DISCLAIMER

This project was conducted with financial assistance from a grant from the Metropolitan Water District of Southern California (Metropolitan), the U.S. Bureau of Reclamation, the Central Arizona Project, the Southern Nevada Water Authority, the Southern California Gas Company, and the Western Resource Advocates through Metropolitan's Innovative Conservation Program (ICP). The ICP provides funding for research to help document water savings and reliability of innovative water savings devices, technologies, and strategies. The findings of this project, summarized in this report, are solely from the project proponent.

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INNOVATIVE CONSERVATION PROGRAM

2018 INNOVATIVE CONSERVATION PROGRAM GRANTS FOR STUDIES
THAT WILL DOCUMENT WATER SAVINGS AND RELIABILITY OF
INNOVATIVE WATER SAVINGS DEVICES, TECHNOLOGIES, AND STRATEGIES

DETECTING WATER LEAKS USING DRONE TECHNOLOGY

Deliverable #5 – Final Report

Due: April 30, 2020

Revisions completed: May 26, 2020

Report Agreement No. 180894

ManageWater Consulting, Inc.

FAA-Certified sUAS Pilot
Silicon Valley, CA

Marty Laporte, M.S., Principal

ManageWaterConsulting.com

Detecting Water Leaks Using Drone Technology

**2018 Innovation Conservation Program – ** Report Agreement No. 180894

Field Sites

1. **UCM1 – Grand Canal site**
   Dates of Surveys: 4/26/19, 7/19/19, 7/20/19, 8/31/19
2. **UCM2 – Barn site**
   Dates of Surveys: 4/26/19, 7/19/19, 7/20/19, 8/30/19
3. **MPWD1 – Hallmark tank site**
   Dates of Surveys: 3/19/19, 3/24/19, 7/26/19, 7/30/19, 8/2/19, 8/22/19
4. **LVVWA1 – Church site**
   Dates of Surveys: 5/26/19, 5/28/19, 10/31/19
5. **LVVWA2 – Transmission line site**
   Dates of Surveys: 5/23/19, 5/24/19, 5/26/19, 5/27/19, 5/28/19, 10/31/19

Pilot in Command:

Marty Laporte, MS.,
FAA Remote Pilot, CN: 3934983
Certified Infrared Thermographer, sUAS, ID: 219260

Visual Observers:

Jonathan Rivas
Megan Byrnes

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1. Acknowledgments

This project would not have been possible without the financial support of the 2018 Innovative Conservation Program (2018 ICP). ManageWater Consulting, Inc., (MW) is especially appreciative for the ICP grant and to program managers: Dr. Marcia Ferreria, PhD, PE., and Ms. Elise Goldman of the Metropolitan Water District, who managed the deliverable reviews and funding process.

This work involved partnerships with field sites and assistance from site personnel. Site personnel were instrumental in assisting with site logistics and made it possible to access sites and information about them. Each site had engaged site representatives.

Dr. Brandon Stark at UC Merced permitted access to project sites at UCM and provided valuable guidance and technical support to MW for the UCM sites: UCM1 and UCM2 and took time to advise about methods and technology.

Mr. Chris Cruz, Department Chair for Park Management, Geospatial and Unmanned Aircraft Technology at West Valley College, introduced the project manager to diverse remote sensing software and workflows that enabled MW develop an integrated approach to capturing field data and processing it into useful information for detecting water leaks.

Mr. Derek Johnson of LVVWA provided access to two field sites – LVVWA1 and LVVWA 2 – for this project by pre-selecting field locations that best fit the project criteria. He took the time to discuss site backgrounds, pipeline leak history, and provided logistics support.

Ms. Tammy Ruddock provided access to the MPWD1 site. Her staff, Brent Chester, permitted access to the MPWD1 site and was instrumental in providing a simulated leak, reviewing the flight paths and maps, and took the time to discuss pipeline condition.

MW greatly appreciates the interest, generosity of time, and access to sites from all the project participants.

This project benefitted greatly from the student assistants. MW sincerely appreciates the work of Jonathan Rivas from the University of California at Merced and Megan Byrnes from Stanford University.

The framework for this project uses information from published studies and personal communication with staff at Anglian Water in Great Britain, who have successfully used drones with thermal infrared sensors to detect thermal anomalies (temperature changes) that lead to finding water leaks.

2. Abstract

Drones with thermal sensors are an evolving and innovative technology for inspecting water infrastructure. For this project ManageWater Consulting, Inc. (MW) used two commercially available quadcopter drones (DJI Phantom 4 Pro, P4P and Matrice 200, M200). The P4P has a visible light sensor and the M200 has two sensors, one for visible light and the second for medium-long-wave thermal infrared (TIR) electromagnetic spectrum (Zenmuse XT2). The XT2 records temperatures on the ground surface. From the temperature patterns, thermal anomalies are identified and interpreted as water leaks.

