NSSN
NSW Smart Sensing Network

Advanced Pipe Sensing to Reduce Leaks and Breaks

Final Report

December 2020

Report prepared by
Dr Don McCallum
NSW Smart Sensing Network

Foreword

Professor Hugh Durrant-Whyte

NSW Chief Scientist and Engineer

The role of the Chief Scientist and Engineer in NSW is to use science and advanced engineering to drive prosperity and deliver economic, environmental and societal outcomes for the State. The NSW Smart Sensing Network (NSSN) *Advanced Pipe Sensing to Reduce Leaks and Breaks* Program is a convergence of a number of fortuitous factors and opportunities: my own work over the past decade with Sydney Water around pipe failure prediction; a pressing unmet need of many Australian water utilities, including Hunter Water and Sydney Water, being local to me, led the call for technology to detect and predict leaks and failures in critical water pipes; and the emergence of the collaborative driving force of the NSSN.

From this convergence, a series of planning workshops ensued, resulting in an innovative, $4 million, research and development Program to develop, test and mature new sensing and machine learning methods – spanning quantum gravity, acoustic sensing and light detection and ranging (LiDAR) mapping technologies – to transform the way leaks and failures in critical water pipes are managed.

I am pleased to present this report describing the research and development work undertaken in this Program. It highlights major outcomes both for the water industry and Australian industry more broadly. The Program has demonstrated new ways of measuring, detecting and responding to leaks and pipe failures and has shown the effectiveness of many new sensing technologies when applied to these problems. I want to congratulate all of those involved in this program for the successful outcomes that have been achieved and for the spirit of applying and translating the very best of research in NSW into commercial reality.

Hugh Durrant-Whyte

Co-chair's report

Mr Craig Crawley

Committee of Management Co-chair

A water supply network is buried and the water it carries is under pressure. Inspection of pipes is expensive, and access may be difficult. This has left water utilities to manage their supply networks in a reactive manner, making repairs when a fault has occurred or planning to renew based on poor historical performance.

There has been a lot of investment in understanding the mechanisms of failure for metallic water mains. Understanding the parameters that can be used to infer the condition of a watermain was a key step toward a proactive approach to management of the water supply network. But a proactive approach will require a lot of data. Sensors are the next step to a proactive approach, allowing for the collection of data at a far cheaper cost and in a more flexible manner. With the right data, the scope and timing of repair and renewal interventions can be planned. This improves service to customers through reduced cost and outages and extends the life of water mains.

This program was formed to find a new way to collect the right data, using sensors. Its success was founded on the approach that was taken. The NSSN brought the leading research institutes and industry expertise to the program, while the water industry set out the problems that needed solutions. Through an initiation workshop, the industry problems were matched to a sensor technology in the best position to be developed into a solution, resulting in five projects going forward. This approach gave greater assurance of successful outcomes and shorter timeframes for the projects.

The research teams approached their task in an enthusiastic and professional manner. At the end of the program all five sensor projects had demonstrated their technology could measure changes and so, from the parameters, infer condition of the water network with calibration and/or interpretation. Two projects: Acoustic Sensing and Data Analytics, were ready to be operationalised and, with this, bring water utilities another step towards predictive repair and renewal of water supply networks. LiDAR, Distributed Acoustic Sensing and Quantum Sensing have shown, once further developed, that they may offer advantages as part of a total package of sensor and monitoring applied across water supply networks to improve performance and ultimately service to customers.

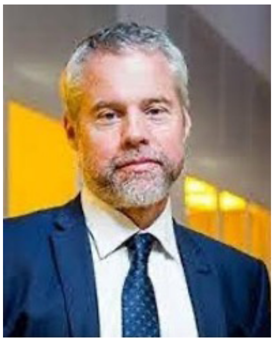
I would like to thank Dr Don McCallum of the NSSN for all his work in managing the program and also Dammika Vitanage and Rebeka Nikoloska of Sydney Water for managing the water industry participation and providing technical direction when required. I also thank my colleague, Paul Higham, who was Co-Chair for part of the Program.

Craig Crawley

Co-chair's report

Professor Ben Eggleton

Committee of Management Co-chair



In my role as Co-director of the NSW Smart Sensing Network, I am honoured to have been involved in the *Advanced Pipe Sensing to Reduce Leaks and Breaks* program, from its inception in the very early planning workshops right through to the final meetings. We have brought together a powerful consortium of universities and industry, working together on a grand challenge project – addressing a local problem that is globally relevant.

This is the first time such a comprehensive smart sensing approach has been taken to address urban water leakage. The program has considered a range of technology readiness levels and configurations, whether it be sensors in the pipe, attached to the pipe, above the ground, in the air or data analytics. We have pushed new technologies into real world systems and have been able to quantify the benefit of smart sensing in terms of reduced water leakage and the associated monetary value. All projects have delivered well on their original promise. The Quantum Sensing project has moved the dial on leading-edge science. The Distributed Acoustic Sensing project has translated technology from another sector – defence – for first-ever trials in the water industry and exposed new markets to companies like Thales.

A robust and evidence-based approach to the design and governance of the program ensured its success. We look forward to seeing Sydney Water and other utilities operationalise the innovations that have been resulted from this project.

The NSW Smart Sensing Network – as one of the NSW Innovation Networks established by the Office of the NSW Chief Scientist and Engineer – exists to foster exactly the type of collaboration between universities, government and industry that made this complex program possible. Translating the world-class R&D found in NSW & ACT universities into real-world impact will result in economic prosperity for the state and position NSW as a global leader in innovation.

Ben Eggleton

Executive Summary

The *Advanced Pipe Sensing to Reduce Leaks and Breaks* Program formally ran from 3 May 2019 to 2 November 2020. Coordinated by the NSW Smart Sensing Network, the collaborative program drew together 13 water utility, university and industry partners with the aim of reducing the loss of water from metropolitan water pipes.

The 13 collaborating partners were:

- Sydney Water
- Australian National University (ANU)
- Downer Group
- Hunter Water
- Intelligent Water Network (IWN)
- Melbourne Water
- NSW Smart Sensing Network
- Queensland Urban Utilities
- SA Water
- UK Water Industry Research in the United Kingdom (UKWIR)
- University of Newcastle (UON)
- University of New South Wales (UNSW)
- University of Technology Sydney (UTS)
- Water NSW

The NSSN was the key managing, facilitating and administrating organisation.

The Program consisted of five projects, each exploring a smart sensing solution to metropolitan water pipe failure:

- Acoustic Sensing
- Data Analytics
- Distributed Acoustic Sensing
- LiDAR Sensing
- Quantum Sensing

While the full impact of the research undertaken by the Program will take years to be realised, Sydney Water has estimated savings of over $3 million per year, directly attributable to the Program. This figure is based on estimates of 600–700 million litres (ML) per year saved from the success of acoustic sensing adoption in the Sydney CBD alone.

Data analytics advancements as part of the Program mean that 80% of the leaks and breaks on all sizes of water pipes can now be predicted with positional accuracy of 200 metres.

The Program succeeded in significantly raising the Technology Readiness Level (TRL) of a range of innovations that will be of use to the water industry. Gravimetry Sensing (gravity measurements of water plumes) has progressed to TRL 5/6; Quantum Sensing Techniques have progressed to TRL 3/4; Distributed Acoustic Sensing in a water pipe configuration has progressed to TRL 6/7; and Drone-mounted LiDAR techniques have progressed to TRL 3/4.

Background

Ageing water mains become increasingly susceptible to small leaks that develop into breaks, or significant breaks occur without warning. Their maintenance has become a major concern for water utilities across the globe, and while detecting and forewarning of leaks has achieved substantial breakthroughs, there remains significant room from progress.

As the largest stakeholder in this Program and one of the world's largest water utilities, Sydney Water's statistics provided the baseline challenge. Every day, Sydney Water supplies 4.6 million customers with over 1.4 billion litres of potable water to homes and businesses. Seven major dams store Sydney's water, with 80% of supply come from Warragamba Dam. Water from the dams is treated at one of nine water filtration plants, then supplied to customers through a network of over 21,000 kilometres of water pipes, 251 reservoirs and 164 pumping stations.

Each day Sydney Water loses around 8% of its water or around 112 ML (112 million litres). This is comparable with the production of a desalination plant. While this figure may seem alarming, in comparison with other global cities, it is a relatively low figure. One study found a global average of 21% water losses, with Montreal at 33% and Rome at 26% (McCarthy, 2016). There are around 175 leaks a year to mains pipes (those >300mm in diameter), and around 6,500 leaks on smaller pipes. The cost of detecting a leak is estimated at around $2,500. The renewal cost of pipes no longer fit for service is around $80 million per year. There exists further risk to human life, property and infrastructure when pipes fail.

The program aimed to:

- Create an improved framework for leak and failure prediction and assessment
- Improve identification of pipes for lining and repair instead of replacements
- Improve water customer satisfaction
- Enhance public perception and reputation of water utilities with government
- Minimise disruption to customers' property, surrounding infrastructure and traffic
- Minimise the disruption of water supply
- Minimise environmental impacts
- Inform position on future Internet of Things (IoT) requirements and any digital implications.

The *Advanced Pipe Sensing to Reduce Leaks and Breaks* Program built on a significant amount of prior research and an immense pool of industry knowledge. Studies from across the world and in the Australian context were referenced heavily as background to the research and development undertaken in this Program. The water utilities involved in the Program are at the forefront of understanding and applying leak detection interventions as well as being acutely aware of the importance of innovation in deploying reliable smart sensing tools to monitor and predict leaks.

All five projects in the Program claim success in that they have achieved and, in some cases, exceeded their research milestones. These five research projects were as follows:

Project One: Quantum Sensing

This project set out to investigate the feasibility of using gravimetry (a gravity meter) to locate underground water plumes caused by a typical leak before break conditions in buried water mains. The project consisted of soil sampling at two test sites, modelling expected water plume dynamics, inducing controlled leaks near test water mains, and measuring the gravitational signals above injected water plume. The work advances development of cold atom quantum sensors.

Project Two: Distributed Acoustic Sensing

The goal of this project was to test and validate the use of arrays of acoustic sensors (hydrophones) to detect leaks in water mains. It was postulated that technology originally developed to be used in open ocean to detect distant ships, submarines and other vessels, could provide a novel and disruptive tool for leak detection via acoustic means.

Project Three: Acoustic Sensing

This project investigated the deployment of commercially available acoustic sensors to detect leaks at localised, critical zones. The project began by reviewing the acoustic technologies for leak detection currently available in the market based on field experience from Australian utilities, and to a certain extent, international water utilities, supplemented by information from vendors and readily available in the public literature. The project then assessed these technologies' suitability for enhancing pipe failure prediction frameworks for the prevention of breaks in water mains. Collaboration with Sydney Water ensured for planning. It then deployed sensors in key trials in a selection of Sydney zones for the detection of leaks and breaks in water mains. There was a review of sensing experiences from utility partners and practical learnings.

Project Four: Data Analytics

This project used data analytics to prioritise zone areas and pipes to reduce pipe breaks and leaks using available data sets and advanced sensing. Pipe failure records, minimum night flow (MNF) records and water consumption data were collected and analysed. Methodologies of advanced machine learning were developed. Methods for generating risk maps and MNF correction were proposed and utilised to generate zone-level and pipe-level prioritisation data. The analysis aimed to demonstrate that the aggregation of pipe failure prediction models and a MNF model would provide an effective approach to a reliable zone prioritisation. This work also considered the prospective deployment of off-the-shelf acoustic sensors in prioritised areas.

Project Five: LiDAR, Soil and Corrosion

Pipe leaks and the corrosion of underground pipelines are related as they both influence the rate of each other occurring. Corrosion of these underground assets has been found to be caused by *free moisture* in the soil, that is water not held by the soil particles, commonly referred to as *above field capacity*. Pipes leaks, that are not repaired, will increase soil moisture, and hence the corrosion potential of pipes. This will eventually lead to thinning of the pipe wall and slow or catastrophic failure. Catastrophic failure leads to large volumes of water being lost from the potable water network and risk of life and property. This project aimed to address problems with both the underground pipeline corrosion and the detection of leaks in pipes by using light detection and ranging technology. The first part of this project investigated LiDAR elevation data for catchment wide terrain analysis to assess the potential accumulation of soil moisture across suburban environments. The second part used localised site-specific drone-based LiDAR laser intensity return (i.e. surface reflectivity measured in the near infrared region of the electromagnetic spectrum) to detect leaks from above the ground based on a change in soil moisture.

Program Management

The NSSN was the key entity in the program and project management. It held primary responsibility for stakeholder engagement, including organising Committee of Management meetings, reporting and record keeping. It kept contractual and financial oversight, aided by UTS. All 13 parties managed their own internal and external affairs. Overall, the program and project management is considered to have been of a very high standard.

Key findings

Project One: Quantum Sensing

The major achievement of this project is the validation of detection of underground water plumes using gravity measurement. The project successfully identified water plumes created via water injection near buried water mains in two trials with varying soil and background conditions.

Project Two: Distributed Acoustic Sensing

This project demonstrated through test and validation that hydrophone arrays could be used to detect leaks in water mains. It confirmed this technology could be translated from open ocean applications to the water industry. Pre-established leaks of various sizes were successfully detected at distances greater than 40 metres; leak types were acoustically characterised in the test pipe environment; background noise recordings were obtained and signal to noise ratios (SNRs) were calculated for all recorded leaks; and a method of array insertion for pipe testing was created and tested.

Project Three: Acoustic Sensing

In the key trials up to October 2020, 37 leaks and two breaks were detected by the various acoustic sensors. A large portion of these hidden leaks were subsequently repaired almost immediately by Sydney Water. Others required further investigations and planning prior to repair. This overall success was based on the review and practical assessment of commercially available acoustic sensors for leak detection; operational integration within Sydney Water for planning and sensor deployment; joint collation, review and report on leak verifications; and review of existing sensing experiences from utility partners and practical learnings. Project savings from sensor deployments have been estimated to be up to $3 million and 700ML/year.

Project Four: Data Analytics

Data on over 365,000 pipes in the Sydney Water network were analysed and a failure prediction model created. This analysis generated a priority list table and heat map to indicate pipes likely to fail. The failure prediction was cross-checked against real failures every three months. The validations are found to be approximately 80% detection rate if 20% pipes are inspected and also spatially predicted within 200m. Very few predictions around the world achieve similar outcomes. Minimum night flow analysis allows Sydney Water to measure MNF values more reliably, and to identify zones with higher leakage probability. Pipe prioritisation in selected zones/areas assists in sensors deployment, including deployment.

Project Five: LiDAR, Soil and Corrosion

LiDAR technology, through elevation and intensity data, can enable the water industry to increase asset management effectiveness. The topographic indices that were calculated from existing airborne LiDAR from the NSW Government estimated relative soil moisture and infer a corrosion pitting depth per year. The drone based LiDAR intensity was able to distinguish between dry background soil moisture and a simulated leak which increased soil moisture. This demonstrated that LiDAR information, either from stored data sets, or specifically acquired using drone fly-bys over target regions, could be used to sense leaking underground pipes,.

Recommendations

These recommendations are the considered consensus from discussions in the Committee of Management, information provided in the final technical reports and other post project communications. The recommendation themes – Commercialisation, Operationalisation, Dissemination, Further Research and Adaptation – are presented in the order that we believe offers the most economic and employment impact to state government and other stakeholders.

Commercialisation

Start-up companies

Where appropriate, start-up companies should be formed to drive the development and sales of the technologies that have been developed. For example, the finalisation of this program coincided with key staff from ANU committing to a new company, Nomad Atomics (https://www.nomadatomics.com). Zedelef (http://zedelef.com.au) should be encouraged in its efforts to further develop acoustic arrays. Consultants could help to consider business models that capitalise on data analytics and acoustic sensing findings.

Commercialisation by Sydney Water and other water utilities

Following the example of IOTA https://iota.net.au owned by South East Water in Victoria, Sydney Water should consider developing a commercialisation entity to exploit the research developments of this program, and Sydney Water's considerable back catalogue of research success.

Commercialisation support by major players

Thales, Downer, UTS, the UK Water Industry Research in the United Kingdom and others should also consider business cases and financial modelling for the exploitation of the research emerging from this Program.

Operationalisation

The water utilities directly involved – Sydney Water, South Australia Water, Queensland Urban Utilities, Melbourne Water and the many utilities represented by the Intelligent Water Network in Victoria and UKWIR – should immediately harness results and develop plans for implementation into their normal operations. Awareness of the outcomes should be raised with other actors in the water sector including Water Services Association of Australia, Water Research Australia, the Australian Water Association, and Water Research Foundation in the USA.

This is particularly with regard to the acoustic sensing and data analytics tools. The projects showed all commercially available sensors are able to detect leaks and deliver substantial cost savings to water utilities. The options offer varying robustness, range, battery life, cost, maintenance, access to raw data, GPS information, download quality, reception, and other operational factors. UTS is well placed to advise and support utilities wishing to take up the technology.

LiDAR and corrosion knowledge allow for the terrain wetness index maps into artificial intelligence maps that are used by water utilities to predict pipe breaks (as per Project Four). LiDAR intensity measurements from drones being flown over large areas and the resulting point can be processed to assess leaks along pipelines. This can provide information on relative wetness and relationship to corrosion, given similar other conditions.

Dissemination

The outcomes of the program should be widely disseminated via:

- Social media such as LinkedIn and Twitter
- Traditional media including television, radio and industry publications
- Technical reports aimed at managers and engineers in water utilities
- Simplified fact sheets that highlight the outcomes
- Research publications that do not impinge on commercial or intellectual property (IP) outcomes.

Further research

Each of the projects has threads of enquiry suitable for further research that will yield greater predictive capacity, better asset and water usage efficiency and ultimately better business outcomes.

Concepts around fusion of multiple sensors and analysis of multiple data sets should be explored by combining the results of this Program and other developments. The considerable amount of research undertaken in this sensor fusion has shown how sensor fusion can be industry driven to meet the needs of water utilities.

Various adaptions and utilisation of fibre optic sensing including simulated Brillion scattering (SBS), use of dark fibre networks and functionalisation of fibre surfaces offer further opportunities for utilities to consider.

A secondary aim of this work was to sense pipes to forewarn of catastrophic failure this should be considered as a subject for a desk study with an extensive global literature review.

Adaptation

Adaption to other industries

The global market for pipeline monitoring systems is estimated at $US5.3 billion in 2020 and is expected to grow to $US7.9 billion in 2027 (ReportLinker, 2020). Outcomes of this research should be disseminated to mining, oil and gas, environmental studies, civil engineering, defence and many other industries where pipe elements and networks exist. Those industries should also be monitored in the future for technology appropriate for uptake by water utilities.

Adaption in other water problems

The findings of this research should be directed towards many other water problems. The techniques, particularly quantum, could contribute to better understanding of the water balance in the Murray-Darling Basin in Australia and to measuring the impacts of mining on surface and ground water resources.

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1. Program of Works

1.1 Program background and rationale

Better understanding and managing leakage is always a high priority for Sydney Water, but was particularly so in the context of the drought that was having a severe impact in eastern Australia in 2018. Exploring emerging sensor technologies was seen as a way to better position the organisation to respond to climate change and customer needs. Sensing, with the right technology and placement, could potentially provide information that would enhance water utilities' ability to predict potential breaks, so they could repair leaks and stop water losses in advance. This would allow utilities to move to proactive management of pipe networks, improving customer service while reducing operating costs.

Discussions between the Managing Directors of Sydney Water and Hunter Water (then Kevin Young and Jim Bentley respectively) and the NSW Chief Scientist and Engineer in 2018 led to an agreement to undertake a research project of this ilk. A collaborative proposal for these projects emerged. The focus was on application and assessment of different sensor technologies for leakage detection, trialling of novel methods and investigating the nature of sensor networks to develop predictive analytics.

Two background reports are of particular note:

Firstly, the Advanced Condition Assessment and Pipe Failure Prediction (ACAPFP) Project. (Kodikara, 2017). *"The ACAPFP project was developed and funded by the Australian, US and UK water industries to undertake fundamental research aimed at solving an intractable problem – the failure of ageing, large diameter (i.e., >300 mm) main ("critical") water pipes. Maintenance of ageing water pipe infrastructure is a major challenge for the world's water industry and can be very costly. Estimates of the total replacement cost of pipe networks in Australia exceed AU$100 billion. Over the five years from 2009, the costs of urgently needed asset replacement were estimated at around AU$5 billion. Estimates of maintenance costs over the same period were some AU$2.5 billion* (Nicholas & Moore, 2009)*."*

Secondly the Sydney Water process flow developed by Professor Hugh Durrant-Whyte (2020). It neatly, clearly and succinctly visualised the flow of water and associated data across agencies, infrastructure and systems. See section 12.2.

1.2 Program scope

Project initiation was driven by Sydney Water and the NSW Smart Sensing Network. Their collaborative spirit was key to the working methodology. There was a desire to include a wide group of stakeholders, including other utilities and industrial partners. There was also open-mindedness around science and technology, particularly for the adaption of technology from other industries, and an increasing awareness that the sensing ecosystem, Industry 4.0, the Internet of Things, Smart Cities, Big Data and so on are real drivers of innovation for industry.

The planning stages considered a range of technologies, deliberately spanning low Technology Readiness Levels, such as quantum, hybrid quantum and magneto-mechanical sensors, right through to high TRL offerings of commercial suppliers. Defence and civil engineering were canvassed for technologies that could be adapted.

A guideline framework (see Figure 1.1) was developed that would allow for these different technologies to be part of a coherent Program that would build towards decision making in water utilities, particularly with regards to asset management.

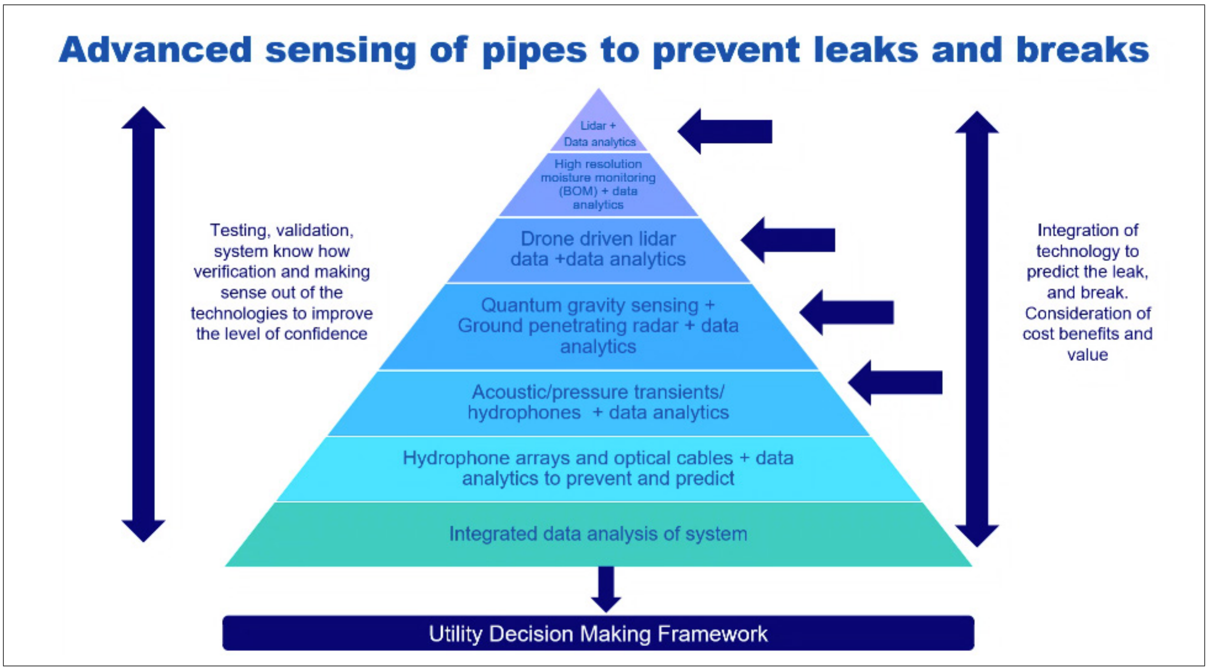


Figure 1.1: Utility Decision Making Framework.

2. Project One: Quantum Sensing

Department of Quantum Science, ANU

2.1 Introduction

This program report section discusses the technical outcomes and achievements by ANU and the University of Canberra for the Program's Quantum Sensing for Underground Pipe Leaks project.

2.2 Scope

High precision sensors capable of measuring gravitational acceleration have been used as effective tools to detect underground density variations in large geological systems such as mineral and hydrocarbon deposits. This project proposed to investigate the feasibility of using commercially available gravimeters as well as new portable quantum gravimeters to detect water plumes created around leaking water mains. It also intended to inform the development of a cold atom gravimeter, a far more advanced device that uses more quantum physics principles and is not encumbered by problems of drift and calibration associated with current available gravimeters.

2.3 Trial parameters

2.3.1 Objectives

The project culminated with an experiment to investigate the feasibility of detection in a simulated leak on an in-field water main. The trial phase consisted of ground-truthing the flow models as well as field measurements of the plume's gravitational signal. The successful completion of two field tests validated the proposed leak detection technique.

2.3.2 Locations

The first field trial was at a Sydney Water site in Potts Hill. Elements of this trial are reported below and a technical report on its objectives, data and outcomes are available on request. Details are provided below on the second trial on the Sydney Water test pipe in Strathfield.

2.3.3 Timeline

Table 2.1: Sequence of activities throughout trial period.

Milestone 1. March 2019 Start of phase 1, including arrangements for gravimeter, UC soil, density and water maps, design of forward modelling strategy and contact with knowledge base: U. Sydney (Eggleton, Cripps), NSSN, GA (Brown), U. Birmingham (Prof Bongs), Dr Lynn Pryer, Sydney Water.
Milestone 2. Delivery CG5 characterisation and measurements in Canberra. UC soil, density and water maps progress. Forward gravity modelling progresses. Increased engagement in broader problems for water utilities.
Milestone 3. Measurements including coring on Strathfield test pipe 20m length. UC soil density modelling in the presence of a pipe leak and ANU's forward modelling of this density field to surface gravity including environmental and sensor noise both performing as expected and successfully produced with current soil data provided by Sydney Water.
Milestone 4. Feasibility paper study interim complete. Comparison between numerical models and Potts Hill measurements (adjustment of location from Strathfield). Report on efficacy of gravity measurements to detect leak before break. Feasibility calculations made.
Milestone 5. Purchasing/hiring decision re CG6 or q-gravimeter.
Milestone 6. Phase 2 commences. Modelling and measurements on operational pipe in urban environment commence. Focus on environmental noise.
Milestone 7. Comparison of modelling and measurement on operational pipe. Modelling and measurement of clear water pipe commences at Strathfield (adjustment of location from Macarthur). Focus on environmental noise.
Milestone 9. November 2020 Reporting. Outcomes of quantum sensing to successfully identify leaks and moisture patches. Commercialisation plan.

2.3.4 Personnel

The list of personnel engaged is shown in Section 7.7.

2.3.5 Equipment

The list of equipment engaged is shown in Table 2.2.

Table 2.2: List of Equipment

Description	**Supplier**
Coring machine	WSP
CG5 gravimeter	Atlas Geophysics
Leak hose and pump system	Sydney Water

2.4 Trial details

2.4.1 Strathfield site

Figure 2.1: Red line showing the approximate location of the Strathfield test pipe relative to local streets and houses.

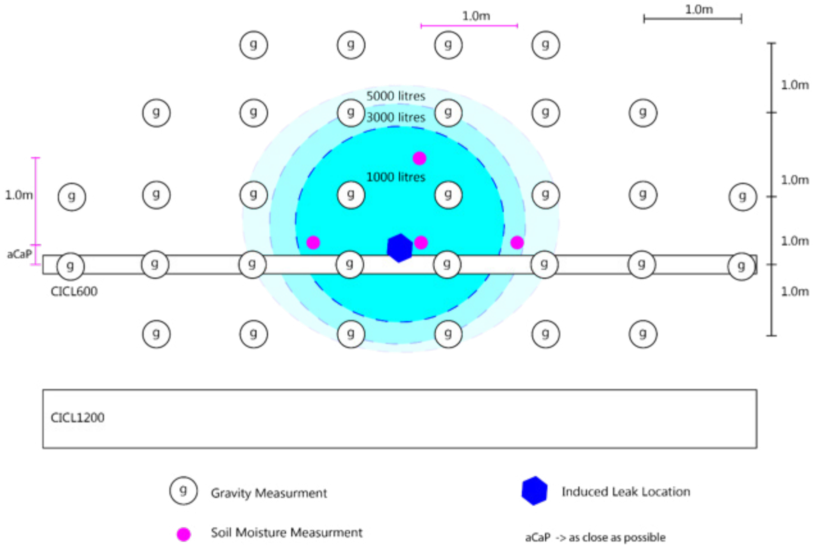


Figure 2.2: Gravity plan for Strathfield test pipe.

2.4.2 Coring

The coring plan for the Strathfield test pipe is shown in Figure 2.3. This consists of five total test cores (shown in red in Figure 2.3) from one side of the test pipe reaching ~2 metres away from the pipe and 1 metre along its length. All cores were taken to a 4 metre depth.

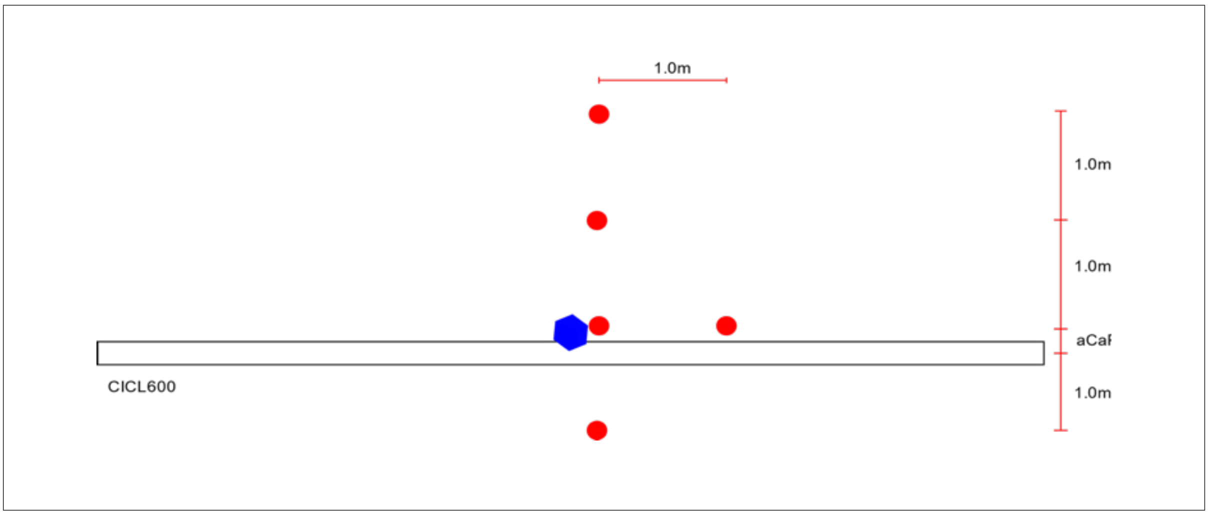
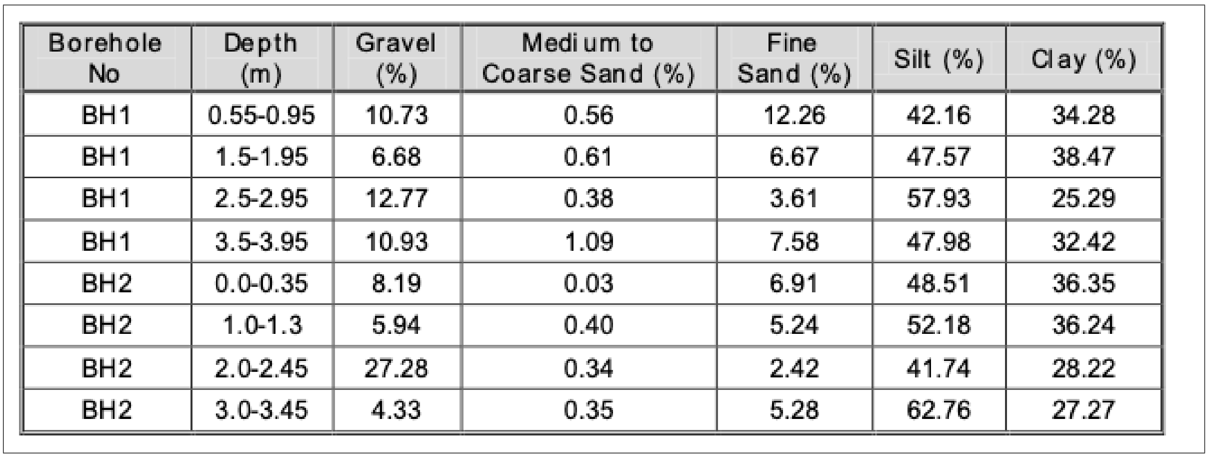


Figure 2.3: Coring plan for the Strathfield test site.

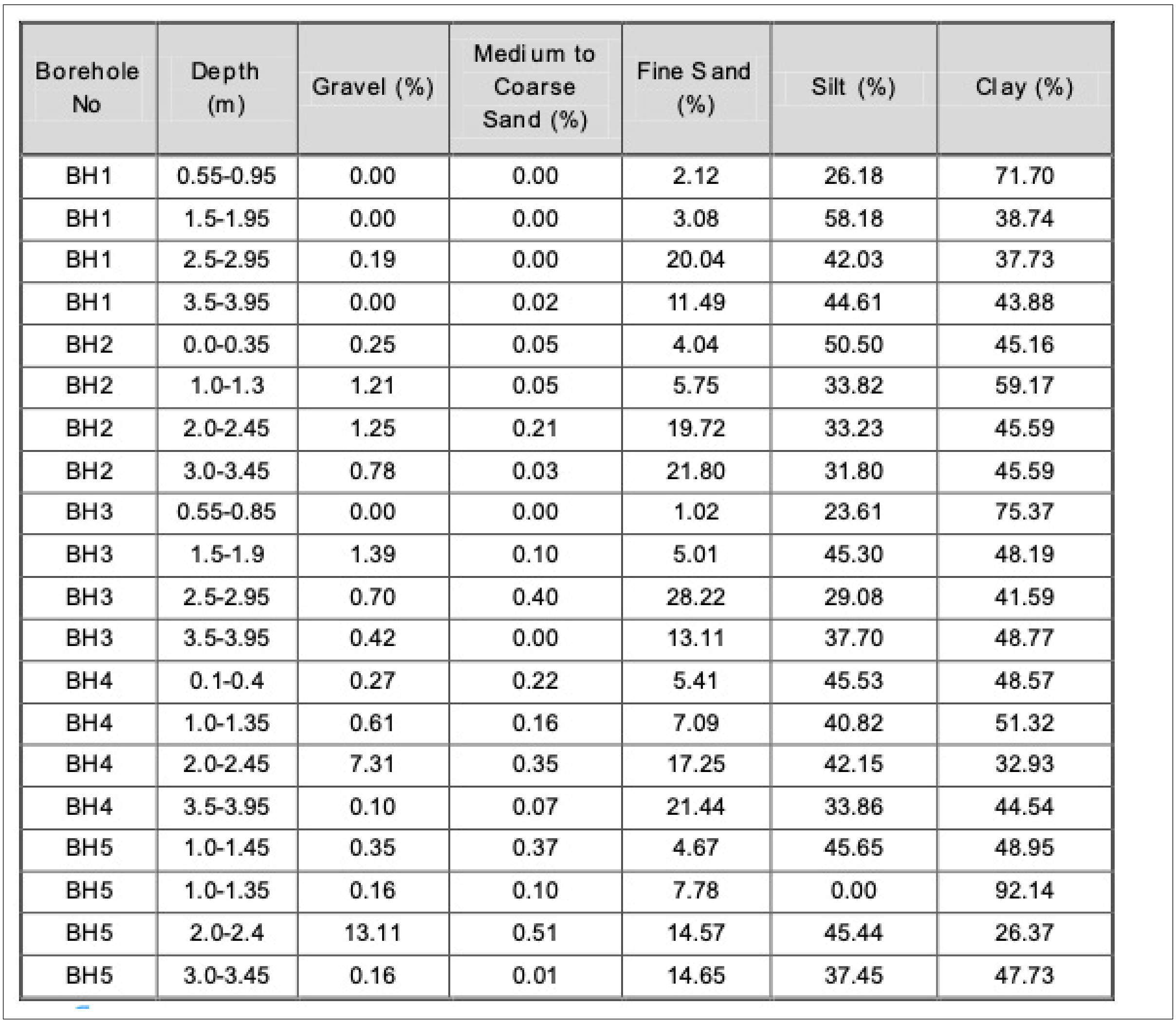
The critical coring information for both the Strathfield and Potts Hill sites are shown in Table 2.3 and Table 2.4. The full soil sampling reports including results of particle size determination test by WSP are held with Sydney Water.

