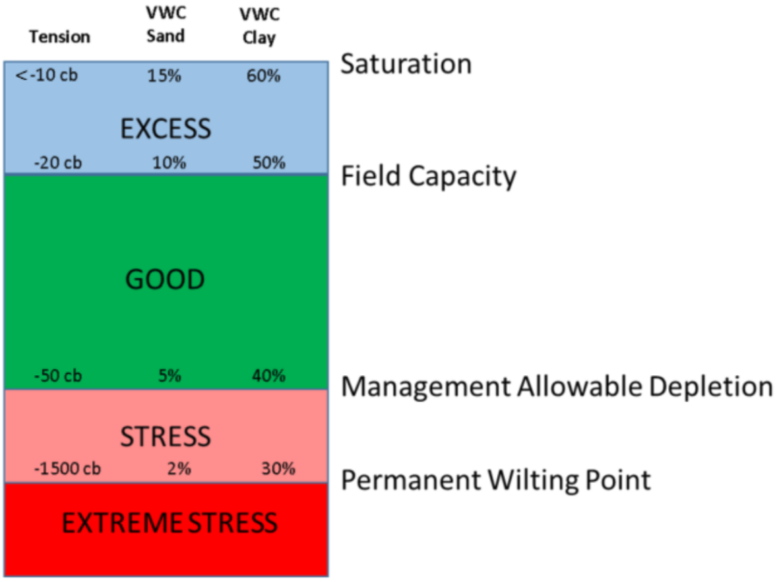


Figure 5: Soil Moisture Terms (Pitts, 2016)

It is very important to note that the levels that each of these water content levels occur are different for different soil types.

Saturation

Saturation is defined as when the water entering the soil is greater that the water moved down due to gravity. Water saturation is defined as "the ratio of water volume to pore volume" (Crain, 2015), where pore volume is the spaces between the particles in the soil. Saturated soil is heavy and lacks air.

Field Capacity

This is the amount of water held in the soil after the excess water has drained away and the gravity acting on the water in the soil has decreased. This usually takes place after rain or watering, and can takes from hours to days depending on the soil type.

Manageable Allowable Depletion

Management Allowable Depletion (MAD) is the lowest moisture level which can be sustained by plants without adverse stress effects (Pitts, 2016). This point would signal when irrigation should occur to avoid any stress on the plant root.

Permanent Wilting Point

As soil is subject to evaporation and withdrawals from plants, water content decreases and tension increases to a point where plants can no longer extract water. Maintaining soil at this level for any length of time can cause permanent damage to plants (Pitts, 2016).

2.3 How Ground Firmness is Measured

The going in Ireland and the UK are quite similar, which is explained by their similar topology and climate. Going definitions in Europe, the United States of America (Benoit, 2013) and Australia (Horse Racing Info, 2019) vary more.

Table 2: Categories of the Going (Wikipedia.org, 2019)

Going Grades in Ireland	Going Grades in UK
Hard	Hard
Firm	Firm
Good to firm	Good to firm
Good	Good
Yielding	Good to soft
Soft	Soft
Heavy	Heavy

Table 2: Categories of the Going (Wikipedia.org, 2019) above, is the list of seven classification of a racecourse called by a clerk. In Ireland, the clerk walks the course with a blackthorn stick – it makes the going definition quite subjective.

The classification of the going is very important to a trainers' selection of horse to be entered for a race. It is also important to the jockey, as to how they are going to ride and manage the horse around the course.

2.3.1 The Clegg Hammer

Figure 6: Clegg Hammer

Dr. Baden Clegg (Clegg, 1976) pioneered the Clegg Impact Soil Tester, CIST or Clegg hammer. The CIST is used extensively in Australia and New Zealand for cricket, football (all codes) and golf to measure the hardness or shock absorbency of a surface.

The CIST is a lightweight, portable, mechanical device that measures the hardness of a sports surface and delivers a digital output. The CIST/883 – 2.25kgs was the CIST model used in the tests. The CIST/883 works on the principle of a weight (the red section in the *Figure 6: Clegg Hammer*) being dropped through a vertical guide tube from a regulated height, and the deceleration of the weight is recorded on impact. The measurement, Clegg Impact Value, CIV is displayed temporally on the CIST and then stored to memory.

The units of the CIVs are gravities, G. This compares the density of the soil compared to a reference density, i.e. G is a ratio. The denser the soil, the harder it is. The CIST was calibrated at purchase.

The CIST/883 is Bluetooth compatible (SD Instrumentation, 2016). With the aid of software from the Clegg Hammer manufacturers, SD Instrumentation, all CIV readings from the CIST can be exported from the Clegg hammer to a computer. The output file format is a comma-separated file. Each reading takes the format of "Time, Date, Drop".

2.3.2 Clegg Hammer in Golf

The STRI report (Windows & Bechelet, 2010) did find a correlation between the soil moisture content and the Clegg values as seen in *Figure 7: The Relationship between Soil Moisture Content and Clegg Hardness Values during 2009 Study (Windows & Bechelet, 2010)*.

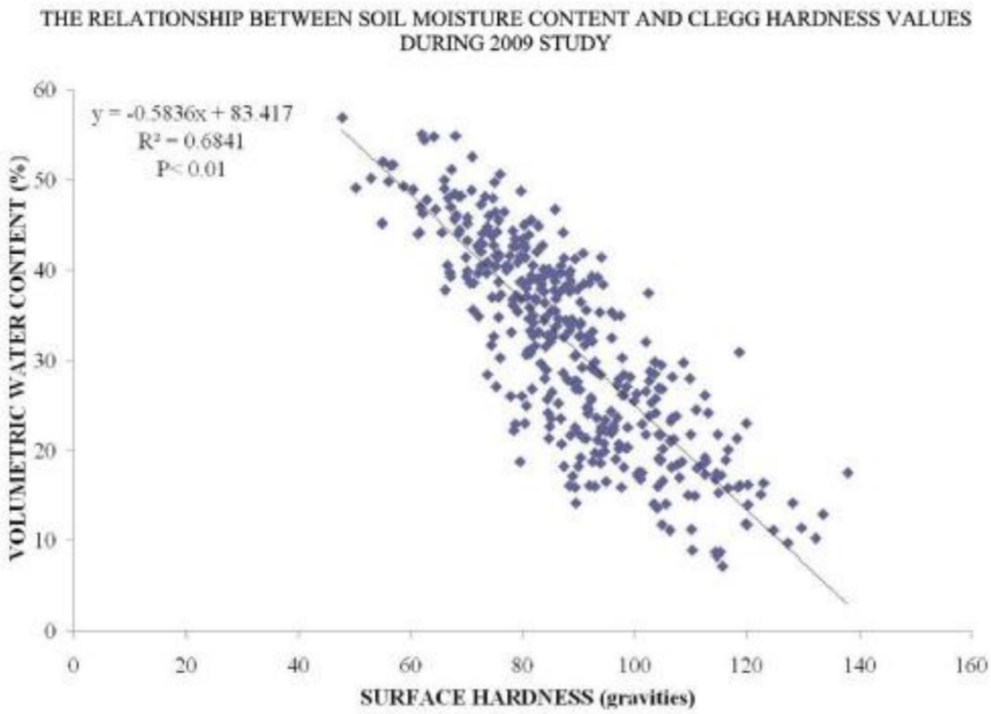


Figure 7: The Relationship between Soil Moisture Content and Clegg Hardness Values during 2009 Study (Windows & Bechelet, 2010)

The STRI defined six categories for green soil firmness. Within these six category, the STRI recommend ideal firmness, as specified by Clegg values, for links and parkland golf courses.

2.3.3 Shock absorption apparatus with a Piezo-resistive accelerometer

FIFA recommends the use of a shock absorption apparatus with a piezo-resistive accelerometer to gauge the shock absorption of the pitch (FIFA, 2015b). *Figure 8: Shock absorption apparatus with a Piezo-resistive accelerometer* shows both an actual photo and a schematic interpretation of the shock absorption apparatus. The apparatus is cumbersome to trial in multiple non-plateaued locations.

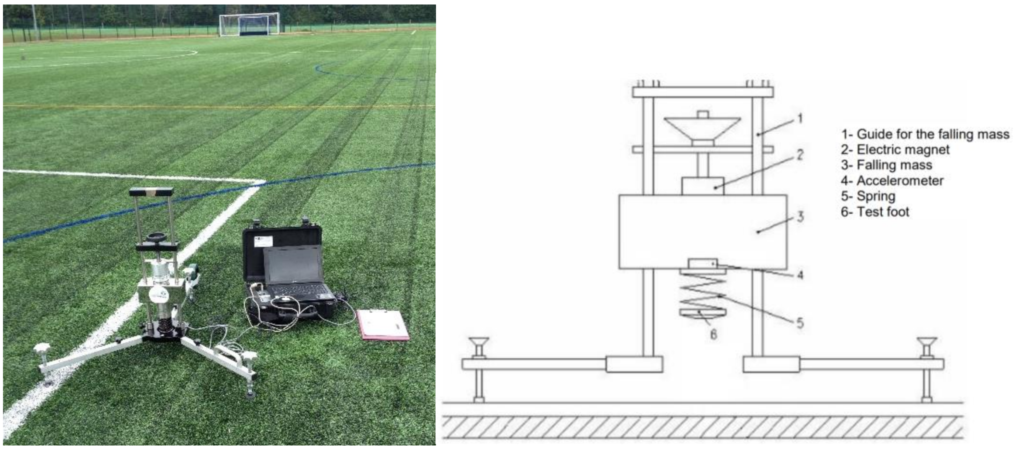


Figure 8: Shock absorption apparatus with a Piezo-resistive accelerometer

2.3.4 Penetrometer

The Penetrometer is predominately used in Australia, South Africa, India and France (Field et al., 1993).

The Penetrometer or Soil Compaction Tester is a simple device used in all turf sports to measure the compaction of the soil.

The penetrometer is lightweight and portable. It can also measure soil compaction at various different depths and compaction zones.

Figure 9: Penetrometer

The analogue (usually colour coded) scale makes it easy to read, however there is no means of automatically saving the data or analysing later (PitchCare, 2019).

2.3.5 GoingStick

There are 60 racecourses spread across the large geography of Britain and there are race meetings seven days a week. The Jockey Club[7] required a solution to standardise the conditions on the tracks (Godfrey, 2016).

The GoingStick was developed in the early 2000s in collaboration with Cranfield University, TurfTrax company and the Jockey Club. The project was to create a device for measuring the firmness and shear on the surface of a turf track.

These two measures taken in combination represent a scientifically based approximation for the firmness of the ground and level of traction experienced by a horse during a race (TurfTrax, 2017). The TurfTrax going index is based on:

Equation 1: Going Index Calculation

$$Going\ Index = 0.69024x_1 + 0.34458x_2 - 0.27064$$

Where x_1 is the penetration output and x_2 is the shear output (Dufour & Mumford, 2008).

Figure 10: GoingStick

Figure 11: Digital output from GoingStick

After extensive development, *Table 3: Categories of the Going and their corresponding TrufTrax going index (Dufour & Mumford, 2008)* was developed.

[7] The Jockey Club were horse racing regulators in the United Kingdom pre-2006. The British Horseracing Authority (BHA) now preform that task.

In January 2009, the use of the GoingStick was mandatory on British racecourses (Wood, G., 2008). Gowran Park in Kilkenny are leading the way in Ireland trying to introduce this technology into grounds keeping on their race and golf courses. Navan are currently trialling the GoingStick. Horse trainer Henry de Bromhead has called for penetrometer devices that help ascertain more accurate ground conditions to be trialled at Irish racecourses (O' Connor, 2019) akin to the GoingStick in the Britain. HRI has not yet adopted such technology.

Table 3: Categories of the Going and their corresponding TrufTrax going index (Dufour & Mumford, 2008)

Going Grades in Ireland	Going Grades in UK	GoingStick	GoingStick Readings
Hard	Hard	Hard	13.0-15.0
Firm	Firm	Firm	11.0-12.9
Good to firm	Good to firm	Good to firm	9.0-10.9
Good	Good	Good	7.0-8.9
Yielding	Good to soft	Good to soft	4.0-6.9
Soft	Soft	Soft	3.0-3.9
Heavy	Heavy	Heavy	1.0-2.9
		Waterlogged	<1.0
		Not in Use	

While the most common readings on the GoingStick are between 5 and 10, there will be some reading between 3 and 12.

The groundskeeper/course clerk takes reading on the GoingStick at various TurfTrax defined waypoints throughout the course. All data is stored in the GoingStick until downloaded via universal serial bus (USB) to TurfTrax software on a computer. This builds a picture of the course conditions for that specific time.

Between the data retrieved from the GoingStick at particular waypoints, the TurfTrax software creates a visual map of the course.

Figure 12: Going Map from TurfTrax

This map is published on the TurfTrax website and by the individual racecourse.

The GoingStick does not ensure compliance. The waypoints are assessed and defined by the TurfTrax company. They are not marked by GPS coordinates. The consumers of the Going Maps are not guaranteed the timing or the integrity of the reading.

2.3.6 Measure of Hardness in Project

The Clegg hammer is well documented in multiple researches and frequently used by industry when new pitches are installed. There was a CIST available on the Technological University of Dublin campus and this device was used for this study.

2.4 Soil Moisture Deficit Model from Met Éireann

Met Éireann generates meteorological data for the agriculture community that are usually more specific than the general weather forecast, e.g. Mean Air Temperature (^{o}C), Mean Soil Temperature (^{o}C), Accumulated Sunshine (hours) and others.

Allen et. al. (1998) laid the foundation for the standardisation of formulae for crop water requirements and published them for the Food and Agriculture Organization for the United Nations (FAO). These formulae are used by Met Éireann for a series of agriculture forecasting requirements.

Met Éireann provide the following graphs based on the FAO formulae:

- Well Drained Soil Moisture Deficit
- Moderately Drained Soil Moisture Deficit
- Poorly Drained Soil Moisture Deficit
- Well Drained Soil Moisture Deficit - Difference from Normal
- Moderately Drained Soil Moisture Deficit - Difference from Normal
- Poorly Drained Soil Moisture Deficit - Difference from Normal (Met Éireann, 2019b)

The Soil Moisture Deficit (SMD) is defined as the amount of rain needed to bring the soil moisture content back to field capacity (further explained in *2.2.3 Water Content Levels*). Schulte et. al. (2005) developed the model for the soil moisture deficiency and it was implemented by Met Éireann in 2006 (Werner et. al., 2019)

Met Éireann use the following formula to calculate soil moisture deficit

Equation 2: Soil Moisture Deficit Calculation

$$SMD_t = SMD_{t-1} - Rain + ET_a + Drain$$

where SMD_t and SMD_{t-1} are the SMDs on a day, t, and the previous day, t-1, respectively, *Rain* is the daily precipitation (mm per day), ET_a the daily actual evapotranspiration (mm per day), *Drain* is the amount of water drained daily by percolation and/or overland flow (mm per day) (Met Éireann, 2019a).

Taking *Equation 2* in terms of soil moisture deficit, this equation could be modified and rewritten in terms of soil saturation:

Equation 3: Soil Saturation Calculation

$$SS_t = SS_{t-1} + Rain - ET_a - Drain$$

where SS_t and SS_{t-1} are the soil saturations on day t and day t-1 respectively, *Rain* is the daily precipitation (mm d^{-1}), ET_a and *Drain* are as previously. This equation can be expanded to include irrigation as well as rainfall.

Equation 4: Soil Saturation Calculation for Irrigation Purposes

$$SS_t = SS_{t-1} + (Rain + Irrigation) - ET_a - Drain$$

The scope of this paper makes allowances for rain and shows the calculations for irrigation. *Equation 4: Soil Saturation Calculation for Irrigation Purposes* will be specifically mentioned when it is used, otherwise *Equation 3: Soil Saturation Calculation* is used.

2.5 Soil Moisture Measurement

There are two types of soil moisture sensors – sensors that measure tension and those that measure volumetric water content.

Table 4: Soil Moisture Sensor Comparison

	Tension Sensors	Volumetric Water Content Sensors
Material	Tensiometer & Gypsum Block sensors	Neutron and Dielectric Probes
Water Levels	Determines the water content levels directly, not the water volume	Measures water content, but needs to be scaled/calibrated
Output	Measures stress on plants	Can predict when next irrigation should occur
Cost	Less expensive that VWC sensors	Tend to be higher cost than Tension sensors
IoT Compatible	No	Yes

Due to the Internet of Things nature of this project, the sensor chosen is a volumetric water content sensor. The SoilWatch 10 from Pino-Tech was used. The details of this sensor are available in the Pino-Tech datasheet (Pino-Tech, 2018).

2.6 Water Loss – Evapotranspiration & Drainage

Evaporation is the process on the surface of a liquid when it changes to gas. Transpiration is the process by which moisture is carried through plants from roots to small pores on the underside of leaves, where it changes to vapour and is released to the atmosphere. Transpiration is essentially evaporation of water from plant leaves (U.S. Geological Survey, 2019).

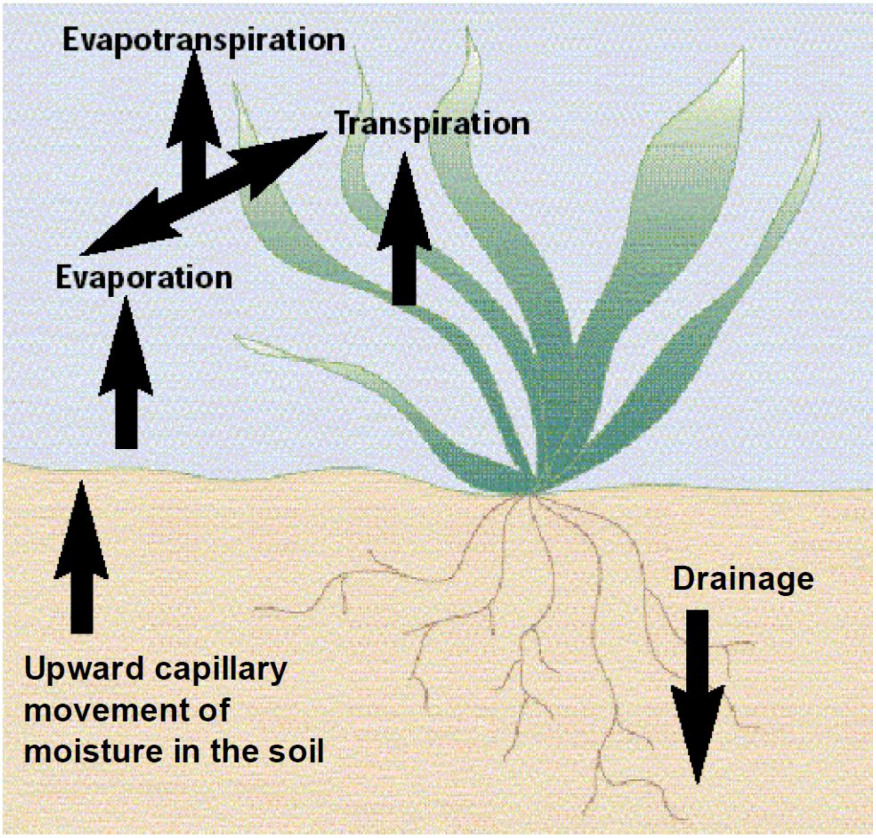


Figure 13: Water loss through evapotranspiration (Mumford, 2006)

Evapotranspiration is the total water flux into the atmosphere, that is the sum of evaporation and water flux through plant stomata (Met Éireann, 2019a).

2.6.1 Actual Evapotranspiration, ETa

Werner et al. (2019) created a detailed analysis of the hydro-climate indices for Ireland for the Environmental Protection Agency, EPA. This included a comparative study of the Consortium for Small-scale Modelling and the Climate Limited-area Modelling Community (COSMO-CLM), the Weather Research and Forecasting model (WRF), and the Met Éireann Re-Analysis (MÉRA) datasets.

The MÉRA model performed best for ETa and SMD variables and was therefore recommended as the dataset to be used as indicative maps of Ireland. The MÉRA is a 35-year high-resolution (2.5km horizontal grid) regional climate reanalysis for Ireland (Met Éireann MÉRA, 2019).

This comprehensive dataset of hydro analysis is available from Irish Centre for High-End Computing (ICHEC). The files have a file extension of *.nc are can be opened from the Panoply java runtime application.

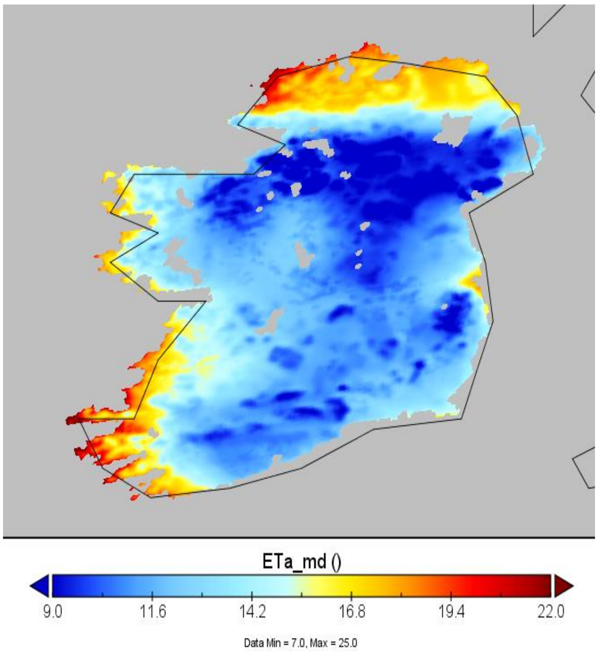


Figure 14: Panoply view of ETa dataset (for January)

The ETa for specific months and for specific latitude and longitude values can be extracted from the dataset (Irish Centre for High-End Computing, 2019).

2.6.2 Drainage Values

Schulte et. al. (2005) defined three classifications of drainage in Ireland - well, moderately and poorly-drained soils. These classifications are used by Met Éireann in their SMD calculations.

Further maths can be performed on the soil saturations values obtained from the sensors that allow a more accurate value of drainage to emerge per sensor, which is per location. This process is explained further in *4.7 Drainage*.

2.7 Using Soil Moisture Data to Make Decisions

Enabling multiple low cost soil moisture sensors ensures that high frequency data is collected, collated and analysed to better understand the soil surface around the race track. Decisions are made regarding irrigation plans for the track.

2.7.1 Sensor Location

Figure 15: Satellite image from Google Maps

Reference has already been made to how the soil type varies within a small range. Ground behaviour can change based on topology, cover, usage and a range of environmental effects, as seen in *Figure 15: Satellite image from Google Maps*.

Figure 16: Satellite image of Fairyhouse Racecourse from Google Maps

A racecourse may have less variance in topology than a farm, put there will be the same issues in terms of usage and cover. The racing line and location of jumps can even be change depending on the condition of the soil.

There are many studies into the mapping of topology and environmental factors. Kumar et al., (2008) looked at the established Land Information System (LIS) for surface modelling of ground measurements, satellite observations and computing tools to add observational sources and assimilation algorithms. Drăguţ & Dornik (2016) looked at land-surface segmentation as a method to create strata for spatial sampling and its potential for digital soil mapping. Zhang M. et al. (2017) and Zhang F. et al. (2019) also published in a similar space.

While the area of a racetrack may not be a large and varied as the domains mentioned in the previous referenced papers, the prototype holds true. A sensor can define collective gatherings of similar topology and conditions, and different variations get different sensors. It is important to classify the track into zones or waypoints.

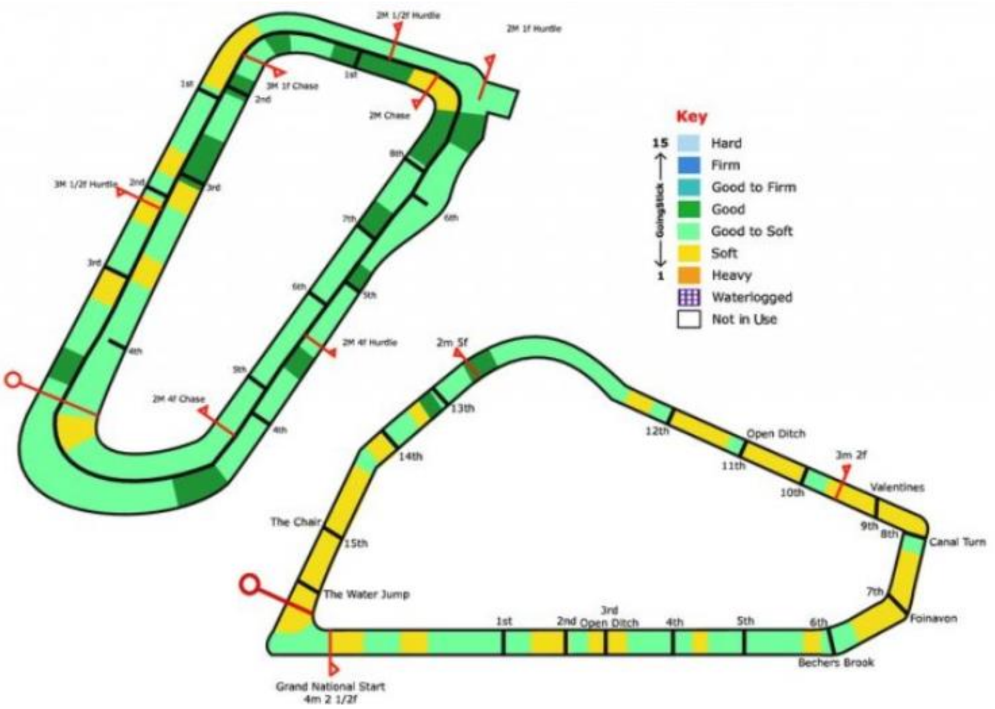


Figure 17: TurfTrax Going Map for Aintree

In the case of TurfTrax and the GoingStick, TurfTrax divide the course up into a number of segments or waypoints e.g. Gowran Park racecourse is divided in 30 waypoints. There are three GoingStick measurements taken at any points within those waypoints. These measurement are averaged and then classified for a Going Map similar to *Figure 17: TurfTrax Going Map for Aintree*.