Environmental conditions impact the quality of aerial data collection. Therefore, in addition to visibility, cloud cover, and wind, MW considered the specific environmental conditions – temperature for air, water, ground, and relative humidity – needed to capture representative thermal data to be used for leak analysis. We document workflows and methodologies used at five field sites to collect and analyze the aerial images. Drone surveys were used to capture visual and thermal data about the water conveyance infrastructure – pipelines and canals with levees.

Temperature and relative humidity data were monitored to target best times to schedule flights with high temperature contrasts (ΔT), for reference during flight, and subsequently for analyzing the captured aerial data. From the environmental data, MW developed a 'daily thermal profile' for the UCM1, UCM2, LVVWA1, and LVVWA2 sites. This information validated the best times for detecting the highest ΔT to capture in the aerial thermal images. The contrasting temperatures made it easier to detect temperatures of distinct patterns on the ground.

Reflectance index maps were developed using aerial thermal images that contain temperature data captured by the M200 drone's XT2 thermal sensor (radiometric data). The recorded radiometric data illustrate specific areas with cooler or warmer temperatures considered as 'thermal anomalies' compared to the surrounding ground. These thermal anomalies potentially reflect a 'leaking' water source. The large ΔTs between the source water and ground at UCM1, UCM2, and MPWD1 permitted easier detection and interpretation of the thermal anomalies.

Using image-processing software to develop aerial orthomosaic visual and 'reflectance index' maps as a first step in analysis makes it possible to detect broader spatial visual and temperature patterns on the ground. Subsequent specific analysis of individual thermal images provides detailed temperature information about smaller areas of interest. Temperature anomalies were detected and verified at three of the five sites.

3. Introduction

Water leaks are prevalent in water conveyance infrastructure. If left undetected, they can lead to significant water loss and other infrastructure damage. The goal of this study was to apply drone and sensor technologies to detect water leaks in pipelines and canals with levees.

In 2018, water conservation legislation [Senate Bill 606 (Hertzberg) and Assembly Bill 1668 (Friedman)] was signed into law, representing a paradigm shift and presenting a new long-term water conservation framework for California. The regulations identify *eliminating water waste* as one of four main focus areas for long-term water conservation in the urban and agricultural sectors. To implement the water loss requirements, the California Department of Water Resources (DWR) and the State Water Resources Control Board (State Water Board) are developing new standards for water loss management. The 2018 legislation applies to the actions of DWR, the State Water Board, and water suppliers.

> Drone aerial surveys can be deployed quickly, inexpensively, and repeatedly to inspect water infrastructure for leaks.

Existing leak detection methods include on-the-ground visual inspections, acoustic sensing, and using various spectral bands from satellite imagery. These methods are costly, labor intensive, and typically do not identify specific areas of leakage. In contrast, drone aerial surveys can be deployed quickly, inexpensively, and repeatedly to inspect water infrastructure for leaks. Drones with visual and thermal infrared (TIR) sensors can fly over areas with suspected leaks to obtain images for further analysis. The aerial images are processed fast enabling quick information for water managers.

Small commercially available quadcopter (multi-rotor) drones can fly vertically, take off and land in small spaces, and can hover over a fixed position at a given height. These features make the multi-rotor drones well suited for water infrastructure inspections. DJI Quadcopter drones with visual and thermal sensors were used for this project. The DJI Phantom 4 Pro visual sensor was used to capture visual images to develop orthomosaic maps with high resolution of the area with water infrastructure. Such maps were used to identify general areas of interest. The DJI Matrice 200 Zenmuse XT2 thermal sensor was used to capture temperature data from the ground surface, enabling analysis of temperature anomalies that may represent water leaks.

This report builds on earlier deliverables 1 through 4, adds documentation from additional fieldwork, and summarizes findings and conclusions.

ManageWater Consulting, Inc., (MW) is a consulting company focusing on integrating innovative technologies and practices for water management. MW has more than 25 years' experience working with diverse projects and technologies to manage water resources. Currently, MW uses DJI Phantom 4 Pro and

Matrice 200 quadcopter drones with sensors for visible light and thermal infrared (Zenmuse XT2) spectral bands to capture aerial data and develop maps for various end-uses.

4. Methodology

The methods used for this project have been developed by ManageWater Consulting, Inc., (MW), based on background research, testing, and fieldwork. Early on in the project MW contacted Anglian Water to discuss their experience and successful use of drones for detecting subsurface water leaks in Great Britain.

Use of drone hardware and software technologies for water infrastructure inspections is relatively new. To obtain representative thermal data for analysis of anomalies that can be used for accurate leak analysis we developed systematic approaches and workflows. The workflows for project and data management are presented in this section.