Table 2.3: Soil sample data from the Potts Hill test site.



Borehole No	Depth (m)	Gravel (%)	Medium to Coarse Sand (%)	Fine Sand (%)	Silt (%)	Clay (%)
BH1	0.55-0.95	10.73	0.56	12.26	42.16	34.28
BH1	1.5-1.95	6.68	0.61	6.67	47.57	38.47
BH1	2.5-2.95	12.77	0.38	3.61	57.93	25.29
BH1	3.5-3.95	10.93	1.09	7.58	47.98	32.42
BH2	0.0-0.35	8.19	0.03	6.91	48.51	36.35
BH2	1.0-1.3	5.94	0.40	5.24	52.18	36.24
BH2	2.0-2.45	27.28	0.34	2.42	41.74	28.22
BH2	3.0-3.45	4.33	0.35	5.28	62.76	27.27

Table 2.4: Soil sample data from the Strathfield test site.



Borehole No	Depth (m)	Gravel (%)	Medium to Coarse Sand (%)	Fine Sand (%)	Silt (%)	Clay (%)
BH1	0.55-0.95	0.00	0.00	2.12	26.18	71.70
BH1	1.5-1.95	0.00	0.00	3.08	58.18	38.74
BH1	2.5-2.95	0.19	0.00	20.04	42.03	37.73
BH1	3.5-3.95	0.00	0.02	11.49	44.61	43.88
BH2	0.0-0.35	0.25	0.05	4.04	50.50	45.16
BH2	1.0-1.3	1.21	0.05	5.75	33.82	59.17
BH2	2.0-2.45	1.25	0.21	19.72	33.23	45.59
BH2	3.0-3.45	0.78	0.03	21.80	31.80	45.59
BH3	0.55-0.85	0.00	0.00	1.02	23.61	75.37
BH3	1.5-1.9	1.39	0.10	5.01	45.30	48.19
BH3	2.5-2.95	0.70	0.40	28.22	29.08	41.59
BH3	3.5-3.95	0.42	0.00	13.11	37.70	48.77
BH4	0.1-0.4	0.27	0.22	5.41	45.53	48.57
BH4	1.0-1.35	0.61	0.16	7.09	40.82	51.32
BH4	2.0-2.45	7.31	0.35	17.25	42.15	32.93
BH4	3.5-3.95	0.10	0.07	21.44	33.86	44.54
BH5	1.0-1.45	0.35	0.37	4.67	45.65	48.95
BH5	1.0-1.35	0.16	0.10	7.78	0.00	92.14
BH5	2.0-2.4	13.11	0.51	14.57	45.44	26.37
BH5	3.0-3.45	0.16	0.01	14.65	37.45	47.73

The data acquired from the soil samples was used to produce fluid flow model prediction of the injected water plumes for estimations of maximum flow rates and the spatial extent of the plume.

2.4.3 Flow models

Potts Hill

The soil data acquired for Potts Hill was used to build accurate flow dynamic models of the injection scheme used in the first field trial. The injection scheme at Potts Hill is discussed in detail in the interim technical reports provided to the Committee of Management. Briefly, water was injected for a number of hours at high flow rates of ~1L/s followed by an extended period of time of no injection. These zero injection times were taken during the gravity measurement times (one hour) and overnight (12-14 hours). Initial data taken from the inground moisture meters suggested that the injected water plume was dissipating and migrating down significantly during these time periods. Behaviour flow models of the Potts Hill site using these flow rates and downtimes were created to attempt to understand this data. The plume dynamics are shown in Figure 2.4.

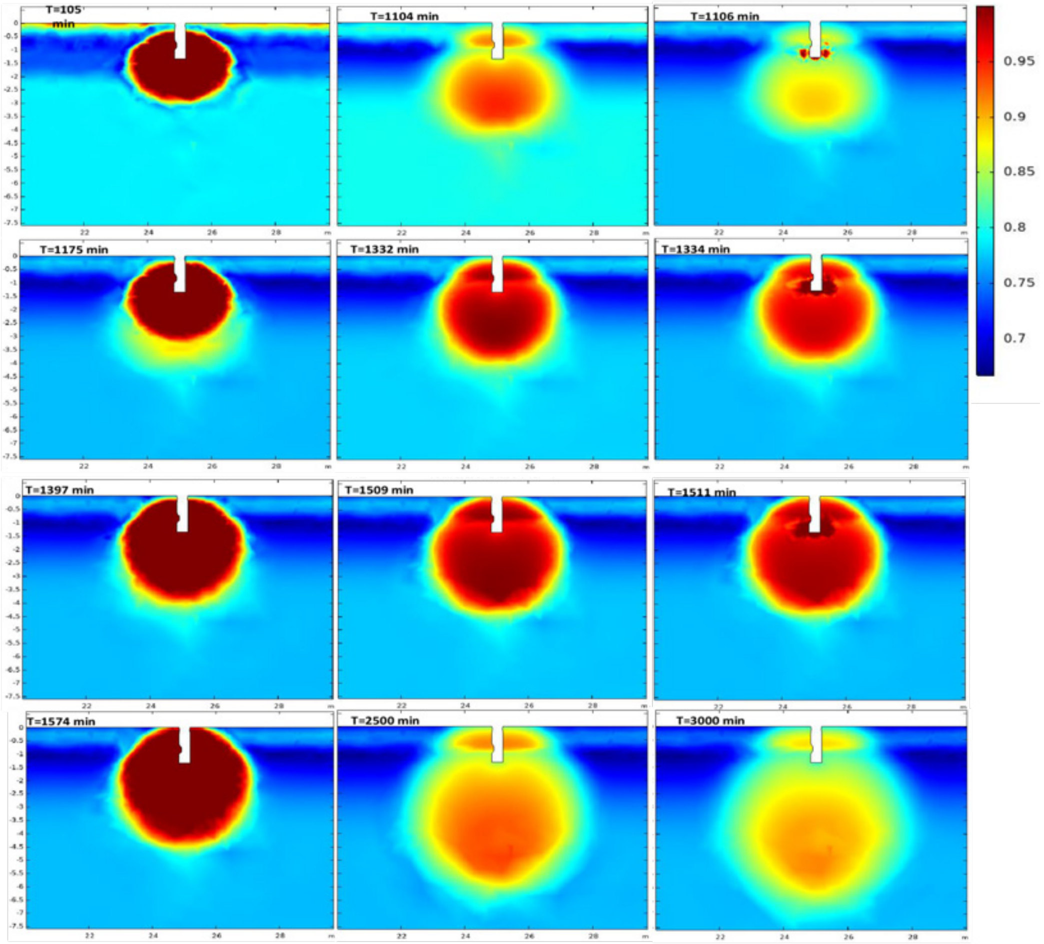


Figure 2.4: Plume flow models for the Potts Hill test site. The progress of images is as follows: The top left image is the resultant plume after ~2 hours of injection, then the flow is turned off and the plume migrates with no injection for 14 hours over the top middle and top right image, the injection is then turned on again for ~2 hours resulting in the second to top left most image. This injection and hold sequence are repeated through the figure until four days of injection and measurements have been completed.

The modelled plumes show qualitative agreement to the measurements made in the field. This suggests that this plume behaviour is a result of the relatively high gravel content of the soil likely caused because the area was formed from backfill from nearby infrastructure projects. Both the field data and modelling confirm that areas of similar soil properties (most likely urban) can sustain large leaks >1L/s without noticeable surface water over long periods of time.

Strathfield

The coring data from the Strathfield test site was used to make predictions about the expected limited injection rate, plume extent and plume migration during times without injection (night). An example of the results for the plume dynamics is shown in Figure 2.5.

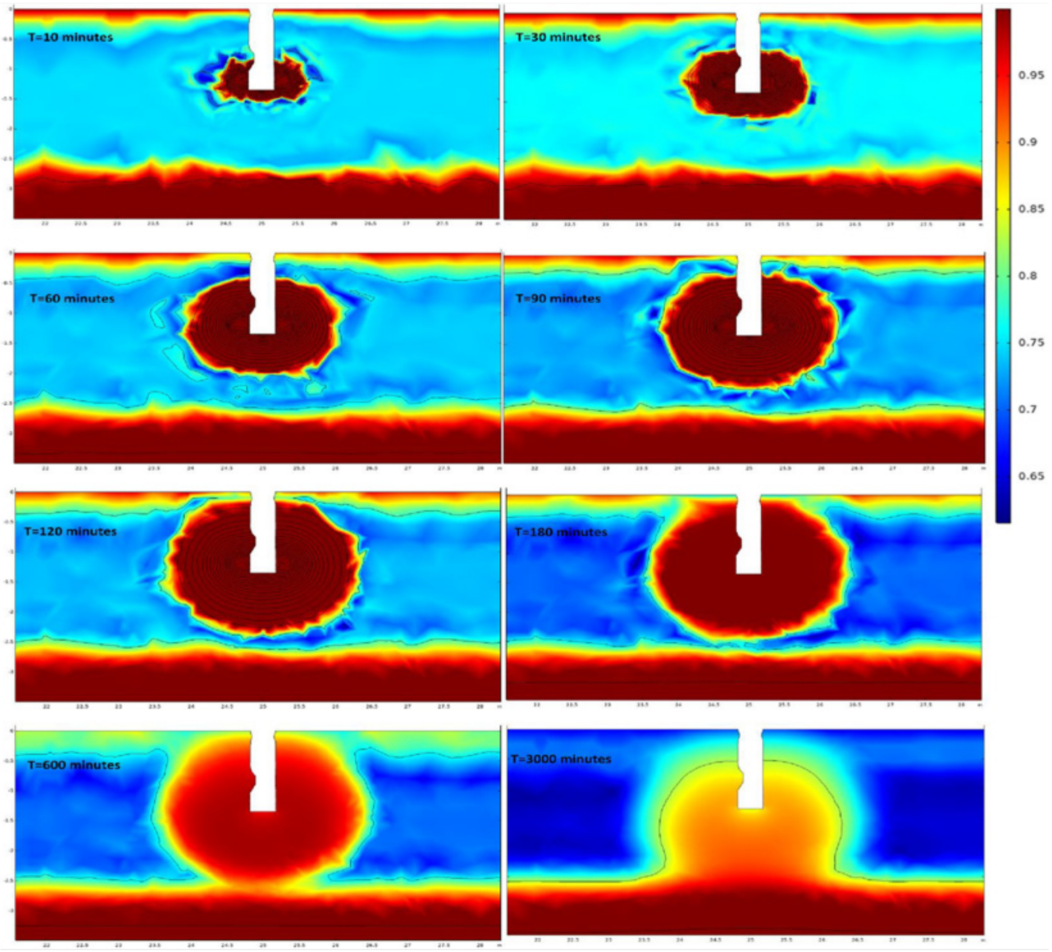


Figure 2.5: Plume flow models for the Strathfield test. The figure image progression moves from to left to bottom right. The first five images are the plume propagation during two hours of injection at 3L/s. The final three images show the plume dissipation and migration over two days of zero injection.

The plume modelling of the Strathfield site gives a number of critical insights. Firstly, the modelling shows that water mains in similar soil types can only maintain long-term leaks of a leak rate <3L/s before surface water will become visible. Additionally, it shows that the water retention of the soil is such that long breaks in injections, such as those needed overnight, do not allow the plume to migrate downward or dissipate substantially, allowing for consistent mass accumulation over the interrupted injection scheme.

2.4.4 Introduction of leak

An artificial leak was introduced to the test pipe 25 metres from West Fitzgerald Cres and as near to the south side of CICL600 as possible, see Figure 2.1. To introduce the leak a small bore was drilled using a 50mm grundomat. An oversized 60mm diameter pipe with drilled end cap was then hammered into the hole to ensure a tight fit. Upon the insertion of the injection pipe, the fit was insufficient to hold the water pressure. To mitigate this a ~40cm deep cone was dug from around the top of the pipe and filled with quick-set cement. See Figure 2.6.

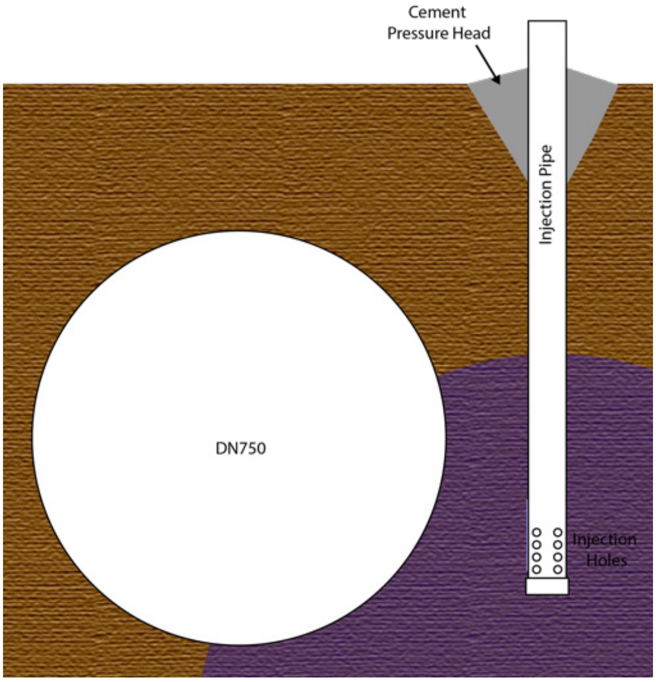


Figure 2.6: Water injection illustration around the standard 750mm diameter pipe. Water is represented by the purple colour emanating into the brown soil around.

With the addition of the cement pressure head flow rates of ~3 litres/minute were achieved. The total water injection at each day was as follows:

- Day 1:1440 litres
- Day 2: 2880 litres
- Day 3: 3880 litres.

2.4.5 Gravity measurements

The gravity measurements were made with a commercially available spring-based classical gravimeter, the Scintrex CG5.

Prior to making measurements on the plume, each measurement grid point location and height was measured using GPS, a height reference and retro reflector surveyor. For a detailed discussion of the gravity surveying technique and gravity corrections for height, air density, tidal forces and more refer to the previous technical report supplied to the Program. The analysed data from the Strathfield test site are shown below.

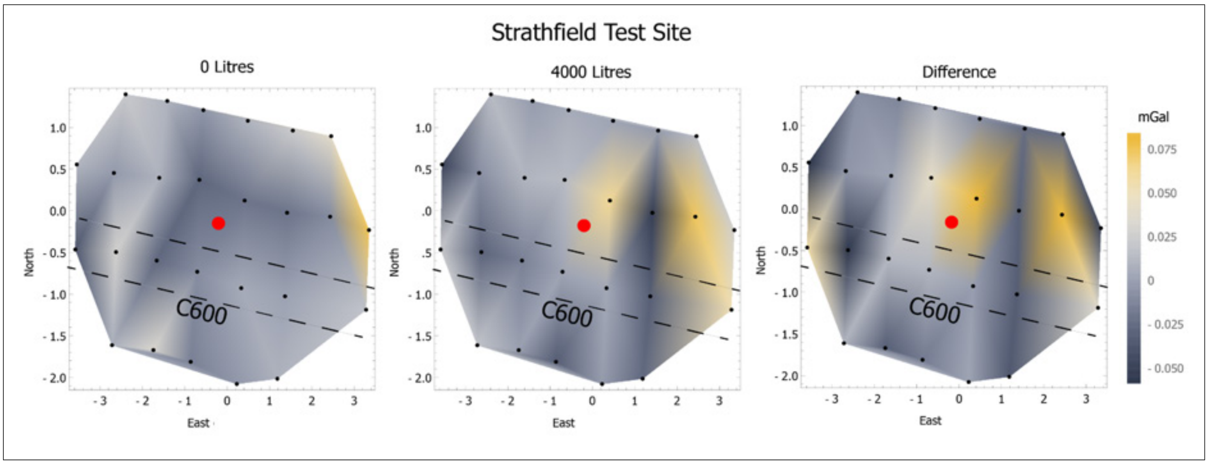


Figure 2.7: Gravity map produced from a CG5 with 0, and 4000l of water injected and the difference. Axis are in metres. Gravity measurements were made on the grid as specified in Figure 2.2*.*

An initial gravity survey taken over the first two days of the trial was performed to provide a baseline measurement prior to injection. Water was then injected over a series of three days at a rate of ~3L/m resulting in ~4000L of injected water. After the final day of injection, a second gravity survey was performed. The gravity measurements are shown in Figure 2.7. The data clearly show a correlation between water injection location, injected water mass and higher measured gravity.

2.5 Results

The analysis of the Strathfield gravity data suggests of a reasonable probability (~1σ, 68% probability) of leak detection without prior background gravity survey. This, in combination with the previous results at the Potts Hills test site, indicates validation of the detection of water plumes through their gravitational signal.

This novel technique may lead to the determining and locating of leaks before breaks in buried water mains via fully passive and unintrusive means. The use of gravity in combination with other technologies under development, including hydrophones, may allow for the location of leaks to the order of ~5 linear metres of mains. This increased resolution in leak determination has the potential to drastically reduce replacement costs.

3. Project Two: Distributed Acoustic Sensing

Electrical Engineering and Telecommunications, UNSW Sydney

3.1 Acknowledgement

This program report section is a reworking of a document produced by Thales: LCS Array for Water Pipe Leak Detection Trial Report 61257007_087-1 Revision A (Arcos, Read, Tyson, & Dent, 2019). Their original authorship is fully acknowledged.

3.2 Purpose

This section documents the Water Pipe Leak Detection Trial in November 2019 using distributed hydrophone arrays (liquid crystal sensor or LCS Array) at the Sydney Water Test Bed (SWTB) in Strathfield. Leak detection results are analysed and observations pertaining to mechanical insertion and recovery of the hydrophone array presented, along with recommendations for the general system design of a leak detection product ready for integration into the Sydney Water pipe network.

3.3 Scope

Technology developed for ocean monitoring was proposed as a solution for smart water management with the aim of leak detection in water mains using acoustic multi-channel systems. To generate a general system design for leak detection, an existing sonar array was tested in the SWTB to understand the capabilities and limitations of leak detection using sonar arrays. The unique property of the LCS system is the ability to provide a multiplexed data in an optic form that is highly vibration insensitive and potentially rugged against mechanical and environmental stresses. Optical data provides the opportunity to develop an array of hydrophones with substantial separation without inducing significant losses.

3.4 Trial parameters

3.4.1 Objectives

The objective of the trial was to detail the functionality and performance of the LCS array in locating simulated leak points, and to gain an understanding of the noise profiles for leaks of varying size.

3.4.2 Location

The leak detection trial took place at the Sydney Water Test Bed in Strathfield. A pipe section approximately 360m in length was used, running from Pit 1 at the Hume Highway end of the SWTB to Pit 2 at Fitzgerald Crescent, just before the Cooks River crossing. A tapping pipe section was installed into the test bed approximately 50m from Pit 2 at Fitzgerald Crescent, which contained four 20mm ball valves used to simulate leaks out of the pipe at different points on the pipe circumference. Details on the dimensions of the test pipe section, including length and testing locations, are illustrated in Figure 3.9. A drawing of the test bed and the pits used is included in Figure 8.1.

3.4.3 Timeline

Table 3.1: Sequence of activities throughout trial period

04/11/2019 – 08/11/2019 Preparation of SWTB by Linbeck contractors. Drag line installed approx. 380m of DN600 pipe section from Pit 2 to Pit 1. Tapping pipe section installed.
11/11/2019 - First day of trial Hydrophone array installation.
12/11/2019 Pipe filling from Pit 2 Test bed filled using standpipe from Fitzgerald Cres. Connected to 50mm ball valve on DN500 flange in Pit 2. Pit 1 reflux valve installation. Reflux valve installed between main and test bed to prevent back flow.
13/11/2019 Array battery unit installation. Pit 1 pipe section re-installation, to seal test bed with LCS array inside. Pit 1 main opened. Test bed connected to mains water supply at Pit 1 to fill the remainder of the pipe. Array moved to location A then location B. Simulation of leaks and data recorded in both locations.
14/11/2019 Array moved to location C then location D. Simulation of leaks, and data recorded in both locations.
15/11/2019 - Trial conclusion Test bed draining. Removal of flange, hydrophone array and tow cable. Site pack up and conclusion of trial.

3.5 Trial details

3.5.1 Installation of array

The array drum was located at Pit 2, and a drag line had been installed into the pipeline in the week prior to the trial. The drag line was connected to the array end cap, and the array and tow cable were dragged from Pit 2 at Fitzgerald Crescent to Pit 1 at the Hume Highway end (Figure 3.1). Once the array had reached Pit 1, with approx. 345m of tow cable lying in the pipeline, the remaining tow cable was unreeled at the Pit 2 end and passed through the DN500 blank flange and cable gland. The tow cable was rolled back onto the drum as it was passed through the flange, and the drum was placed on the ground outside Pit 2 where it could be connected to the inboard processing system (Figure 3.2).

Figure 3.1: Array pulled from Pit 2 to Pit 1 using drag line installed week prior to trial.

Figure 3.2: Tow cable and array off drum and into pipe through gap in plates. Drum and inboard system were placed on ground outside pit for duration of trial.

The DN500 blank flange was then installed on the end of the pipe in Pit 2. A DN600 to DN500 taper was installed to reduce the DN600 pipe down to the provided DN500 flange. With the taper and flange secure, the polyurethane casting was installed into the Conax cable gland, with the securing nut then torqued slightly to provide a water-tight seal around the armoured 2.15mm diameter Kevlar tow cable.

Figure 3.3: Sealing method around 2.15mm armoured tow cable. Conax cable gland used with polyurethane casting.

Following installation of the cable gland, the pipeline was completely sealed at Pit 2, with an open pipe end at Pit 1. The pipe was then filled with water using a hydrant at Pit 2, gradually increasing the water level in the pipe until water began to emerge from the pipe end at Pit 1 (Figure 3.4). The water filling process took approximately six hours through a 50mm connection in the DN500 flange at Pit 2. With the majority of the pipe full of water, the battery pack was installed on the end of the array at Pit 1 on the morning of Wednesday 13/11/2019 (Figure 3.4). Battery usage tests indicated that the array would function for approximately three days on the current battery setup (four AA batteries wired in series).

Figure 3.4: Hydrophone array in Pit 1 with battery pack attached. Array close to filled. Photo taken just prior to pipe section reinstalled at Pit 1 and test bed fully filled. 6.2

3.5.2 Recovery of array

Upon finalising all simulated leak testing, the draining of the test bed began on the morning of Friday 15/11/2019. The water was drained from the system by opening the 60mm ball valve on the DN500 blank flange (causing Pit 2 to fill with water), and then pumping the water from Pit 2 into the Cooks River. As the water was being pumped out of Pit 2, it was monitored by Sydney Water personnel for chemical imbalances, and was dechlorinated in order to protect the marine ecosystem downstream. Upon completion of draining, the DN500 blank flange was unbolted from the test bed, and removed from Pit 2 with the array still laying in the pipe and the tow cable still in place in the cable gland. The array was then dragged out of the test bed and rolled onto an auxiliary storage drum. Due to the inability to disconnect the mini-streamer section from the tow cable, the tow cable had to be passed through the blank flange and gland until fully rolled onto a storage drum. Following this, the cable gland was removed from the blank flange. Sydney Water personnel and Linbeck contractors finalised the site pack-up in the days following the test.

3.5.3 Array positioning

The positions of the array during testing are illustrated in Figure 3.5. Leaks were simulated at the Simulated Leak Point with the array centred on locations A, B, C and D. After the pipe was fully filled, the array was dragged (from the Pit 2 end) to be centred on Array Location A. As the hydrophone array is negatively buoyant, the array settled on the bottom of the pipe, contacting the pipe surface. After conducting all planned tests, the array was then dragged to location B, C and D, with a series of recordings made at each location. The array was dragged by hand from Pit 2, with one person pulling the tow cable and array and another rolling the cable onto the storage drum.

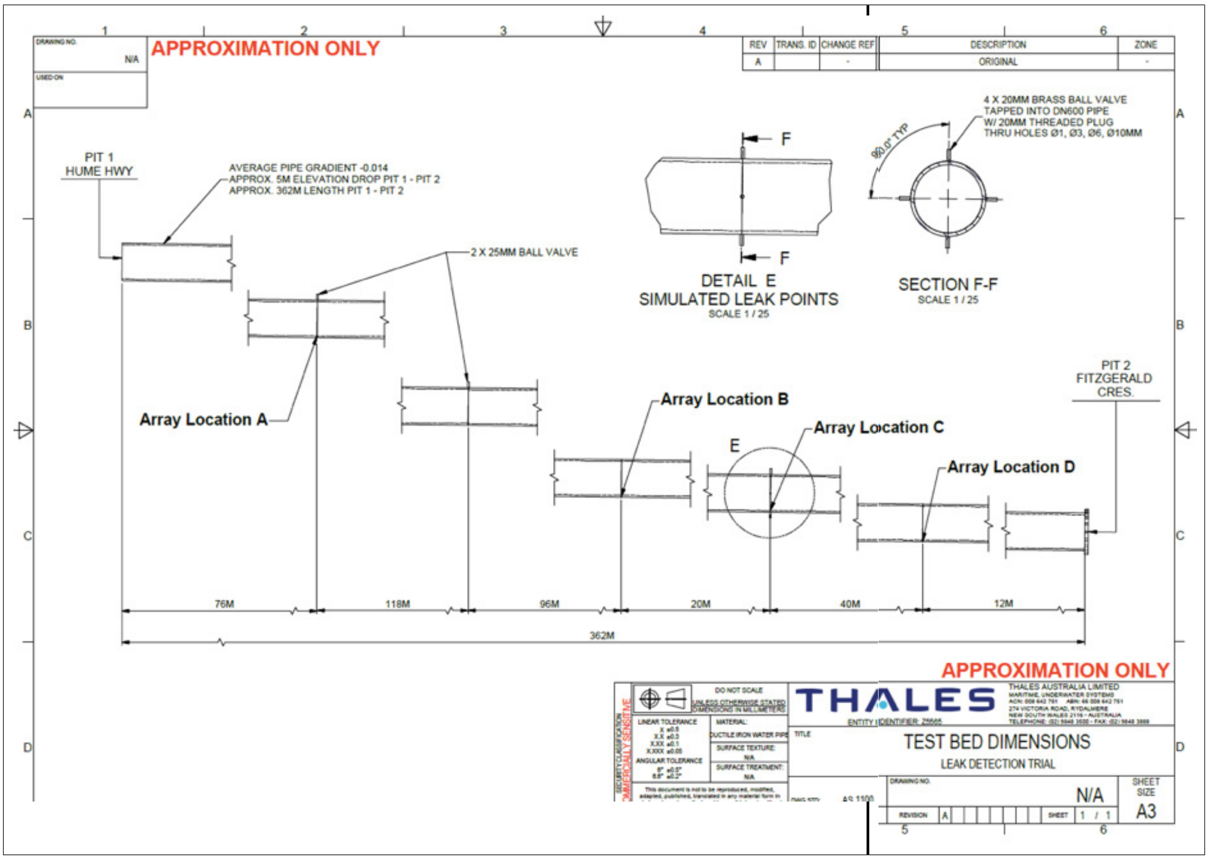


Figure 3.5: Test Bed dimensions, including array locations and simulated leak point location.

3.5.4 Leak induction

The simulated leak point (coincides with Array Location C in Figure 3.5) comprised a DN600mm pipe section approximately 3m in length. Four 20mm brass ball valves were tapped into the wall of this pipe section at 0, 90, 180 and 270° around the circumference. The brass ball valves enabled the creation of leaks from these four points.

Figure 3.6: The simulated leak points were tapped into a pipe section at 3, 6, 9 and 12 o'clock around the pipe circumference. Three leak points visible and circled.

In order to characterise the leak intensity, 20mm brass plugs with through-holes were threaded into the brass ball valves (Figure 3.7). The 20mm brass plugs contained 1, 3, 6 and 10mm through-holes, and were rotated around the different leak positions to determine the impact of varying leak location and intensity. An example of a 3mm leak is illustrated in Figure 3.7.

Figure 3.7: (Left) Example of simulated leak point, brass 20mm ball valve with a 10mm diameter leak fitting. Example of leak flowing out of a simulated leak point. (Right) A 3mm leak diameter with an approximate flowrate of 5 L/min.

For the top ball valve, a length of flexible tubing was used to mitigate the sound of leaking water falling back onto the pipe, and to prevent water spraying out of the pit during testing. Water was redirected from the leak point onto the floor of the pit. For other leak locations, the leaking water was not redirected. The sound of the water spraying out of the side and bottom ball valves was perceived as negligible in creating unwanted noise in the test, due to the high acoustic impedance between air and the pipe surface. For the top ball valve, the impact of a water spray falling back onto the pipe may have caused unwanted system noise due to the physical impact of the water on the pipe surface, emphasising the need for the flexible tubing to create a consistent test.

Figure 3.8: Flexible tubing used to redirect flow from the top leak point onto the floor of the pit.

Table 3.2 denotes average leak flowrates for the leak diameters drilled into the 20mm brass plugs that were installed onto the simulated leak points. The flowrates from each diameter were relatively consistent over the entire testing period, indicating that the loss of pressure from leak simulation had a negligible impact on leak intensity.

Table 3.2: Average leak flowrate for varying leak diameters.

Leak diameter (mm)	Average flowrate (L/min)
1	0.6
3	4.6
6	16.6
10	50

3.6 Data analysis

A summary follows of findings from recordings obtained during the trial. This includes key characteristics of the signals (e.g. frequency and amplitude) associated with the induced leaks. Findings are presented by referencing Figure 3.9 showing the different locations at which recordings were captured, including variations in the signals as the hydrophone array was dragged along the pipe from Array Location A to Array Location D. Location C (datum) at 0 metres represents the location in the pipe where leaks were induced.

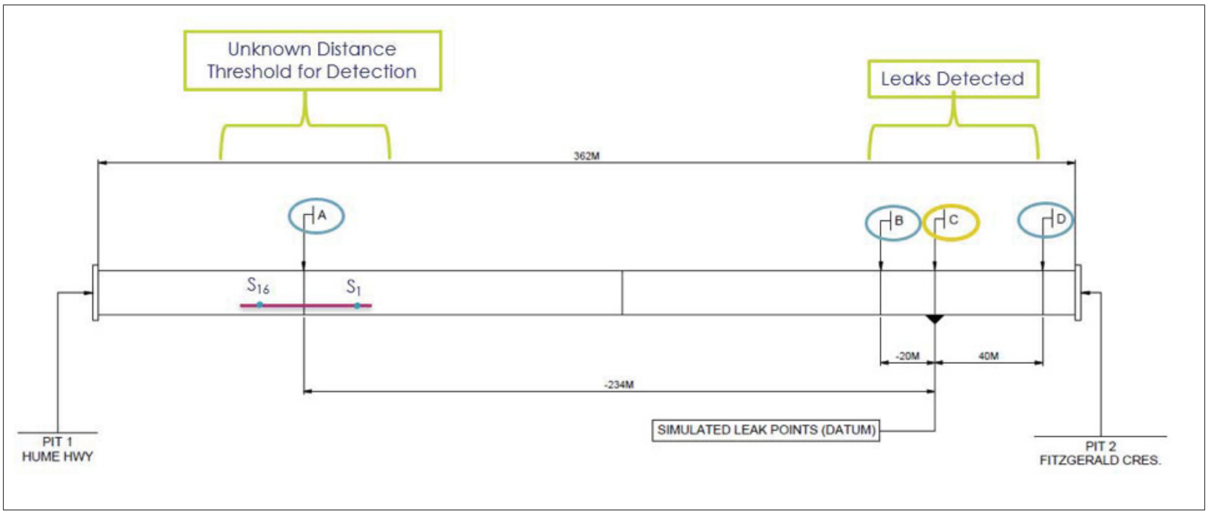


Figure 3.9: Array location in pipe at Points A, B, C and D.

3.6.1 Approach

For each run, recordings were extracted using the strongest channel in the array and the time-series were processed for feature extraction of frequencies and amplitudes associated with a leak. The root-mean-square (RMS) of the signal captured per channel was computed per run, to determine the strongest channel in the hydrophone array. The signal's spectrogram was computed by calculation of the short-time Fourier transform along segments of the signal to determine frequencies associated with the signal over time. The power spectral density (PSD) of the signal was evaluated to identify spectral components of the signal and their associated power, per unit frequency. The signal-to-noise ratio was calculated as a parameter to measure leak detection.

The above signal processing techniques were used as tools to successfully detect leaks that were induced at point C. For this trial, this was achieved by using the strongest channel in the hydrophone array to detect leaks at 20 metres (point B) and 40 metres (point D) away from point C. Induced leaks were not detected at 234 metres (point A). Envisaged future trials will focus on stepping to this distance at smaller intervals to identify the threshold at which a leak may be more difficult to detect. In total 64 data points (i.e. recordings/ runs) were successfully captured and analysed. These included ambient and leak measurements as summarised in Table 3.3.

Table 3.3: Number of recordings across categories.

Category	Number of Recordings
Leak	54
Ambient	9
Ball valves	1
Total	**64**

3.6.2 Reference hydrophone

Ambient noise was measured with a TC4013 Teledyne Reson Hydrophone positioned at the ball valve near array location A, shown in Figure 3.5. The conditions in the water pipe were either *No waterflow* or *Depressurised*. Figure 3.10 shows the spectrum of frequencies associated with the ambient noise as it varies with time. Frequencies below 500 Hz are present, more predominantly below 100 Hz, including other spectral components at 131.8, 219.7, 253.91 and 327.1 Hz. These frequencies were estimated by computation of the power spectrum of the signal.