2.8 Irrigation Management

In the section *2.2.3 Water Content Levels*, the water content levels were given their physical meaning. This allows the saturation numbers to have a more practical application. Once the soil is learned as a result of the soil moisture sensor, the ground can then be managed. The different physical meanings can have a trigger effect on when, where and how the irrigation plan should work.

In *Figure 18: Soil Moisture Physical and Management meanings* below, show that the definitions of the water content levels can be overlaid with real action items for soil management.

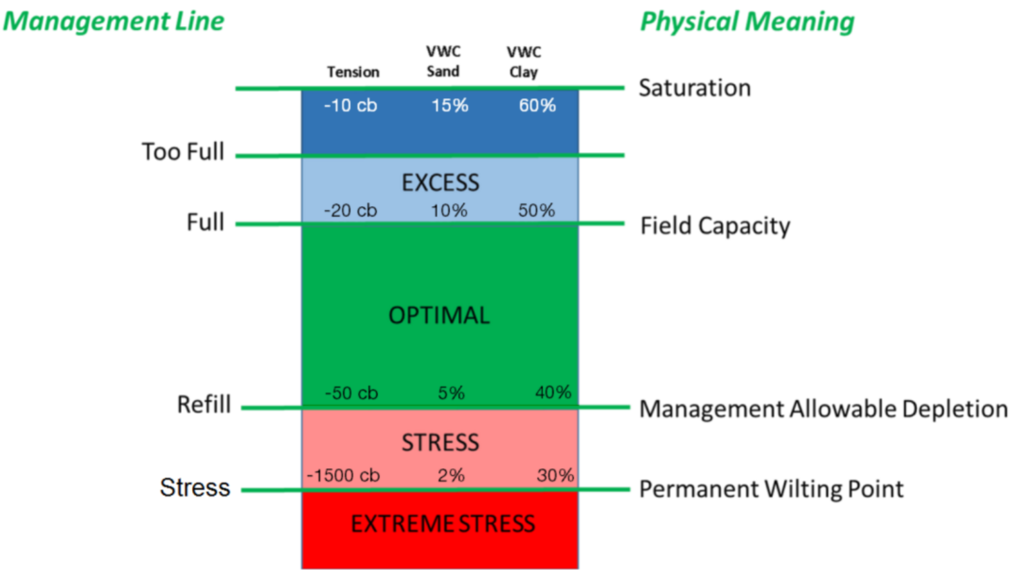


Figure 18: Soil Moisture Physical and Management meanings

Following on from the soil saturation data being delivered in real time, information and instructions can be issued to the consumers of the data.

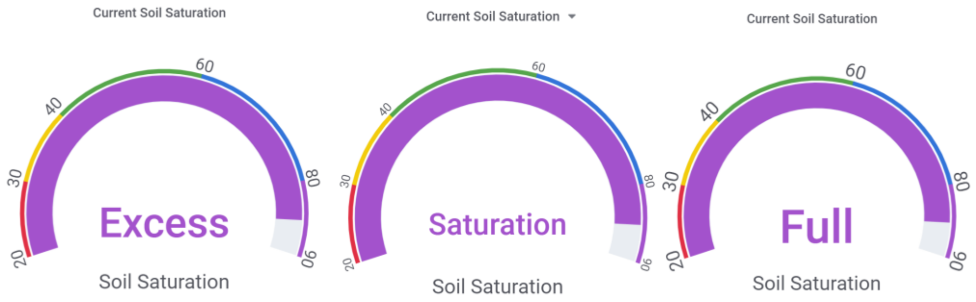


Figure 19: Examples of how the current Soil Saturation levels could be viewed

On well-drained land such as most sporting facilities, it is easier to decipher when the soil needs to be irrigated. The sensors can show where the ground needs watering and by how much.

2.9 Going Trends

The soil moisture sensor is a linear scale with a range of 0-1000, as described in *3.2.1 Soil Moisture Sensor*. This scale could read as a 0-100% in terms of presence of water. The soil management lines can be overlaid on this 0-100% range to indicate an irrigation plan. Likewise, the going bands can be overlaid on soil moisture scale to declare the going for the ground.

Mumford (2006) completed an in-depth analysis of the Leicester and Newcastle racecourses. He drew a linear relationship between the Soil volumetric content (%) and the Going for the sandy loam soils of both racecourses. The results can be seen in *Figure 20: Soil Volumetric Moisture Content v Going (Mumford, 2006)* below.

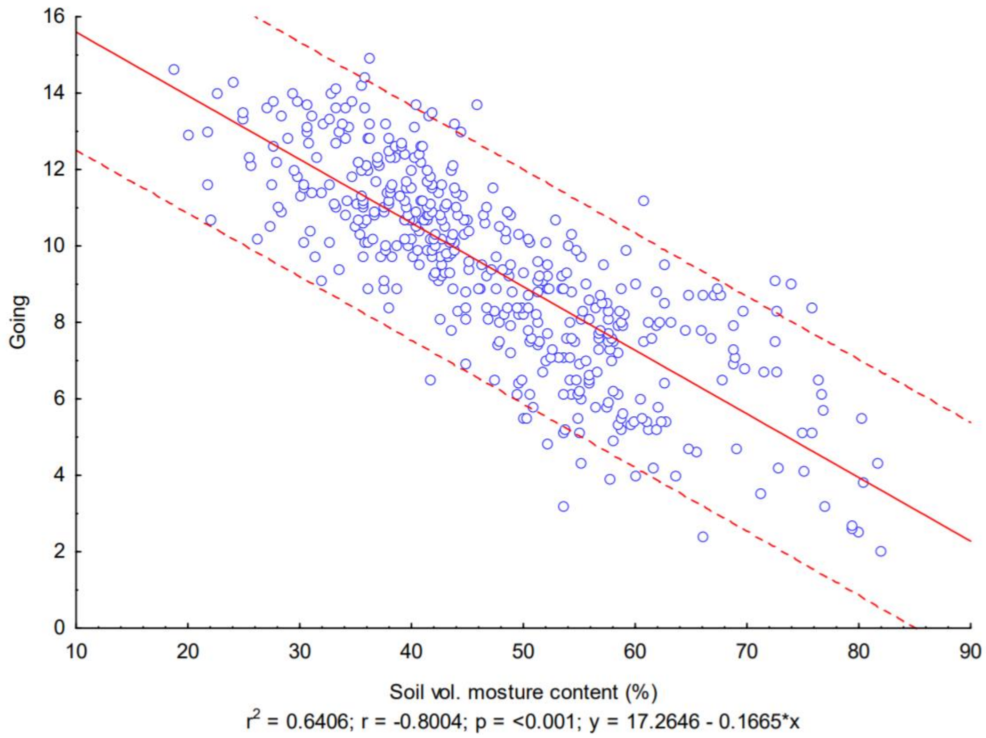


Figure 20: Soil Volumetric Moisture Content v Going (Mumford, 2006)

This strong correlation of the linear definition denotes that the soil moisture content gives an accurate prediction of the going. It is important to point out that both Mumford and TurfTrax, include shear resistance when the going is calculated. This sample study is only looking at soil moisture values and their relationship with the going.

The linear relationship that is used for soil moisture content (%) and the going is defined as *Equation 5*.

Equation 5: Going Calculation based on Soil Moisture

$$Going = 17.2646 - 0.665 * Soil\ Moisture\ Content(\%)$$

This equation can be used in conjunction with *Table 3: Categories of the Going and their corresponding TrufTrax going index (Dufour & Mumford, 2008)* to convert raw soil moisture data in usable categories for racing.

2.10 Mapping Data Collection

The placement of sensor around a track should include corners/bends, peaks and troughs and any other key attributes on the track, like jumps and high density areas.

The sensors can also include GPS coordinates to verify the position that the moisture content data is coming from. This ensures validation of data from a particular GPS position, and a timestamped moment in time with a known instrument i.e. the sensor. All of these attributes contribute to the integrity of the readings.

The GPS coordinates could be overlaid on an open-source mapping tool like Street Maps to place the sensors onto a graphical map. Mitchell et al. (2018) looked at a tool for semi-automated thematic maps, which could work well in a small area. This is outside the scope of this project. Grafana has a mapping add-on tool to graphically represent the data in geographical maps.

2.11 Other Weather Correlations

There are multiple studies into the correlation of soil hardness and weather data. This project used rainfall and soil saturation, but wet bulb temperature and sea level pressure could have taken the project in a different trajectories.

2.11.1 Wet Bulb Temperature Correlation

Eltahir & Pal (1996) suggested a link between rainfall and wet bulb temperature under particular conditions. Wet bulb temperature is an indicator of surface conditions, of which soil moisture is one.

"The rate at which soil water can be removed is a property of the unsaturated hydraulic conductivity of the soil… in exfiltration processes is not the moisture content, θ, but rather the soil saturation, θ/n, where n is the porosity, that is the controlling parameter. Therefore, soil saturation is used as an indicator of the overall soil water condition"

(Findell & Eltahir, 1997). This study used a 21-days moving average for their calculations.

Pan et. al (2003) took a partial differentiation formula from a Findell & Eltahir (1997) and expands it to the following formula:

Equation 6: Estimated Soil Moisture formula (Pan et. al, 2003)

$$\theta_1 = \theta_n e^{-\frac{\eta}{Z}(t_1 - t_n)} + \gamma B$$

Where, $B = \sum_{i=1}^{n-1} \frac{[P_i/(t_i - t_{i+1})}{\eta} [1 - e^{-\frac{\eta}{Z}(t_i - t_{i+1})}] e^{-\frac{\eta}{Z}(t_1 - t_i)}$

Where, θ is the soil moisture at a specific point in time, t. t_1 is now, t_2 is the previous time interval and so on back to n time intervals. Each time interval is denoted by the P_i. η is the loss coefficient of the soil. Z is the thickness of the soil. γ is the infiltration coefficient used to represent the ratio of infiltration rate to net rainfall rate.

Equation 6: Estimated Soil Moisture formula (Pan et. al, 2003) shows that as the timeline increases, the exponential term, $e^{-\frac{\eta}{Z}(t_1 - t_n)}$ approaches zero, and the importance of the initial soil moisture, θ_n decreases. The second term in *Equation 6: Estimated Soil Moisture formula (Pan et. al, 2003*) contains the weighted average cumulative rainfall depth and the current soil moisture is evaluated from this.

On the other hand, the further beyond t_1, the smaller the precipitation term, and the lower the contribution of the rainfall to the soil moisture at time t_1 (Pan et.al, 2003).

2.11.2 Sea Level Pressure Correlation

Met Éireann produce numerous weather outputs – daily, weekly and monthly comma separated values/files (CSVs) for each weather station. These data files are available at the end of each calendar month. One of these outputs, the hourly data, contains sea level pressure (or atmospheric pressure at mean seasonal sea level).

A correlation matrix is a tool to identify what are the significant variables that correlate to the variable that is been tested. Using the information available from Met Éireann, and the data from the soil sensor, a correlation matrix can be produced.

Table 5: Correlation Matrix with Weather and Soil Saturation Levels in Excel

	date	*Soil Sat*	*Rain*	*Temp*	*WetBulbTemp*	*DewPt*	*VapPressure*	*Rel Hum*	*SeaLevelPressure*
date	1								
Soil Sat	-0.4095	1							
Rain	0.0163	0.2849	1						
Temp	0.1114	0.0130	-0.0568	1					
WetBulbTemp	0.0696	0.2559	0.0234	0.9194	1				
DewPt	-0.0111	0.5532	0.1303	0.5037	0.8007	1			
VapPressure	0.0079	0.5306	0.1267	0.5146	0.8079	0.9968	1		
Rel Hum	-0.1129	0.5228	0.1856	-0.5273	-0.1543	0.4649	0.4532	1	
SeaLevelPressure	0.5544	-0.6838	-0.2130	0.0218	-0.1571	-0.3707	-0.3590	-0.37994	1

The only strong correlation between soil saturation levels and the weather data is the relationship with Sea Level Pressure measured in hectopascal, hPa. The strong correlation of -0.6938 could be delved into further if rainfall wasn't the main focus of this project.

The data that was used in this correlation matrix corresponds with very low rain. This may explain why the Rain and Soil Saturation correlation was so low.

3 Research Methodology

"*Data is the new oil*" - Clive Humby, data scientist and author.

There is a lot of data available on open source sites. Irish sites such as data.gov.ie, osi.ie and data.smartdublin.ie are some of the resources that are available with data specific to Ireland. This project uses primary and secondary data sources.

3.1 System Architecture

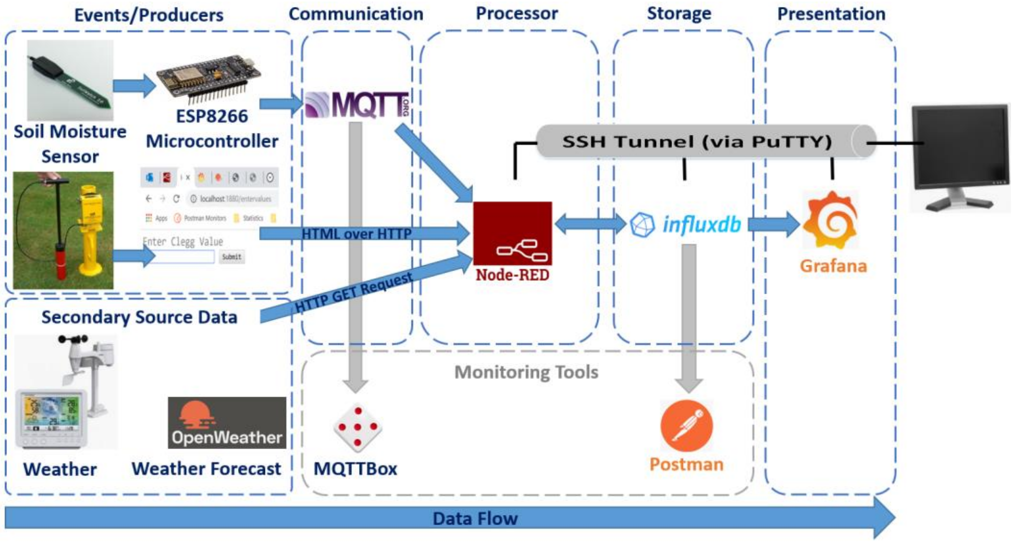


Figure 21: System Diagram

From the *Figure 21: System Diagram* above, the primary and secondary data comes under the Event/Producers banner. The soil moisture sensor collecting data from the ground is explained in *3.2.1 Soil Moisture Sensor* and *3.2.2 The Microcontroller*. Daily readings are taken on the Clegg hammer and entered into the system via a web-based screen. This process is explained in *3.4 Readings from the Clegg Hammer*.

The secondary data sources are from open application programming interfaces, APIs. Met Éireann was used for the closest weather station, and OpenWeather was used for the weather forecast. Section *3.5 Met Éireann Weather Data* explains how the weather data was collected and *3.7 Weather Forecast Data* explains where and how the rainfall forecasts were gathered.

The communication is handled via MQTT[8] over WIFI and HTTP[9]. The Node-RED processor, InfluxDB storage and Grafana presentation are covered in *3.3.4 The Node-RED Server*, *3.3.5 The InfluxDB Database* and *3.12 Grafana* respectively.

3.2 Soil Saturation Producers

There are two physical components associated with collecting the soil moisture data. The soil moisture sensor and the and microcontroller.

Figure 22: Soil Moisture Sensor and Microcontroller in-situ

3.2.1 Soil Moisture Sensor

Figure 23: PinoTech SoilWatch 10

The SoilWatch 10 3Volt version from Pino-Tech is a capacitive soil sensor with no exposed electrodes (Pino-Tech, 2019). The SoilWatch 10 specifications are available from Pino-Tech datasheet (2018).

The 0-1000 range in the raw values received from the sensor directly equates to a 0-100 linear scale of soil moisture content. In the sensor range, zero

[8] MQTT is a lightweight messaging protocol for small sensors and mobile devices. It is an ISO standard publish-subscribe-based messaging protocol. It works on top of the TCP/IP protocol.

[9] HTTP is the underlying protocol used by the World Wide Web. This protocol defines how messages are formatted and transmitted, and what actions Web servers and browsers should take in response to various commands.

denotes no presence of water, and 100 is the equivalent of placing the sensor into 100% moisture.

3.2.2 The Microcontroller

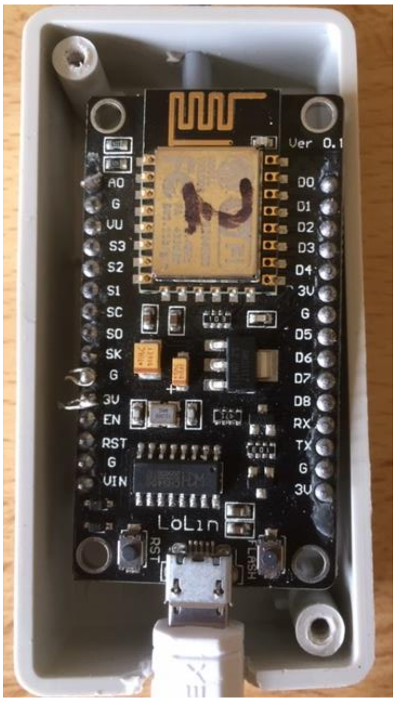


Figure 24: ESP8266 Microcontroller in plastic housing

The SoilWatch 10 is physically connected to a Wi-Fi enabled ESP8266 microcontroller unit (mcu). The mcu is housed in a plastic container to seal the electronics away from any moisture/rain. The microcontroller also requires a mains power supply.

The ESP8266 has a 3.3 voltage, more than the 3 volts coming from the SoilWatch10 sensor. This is the reason that the raw values from the soil moisture sensor are 0-1000 rather than the typical 0-1024 on a typical 2^{10} bit component.

The ESP8266 is wired for ground, 3V, and analog to digital converter, ADC. The analog input from the soil moisture sensor (voltage increments) are converted into a usable 0-1000 linear scale.

There are two lua scripts – Init.lua and Script4.lua - running on the ESP8266 to programme and capture the data coming from the SoilWatch 10. The code for the lua scripts are included in the appendix, *9.4 Lua Scripts*.

Init.lua Script

The Init.lua script detailed in *Figure 106: Init.lua script*, programs the ESP8266 to connect to a specific wi-fi with password. There are some print executes to get the media access control (MAC) address back to the consumer. This is useful when the

ESP8266 is being set-up and programmed using ESPlorer[10]. The Init.lua file calls Script4.lua.

Script4.lua Script

The Script4.lua detailed in *Figure 107: Script4.lua*, allows the ESP8266 to connect to a MQTT broker in a virtual machine setup in Azure. The script4.lua:

- defines the location of the MQTT broker,
- constructs the message containing the raw value from the sensor,
- publishes the message to the MQTT broker under a specific topic,
- waits 60000 milliseconds and executes the loop again.

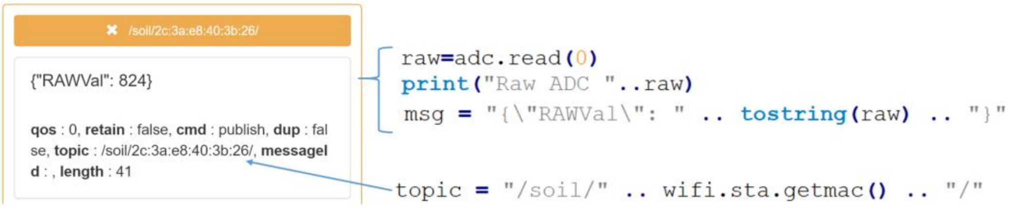


Figure 26: Construction of MQTT message, as seen from MQTTBox[11]

Both lua scripts are created in Notepad and uploaded to the ESP8266. The ESP8266 is programmed to publish soil moisture data to the MQTT every 60 seconds.

3.3 The Infrastructure, Processor and Storage

The cloud-based components of the data collection are associated with transporting and storing the data into the correct location. These include the MQTT broker, Node-RED and InfluxDB.

10 ESPlorer — Integrated Development Environment (IDE) for ESP8266 developers.
[11] MQTTBox is a useful monitoring tool to subscribe to topic on an MQTT broker.

3.3.1 The MQTT Broker

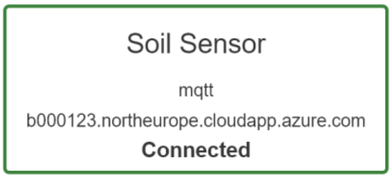


Figure 27: MQTT Broker

The MQTT broker is on a Microsoft Azure virtual machine running remotely. Once the virtual machine was set up, an MQTT container was placed on the machine. The Script4.lua on the ESP8266 contains a pointer to the virtual machine via its domain name system, DNS.

In accordance to the Script4.lua program on the ESP8266, the soil saturation data is published to the MQTT broker every minute. The MQTT broker does not process this information, merely acts as a holding area for any MQTT clients to subscribe to that information.

3.3.2 Virtual Server and Putty Connection

Another virtual machine was created using Microsoft Azure.

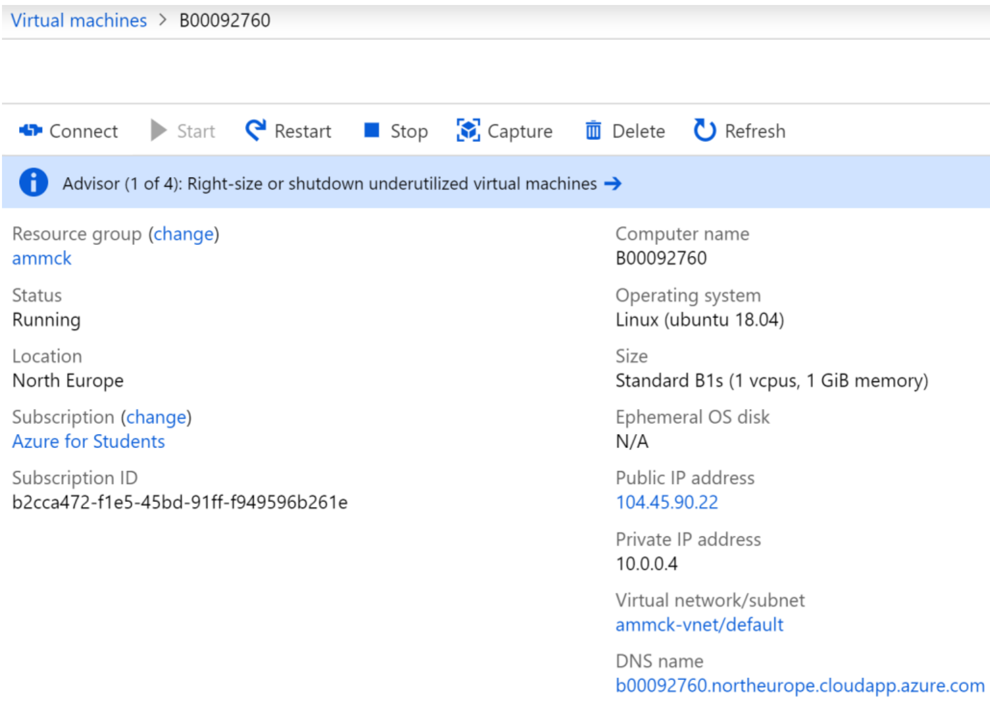


Figure 28: Virtual Machine setup on Microsoft Azure

The virtual machine was setup to add a level of detachment between the host and the client. Docker was installed on the virtual machine to enable multiple containers containing applications that can be deployed and run as separate units.

InfluxDB, Node-RED and Grafana were installed into separate containers on the virtual machine. These applications can be accessed from any browser if there is a secure shell, SSH, tunnel to the virtual machine.

PuTTY is a free and open-source terminal emulator, serial console and network file transfer application (putty.org, 2019). PuTTY is used to create a SSH connection to the virtual machine.

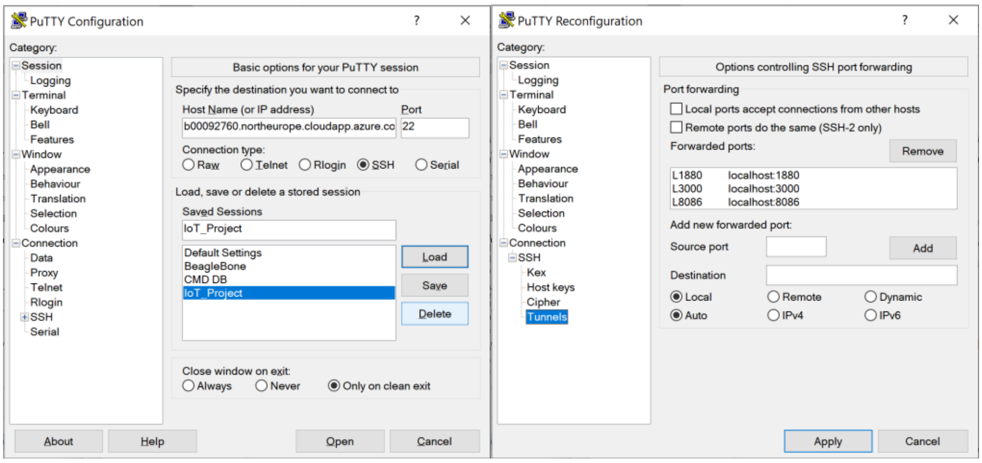


Figure 29: Putty configuration

Once the connection is established, SSH tunnels are then configured to link local ports to the virtual machine containers:

- Port 8086 to connect to InfluxDB
- Port 1880 to connect to Node-RED
- Port 3000 to connect to Grafana

The virtual machine is always on, and processing data or flows. Direct access is gained via PuTTY.

3.3.3 The MQTT Client

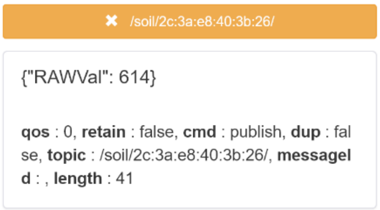


Figure 30: MQTT Client

The application MQTTBox can be used to monitor MQTT messages. Once the application connects to the MQTT broker, topics can be subscribed to. This allows the user to see that information is being collected from the soil moisture sensor and being published automatically. All or specific topics can be subscribed to from any machine anywhere that has the credentials for the MQTT broker.

A PuTTY connection is not required for the MQTTBox monitor. The DNS of the MQTT broker and password is required for the connection.