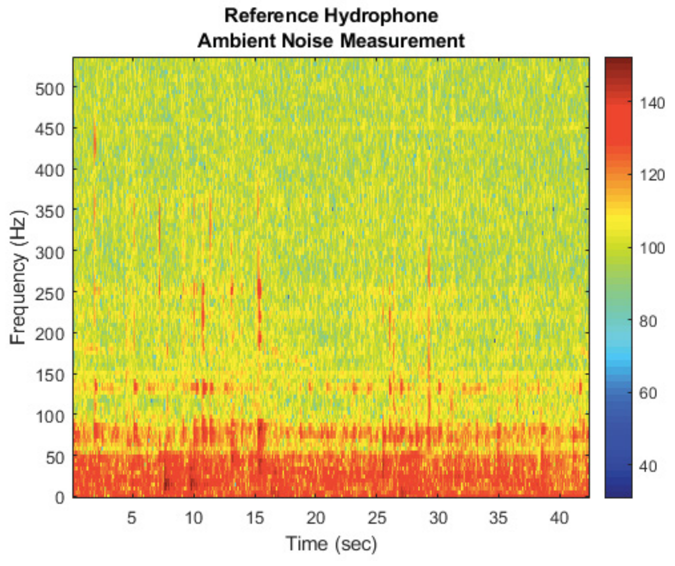


Figure 3.10: Spectrogram of ambient noise using reference Hydrophone at ball valve 1.

3.6.3 Leak position comparison

As described in section 0, simulated leak points were tapped into four different points of the wall of the pipe at Array Location C. At this stage, analysis of the recordings at other array locations away from C indicate that the point of leak induction does not have an effect on the detection of leaks by the hydrophone array. Acquiring more data in future trials would show if this is the case.

3.6.4 Array position comparison

Figure 3.9 shows the array location at points A, B, C and D. In total 54 recordings were obtained corresponding to induced leaks, as well as nine recordings of ambient noise. The approach for data analysis involved signal processing techniques outlined earlier to identify frequency and amplitude characteristics associated with the induced leaks. The signal-to-noise ratio was calculated for signals corresponding to runs during which leaks were induced. Table 3.4 summarises the detection of leaks depending on SNR values. Successful detection corresponds to SNR >= 3 dB. SNR values for all runs are kept on record. For SNR values between 3 dB and 4 dB, detection of leaks was confirmed by analysis of the spectrogram of the signal to identify transients corresponding to the induced leaks.

Table 3.4: Distribution of leak detections along positions A, B, C and D.

Array location	Distance from C	Detection	No Detection	Inconclusive*
A	234 metres	0	6	0
B	20 metres	11	5	0
C	0 metres	16	0	0
D	40 metres	6	9	1
Total		33	20	1

* In the inconclusive recording, the signal could not be distinguished from the noise present.

A total of 33 leaks were successfully detected. In addition to the evaluation of the SNR as a measure for leak detection, further spectral analysis of the signals was completed to extract frequency features of the signal corresponding to leaks in contrast to those of ambient noise. By computation of the power spectrum of each recording, a set of frequencies were identified as shown in Table 3.5. Identifying these set of frequencies would be significant to implement a rule-based detector for leaks. In the future, this could be approached by creating labelled datasets that could be used to train a model to classify the conditions in pipes as either corresponding to a leak or no leak. In addition, these could be used to more robustly measure the SNR of a signal around these frequencies and more accurately determine thresholds that would classify a signal as a leak.

Figure 3.11 shows the power levels of the signal in comparison to those of the noise, including the associated frequencies.

Table 3.5: Frequencies associated with leaks for recordings captured at positions A, B, C and D

Array location	**Distance from C**	**Leak frequencies (Hz)**	**Noise frequencies (Hz)**
A =	234 metres	No leak detection	136.7, 175.8, 234.4, 292.9
B	20 metres	449.2, 507.8, 527.3, 546.9, 585.9	253.9, 234.4, 468.8, 488.3
C	0 metres	332, 449.2, 507.8, 527.3, 546.9	214, 390.6, 410.2, 468.8, 488.3
D	40 metres	332, 312.5, 351.6, 371.1, 507.8, 527.3, 546.9	253.9,390.6, 410.2, 429.7

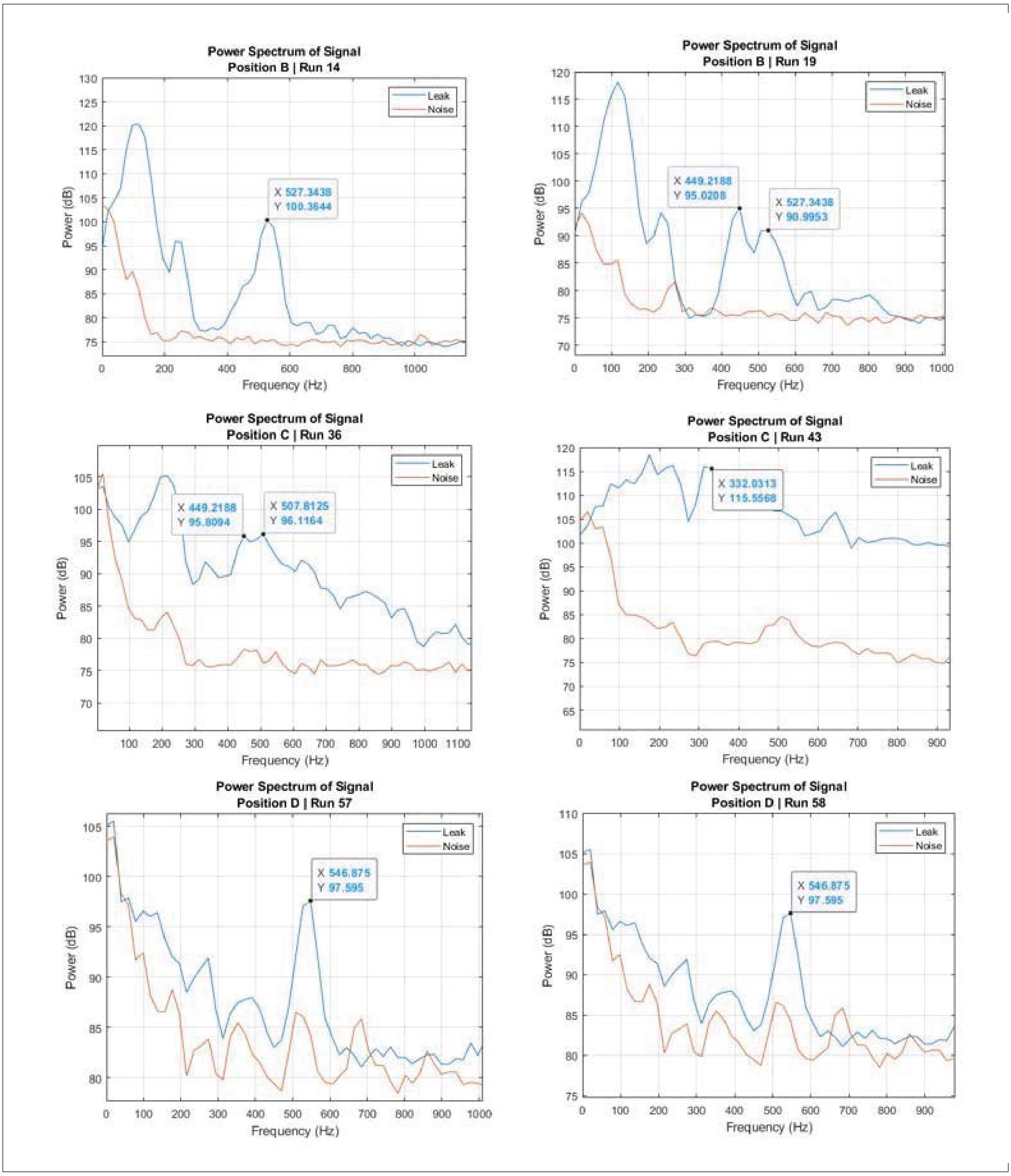


Figure 3.11: Power spectrum of signals (leak and noise) for recordings 14, 19, 36, 43, 57 and 58 at positions B, C, D.

Figure 3.12 shows the spectrogram of the signals previously shown in Figure 3.11. Transients corresponding to the start and end of leaks are evident. For likely future trials, ambient noise will be recorded for longer periods of time to enable better characterisation of the leaks, including more evident visualisation of the transients and shown in recordings 14, 19, 36 and 43, in comparison to 53 and 58. Despite noise and transients, leaks were detected across all these runs. Spectrogram plots were generated for all runs and have been included as Matlab figures in the project partner organisation's records.

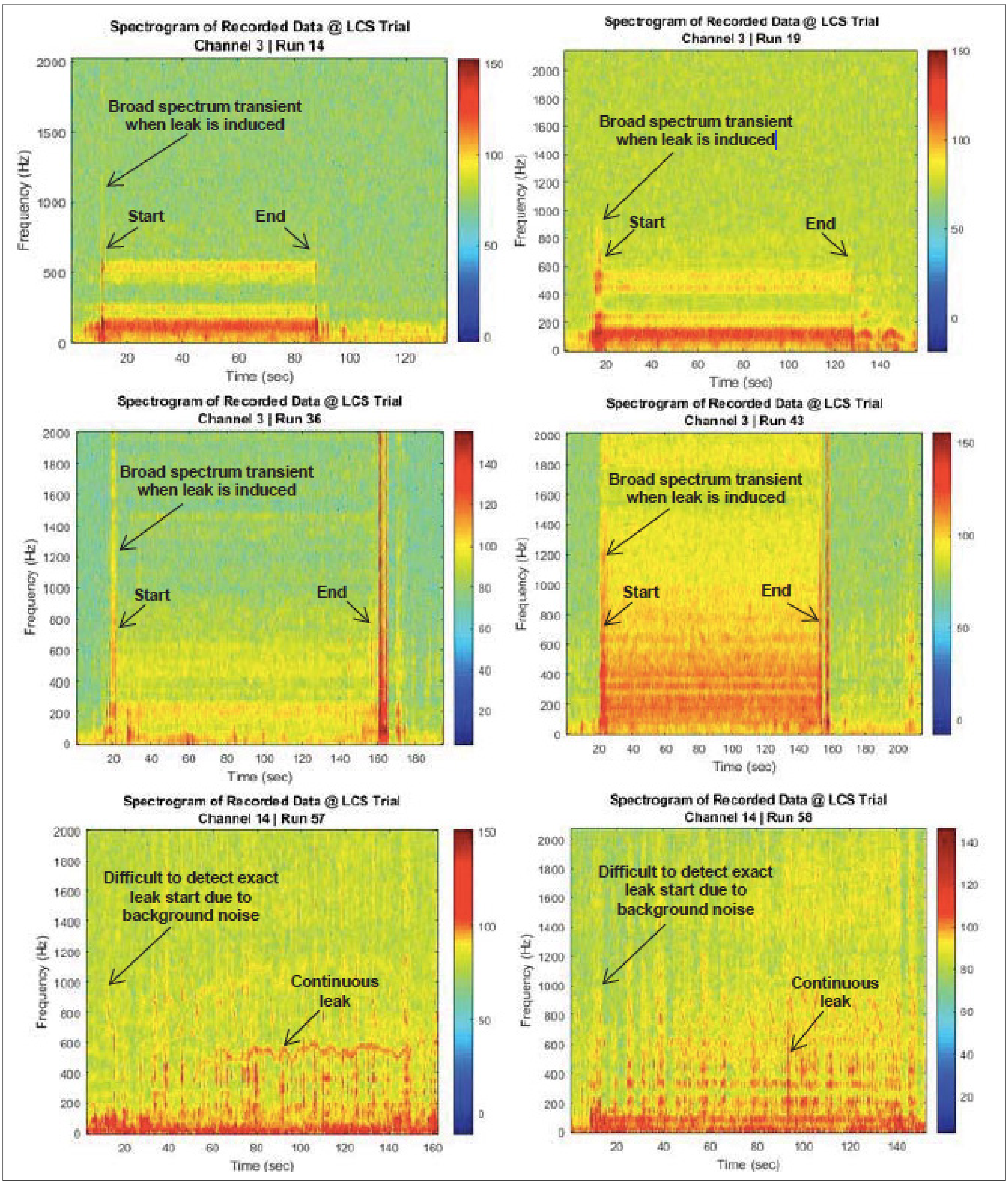


Figure 3.12: Spectrogram of signals for recordings 14, 19, 36, 43, 57 and 58 at positions B, C, D.

3.6.5 Channel comparison

Variation in RMS levels of the channels across points A, B, C, D were detected. This suggests that channel calibration may be required. Figure 3.13 shows the power spectrum of signals corresponding to detected leaks and ambient noise. In reference to these set of runs, further analysis was incorporated to identify variations in the RMS levels of each channel between runs at different locations along the water pipe. Noting that the hydrophones in the array are positioned in the order S16 to S1 as shown in Figure 3.13 the following is important to highlight:

- At positions A and B, Hydrophone 1 (S1) is closest to position C (datum); Hydrophone 16 (S16) is furthest away
- At position C all hydrophones (S1 to S16) are directly beneath the pipe location where leaks were being induced
- At position D Hydrophone 16 (S16) is closest to position C (datum); Hydrophone 1 (S1) is furthest away.

The overall RMS levels of the array channels vary in respect to the location in the pipe for comparison against RMS levels of the channels against other recordings/runs.

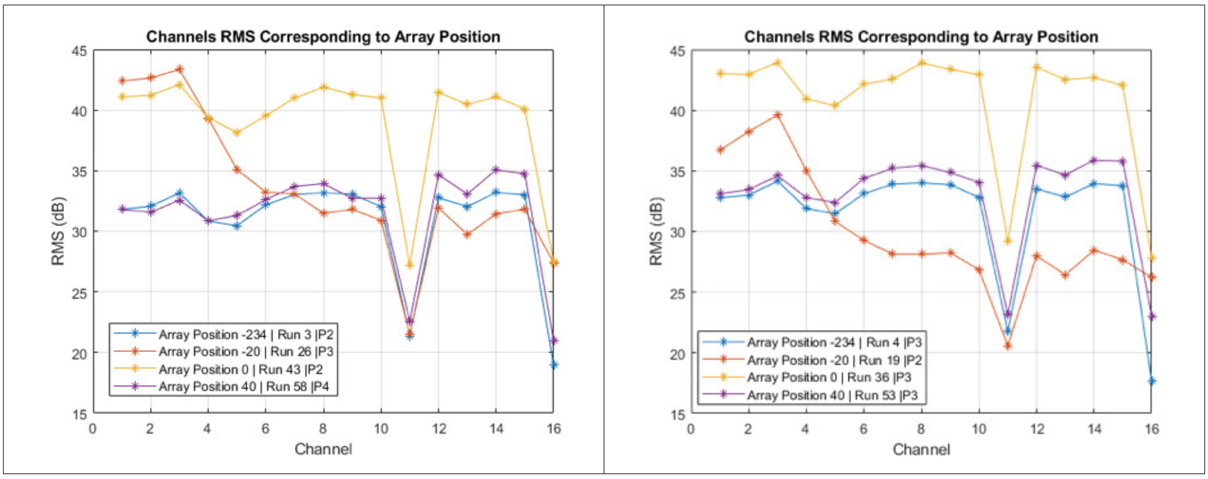


Figure 3.13: Channel RMS levels corresponding to recordings 3 and 4 (position A); 19 and 26 (position B); 36 and 46 (position C); 53 and 58 (position D).

Figure 3.13 shows the variation in the overall RMS levels of the array channels across different locations in the pipe. These correspond to a set of different recordings for comparison. The blue and purple curves corresponding to locations A and D show the smallest RMS channel levels as the array is further away from location C. In contrast, the red and yellow curves corresponding to locations C and B generally show stronger RMS channel levels. An exception is observed for channels 5 to 16 in the red curve at point B for which RMS levels are dropping. This was further investigated by plotting the RMS levels of all channels across time for the same recordings. Figure 3.14: Channel RMS levels corresponding to recordings 3 and 4 (position A); 14 and 19 (position B).

And Figure 3.14 shows the RMS variation is consistent with RMS values shown in Figure 3.13. Future trials would benefit from acoustic calibration of the complete system.

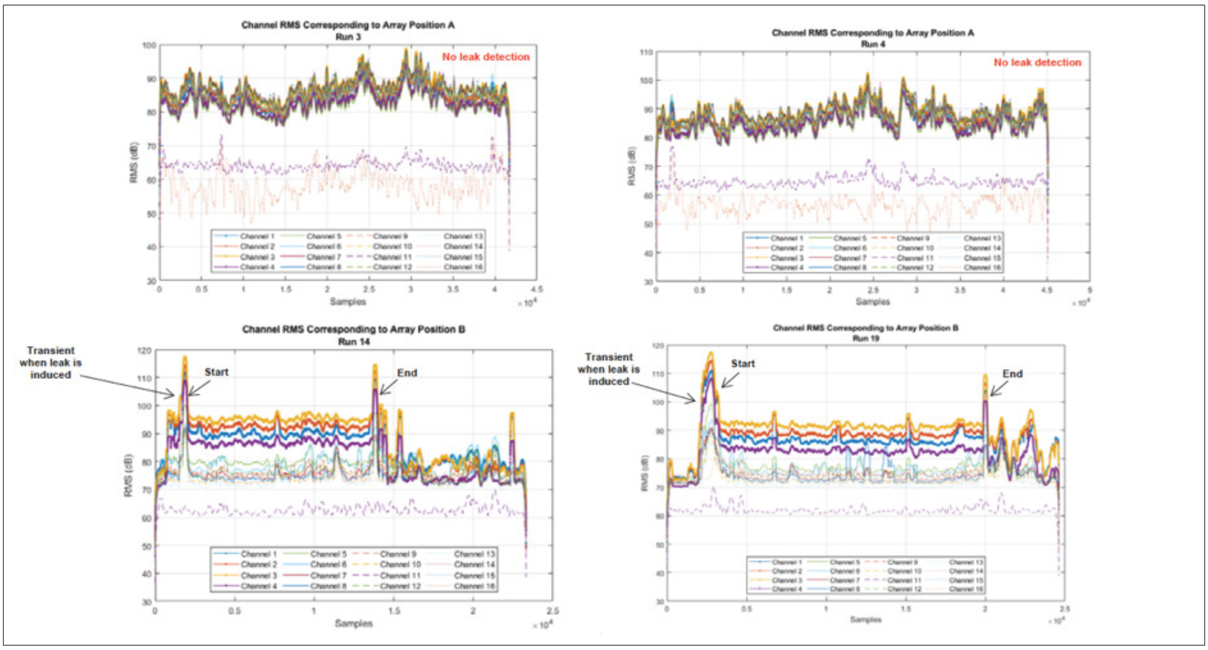


Figure 3.14: Channel RMS levels corresponding to recordings 3 and 4 (position A); 14 and 19 (position B).

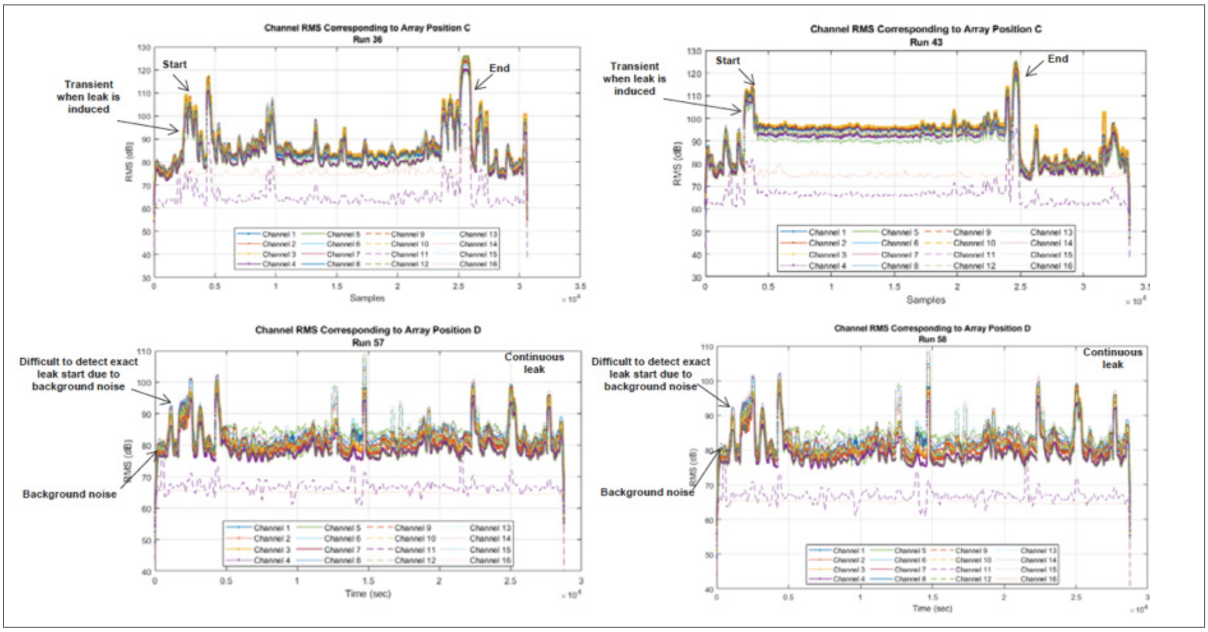


Figure 3.15: Channel RMS levels corresponding to recordings 36 and 43 (position A); 57 and 58 (position B).

3.6.6 Leak size comparison

Variations in the signal intensity were identified for different leak size. Table 3.6 summarises the effect of varying the size of the leak to the average amplitude of the signal measured. At array locations B, C, D for which leaks were detected in the water pipe, the average amplitude of the signal increases with larger leak size and greater flowrate. At position C, the amplitude of the recorded signal is on average greater than at B and D. This is consistent with the array being directly underneath the point where leaks were being induced. In comparison to B and D, the amplitude of the signal follows the same trend with a slight increase in overall amplitude of the recorded signals at position D. There is less variation at position D due to more noise interference. SNR of signals at position B and C are higher in comparison to D. This is consistent with an increase in background noise levels as the array is further away from position C.

These results suggest two potential areas of focus in future trials, as discussed below.

Overall, the general trend of a signal's amplitude increasing for larger leak diameters provides a potential mechanism to measure and identify the leak size in a pipe network.

Table 3.6: Amplitude of signals associated with different leak sizes at positions B, C and D.

Leak grouping	**Leak Size (mm)**	**Average Amplitude Array Position B = 20m (dB re 1 V / Hz)**	**Average Amplitude Array Position C = 0m (dB re 1 V / Hz)**	**Average Amplitude Array Position D = 40m (dB re 1 V / Hz)**
Group 1: small	1	82	90	87.5
Group 1: small	3	79	90.66667	94.33333
Group 2: large	6	87	90.66667	94.2
Group 2: large	10	100	115.75	98.75

3.7 Recommendations

It is recommended that future trials take place focused on the following aspects:

- Acquiring more data for longer periods of time to enable further characterisation of features associated to leaks in comparison to those of the noise. This will also require dragging the array at smaller distance intervals to determine the threshold of detection in varying conditions
- Improvements in Acoustic calibration of the complete system are needed, given the array used in this project was built as a concept demonstrator. This recalibration will ensure signal detections can be measured and classified from a calibrated system perspective, providing measurable, repeatable, comparable and classifiable results

- Implementing a leak noise correlator for both detection and location of leak in pipes by estimating the time delay between signals measured at two sensor locations of the hydrophone array. This requires knowing the propagation speed of sound in the water pipe (specific to each pipe's characteristics). A time delay is then estimated using cross-correlation approaches of the measured signals between the two or more sensor locations in the array to approximate the location of the leak
- Isolating background noise components interfering with those corresponding to induced leaks, in particular at distances further away from the point where a leak is located.

3.8 Conclusion

3.8.1 Summary

Key project achievements are as follows:

- Pre-established leaks of various sizes (i.e. of various flows as measured in litres/minute) were successfully detected at distances greater than 40 metres (see Section 3.1)
- Leak types were acoustically characterised in the test pipe environment, which will inform future development of leak detection algorithms
- Background noise recordings for the test period were gathered against the leak data for future reference and will also inform future development of leak detection algorithms
- Signal to Noise Ratios were calculated for all recorded leaks
- The project team created and tested an experimental method of array insertion for pipe testing which will inform the design of an operator useable array in subsequent development work.

Given the positive results obtained, the project team proposes to extend the original feasibility study with the development of tailor-made monitoring/detection systems adapted to Sydney Water's requirements. Discussions between various parties (Thales, Zedelef, Sydney Water) continued after the project (see section 8.3.2).

3.8.2 Potential for design evolution

The transmission of data captured by the hydrophones in the array, coupled with the use of optical technology provides:

- An opportunity to develop an array of hydrophones with substantial separation without inducing significant losses
- Capability of regularly monitoring large areas of a water network with the design of a longer sonar array
- Distribution of hydrophone arrays to monitor pipes in a water network, transmitting data back to a control centre for data processing and visualisation, as shown in Figure 3.16.

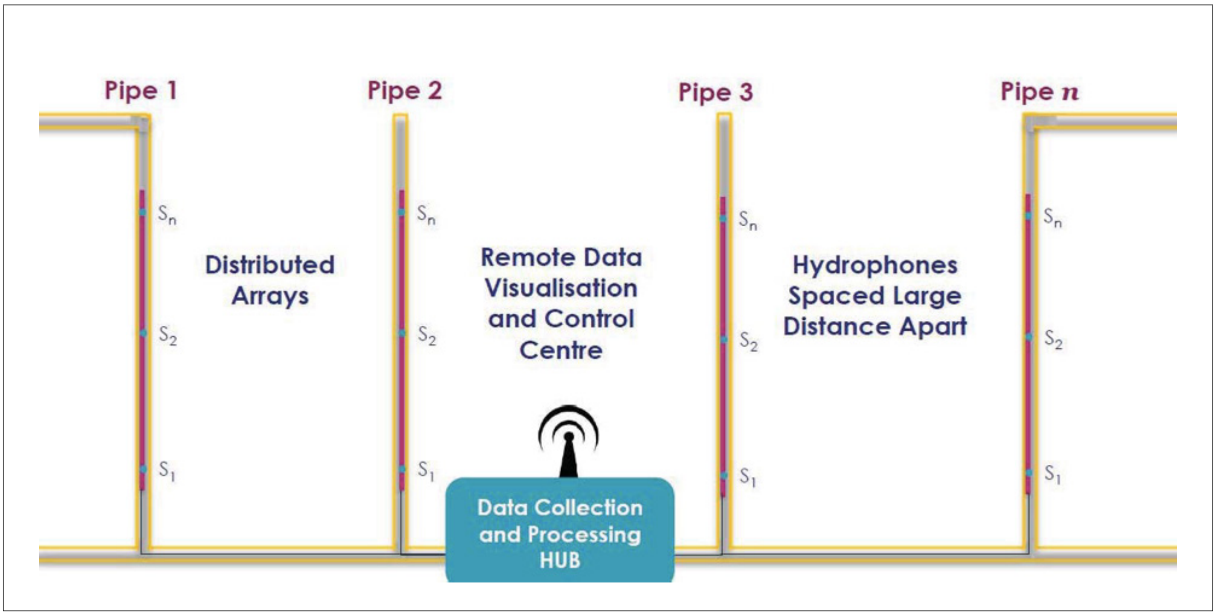


Figure 3.16: Evolution of design – leak monitoring and control using hydrophone arrays.

The overall existing array design was designed for bottom deployment within the ocean and towing from small ocean-going vessels. For routine deployment within pipes the array will need a complete mechanical redesign although many of the existing sub-elements are likely to be re-used.

3.8.3 Systems perspective

Subsystem elements in the overall system can be configured in different ways, refer Figure 3.17 below. Potentially the array assembly would consist of a set of sensor elements that could be connected in different physical positions and lengths via optic fibre cable connectors. This way the armoured optic fibre could run either external or internal to the pipe as most suitable the particular pipe location to be measured. Sensor sets could be positioned at varying distances apart depending on the best locations identified to record pipe condition.

Further work will be required on the reference calibration of the channels which would need adjustment factors to be implemented to deal with varying the length of optic fibre between channels. As also identified in figure below such a system would involve parts of Zedelef and Thales technology, and would require a business arrangement to facilitate the further development work required.

3.8.4 System maturity and commercial considerations

Thales considers the Technical Readiness Level of the system in its current evolution for maritime use to be TRL-7 built as a technical demonstrator. Considering the differences in requirements for sensing in pipes, Thales considers the system to be TRL-6 for this project, requiring further development effort before it is ready for commercialisation.

The primary areas of development effort still required are:

- A mechanical design suitable for deployment and use in pipe conditions monitoring
- Investigation into the system calibration end-to-end including investigation into areas of Thales and Zedelef scope. Elements include voltage sensitivity and linearity of LCS transducer to enable greater sensitivity; inboard electronics behaviour and channel management to enable absolute sensitivity calibration; and an increase of the number of channels per chain available in the LCS array currently set at 16
- Improvements to design and robustness of the inboard data acquisition system. This would comprise implementation of data processing onto dedicated cards to reduce inboard cost (currently using a high-end National Instruments data acquisition modular test system); and environmental testing, shock and vibration
- Development of specific sonar algorithms for interpretation of signals from the pipe sensing system. This would involve recording and collation of sufficient pipe condition data sets to enable a classification database to be collected
- Development of a Human Machine Interface (HMI) including a tailored pipe sensing interface for use on the developed system. The HMI's required features would be workshopped with users and designed to suit their needs.

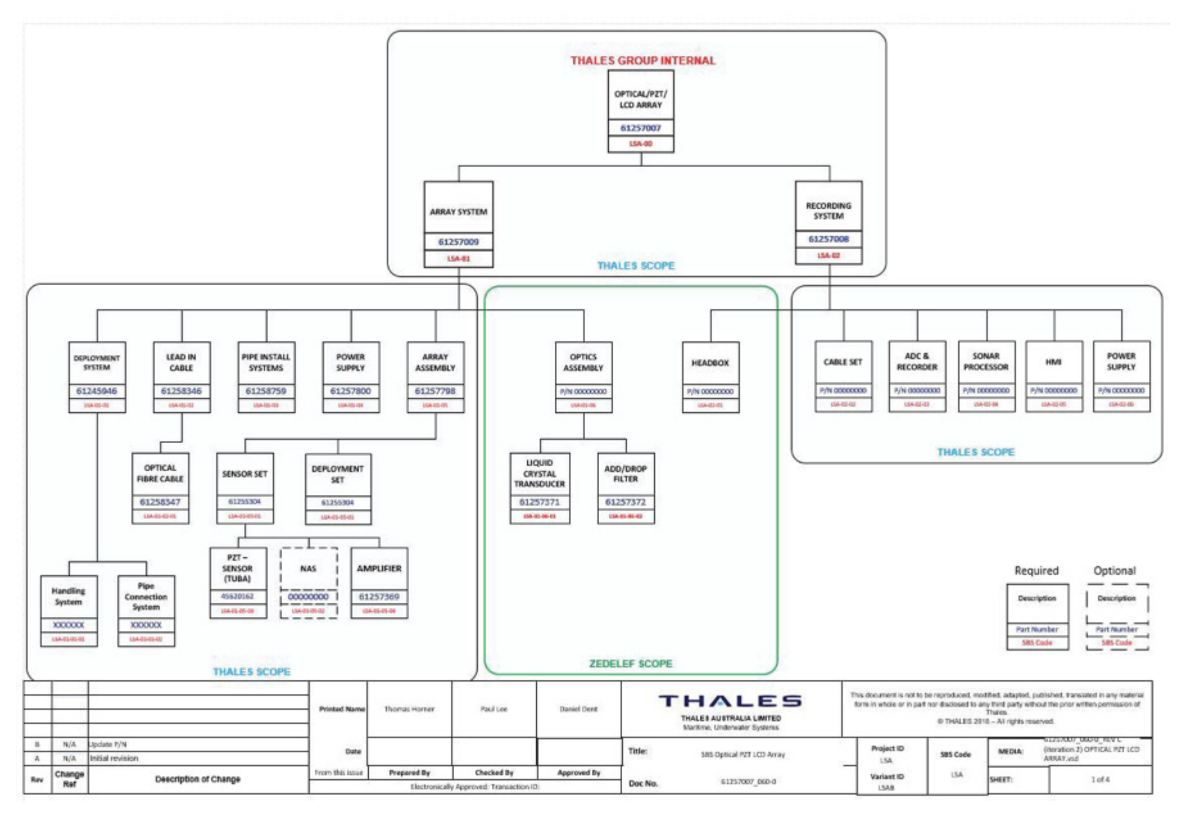


Figure 3.17: System breakdown structure for pipe sensing array design. (Graphics in this report have been copied from separate reports. Please contact the NSSN if you require high resolution images.)

4. Project Three: Acoustic Sensing

Centre for Autonomous Systems, UTS

4.1 Purpose

This report compiles the outcomes from research led by CAS, UTS into the deployment of acoustic sensors for the detection of leaks and breaks in water mains. Aiming to improve customer service and enhance Sydney Water's leak prevention program, a variety of acoustic sensors (204 total) have been deployed and are being monitored in five CBD areas (Sydney, Liverpool, Bankstown, Chatswood, and Penrith), as prioritsed by the Sydney Water-UTS pipe failure prediction tool model.

4.2 Project parameters

4.2.1 Timeline

02/05/2019 to 02/08/2019 Literature review of leak and pressure sensing, from vendors' and utilities' experiences.
02/05/2019 to 02/08/2019 Performance review of SebaKMT sensors currently deployed in the Sydney CBD area.
02/05/2019 to 02/11/2019 Strategy for leak detection and pressure transient monitoring in selected zones within SW in close collaboration with SW personnel. SW tender document and process participation. (Tender finalised and awarded).
02/05/2019 to 01/05/2020 (extended to 10/2020 for additional Sydney Water sensing needs and COVID-19) Finalised field deployment in selected zones.

4.2.2 Locations

Six zones were completed in the Sydney area: in the Sydney CBD (two), Penrith, Liverpool, Bankstown and Chatswood. Further Sydney Water logger deployments were also completed.

4.2.3 Personnel

Research and industry partners who were involved in the Project are detailed in Section 7.7.

4.3 Sensor review

Following a review of leak sensing technology in the early stages of this project, permanent acoustic sensors were deemed best suited for deployment in the SW network. Acoustic sensors can theoretically detect vibrations induced due to the pressure differential between the inside and outside of a pipe. Since acoustic waves can travel through both the pipe material and water, by attaching acoustic sensors to the outside of pipes, or other connected assets such as hydrants or valves, a leak noise can be measured. Some of the known advantages and limitations of permanent acoustic sensors for leak detection are summarised thus.

Advantages:

- Continuous monitoring for leaks and daily updates allows for quick discovery and proactive repair of leaks
- Small form factor which allows for ease of deployment in most of the areas
- Minimally intrusive. Deployed remotely to identify and pinpoint leak locations.

Limitations:

- Limited guidance on applicability and deployment based on their operating scientific principles
- Acoustic signal is more severely attenuated as it propagates through the wall; thus, impact of different materials, sizes, operating conditions, environmental conditions etc. more pronounced for accurate signal analysis
- Limited battery life: in most cases pipes are not readily connected to mains power supply and are battery-operated. Frequency of battery changes depends on observation configuration, trade-off between continuous monitoring and data transfers
- Access points to install sensors must be available at desired sensor spacing, otherwise “potholing” is required to access pipe
- Accelerometers are more sensitive to environmental noise. The availability of fittings (valves, etc) influences the placement and spacing of the loggers
- Permanent network requires either a wireless network to be set up, and/or use of communication modules. Some sensors (e.g. Gutermann) require civil infrastructure (repeater stations) and line of sight. They may also require dedicated communication frequencies
- Scalability: large volume of devices required (generally one needed every 100-200m)
- Less effective in plastic pipes
- Quick installation means sensors can be easily stolen or vandalised
- Sensor spacing is influenced by variables such as pipe diameter and material due to the attenuation of the acoustic signal. When pipes degrade and are replaced with new ones, accuracy in pinpointing leaks generally reduces with mix of materials
- Indications of leak severity generally not provided.

Following an extensive review of existing sensing technology (Valls Miro, 2019), an analysis of the technology maturity and access to close-to raw sensor data (for further analytics processing and integration into custom/in-house platforms), several acoustic sensors were selected for use in the SW network in the ensuing phase of the project collected in this document, summarised in Table 4.1

Table 4.1: Summary of permanent acoustic leak sensing technology capabilities.

Sensor model	**Manufacturer (AU Provider)**	**Users**	**Maturity**	**Raw data availability**	**Applicable pipe size + materials**
ORTOMAT-MTC	Von Roll (Detection Services)	SAW, SEW, HW	High	Audio files and noise level recordings via FTP server (Von Roll needs to provide access credentials – somewhat difficult to negotiate) & cloud portal (beta, also not yet available to all users)	S/M
Sebalog N-3	SebaKMT (WaterGroup)	SW	High	Audio files and noise level recordings via FTP server through provider login.	S/A
Enigma3m	Primayer (Ovarro)	Wessex Water, South Staffordshire (UK)	High	Audio files via cloud portal & API call	S/M
PermaNET+	HWM (Detection Services)	Yorkshire Water, United Utilities, Portsmouth Water (UK)	High	Audio files and noise level recordings via cloud portal & API call	S/M

Legend: S - Small size (100 mm-375mm); **M, A** - Metallic pipes, all pipes

4.4 Deployment process

The process for a given zone deployment was two-fold:

- Firstly, a pipe failure prioritisation prediction tool based on the assessment of Minimum Night Flow (MNF) was first used to assess high-risk pressure zones and pipe assets for acoustic sensor deployments (Chen & Wang, 2020)
- Secondly, after zone assessment with key Sydney Water stakeholders and commercial vendors, a fleet of acoustic sensors was then deployed to a given zone by installing on assets covering at minimum the higher risk zones. Data is collected daily for analysis of potential leaks in the sensor coverage area.

4.4.1 Pipe failure prioritisation prediction tool

A pipe failure prioritisation prediction tool (see Project Four: Data Analytics) based on the assessment of Minimum Night Flow (MNF) has been developed by UTS Data Science Institute to integrate multi-source data collected from Sydney Water and public data sources to assist with sensor deployment.

MNF for a pressure zone is defined as the water flow measured between 1 am to 5 am, connected to industry, commercial and residential demand. The motivation for choosing this time range is that the amount of water consumption is minimal over the whole day. This model enhances the “situational awareness” of network and operations.

The model of the tool is trained using the latest Sydney Water historical records. The trained model can produce failure likelihoods for various levels: pipes, shutdown blocks, and trunk mains. The prediction results from the model have been leveraged to prioritise risky zones and pipes to assist sensor deployment.

To prioritise zones/areas for sensor deployment, a priority map at zone level is also obtained based on the failure likelihoods from the pipe failure prediction tool. Specifically, a ranking score of the pressure zone is aggregated by summing up all failure likelihoods of the pipes in that zone.

As illustrated in Figure 5.7, all pressure zones are colour coded to represent different priority levels. In addition, the top 10 CBDs are listed. Four highlighted CBDs (Sydney, Liverpool, Bankstown, and Penrith) have been selected for acoustic sensor deployment. In addition to the priority map at zone level, priority maps are generated at pipe level for each zone to guide the sensor deployment. Based on the failure likelihood of pipes, the top 5% prioritised pipes are highlighted, and colour coded. The top of Figure 5.9 shows an example of a priority map for the Sydney CBD.

4.4.2 Logger deployment plan

Once a zone or area has been selected based on the pipe failure prioritisation prediction tool, the logger deployment is then planned. For the five CBD areas selected in this NSSN project, the entire pressure zone is first considered. However, Sydney Water's preferred area of monitoring is in the CBD regions of a given zone. Therefore, the CBD areas are then focussed on, suitable assets for mounting sensors are identified, and the top 5% at risk pipes are considered (Figure 4.1).

Suitable assets are determined based on the manufacturer reported range of the sensors, the pipe material and ideally any bends or fixtures on the pipes between loggers. Where possible, PVC or other plastic pipes are avoided, since accelerometers do not produce satisfactory results. This is due to the viscoelastic property of the plastic material which dampens the signal, resulting in prominent levels of attenuation which effectively isolate the leaking source from the sensor.

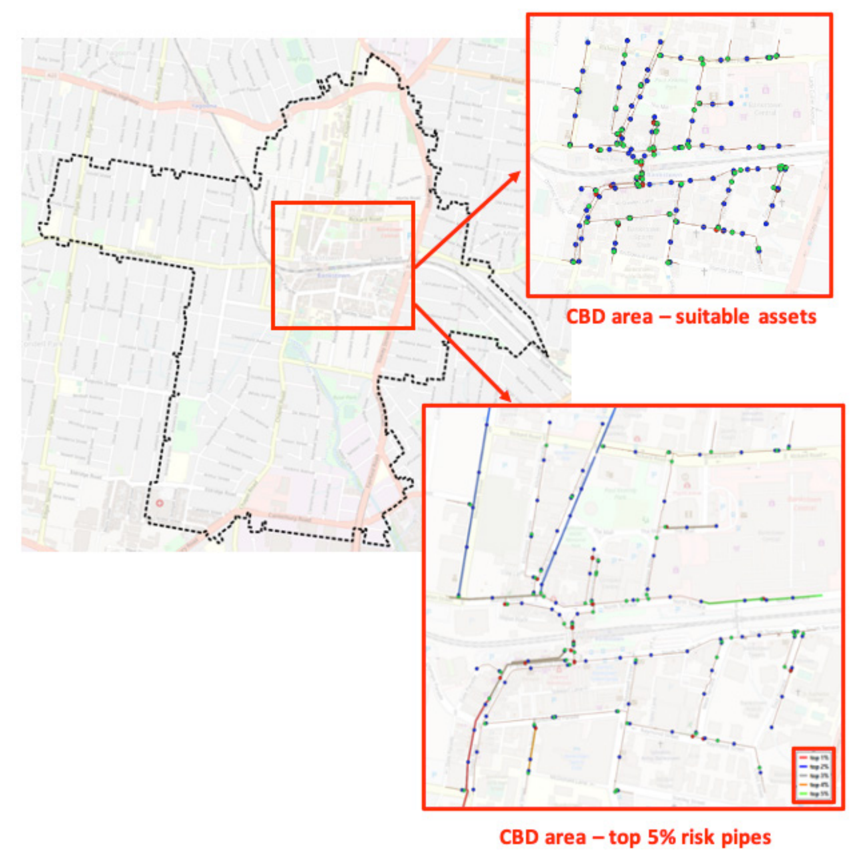


Figure 4.1: Example logger deployment plan: Bankstown CBD.

An audit of the assets should also be undertaken prior to deployment to ensure that the assets, typically either hydrant or stop valve chambers, are suitable (see Figure 4.2). This included ensuring they:

- Exist in the real world (not just in GIS maps), and in the expected locations
- Are accessible (e.g. not covered over with concrete/pavers, or unable to open)
- Have sufficient room for leak logger equipment to be installed correctly
- Are not full of debris or water.

Figure 4.2: Examples of unsuitable chambers for logger installations.

The loggers are then programmed in preparation for deployment, with all basic functionality being tested prior to installation. Information tags are also manufactured, to be attached to the leak sensing equipment

Figure 4.3: Sensor information tag.

4.5 Logger deployments and results

As shown in Figure 8.2 a total of 204 acoustic sensors have been deployed across five CBD areas (Sydney, Liverpool, Bankstown, Chatswood, and Penrith) since December 2019 up until the end of June 2020. As previously indicated, these zones were prioritised for deployments using the Sydney Water-UTS pipe failure prediction tool model.

4.5.1 Loggers deployed

Many models of acoustic loggers exist, each with unique sensing technologies, processes, and suppliers. Each of the four different loggers installed in the five CBD areas for this project (Von Roll, SebaKMT, HWM and Primayer) are functionally equivalent; with each containing hardware consisting of an acoustic sensor and a data logger, amongst other peripherals such as GSM transmitters. The key differences between the loggers lie in the quality of the hardware used, and the level of processing of the data, both on the logger and cloud-based portal sides. Generally, leak alerts are automatically raised via proprietary interpretation systems in the cloud using pre-set noise level threshold, which has been proven to lead to large percentage of false positive leak alerts.

The acoustic sensors are magnetically attached to pipe assets (either on a hydrant or a valve) and measure vibrations in the pipe network, logging noise levels and short audio files for correlations and further analysis. Noises in the pipe network are measured every day at a time of low water usage and theoretically low environmental noise (typically 2 am to 4 am). The data collected is transmitted to a cloud-based server using GSM transmission, with each sensor provider having their own portal in which to analyse the data further.

To effectively monitor a particular area in a pipe network, multiple sensors are attached at select locations, where the direct linear spacing between sensors is dictated by many factors such as the pipe diameter, material, number and type of joints, etc. For metallic pipes, a maximum distance of around 100-150m is typically recommended by sensor manufacturers. Due to poorer transmission of noise in plastic pipes, this figure is dramatically lower, at around 50m maximum, or discouraged altogether.

Data across multiple sensors and days can be compared and monitored for changes, allowing for hidden leaks to be detected and actioned - for repairs to minimise NRW, or before they may develop into breaks.

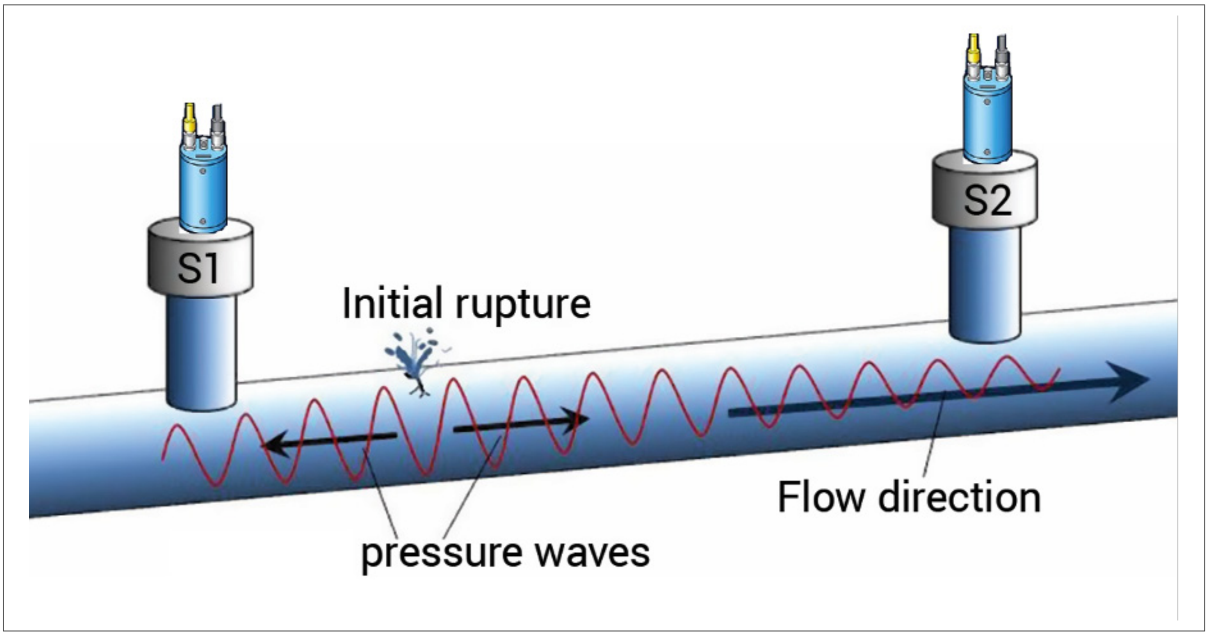


Figure 4.4: External acoustic sensors to monitor leaks in pipes.

Von Roll Ortomat (Syd CBD, Bankstown): Two different versions of the Von Roll Ortomat logger were installed in the Sydney CBD (40 MIKC-BT-3G units as an in-kind contribution from SA Water, December 2019) and Bankstown (20 MIKC-IR-4G units, engaging Detection Services for deployment from March 2020).

Von Roll sensor and logger: Both the MIKC-BT-3G and MIKC-IR-4G units use the same acoustic sensor which communicates with the logger over a cabled connection. The acoustic sensor mounts to an asset using magnetic adhesion, as can be seen in Figure 4.6. The only major difference between the two logger units is their form factor (see Figure 4.5).

Figure 4.5: Von Roll unit: Acoustic sensor (left) Ortomat MIKC-BT-3G (middle), Ortomat MIKC-IR-4G (right).

Figure 4.6: Von Roll Ortomat loggers: Sydney CBD (left), Bankstown (right).

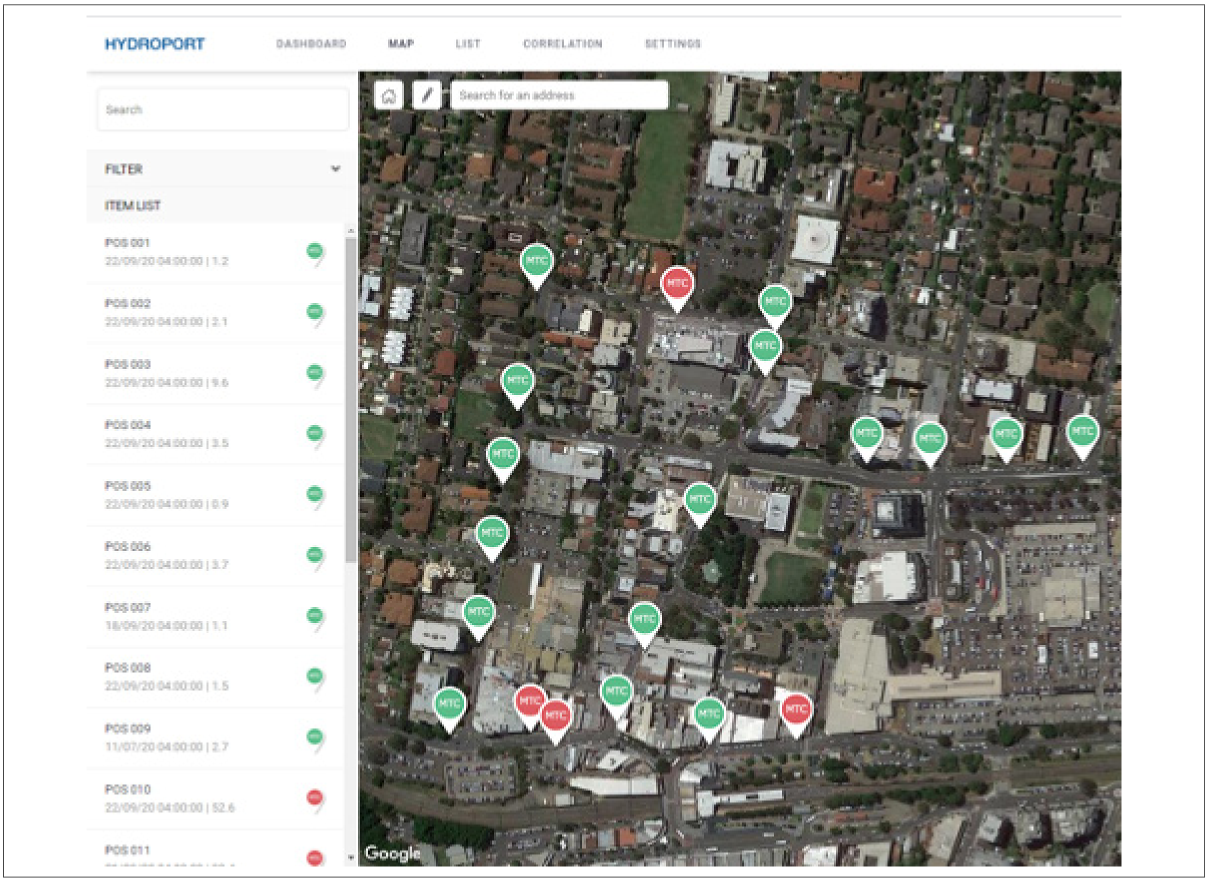
Both loggers record an RMS noise level 24/7 (at a user defined interval), along with a higher sampling rate RMS noise level during a leak determination period (typically 2 am to 4 am). A 10 second audio file is also recorded at a set time each day. These intervals are user-configurable and impact the battery life. The two types of loggers were programmed to record as summarised below.

Table 4.2: Von Roll logger programmed settings (Sydney CBD and Bankstown)

Logger	24/7 RMS noise interval	Leak Determination Period		Audio recording time
		Time	RMS noise interval	
MIKC-BT-3G	10 mins	2-4am	5 mins	1 file, 2:05am
MIKC-IR-4G	30 mins			

The cable connecting the sensor to the logger contains an integrated FM antenna. Each audio recording is 16 seconds long, with 3 seconds of FM radio at the start and end of a 10 second leak noise recording. The FM radio recording is used to time-synchronise loggers, enabling correlations between loggers to be performed in the online portal (Hydroport).

Von Roll portal: Von Roll's online portal, Hydroport allows a user to view data from each logger in either a map view (Figure 4.7) or a list view (Figure 4.8).



POS 001
22/09/20 04:00:00 | 1.2

POS 002
22/09/20 04:00:00 | 2.1

POS 003
22/09/20 04:00:00 | 9.6

POS 004
22/09/20 04:00:00 | 3.5

POS 005
22/09/20 04:00:00 | 0.9

POS 006
22/09/20 04:00:00 | 3.7

POS 007
18/09/20 04:00:00 | 1.1

POS 008
22/09/20 04:00:00 | 1.5

POS 009
11/07/20 04:00:00 | 2.7

POS 010
22/09/20 04:00:00 | 52.6

POS 011

Figure 4.7: Hydroport map view for Bankstown Von roll loggers.

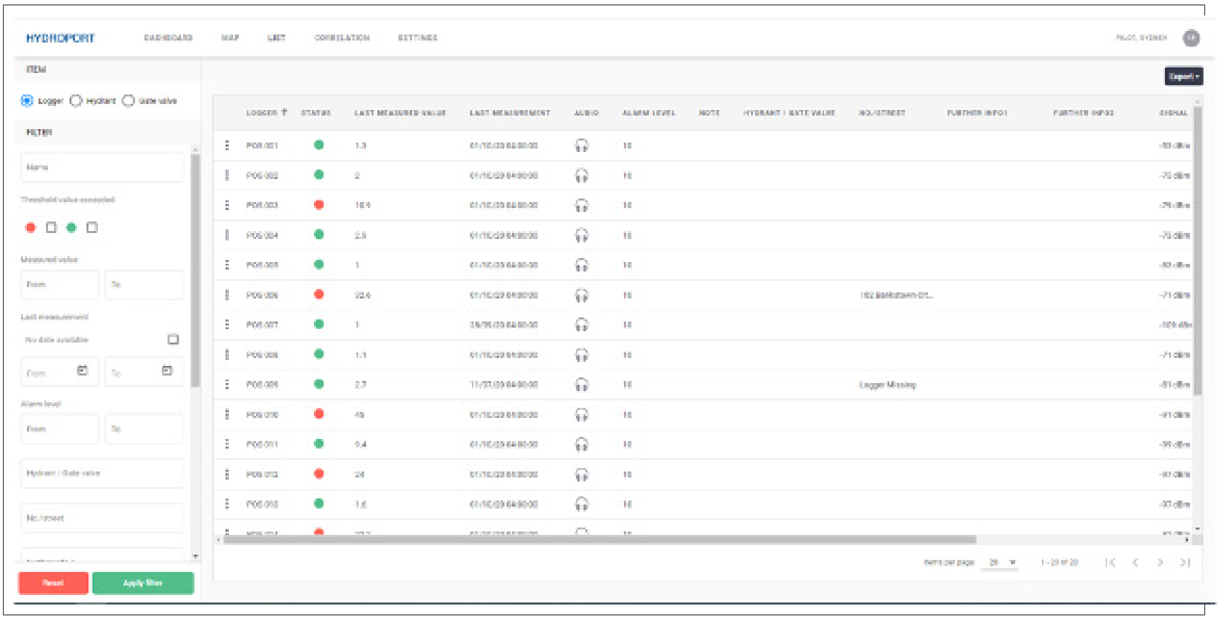


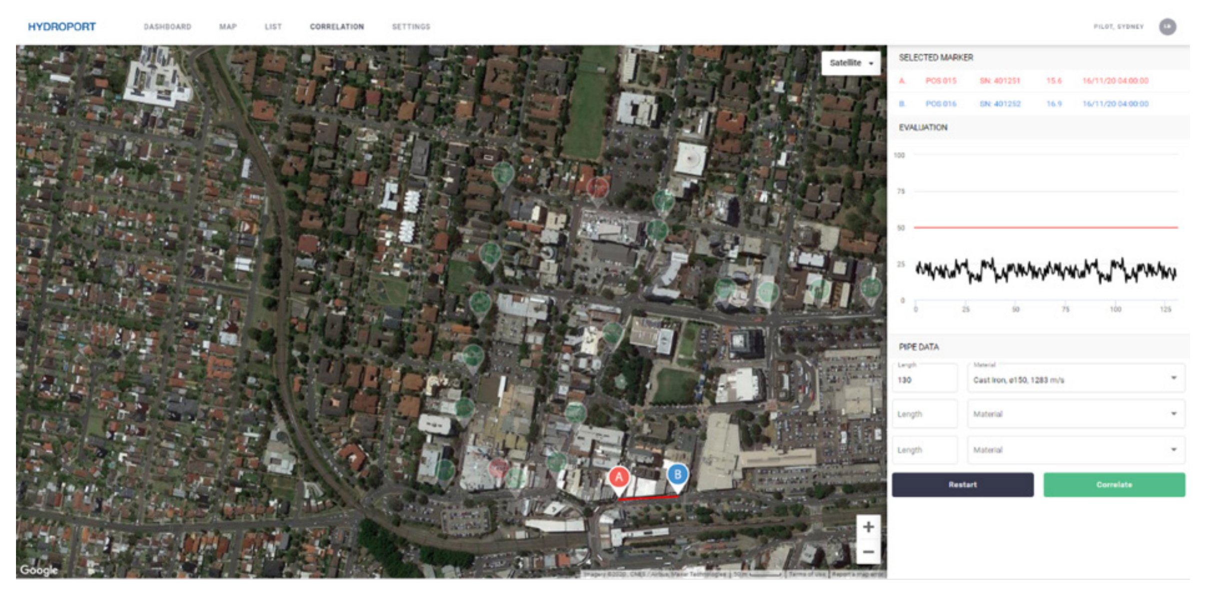
Figure 4.8: Hydroport list view for Bankstown Von roll loggers.

The portal can display all historical noise data (24/7 RMS noise data from Table 4.2) which is user selectable by adjusting the slider shown at the bottom of Figure 4.9. Only the most recent audio file is displayed for a given logger. The user can listen and download the latest audio file.

LOGGER	STATUS	LAST MEASURED VALUE	LAST MEASUREMENT	AUDIO	POS.
POS 003	🟥	10.9	01/10/20 04:00:00		✓
POS 004	🟩	2.9	01/10/20 04:00:00		
POS 005	🟩	1	01/10/20 04:00:00		

Figure 4.9: Historical noise data for Von Roll logger POS003 in Bankstown.

Correlations between two loggers can also be performed in the portal by selecting the loggers from the map view, entering the relevant pipe details (if not pre-populated by the system, which requires GIS information to be uploaded to the portal) and running the correlation.



A.	POS 015	SN: 401251	15.6	16/11/20 04:00:00
B.	POS 016	SN: 401252	16.9	16/11/20 04:00:00

Length: 130
Material: Cast Iron, ø150, 1283 m/s

Figure 4.10: Correlation for Von roll loggers POS015 and POS016 in Bankstown.

SebaKMT Log-N3 (Syd CBD, Liverpool): In June 2017, WaterGroup installed 42 Log N-3 loggers in the Sydney CBD. These loggers fell into disrepair over the course of a few years and were scheduled to be brought back online (through battery replacements, firmware updates and unit replacements) from April 2020. All functioning loggers, transmitters and antennas were salvaged from the 2017 deployment, while a number of units had varying issues (Figure 4.10). Since 2017, one hydrant had been refurbished and the logger, GSM transmitter and antenna were all missing. In May 2020, WaterGroup installed a fleet of 23 Log N-3 loggers in Liverpool.

Figure 4.10: Seba Log-N3 hardware issues from 2017 deployment.

Seba sensor and logger: The complete sensor system deployed in a single hydrant chamber consists of a logger/sensor (Log N-3), transmitter (Log GT-3-S) and GSM/GPS antenna (see Log N-3 communicates wirelessly to the GT-3-S unit, which then communicates data to the cloud).

Figure 4.11: SebaKMT Log N-3 (sensor+logger, left), Log GT-3-S transmitter (top right) and GSM/GPS antenna (bottom right).

Despite being equipped with a GSM/GPS antenna, the antenna cannot be positioned in the hydrant chamber in such a way that allows for the GPS signal to reach enough satellites for GPS transmission. Since the correlation function depends on GPS synchronisation of the logger clocks, accurate correlations cannot be performed using the current Log N-3 system. To have functioning GPS transmission, the 2017 Log N-3 deployment mounted the GPS antennas on the underside of the chamber lid, where the access hole to lift the lid is located (Figure 4.12). This mounting position proved to cause issues with the stability of the Log N-3 system: when the chamber lids are opened, the antennas are displaced, damaged and in many cases, the cables connecting to the Log GT-3-S were also severed.

Figure 4.12: Chamber lid mounting of GPS antenna.

Since the GPS transmission was unreliable in the Sydney CBD, during the 2020 upgrade of the system, several antennas were replaced with a (non-GPS) stubby antenna. All Log N-3 installations in Liverpool use a stubby antenna on the Log GT-3-S. With this, the loggers lose their ability to correlate signals picked up by close-by sensors to pinpoint the location of a leak. It must be then done in-situ by a technician with additional mobile acoustic logger equipment.

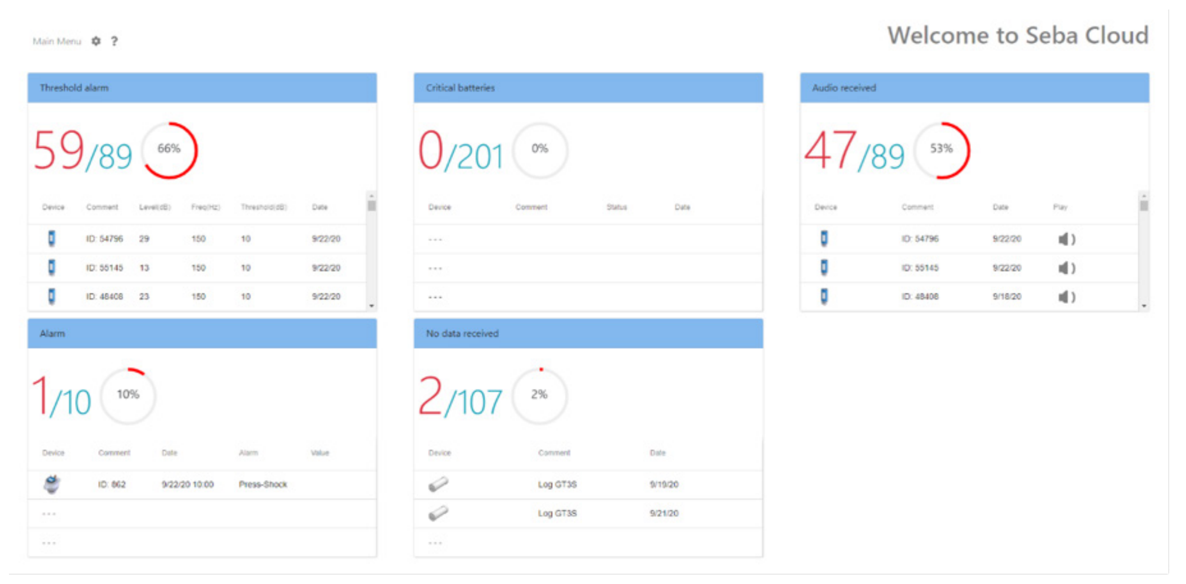
Figure 4.13: Seba Log N-3 Sydney CBD upgrade. GPS/GSM antenna left, GSM stubby antenna right.

The Log N-3 unit mounts to an asset using magnetic adhesion, either through direct connection to the asset, or through the use of an angle mounting bracket proposed during the upgrade, as seen in Figure 4.14 (top left).

Figure 4.14: Log N-3 installations in Sydney CBD and Liverpool (right angle adapter top row, bottom left) and directly mounted to asset (bottom right).

Every day between 2 am and 4 am, the loggers take 100 measurements of the noise level (measured in dB) and signal frequency. The loggers also record a 2-second audio file at 2 am. The logger will only send the audio file if the lowest measured noise level exceeds a set (user configurable) threshold noise value and frequency (currently set to 10dB and 100Hz respectively). The audio files and histogram data of the 100 measurements can be accessed on the Seba Cloud portal. When a leak alarm persists for more than 2 days (indicative of the leak not being repaired), the transmission of audio data will cease to save battery. The loggers will continue to record a daily audio file, which can then be requested through the Seba Cloud portal.

Seba portal: SebaKMT's online portal, Seba Cloud, upon login displays a dashboard of all current logger alerts, battery level alerts and communication statuses (Figure 4.15) From the cloud portal, the user can listen to audio files, and view the data in a variety of forms. Once logged in and a logger zone is selected the user can view the current logger status in a map view (Figure 4.16).



Main Menu ⚙ ?

Welcome to Seba Cloud

Threshold alarm

59/89 66%

Device	Comment	Level(dB)	Freq(Hz)	Threshold(dB)	Date
	ID: 54796	29	150	10	9/22/20
	ID: 55145	13	150	10	9/22/20
	ID: 48408	23	150	10	9/22/20

Critical batteries

0/201 0%

Device	Comment	Status	Date

Audio received

47/89 53%

Device	Comment	Date	Play
	ID: 54796	9/22/20	🔊
	ID: 55145	9/22/20	🔊
	ID: 48408	9/18/20	🔊

Alarm

1/10 10%

Device	Comment	Date	Alarm	Value
	ID: 862	9/22/20 10:00	Press-Shock	

No data received

2/107 2%

Device	Comment	Date
	Log GT3S	9/19/20
	Log GT3S	9/21/20

Figure 4.15: SebaKMT dashboard display.

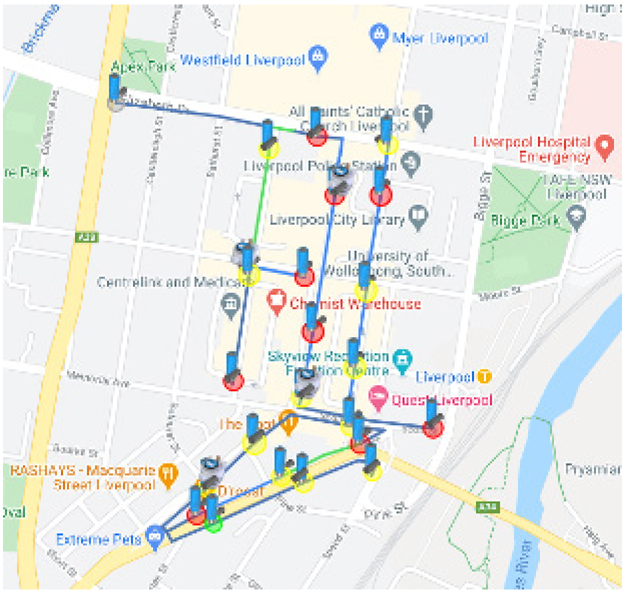


Figure 4.16: SebaKMT cloud map view with leak probability (F threshold 140Hz, L threshold 10dB) – Liverpool.

The logger status' shown are colour coded based on leak probability, with the noise level and frequency threshold both user configurable. Alternative colour codes can be seen by changing various settings in the portal.

The SebaKMT portal contains an algorithm, Enhanced Spectrum Analysis, that combines the noise level and frequency to give a score from 0 to 100 relating to leak probability. A score of 0 means a leak is unlikely, with a score of 100 denoting a very likely leak. The concept is that the user can look for the highest ESA value in either the history table or the map view to find the logger closest to the leak noise. This concept is also intended to assist with the identification of any leakage hot spots when observing the map view

HWM PermaNET+ (Penrith, Bankstown): In March 2020, 40 HWM PermaNET+ units were installed in Bankstown (20) and Penrith (20, engaging Detection Services for deployment).

HWM sensor and logger: The HWM leak noise sensor communicates with the PermaNET+ logger over a cabled connection, as shown in Figure 4.17. The acoustic sensor mounts directly to an asset using magnetic adhesion and the logger communicates data to the cloud via the stick antenna shown to the left of Figure 4.17. The logger also contains a GPS module, which provides the ability to automatically synchronise the internal clock (for correlations), but also to track the logger’s location.

Figure 4.17: HWM PermaNET+ Logger and leak noise sensor. The left side image is as deployed.

The controlling software allows for several user configurable settings. With default settings, the logger will only record and send a 10-second audio file to the cloud when the logger enters a leak state. While still in a leak state, the logger will not record and send any further audio files. A leak state is triggered by the leak noise level and the leak noise spread. Once the logger records a noise above the leak noise threshold, the logger has its own logic which uses the loudness of the leak noise minus the spread of the noise to determine if it is a leak. If this value is above the defined threshold it will be flagged as a leak.

The loggers deployed in Bankstown and Penrith have been programmed to record a 10-second audio file every day at 3:45 am, regardless of the leak state determined by the logger

HWM portal: HWM’s online portal, PermaNET Web, upon login displays a dashboard of all current logger status, including active devices, the number of devices in a leak state, and those with new leak alerts in the last 24 hours, see Figure 4.18.