The MQTT Box is sufficient to temporarily view the soil moisture numbers from the sensor. However, to keep and analyse these number, it is required to write this data to a database.

3.3.4 The Node-RED Server

Node-RED is a flow-based development tool for visual programming for wiring together hardware devices, APIs and online services as part of the Internet of Things (Open-JS Foundation, 2019). Node-RED was extensively used in this project.

The first application of a Node-RED flow allows subscription to the MQTT broker to collect the soil moisture levels. This flow can be seen in *Figure 31* below.

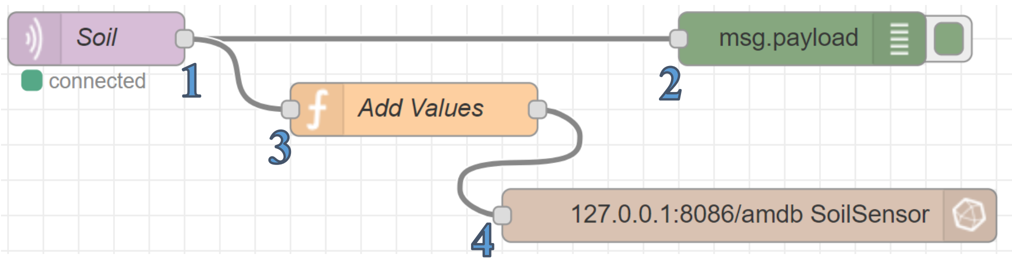


Figure 31: Node-RED flow to monitor MQTT broker and write to InfluxDB

Node-RED has built-in MQTT functions to subscribe to MQTT topics. The MQTT function node (1) is configured to watch a specific MQTT broker and a specific topic. Updates to the MQTT broker are auto-detected, so there is no requirement to continuously poll the MQTT broker. The msg.payload (2) node is a simple debug node. This clarifies that the data from the soil moisture sensor is automatically gathered, as the debug displays the data in the Node-RED development environment. The Add Values function node (3) parses the data and forms a JSON object of suitable format for the database. The InfluxDB output node (4) specifies where the JSON object should be stored in the database.

The InfluxDB resides on the Azure virtual machine. The database is set a localhost with a port of 8086, to use the SSH tunnel in PuTTY to the virtual machine. The database is local, using port 8086, the database name is amdb and the table/measurement is called SoilSensor.

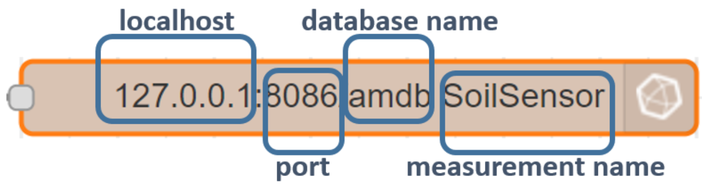


Figure 32: InfluxDB output node configured

3.3.5 The InfluxDB Database

InfluxDB is an open source time series database. InfluxDB was installed on a container on the virtual machine, to give a level of separation from application to client.

The Node-RED script seen in *Figure 31: Node-RED flow to monitor MQTT broker and write to InfluxDB* takes the data from the MQTT topic and stores it to the database. In step 3 of *Figure 31*, the GPS coordinates are attached to the JSON object. Once the data is written to the database, the soil moisture record is given a timestamp from the database. The data flow from soil sensor to database is completely automatic.

The soil moisture data can be retrieved from the database using Node-RED. The data from the InfluxDB database can be returned in multiple formats. This project retrieves data from the database in JSON format.

While most of the writing to and querying of the database is automated using Node-RED, Postman may also be used to write and query the database. Postman is a Chrome app for interacting with HTTP APIs such as InfluxDB. All database queries and continuous queries were tried and tested in Postman before used in Node-RED.

3.4 Readings from the Clegg Hammer

As well as continuous collection of soil moisture data from the sensor, the information pertaining to the hardness of the ground is also collected. The Clegg Impact Soil Tester, CIST, or Clegg Hammer is a widely used device to measure impact or hardness to the ground.

Figure 33: CIST Display

The CIST displays results on a digital readout immediately after a hardness reading is conducted. The Clegg Impact Value (CIV) is stored automatically to the CIST. These reading can be accessed via a wireless Bluetooth download of the CIST to a laptop or via an application on an android device. The download is in comma separated values (csv).

The CIVs can also be written to the InfluxDB database via a hypertext markup language (html) page, as shown below.

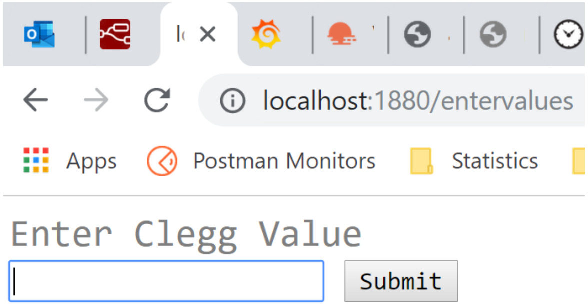


Figure 34: CIST HTML Input page

This html page can be generated from Node-RED and also has some processing hidden behind it. The code in the Node-RED flow, for processing and html displays are outlined in the Appendix *8.1.2 Clegg Hammer Flow*.

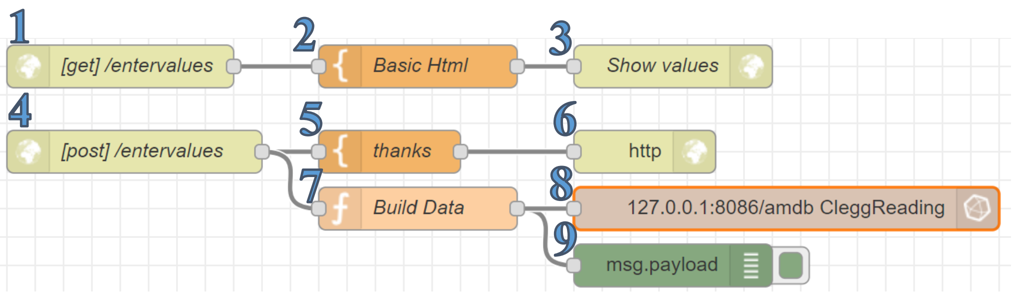


Figure 35: Node-RED flow to capture Clegg Values

For any html page to be generated from Node-RED, html request (1, 4) and html response (3, 6) nodes are required. The GET request (1), along with the uniform resource locator (URL) /entervalues specifies where the html screen will appear. The function node (2) constructs the page and the html request node (3) delivers the page.

The html request [post] /entervalues (4) is called from the submit button on the previous /entervalues page (the html page constructed in (2)). The POST request takes the Clegg values that are entered and completes two tasks.

Firstly, it constructs a simple html screen (5) to tell the user that the information has been captured and display this to the user (6). Secondly, the information captured is formed into a JSON object (7) and written to the database (8).

Figure 36: Clegg Reading JSON object

The debug node (9) shows what the JSON object looks like in Node-RED, as displayed in *Figure 36: Clegg Reading JSON object* above.

3.5 Met Éireann Weather Data

Met Éireann is the meteorological service of Ireland and part of the government Department of Housing, Planning, Community and Local Government. It provides weather services to the public and private organisations throughout Ireland. Met Éireann collects meteorological data from weather stations around the country. The categories of data available from each station can vary slightly depending on the scale of the resource available.

Fairyhouse racecourse is in the process of installing their own weather station (Roe, 2018). Currently they triangulate their weather information from the three Met Éireann weather stations closest to them: Dunsany, Co. Meath, Dublin Airport and Phoenix Park – both in Co. Dublin.

Met Éireann publishes weather data to the national open data portal (Department of Public Expenditure and Reform, 2019) as the data becomes available. The data is only available for the current day. After midnight, the dataset is archived and not released again until the end of the calendar month. The archive data can be downloaded in csv format from the Met Éireann website (www.met.ie).

```
[{"name":"Phoenix Park","temperature":"15","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 89 ","rainfall":" 0.0 ","pressure":"1019","dayName":"Saturday","date":"03-08-
2019","reportTime":"00:00"},{"name":"Phoenix Park","temperature":"15","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 92 ","rainfall":" 0.0 ","pressure":"1019","dayName":"Saturday","date":"03-08-
2019","reportTime":"01:00"},{"name":"Phoenix Park","temperature":"15","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 89 ","rainfall":" 0.0 ","pressure":"1018","dayName":"Saturday","date":"03-08-
2019","reportTime":"02:00"},{"name":"Phoenix Park","temperature":"15","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 90 ","rainfall":" 0.0 ","pressure":"1018","dayName":"Saturday","date":"03-08-
2019","reportTime":"03:00"},{"name":"Phoenix Park","temperature":"15","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 91 ","rainfall":" 0.0 ","pressure":"1018","dayName":"Saturday","date":"03-08-
2019","reportTime":"04:00"},{"name":"Phoenix Park","temperature":"16","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 88 ","rainfall":" 0.0 ","pressure":"1018","dayName":"Saturday","date":"03-08-
2019","reportTime":"05:00"},{"name":"Phoenix Park","temperature":"16","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 86 ","rainfall":" 0.0 ","pressure":"1017","dayName":"Saturday","date":"03-08-
2019","reportTime":"06:00"},{"name":"Phoenix Park","temperature":"16","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 87 ","rainfall":" 0.0 ","pressure":"1017","dayName":"Saturday","date":"03-08-
2019","reportTime":"07:00"},{"name":"Phoenix Park","temperature":"17","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 87 ","rainfall":" 0.0 ","pressure":"1017","dayName":"Saturday","date":"03-08-
2019","reportTime":"08:00"},{"name":"Phoenix Park","temperature":"18","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
","cardinalWindDirection":"-99","windDirection":0,"humidity":" 80 ","rainfall":" 0.0 ","pressure":"1017","dayName":"Saturday","date":"03-08-
2019","reportTime":"09:00"},{"name":"Phoenix Park","temperature":"18","symbol":"","weatherDescription":"N\/A","text":"","windSpeed":"NA","windGust":"-
```


Figure 37: Sample weather data from the Met Éireann API

The closest Met Éireann weather station to the project sensor is Phoenix Park, Co. Dublin. This weather station is approximately 10.5 kilometres from the sensor location, so the weather data collected may not be completely accurate. *Figure 37: Sample weather data from the Met Éireann API* above, displays the output from the https://prodapi.metweb.ie/observations/phoenix-park/today API link which is accurate for its location in the Phoenix Park in Dublin.

A Node-RED flow is used to collect the data from Met Éireann, as shown in *Figure 38: Node-RED flow to capture Weather data from the Phoenix Park*. An hourly request (1) from an inject node is sent to the API (3) via a http request. The delay node (2), set to 15 minutes, is to ensure that the weather station has updated with data from the previous hour.

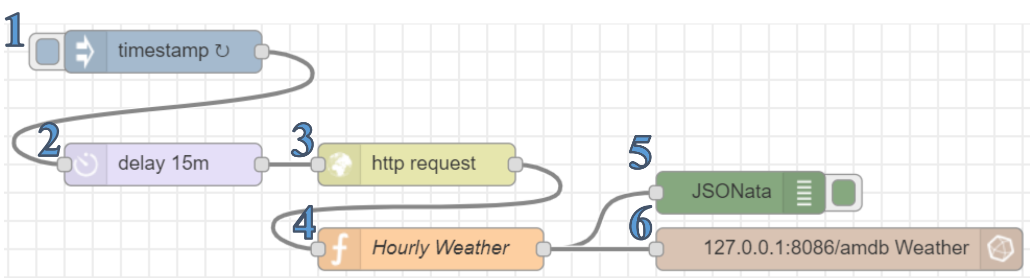


Figure 38: Node-RED flow to capture Weather data from the Phoenix Park

The http request node (3) will capture all the data on the API and put it into an array of the hourly updates. Using a function node (4), the final entry in the array is extracted from the array and put into an JSON object on its own. This information published from the weather station hourly can be seen in this object using a debug node (5). The object structure is already in a JSON format for the database. An InfluxDB output node (6) writes the data to the Weather measurement in the database.

Figure 38: Node-RED flow to capture Weather data from the Phoenix Park shows the details of the JSON object extracted from the Met Éireann API. On entry to the database, an entry time timestamp is assigned to the data record. Currently, this project utilises the rainfall attribute only.


```
▾object
  name: "Phoenix Park"
  temperature: "19"
  symbol: ""
  weatherDescription: "N/A"
  text: ""
  windSpeed: "NA"
  windGust: "-"
  cardinalWindDirection: "-99"
  windDirection: 0
  humidity: " 74 "
  rainfall: " 0.0 "
  pressure: "1014"
  dayName: "Saturday"
  date: "03-08-2019"
  reportTime: "19:00"
```


Figure 39: Example of hourly weather data from Phoenix Park

3.6 Evapotranspiration & Drainage

The two other key pieces of data required for *Equation 3: Soil Saturation Calculation* are actual evapotranspiration, ETa, and drainage.

3.6.1 Evapotranspiration

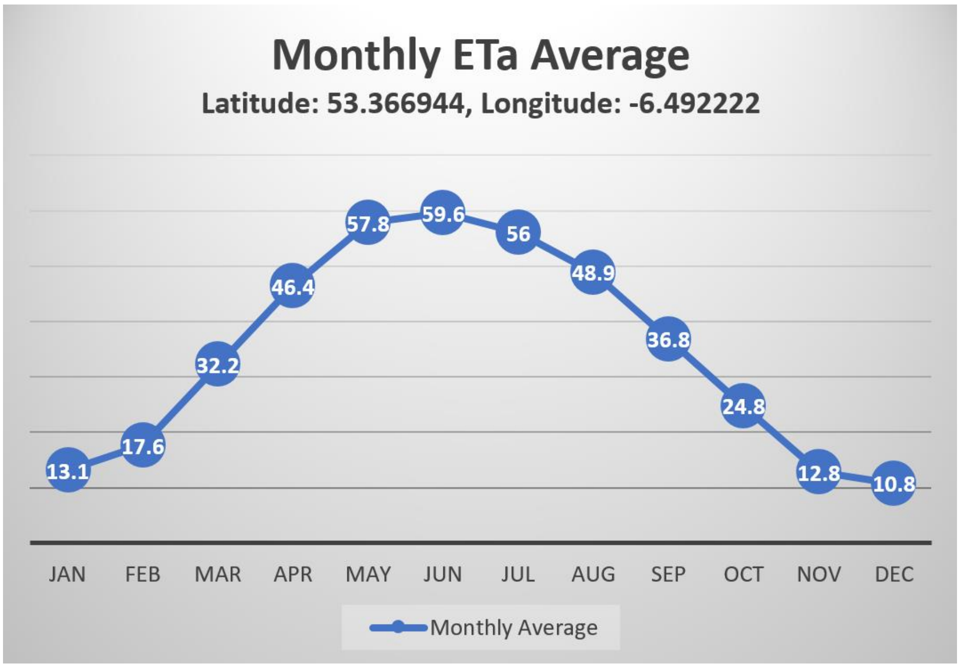


Figure 40: Monthly ETa values for a specified latitude and longitude

The ETa values for specific areas were extracted from Panoply and added to the database in the measurement ETa.

3.6.2 Drainage

In accordance with drainage values used by Met Éireann for soil deficiency calculations, the soil was classified into three categories:

- Well drained soil - value not applicable
- Moderately drained soil – 10mm/day
- Poorly drained soil – 0.5mm/day

Each of these categories have a predefined value for the drainage (Schulte et. al., 2005), in accordance with the values used by Met Éireann.

These values are kept in the database in the measurement Drainage. A more accurate values can be deciphered per sensor from the data obtained from the soil moisture sensor, as described in *4.7 Drainage*.

3.7 Weather Forecast Data

Any estimate of the ground conditions is heavily predicated on the amount of rain/irrigation applied to the ground. In order to estimate the hardness of the soil, some indication of the volume or quantity of precipitation is required. Open Weather (Open Weather, 2019) has an open API for weather forecasts in local areas. Access codes for specific locations are available from the site. Weather forecast information for the next five days is available on this site. The data is updated every three hours.

A Node-RED flow is used to extract this data.

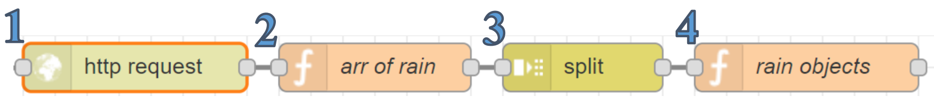


Figure 41: Node-RED flow to capture Weather Forecasts from OpenWeather.org

A http request is made every three hours to the OpenWeather.org API (1) at http://api.openweathermap.org/data/2.5/. The http request retrieves an array of 120 elements indicating various aspects of the weather forecast for five days hence, in three-hourly intervals. The rainfall is the only data that is required for this analysis, therefore, only the rain and forecast time is captured (2) in this flow. Steps 3 and 4 filter and clean the data retrieved, that is, replacing nulls with zeros and handling JSON attributes that start with a numeric value.

Later in the calculations, the arrays are collated into 3-hour, 24-hour and 5-day bundles to estimate the rain and ground conditions. The rainfall forecast every three hours are kept for analysis of the variation between it and the actual rainfall at the Phoenix Park weather station. Any discrepancy between actual rainfall and forecasted rainfall will lead to discrepancies in the soil saturation forecast calculations.

3.8 Regression

Much like the data retrieved from *Figure 7: The Relationship between Soil Moisture Content and Clegg Hardness Values during 2009 Study (Windows & Bechelet, 2010),* it was important to plot the correlation of soil saturation values against daily Clegg values.

There is a variance in the Clegg hammer reading taken across a small section of land. Clegg (1976), Vlcek and Valaskova (2018), Caple (2011) and others, all advocate multiple Clegg hammer drops. The average of these drops was taken to produce a daily result.

Using Excel, regression testing was performed on the data coming from the soil moisture sensor and the daily Clegg hammer values. *Figure 42: Correlation between Surface Hardness and Soil Saturation levels* below is the correlation of 88 data points collected during the data gathering.

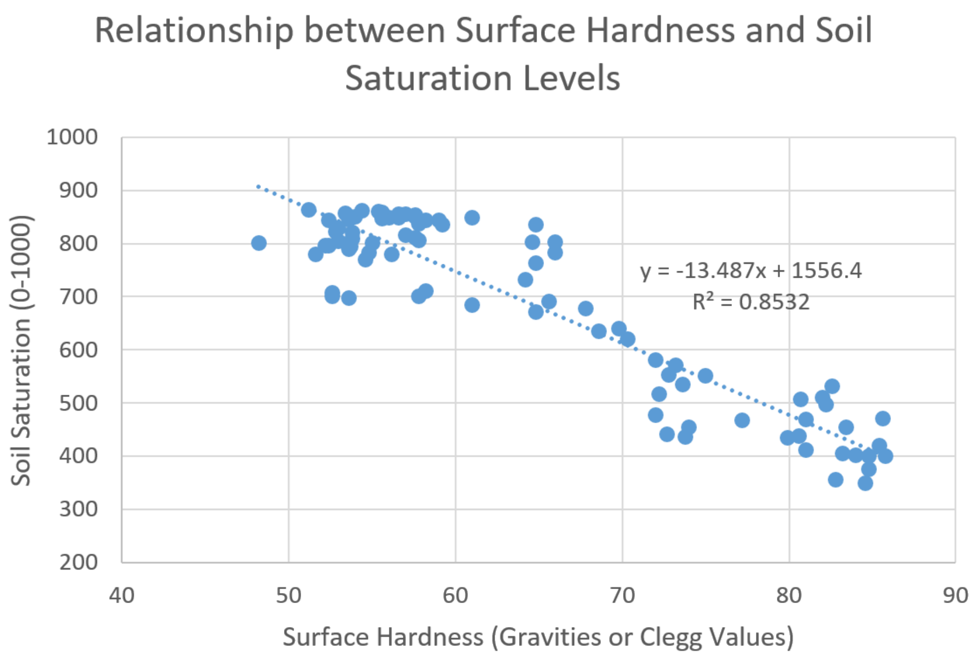


Figure 42: Correlation between Surface Hardness and Soil Saturation levels

While other polynomial regressions were explored, linear regression consistently gave the highest correlation coefficient. Analysis for the data showed that datasets with less than 45 data points gave a correlation index of 0.60. With the moving dataset of 55 data points the correlation index was always above 0.80. A moving dataset was used to allow for any deterioration or flux in the soil sensor.

Owing to the fluid nature of the data being captured, the results set was also ever-changing. Node-RED was used to capture how the results changed. A flow was created in Node-RED to calculate a daily linear regression estimate and this data was saved to the database for further analysis.

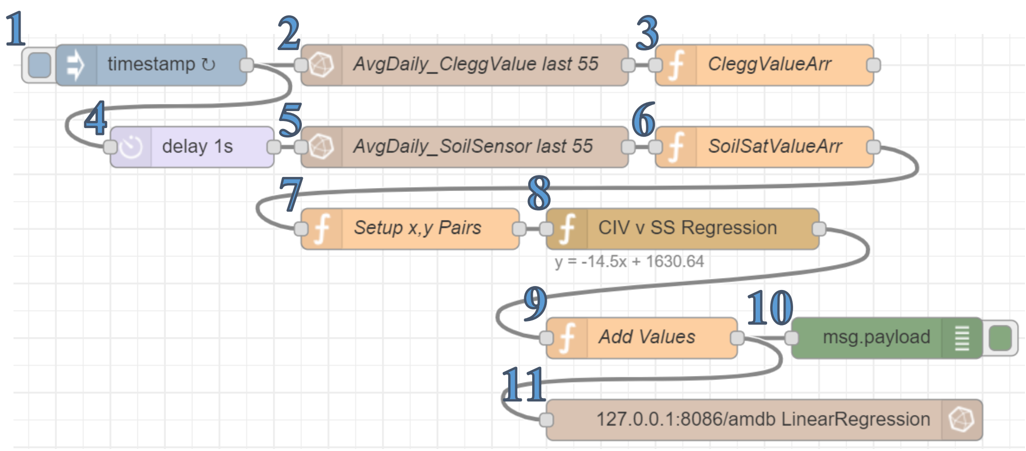


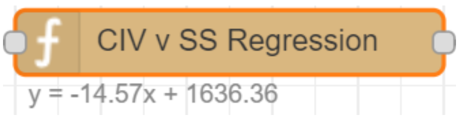
Figure 43: Node-RED flow to calculate daily Linear Regression

The timestamp (1) is set to run immediately after midnight, every night. The Clegg values are gathered daily and averaged. As a result, the linear regression only needs to be calculated daily. The input InfluxDB node allows Node-RED to query the database on the AvgDaily_CleggValue (2) measurement for the last 55 records. The SELECT statement below specifies the number of records to be returned and that they are ordered to be the most recent records.

```
SELECT CleggValue FROM AvgDaily_CleggValue ORDER BY time
DESC LIMIT 55
```

A function node (3) then places the data returned from the database into an array of all the Clegg Values. The second array (6) is an array of 55 data points of the average daily soil moisture values (5). A short delay (4) is put in place so that step 7 is completed after both arrays (3,6) are created. Step 7 takes both of these arrays and pairs the Clegg value with the soil saturation value for each day in the dataset. This (x,y) array format is required for the Node-RED linear regression node.

The regression node was imported from npm (Node Package Manager) as an add-on to Node-RED. The node (8) was configured to take the array of 55 Clegg values and soil saturation values and output the linear regression results.



Every time the flow is run, the line equation output displays under the node.

Figure 44: Node-RED Regression node and its output

The results of the regression node (8) are formatted into a JSON object (9) and written to the database (11). Step 10 is a debug node to watch the results of the regression node in Node-RED.

3.9 Estimating Soil Saturation and Ground Hardness

Once the forecasted rainfall is obtained, all the elements of the prediction equation, *Equation 3: Soil Saturation Calculation* are in place. All these variables are required to estimate how the soil saturation levels and the soil hardness will behave in set periods.

For this project the forecasting periods were selected as 3 hour, 24 hour and 5 day forecasts. When irrigation is applies in Gowran Park, the ground is left for three hours before the going is re-tested (Scally, 2018).

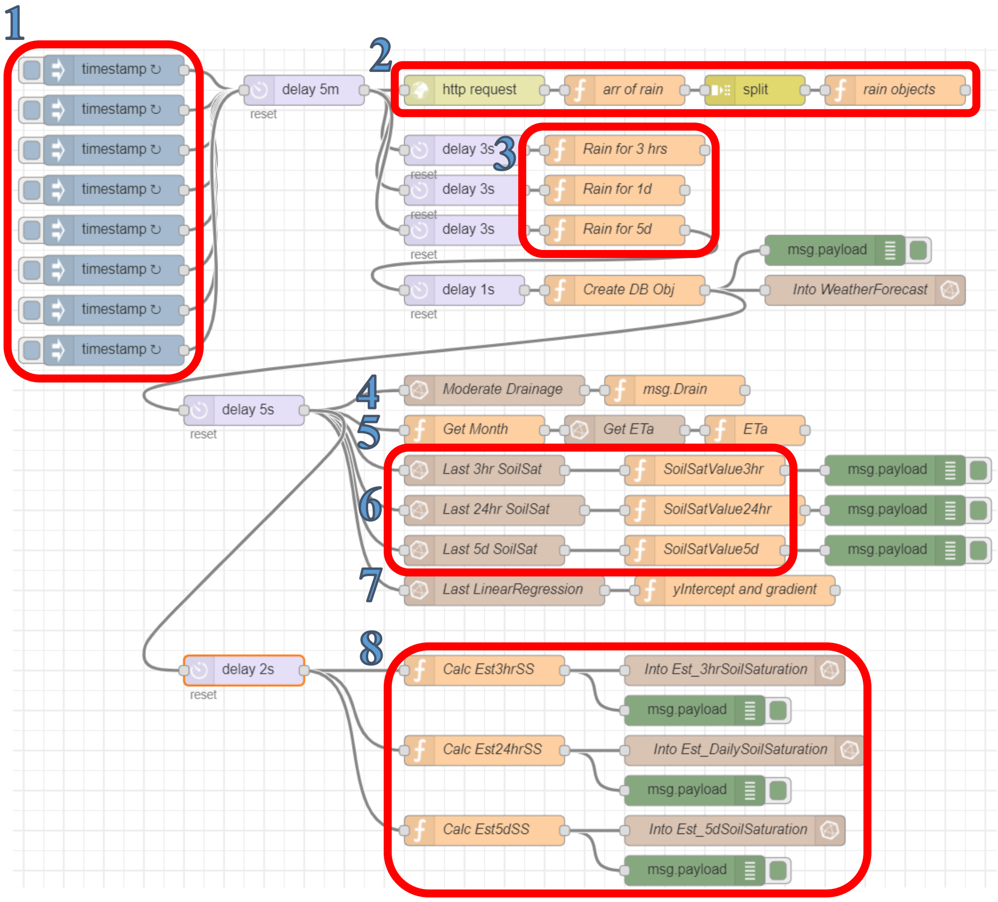


Figure 45: Node-RED flow to Calculate Estimate Soil Moisture Saturation and Soil Hardness

The calculations are conducted every three hours. A bank of timestamps (1) are set at three hour intervals and they run every day. As explained in *3.7 Weather Forecast Data* the weather forecast is sought (2). The quantity of rainfall is totalled into 3-hour, 24-hour and 5-day bundles (3). This information is collated and stored in the database. The information for Drainage (4) and the current month's actual evapotranspiration (5) are retrieved from the database.