Current DMA : Bankstown Loggers

Active Devices 20

Number in Leak 4 20.00%

New Leaks in Last 24 Hours 0 0.00%

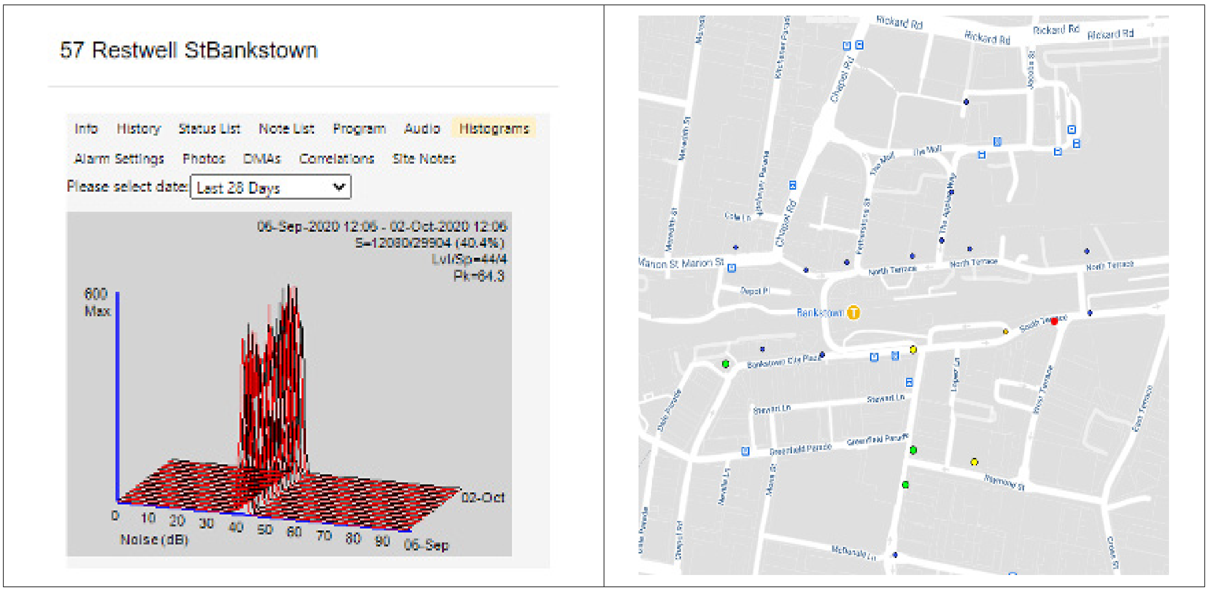
Leaks: 4
No Leak: 16

Leaks Not Categorised: 1
Investigation Ongoing: 0
Awaiting Repair: 3
Investigation Cleared: 0

* Only displaying active communicating sites

Figure 4.18: HWM PermaNET Web dashboard display.

The software allows for a high degree of functionality including correlation and graphical information to help identify leaks, see Figure 4.19.



57 Restwell StBankstown

Please select date: Last 28 Days

06-Sep-2020 12:06 - 02-Oct-2020 12:06
S=12080/29904 (40.4%)
Lvl/Sp=44/4
Pk=64.3

Figure 4.19: HWM PermaNET portal functionality including sound files and map location (red dot signifies a leak).

Primayer Enigma3m (Chatswood): In May 2020, 40 Primayer Enigma3m units were installed in Chatswood, engaging Veolia via Ovarro for deployment (due to COVID-19 travel restrictions).

Primayer sensor and logger: The Primayer Enigma3m units (Figure 4.20) are a correlating noise logger consisting of an integrated logger and sensor unit, with an external antenna for data transmission over 3G/GPRS communications. The loggers perform a daily time GPS synchronisation to enable correlations to be performed between many loggers for accurate leak location.

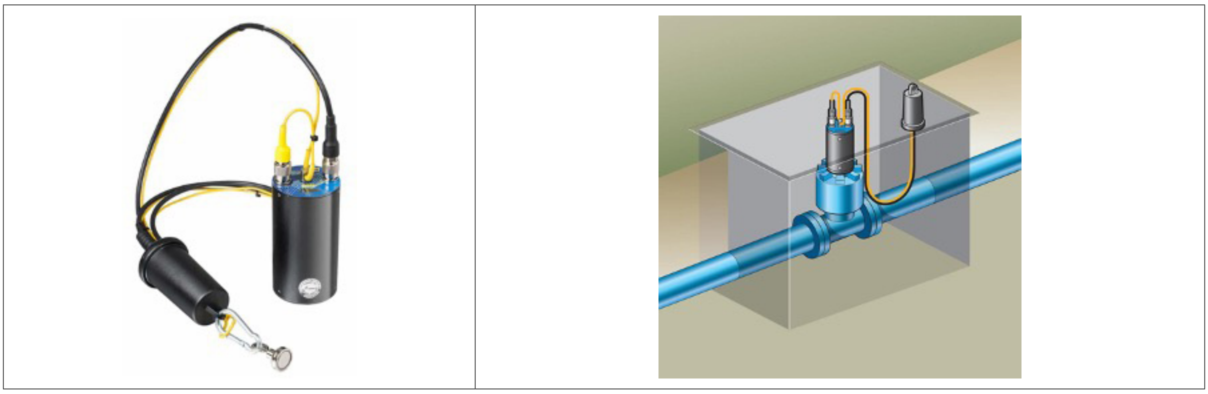
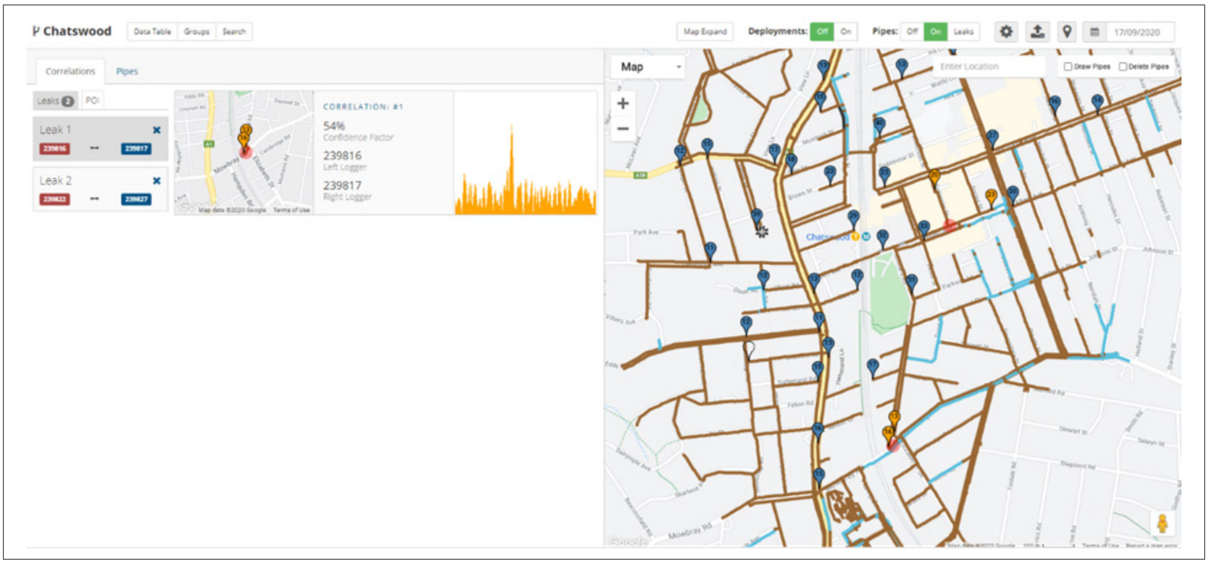


Figure 4.20: Primayer Enigma3m remote correlating noise logger.

Daily leak noise data in the form of a 10 second audio file is transmitted via the 3G or GPRS communication networks to a server. The loggers also take 900 samples of the noise level between 2 am to -2:15 am (one measurement per second). This data is used to determine the lowest level of noise and is referred to as the Critical Noise Value (CNV). The length of the audio recording, how often, time of recording are all variables that are user programmable, but the recording length and sampling are refined for the size/battery life/optimum correlation trade off. Figure 4.21 shows examples of some of the deployed loggers in Chatswood.

Figure 4.21: Primayer Enigma3m loggers installed in Chatswood.

Primayer portal: Primayer's online portal, PrimeWEB, upon login displays a dashboard summary of all current logger statuses, including active devices, the number of leaks and the highest confidence correlations for the current day. Data from the loggers can be viewed in either a table view or a map view (see Figure 4.22). The software has a functionality for the CNV, which is a measure of the lowest leak noise, which can be used to determine how close the logger is situated to the leak, measured as a value in decibels (dB). The LCF (Leakage Confidence Factor) is a value corresponding with the percentage value of the quality of a correlation. The LCF value can take on a value of 1 (<50% correlation confidence), 3 (51-80%) or 4 (81-100%). By clicking the CNV value for a given day from the table view, further details can be observed. The user can also listen to audio files.



CORRELATION: #1

54%
Confidence Factor

239816
Left Logger

239817
Right Logger

Figure 4.22: PrimeWEB map view.

4.6 Technical Comparison

The following tables present summary information comparing the transmission, sensing and logging capability of the various brands.

Table 4.3: Transmitter comparison

Manufacturer	**Von Roll**		**SebaKMT**	**HWM**	**Primayer**
Logger Model	*Ortomat-MIKC-BT-3G*	*Ortomat-MIKC-IR-4G*	*Log N-3*	*PermaNET+*	*Enigma 3m*
Transmitter integrated with logger?	Yes	Yes	No	Yes	Yes
Estimated battery life (years)	N/A	N/A	5	N/A	N/A
Battery replacement method	N/A	N/A	Unit lid unscrews without need for tools, battery housing can be removed, and the battery replaced	N/A	N/A
Dimensions (mm)	N/A	N/A	H 190 x dia 69	N/A	N/A

Table 4.4: Sensor comparison

Manufacturer	**Von Roll**		**SebaKMT**	**HWM**	**Primayer**
Logger Model	*Ortomat-MIKC-BT-3G*	*Ortomat-MIKC-IR-4G*	*Log N-3*	*PermaNET+*	*Enigma 3m*
Sensor frequency range (Hz)	0-2341		0-3277	0-2048	0-2500
Sensor integrated with logger?	No, tethered with comms cable		Yes	No, tethered with comms cable	Yes
Dimensions (mm)	(H x dia.) incl. cable 90 x 40		See logger dimensions	H 80 x dia. 50	See logger dimensions

Table 4.5: Logger comparison

Manufacturer	**Von Roll**		**SebaKMT**	**HWM**	**Primayer**
Logger Model	*Ortomat-MIKC-BT-3G*	*Ortomat-MIKC-IR-4G*	*Log N-3*	*PermaNET+*	*Enigma 3m*
Estimated battery life (years)[1]	4	4	5	5	5
Battery replacement method	Use Allen key to unscrew bolt on logger cover, slide out battery PCB, replace.	No tools needed. Unscrew logger cap, replace AA batteries.	Must be returned to SebaKMT to maintain IP68 rating	Screwdriver is used to unscrew bolts on logger face plate. Battery can then be disconnected and replaced.	Must be returned to Primayer to maintain IP68 rating
Dimensions (mm)	L 102 x dia. 41	dia. 43.4 x L 123	H 115 x dia. 45	H 85 x W 115 x D 114	L 123 x dia. 58

---

[1] Under default program settings

Programming method	Via USB BT dongle ONLY	Pre-programmed by Von Roll, some settings can be changed remotely (FM channel, threshold, channel scan on/off)	Via USB dongle (Log RI [Radio Interface]), can also be programmed remotely (limited changes to settings) once set up.	Pre-programmed with basic leak detection settings. Site specific settings are programmed using a cable, while some other HWM loggers use an IR reader. Remote programming possible through the HWM portal once set up.	Via Communications Module (infra-red, 0.5m range)
Default settings	Record a 10 second audio file and noise level readings every day. Send files daily to a server.		Record a 2.5 second audio file every day and noise level data between 2-4am. Only send to a server if the logger is in a 'leak state'. Logger only sends audio data from two consecutive days to preserve battery.	Record a 10 second audio file when the logger enters a leak state. Only record and send for one day if logger is in leak state.	Record a 10 second audio file and send to a server every day.
Raw data access	FTP server		FTP server	API call	API call
Can correlate?	Yes, sensor cable has integrated FM antenna for sync (no GPS)		Yes, if GPS antenna is used	Yes (GPS)	Yes (GPS)

4.7 Results

All sensors studied have proven they can detect leaks.

By the end of June 2020, when all sensor deployments scheduled on the project were completed, 37 leaks and two breaks had been detected by the various acoustic sensors. A large portion of these hidden leaks were repaired by Sydney Water in the course of, and immediately after the project. Some required further investigations and planning prior to repair.

Table 4.6: Summary of leaks detected.

CBD area	**Deployment date**	**Detected (possible) leaks**	**Verified by Sydney Water**
Sydney	Von Roll: 11/12/2019 SebaKMT: 16/04/2020	23	18 leaks, 1 break
Penrith	11/03/2020	2	2 leaks
Bankstown	16/03/2020	10	5 leaks, 1 break, 1 suspected private service leak, 1 noisy service
Liverpool	1/05/2020	1	1 leak
Chatswood	27/05/2020	3	1 leak
TOTAL	**-**	**39**	**27 leaks, 2 breaks, 2 others**

Potential leaks found through sensors were discussed in weekly analysis meetings and verified by Sydney Water in the field through close collaboration.

The sensor review produced a practical assessment of commercially available acoustic sensors for leak detection. Existing sensing experiences from utility partners and practical learnings were reviewed.

Sensors/loggers functionally remains similar, in accordance with pre-selection criteria and market leadership. The end user would need to weigh up a number of operational options across the sensing manufacturers – quality and sensitivity of sensor (affecting range between loggers), battery life, cost, maintenance, access to raw data (for in-house interpretations), ease of portal use and interpretation of leaks/correlations.

In broad terms, the shared experiences point towards HWMs representing good value for money, yet with also a shorter range than Von Rolls (i.e. theoretically more sensors needed to cover the same pipe distance). Both noise loggers can receive GPS fixtures for correlation analysis. SebaKMTs presents some limitations to the audio download ability for automatic in-house analysis, as well as challenges with GPS antenna reception in the SW chambers. They are also noise loggers with a correlation feature.

On the other hand, the Primayer loggers proposed by the provider for the trial are specifically referred to as correlating loggers, and data collected in the cloud is shown as being manipulated differently, with substantial amplification. Given subsequent field investigation protocols the full correlation feature maybe less attractive for leak identification, especially should the signal to noise ratio be affected. (No comparison with plain Primayer noise loggers was performed in the project.)

4.7.1 Solutions to challenges

COVID-19 restrictions/limitations created project challenges. Detailed test procedure for custom designed sensor mounting were planned but the pandemic necessitated restricting testing to lab and home.

Communication with Sydney Water became more effective over time progressed.

- Weekly video conference meetings facilitated information transfer and clarity with wider Sydney Water teams and sensor providers regarding potential leak locations, investigations and work order (WO) follow ups).
- Communications regarding which areas/loggers have been investigated and what further actions were planned was overcome in the Sydney CBD through area managers consistently assigning WOs to specific network teams (NTs) for leak investigations and correlations.
- A new common resource set-up in the cloud to track actions was taken up by some key personnel at Sydney Water. The preferred option for information transfer shifted from spreadsheets to weekly video conference meetings.

This project contributed not just to the science and engineering around sensing but also offered areas for improvement in management and human resources issues. SW does not have a category for hidden leak investigation in their WO system (Maximo). This project represents a shift in current leak practices. As such, clear information transfer to NTs is problematic as at times as it is unclear to them why they are attending a particular site, particularly if no water is apparent on the surface. Engagement with SW Customer Delivery teams in new zones, to bring it up to level of Sydney CBD, should be more extensively trialled. Again, this was affected by COVID-19.

- Further room for improvements in implementing repairs, particularly for hidden leaks, include:Getting NTs at the right time of the day (during the quiet periods at night, when the sensors also operate) for correlations and investigations
- Skill development among NTs and greater knowledge of the sensor project
- More structured information available in the work order (Maximo) system for hidden leak WOs
- There is also a general trend in NT lack of knowledge of the leak detection project, so there is certain detachment there. Better informed field personnel would be advantageous to the successful outcomes in finding/validating leaks picked up by the sensor network.

4.8 Conclusions

A cohort of utility-driven field-tested acoustic sensing technologies have been trialed, studied and compared across five CBD areas in Sydney as part of the NSSN Project Three. All sensors can detect leaks when used properly. This report has detailed the outcomes and learnings from these acoustic sensor deployments.

A comparative study of validated leaks in the various zones with the 4 sensors manufacturers engaged is supplied, alongside with technical insights from field deployment experiences. While the loggers are functionally equivalent, their varying capabilities in relation to their physical placement in the environment, size, communication abilities, programmability, data accessibility etc. can have a significant impact on the amount and quality of the data available for analysis. For example, a logger deployed in Bankstown near two major stormwater assets records noise that could easily be misinterpreted as leak noise during periods of rainfall. Ultimately, it is expected the data collected in this report can be used to inform each utility to make a decision according to their individual needs and operational preferences when it comes to leak detection.

To end of June 2020 - when all sensor deployments scheduled on the project were completed, 39 possible leaks were detected by various acoustic sensors, with 31 confirmed by Sydney Water as a leak (27), break (2) or other leak related noise (2). A large portion of these hidden leaks have subsequently been repaired by Sydney Water. Some still require further investigations and planning prior to repair. Project savings from sensor deployments have been estimated to be up to $3 million and 700ML/year.

Following the close engagement and collaborative relationships built with sensor providers and manufacturers, UTS has negotiated access to raw data from each sensor manufacturers, through FTP servers and/or API calls. UTS is currently working to further understand the built environments around deployed loggers to aid in developing an automated methodology for a consolidated analysis of all data from the various acoustic sensors.

It is hoped the outcomes of this research study can aid utilities, in particular Sydney Water where the loggers have been deployed and tested, in building a strategy to target acoustic sensing to be more agile and mobile in urban areas, ensuring water distribution that provides 24 hours of reliable and resilient services to customers.

5. Project Four: Data Analytics

Data Science Institute, UTS

5.1 Purpose

This report section summarises research on prioritising zone areas and pipes in order to reduce pipe breaks and leaks using advanced sensing techniques. It sets out multi-modal approaches data analytics to prioritise sensing and developing predictive analytics.

5.2 Scope

In this project, pipe failure records, minimum night flow records, and water consumption data were collected and analysed. Analytical methods for generating risk maps and minimum night flow correction were proposed and used to generate zone-level and pipe-level prioritisation data. The analysis demonstrated that the aggregation of pipe failure prediction model and the MNF model provide effective, reliable zone prioritisation.

More cost-effective, real-time sensing information can improve the performance of predictive tools, especially in high density, variable urban environments. The focus of this project is providing more targeted data-driven information to better predict priority areas around specific asset classes, especially in the task of detecting *leaks before breaks*.

5.3 Background

Data driven insights offer a way for water utilities to reduce their asset renewal budget by becoming more targeted in preventative asset replacement, before pipes fail.

5.3.1 Previous research

Extensive previous research by the UTS Data Science Institute (DSI), Sydney Water and other research partners has identified several key factors and associated predictive models for prioritising areas of need. These include:

- Models created around distribution network parameters, including identifying the asset type, lining, material and asset critical metadata
- Failure data and models, including understanding factors contributing to historical asset failures
- Environmental factors and models that incorporate the environmental conditions that contribute to pipe failure

Real time sensing of leaks over time will provide learning data with multiple modalities to pick up leaks and breaks prior to occurrence. Machine learning and multi-modal data analytics offer ways to choose the pipe assets the sites for sensors that provide best business and technical value for repair prioritisation. Validated leak predictive model outputs, using real-time and mobile sensing data, can facilitate the categorisation and prioritisation of pipes, which can be integrated with other evolve condition assessment techniques to select the cohort of pipes to be replaced at their actual *end of life*.

5.4 Data sources and processing

Pipe leakage behaviours are highly related to characteristics such as material, sizes and pressures. Various kinds of information are managed from multiple sources. Sydney Water has recorded a large volume of historical data, pipe attributes and operational data but some of the raw data may be incomplete and may differ across systems.

When raw data are gathered from multiple sources, and prior to adoption of advanced analytic techniques it is essential to conduct data processing, including data quality check, data cleaning, and failure records matching with the network data. This can help to identify gaps in the collected data.

5.4.1 Failure records

Pipe failures are caused by different reasons and recorded as different failure types by Sydney Water. Sydney Water provided its latest pipe failure records for the project. Each record includes failure information, such as failure type, reported date and related pipe ID. In this project, five main failure types were considered and analysed, i.e. WR1A, WR1B, WP1C, WD8C, and WR3M. Table 2.1 lists the basic information of these failure types. The matching rate in this table refers to how many records in this failure records can be matched with the water pipe dataset.

Table 5.1 Basic information of failure records

Task Code	Failure Type	Start	End	# Records	Matching Rate
WR1A	Break	May 1998	Jan 2020	68,540	96.4%
WR1B	Leak	Oct 1997	Jan 2020	30,294	94.7%
WP1C	Active leak detection	Jun 2000	Aug 2019	3,356	69.9%
WD8C	Reactive main-to-meter failure	May 2002	Nov 2019	15,326	3.7%
WR3M	Active main-to-meter failure	Jun 1998	Dec 2019	154,256	90.1%

In addition, further statistics have been performed at cohort-level. Figure 5.1 shows the distribution of records for different cohorts of pipe size and material. It can be seen that most failures happen in pipes of small sizes and CICL material.

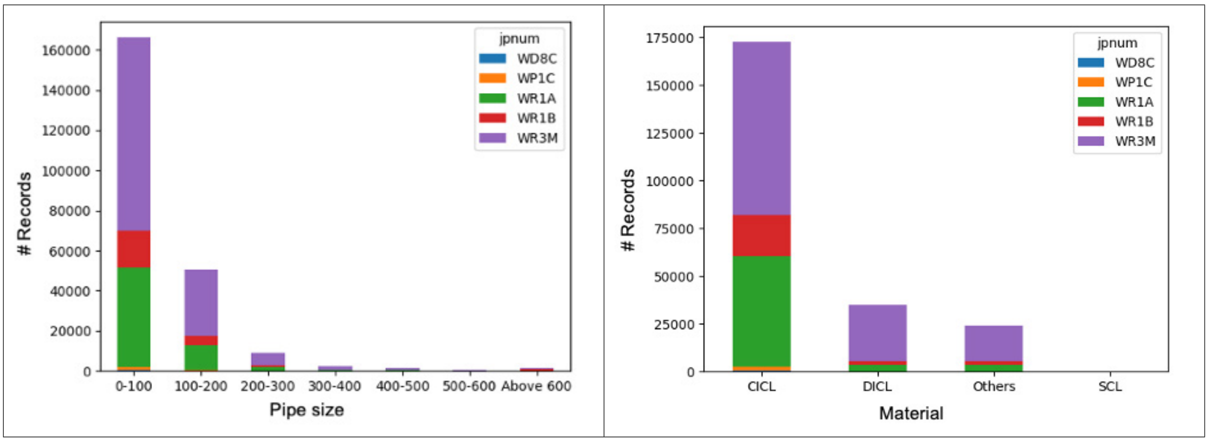


Figure 5.1 The distribution of failures for different cohorts: pipe size and material.

5.4.2 Customer consumption data

The project dataset included the historical water consumption for each pressure zone. This data was interpolated to produce yearly estimates of the water used by each pressure zone. Customers are divided into two basic types, residential and non-residential, and each is divided into sub-types.

Most residential customers normally use much less water at night, so non-residential customers consumption needs were further analysed. As shown in Figure 5.2, non-residential consumption accounts for about one quarter of the total water consumption over the year of 2019. The sub-types of “Commercial” and “Industrial” occupy most water consumption in the non-residential customer type.

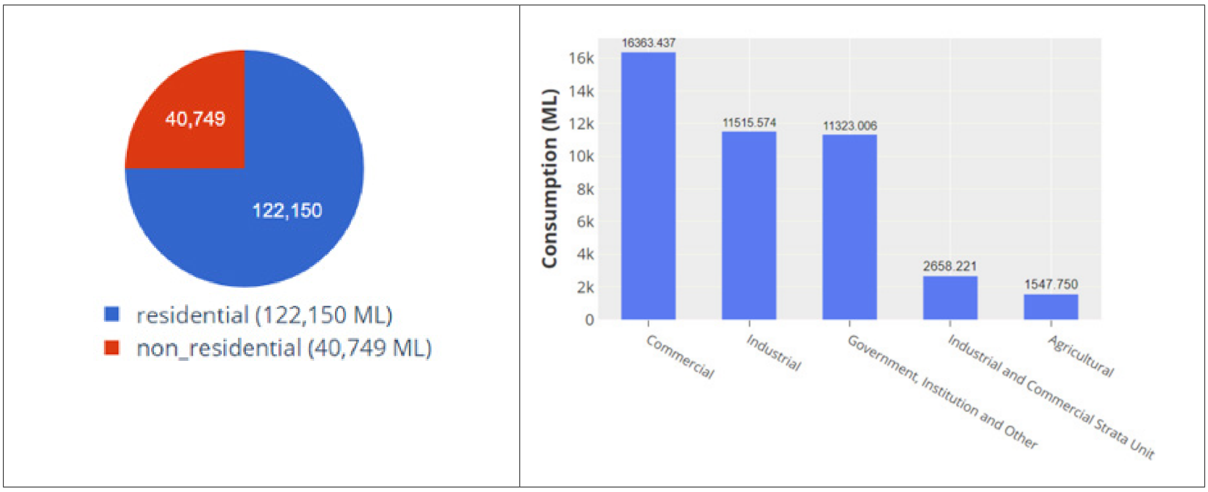
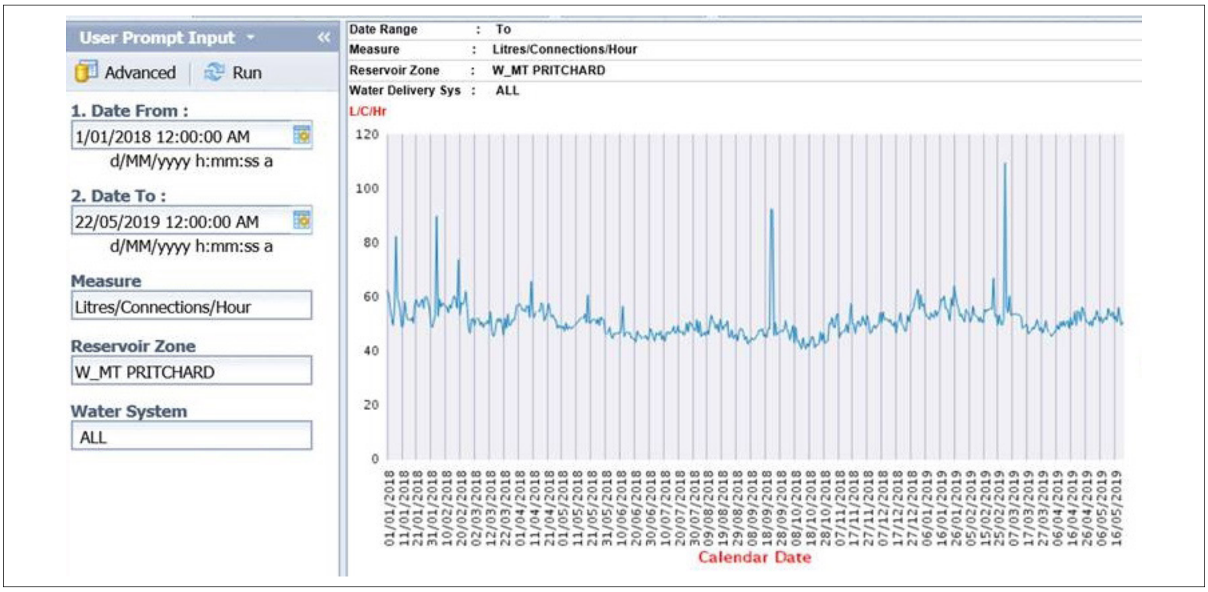


Figure 5.2: Customer consumption of non-residential types in the year 2019.

5.4.3 Minimum Night Flow records

Minimum Night Flow (MNF) for a pressure zone is defined as the water flow measured between 01:00 hrs to 05:00 hrs. The MNF helps in narrowing pressure zones for active leak detection (ALD). High MNF indicates high usage, leakage or an open valve. If the recorded MNF for consecutive days deviates substantially from its historical records, then it might be either due to occurrence of leaks or a valve is accidentally left open which allows water flow between neighbouring pressure zones. Monitoring MNF is therefore a quick way to estimate the unreported leaks in pressure zones. An example of MNF monitoring is shown in 510. It shows the MNF for Mt Pritchard is high, 45 to 60 litres/connection/hour.



1. Date From :
1/01/2018 12:00:00 AM
d/MM/yyyy h:mm:ss a

2. Date To :
22/05/2019 12:00:00 AM
d/MM/yyyy h:mm:ss a

Measure
Litres/Connections/Hour

Reservoir Zone
W_MT PRITCHARD

Water System
ALL

Date Range : To
Measure : Litres/Connections/Hour
Reservoir Zone : W_MT PRITCHARD
Water Delivery Sys : ALL

Figure 5.3: MNF for Mt. Pritchard.

However, MNF monitoring is highly susceptible to system errors such as malfunctioning of water-consumption meters. Therefore, one needs to filter zones where MNF is reliable i.e. not showing large fluctuations throughout the data period. Once zones with reliable MNF recordings are identified, it still requires further processing to eradicate the influence of non-residential consumption as high non-residential consumption might conceal actual water leakage occurring within the pressure zone.

The MNF dataset for the project consisted of MNF values from 374 pressure zones observed from 01/09/2018 to 19/09/2018. Further details of the dataset are provided in Table 5.2. Additionally, each pressure zone is labelled either as reliable or not reliable by Sydney Water. The reliability of a pressure zone is calculated by observing fluctuations in the MNF observations. A zone with frequent fluctuations in the MNF observations is assumed to be unreliable as its MNF is influenced by noises (miscalibrations) in the apparatus.

Table 5.2 Details of MNF records

Date range	01/09/2018 – 12/09/2019
# zones	374
ML/day	383.81
L/day/connection	11.45

The reliable zones are further labelled into five different categories based on the pattern of the MNF observations: “falling”, “step down”, “rising”, “step up” or “others”. The categorical distributions of pressure zones based on their observed (raw) MNF values are shown in Figure 5.4. It can be seen that around 60% of the pressure zones have reliable MNF observations.

The observed MNF values for each pressure zone were further processed in order to estimate MNF for each day. In this regard, the observed MNF value for the whole period of time was added (the positive or negative nature of the observed MNF is accounted for when compiling) and normalised by the number of connections in each zone. The obtained value was then converted into megalitres per hour and normalised over the whole period i.e. 389 days. This value signified litres/#connections/hour (L/NC/H), which can be utilised to perform correction tasks.

After normalisation, the analysis excluded pressure zones with L/NC/H <0. That gave a candidate list of 204 pressure zones5.6. One pressure zone (Marsfield) was eliminated from the list because its L/NC/H was too high and was considered as an outlier.

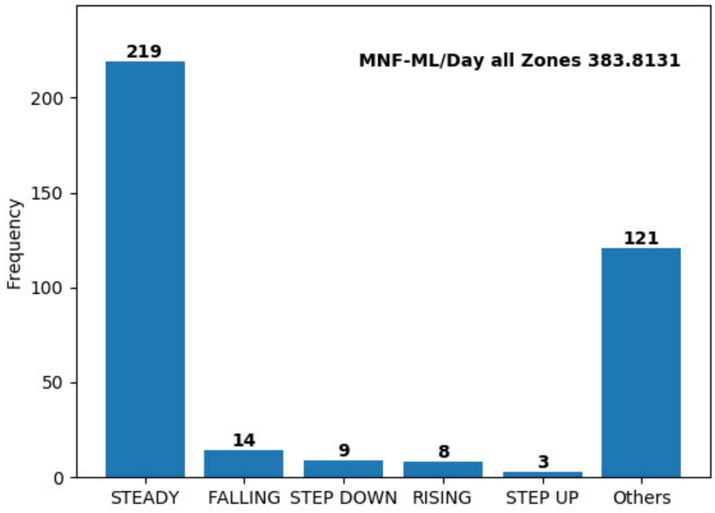


Figure 5.4 Pressure zones categorical distribution.

5.5 Pipe prioritisation and risk maps for sensor deployment

5.5.1 Failure prediction performance

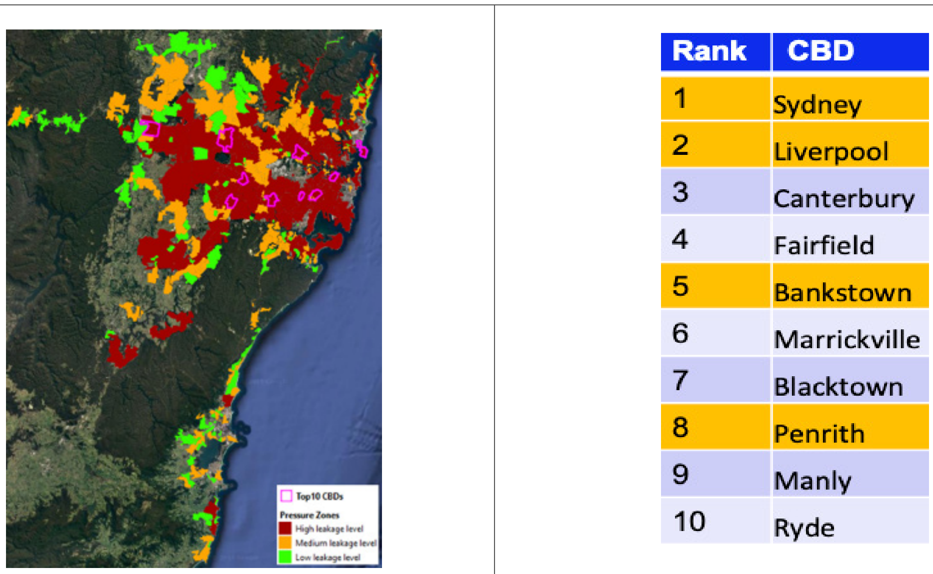
With the collaboration with Sydney Water, a pipe failure prediction tool has been developed by DSI to integrate multi-source data collected from Sydney Water and public data sources, and to enhance situational awareness of network operations. This tool was used to conduct data analysis at pressure zone and pipe level, to assist in sensor deployment. The model of the tool is trained using the latest historical records. The trained model can produce failure likelihoods for various levels: pipes, shutdown blocks and trunk mains. Hence, the prediction results from the model can be leveraged to prioritise risky zones and pipes to assist sensor deployment.

The failure prediction tool has been evaluated using all pipes based on historical records and the results are shown in Figure 5.6. The x-axis represents the cumulative percentage of inspected water pipes, the y-axis indicates the percentage of detected pipe failures. It shows that if the top 20% pipes of the priority list are inspected, about 80% failures can be detected.

Figure 5.5: Failure prediction performance.

5.5.1.1 Risk map at zone level

A risk map at zone level was obtained based on failure likelihoods from the pipe failure prediction tool. The risk score of the pressure zone was aggregated by summing up all failure likelihoods of pipes in that zone. As illustrated in Figure 5.6, all pressure zones are colour-coded to represent risk levels. The ten most risky CBDs are listed. The four highlighted CBDs (Sydney, Liverpool, Bankstown and Penrith) were selected by Sydney Water for deployment.



Rank	CBD
1	Sydney
2	Liverpool
3	Canterbury
4	Fairfield
5	Bankstown
6	Marrickville
7	Blacktown
8	Penrith
9	Manly
10	Ryde

Figure 5.6: Risk map at zone level and the ten most risky CBDs.