As the weather forecast data estimates the rainfall to come, the *Equation 3: Soil Saturation Calculation* requires the soil saturation figure for the last 3 hours, last 24 hours and last 5 days. The flow queries the Avg_SoilSat measurement (6) and assigns these soil saturation values in the flow as a variable for the calculation. The final variables required are the latest linear regression coefficients (7). The linear regression variables are used to calculate the ground hardness after the soil saturation numbers are estimated.

Once all of the *Equation 3: Soil Saturation Calculation* variables are declared within this flow, the calculation for the predicted soil saturations are executed. The *Equation 3: Soil Saturation Calculation* equation is executed three times - once for each of the time intervals (8). The Clegg value for the estimated soil saturation is also calculated. The predicted time associated with the estimation is assigned to the calculations. This is important, as the estimated soil saturation and Clegg value can be submitted to the database at the time that they are predicted for. Analysis can be performed in the database to test how good the estimates are.

3.10 Irrigation

The Node-Red flow for Irrigation is very similar to the estimation soil saturation flow outline in section *3.9 Estimating Soil Saturation and Ground Hardness*. However, for irrigation the calculation is set to three hours and is not committed to the database. The details of the irrigation flow are shown in *8.1.6 Irrigation Flow* in the Appendix.

3.11 Calculating the Drainage per Sensor

Met Éireann issues Soil Moisture Deficits based on three different drainage types, as discussed in *3.6.2 Drainage*. However, analysis of soil moisture data when there is no rain produces a coefficient for the drainage. Plotting the rainfall and the soil moisture over time shows a clear overlap of the two variables.

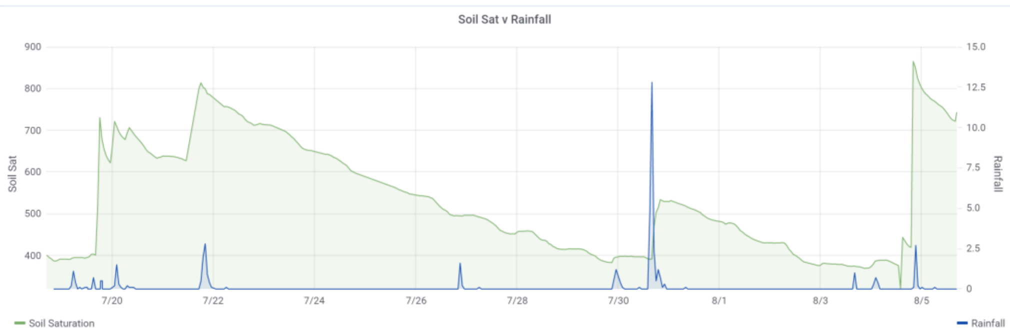


Figure 46: Rain & Soil Moisture over Time

The rainfall and the soil saturation occur at the similar times. The soil saturation increases very soon after the rain starts. The soil starts to dry as soon as the rain stops. From *Figure 46: Rain & Soil Moisture over Time*, the rate of drying appears to be similar after each occasion of rain. This suggests that a model may follow a pattern of

Equation 7: Drying pattern associated with a soil moisture sensor

$$SoilSaturation = Time * Constant + RainVolume$$

Where Time * Constant represents the regular rate of drying, and RainVolume is a moving average of rainfall.

By moving this Soil Saturation and rain data into Microsoft Excel, a potential coefficient for the drainage can be calculated.

3.12 Grafana

Grafana was used to visualise some of the results of this project. Grafana is an open source, free tool to visualise metrics. Grafana was installed in a container on the Azure virtual machine. With the PuTTY connection from any computer to the virtual machine, Grafana may be used from any browser. While Grafana and InfluxDB are installed on the same virtual machine, Grafana still needs to be configured to point to the InfluxDB database.

4 Results & Analysis

As a result of this project, a lot of data was gathered in the InfluxDB database. Grafana was an excellent resource to visualise some of this data. Grafana can display real-time data input over a time series.

All graphs that are shown in this chapter are repeated on a larger scale in *9.2 Grafana Output Visualisations* in *Appendix* B.

4.1 Soil Moisture Levels and Rainfall

It is easy to assume that soil moisture levels are closely bound to the rainfall. The behaviour of the soil moisture levels is dependent on the quantity and frequency of the rainfall. *Figure 47: Soil Moisture Levels and Rainfall over Time* below gives a graphical output of this relationship.

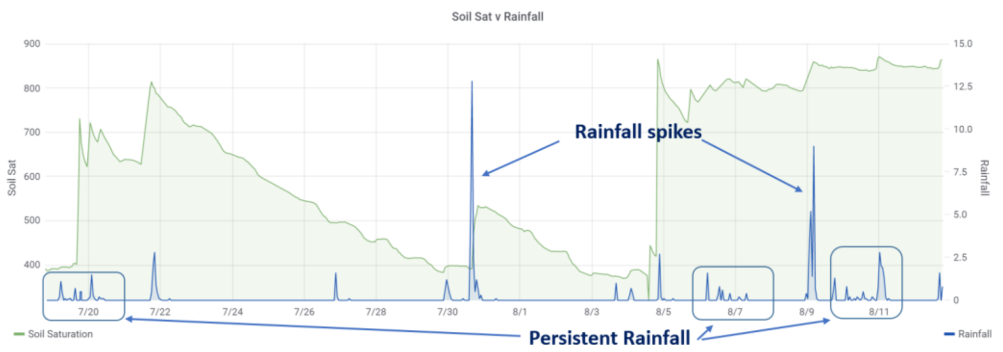


Figure 47: Soil Moisture Levels and Rainfall over Time

While the database is collecting data of actual rainfall recorded at a nearby weather station, weather forecast data is also being collected for use in forecast estimates for soil saturation and ground hardness. The forecasted weather data is assigned to its appropriate forecasted time in the database. This ensures that the actual rainfall and the forecasted rainfall are compared at their appropriate times.

There are discrepancies between the actual rainfall and the forecasted rainfall as seen in *Figure 48: Rainfall variations between actual and forecasted*.

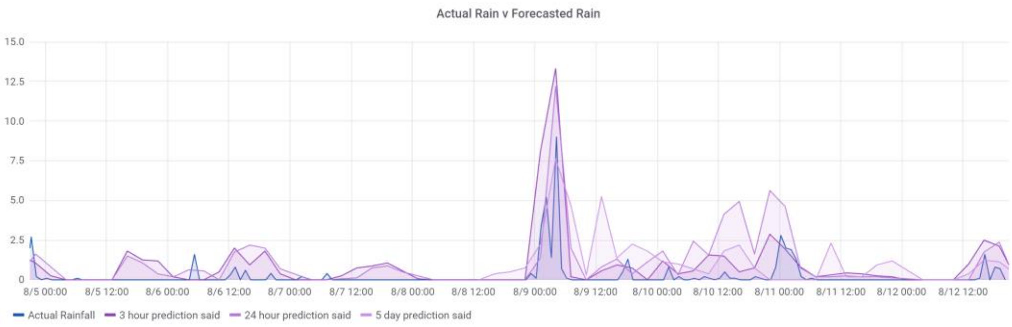


Figure 48: Rainfall variations between actual and forecasted

These discrepancies have a large bearing on the accuracy of the soil saturation and Clegg impact value estimates.

4.2 Soil Moisture Levels and Ground Hardness

The Clegg Impact values were taken on a daily basis. These values were averaged, as the values can vary slightly depending on the roughness of the ground. Generally, five tests were taken and then averaged for an average daily Clegg value.

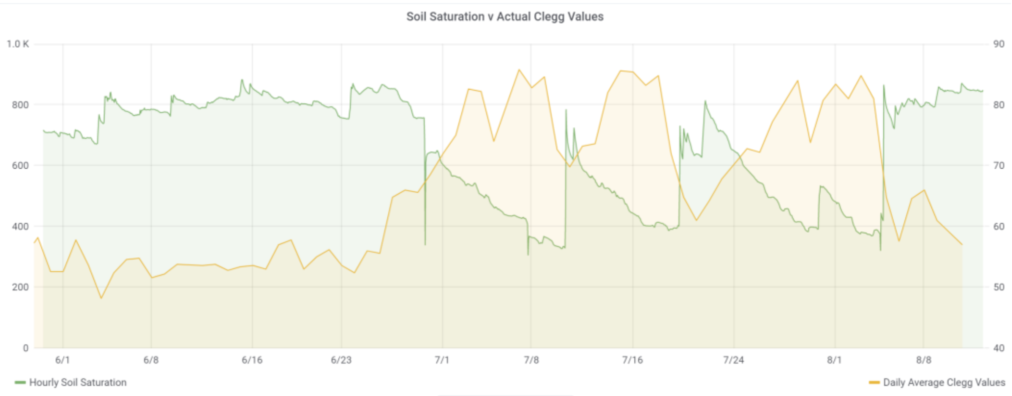


Figure 49: Soil Moisture levels v Clegg Impact values over Time

Note 1: There are two vertical axes in use with different scales. Note 2: The green Hourly Soil Saturation is displaying hourly data, whereas the yellow Daily Average Clegg Values is displaying daily data. The different time periods explain why the yellow line is less jagged than the green.

On visual inspection there is a negative correlation between the soil moisture levels and the hardness of the ground, that is, when soil moisture levels were high, Clegg impact values were low; and conversely when soil moisture levels were low, Clegg impact values were high. This visually shows that when the ground is wet it gets softer, and as the ground dries, it gets harder.

In *Figure 7: The Relationship between Soil Moisture Content and Clegg Hardness Values during 2009 Study (Windows & Bechelet, 2010)* there was a clear linear relationship between volumetric water content and soil hardness. The data that was gathered reaffirms this.

If the Clegg impact values (CIV) are averaged daily, the corresponding soil moisture values were also averaged over the course of 24 hours to equalise the time delimiter between the data. *Figure 42: Correlation between Surface Hardness and Soil Saturation levels* was based on 88 data points and gave a correlation coefficient (r^2) of 0.8532. The relationship that Windows and Bechelet observed is confirmed by this data.

As discussed in *3.8 Regression*, datasets with less than 45 data points gave a correlation index of less than 0.60. With the moving dataset of 55 data points the correlation index was always above 0.80. Since the correlation coefficient has been captured in the databasse, it has remained above 0.80.

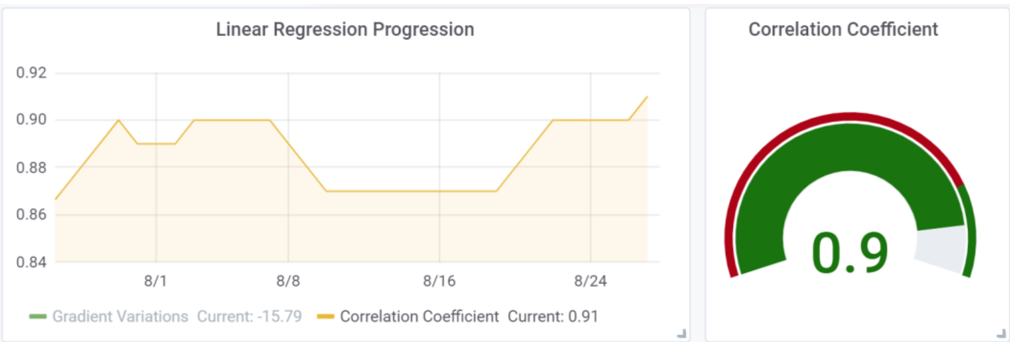


Figure 50: Correlation Coefficient of Linear Regression over Time and Current

The nature of the change in linear regression is being captured in the database. This could be used for future analysis to show how the relationship between the soil saturation and Clegg values are changing.

4.3 Applying Regression Results

Owing to the clear and consistent correlation between the soil moisture levels and Clegg impact values, an hourly estimated Clegg impact value can be calculated from the soil saturation.

The soil saturation values plotted against the Clegg impact values, as seen in *Figure 42: Correlation between Surface Hardness and Soil Saturation levels* produced the formula:

Equation 8: Linear regression between Soil Saturation and Clegg values

$$y = -13.487x + 1556.4$$

In terms of the variables that are being used, that is

Equation 9: Linear regression of Soil Saturation and Clegg impact variable

$$Soil\ Saturation = -13.487Clegg + 1556.4$$

These values were calculated initially and then the values for linear regression are being reassessed daily. The confidence of the correlation is measured in the correlation coefficient, r^2, and displayed in *Figure 50: Correlation Coefficient of Linear Regression over Time and Current*. This shows the variation in the correlation over time and the current correlation coefficient, r^2.

With this (ever changing) formula, an hourly estimate for the Clegg impact value can be calculated. This hourly estimate is then compared to the daily average Clegg impact values, and plotted in *Figure 51: Actual Daily Clegg Impact values plotted against estimated Clegg Impact values*.

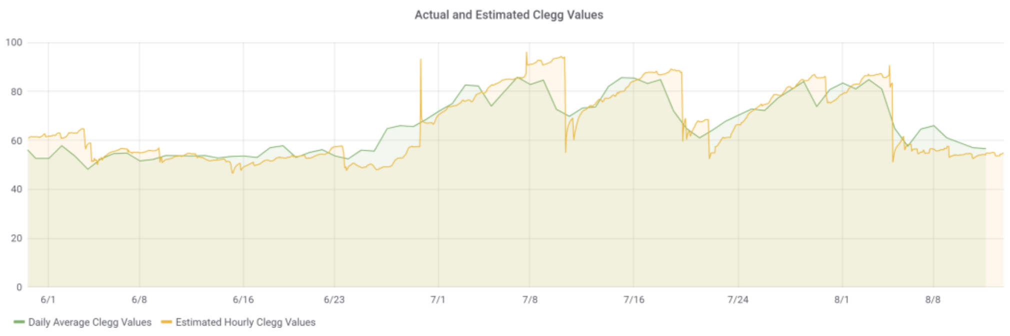


Figure 51: Actual Daily Clegg Impact values plotted against estimated Clegg Impact values

The results shadow each other very closely. The hourly results are more jagged owing to the increased frequency of the data.

4.4 Soil Saturation Prediction

With the weather forecast from Open Weather and the actual and historic data on soil saturation, soil saturation can be modelled with the forecasting equation.

Recalling *Equation 3: Soil Saturation Calculation*

$$SS_t = SS_{t-1} + Rain - ET_a - Drain$$

Calculations are made for 3-hour, 24-hour and 5-day periods on a three-hourly cycle.

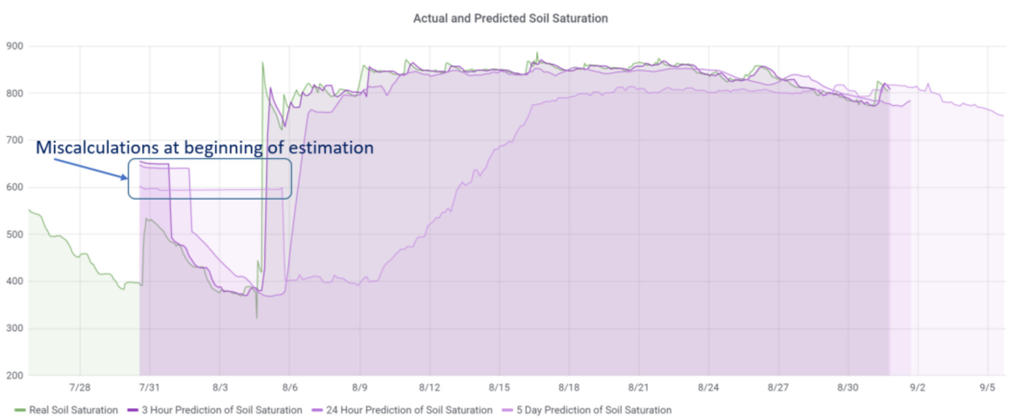


Figure 52: 3-hour, 24-hour and 5-day Estimates and Actual Soil Saturation

The 3-hour and 24-hour perform well on the estimates, but the 5-day estimate has a longer ramp-up time. The biggest variation in these estimates is the forecasted rainfall.

From *Figure 48: Rainfall variations between actual and forecasted*, the variation in the 5 day rainfall forecast is the main reason for the forecast estimates being less accurate.

4.5 Clegg Value Prediction

The accuracy or otherwise of the soil saturation prediction has a direct bearing on the Clegg Value predictions. The calculations for the soil saturation are already done for 3-hour, 24-hour and 5-day and this data is then converted in to Clegg values using the latest linear regression coefficients.

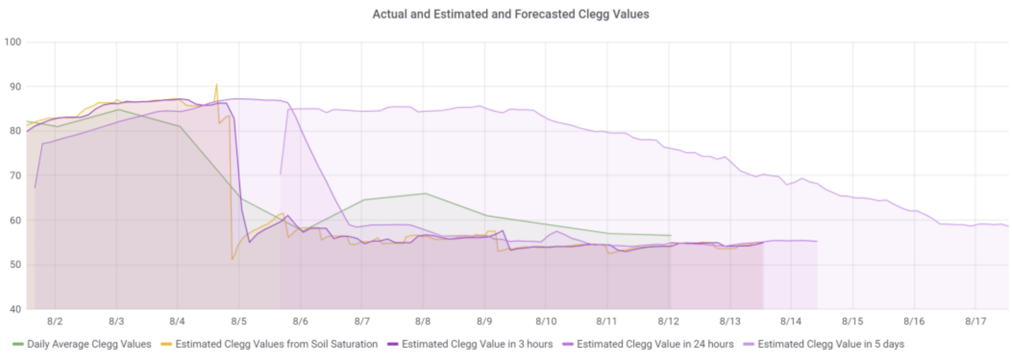


Figure 53: 3-hour, 24-hour and 5-day Forecasts and Actual Clegg Values

4.6 Irrigation

The irrigation prediction operates similarly to the 3-hour prediction of rainfall. Given that the estimate of the water applied in irrigation is probably more accurate than the rainfall expected over the three-hour period, the results are likely to be quite accurate.

Irrigation Analysis

With irrigation of *3mm*, the following is the estimated change in soil hardness at *Fri Aug 30 2019 17:35:28 GMT+0000 (UTC)*

	Current	**Estimated**
Saturation	783.2333333333332	784.7861559139784
Clegg	60.08500417710945	59.98770952919935
Going	Yielding / 4.223765000000002	Yielding / 4.19791050403226

Click here to enter another value

Figure 54: Irrigation Analysis screenshot

The screen shots and the Node-RED flow that is used for irrigation is outlined in *8.1.6 Irrigation Flow*. This data is not currently committed to the database; it is only for the purposes of estimation.

4.7 Drainage

Referring back to *3.11 Calculating the Drainage per Sensor*, the behaviour of the soil drying (draining) when there is no additional precipitation is quite consistent. Met Éireann use constant values (discussed in *3.6.2 Drainage)* to denote the three different drainage types – well-, moderately- and poorly-drained soil. The values from the soil sensor for any given location can produce an area specific drainage coefficient.

Rainfall and the soil saturation spikes occur at the similar times. The soil starts to dry as soon as the rain stops. Inbetween rain events, soil dries in a uniform fashion that was categorised as

$$SoilSaturation = Time * Constant + RainVolume$$

in *Equation 7: Drying pattern associated with a soil moisture sensor*. Analysing the time period between rain events removes the y-intercept or RainVolume in the equation.

Taking two time periods with no rain events and plotting the soil saturation over time, the following graphs were obtained. For both graphs the y-axis is the Soil Moisture values from the soil sensor and the x-axis is time, delimited in hours.

This first plot *Figure 55: Soil Saturation over Time with no Rainfall*, has 111 data points, one hour apart, and the linear regression gives a correlation coefficient 0.9807.

The second spell of no rain events, plotted in *Figure 56: Second plot of Soil Saturation over Time with no Rainfall* has 55 data points and correlation coefficient 0.9734.

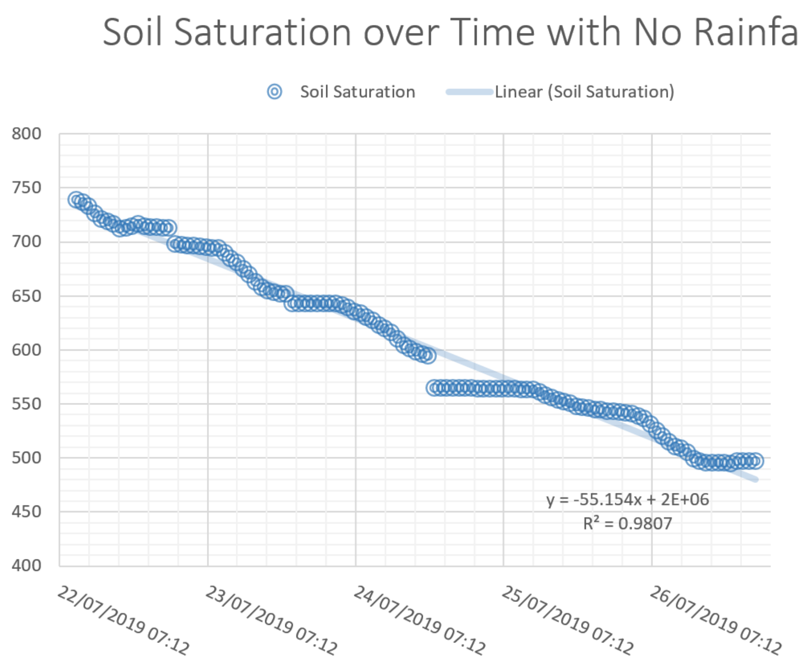


Figure 55: Soil Saturation over Time with no Rainfall

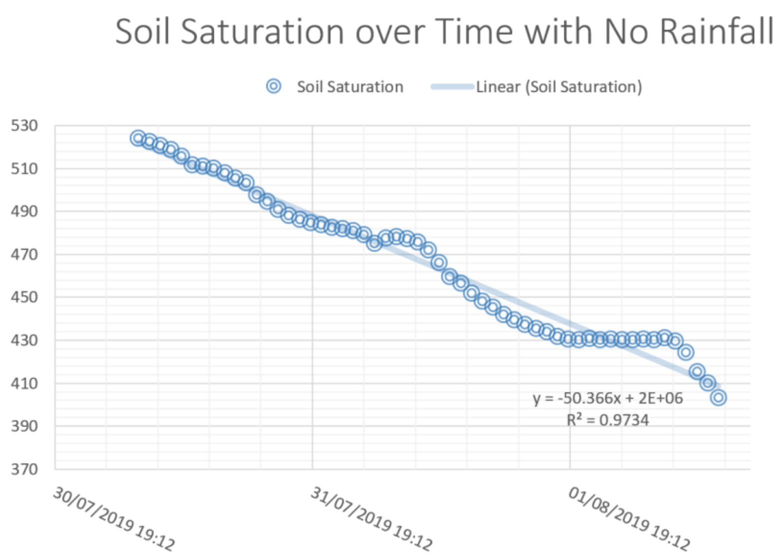


Figure 56: Second plot of Soil Saturation over Time with no Rainfall

The slope of the line corresponds to the coefficient for the drainage for that sensor location. Even though the slope of the two lines are not the same, an estimate of -50.366

to -55.154 is closer to an actual value for drainage for the ground surrounding the sensor that the generic bands used to denote three general categories.

4.8 The Going

Grafana captures real-time data and converts it to an easy to read graphical interpretation. A going number (ranging from 0-15) can be calculated from the current soil saturation value and the *Equation 5: Going Calculation based on Soil Moisture*. This number can then be given a literal meaning from the *Table 3: Categories of the Going and their corresponding TrufTrax going index (Dufour & Mumford, 2008).*

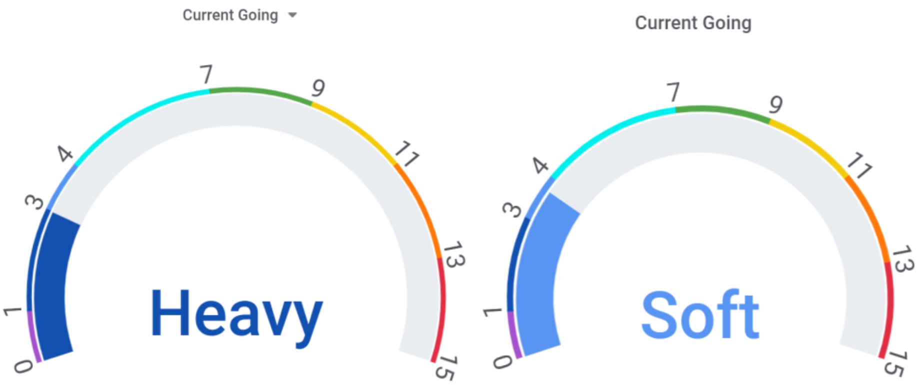


Figure 57: Examples of the Current Going displayed from Grafana

This process can be repeated for the 3-hour, 24-hour and 5 day projections and displayed in Grafana.

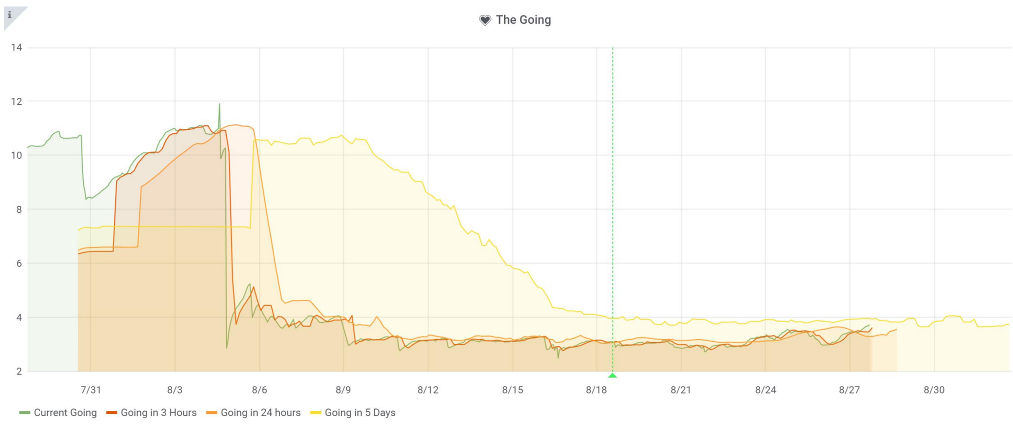


Figure 58: Current and Predicted Going

5 Discussion

Predicting the hardness of a turf surface from a soil moisture sensor has been shown to be possible. The methods that were deployed were good but could be improved and there was also some nuances in the data.

5.1 Data Collection

5.1.1 Data Collection Management

MQTT and Node-RED worked exceptionally well as the data collectors and processors.

MQTT is a light-weight messaging protocol that works very well in this project. MQTT also works very well for scalability. Multiple sensors can publish to one topic for a specific location e.g. Fairyhouse racecourse, but also be part of a bigger topic e.g. all HRI racecourses.

Node-RED processed the data in terms of scheduling, subscribing to MQTT topics, calculating and writing to the database. Node-RED easily interacted between different applications with ease. It was an excellent tool for this project.

The data was collected from primary and secondary data sources and in different formats. The common thread in all the data is the attributed timestamps. The fusion of data from the different data sources lends itself to a large volume of easy-to-read data.

The weather and the weather forecast data would not vary across a racecourse. However, data collection from a Clegg hammer may have to include an algorithm to attribute data to the closest sensor. Something along the lines of the nearest neighbour would attribute Clegg values to specific sensors.

5.1.2 Data Frequency

The primary source data came from two sources:

- The SoilWatch 10 soil moisture sensor from Pino-Tech. The data range was originally tested for accuracy and the sensor behaved as expected. The soil sensor delivered readings every minute over a period of over 100 days – that is in excess of 144,000 readings.
- The Clegg hammer which constituted of five readings daily and average for one daily mean Clegg value.

While the soil sensor was gathering 1,440 readings daily, the Clegg hammer had only one mean value daily. However, the Clegg readings were taken to calibrate the soil sensor against an industry standard. This data is considered to be low-frequency accurate data that should not be distilled into hourly delimiters.

The secondary data sources were mined from open APIs, they were:

- Actual weather from the closest weather station in the Phoenix Park, with thanks to Met Éireann open source data. This data was retrieved by Node-RED hourly.
- Forecasted weather data was retrieved from OpenWeather. This data was retrieved 3-hourly and gave forecasted weather for the next 3 hours, 24 hours and 5 days.

These four data sources were stored to the time series database, InfluxDB and visualised graphically using Grafana.

5.1.3 Data Transmission

The data transmission via WI-FI was over-compensation for the quantity of data that was been sent and impractical in a real racecourse. In this project, the microcontroller was programmed to publish raw soil moisture value to the MQTT broker every minute. Initially, this was very beneficial, especially if the connectivity of the sensor needed to be tested to ensure that the data was updating every minute. However, as the project matured, a low powered wide-area network, LPWAN solution would have solved the problem with long range communication. In most sports locations, WI-FI does not extend onto the field of play, and especially around low populated area like a racecourse.

There are many LPWAN solutions available like LoRa and sigfox that would deliver less frequent data across a larger geography.

5.1.4 Hardware Portability

Multiple sensors would be required for sports grounds with undulations. This is less necessary with flat pitches; however different areas of a pitch surface behave differently depending on the openness and shaded areas in the ground. It is far more beneficial to have battery-operated sensor rather mains-controlled.

5.1.5 Errors in Data Collection

All information collected in this project was used in the analysis, even when the data seemed incorrect. At three points in the project there was a sudden drop in soil saturation.

Sudden drops in the soil saturation is clearly visible on the display, but sometimes they are less obvious as seen in *Figure 59: Errors in Soil Moisture Data Collection* below.

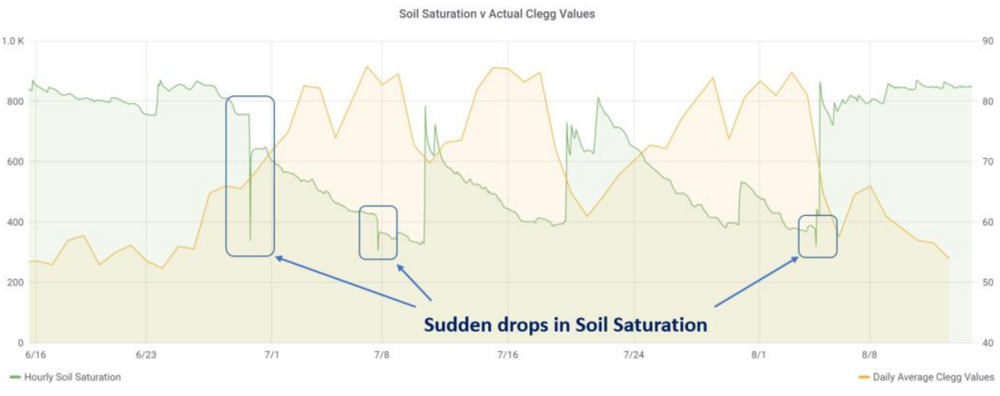


Figure 59: Errors in Soil Moisture Data Collection

These three events correspond with the soil sensor being withdrawn from the ground for the grass to be cut!

Sharp rises in the soil saturation coincide with large intense downpours of rainfall.

5.2 Data Accuracy

The predictive formula in this project are heavily influenced by the accuracy of the variables used. The soil saturation data the Clegg impact values are primary data sources. The external secondary data sources are more problematic.

5.2.1 Met Éireann Weather Data

While weather data throughout a sports site will not have meaningful variations, distance of the soil sensors to the weather station is important. The GAA Centre of Excellence record their own weather data, whereas Fairyhouse racecourse triangulates data between three different sites (approximately 15, 20 and 22 kilometres away from Fairyhouse). The most accurate method of recording rainfall in a specific site is to gather weather data on-site.

This project used a weather station in the Phoenix Park for the actual rainfall data. The Phoenix Park is approximately 10.5 kilometres from the project sensor.

5.2.2 Open Weather Forecast

While trying to make predictions for the soil moisture levels and the soil hardness, the calculations are dependent on the weather predictions of another outlet. From *Figure 48: Rainfall variations between actual and forecasted*, the actual rainfall can vary considerably from the forecast.

Weather forecasts are calculated forecasts based on many parameters. Weather forecasts are generally more accurate for the near future and less accurate for longer range forecasts. These variations have a direct impact on the soil saturation estimation figures.

5.2.3 Drainage and ETa

Using the soil saturation to measure the drainage factor of the surface gave clear results. Specific computation of the drainage coefficient leads to greater accuracy in the calculations.

Using this simple method of data collection to measure the drainage could have a large impact on understanding environmental changes in the land. This information could have a significant impact in agriculture (crop production, irrigation, pest detection and control), forestry (i.e. forest fire predictors), civil engineering, flood forecasting and erosion projects.

Further work could also follow with the actual evapotranspiration data. There are multiple formulas available to calculate this. The MÉRA dataset to also a wealth of information. Ideally, integration between Node-RED and Panopoly would need to be investigated to gain accuracy for multiple locations.

5.3 Data Storage – InfluxDB

The InfluxDB database is collecting and storing the data retrieved from the soil sensor, the Clegg hammer and APIs for weather and forecasting and all other calculations. All of the commits to the database are performed via Node-RED.

Monitoring the data in the database is performs via multiple channels:

- Postman – allows for data reading and writing to the database, in a database administrator capacity, that is, using "expressive SQL-like query language" (InfluxDB, 2019).
- InfluxDB performs continuous queries on the database, similar to stored procedures in structured databases.
- Grafana – using structured query language, SQL statements on the database to present visual analysis on the database.

InfluxDB is an easy open-source time-based database. The datatype of measurement attributes is accessed and assigned on first creation of the attribute in a measurement. Measurements are easily expanded to include changes that are required.

5.4 Security and Scalability

5.4.1 Azure Virtual Machine

Using a virtual machine to manage all the applications that were used - MQTT, InfluxDB, Node-RED and Grafana - gave a level of abstraction to the data. These applications could operate on four different virtual machines if needed.

Grafana is the only application that the user needs or should be allowed to connect to. MQTT, InfluxDB and Node-RED should only be accessed by an administrator.

The usage on a virtual machine is easy to track and easy to scale if required. Docker containers containing the applications can be duplicated and moved to different machines.

5.4.2 MQTT

Sensors publishing to a MQTT broker can publish under a common topic. These topics can signify a geographical area, such as multiple sensors on a racecourse. Multiple topics can be grouped together under various headings, such as, provincial courses, jump versus flat courses or all HRI courses. This would be very beneficial for arranging alternative venues for cancelled meetings, or having a good overview of different courses.

5.4.3 Secure Shell Tunnels

Access to the virtual machine is managed from a secure shell (SSH) tunnel via PuTTY. This allows ports on the client machine to connect to ports on the virtual machines. Microsoft Azure also have security setting to allow only specific access controls and security to shut down the data from unknown users.

5.5 Ethics

The racecourse clerks declare the going leading up to and including the race day. On some rare occasions the going is reassessed during the race meeting. The owner and trainer sign up to specific races depending on the going. Some trainers walk the race course before a meeting to get their own judgement of the racetrack before a meeting. Jockeys ride specific areas of the course based on the going declarations. The safety of the jockey and horse are a consideration to the groundskeeper and the race clerk. Adjusting the irrigation plan to target a specific going for a race meeting has considerable benefits to trainers and jockeys.

The horseracing industry relies heavily on betting and ground conditions are an intricate part of honesty to the betting punter. The data being collected is real-time information on these ground conditions and would have a value to the betting public. Making this data available to the public has different implications than to the trainers and jockeys.

Some racecourse managers come under pressure from influential trainers to water their course so it suits particular horses – although this is a feature in most sports.

The decision to make this information public would be a consideration for the racecourses or the HRI. Making this data available to the jockeys and trainers would underpin that safety of the horses and jockeys, which is central to the horseracing industry.

5.6 Data Integrity

Data integrity refers to the accuracy and consistency of the data in the database.

IoT offers an advantage over manual readings through the timestamping of the data. The readings from the soil moisture sensor are immediately associated with a time. The

Clegg hammer readings do not require the same level of time integrity as they are a daily average used for calibrating.

Both the weather and the weather forecast data could be more precise. The weather data is accurate but the proximity to the weather station could be reduced, which would reduce errors. Similarly, the weather forecast could be specific to the weather station producing the weather data. Weather forecast data will always have a degree for variance associated with it.

GPS data on a sensor or Clegg hammer can accurately geographically pinpoint data. Algorithms such as nearest neighbour and k-nearest neighbour would work well to bundle Clegg values together especially for Clegg hammer readings and their association with a soil sensor. A commercial application of this project would need to investigate this further.

Once the soil moisture sensor is calibrated, the data response on the hardness of the soil is hourly. This is more frequent than alternate methods such as the GoingStick or a penetrometer. Soil saturation levels and their associated ground hardness data calculations are preformed automatically and remotely, therefore it does not require someone to walk the track every hour.

The accuracy of the soil sensor and the ESP8266 can also be monitored via the regression analysis. Deteriorations or sudden changes in the linear regression of between soil moisture sensor and Clegg values may indicate deterioration in the equipment used. Grafana is visually monitoring these changes and alarms can be placed on measurement to signal alerts to the consumer.

Alarms can alert the consumers to boundary conditions being trespassed. So a change in going could trigger an email to the consumer.

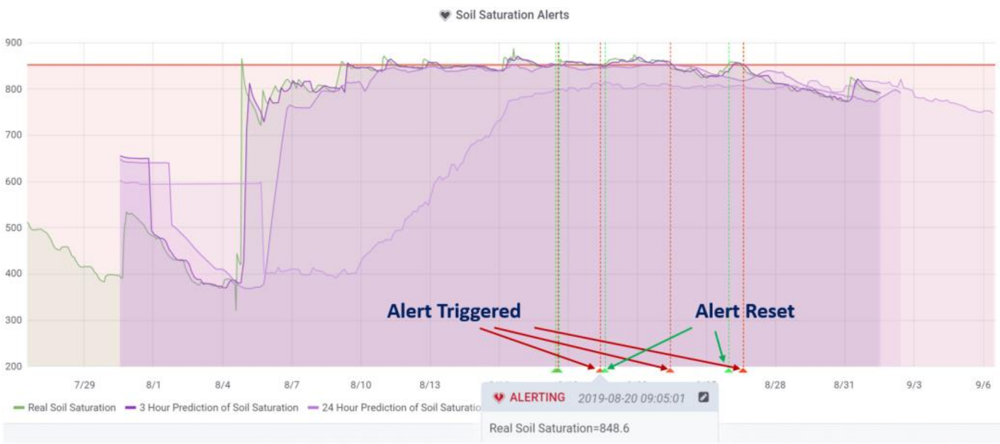


Figure 60: Visualisation of Alerts in Grafana

Grafana visualises these alerts in graphical format. Note that the alert in *Figure 60: Visualisation of Alerts in Grafana* is set to an arbitrary value only to show how alerts look. Soil saturation alerts would generally be set if irrigation was required, however the soil saturation values were high at the time of implementation.

6 Conclusion

This thesis has presented a system where the ground hardness can be predicted based on data that is collated from a number of different sources, mainly rainfall, drainage, evapotranspiration, irrigation and soil moisture data. This required primary and secondary data collection and storage. For evapotranspiration, further integration to the data source is required. For drainage, a more specific drainage coefficient was obtained from the data analysis.

6.1 Revisiting Hypothesis

The original hypothesis was framed as three questions.

1. Can a low-cost, high-frequency soil moisture IoT sensor be automatically calibrated by a high quality infrequent manual soil hardness instrument? And as a result, can the IoT sensor accurately determine the soil hardness?

The equipment used was inexpensive. The SoilWatch 10 costs approximately €20 to purchase. The ESP8266 can be bought for €4. The SoilWatch 10 doesn't normally output a scientific measurement/number, but when used in the proposed system the output is converted in the appropriate scientific quantity similar to an industry standard Clegg hammer. The Clegg hammer is used for measuring the ground firmness and retails for just over €2000 (Pitchcare, 2019).

The data from the IoT sensor was correlated with the Clegg hammer and produced a linear regression model with a consistent correlation coefficient of > 0.8.

The IoT soil moisture sensor produces high frequency data (every 60 seconds) in comparison to the low-frequency high accuracy daily Clegg data. With the elimination of the Clegg hammer as the calibration tool, the hardness of the soil is calculated hourly in Node-RED and displayed in real-time in Grafana. These frequent calculations have a big advantage during dramatic weather events, and during a race meeting.

A low-cost, high-frequency soil moisture IoT sensor can be calibrated by a high quality infrequent manual soil hardness instrument. The IoT can sensor accurately determine the soil hardness.

2. Can this data determine the characteristics of the drainage of the surrounding soil?

It was observed in *Figure 46: Rain & Soil Moisture over Time* that soil moisture decreases in a similar patterns. On closer inspection of these patterns in the absence of precipation, as in *Figure 55: Soil Saturation over Time with no Rainfall* and *Figure 56: Second plot of Soil Saturation over Time with no Rainfall*, a constant of drying is the drainage coefficient for the soil where the IoT sensor is. While the two drying periods do not produce the exact same number, the specific of the drainage constant that is deciphered, is more accurate than the drainage categories from Met Éireann. The drainage constant is also valid while it is raining, it is just more difficult to see in the graphs, owing to the input of moisture.

This analysis needs to be rolled out across other sensors and other locations and drainage characteristics to ensure correct testing. However, the drainage characteristics for a soil surrounding a sensor can be determined more specifically than the Met Éireann categories.

3. Can the automatically collected data, along with the weather forecast, predict the future soil hardness?

The determination of soil saturation and hence ground hardness is determined by four factors. They are previous soil saturation, rain or irrigation, evapotranspiration and drainage. The project calculations delivered good data for previous soil saturation (primary source data in the database), evapotranspiration from Met Éireann and drainage. However, predicting rainfall is not an exact science. The forecast soil saturation is only as good as the forecast for the rainfall.

In *Figure 47: Soil Moisture Levels and Rainfall over Time*, the variations between the actual rainfall and the forecasted rainfall are graphically represented. Forecasting the soil saturation (and latterly the ground hardness) is based on the rainfall predictions. Therefore, the soil saturation and ground hardness predictions are only as good as the rainfall forecast.

These variations in rainfall are usually quite slight for 3-hour and 24-hour forecasts, and much of the variation comes in the 5 day forecasts. Likewise, the predictions for the soil saturation and the ground hardness are quite accurate for 3-hour and 24-hour spans but tend to be more wayward for the 5-day prediction.

6.2 Strengths of the Research Methodology

While the information collected was just for one sensor, the processes are in place and the project could be scaled up. If the information was overlaid onto a map and information would have a much greater visual impact. Grafana has a mapping tool plug-in that could be used.

Most of the processing was performed through Node-RED. Node-RED is a mature application with add-on integrations to multiple devices and applications. There are videos and documentation readily available to help. It is an easy IoT application to use and understand.

Grafana is another good resource to use. The real-time data can be set to update at specified increments and it allow for a lot of information to be seen on one page.

For anyone embarking on a IoT project, there is a lot of open source data available to access. The local government and state departments have put a lot of information in standard formatting available for wider use. This project used an open API from Met Éireann where the data was in JSON format and well documented.

6.3 Weakness of the Research Methodology

While WI-FI is easily accessible for this project, LPWAN would be the transmission protocol that should be used. The data collect from the soil sensor was collected too frequently, this could be less frequent and this would allow the data to fit into a sigfox model.

Ideally the sensors and the weather station would be closer to each other and this would provide a greater accuracy in the data.

6.4 Study Strengths

The sensor and the open data utilised in this project reinforce how easy it is to gather data. The open data source https://data.gov.ie shows some of the variety of projects available in Ireland. Most of these projects are aimed at simple improvement that can be made. So while most groundkeepers and farmer understand the nuances of their land, all that information is not collated anywhere, and patterns and cycles get lost over time.

By immersion in this project, it is easy to see the importance of standardisation and documentation so that all this data can be reused.

6.5 Study Limitations

Time is the biggest limitation. It would be interesting to extend this project beyond the masters' timeframe. A longer periods of time could include acute weather patterns, such as frost, snow or even a long dry spell like Summer 2018. A longer time period would also allow for climatic patterns to be included in the weather.

More time and LPWAN would also allow for a closer collaboration with a racecourse. This would give time to develop an application than may be taken up in by the HRI.

The GAA Centre of Excellence in Abbotstown understand of the importance of data and upkeep of the ground conditions. This project would closely align with their willingness to bring technology into the ground upkeep. Racecourse are moving more slowly towards more technology.

The drainage coefficient was evaluated under a mixture of wet and dry periods. This coefficient should be tested under extended wet and dry periods.

6.6 Further Work

Overlaying this information on to an open source map would be an excellent addition to this project. It would continue to make the information as accessible and easy to read as possible.

Met Éireann and other European meteorological agencies use an application called Surfex (also open source) includes the physics of modelling natural land surfaces such as soil and vegetation, urban areas, lakes, seas and oceans as well as chemistry and aerosol processes (Met Éireann, 2019). This application could feed into that information.

University of Limerick developed a comprehensive report for the IRFU regarding injuries on players (Yeomans et. al., 2018). While the report covered the positions on the pitch where the injury occurs, ground conditions or location of the pitches were not included. Further analysis could give a greater understanding to all factor leading to injuries.

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8 Appendix A

8.1 Node-RED Flows

8.1.1 Soil Sensor Flow

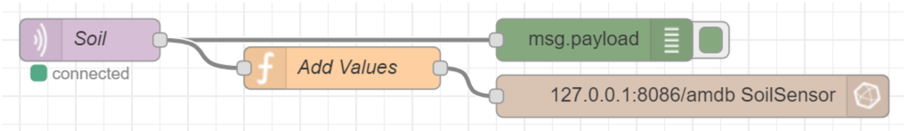


Figure 61: Node-RED Soil Sensor flow

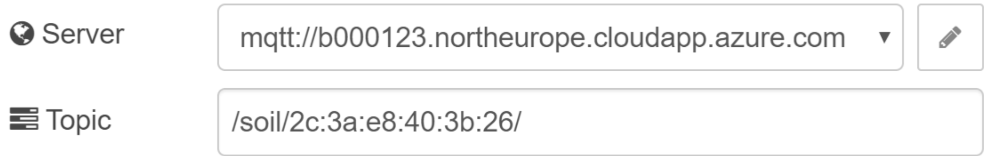


Figure 62: Properties of the Soil MQTT node

```

var x = JSON.parse(msg.payload);

msg.payload={

    SoilSatValue:msg.payload,
    SoilSatRawValue:x.RAWVal,
    Type: "Soil Saturation Sensor",
    Latitude:53.366944,
    Longitude:-6.492222
}
return msg;
```

Figure 63: Code in the Add Values function node

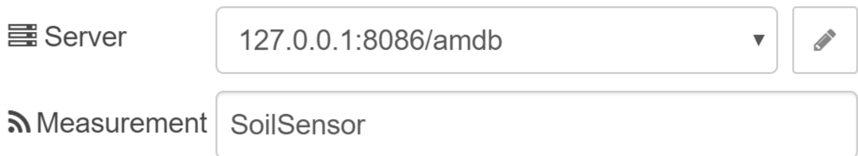


Figure 64: Properties of the InfluxDB node

8.1.2 Clegg Hammer Flow

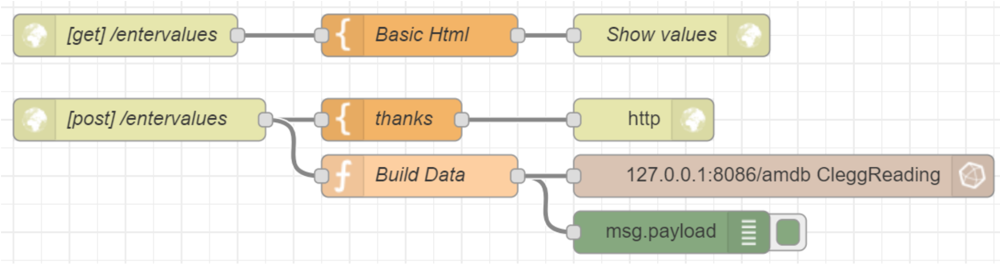


Figure 65: Node-RED Clegg Hammer Flow

```
<html>
    <head></head>

    <body style="background-color:white; font-family:monospace; font-size: 20px; color:grey;">
        <div id="idhello"><span id="idnameout">Enter Clegg Value</span></div>

        <form id="idform" action="/entervalues" method="post">
            <div>
                <span>
                    <input type="text" name="Reading" id="var1" autofocus/>
                </span>
                <span>
                    <input style="font-family:monospace;" type="submit" value="Submit" id="idsubmit" />
                </span>
            </div>
        </form>
            <script src="//ajax.googleapis.com/ajax/libs/jquery/1.9.1/jquery.min.js"></script>
        <script type="text/javascript">
                $(document).ready(function() {
                $('#idhello').show();
                $('#idform').submit(onSubmitClicked);
            });

            function onSubmitClicked(event){
                $('#idnameout').text($('#var1').val())
                $('#idhello').show();
                $('idform').hide();
            }
        </script>
    </body>
</html>
```

Figure 66: HTML code from Basic Html node

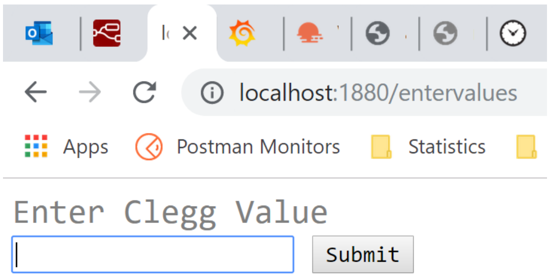


Figure 67: HTML page generated from Basic Html node

```html
<html>
    <head></head>
    <body>
        <h1 style="background-color:white; font-family:monospace; font-size: 20px;
        color:grey;">Got it!</h1>
        <p style="background-color:white; font-family:monospace; font-size: 15px;
        color:grey;">Click <a href="http://localhost:1880/entervalues">here</a> to
        enter another value</p>
    </body>
</html>
```

Figure 68: HTML code in the thanks node

Got it!