A variety of vibration-induced sensors are being installed in the selected zones shown in Figure 5.7. Sensing data recorded from different events (leaks, environmental and operational noises, others vibration sources) exhibit different characteristics for leak monitoring. Signal processing analysis will be conducted on field sensor data collected from different events and locations to help discriminate leak patterns under various situations.

Figure 5.7: Plan of the sensor deployments

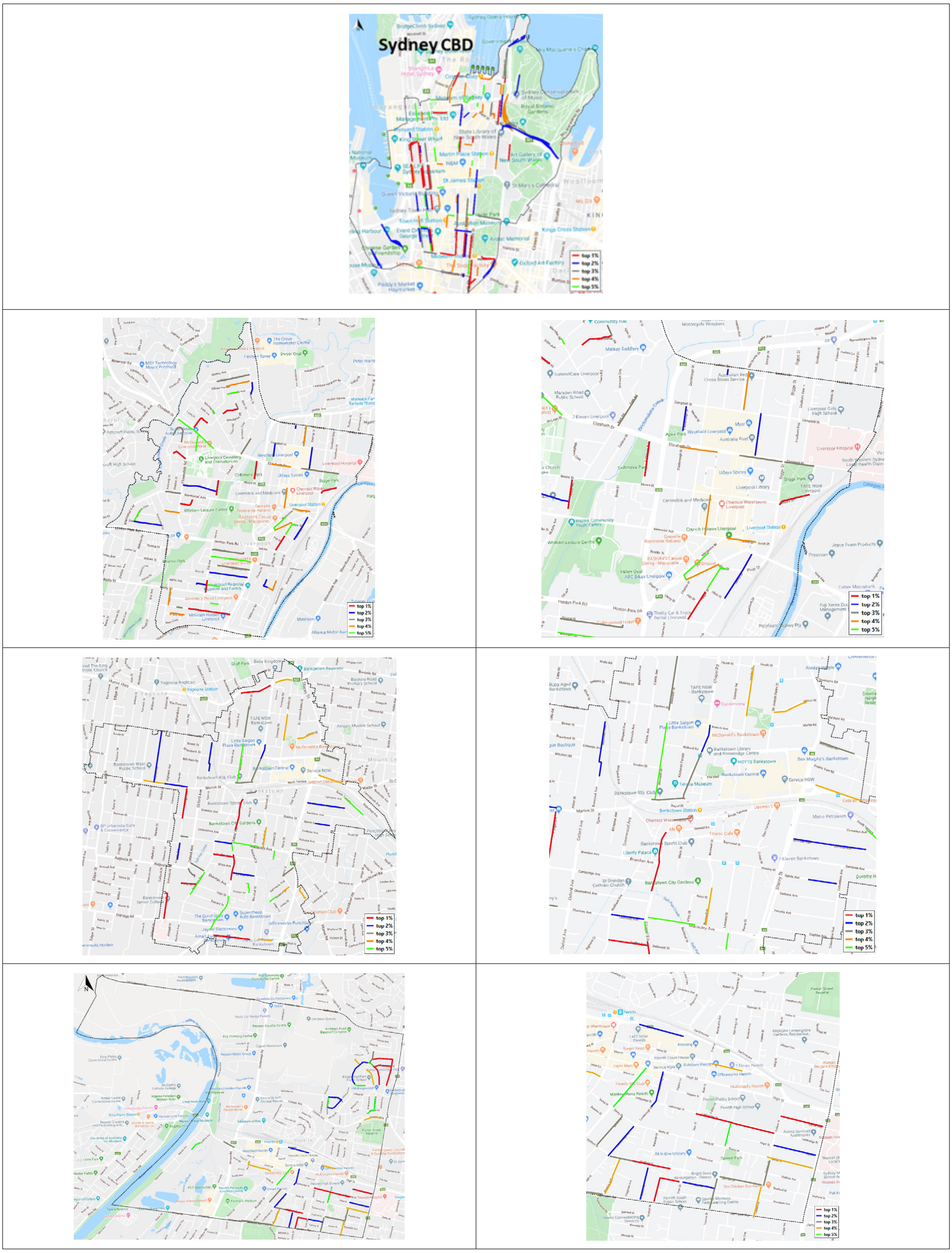


Figure 5.8 Risk maps of the selected central business districts.

5.5.1.2 Risk maps at pipe level

Risk maps at pipe level for each zone can guide sensor deployment. Based on the failure likelihood of pipes, the top 5% risky pipes are highlighted and coded in different colours in Figure 5.9, shows the risk maps of the Sydney , Liverpool , Bankstown and Penrith CBDs.

5.6 Minimum night flow analysis

5.6.1 Correlation analysis

While the residential water consumption is assumed to be minimal at night, no such assumption can be drawn for non-residential consumption. Besides, the consumption cycle from non-residential consumers depends, e.g. a poultry farm might consume more water in the daytime compared to clubs which consume more water at night. Since the number of non-residential consumers and their types are unequal within the pressure zones, one cannot deduct a constant factor from each pressure zone to alleviate their influence. Therefore, estimation and eradication of non-residential water consumption from observed MNF becomes non-trivial.

In this regard, with the project team summarised non-residential consumers according to their type and water consumption demand. Results are shown in Figure 5.9. The obtained frequency of non-residential water consumption concludes that the paramount non-residential water consumption is from commercial, industrial, and government institution and other consumers.

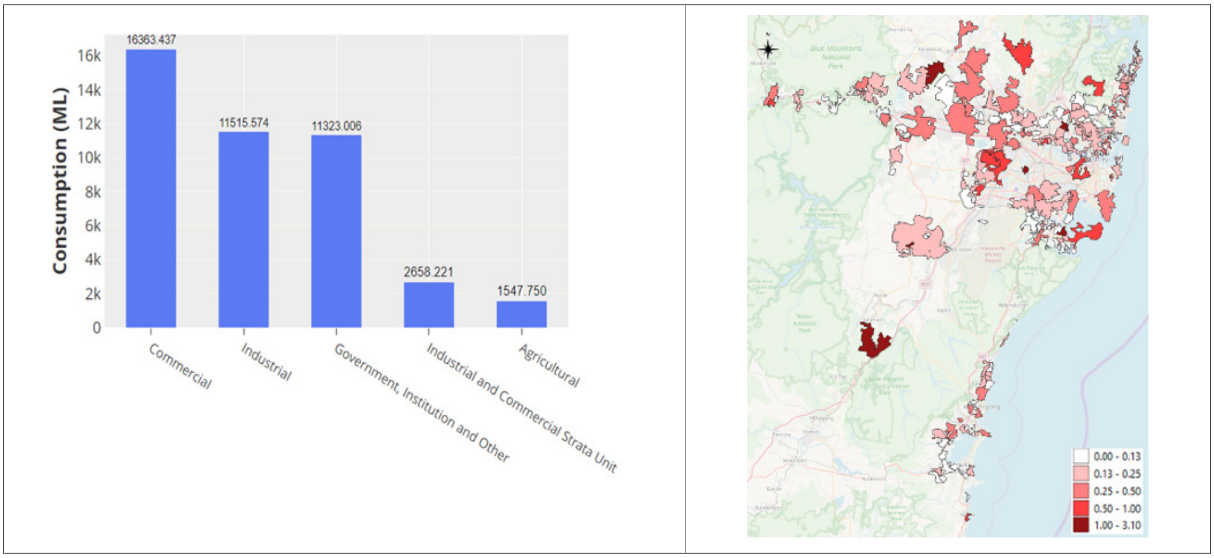


Figure 5.9: Left: Non-residential consumption usage. Right: Non-residential consumption ratio map.

This helps to narrow the type of non-residential consumers that might affect MNF observations. The project team therefore calculated the correlation between each consumption type and observed MNF, as an indicator of the cumulative influence of non-residential consumption types on pressure zones. A positive correlation value indicated the strength of non-residential consumption type on MNF observations and non-residential types with a high correlation coefficient were selected to model the non-residential usage in observed MNF. The team performed correlation analysis with 203 reliable pressure zones and five non-residential fields. The results is presented in Figure 5.10.

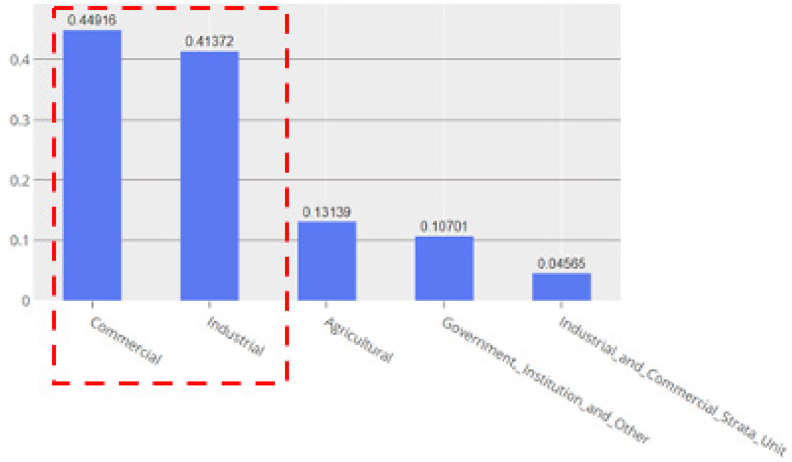


Figure 5.10: Correlation results between non-residential consumption ratio and MNF.

It is clearly visible from the correlation strength in Figure 5.10 that only commercial and industrial consumers highly influence the observed MNF values. These two types were therefore utilised to estimate the non-residential consumption or usage in the observed MNF.

1.1.1 Leakage modelling

To alleviate the influence of non-residential consumption from MNF, the team estimated the non-residential consumption in the MNF denoted as Q_{NRES} and deducted this value from the recorded value of MNF denoted as Q_{MNF}.

This withdrawal gave estimation of the true value of MNF denoted as $L_{zone@tMNF}$, which was utilised to identify pressure zones with water leakage. Technically, the deduction of non-residential consumption from recorded MNF is as in Equation 1

$$L_{zone@tMNF} \approx Q_{MNF} - Q_{NRES} \qquad (1)$$

where L is the water loss of zone at the MNF time, Q_{MNF} is the MNF and Q_{NRES} denotes non-residential usage at the MNF time.

5.6.3 Regression model

The basic linear regression model was selected without the intercept term for estimating the non-residential consumption ratio to force the regression error to be non-zero, as the value of this error is a measure of the strength of the regression estimate. The mean of MNF/day for the pressure zones with negligible non-residential rate (30 pressure zones in total) was approximately 6.8 L/NC/H, and the closer the error term is to this value, the better the regression estimates. The project's regression model is shown in Figure 5.11.

Figure 5.11: Block diagram of regression scheme.

5.6.4 Maps with MNF

The corrected MNF following the procedure leads to a revised ranking of pressure zones. The distribution of pressure zones with observed (raw) MNF values and with corrected MNF values are shown in Figure 5.14. The top ten pressure zones with high MNF values (corrected MNF values) are listed in Table 5.3. The corrected values of MNF can be used to perform prioritisation at zone level.

Table 5.3: Top 10 pressure zones - MNF values measured in litres/#connections/hour.

P_WARRINGAH_REM
P_BANTRY_RED_3
P_DURAL_SOUTH_RED_1
P_WAVERLEY_EL_BOOST_1
P_BANTRY_REM
P_NEEPAN
P_HERMITAGE_RED_5
P_TERREY_HILLS_EL
P_TOORAH_EL
P_SPRINGWOOD_REM

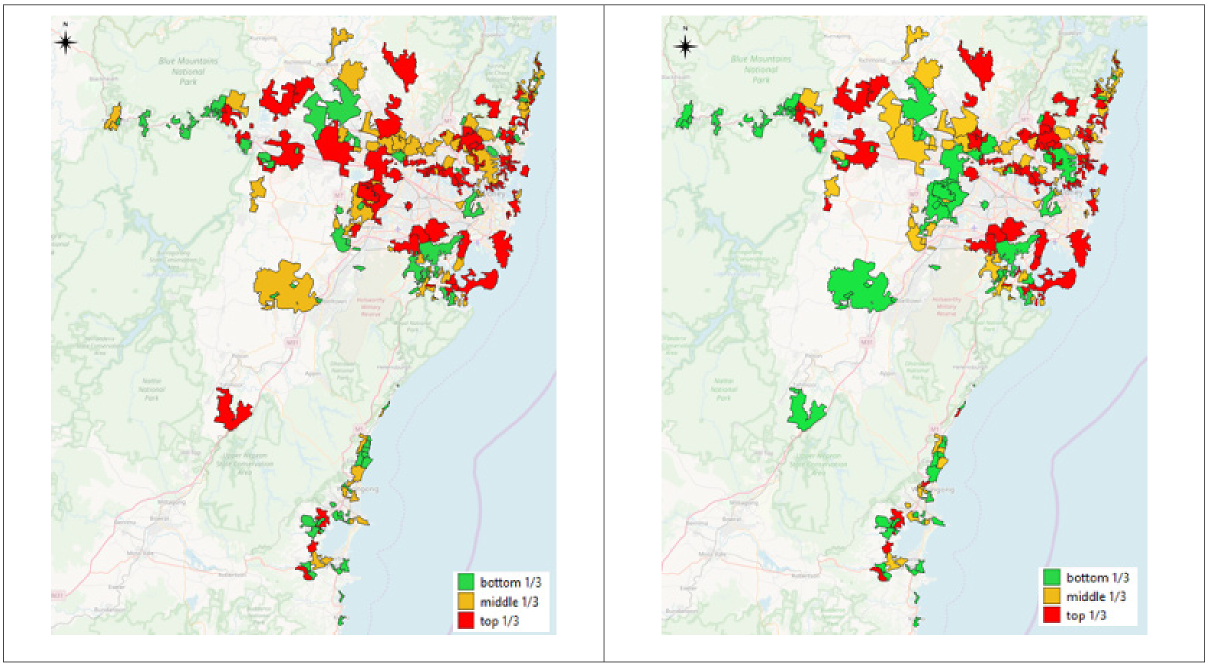


Figure 5.12: Left: Observed MNF distribution at zone level. Right: Corrected MNF distribution at zone level.

5.6.5 Zones prioritisation

The project team also obtained zone prioritisation by consolidating the zone-level failure likelihoods and corrected MNF values. They ranked pressure zones based on their aggregated risk scores in descending order, i.e. the pressure zone with maximum risk probability was allocated rank 1, the second maximum risk probability zone rank 2 and so on.

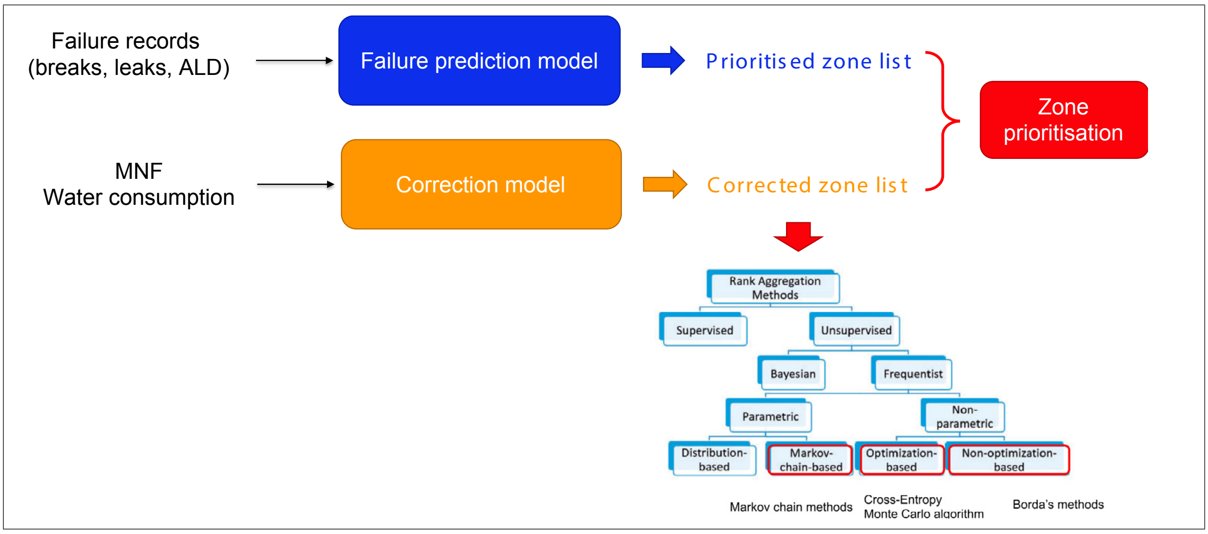


Figure 5.13: Rank Aggregation Schema. (Contact the authors for detailed drawings).

Similarly, they ranked 203 pressure zones based on the corrected MNF value in descending order. These two rankings of pressure zones were aggregated with various rank aggregation schemes such as Borda-Count (L2 norm, Geometric Mean, etc.) and Markov-Chain based methods. The rank aggregation schema is presented in Figure 5.13.

Before proceeding with rank aggregation, the validity of the pressure zones, such as number of overlapping pressure zones in the Failure records ranked list and Corrected MNF ranked list, was verified. A total of 195 pressure zones were found to be overlapping between the two ranked lists and were utilised to perform rank aggregation.

Since no ground-truth was available to validate the effectiveness of rank-aggregation schemes, Sydney Water anticipated which pressure zones were high risk, as listed in Table 5.4.

Further multiple ranked lists were based on combinations of failure records, which yielded different failure probabilities and hence a different ranked list. The combinations of failure records utilised to obtain failure-probability are as follows:

- Combination-A: WR1A and WR1B
- Combination B: WR3M and WD8C, and WP1C
- Combination C: WP1C
- Combination D: WR1A and WR1B and WR3M and WD8C, and WP1C.

Table 5.4: Pressure zone list

CBD	Pressure zones
Sydney	P_CENTENNIAL_PARK
	P_CROWN_STREET
Liverpool	P_MT_PRITCHARD
Bankstown	P_WILEY_PARK_EL_RED_1
	P_CONDELL_PARK_EL_REM
Penrith	P_PENRITH_NORTH
	P_BRINGELLY_ROAD_REM
Chatswood	P_PYMBLE_REM
	P_KILLARA_REM
	P_BANTRY_RED_2
	P_HOLROYD_RED_1
	P_WAHROONGA_RED_8

The ranked list from these combinations were utilised with the ranked list from Corrected MNF values to obtain aggregated ranked lists and the effectiveness of the rank-aggregation was measured by calculating Kendall-Tau Distance and Spearman’s Distance.

5.6.6 Results aggregation

The project performed multiple rank aggregations by utilizing either a single or two ranked lists from failure records combinations together with the ranked list obtained from corrected MNF. The combination which simultaneously achieved the lowest Kendal-Tau Distance (8738) and Spearman's Distance (11958) was combination A with corrected MNF. The wining algorithm for the rank aggregation achieving this distance is Borda-Count with Geometric mean. Figure 5.14 Final ranked zone map is the final ranked zone map and the top 10 zones are listed in Table 5.5.

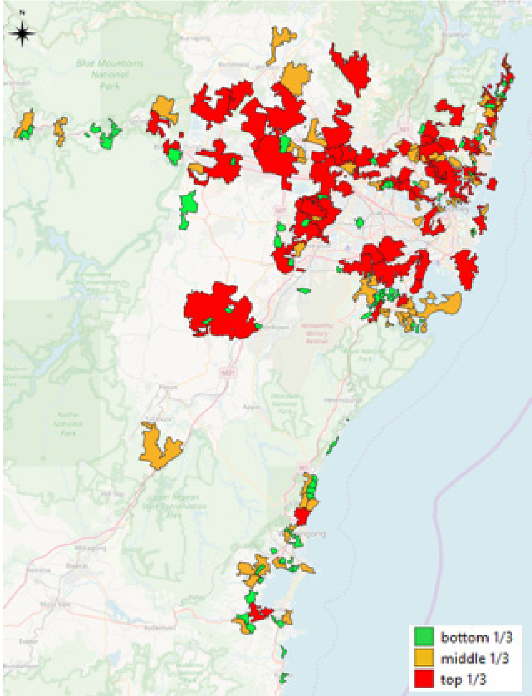


Figure 5.14: Final ranked zone map.

Table 5.5: Top 10 ranked pressure zones.

Top 10 Pressure Zones	**Related CBD**
P_MINCHINBURY_REM	
P_KILLARA_REM	Chatswood
P_WILEY_PARK_EL_REM	
P_PENSHURST_EL_REM	
P_MAROUBRA	
P_NARELLAN_SOUTH_REM	
P_BRINGELLY_ROAD_REM	Penrith
P_PROSPECT_HILL_REM	
P_LIVERPOOL_REM	
P_PYMBLE_REM	Chatswood

5.7 Conclusions

The schemes developed by the Data Science Institute at UTS encapsulate procedures for obtaining pipe prioritisation risk maps, correction of minimum night flow and zone prioritisation by consolidating failure records and corrected MNF observations.

5.7.1 Future developments

It would be highly beneficial for utilities to develop more reliable and targeted smart sensing tools (including mobile and fixed real-time sensors) to monitor priority areas to further validate and more accurately predict leaks and breaks, using reliable, easy to acquire data. These advances could be in the development of a universally applicable *leak before breaks* model.

5.7.2 Acknowledgements

During this study, many professional collaborators contributed their knowledge and ideas to this project. The project benefitted enormously from the insightful comments and helpful suggestions provided by many individuals and organisations. They are listed in Section 7.7.

6. Project Five: LiDAR, Soil and Corrosion

School of Engineering, University of Newcastle

6.1 Purpose

This section of the program report outlines the aims and provides a short summary of the technical work that was performed for the project on LiDAR, soil and corrosion. Technical details can be found in three publications and another in preparation as at the time of this report's publication (see section 8.1). The implications for the water utilities of the findings are described and a scenario for future developments presented.

6.2 Scope

Water leaks from underground water supply pipelines and external corrosion of pipelines are critical to management of the physical infrastructure for the supply of potable (drinking) water. Because of the historical development of water supply networks many older systems are composed mainly, or to a large extent, of cast iron pipes, some of which are still in sound service more than 130 years after being deployed. However, others have lasted much less time and have been responsible for leaks and breaks, sometimes with spectacular, catastrophic results, putting life and property at risk, and causing major disruption to cities and towns.

For water utilities, leaks and breaks have considerable potential for direct costs, damage reparations and, in some jurisdictions, financial penalties for water loss or wastage. The present project focused on the use of LiDAR technology to try to estimate the amount of corrosion that is likely to occur at a given location and also the likelihood of water leakage occurring. The next section gives some background necessary for understanding the reason for the choice of LiDAR technology and the use of drones. The following section outlines the experimental work performed to try to assess the feasibility and the likely accuracy of using the LiDAR technology together with established algorithms to estimate free water available for corrosion, or the free water arising from pipe leakage. This is followed by a discussion of the results obtained and the potential usefulness of the LiDAR technology and associated algorithms for the practical management of water utility drinking water pipe networks. This is followed by a summary of the findings and suggestions for further research and development.

6.2.1 Background

Previous research (Melchers, 2020) has shown a strong relationship between water leaking from a pipe, such as at a deep, often quite localised corrosion penetration (Fig. 3) into the cast iron wall from the surrounding soil inwards, and the eventual fracture of the pipe wall. The highly localised corrosion usually occurs along the bottom of the pipes. It has been attributed to local air-voids caused by the practical difficulty of backfill soil compaction in that region. The ultimate driver for corrosion at this location and other areas of poor compaction is the availability of oxygenated free moisture.

Figure 6.1: Example of localised corrosion along the bottom of a 100 year old cast iron pipe recovered from a Brisbane suburb (© RE Melchers).

Previous work (Melchers, 2020) has also shown that the localised corrosion of pipes buried in excavated trenches specifically dug for the pipes is related to the moisture that can actually reach the pipe wall surface. This 'free moisture' in the soil is water not held by the soil particles, also known as "above field capacity". This water can originate from rainfall or indirectly from runoff (Figure 6.2). It also can originate from pipes leaks not repaired. The resulting corrosion will eventually lead to localised thinning of the pipe wall and potentially eventually to catastrophic failure.

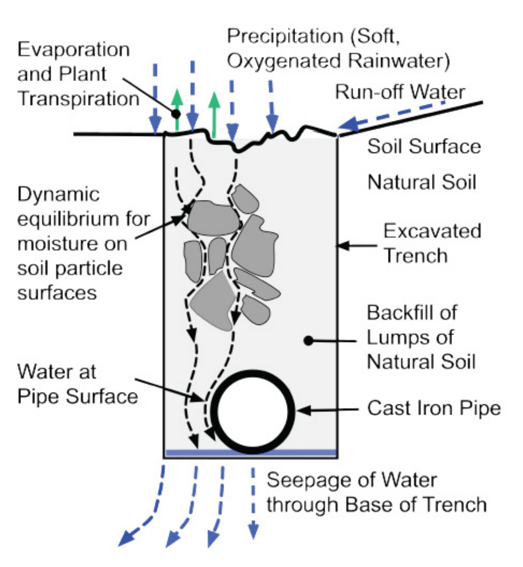


Figure 6.2: Schematic of trench and pipe system showing sources of free, oxygenated water that can reach the cast iron pipe.

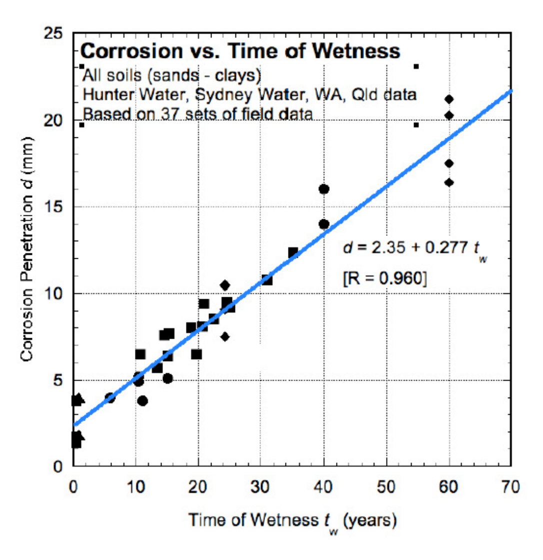


Figure 6.3: Relationship between corrosion penetration and duration of wetness at the critical locations.

An important outcome of this earlier work is that pipes subject to longer durations of moisture are prone to greater corrosion, in particular depth of penetration, irrespective of precise soil type (Figure 6.3). It follows that parts of a pipe network prone to longer effective periods of wetness are more likely to suffer greater corrosion and are more likely to have leaks.

Since the pipes are buried, typically 1.2m or more in the ground, direct visual inspection and measurement of free moisture is impractical. It could be done with moisture sensors placed along pipes, but this would require thousands of such sensors and many kilometres of cabling or wireless transmission equipment.

One surrogate for estimating the likelihood of water at the pipe is to estimate the free water at the top layers of backfill soil in the trench (Figure 6.2) on the basis that whatever is there will reflect what is likely to, fairly quickly, be free water at the level of the pipe, noting that the permeability of the back-fill soil is likely to be much greater than that of the native, undisturbed soil.

The approach for estimating the free soil moisture used in the present project makes use of light detection and ranging technology. In its simplest form LiDAR essentially determined surface topography (elevation data) at a detailed level. That information can be converted, using established algorithms, to free soil moisture estimates, as explained below, and available in the literature and papers produced in this project, as listed in Section 8 (Bretreger et al. 2020a, b, *in prepn*.)

6.2.2 Locations

The first part of the project used data from the NSW Government for a small number of selected extended suburban environments. It was extrapolated to a range of catchments across the Hunter Water area of operations.

In the second part of the project experiments were performed over two sites selected for their range of conditions.

6.3 Experimental details

The first experimental part of the project used existing LiDAR elevation data, available from the NSW Government, for catchment terrain analysis to assess the potential accumulation of soil moisture. This was done for a small number of selected extended suburban environments. The technology involved creates a measure of relative soil moisture. This was validated with a series of soil moisture field campaigns across multiple catchments and degrees of wetness (i.e. time after rain). After validation, the potential soil moisture accumulation was extrapolated to a range of catchments across the Hunter Water area of operations. Corrosion pit depth data for these areas came from studies previously conducted by The University of Newcastle. As expected on the basis of Figure 6.3, this work showed a strong correlation between corrosion depth and terrain wetness indices, indicating that, for a given soil, corrosion increased for pipes located in wetter areas. That agreed with, and complemented, previous studies by UON that found corrosion increased with greater precipitation.

The second part of the project used drone-based LiDAR measurements especially conducted for the present project, funded by Hunter Water. It used laser intensity returned to the LiDAR equipment to detect leaks from above the ground, based on the notion that a change in laser intensity as returned is related to a change in soil moisture. (Surface reflectivity in the near infrared region of the electromagnetic spectrum is ~1065 nm).

This part of the project was done by first using drone-based LiDAR to scan a nominally dry region so as to obtain a 'background' image. A pipe leak was then simulated by discharging approximately 1000 litres of water over the same area, followed by further scanning of the same region. The results showed a clear change in LiDAR intensity compared with those from the experiments with dry background conditions. In one case there were very wet background conditions, and this made distinguishing the simulated leak through the change in LiDAR intensity more difficult, although statistical differences were still evident. During all the experiments soil moisture sensors were used for calibration. It was found that LiDAR intensity readings were able to detect soil moisture changes for those experiments that had a dry background.

Further details about these experiments are available in publications listed in Section 8.

6.4 Potential benefits

LiDAR technology, through elevation and intensity data and associated algorithms provides the possibility for the water industry to have greater investigative power in regard to water leaks and to corrosion potential for water pipes, particularly cast iron water pipes. These tools, judiciously applied, could increase effectiveness of water supply pipe asset management.

The feasibility of drone-based LiDAR technology, including intensity, for fast and dynamic assessment of leaks over large areas, signals a tool for reduction in water loss, as does the added knowledge to pipe corrosion trends to assess likelihood of pipe corrosion.

Water loss can be reduced by the detection of previously unnoticed leaks and breaks, with pinpointing to location of leaks and breaks, enabling quicker repairs. This also tends towards Increased water customer satisfaction.

Reduction in pipe network renewal costs are envisaged by using pipe corrosion trends to improve schedules for proactively repairing 'at-risk' pipes. LiDAR intensity may be able to locate leaks along a pipeline, allowing faster detail investigation by field staff. Costs can be further reduced by improved accuracy of predictive corrosion model; identifying of location of leaks and breaks to reduce time and cost associated with digging dry holes; and more efficient scheduling of field resources by reducing reactive maintenance jobs, and improved proactive replacement of pipelines as they are close to failure.

Corrosion modelling that will improving pipe repair/maintenance schedule will likely reduce catastrophic pipe failure and other hazards.

With further research, potential for drone LiDAR intensity process could be commercialised, while the improved corrosion model based on previous work has commercial potential

6.5 Future research and development

Following are some areas for further research and development to help bring this project's developments to practical fruition and potentially practical implementation for water utilities. In LiDAR and fusion of remote sensing technology for detecting surface wetness:

- Improvement in accuracy of measurements and robustness, including calibration of LiDAR and algorithm outputs against different soil types and topography
- The aspects of LiDAR angle and range correction so drones might be deployed in a more versatile manner and across different sites
- Incorporation of different sensors (e.g. optical, thermal, and microwave) from multiple platforms (unmanned aerial vehicles, airborne and satellites) with LiDAR to enhance accuracy and sensitivity of the overall process for routine and continuous monitoring
- Greater compatibility or translational capability for data outputs for different makes of sensors, or improved sensor calibration for different makes of sensor, so as to avoid recalibration when different sensors are employed.

In sensing and modelling soil moisture near the pipes for improved corrosion modelling:

- Evaluation of the potential of emerging non-invasive technology (e.g. cosmic ray neutron probe) for sensing deeper soil moisture (i.e. closer to the buried pipes) and improving LiDAR remote sensing
- Improvement in soil moisture modelling (e.g. with reference to the Australian Landscape Water Balance (AWRA-L) model from Bureau of Meteorology) to predict soil moisture at a high spatial resolution (i.e. over the pipes) with LiDAR topographic metrics and soil database
- Combination of LiDAR (and other) remote sensing and soil moisture modelling to improve the estimation of likely corrosion over pipe networks.

At present there is little standardisation for LiDAR intensity measurements. This is an area in which industry is expected to take a lead to avoid difficulty in processing data using different sensors.

6.6 Conclusions

The project addressed the problem of estimating the amount of water originating from a pipe leaks when the corrosion penetration of the pipe wall is still modest and the proneness of the pipe trench system to collect and retain water at the base of the pipe to cause pipe-wall corrosion.

The topographic indices that were calculated from existing airborne LiDAR from the NSW Government were able to predict relative soil moisture from which, with calibration to field data, corrosion pit depths can be estimated.

The drone-based LiDAR intensity measurements allowed dry background soil moisture to be distinguished from soil moisture arising from a simulated leak that increased soil moisture. This approach was particularly sensitive when there was a high degree of contrast between background soil moisture conditions and those created by a leak or water.

A number of potential advances that can be made using LiDAR technology, and LiDAR technology supplemented with other indirect sensing technologies (e.g. optical, thermal, and microwave sensing), to both improve local free moisture sensing and wide-area sensing.

Airborne LiDAR data, such as available from the NSW Government, while useful, appears to be less suitable to detailed analysis. This is owing to the high spatial resolution requirements and a vast range of environmental conditions being sensed (e.g. different surface covers such as grass, soil, sand, concrete).

Overall, the present project has demonstrated that a drone equipped with a suitable LiDAR sensor may be flown over large areas, including along pipeline easements, to generate point cloud data that then may be processed, together with suitable, already available algorithms to provide a relative wetness measure where the conditions are similar (i.e. soil type, climate, background soil moisture, sensor). This can provide information on the state of moisture, including those generated by pipeline leaks, along pipelines. These outcomes should be of direct benefit to overall asset management for water utility water pipeline network asset management.

6.7 Acknowledgements

The authors acknowledge the support of Hunter Water and in particular Robert Main, Duncan Whiteley and Ian Hiles and that of Sydney Water, in particular Dammika Vitanage, as well as the close collaboration with NSSN and industry, particularly Brian Hammonds (Fyfe). They also acknowledge the support of a number of undergraduate and graduate students and research associates in donating their time for the field studies.

The UON Faculty of Engineering and Built Environment provided the funding to secure the following infrastructure to support this project. With this generous support, the UON team is well placed to lead the next phase of this project as outlined above, e.g. improve LiDAR capability (and fusion with other sensors), and soil moisture and corrosion modelling to detect leaks.

6.8 Data availability

LiDAR point clouds were generated during the drone flights conducted for the present project. The data are stored securely with UON. If required, this information can be shared for research purposes. It is not publicly available.

7. Program management

7.1 The Collaborative Research Agreement

Thirteen parties agreed to collaborate and undertake the works in accordance with the terms and conditions of the Collaborative Research Agreement (CRA), titled Advanced Pipe Sensing to Reduce Leaks and Breaks, executed on 2 May 2019.

The CRA set out that, "*The Parties wish to collaborate to explore breakthrough sensor technologies for leak detection and predictive management of water supply networks through a program of work comprising a number of projects (and others which may be added as required, including if other parties join this Agreement).*"

The CRA and Revisions were legally executed by all parties.