Click here to enter another value

Figure 69: HTML page generated from the thanks node

```javascript
p=msg.payload;

msg.payload={
    Reading: parseInt(p.Reading),
    Type: "Clegg Hammer",
    Latitude:53.366944,
    Longitude:-6.492222
}
return msg;
```

Figure 70: Code from the Build Data function node

8.1.3 Weather Flow

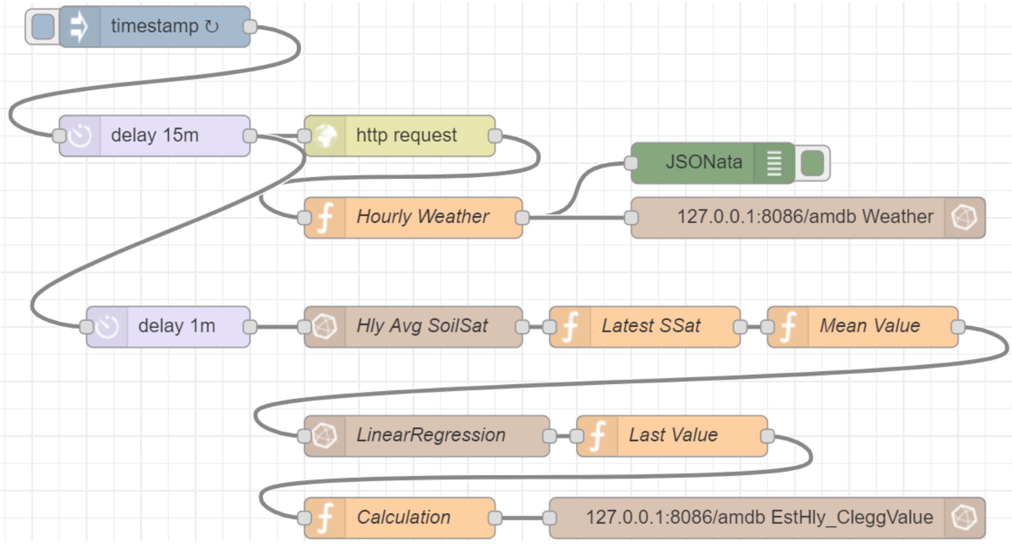


Figure 71: Node-RED Weather flow

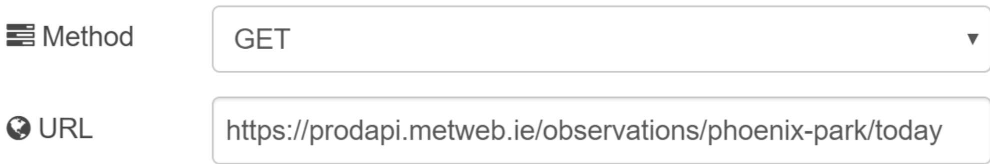


Figure 72: http request node configuration

```
p=msg.payload;

var HlySoilSat=flow.get('HlySoilSat');
var EstCleggValue = (HlySoilSat-p.yIntercept)/p.gradient;
msg.payload={
    EstCleggValue: EstCleggValue
}

return msg;
```

Figure 73: Code from Calculation node

8.1.4 Forecast Flow

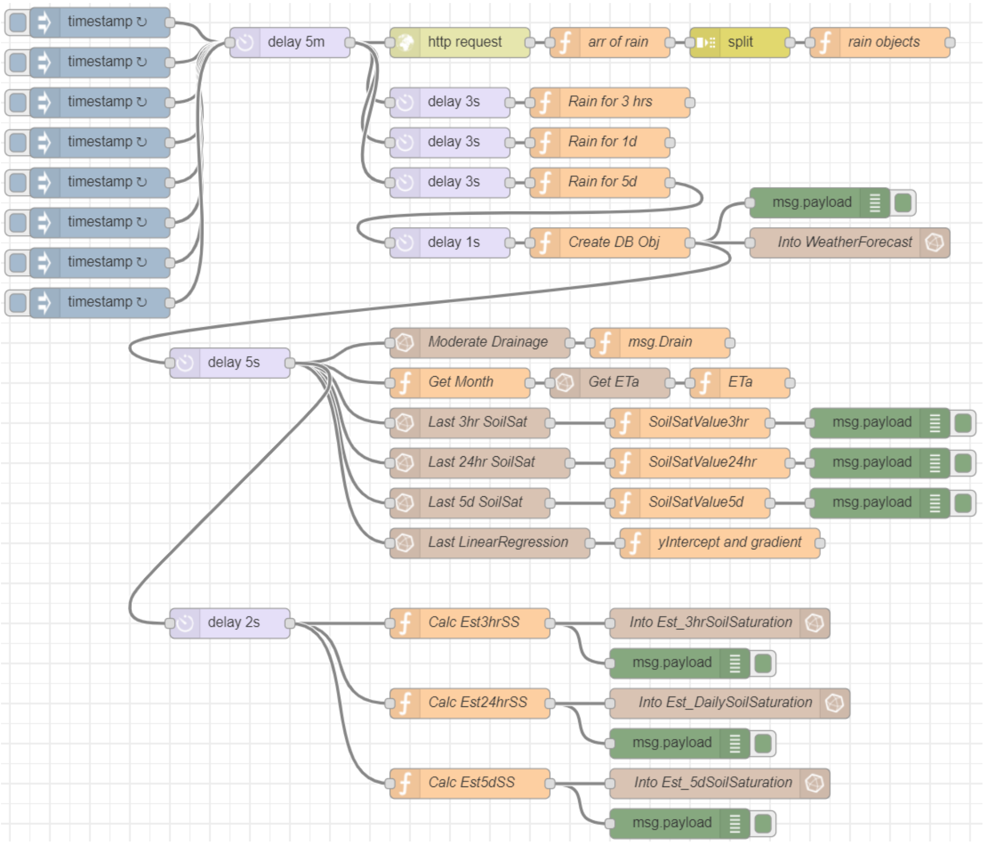


Figure 74: Node-RED Forecast flow

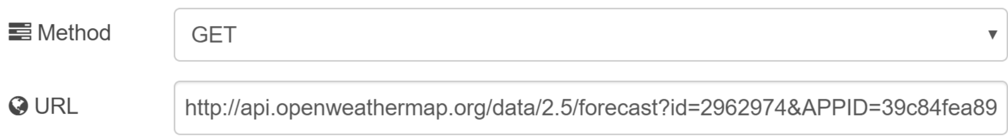


Figure 75: http request node configuration

```
p=msg.payload;
var rain = [];

p.list.forEach (function(weatherItem) {
    var rainItem = weatherItem.rain;
    rain.push(rainItem);
});

var AllRainfall = [];
flow.set('AllRainfall',AllRainfall);

msg.payload = rain;
return msg;
```

Figure 76: Code from arr of rain function node

```
var curr = flow.get('AllRainfall');
var x;
if (typeof(msg.payload) !== "undefined" && msg.payload !== null)
{
    x = {"Rainfall": msg.payload['3h']};
} else {
    x = {"Rainfall": 0};
}
curr.push(x);

flow.set('AllRainfall',curr);
msg.payload = curr;
return msg;
```

Figure 77: Code from rain object node

```
var curr = flow.get('AllRainfall');

var x=[], total, i;
for (i = 0; i < 1; i++) {    //first item in array is 3 hours
    if (typeof(curr[i].Rainfall) !== "undefined" && curr[i].Rainfall !== null)
        {x.push(curr[i].Rainfall);}
    else {}
}

function getSum(total, num) {
  return total + num;//Math.round(num);
} //sum the rainfall numbers

var rainfall3hrs=x.reduce(getSum, 0);
flow.set('rainfall3hrs',rainfall3hrs);

msg.payload = rainfall3hrs;
return msg;
```

Figure 78: Code from Rain for 3 hrs function node

```
var curr = flow.get('AllRainfall');

var x=[], total, i;
for (i = 0; i < 8; i++) {    //first 8 items in array is 24hrs
    if (typeof(curr[i].Rainfall) !== "undefined" && curr[i].Rainfall !== null)
        {x.push(curr[i].Rainfall);}
    else {}
}
var RainfallAt24hrs = curr[7].Rainfall;
flow.set('RainfallAt24hrs',RainfallAt24hrs);

function getSum(total, num) {
  return total + num;//Math.round(num);
} //sum the rainfall numbers

var rainfall24hrs=x.reduce(getSum, 0);
flow.set('rainfall24hrs',rainfall24hrs);

msg.payload = rainfall24hrs;
return msg;
```

Figure 79: Code for Rain for 1d function node

```
var curr = flow.get('AllRainfall');

var x=[], total, i;
for (i = 0; i < curr.length; i++) {
    if (typeof(curr[i].Rainfall) !== "undefined" && curr[i].Rainfall !== null)
        {x.push(curr[i].Rainfall);}
    else {}
}

var RainfallAt5d = curr[curr.length-1].Rainfall;
flow.set('RainfallAt5d',RainfallAt5d);

function getSum(total, num) {
  return total + num;//Math.round(num);
} //sum the rainfall numbers

var rainfall5d=x.reduce(getSum, 0);
flow.set('rainfall5d',rainfall5d);

msg.payload = rainfall5d;
return msg;
```

Figure 80: Code for 5d function node

```
var rainfall3hr =flow.get('rainfall3hrs');
var rainfall24hr =flow.get('rainfall24hrs');
var rainfall5d =flow.get('rainfall5d');

msg.payload = {
                "name" : "Leixlip",
                "longitude": -6.49556,
                "latitude": 53.365829,
                "RainForecast_3hrs" : rainfall3hr,
                "RainForecast_24hrs" : rainfall24hr,
                "RainForecast_5days" : rainfall5d
                }
return msg;
```

Figure 81: Code for Create DB Obj function node

```
p=msg.payload;

var Drain= msg.payload[0].Drain;
flow.set('Drain', Drain);   //flow.set Drain

return msg;
```

Figure 82: Code in msg.Drain function node

```
if ( !msg.timestamp ) msg.timestamp = Math.round(+new Date());

var dt = new Date(msg.timestamp);
var month = dt.getMonth() + 1;

msg.query = "SELECT DailyAvg FROM ETa where MonthNo = " + month;
return msg;
```

Figure 83: Code in Get Month function node

```
p=msg.payload;

var DailyETA= msg.payload[0].DailyAvg;
flow.set('DailyETA', DailyETA); //flow.set ETa

return msg;
```

Figure 84: Code in ETa function node

```
p=msg.payload;

var x=[], total, i;
for (i = 0; i < p.length; i++) {
        {x.push(p[i].mean)}
}
function getSum(total, num) {
  return total + num;
}
var SoilSatValue3hr= x.reduce(getSum, 0)/p.length;
flow.set('SoilSatValue3hr', SoilSatValue3hr); //flow.set SoilSatValue
msg.payload = SoilSatValue3hr;
return msg;
```

Figure 85: Code in SoilSatValue3hr function node

```
p=msg.payload;

var x=[], total, i;
for (i = 0; i < p.length; i++) {
        {x.push(p[i].mean)}
}
function getSum(total, num) {
  return total + num;
}
var SoilSatValue24hr = x.reduce(getSum, 0)/p.length;
flow.set('SoilSatValue24hr', SoilSatValue24hr); //flow.set SoilSatValue
msg.payload = SoilSatValue24hr;
return msg;
```

Figure 86: Code in SoilSatValue24hr function node

```
p=msg.payload;

var x=[], total, i;
for (i = 0; i < p.length; i++) {
        {x.push(p[i].mean)}
}
function getSum(total, num) {
  return total + num;
}
var SoilSatValue5d = x.reduce(getSum, 0)/p.length;
flow.set('SoilSatValue5d', SoilSatValue5d); //flow.set SoilSatValue
msg.payload = SoilSatValue5d;
return msg;
```

Figure 87: Code in SoilSatValue5d function node

```
p=msg.payload;

msg.payload = {
                "yIntercept" : p[0].yIntercept,
                "gradient" : p[0].gradient
}

flow.set('yIntercept', p[0].yIntercept); //flow.set yIntercept
flow.set('gradient', p[0].gradient); //flow.set gradient

return msg;
```

Figure 88: Code in yIntercept and gradient function node

```
p=msg.payload;
var DailyETA=flow.get('DailyETA')/8;     //ETa for 3hrs
var SoilSatValue=flow.get('SoilSatValue3hr');
var rainfall=flow.get('rainfall3hrs');
var Drain=flow.get('Drain')/8;            //Drainage is stored per day aswell
var yIntercept=flow.get('yIntercept');
var gradient=flow.get('gradient');

var Est3hrSS=SoilSatValue+rainfall-DailyETA-Drain;
var Est3hrClegg = (Est3hrSS - yIntercept) / gradient;

var now = new Date();
now.setHours(now.getHours() + 3);

msg.payload={
    "time" : now,
    "ForecastRainfall" : rainfall,
    "SoilSatValue" : SoilSatValue,
    "Drain" : Drain,
    "ETa" : DailyETA,
    "Est_SoilSat" : Est3hrSS,
    "Est_CleggValue" : Est3hrClegg,
    "CurrentForecastedRainfall" : rainfall
}
return msg;
```

Figure 89: Code in the Calc Est3hrSS function node

```
p=msg.payload;
var DailyETA=flow.get('DailyETA');
var SoilSatValue=flow.get('SoilSatValue24hr');
var rainfall=flow.get('rainfall24hrs');
var Drain=flow.get('Drain');
var yIntercept=flow.get('yIntercept');
var gradient=flow.get('gradient');
var RainfallAt24hrs=flow.get('RainfallAt24hrs');

var Est24hrSS=SoilSatValue+rainfall-DailyETA-Drain;
var Est24hrClegg = (Est24hrSS - yIntercept) / gradient;

var now = new Date();
now.setHours(now.getHours() + 24);

msg.payload={
    "time" : now,
    "ForecastRainfall" : rainfall,
    "SoilSatValue" : SoilSatValue,
    "Drain" : Drain,
    "DailyETA" : DailyETA,
    "Est_SoilSat" : Est24hrSS,
    "Est_CleggValue" : Est24hrClegg,
    "CurrentForecastedRainfall" : RainfallAt24hrs
}
return msg;
```

Figure 90: Code in Calc Est24hrSS function node

```
p=msg.payload;
var DailyETA=flow.get('DailyETA') * 5;    //5 times daily average
var SoilSatValue=flow.get('SoilSatValue5d');
var rainfall=flow.get('rainfall5d');
var Drain=flow.get('Drain') * 5;          //5 times daily average
var yIntercept=flow.get('yIntercept');
var gradient=flow.get('gradient');
var RainfallAt5d=flow.get('RainfallAt5d');

var Est5dSS=SoilSatValue+rainfall-DailyETA-Drain;
var Est5dClegg = (Est5dSS - yIntercept) / gradient;

var now = new Date();
now.setHours(now.getHours() + 120);

msg.payload={
    "time" : now,
    "ForecastRainfall" : rainfall,
    "SoilSatValue" : SoilSatValue,
    "Drain" : Drain,
    "ETa" : DailyETA,
    "Est_SoilSat" : Est5dSS,
    "Est_CleggValue" : Est5dClegg,
    "CurrentForecastedRainfall" : RainfallAt5d
}
return msg;
```

Figure 91: Code in Calc Est5dSS function node

8.1.5 Regression Flow

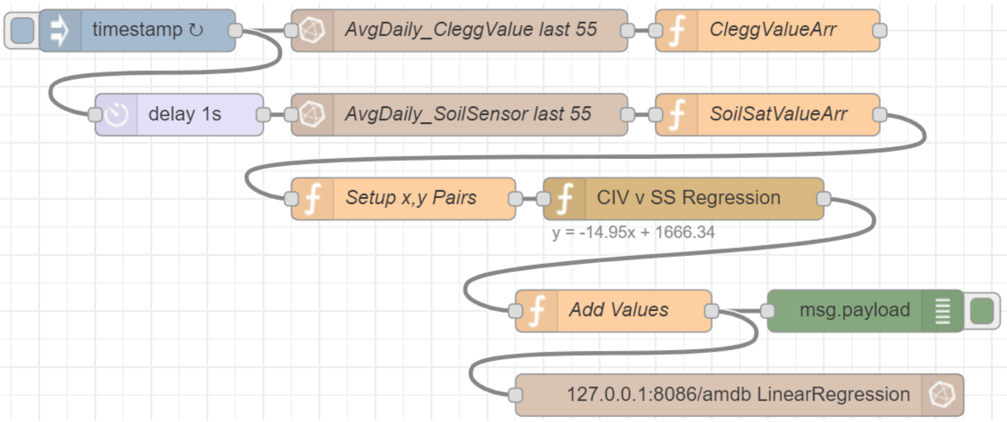


Figure 92: Node-RED Regression flow

```
p=msg.payload;

var i, x=[];

for (i = 0; i < msg.payload.length; i++) {
  x.push(msg.payload[i].CleggValue);
}

var CleggValueArr = x;
flow.set('CleggValueArr', CleggValueArr); //flow.set CleggValueArr

msg.payload=x;
return msg;
```

Figure 93: Code in CleggValueArr function node

```
p=msg.payload;

var i, x=[];

for (i = 0; i < msg.payload.length; i++) {
  x.push(msg.payload[i].SoilSatValue);
}

var SoilSatValueArr = x;
flow.set('SoilSatValueArr', SoilSatValueArr); //flow.set SoilSatValueArr

msg.payload=x;
return msg;
```

Figure 94: Code in SoilSatValueArr function node

```
p=msg.payload;
var SoilSatValueArr=flow.get('SoilSatValueArr');
var CleggValueArr=flow.get('CleggValueArr');
var i, j, pairs=[], x;

for (i = 0; i < msg.payload.length; i++) {
    x = []
    x.push(CleggValueArr[i]);
    x.push(SoilSatValueArr[i]);
    pairs.push(x);
}
msg.payload=pairs;
return msg;
```

Figure 95: Code in Setup x,y Pairs function node

```
msg.payload={
    gradient: msg.Output.equation[0],
    yIntercept: msg.Output.equation[1],
    r2: msg.Output.r2
}
return msg;
```

Figure 96: Code in Add Values function node

8.1.6 Irrigation Flow

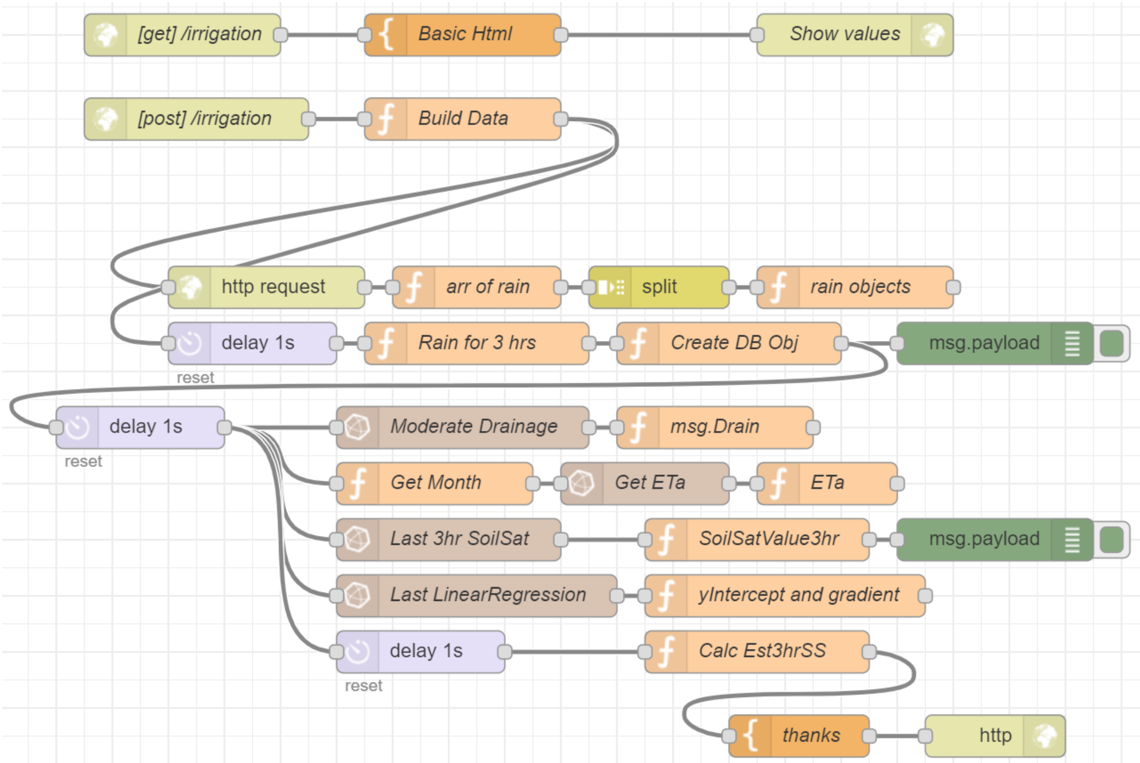


Figure 97: Node-RED Irrigation Flow

```html
<html>
    <head>
        <style>
            body {background-color:white; font-family:monospace; font-size: 20px; color:grey;}
            input {font-family:monospace;}
        </style>
    </head>
    <body>
        <div id="idhello"><span id="idnameout">Enter Irrigation Quantity (mm)</span></div>
        <div id="idwait"><span id="idwaitout">Wait a couple of seconds while all the magic happens...</span></div>

        <form id="idform" action="/irrigation" method="post">
            <div>
                <span>
                    <input type="text" name="Reading" id="var1" autofocus/>
                </span>
                <span>
                    <input type="submit" value="Submit" id="idsubmit" />
                </span>
            </div>
        </form>
            <script src="//ajax.googleapis.com/ajax/libs/jquery/1.9.1/jquery.min.js"></script>
        <script type="text/javascript">
                $(document).ready(function() {
                $('#idhello').show();
                $('#idwait').hide();
                $('#idform').submit(onSubmitClicked);
            });

            function onSubmitClicked(event){
                $('#idnameout').text($('#var1').val())
                $('#idhello').show();
                $('#idwait').show();
                $('#idform').hide();
            }
        </script>
    </body>
</html>
```

Figure 98: Html code in the Basic Html node

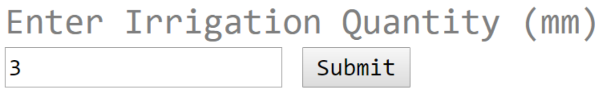


Figure 99: Input HTML page formed in Basic Html function node

```
p=msg.payload;

var Irr= parseInt(p.Reading);
flow.set('Irr', Irr); //flow.set Irr

msg.payload={
    ValueEntered: parseInt(p.Reading),
    Type: "Irrigation"
}
return msg;
```

Figure 100: Build Data function node

```
p=msg.payload;
var DailyETA=flow.get('DailyETA')/8;    //ETa for 3hrs
var SoilSatValue=flow.get('SoilSatValue3hr');
var rainfall=flow.get('rainfall3hrs');
var Drain=flow.get('Drain')/8;          //Drainage is stored per day aswell
var yIntercept=flow.get('yIntercept');
var gradient=flow.get('gradient');
var CurrGoing=flow.get('CurrGoing');
var Irr = flow.get('Irr'); //get Irrigation from user
var Prev_Clegg = (SoilSatValue - yIntercept) / gradient;

var CurrGoingCategory
if (CurrGoing < 1) {CurrGoingCategory = "Water logged";}
    else if (CurrGoing < 3) {CurrGoingCategory = "Heavy";}
    else if (CurrGoing < 4) {CurrGoingCategory = "Soft";}
    else if (CurrGoing < 7) {CurrGoingCategory = "Yielding";}
    else if (CurrGoing < 9) {CurrGoingCategory = "Good";}
    else if (CurrGoing < 11) {CurrGoingCategory = "Good to Firm";}
    else if (CurrGoing < 13) {CurrGoingCategory = "Firm";}
else  {CurrGoingCategory = "Hard";}

var Est3hrSS=SoilSatValue+rainfall+Irr-DailyETA-Drain;
var Est3hrClegg = (Est3hrSS - yIntercept) / gradient;
var EstGoing = (Est3hrSS*-0.01665)+17.2646;

var EstGoingCategory
if (EstGoing < 1) {Est_GoingCategory = "Water logged";}
    else if (EstGoing < 3) {Est_GoingCategory = "Heavy";}
    else if (EstGoing < 4) {Est_GoingCategory = "Soft";}
    else if (EstGoing < 7) {Est_GoingCategory = "Yielding";}
    else if (EstGoing < 9) {Est_GoingCategory = "Good";}
    else if (EstGoing < 11) {Est_GoingCategory = "Good to Firm";}
    else if (EstGoing < 13) {Est_GoingCategory = "Firm";}
else  {Est_GoingCategory = "Hard";}

var now = new Date();
now.setHours(now.getHours() + 3);

msg.payload={
    "time" : now,
    "ForecastRainfall" : rainfall,
    "Prev_SoilSat" : SoilSatValue,
    "Prev_CleggValue" : Prev_Clegg,
    "Prev_Going" : CurrGoing,
    "Prev_GoingCategory" : CurrGoingCategory,
    "Drain" : Drain,
    "ETa" : DailyETA,
    "Est_SoilSat" : Est3hrSS,
    "Est_CleggValue" : Est3hrClegg,
    "Est_Going" : EstGoing,
    "Est_GoingCategory" : Est_GoingCategory,
    "Irrigation" : Irr
}
return msg;
```

Figure 101: Irrigation calculation in the Calc Est3hSS function node

```html
<html>
    <head>
        <style>
            h1 {background-color:white; font-family:monospace; font-size: 20px; color:grey;}
            p {background-color:white; font-family:monospace; font-size: 15px; color:grey;}
            table {background-color:white; font-family:monospace; font-size: 15px; border-style: solid; border:2}
            td {text-align: left; width:200px; height: 30px; color:grey;}
            th {text-align: left; width:200px; height: 30px; color:"black";}
        </style>
    </head>
    <body>
        <h1 style="">Irrigation Analysis</h1>
        <br><br>
        <p>With irrigation of <b><i>{{payload.Irrigation}}mm</i></b>, the following is the estimated change in soil hardness at <b><i>{{payload.time}}</i></b></p>
        <table>
            {{#payload}}
            <tr>
                <th></th>
                <th>Current</th>
                <th>Estimated</th>
            </tr>
            <tr>
                <th>Saturation</th>
                <td>{{Prev_SoilSat}}</td>
                <td>{{Est_SoilSat}}</td>
            </tr>
            <tr>
                <th>Clegg</th>
                <td>{{Prev_CleggValue}}</td>
                <td>{{Est_CleggValue}}</td>
            </tr>
            <tr>
                <th>Going</th>
                <td>{{Prev_GoingCategory}} / {{Prev_Going}}</td>
                <td>{{Est_GoingCategory}} / {{Est_Going}}</td>
            </tr>
            {{/payload}}
        </table>
        <p>Click <a href="http://localhost:1880/irrigation">here</a> to enter another value</p>
    </body>
</html>
```

Figure 102: HTML code in the thanks function node

Irrigation Analysis

With irrigation of ***3mm***, the following is the estimated change in soil hardness at ***Fri Aug 30 2019 17:35:28 GMT+0000 (UTC)***

	Current	Estimated
Saturation	783.2333333333332	784.7861559139784
Clegg	60.08500417710945	59.98770952919935
Going	Yielding / 4.223765000000002	Yielding / 4.19791050403226

Click here to enter another value

Figure 103: Output HTML page formed in thanks function node

8.1.7 Miscellaneous Flow

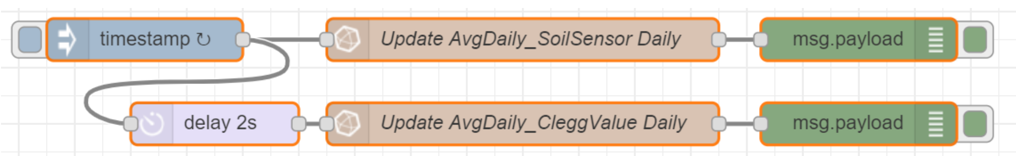


Figure 104: Node-RED flow to auto-update Average Daily Soil Sensor and Clegg Values

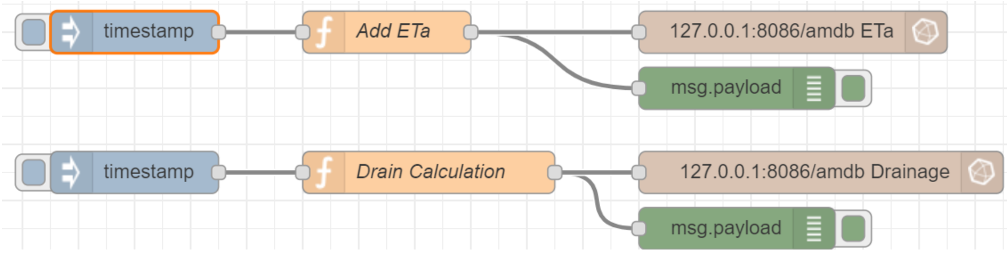


Figure 105: Node-RED flow to add data to the databas

8.2 Database

8.2.1 AvgDaily_CleggValue Measurement

Automatically updated from Node-RED at 7am for previous day.

Attribute	Data Type	Description
time	Unix time	Timestamp of record (ISO-8601 date representation)
CleggValue	Integer	Average daily value from CleggReading

8.2.2 AvgDaily_SoilSensor Measurement

Automatically updated from Node-RED at 7am for previous day.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
SoilSatValue	Integer	Average daily value from SoilSatValue

8.2.3 Avg_SoilSat Measurement

Hourly Soil Moisture Values

Attribute	Data Type	Description
time	Unix time	Timestamp of record
mean	Integer	Average Hourly Soil Moisture values, collated from SoilSensor

This is auto updated from the continuous query outlined in *8.3 Continuous Query*.

8.2.4 CleggReading Measurement

Readings from the Clegg Hammer, usually five readings taken around evening time.

Reading are entered from a html screen.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
CleggValue	-	Not used
Latitude	Integer	Hardcoded from Node-RED
Longitude	Integer	Hardcoded from Node-RED
Reading	Integer	Reading from Clegg hammer
Type	String	hardcoded from Node-RED
reading	-	Not used

8.2.5 Drainage Measurement

Pre-populated from Node-Red with the three Met Éireann categories.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
Category	String	Poor/Moderately/Well Drained
Drain	Integer	Drainage in mm per day

8.2.6 ETa Measurement

Pre-populated from Node-Red with monthly values for the sensor location.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
DailyAvg	Integer	MonthlyAvg/No. of days in the month
Latitude	Integer	Hardcoded from Node-RED

Longitude	Integer	Hardcoded from Node-RED
Month	String	Name of Month
MonthNo	Integer	Month as a two digit integer, 01,02, etc.
MonthlyAvg	Integer	As taken from Panoply

8.2.7 EstHly_CleggValue Measurement

Auto populated from Node RED hourly. Using the most recent coordinates for yIntercept and gradient from Linear Regression and Avg_SoilSat.

Generated using:

```
localhost:8086/query?db=amdb&q=SELECT (mean - yIntercept)/gradient AS "EstCleggValue"

    INTO "EstHly_CleggValue"

    FROM "Avg_SoilSat"
```

Attribute	Data Type	Description
time	Unix time	Timestamp of record
EstHly_CleggValue	Integer	Average Hourly Clegg Value based on the hourly average Soil Moisture values (Avg_SoilSat) and Linear Regression data.

8.2.8 Est_3hrSoilSaturation Measurement

Est_3hrSoilSaturation is are populated from Node-RED. Once the forecast is collected, the estimates for the soil saturation and Clegg values are generated.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
CurrentForecastedRainfall	Integer	Sum of forecasted rainfall in next 3 hours
DailyETA	Integer	Daily ETa value for that month
Drain	Integer	Drainage for 3 hours
ETa	Integer	ETa/8 for a 3 hourly value
Est_CleggValue	Integer	Calculate estimate Clegg from estimated soil saturation
Est_SoilSat	Integer	Calculated estimate soil saturation
ForecastRainfall	Integer	Forecasted rainfall in 3 hours
SoilSatValue	Integer	Soil Saturation value for last 3 hours

8.2.9 Est_5dSoilSaturation Measurement

Est_5dSoilSaturation is populated from Node-RED. Once the forecast is collected, the estimates for the soil saturation and Clegg values are generated.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
CurrentForecastedRainfall	Integer	Sum of forecasted rainfall in next 5 days
DailyETA	Integer	Daily ETa value for that month
Drain	Integer	Drainage for 5 days
ETa	Integer	ETa*5 for a 5-day value
Est_CleggValue	Integer	Calculate estimate Clegg from estimated soil saturation

Est_SoilSat	Integer	Calculated estimate soil saturation
ForecastRainfall	Integer	Forecasted rainfall in 5 days
SoilSatValue	Integer	Soil Saturation value for last 5 days

8.2.10 Est_DailySoilSaturation Measurement

Est_DailySoilSaturation is populated from Node-RED. Once the forecast is collected, the estimates for the soil saturation and Clegg values are generated.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
CurrentForecastedRainfall	Integer	Sum of forecasted rainfall in next 24 hours
DailyETA	Integer	Daily ETa value for that month
Drain	Integer	Drainage for 24 hours
ETa	Integer	ETa for a 24 hour value
Est_CleggValue	Integer	Calculate estimate Clegg from estimated soil saturation
Est_SoilSat	Integer	Calculated estimate soil saturation
ForecastRainfall	Integer	Forecasted rainfall in 24 hours
SoilSatValue	Integer	Soil Saturation value for last 24 hours

8.2.11 LinearRegression Measurement

Auto calculated from Node-RED every 24 hours just after midnight.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
Gradient	Integer	Slope of the straight linear from linear regression
yIntercept	Integer	Y Intercept from linear regression
R2	Integer	Correlation coefficient from the linear regression

8.2.12 SoilSensor Measurement

Auto generated from ESP8266 every minute from ESP8366 via MQTT and Node-RED.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
Latitude	Integer	Hardcoded from ESP8266 (53.366944)
Longitude	Integer	Hardcoded from ESP8266 (-6.492222)
SoilSatRawValue		Not used, was initially for the raw value – wrong syntax
SoilSatValue	Integer	Raw value output (0-1000) from ESP8266
Type	String	Hardcoded from ESP8266 ("Soil Saturation Sensor")

8.2.13 Weather Measurement

All fields are auto populated from https://prodapi.metweb.ie/observations/phoenix-park/today every hour via node-RED.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
cardinalWindDirection	String	Wind direction in N, NE, E etc.
Date	String	dd-mm-yyyy
DayName	String	Day name
Humidity	String	Relativity humidity as a percentage
Name	String	Weather station name e.g. Phoenix Park
Pressure	String	Pressure in hPa
Rainfall	String	Rainfall in mm
reportTime	String	hh:mm the time associated with the record
Symbol	String	Graphical symbol associated with some readings
temperature	String	Temperature in degree Celsius
Text	String	N/A
weatherDescription	String	N/A
windDirection	Integer	Wind direction in degrees 0-360
windGust	String	N/A
windSpeed	String	N/A

Only time & rainfall are possibly the only pieces of information to be used.

8.2.14 WeatherForecast Measurement

OpenWeatherMap.org

http://api.openweathermap.org/data/2.5/forecast?id=2962974&APPID=39c84fea895b2d82f9e0e05d63efe853 is queried every three hours. There is a lot of data that is captured in the query. This database takes the following form.

Attribute	Data Type	Description
time	Unix time	Timestamp of record
RainForecast_24hrs	Integer	Sum of forecasted rainfall in next 24 hours
RainForecast_3hrs	Integer	Sum of forecasted rainfall in next 3 hours
RainForecast_5days	Integer	Sum of forecasted rainfall in next 5 days
Latitude	Integer	Latitude of area
Longitude	Integer	Longitude of area
Name	String	Name of area for weather forecast

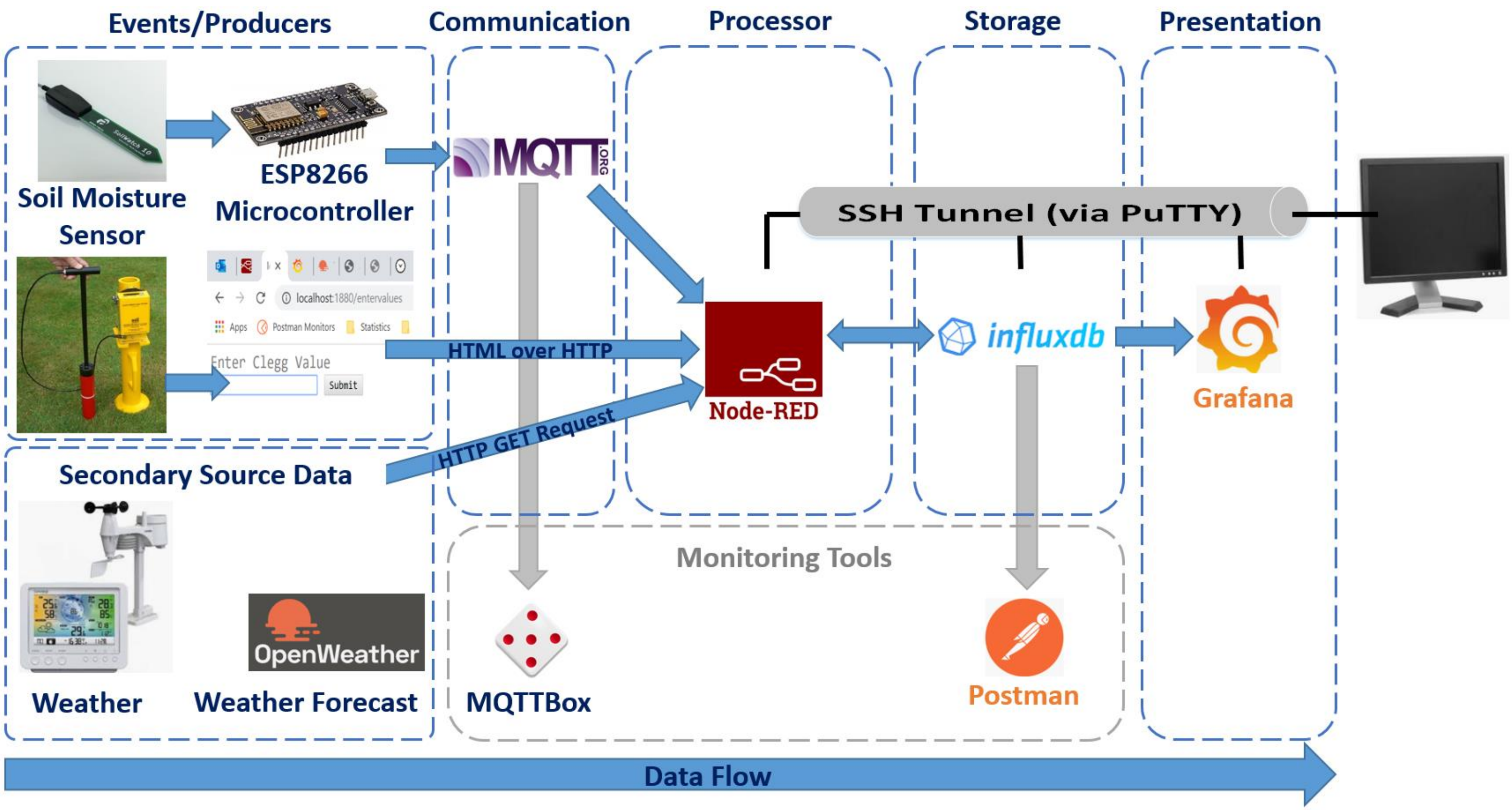
8.3 Continuous Query

There is one continuous query in the database. A continuous query in an InfluxDB database is similar to a stored procedure in a structured SQL database.

```
CREATE CONTINUOUS QUERY cq_basic ON amdb BEGIN SELECT mean(SoilSatRawValue) INTO amdb.autogen.Avg_SoilSat FROM amdb.autogen.SoilSensor GROUP BY time(1h) END"
```

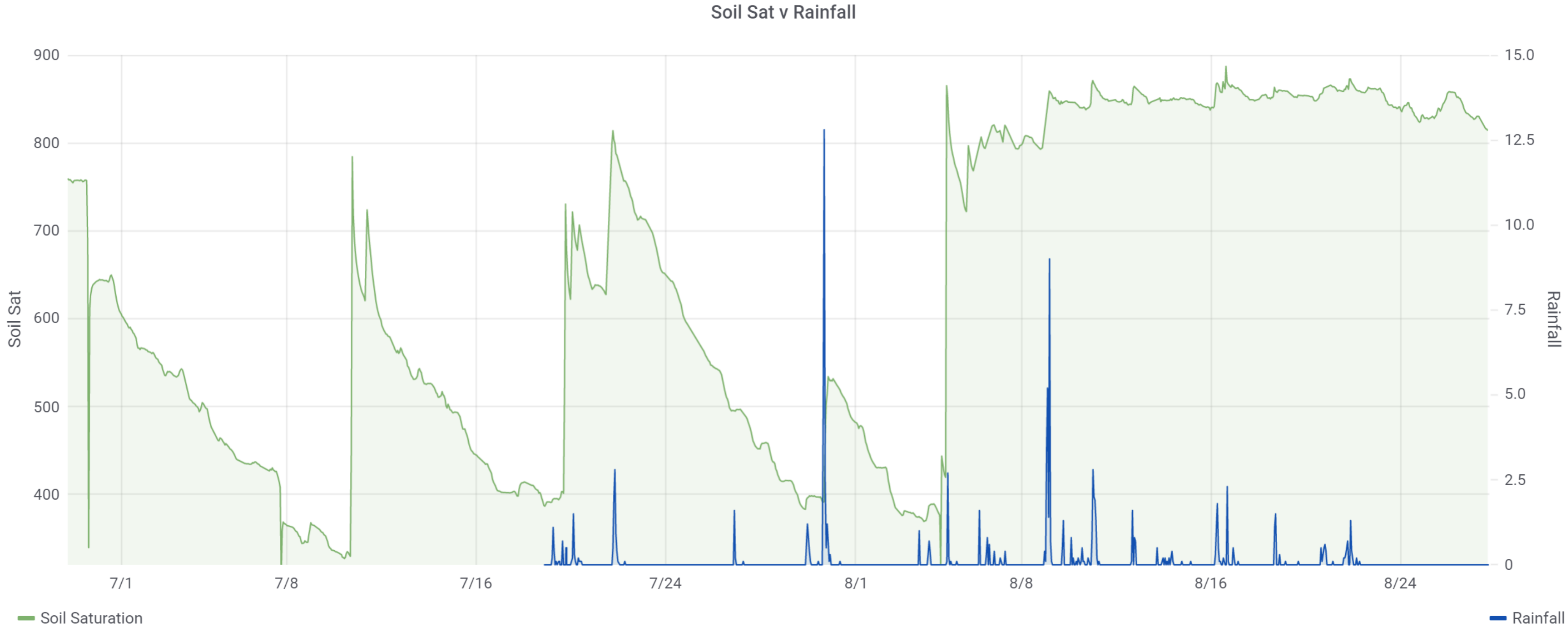
9 Appendix B

9.1 System Architecture

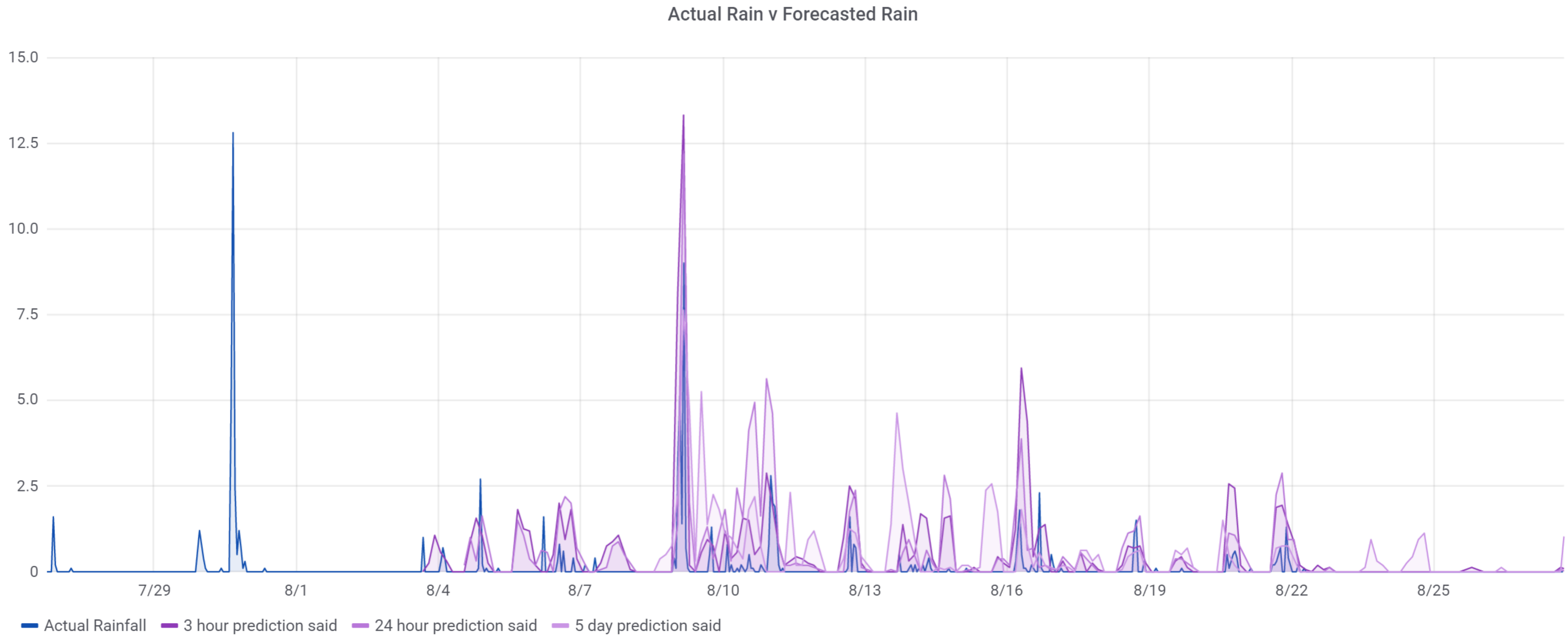


9.2 Grafana Output Visualisations

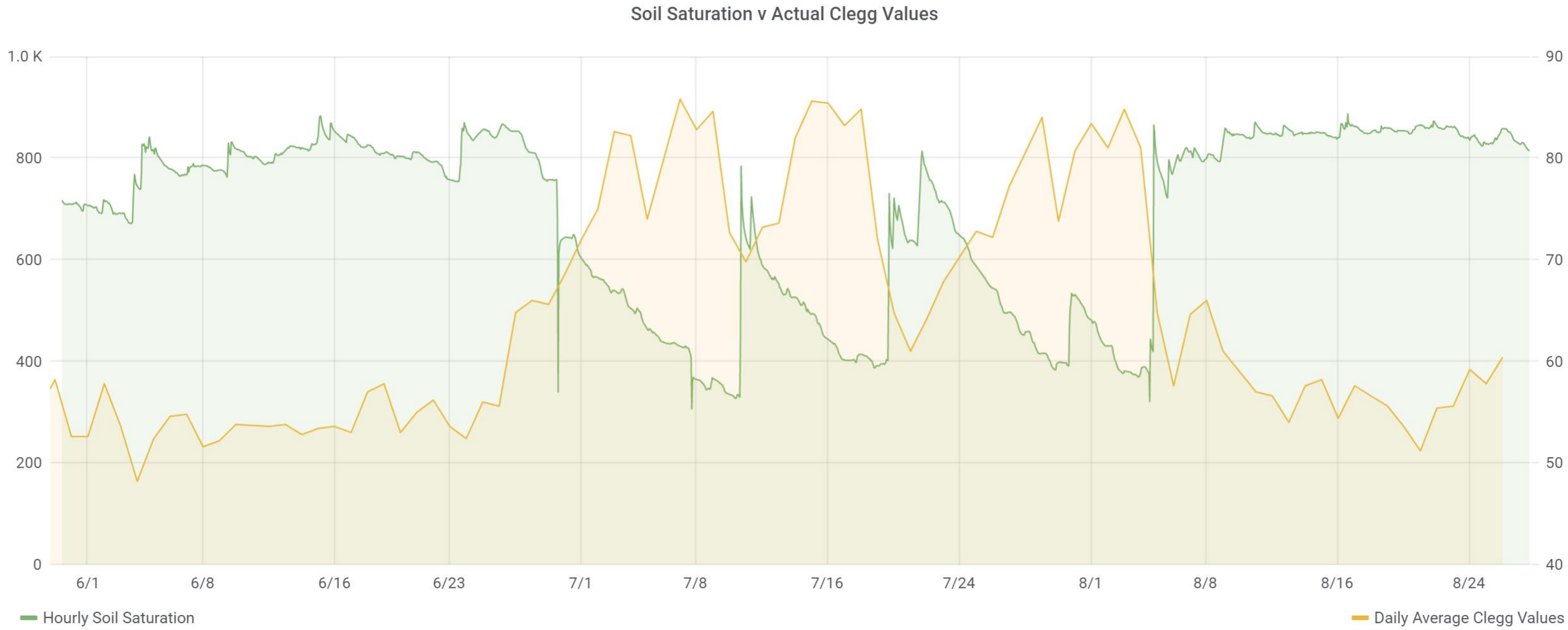
9.2.1 Soil Saturation Levels plotted against Rainfall



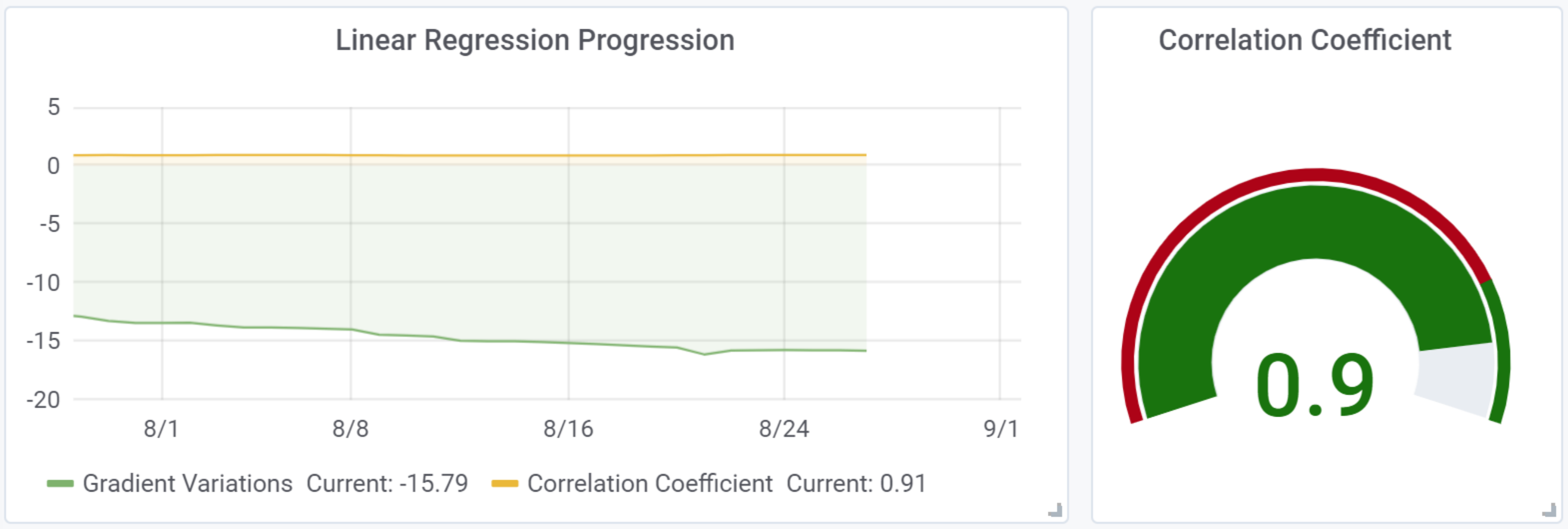
9.2.2 Actual Rainfall plotted against Forecasted Rainfall