There were two revisions to the CRA.

- CRA Revision 1 completed on 6 August 2019 allowed for the addition of three more partners — Downer, UKWIR and Water NSW — and associated updating of funding.
- The COVID-19 pandemic put many milestones for the Advanced Pipe Sensing to Reduce Leaks and Breaks program at risk. During the April 2020 Technical Meeting, an extension to the program was proposed. A new schedule, appended to the CRA created CRA Revision 2, to allow for an extension in time from the original end date of 2 May 2020 to a new end date of 2 November 2020.

7.2 Committee of Management

The Committee of Management was charged with strategic oversight and governance of the Program. The full details of its role and function are set out in the CRA and are, in summary, to:

- act as a forum for keeping Parties informed on the progress of the Program
- approve all milestones and invoicing after advice from the Project Leader and not unreasonably withhold or delay such approval
- provide strategic direction
- discuss any issues that may arise during the course of the Program that are considered necessary to be discussed in order to effectively carry out the Program
- make decisions, give consents and allocate resources as required under the CRA in order to meet the objectives of the Program.

7.2.1 Composition of the Committee of management

Committee Member and Affiliation	**Period**
Craig Crawley (Co-chair) – Sydney Water	Jan to Nov 2020
Paul Higham (Co-chair) – Sydney Water	April to Dec 2019
Ben Eggleton (Co-chair) – The University of Sydney	April 2019 to Nov 2020
Dammika Vitanage – Sydney Water	April 2019 to Nov 2020
Duncan Sinclair - Intelligent Water Network	April to Aug 2019
Samar Patel – Intelligent Water Network	Aug 2019 to Nov 2020
Thomas Kuen – Melbourne Water	April 2019 to Nov 2020
Ethan Bartier – Queensland Urban Utilities	April 2019 to Nov 2020
Robert Main– Hunter Water	April 2019 to Nov 2020
Mark Stephens – SA Water	April 2019 to Nov 2020
Lisa Hamilton – Water NSW	Sep 19 to Nov 2020
Oluseyi Onifade – UKWIR	Sep 19 to Nov 2020
Brian Radford – Downer Group	Sep 19 to Nov 2020
Ex-Officio	
Don McCallum – NSSN	April 2019 to Nov 2020
Nick Haskins – NSSN	April 2019 to Nov 2020
Kyle Hardman – ANU	April 2019 to Nov 2020
François Ladouceur – UNSW	April 2019 to Nov 2020
Fang Chen – UTS	April 2019 to Nov 2020
Yang Wang – UTS	April 2019 to Nov 2020
Jaime Valls Miro – UTS	April 2019 to Nov 2020
Rob Melchers – University of Newcastle	April 2019 to Nov 2020
Rebeka Nikoloska – Sydney Water	Jan to Nov 2020
Peter Runcie - Consultant and NSSN Board Member	Jan to Nov 2020

7.2.2 Occurrences of Committee of Management

The committee met quarterly. All meetings were formally chaired and minuted. Minutes with actions for all meetings are kept on file.

Meeting	**Venue**
17 April 2019	UTS Tech Labs, Botany
3 June 2019	Sydney Nano, University of Sydney
17 September 2019	UTS Tech Labs, Botany
25 February 2020	Sydney Water, Smith Street, Parramatta
18 May 2020	Online due to COVID-19
19 August 2020	Online due to COVID-19
21 October 2020	Online due to COVID-19

7.2.3 List of events

The partners participated in a wide range of events, meetings and conferences, both face-to-face and online, over the course of the Program.

Event	Date	Venue
Presentation of ideas to Water Services Association of Australia (WSAA)	14 Mar 2018	WSAA Offices, Sydney City
Sydney Water's Strategic and Operational Monitoring and Data Analytics Needs	18 May 2018	The University of Sydney
Better prediction of leaks and breaks of water mains with intelligent sensing and analytics	9 Nov 2018	UTS Tech Lab
Technical and Planning Meeting: Critical Underground Pipe Sensing	22 Mar 2019	UTS Tech Lab
Frontiers in Sensing: Quantum Sensing workshop with Prof Kai Bongs	15 May 2012	NSW Parliament House
Sydney Water Science Week: Wider Application of Quantum Sensing for Water Resources	2 Aug 2019	Sydney Water, Parramatta
NSW Water Industry Innovation Workshop	2 Oct 2019	Park Royal Hotel, Darling Harbour, NSW
IEEE Sensing Conference and Technical Meeting	2 Dec 2019	Macquarie University
Program Technical Meeting	2 April 2020	Online

7.3 Workplace health and safety

No incidents or injuries were reported over the course of the Program.

The following points were noted:

- Additional measures including social distancing and hand washing imposed by COVID-19, adhered to by UTS procedures.
- Need to visit heavy traffic areas (various CBDs in Sydney) for sensor deployment locations.
- Working in hydrant chambers which may contain dirty/hazardous materials
- Field work is carried out with Sydney Water personnel and their WHS procedures followed.

7.4 Budget

The budget was measured in terms of Cash and In-Kind Contributions, to realise a full Program value of $3,423,276. With additional works and delays, particularly due to COVID-19, the actual cost of Program activity is likely to exceed $4 million.

Table 7.1: Overall contributions

Type	$ in 2019	$ in 2020	$ Total
Cash	888,895	620,000	1,513,355
In-Kind	861,275	1,048,664	1,909,921
Total	**$1,750,170**	**$1,668,664**	**$3,423,276**

7.4.1 Cash income and expenditure

The cash budget was managed by George Pang and Sandra Martin of UTS, with oversight from the NSSN and Committee of Management. The Program reports a balanced budget with all expenditure efficiently allocated to Project activities in accordance with the CRA.

Table 7.2: Program income by Party and year

Party	$ in 2019	$ in 2020	$ Total
Sydney Water	600,000	400,000	1,000,000
NSSN	50,000	50,000	100,000
Hunter Water	55,000	20,000	75,000
SA Water	50,000	100,000	150,000
Melbourne Water	20,000		20,000
QUU	25,000	25,000	50,000
IWN	25,000	25,000	50,000
Downer Group	20,000		20,000
UKWIR	28,355		28,355
Water NSW	20,000		20,000
Totals	**$888,895**	**$620,000**	**$1,513,355**

Table 7.3: Program Expenditure by Party (Project) and reference.

Party	Reference	$ per payment	$ Total
ANU (Project1)	471602	178,000	
ANU (Project1)	475263	108,000	
ANU (Project1)	477641	108,000	
ANU (Project1)	478922	90,893	
ANU			484,893
UNSW (Project Two)	GRP0267195	150,000	
UNSW (Project Two)	GRP0268600	86,948	
UNSW (Project Two)	TBC	10938	
UNSW			247426
UON (Project Five)	SDG89859	50,000	
UON (Project Five)	GDI0000637	50,000	
UON (Project Five)	GDI0002874	50,000	
UON (Project Five)	GDI0004289	43,184	
UON			193184
UTS (Project Three)	UTS Internal	289776	289776
UTS (Project Four)	UTS Internal	293616	293616
All parties final payment	5 x 892 each	4460	4460
Total			**$1,513,355**

7.4.2 In-kind contributions

In addition to cash flow, considerable in-kind contributions have been made by all partners. In the case of the water utilities this was often represented by supply of labour, parts and materials, real internal transactions and payments to suppliers and contractors. More broadly all Parties contributed advice, reports, industry sector knowledge, participation in meetings, review of Project progress and so on. University partners made considerable knowledge contributions and professorial research leadership of Projects. Sydney Water and the NSSN contributed significantly to management, administration, reporting and communications.

Table 7.4: In-kind contributions by Party and year.

Party	**$ in 2019**	**$ in 2020**	**$ Total**
Sydney Water - Non-labour	100,000	400,000	500,000
Sydney Water - Other	250,000	250,000	500,000
NSSN	50,000	50,000	100,000
UTS	75,000	75,000	150,000
UNSW	25,000	25,000	50,000
ANU	112,500	37,500	150,000
UON	36,482	21,889	58,371
Hunter Water	54,000	21,000	75,000
SA Water	75,000	75,000	150,000
Melbourne Water	Nil	10,000	10,000
QUU	25,000	25,000	50,000
IWN	25,000	25,000	50,000
Downer Group	10,000	10,000	20,000
UKWIR	13,275	13,275	26,550
Water NSW	10,000	10,000	20,000
Total	**$861,275**	**$1,048,664**	**$1,909,921**

7.5 List of Partners

7.5.1.1 Sydney Water

Sydney Water was the lead partner on the project, contributing significantly to its funding and delivery.

7.5.1.2 NSW Smart Sensing Network

The NSSN was responsible for the ideation of the program, the bringing together of stakeholders and ensuring their ongoing engagement. It held considerable responsibility for many aspects of the program and project management, including financial oversight, administration, running of meetings and events, and documentation and communications.

7.5.1.3 SA Water

SA Water made critical contributions to the Program, in particular the Acoustic Sensing project. It lent and donated acoustic sensors worth many thousands of dollars. It is a considered a world leader in the deployment of acoustics sensors, and the project success heavily depended on its sharing of knowledge.

7.5.1.4 Queensland Urban Utilities

QUU was a fully engaged contributor to the project. It kept the Program informed of other sensing trials, such as sniffer dogs from Bellden http://www.belldenenvironmentalservices.com.au/ and active acoustic sensing from Leakster https://www.leakster.com.au/.

7.5.1.5 Hunter Water

Hunter Water was instrumental to the organisation and facilitation of Project Five: LiDAR, Drones and Corrosion. It brought considerable experience in the use of drones and imparted considerable knowledge to the Program.

7.5.1.6 Downer

Downer, as a major supplier of infrastructure to the water industry, was a valuable source of knowledge from private industry.

7.5.1.7 UKWIR

UKWIR has been shaping the UK water industry for over 25 years. It facilitates, manages and delivers research projects for its members, the water companies of the UK and Ireland, to address challenges they face. UKWIR provided international perspectives on the state-of-the-art of water sensing and is seen as a valuable audience for the outcomes of the work. Joey Durham from Wessex Water and Adam Smith from Yorkshire Water, among others, provided insights and facilitated global conversations. Oluseyi Onifade assisted with international administration.

7.5.1.8 Water NSW

As the chief operator of the NSW water supply, Water NSW has a keen interest in the outcomes of the Program.

7.5.1.9 Intelligent Water Network

The Intelligent Water Networks Program investigates new technologies and innovations to meet common challenges such as population growth, ageing infrastructure and climate variability in a more efficient manner. IWN is a partnership between VicWater, 16 Victorian water corporations and the Victorian Department of Environment, Land, Water and Planning. It provided valuable information to the projects and is seen as an excellent audience for uptake of outcomes.

7.5.1.10 Melbourne Water

Melbourne Water has been an active and wise source on information and knowledge and a vocal contributor to the Committee of Management.

7.5.1.11 ANU

ANU led investigations into Project One: Quantum sensing. It was aided by the University of Canberra for soil hydrology.

7.5.1.12 UTS

UTS led Projects Three: Acoustic Sensing and Project Four: Data Analytics. It also assisted with venues, contracting, legal advice and financial management.

7.5.1.13 UNSW Sydney

UNSW led the work into distributed acoustic sensing. It was assisted by Thales and Zedelef.

7.5.1.14 University of Newcastle

UON led Project Five: LiDAR, Drones and Corrosion. Its Faculty of Engineering and Built Environment provided funding to secure infrastructure to support this project.

7.6 List of suppliers

We thank the following suppliers of materials and services.

University of Canberra: School of Design and Built Environment under the leadership of Professor Charles Lemckert, supplied the Quantum Science project with hydrogeological modelling and excellent academic leadership.

Atlas Geophysics: Leon Mathews, provided the hire of the CG5 for gravity surveying in the first run of the gravimetry experiments.

UltraMag: Philip McClelland, provided the hire of the CG5 for gravity surveying in the second run of the gravimetry experiments.

Geotechnique: Indra Jworchan, provided soil sampling and testing.

Detection Services: Steve Simmons, Director, shared product details, tender, quotes, deployment. Supply of Von-Roll and HWM sensors,

Detection Services: Alex Norman, NRW Project Manager, provided sensor deployment planning and execution, logger maintenance, leak investigations/data validation.

Fyfe Pty Ltd: Brian Hammons, UAV Pilot assisting with drones and LiDAR.

Ovarro /Servelec: Etienne Clauw Sales Manager AU, NZ, shared product details, tender, quotes, deployment.

Ovarro /Servelec: Chris Moore, Associate Product Line Manager - Leakage, provided sensor deployment planning and execution, logger maintenance and leak investigations/data validation.

Water group: Gunter Hauber-Davidson, Managing Director, shared product details, tender, quotes, deployment. Supply of SebaKMT

Water group: Ijaz Ahmad, Smart Metering Engineer, provided sensor deployment planning and execution, logger maintenance and leak investigations/data validation.

Gutermann: Julian Wilkinson BDM, shared product details, quotes, deployment.

Syrinix UK: James Dunning, CEO, shared product details, quotes, deployment information pressure transients

Xylem: Roberto Mascarenhas, BDM, shared product details of Visenti.

7.7 List of participants

7.7.1.1 Project leads

The following eminent individuals are recognised leaders in Australian research.

Project One: **Professor John Close**

Head of Department of Quantum Science, Research School of Physics, ANU

Project Two: **Professor Francois Ladouceur**

Professor in Photonics and Industry Liaison, School of Electrical Engineering and Telecommunications, Faculty of Engineering, UNSW Sydney

Project Three: **Associate Professor Jaime Valls Miro**

Centre for Autonomous Systems, Faculty of Engineering and IT, UTS

Project Four: **Professor Fang Chen**

Executive Director and Distinguished Professor. Data Science, UTS

Project Five: **Professor Rob Melchers**

School of Engineering, The University of Newcastle

7.7.1.2 Key researchers

Mr David Bretreger: School of Engineering, The University of Newcastle, PhD Candidate, Project Five.

Dr Lili Bykerk: Centre for Autonomous Systems, FEIT, UTS Research Associate, Project Three.

Dr Kyle Hardman: Department of Quantum Science, Research School of Physics, College of Science, ANU, Project One.

Ms Nasrin Taghavi: Faculty or Arts and Design University of Canberra, Project One.

Associate Professor Yang Wang: Institute for Data Science, UTS, Project Four.

Associate Professor In-Young Yeo: School of Engineering, The University of Newcastle, Project Five.

7.7.1.3 Contributing personnel

Ms Shahrzad Abbasi: NSSN, Communications and Media

Ms Nigar Afrozar: Sydney Water, Customer Hub, Data review and SW engagement

Mr Greg Alford: Sydney Water, Networks Ops West (Penrith)

Ms Georgiana Anderson: Sydney Networks Ops South (CBD)

Ms Nicole Arbon: South Australia Water, Asset Analytics

Dr Zourab Brodzeli: Zedelef Pty Ltd, Project management

Mr Andrew Bui: Sydney Water

Mr David Cantlon: Sydney Water, Networks Ops West (Penrith)

Mr Brendan Cantlon: Sydney Water, Networks Ops South (Bankstown)

Mr Darren Cash: Sydney Water, Technical acumen

Mr Frederik Crous: UNSW, EE&T Mechanical engineer

Mr Ronith Cheriyan: Sydney Water

Mr Daniel Dent: Thales, Under Water Systems, Project management

Professor Gamini Dissanayake: Centre for Autonomous Systems, FEIT, UTS, Project Investigator

Dr Chris Freier: Gravity Engineer, ANU, Project One.

Mr John Garton: South East Water, IWN, Reliability Planning - Networks

Mr Ian Hiles: Hunter Water Corp, Intelligent Networks

Ms Sandra Arcos Holzinger: Thales, Under Water Systems, GSS Engineer

Ms Tin Hua: Sydney Water, Technical acumen

Dr Mahdi Hussein: Centre for Autonomous Systems, FEIT, UTS, Research Engineer

Ms Indra Jworchan: Principle Geotech. Eng., WSP, Project One

Mr Krish Krishnananthan: Sydney Water, Technical acumen

Professor Charles Lemckert: Faculty of Art and Design, University of Canberra

Dr Zhidong Li: FEIT, University of Technology Sydney, Team member

Dr Bin Liang: FEIT, University of Technology Sydney, Team member

Dr Shuming Liang: FEIT, University of Technology Sydney, Team member

Ruben MacNeil: Hunter Water, Intelligent Networks, Service Delivery for Customers

Mr Robert Main: Hunter Water Corp, Intelligent Networks

Ms Sandra Martin: UTS, Contracting and legal advice

Mr Philip McCelland: CG5 Surveyor, UltraMag, Project One

Mr Chau Nguyen: Sydney Water Networks Ops (Liverpool)

Mr George Pang: UTS, Financial Administration

Mr Pradeep Perera: Sydney Water, Networks Ops (Chatswood)

Mr Samuel Read: Thales, Under Water Systems, Mechanical Engineer

Mr Abdul Rehman: Sydney Water, Networks Ops South (CBD), Action follow-up and field technician management

Ms Aravinda Stanley: Sydney Water

Mr Kieran Tyson: Thales, Under Water Systems, Project Technical Lead

Jamie Uy: Sydney Water, Networks Ops (Liverpool).

Mr Sunny Verma: DSI, FEIT, University of Technology Sydney, Team member

Mr Duncan Whiteley: Hunter Water Corp, Intelligent Networks

Mr Johnny Xiao: Sydney Water, Customer, Strategy & Regulation

Dr Jack Xu: Data Science Institute, University of Technology Sydney

7.8 Program data

The date generated by Project One is stored on an internal server at ANU.

The data generated in Project Two has been collected and is managed by Thales, stored securely and available upon request to Program Partners.

Significant data has been collected and part of Project Three. The data are stored securely on each of the sensor manufacturer's online portals and data servers. Data retrieved by UTS for its research is then kept in accordance to its data storage solutions to assure safety and security. This includes UTS eResearch Store – accessible through the UTS network or VPN, for long-term storage, and OneDrive/Sharepoint. Both guarantee confidentiality, with encryption both at rest and in transit. Moreover, ARRNET Cloudstor may also be used for exchange of large UTS data files with applicable third parties, which guarantees secure access to sensitive data.

The data from Project Three is NOT available to Program Partners. It is shared between Sydney Water, UTS and service providers (as applicable) within the given protocols established by a research agreement between the parties (as applicable).

Data from Project Four is not publicly available.

In Project Five drone LiDAR point clouds have been generated from flights. The data are stored securely with UON. If required the team at UON can share this information, although it is not publicly available.

8. Outcomes

8.1 Academic publications

8.1.1 Published

Bretreger, D., Yeo, I-Y., Melchers, R. 2020. LiDAR Derived Terrain Wetness Indices to Infer Soil Moisture Above Underground Pipelines. International Journal on Smart Sensing and Intelligent Systems 13(1): 1-7

Bretreger, D., Yeo, I-Y., Melchers, R. 2020. Terrain wetness indices derived from LiDAR to inform soil moisture and corrosion potential for underground infrastructure, Science of the Total Environment, 27 November 2020. https://doi.org/10.1016/j.scitotenv.2020.144138

Chen, F., Wang, W., et al. “Advanced Pipe Sensing to Reduce Leaks and Breaks – Data Analytics: Multi-modal approaches data analytics to prioritise sensing and developing predictive analytics”, Data Science Institute, UTS, May 2020.

Ladouceur, F., Silvestri, L. 2109. Distributed sonar arrays for leak detection, Thirteenth International Conference on Sensing Technology (ICST 2019), December 2–4, 2019, Sydney, Australia

Melchers, R. 2020. “Models for prediction of long-term corrosion of cast iron water mains”, Corrosion, 76(5) 441-450

Nikoloska, R., Bykerk, L., Arbon, N., Vitanage, D., Valla Miro, J., Stephens, M., 2020. Enhancing acoustic monitoring in Sydney Water’s CBD networks. Sydney Water eJournal 200505

Nikoloska, R., Bykerk, L., Vitanage, D., Valls Miro, J., Chen, F., Wang, Y., Liang, B., Verma, S. 2020 Enhancing Sydney Water’s Leak Prevention Through Acoustic Monitoring: New Approaches to the Application of Sensing for Leaks. Water e-Journal. 2020; Vol 5 (2)

Valls Miro, J. “Review of Acoustic Sensing for the Prediction of Leaks and Breaks in Water Mains – A technical report for the Sydney Water led collaborative research project on Enhancing Predictive Management of Water Networks, under the umbrella of the NSW Smart Sensor Network”, Jaime Valls Miro, November 2019.

Vitanage, D., Crawley, C., Holland, D., Cash, D., Zhang, D., Karunatilake, N., Xiao, J. Sydney Water Innovative Approaches to Predict, Discover and to Repair Leaks and Breaks, Ozwater 2020.

8.1.2 Future planned publications

As is normal in academic studies, it may be several months from program completion before results are translated into publication. Project participants have indicated likely future papers.

Bretreger, D., Yeo, I-Y., Melchers, R. ‘DRAFT’. Airborne LiDAR Intensity to Identify Water Pipe Leaks and Changes in Soil Moisture

Hardman, K., Close, J., Taghavi, N., Lemckert, C. Publication discussing modeling methods for identifying underground density variations. Modeled water plume gravity is used for this. Bayesian optimization with parametric models via sequential Monte Carlo with University of Sydney

Hardman, K., Close, J., Taghavi, N., Lemckert, C. Publication outlining results of field trial. Detection of water mains leaks with gravimetry

Hardman, K., Close, J., Taghavi, N., Lemckert, C. Publication detailing modelling of ground water dynamics from local (leaking pipes) to regional systems (aquifers)

8.2 Communications and media

The Program has committed professional staff to ensure excellence in media and communications. Selected media and communications highlights include:

Channel 7 News: The development of quantum sensors for identifying leaks in underground water mains was featured on 7News as a result of this project. 6 August 2020. https://www.facebook.com/watch/?v=2678887679025578 .

Engineers Australia: Applied IoT Engineering Community: Webinar "Advanced Pipe Sensing for Leaks and Breaks" was presented to an audience of 300. 20 August 2019. https://engineersaustralia.org.au/event/2019/06/advanced-pipe-sensing-leaks-and-breaks

YouTube: A promotional video was produced and is stored on YouTube: "Smart water management: NSSN and Sydney Water smart pipe sensing for leaks and breaks R&D" https://www.youtube.com/watch?v=7UtiwJ_TcUw

There has been considerable further exposure for the project via social media sites LinkedIn and Twitter, in trade magazines, on university websites and via press releases.

Table 8.1: Selected list of print and online media articles.

Publication	Date	URL
The Fifth State	27/02/2020	https://www.thefifthestate.com.au/articles/why-our-driest-state-leads-the-way-on-water/
Utility Magazine	22/01/2020	https://utilitymagazine.com.au/sa-waterssmart-sensor-technology-deployed-insydney
PACE Today	08/01/2020	https://pacetoday.com.au/acoustic-sensingproject-help-sydney-water-prevent-pipebreakage/
PACE Today	27/11/2019	https://pacetoday.com.au/nssn-partneringuniversities-water-utilities-advanced-breakdetection-research/
Utility Magazine	10/10/2019	https://utilitymagazine.com.au/sydneywaters-innovative-approaches-to-predictdiscover-and-repair-leaks/
UC News	30/09/2019	https://www.canberra.edu.au/about-uc/media/newsroom/2019/september/uc-joinsnsw-smart-sensing-network-to-find-practicalsolutions
UTS News	08/082020	https://www.uts.edu.au/research-andteaching/our-research/data-science/ourresearch/prevention-better-cure-whenmanaging
Trenchless Australasia	25/07/2019	https://www.trenchless-australasia.com/2019/06/25/collaboration-drives-waterindustry-innovation/
Water Source	21/06/2019	https://watersource.awa.asn.au/technology/innovation/sydney-water-and-unswcollaborate-to-locate-leaks/
Australian National Fabrication Facility	10/062019	https://www.anff-nsw.org/anff-nsw-users/unsw-researchers-tasked-to-locate-leaks-in-the-sydney-water-network/
PACE Today	03/062019	https://pacetoday.com.au/sydney-waterteams-unsw-thales-zedelef-detect-waterleaks/
The CSR Times	02/06/2019	https://www.thecsrtimes.com/2019/06/03/unsw-leak-detection-tech-mig
IT News	30/05/2019	https://www.itnews.com.au/news/sydneywater-taps-unsw-fibre-optic-sonar-to-findleaks-525862
Fluid Handling	29/05/2019	https://fluidhandlingmag.com/news/researchers-to-locate-sydney-water-leaksusing-optical-sonar-array-tech/

UNSW	28/05/2019	https://newsroom.unsw.edu.au/news/ science-tech/unsw-researchers-taskedlocate- leaks-sydney-water-network-0
Industry Update	02/052019	https://www.industryupdate.com.au/article/ smart-sensing-technologies-secure-watersupplies
Government News	26/03/2019	https://www.governmentnews.com.au/ sydney-waters-anti-leak-pipe-dream/

8.3 Technology transfer

The Program was designed from the outset with intention that all research work would lead to technology transfer to industry. The different Projects have adopted distinct pathways for that transfer.

8.3.1 Technology transfer: Quantum Sensing

The major achievement of this project is the validation of detection of underground water plumes using gravity to within a distance of about 5 metres from the leak. The project successfully identified water plumes created via water injection near buried water mains in two separate trials with varying soil and background conditions. This ability to sense leaking pipes without digging and knowing that nothing can normally shield a gravity signal, and that the presence of roads, buildings or vegetation has virtually no effect on the measurement, should make the technology attractive to further investigation by water utilities.

A potential opportunity for knowhow generated in the project lies with the finalisation of this project coinciding with key staff (Kyle Hardman) leaving his academic post to work full time with a start-up company Nomad Atomics https://www.nomadatomics.com/. Nomad Atomics specialises in the development of high precision quantum sensors. By exploiting the natural properties of atoms and their interaction with light, they produce state of the art sensors for the measurement of gravity, accelerations, magnetics and time. These sensors provide a step change in data acquisition and performance of hardened field ready systems for deployment in resource monitoring, resource exploration, climate science, underground infrastructure exploration and inertial navigation. This will greatly improve the accuracy of gravity measurements taken with *spring based* gravimeters that were used in this study.

The ANU has also applied for an Australian Research Council (ARC) Linkage Infrastructure, Equipment and Facilities (LIEF) scheme for the purchase of a CG5 Gravimeter to allow ongoing development of baseline gravity measurements. The collaborative application is seeking to purchase a working pair of state-of-the-art gravimeter to allow field gravity surveys. The instruments are unique to Scintrex, a US manufacturer. They have sufficient short-term sensitivity to allow field measurements that will enable a variety of applications in water resource management, mineral exploration, inertial navigation and space-based applications of gravimetery. Having this device readily available to Australian researchers and water utilities offers great potential.

While the findings in this project have significant potential for use in urban pipe networks, the findings have potential translation to catchment level analysis. A concept paper titled "Where Is All the Water?" (McCallum, Close, & Cripps, 2020) sets out how to combine new sensing technology and gravitational data, with existing telemetry of flows, surface and ground water to greatly enhance understanding of water flows in large catchments, such as tributaries to the Murray-Darling and the basin as a whole. This offers greater knowledge for policy setting and aligns with issues raised in the recent "Review of water-related data collections, data infrastructure and capabilities" (Durrant-Whyte, 2020) by the NSW Chief Scientist and Engineer, such as a "lack of long-term monitoring infrastructure planning" and "a lack of *point of truth* for raw monitoring data".

The work is also of interest as a method to measure the impacts of mining, coal seam gas extraction and other process that may have geological impacts on ground and surface water. The quantum gravitational techniques are also of interest in measuring water retention where *slowing the flow* and other rehydration practices are being implemented.

8.3.2 Technology transfer: Distributed Acoustic Sensing

This project demonstrated what is essentially an entirely new way of sensing leaks in pipes.

The following achievements are noted:

- With reference to Figure 8.1, leaks were successfully detected at distances greater than 40 meters (position B, C, D).
- Leaks types were acoustically characterised in the test pipe environment, which will inform the development of leak detection algorithms in future.
- Background noise recordings for the test period were also gathered against the leak data for future reference and will also inform the development of leak detection algorithms in future.
- Signal to noise ratios were calculated for all recorded leaks.
- The project created and tested an experimental method of array insertion for pipe testing which will inform the design of an operator useable array in subsequent development work.

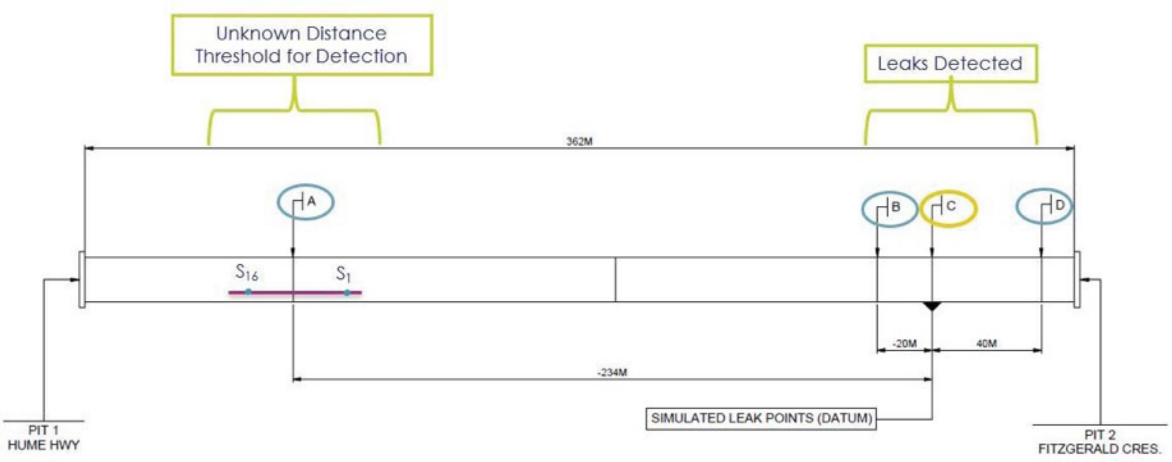


Figure 8.1: Schematic representation of array and leaks positions along the test pipe. Leaks were successfully located at position B, C and D.

There exists capability for the exploitation for research outcomes with the Sydney based company Zedelef (http://zedelef.com.au/wp/), and the global giant Thales (https://www.thalesgroup.com/en). However, both companies require the involvement of major stakeholders in the water industry, such as the utilities, to be drivers of the work. Many of the physical and signal processing parameters that were part of this work were designed for a different purpose and there is a clear path to improvement by tailoring the system to water pipes. Since the successful test runs, and in preparation to a second phase, meeting between UNSW, Thales, Zedelef and Sydney Water were held:

- Technical debriefing meeting, Thales Rydalmere, 8 January 2020. UNSW, Thales and Zedelef put together a proposal for a second phase preliminary entitled Acoustic Distributed Leak Detection (ADLD).
- Productisation meeting, Thales Rydalmere, 13 January 2020. High level commercialisation discussion between Sydney Water (Paul Higham), Thales (Gaelle Mahevas) and Zedelef (François Ladouceur).
- Technical meeting, Thales Rydalmere, 15 January 2020. Technical specification meeting with Sydney Water (David Oblati, Dammika Vitanage), Thales (Daniel Dent, Kieran Tyson) and Zedelef (François Ladouceur, Zourab Brodzeli).

Since completion of the experimental phase in December 2019 and the report in early 2020, the project leads have sought additional funds, including from the NSW Physical Sciences Fund.

The full technical report by Thales detailing approach taken and results obtained is entitled “LCS Array for Water Pipe Leak Detection Trial Report”, Sandra Arcos Holzinger, Internal document number 61257007_087-1. This report is Commercial in Confidence and requests for information should be made to the Project Lead or NSSN.

The exact nature of this technology transfer is yet to be precisely defined but the prevalent mechanism would see Thales as a technology integrator while Zedelef would act as an OEM providing specialised opto-electronics subsystems.

The project cannot claim an immediate impact on the research field or industry practices, but the proposed next phase might. Likewise, the project yielded no IP opportunities so far as it was simply testing existing technology in a new environment. The evolution of the technology into a tailor-made tool for leak detection will probably generate such opportunities as many aspects of the problem will need to be tackled (insertion, network topologies, leak detection algorithms, sensor optimisation, etc.)

8.3.3 Technology transfer: Acoustic Sensing

Mechanisms are now in place in the five CBD zones between sensor providers, UTS and Sydney Water to directly raise alarms from the sensor data analysis. This is a modification of past practices at Sydney Water in relation to leaks.

Sydney Water is now proactively addressing the repairs of leaks before breaks, as raised by sensors, instead of reactively, therefore saving water and preventing breaks and customer inconvenience. Indirectly, this also bring benefits to the image of Sydney Water in the community. A link between SA Water analytics software and UTS and Sydney Water during the pilot scheme was established so that alarms could be studied and considered directly by key stakeholders at Sydney Water and UTS.

A direct link between sensor providers and the UTS sensing team, and Sydney Water, has also been established since so that alarms can now be studied and considered directly by key stakeholders at Sydney Water and UTS. In this regard, weekly meetings took place for a period after the sensors were deployed in their respective zones.

Sensor providers (Detection Services, WaterGroup and Ovarro) arranged for direct access to raw data from sensor providers to UTS/Sydney Water in assisting with the development of an integrated web portal for Sydney Water.

A publication of the joint learnings from CBD deployments was published in the Australian Water Association e-Journal in 2020 (see section 8.1.1). It shared preliminary results of the project.

Considerable communication with key stakeholders (field and management personnel) in Sydney Water continues on a regular basis.

Leaks have been found in the five Sydney Water CBD zones that may have not been found otherwise. This is the key objective of the overall project, thus minimising impact of breaks in the community, and preventing loss of water.

Operationalisation of acoustic sensors

20 (+5) HWM PermaNET+
3 potential leaks raised with SW
3 leaks confirmed by SW

23 (+4) SebaKMT Sebalog N3
7 potential leaks raised with SW
5 leaks confirmed by SW
2 to be investigated

40 (+5) Primayer Enigma3m
3 potential leaks raised by SW
1 leak confirmed by SW
2 to be investigated

65 HWM PermaNET
23 potential leaks raised with SW
16 confirmed by SW
5 to be investigated

41 SebaKMT Sebalog N-3
21 potential leaks raised with SW
9 confirmed by SW
12 to be investigated

20 (+5) VonRoll Ortomat-MIKC-IR-4G
20 (+5) HWM PermaNET+
13 potential leaks raised with SW
11 leaks confirmed by SW
2 suspected private leaks repaired (1 location)

Total estimated water saved 700ML/year. Approximate water production cost saved >$3M.

Leaks score card November 2020
70 likely with 44 confirmed
~ <75Km
Leaks surfaced only 2. All leaks detected by sensors and not customer complaints

Acoustic sensors and (+pressure transient sensors)
🟪 Acoustic sensor type
🟦 Online leaks detected

Figure 8.2: Location and types of acoustic sensors deployed across Sydney.

8.3.4 Technology transfer: Data Analytics

A tool has been developed to translate the research outcomes to practical usage. It can be and is being used to conduct pipe failure prediction by Sydney Water.