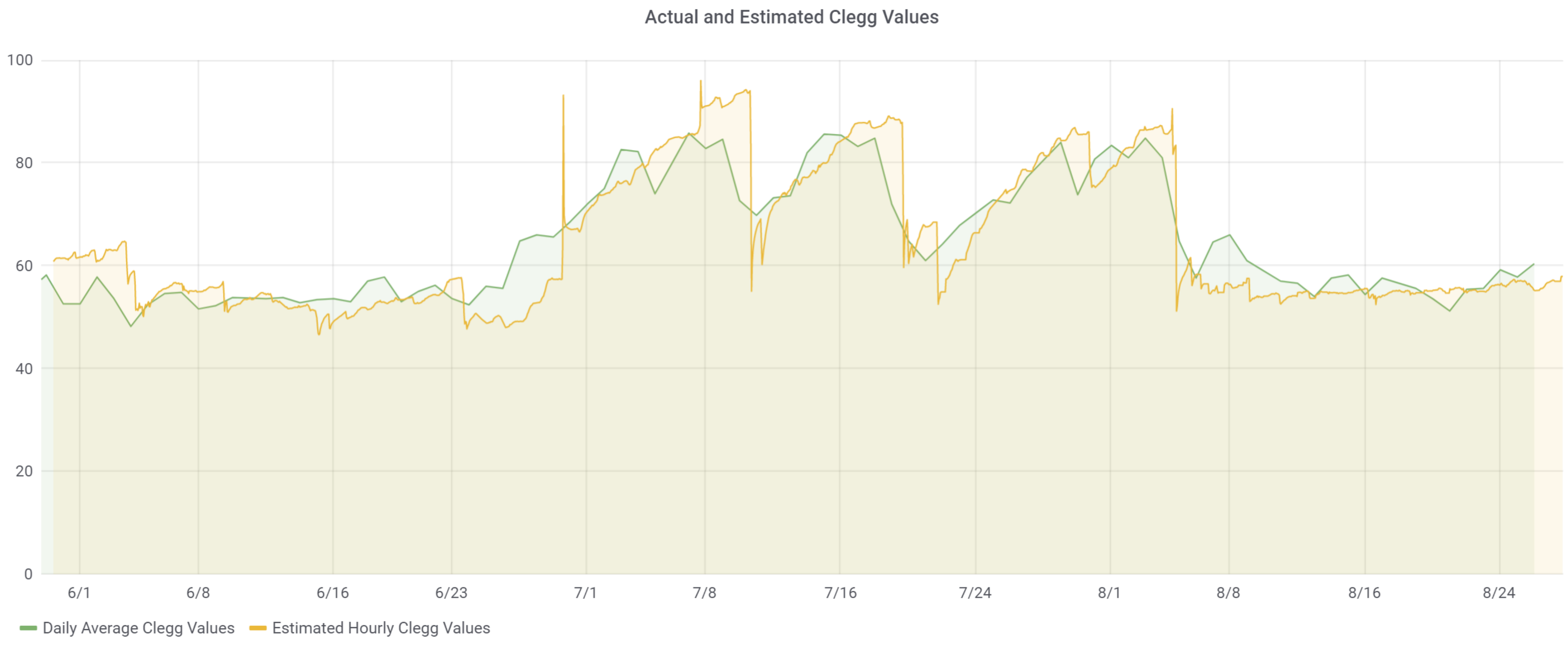
9.2.3 Hourly Soil Saturation plotted with Daily Clegg Values



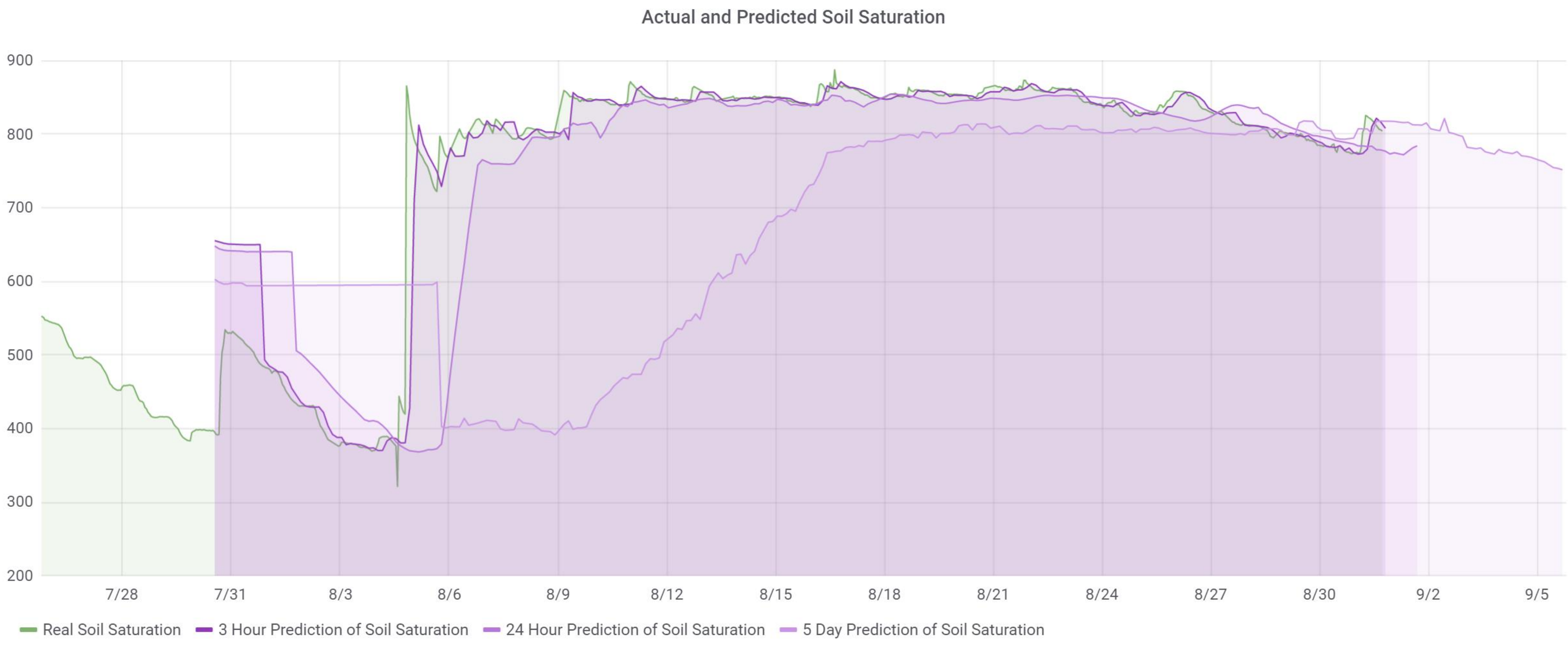
9.2.4 Linear Regression variations and Current Correlation Coefficient



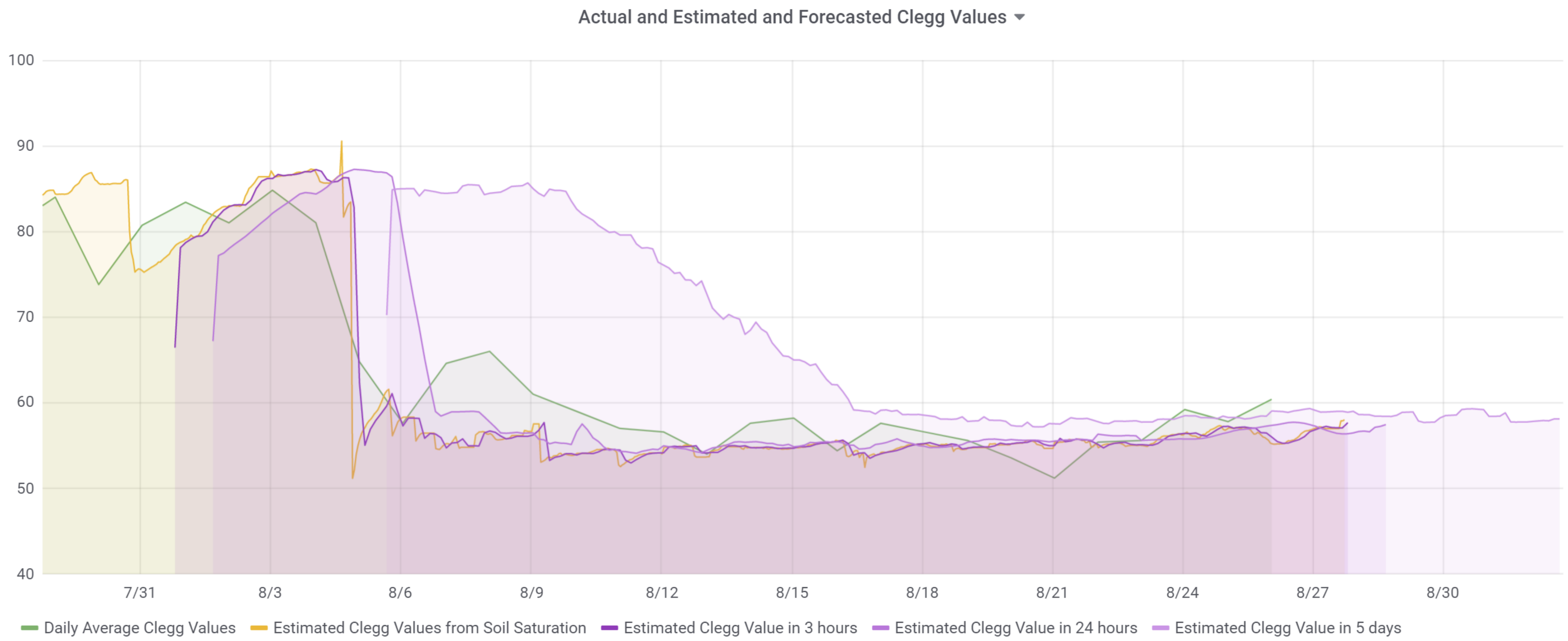
9.2.5 Daily and Estimated Hourly Clegg Hammer Values



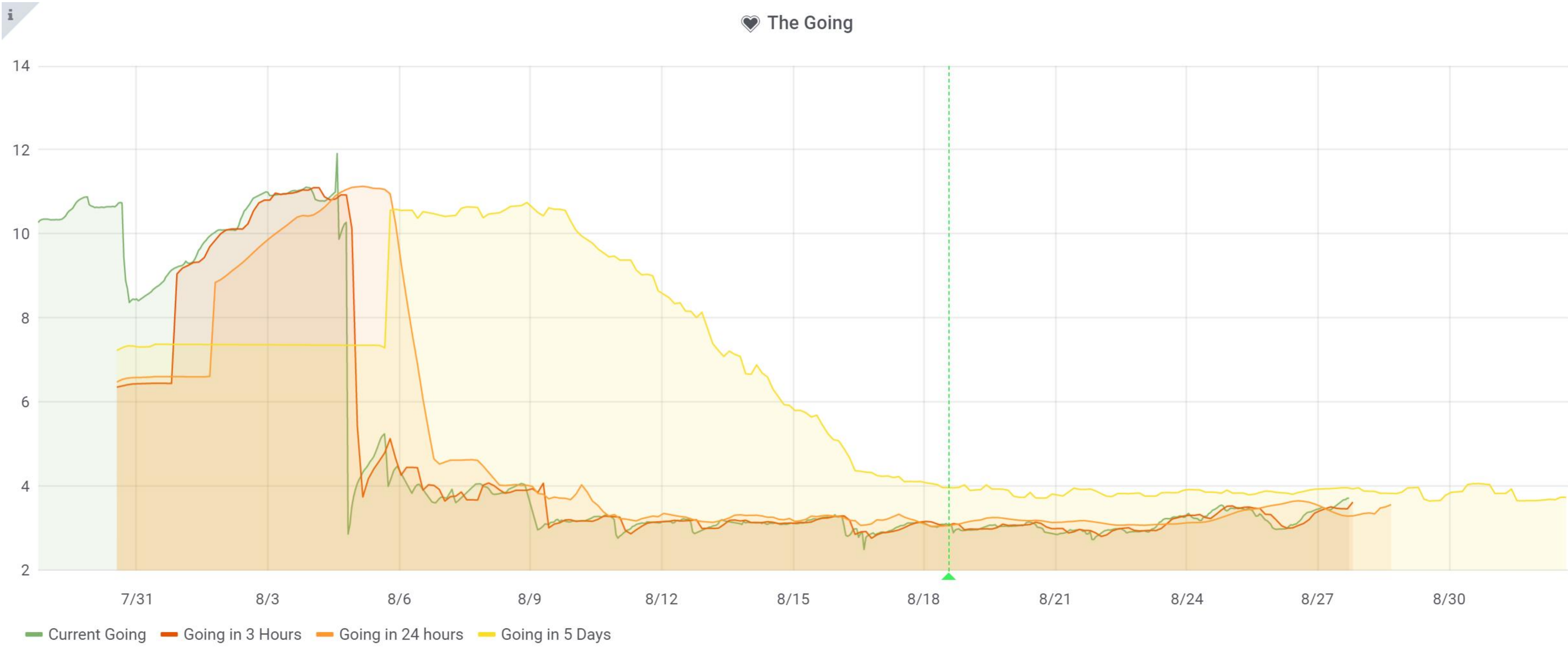
9.2.6 Actual and Estimated Soil Saturation Values



9.2.7 Actual, Estimated and Forecasted Clegg Values



9.2.8 Actual and Estimated Going



9.3 GAA Data Collection

Table 6: Environmental Data taken from the GAA National Games Development Centre

Date	Min Air Temp (C)	Max Air Temp (C)	Average Air Temp (C)	Rainfall (mm)	Growth Degree Days	Cumulative GDD (Month)	Cumulative GDD (Year)	Growth Potential	Cumulative GP (Month)	Cumulative GP (Year)	Soil temp (C)
01 October	2.9	14.6	8.75	0.2	2.75	2.75	1440.5	0.24	0.24	130.38	
02 October	11.8	17	14.4	1	8.4	11.15	1448.9	0.81	1.05	131.19	13.8
03 October	11.7	16.3	14	0	8	19.15	1456.9	0.77	1.82	131.96	14.2
04 October	11.5	17.6	14.55	6.4	8.55	27.7	1465.45	0.82	2.64	132.78	
05 October	7.3	12	9.65	4.8	3.65	31.35	1469.1	0.32	2.96	133.09	
06 October	1.8	13	7.4	0	1.4	32.75	1470.5	0.16	3.11	133.25	
07 October	1.4	15.3	8.35	0	2.35	35.1	1472.85	0.21	3.33	133.46	
08 October	12.9	16.2	14.55	0	8.55	43.65	1481.4	0.82	4.15	134.29	12.5
09 October	13.2	18.2	15.7	0	9.7	53.35	1491.1	0.92	5.06	135.20	13.4
10 October	11.6	20.2	15.9	0	9.9	63.25	1501	0.93	5.99	136.13	
11 October	10.6	17.1	13.85	0.4	7.85	71.1	1508.85	0.75	6.75	136.88	
12 October	11.6	16.4	14	4.2	8	79.1	1516.85	0.77	7.51	137.65	
13 October	8.8	13.2	11	16.2	5	84.1	1521.85	0.44	7.96	138.10	
14 October	3.3	14.1	8.7	0	2.7	86.8	1524.55	0.24	8.20	138.34	
15 October	3	14.1	8.55	0	2.55	89.35	1527.1	0.23	8.43	138.56	
16 October	4.1	15.9	10	0	4	93.35	1531.1	0.35	8.77	138.91	
17 October	2.6	13.9	8.25	0	2.25	95.6	1533.35	0.21	8.98	139.12	9.9
18 October	1.1	13.7	7.4	0	1.4	97	1534.75	0.16	9.14	139.28	8.2
19 October	3.4	15.3	9.35	0	3.35	100.35	1538.1	0.29	9.43	139.57	10.6
20 October	8.8	17.6	13.2	0	7.2	107.55	1545.3	0.68	10.11	140.25	
21 October	5.3	15.3	10.3	0.6	4.3	111.85	1549.6	0.38	10.49	140.62	
22 October	3.2	12.9	8.05	0.2	2.05	113.9	1551.65	0.19	10.68	140.82	9.3
23 October	7.9	13.6	10.75	0	4.75	118.65	1556.4	0.42	11.10	141.24	9.5
24 October	8.8	11.7	10.25	0	4.25	122.9	1560.65	0.37	11.47	141.61	10.7
25 October			0		0	122.9	1560.65	0.00	11.48	141.61	10.9
26 October			0		0	122.9	1560.65	0.00	11.48	141.62	
27 October			0		0	122.9	1560.65	0.00	11.48	141.62	
28 October			0		0	122.9	1560.65	0.00	11.49	141.63	
29 October			0		0	122.9	1560.65	0.00	11.49	141.63	
30 October			0		0	122.9	1560.65	0.00	11.50	141.64	
31 October			0		0	122.9	1560.65	0.00	11.50	141.64	
Monthly Average/Total	7.03	15.22	8.61	34.00	122.90	122.90	1560.65	11.50	11.50	141.64	11.18182

9.4 Lua Scripts

```lua
--init.lua
wifi.setmode(wifi.STATION)

station_cfg={}
station_cfg.ssid="myWIFI"
station_cfg.pwd="myWIFIPwd"
station_cfg.save=true
wifi.sta.config(station_cfg)


wifi.sta.connect()
tmr.alarm(1, 1000, 1, function()
    if wifi.sta.getip() == nil then
        print("IP unavaiable, Waiting...")
    else
        tmr.stop(1)
        print("ESP8266 mode is: " .. wifi.getmode())
        print("The module MAC address is: " .. wifi.ap.getmac())
        print("Config done, IP is "..wifi.sta.getip())
        dofile ("script4.lua")
    end
end)
```

Figure 106: Init.lua script

```lua
-- initialize mqtt client with keepalive timer of 60sec
m = mqtt.Client("CLIENTID", 60, "dp", "miot") -- Living dangerously. No password!

-- When client  c onnects, print status message and subscribe to cmd topic
m:on("connect", function(m)
    -- Serial status message
    print (" connected to MQTT host \n\n")

    -- Subscribe to the topic where the ESP8266 will get commands from
    m:subscribe("/mcu/cmd/#", 0,
        function(m) print("Subscribed to CMD Topic") end)
end)

m:on("message", function(m,t, pl)
    -- Serial status message
    print (" got Message " )
    print("PAYLOAD: ", pl)
    print("TOPIC: ", t)

   if pl~=nil then
        if pl == "1" then
            print("ON")
            gpio.mode(4, gpio.OUTPUT)
            gpio.write(4, 1)
        else
            print("OFF")
            gpio.mode(4, gpio.OUTPUT)
            gpio.write(4, 0)
        end
    end

    -- Subscribe to the topic where the ESP8266 will get commands from
end)

```

```lua
-- Set up Last Will and Testament (optional)
-- Broker will publish a message with qos = 0, retain = 0, data = "offline"
-- to topic "/lwt" if client don't send keepalive packet
m:lwt("/lwt", "Oh noes! Plz! I don't wanna die!", 0, 0)

-- Connect to the broker
m:connect("b000123.northeurope.cloudapp.azure.com", 1883, 0, 1)

 local pir_in =0
 local last_pir_in=0
 local seconds=0
 local count_val = 0

gpio.mode(4, gpio.OUTPUT)

tmr.alarm(0,60000, 1, function()

   gpio.write(4, 1)
   tmr.delay(100);

   raw=adc.read(0)

   gpio.write(4, 0)

   print("Raw ADC "..raw)

    msg = "{\"RAWVal\": " .. tostring(raw) .. "}"

    topic = "/soil/" .. wifi.sta.getmac() .. "/"

    m:publish(topic, msg, 0, 0,function(m) print("Publishing") end)

end)
```

Figure 107: Script4.lua

9.5 Weather Data from Met Eireann

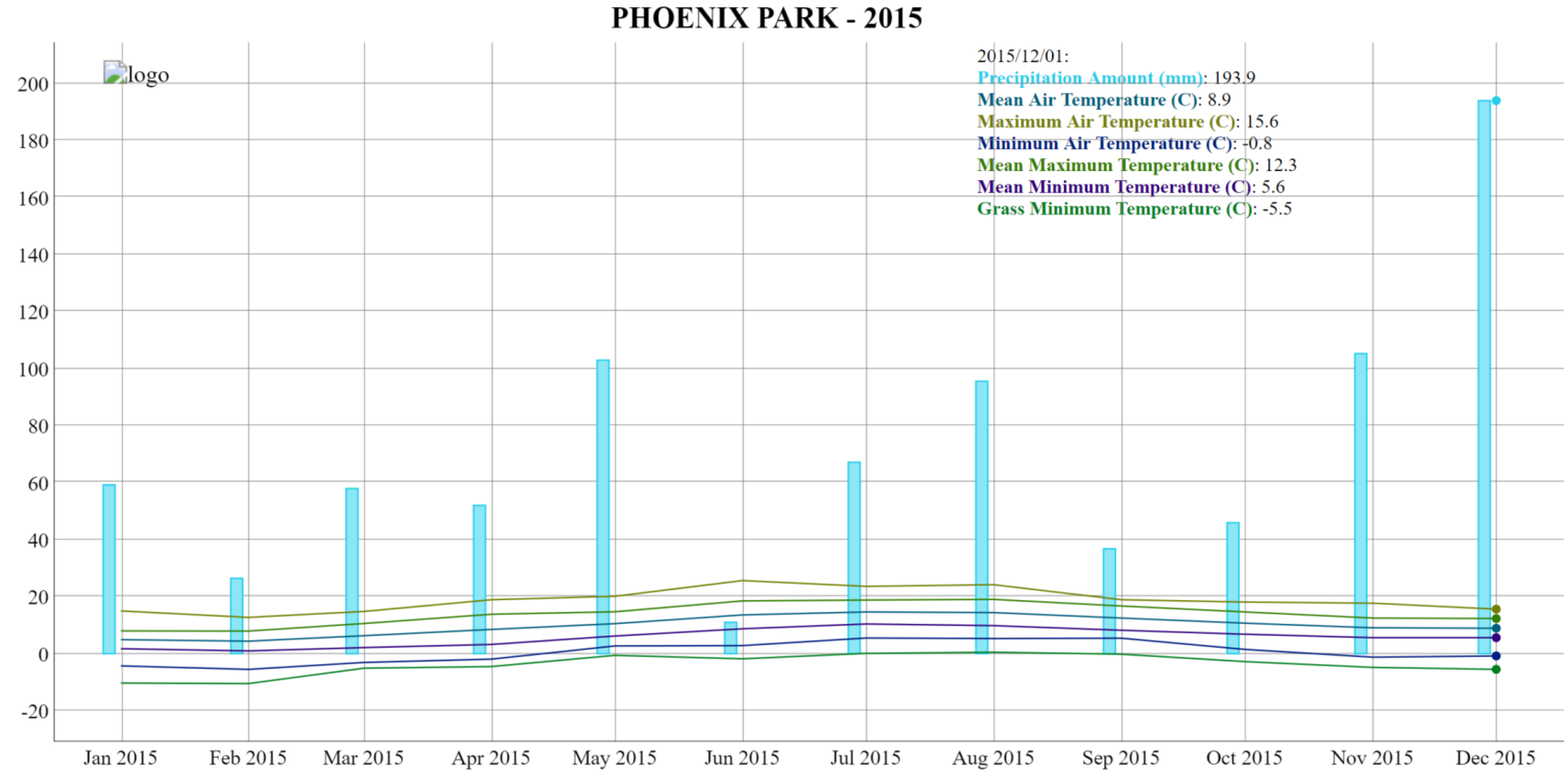


Figure 108: Annual Weather Data for 2015 from Met Éireann

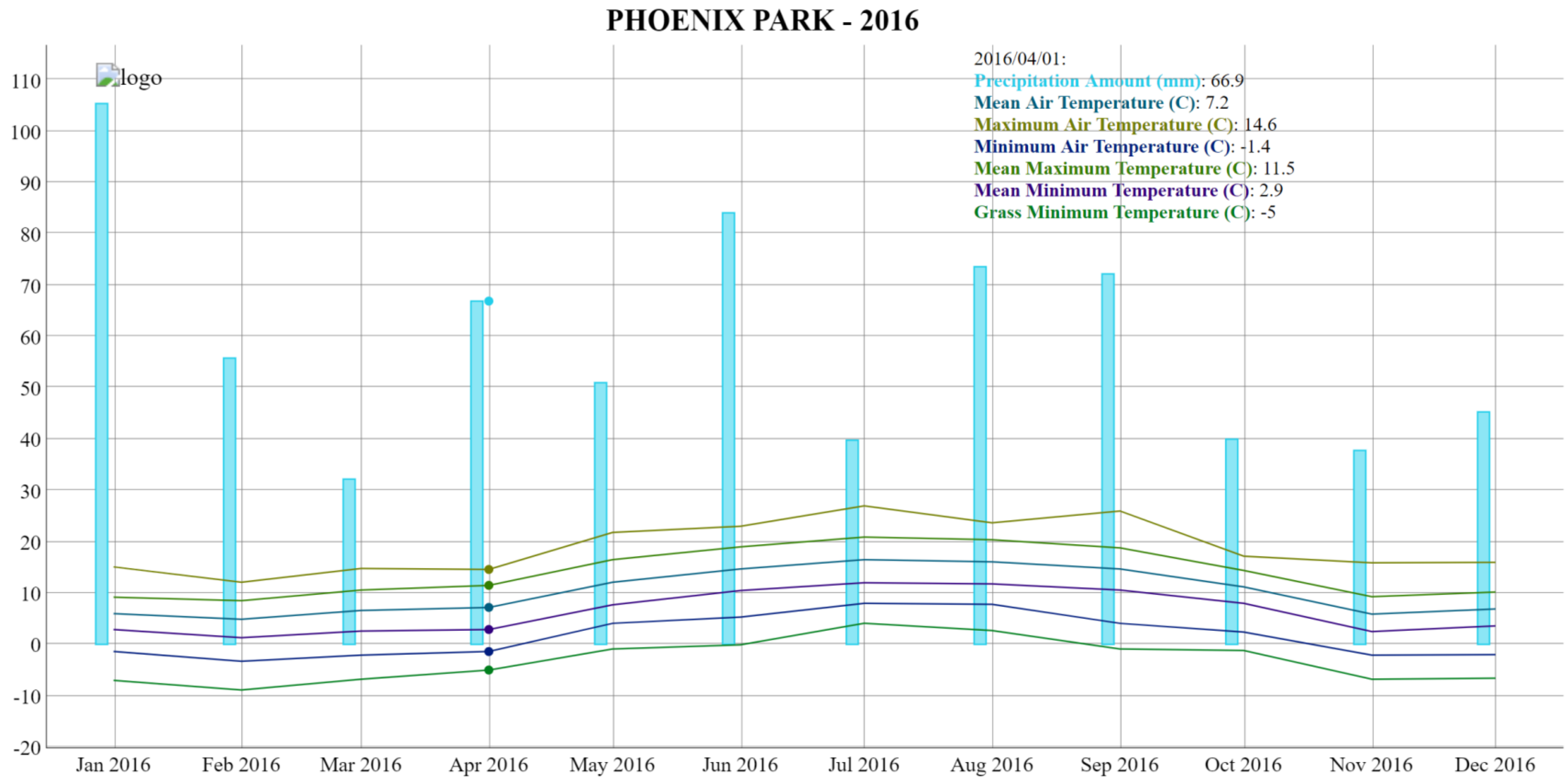


Figure 109: Annual Weather Data for 2016 from Met Éireann