Presentations and reports have been provided to explain the methodologies used in the project. The method has been validated by client regularly demonstrating that:

- 80% of failures can be detected within top 20% prioritised pipes.
- 80% of the predicted failure locations are within 200m to the actual failures.
- The prioritised zones and pipes have been used to support the plan of sensors development.

8.3.5 Technology transfer: LiDAR, Drones and Corrosion

The Project demonstrated the use of LiDAR technology to detect pipe leaks and long-term corrosion of cast iron water supply pipes. Hunter Water has been close to this project and other utilities are welcome to make contact for further exploitation of the techniques.

Previous work identified that, apart from workmanship issues associated with the initial installation of the pipes and their burial, a major factor in the corrosion of the pipes at depth is the free water that can make its way from the surface through the backfill soil to the pipe exterior walls. The major contributor to this free water is rainfall, and the associated accumulation of water in the soil surrounding the pipe. Since this cannot be economically measured at pipe depth, a surrogate is to examine the free water available on the soil surface above the pipe. This can also be used for leak detection across the water distribution network. The project used both existing and new light detection and ranging technology to help determine wetness on the soil surface.

NSW Land and Property Information (LPI) (now known as Spatial Services) can provide data collected using airborne LiDAR systems. The data are in the form of surface elevations determined from laser returns collected from an aeroplane. Typically, the data are in the form of a so-called point cloud (Figure 8.3, left). The project is using the elevation data so obtained and is processing it to calculate a Topographic Wetness Index (TWI), or SAGA Wetness Index (SWI). It is based on routing runoff through a catchment, and thereby identifying wet spots. It is a well-tried and proven technique for larger topographical areas (Beven and Kirkby, 1979). The TWI/SWI is based on elevation changes, slope of the land and the area contributing to the point being considered. For a given topographical catchment area, the outcome is an image of wetter and drier spots over that catchment (Figure 8.3, right).

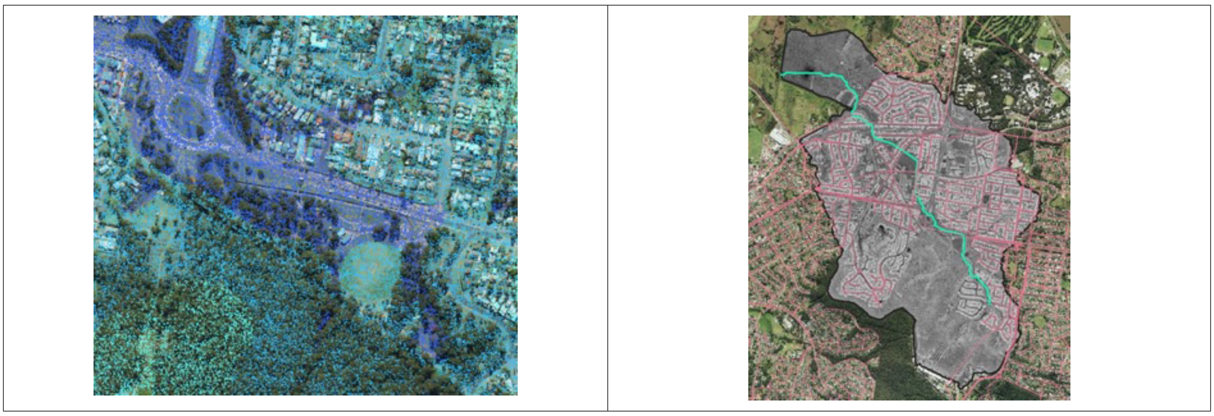


Figure 8.3: Airborne LiDAR elevation (left) and the SWI output over a catchment in Hunter Water Corporation's area of operations (right).

In the first part of Project Five of this program, the SWI was compared to physical soil wetness measurements so as to assess to the capability of the SWI for the much smaller urban catchments relevant to easements and immediately surrounding catchment areas relevant to water supply pipes. This was applied to selected water supply pipelines in the Hunter Water area of operations. It covered a wide range of conditions. Soil moisture measurements were taken, which successfully validated the ability of the SWI. Extrapolating the SWI analysis to the Hunter Water area of operations allowed it to be compared with corrosion measurements previously collected by UON. Figure 8.4 shows how the different soil textures impact the rate of corrosion for the accumulation of soil moisture. This is in agreeance with previous studies by UON.

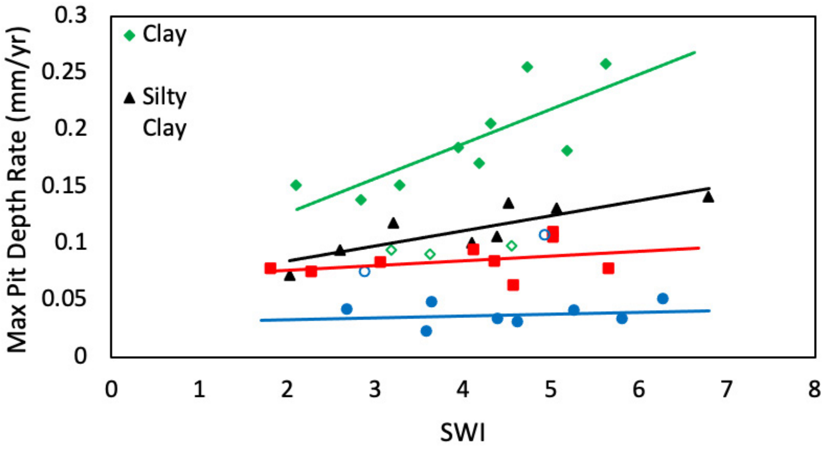


Figure 8.4: Corrosion pitting depth and the SWI based on soil classifications.

The second part of the project used LiDAR measurements made from drones flying at relatively close range (altitude) to the pipe easements of interest. This provided a dynamic measurement of wetness, using another feature of LiDAR, namely the intensity signal. This is based on the fact that the near infrared intensity signals of LiDAR sensors are reduced when sensing water. It was expected that something similar would be seen for particularly wet soils. This was tested by first scanning a dry 'background' image with the drone and then after simulating a leak by emptying approximately1000 litres of water over the area, scanning with the drone again. Results showed a clear change when analysing results from experiments with dry background conditions (Figure 8.5 and Figure 8.6). Experiments with wet background conditions made distinguishing the simulated leak harder, although statistical differences were still evident.

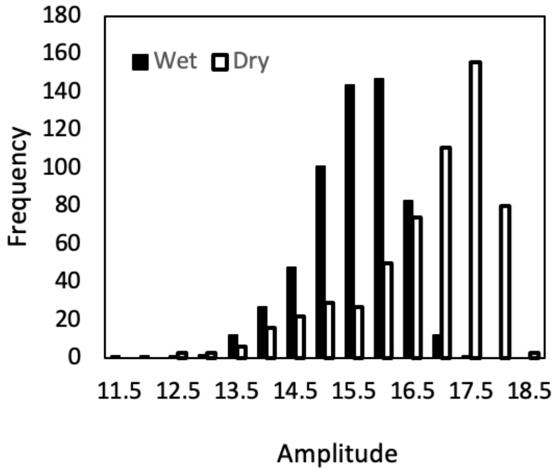


Figure 8.5: Histogram showing the change in the amplitude of intensity return strength caused by the simulated leak.

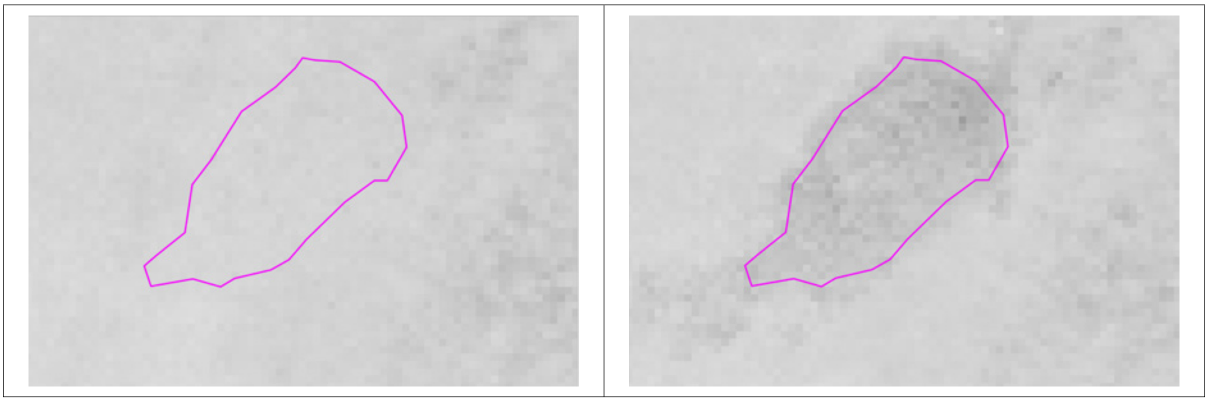


Figure 8.6: The intensity return signal of the background (left) and simulated leak (right) drone scans.

The project showed the use, and eventual implementation, of a drone to make relatively close-range measurements of soil wetness in the pipe catchment area compared with the surrounding zones. This should provide a practical and relatively economic opportunity for inspection of large sections of pipeline networks extremely quickly. The extension of corrosion research of pipes may improve pipe replacement scheduling reducing the frequency of catastrophic failures and significant water loss.

Water utilities see three key potential uses of being able to relate surface topography to soil wetness:

- Usage of the techniques for leak prioritisation, particularly if permeable hard areas can be included, not just grassed areas
- As corrosion predication tool, given the good correlation between SWI and corrosion
- As an overall planning aid to identify high moisture areas.

8.4 Benefits realisation

8.4.1 Benefits realisation for program objectives

While the full list of aims for the project is given in the Executive Summary, for the purpose of analysis we can summarise that the objectives of the Advanced Leaks and Breaks program are to develop sensing technologies that will be enable:

- a reduction in the amount of water lost within the water distribution network
- reduction in the cost of maintaining the water distribution network.

In both cases Sydney Water's goals are to improve water loss and renewal costs by at least 10%.

Table 8.2: Benefits and impact measurements.

Benefit	**Impact Measurements**	**Program contribution to this target**
Reduction in water loss	% water unaccounted for (e.g. from 8% to <7%)	Project Three is likely to have significant impact on this goal. Although analysis not yet completed, at this stage the saving is estimated at $3 million per year, based on estimates of 600 to 700 ML per year saving. These techniques should identify more than 100 major leaks and identify another 75 situations where preventative measures can be put in place. Full quantification is expected to be confirmed and agreed in the medium term in conjunction with Sydney Water operational figures. Sydney Water has also stated that Project Four has made significant efficiency to the reduction of water loss, but this has not been quantified at the time of writing. Project Five has added foundational work in assessing the role of drone-based LiDAR intensity for quickly and dynamically assessing leaks over large areas from above ground. It has added knowledge on pipe corrosion trends to assess how pipes are likely to corrode and eventually fail, losing water. It is premature to analyse Quantum Sensing or Distributed Acoustic Sensing in relation to this target.
Reduction in pipe network renewal cost	Water pipes renewal cost per annum (from $90M to <$80M)	Projects Three and Four are likely to contribute significantly to this target. There is the possibility to combine their findings with other techniques such as smart lining. Pipe corrosion trends can be used to improve schedules for proactively repairing ‘at-risk’ pipes. LiDAR intensity may be able to accurately find leaks along a large pipeline, meaning staff on the ground can be dispatched to the correct area with higher accuracy.

8.4.2 Benefits realisation for operational improvements

The program seeks to measure and state the impact of Operational improvements either quantitively or qualitatively.

Table 8.3: Benefits, operational measurements with current and target metrics.

Benefit	**Operational Measurements**	**Metrics – Current and Target**
Reduce water loss	Acoustic sensing has allowed identification of previously unnoticed leaks and breaks. 37 leaks and two main breaks found through sensor data in Sydney CBD, with significantly higher figures when transposed across all CBDs as part of 'lift and shift' operations Quantum Sensing: Potentially allows pinpoint location of leaks and breaks enabling quicker repairs Data Analytics means utilities can prioritise risky pipes and zones and predict where leaks are most likely to occur LiDAR and drones will allow for detection of previously unnoticed leaks and breaks to pinpoint location of leaks and breaks enabling quicker repairs	All projects can develop metrics around: • Number of leaks detected • Number of leaks and breaks p.a per km pipe • Number of leaks and breaks per km pipe p.a. • Number of kilometres of pipeline checked for leaks • % of network integrity checked per year Quantum Sensing: Successful identification of two simulated leaks at different field test sites. Shows the ability to locate water plumes to ~5m of pipe length Data Analytics: 80% of failures can be detected within top 20% prioritised pipes; 80% of the predicted failure locations are within 200m of the actual failures.
Reduce Pipe Renewal Cost	Gravity sensing allows one to pinpoint location of leaks and breaks to reduce time and cost associated with digging dry holes. LiDAR and drones have been shown to improve accuracy of predictive corrosion models; pinpoint location of leaks and breaks to reduce time and cost associated with digging dry holes; enable more efficient scheduling of field resources by reducing reactive maintenance jobs; and reduced damage to equipment from catastrophic failure	All techniques can improve: • Productivity of field crews • Time to repair once on site • Time spent by crews travelling to jobs • Average cost per repair • Equipment maintenance costs Quantum sensing foreshadows cost reductions from minimising overall repair time and extent

8.4.3 Additional benefits

There are expected to be additional advantages for a range of stakeholders:

Table 8.4: Additional benefits.

Benefit	Operational Measurements	Metrics – Current and Target
Increased customer satisfaction	Acoustic Sensing and Data Analytics will reduce unplanned disruptions by reducing reactive leak repair/maintenance jobs and improve customer perception of Sydney Water by reducing leaking water on pavement/roads Improved corrosion modelling will allow improved proactive replacement of pipelines as they are close to failure	Existing customer satisfaction metrics through less disruptive and damaging breaks • Reduced # of calls received about leaks and breaks • # of leaks detected pre-emptively
Reduce safety hazards from catastrophic pipe failure	Data Analytics: The developed method and tool can help Sydney Water prioritise which pipes need maintenance Corrosion modelling improving pipe repair/maintenance schedule will likely reduce catastrophic pipe failure Quantify the established leak-before-break concept, from the earlier ACAPFP project (Kodikara, 2017), catching leaks early is proven to lead to reduction of mains breaks	DA: 80% of failures can be detected within top 20% prioritised pipes Less catastrophic pipe failure Number of breaks in zones being actively monitored with semi-permanent leak sensing vs. other non-instrumented similar zones, or the same zone from past historical records
Commercialisation	A next step for the commercialisation of Quantum Sensing will be operationalising current gravimeter technology for leak before break detection Data analytics: A tool has been developed to translate the research outcomes to practical usage Improved corrosion model based on previous work With further research, potential for drone LiDAR intensity process could be commercialised Acoustic Sensing should enable financial advantage by routine uptake of the techniques and associated efficiency savings	Quantum Sensing: TRL improved from 3 to 6. Start-up established Data Analytics: used by the utility to prioritise high risk pipes and zones

8.5 Foundations for future work

Sydney Water has begun to map out potential pathways forward for the completed work as part of Leakage Management Plan and Asset Strategy. This includes:

- Alignment of the technologies with the Leakage Management Plan
- Operationalisation of the technologies at TRL 8 to 9 (Acoustic Sensing and Data Analytics) to meet business fit
- Integration in Operations as business as usual
- Further consideration given to development of the lower TRL projects.

Leakage Management Activities are classified under four key themes:

- Pressure Management
- Active Leak Control
- Speed and Quality of Repairs
- Asset Management (Renewals)

These in turn are defined by a number of tasks:

- Network Calming
- Program Optimisation
- District metering
- Trunk Main Monitoring
- Minimum Night Flow Analysis
- Advanced Data Analysis
- Sensor Technology Development
- Pipe Repair Technology Development

8.5.1 Future work: Quantum Sensing

In the immediate future (+ 1year) there exists an opportunity to operationalise the current surveying techniques with the classical gravimeter technology (Scintrex CG5). Field tests on identified leaks on operational water mains should be completed to move the TRL level from the achieved 6 to 8.

There is support for the development over two or more years and application of quantum sensors of gravity for leak before break detection. These sensors provide higher sensitivity and will allow for more cost-effective identification of leaks. Timeline for field deployable sensors is ~18 to 24 months.

Five years would allow for complete integration of gravity sensors for leak detection and water monitoring across all water infrastructure including water mains, sewage, aquifers, dams and catchments.

8.5.2 Future work: Distributed Acoustic Sensing

An optimistic scenario would see the development of a minimally viable product over the next 12 months, a full set of products and services over the next three years and an important international presence in the following years.

8.5.3 Future work: Acoustic Sensing

Immediately follow-on tasks that could improve results include:

- Continued leak detection in Sydney's CBD areas, engagement with Sydney Water field ops team leaders for co-ordinated leak investigations
- Moving of loggers to new CBD areas/zones for further leak detection
- Full statistical analysis of leaks during the periods of deployment in the Sydney Water zones for overall assessment of logger leak identifications, as this was only partially achieved during the project given the difficulty on securing and curating the relevant network data
- Ascertaining how the quality and consistency of the data might be affected by the sensor's mounting point on an asset. For permanent deployments, it would be desirable to install the loggers on a more secure attachment interface between sensors and pipe network to ensure reliable connections with the asset, and minimise the chances of dislodgement by crew personnel or other events during the normal operation of the asset. Testing and validation of such custom designed sensor mounting unit, including validating with induced leaks in the Sydney Water network (procedure to be confirmed), has been proposed.

Tasks to be considered for a one year plus time frame include:

- Cloud platform integrated in a common web portal (see Figure 8.7) developed with Sydney Water IT systems for simplified use by Sydney Water as "business as usual". This web portal would consolidate all acoustic sensor data from multiple providers, providing a dashboard display for accurate current leak alerts for action by Sydney Water, and to identify predicted areas for leak and break concern with additional network data analytics (MNF, pressure transients, vegetation, asset length, etc).
- Automated Leak analysis: continuing to interpret the data from the acoustic sensors to train analytics model to improve detection of leaks, most notably to identify them before they may develop into breaks. Once an algorithm has been sufficiently trained and validated, a proactive process for the repair and maintenance of leaks and breaks will be integrated into Sydney Water's business-as-usual practice
- Subject to final contractual agreements, as part of post-project operationalization and implementation, the expectation is to deliver an enhanced acoustic framework and integrated portal by December 2021, with potential commercialisation opportunities realisable from February 2022.

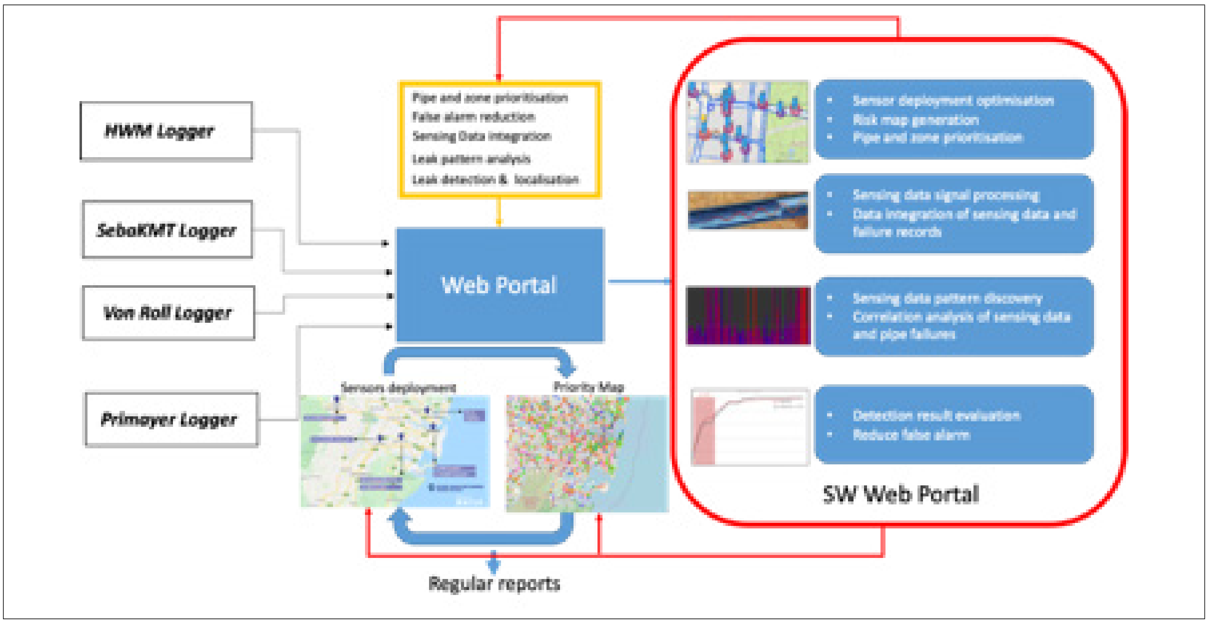


Figure 8.7: Future web portal work flow.

8.5.4 Future work: Data analytics

The project outcomes can be utilised and extended to more areas/zones in Sydney Water's network.

8.5.5 Future work: LiDAR, drones and corrosion

LiDAR derived terrain indices could be combined with Bureau of Meteorology soil moisture modelling for improved corrosion modelling over large spatial extent with different soils, at a high spatial resolution (three years).

Calibration of LiDAR intensity for the various environmental/sensor factors influencing the output would improve intensity reading accuracy. Integration of different sensing technologies (e.g. optical, thermal, and microwave sensing, from the airborne to satellite) could detect surface wetting conditions under different conditions to infer leaks (three years).

The feasibility of emerging, non-invasive sensing technology (e.g. cosmic ray neutron probes) to infer soil moisture near the pipes from above ground could be explored. The capability of LiDAR (and other sensing technologies) and prediction from the Bureau's model to infer deeper soil moisture could be strengthened (three years).

There is practically no industry standard for LiDAR intensity measurements and processing making an operational product difficult to create and interpret.

Specialised knowledge on data processing and field validation (ground truth data) are required to demonstrate the feasibility of the technology.

9. Glossary and abbreviations

ACAPFP	Advanced Condition Assessment and Pipe Failure Prediction (ACAPFP) Project
ADC	Analogue to digital converter
ALD	Active leak detection
ARC	Australian Research Council
AWA	Australian Water Asscoation
AWRA-L	Australian Landscape Water Balance
Catastrophic failure	A significant burst or other break in a water pipe that has the potential to risk human life, considerable property damage and/or disruption to the public.
CICL	cast iron concrete lined
DA	Data Analytics
DSI	Data Science Institute
GSD	general system design
GSS	general sonar studies
HMI	human machine interface
IoT	Internet of Things
IP	Intellectual property
JSEA	Job Safety and Environmental Analysis
LCS	Liquid Crystal Sensor
LiDAR	Light detection and ranging
LIEF	Australian Research Council Linkage Infrastructure, Equipment and Facilities
L/NC/H	litres/#connections/hour
mGal	Milligal cm/s^2. Acceleration measurement used in gravimetry
MNF	Minimum Night Flow
NAS	Non-Acoustic Sensor
N/A	Not Applicable
NSSN	NSW Smart Sensing Network
NT	Network Teams
PMFL	Performance Monitoring Fault Localisation
PSD	Power Spectral Density
RMS	Root mean square
SBS	simulated Brillion scattering
SNR	Signal-to-Noise Ratio
SW	Sydney Water
SWI	Soil wetness index
SWTB	Sydney Water Test Bed
TA	Thales Australia
TBA	To Be Advised
TBD	To Be Determined
TRL	Technology Readiness Level
TWI	Topographical Wetness Index

UKWIR	UK Water Industry Research
UWS	Underwater Systems
WSAA	Water Services Association of Australia
w.r.t.	With respect to

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11. Acknowledgments

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Program management was driven by the indefatigable efforts of Mr Dammika Vitanage of Sydney Water and Dr Don McCallum of the NSW Smart Sensing Network.

12. Appendices:

12.1 Leak Summaries for 5 CBD Areas – Project Three

Table 12.1: Sydney CBD Von Roll Leak Summary

Leak #	Logger IDs (UTS)	Location	Date fixed	Relevant WO/s	WO & Leak Details	Estimated Leak Rate (L/s)
1	20 & 21	Macquarie St.	UNKNOWN	78970520	LEAK - Public reported water on footpath on 23rd Jan, leak was identified as a private service valve problem at Sydney Hospital.	1
2	77 & 80	Pitt St & Macquarie Pl.	20/04/20	79000751, 79098537	LEAK - Main tap popping out of main semi-encased in anchor block of pole.	2
3	83, 84 & 85	Dalley St.	02/03/20	79050967	LEAK - Faulty main tap replaced with a bolted clamp.	3
4	59 & 60	Young St.	31/05/20	79000725, 79115237, 79664380	LEAK - DV issue. DV replaced.	N/A
5	75 & 77	Reiby Pl.	29/04/20	79000777	LEAK - Leaking valve found and stopped.	5
6	75	Reiby Pl.	15/03/20	79119108	BREAK - Broken back on 150mm main. Installed a silver bullet (leak clamp) around the crack.	5
7	23	Macquarie St.	05/04/20	79213976	LEAK - DV issue. DV replaced.	N/A
8, 9 & 10	51 & 55	Circular Quay	19/03/20	79213929, 79213996	LEAK - Two private leaks found at the piers. Private leak possibly fixed on 19th March. Third leak was on SW asset.	3 (SW leak)
11	83, 84, 85	George St.	07/04/20	79232158	LEAK - Leak on elbow of a main tap. It was shut off and capped.	3
12	5 & 6	Castlereagh St.	27/03/20	79283726	LEAK - Defective service valve.	N/A
13	86 & 87	Jamison St.	02/04/20	79329481, 79346625	LEAK - Leaking hydrant.	0.3

14	83, 84, 85	George St.	20/05/20	79371443	LEAK - Leaking main tap - closed but not capped. Likely the washer failed, and water was running into the ground.	0.3
15	51 & 55	Circular Quay	-	79687067	LEAK - large leak. Previous private leaks fixed (leaks 8, 9 & 10). Further investigation required - very difficult main trace due to the number of assets interfering and hydrants paved over.	N/A
16	23	Macquarie St.	N/A	79687067	LEAK - leak on control hydrant in Bridge St, needs to be capped off.	N/A
17 (?)	69	Spring St	-	79687067	UNCONFIRMED - being investigated.	-
18	68 & 71	Pitt St	N/A	79699476	LEAK - leaking hydrant ball- asset no 2098353	0.01

Table 12.2: Sydney CBD SebaKMT Leak Summary

Leak #	Logger IDs	Location	Date fixed	Relevant WO/s	WO & Leak Details	Estimated Leak Rate (L/s)
1	48342, 63939	314 Kent St	N/A	79756225	LEAK - Water on road. Leak marked out (16th June); job referred and marked up ready for a crew (18th June).	N/A
2 (?)	63937, 55212, 63929	375-377 Kent St	-	79957728	UNCONFIRMED	-
3 (?)	63930	348 Pitt St	-	79957744	UNCONFIRMED	-
4 (?)	54796	249 Castlereagh St	-	79957754	UNCONFIRMED	-
5	55280	341 Pitt St	N/A	79613366	LEAK - 18th May - Job came in from council at Castlereagh and Liverpool St. Water on footpath, constant leak, 100m down on Elizabeth st side in front of Downing Centre.	N/A

Table 12.3: Penrith Leak Summary

Leak #	Logger IDs	Location	Date fixed	Relevant WO/s	WO & Leak Details	Estimated Leak Rate (L/s)
1	SWT1, SWT2	Doonmore St	20/03/2020	79255961	LEAK - Leaking hydrant. Loggers picked up leak noise, but too early in deployment to issue WO for repair.	N/A
2	SWT19	High Street	27/05/2020	79583449, 79597255	LEAK - Leak on screwing gauge service. Cut out leaking section and installed path tap at boundary for future use.	N/A

Table 12.4: Bankstown Leak Summary

Leak #	Logger IDs	Location	Date fixed	Relevant WO/s	WO & Leak Details	Estimated Leak Rate (L/min)
1	POS007, POS008	Meredith Street/ Marion Street	04/30/20	79451457, 79378232	NO LEAK - 150mm service disconnected. Work conducted between 7pm on 30/04-2am on 01/05. Sensors picked up on noise from service.	N/A
2	SWT24, SWT25, SWT33, SWT34, SWT35, POS016	The Appian Way/ North Terrace	14/05/20	79415496, 79415473, 79573793	BREAK - Broken back on pipe (3/4 circumferential pipe failure), leak found running through sand into SM. Leak clamp installed.	5-10
3 (?)	SWT29, SWT31	Raymond Street/ Restwell Street	-	79426874	UNCONFIRMED - Possible hidden leak. To be investigated.	-
4 (?	SWT39	38-40 Old Town Centre Plaza	-	79426874	UNCONFIRMED - Possible hidden leak. To be investigated.	-
5	POS004	Rickard Road/ The Appian Way	N/A	79653769	LEAK - Water on footpath. Leak stopped without WO being actioned.	N/A

6	SWT25	The Appian Way/ North Terrace	N/A	79653923	LEAK - Water on footpath. Leak stopped without WO being actioned.	N/A
7	POS001, POS002	Rickard Road	1st June - significant change in sensor data since 30th May. 4th June - Detection Services confirm a noisy service was found from McDonald's. 9th June - leak appears to have been fixed. No works were conducted by SW, leak is assumed to have been a private leak that was resolved. No further details are available.			
8	POS010	Marion St nr Depot Pl	N/A	79800448	LEAK - Leak confirmed as a minor noise on the fire service. Sydney Water can't justify digging up the new footpath to repair the leak. Job closed. Leak will be monitored.	N/A
9	POS011	French Ave nr Kitchener Parade	N/A	79782975	LEAK - Leak confirmed, repair pending.	N/A
10	POS004, SWT33	Rickard Road/ The Appian Way	N/A	N/A	LEAK - Leak noise caused by standpipe at construction site. Leaking SV near POS004, chamber full of water.	N/A

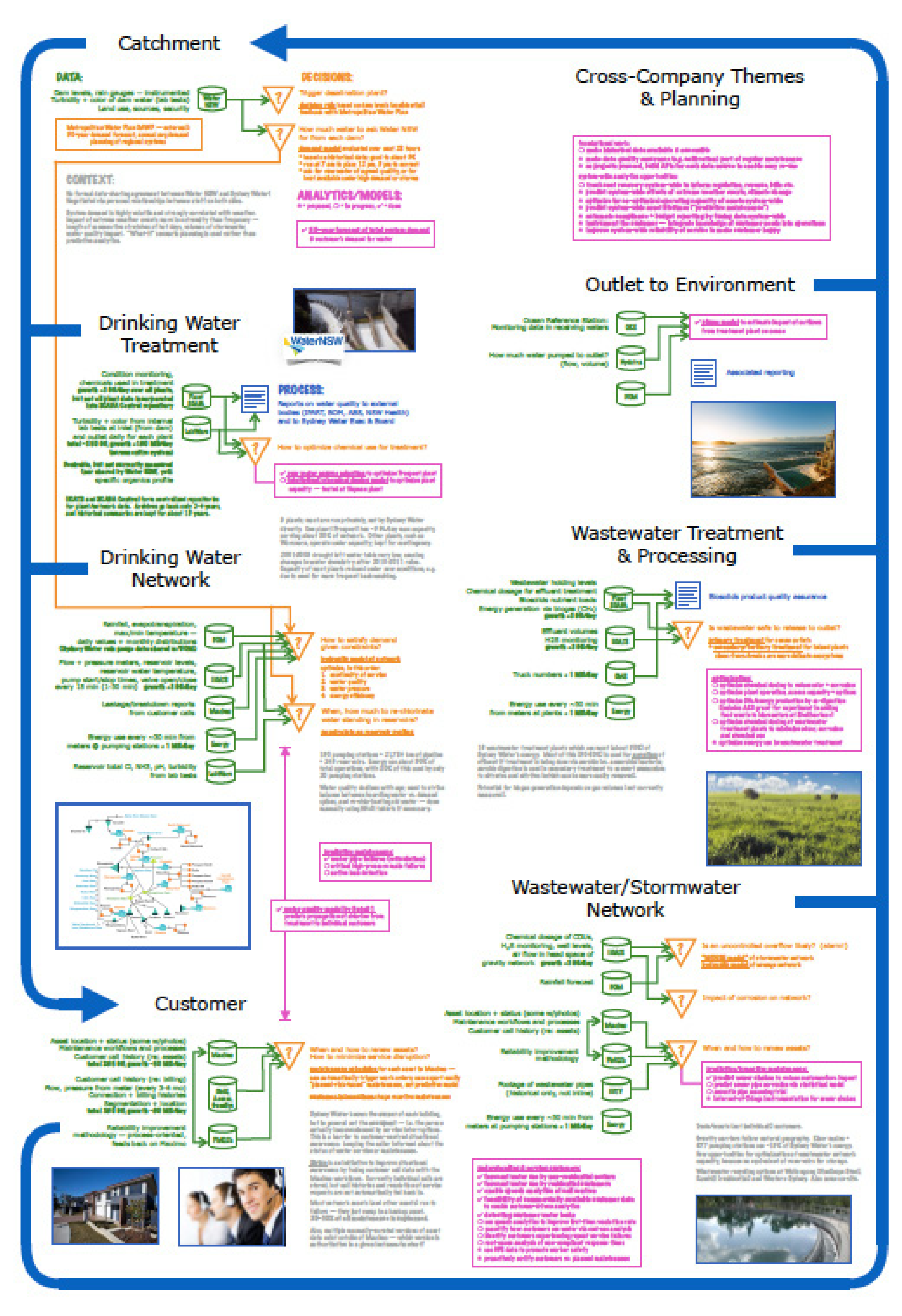
Table 12.5: Liverpool Leak Summary

Leak #	Logger IDs	Location	Date fixed	Relevant WO/s	WO & Leak Details	Estimated Leak Rate (L/s)
1	55355	1 Speed Street	21/05/20	79620595, 79630293, 79630288	LEAK - Hole in 50mm copper service and 2 buried fire service valves. on DN150 WM	2 - 3

Table 12.6: Chatswood Leak Summary

Leak #	Logger IDs	Location	Date fixed	Relevant WO/s	WO & leak Details	Estimated Leak Rate (L/s)
1	239814, 239815	Pacify Hwy around Gordon St	19/06/20	79762540, 79779928	LEAK - Leaking main tap. Heavy gushing could be heard in basement.	N/A
2 (?)	239812, 239821, 239816, 239817	Along Albert Avenue,	-	-	UNCONFIRMED - Noise is believed to be coming from Westfield shopping centre. Difficult to spatially locate possible leak within a large concreted area. Along Albert Avenue, with multiple leak correlations showing between Spring Street and Victor Street.	-
3 (?)	239809, 239810, 239811, 239828, 239829	Around Chatswood train station	-	-	UNCONFIRMED - Ovarro to perform leak investigation with Lift and Shift loggers to help locate leak/s.	-

12.2 Sydney water process poster



12.3 Technology readiness levels

TRL 1 – Basic principles observed

TRL 2 – Technology concept formulated

TRL 3 – Experimental proof of concept

TRL 4 – Technology validated in lab

TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – System prototype demonstration in operational environment

TRL 8 – System complete and qualified

TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)