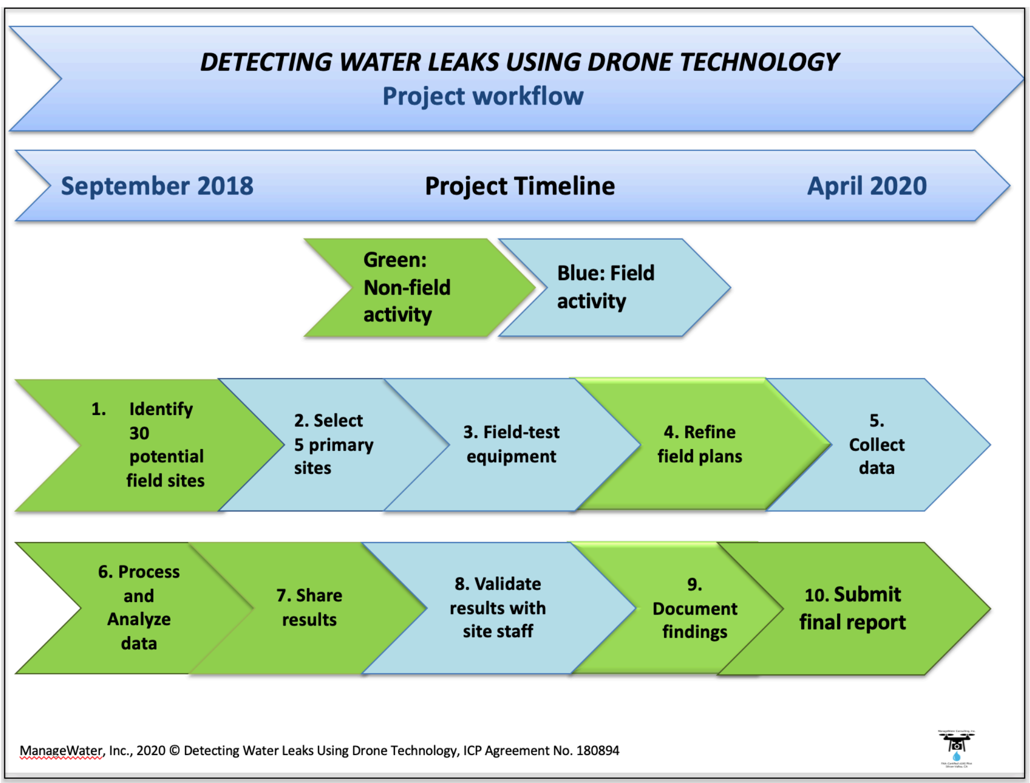


Figure 1. The workflow for this project includes 10 main steps – planning for fieldwork, capturing aerial data at five field sites, and processing and analyzing the captured data.

Note: Validation in Step 8 included observing indicator features on the ground (e.g., green vegetation, moist soil), sharing, and discussing findings with site representatives.

4.1 Field site selection

Field site selection for this project was based on the following key factors:

1. safety and air space conditions for field operations,
2. locating distribution pipes in dry ground (no surrounding moisture, e.g., recent rain, lush vegetation),
3. locating pipes with known leaks (moisture present from continued leakage),
4. site access and proximity,
5. ease of aerial and ground survey implementation, and
6. logistics to coordinate with site staff.

The above criteria were discussed in detail in deliverable 2. We noted that if some site criteria could not be met within the task schedule, alternate methods would be used. For example, if sites with leaks were not available for this project, then we would collect aerial data at sites with simulated leaks.

To encourage and facilitate participation in this project, MW sent Fact Sheets about the project to 26 water agencies that are part of the Bay Area Water Supply and Conservation Agency (BAWSCA). Requests for participation were also sent to: Valley Water Agency (formerly SCVWD), Southern Nevada Water Authority, and University of Nevada, Las Vegas. Additionally, MW contacted Moulton Niguel Water District and Dr. Brandon Stark at the University of California, Merced (UCM). Dr. Stark leads the UC System Drone Program. The UCM campus has several canal and levee leaks.

Five field sites were selected for this project**:**

1. UCM1 – University of California, Merced campus, Merced, CA
2. UCM2 – University of California, Merced campus, Merced, CA
3. MPWD1 – Mid Peninsula Water District, Belmont, CA
4. LVVWA1 – Las Vegas Valley Water Authority, Searchlight, NV
5. LVVWA2 – Las Vegas Valley Water Authority, Searchlight, NV.

The five sites are discussed individually in this report, in Section 4, ‘Field Reports’.

4.2 Pre-flight, Health and Safety

Prior to doing fieldwork, MW developed checklists for:

- Field site safety and risk mitigation,
- Site information and hazard assessment, and
- Flight mission planning checklists to prepare equipment, review environmental conditions, and log fieldwork.

The checklists were presented in Deliverable 2 and were adjusted to site-specific conditions when necessary.

4.3 Field logs

MW documented the site conditions during fieldwork using an online application from ESRI, Survey123. The field log checklist we developed facilitates consistent documentation of environmental conditions with automatic geo-location for each site.

The environmental data that were collected include:

- temperatures for air, ground surface, water source;
- weather, wind speed, visibility; and
- relative humidity (collected prior to flights with thermal M200 Zenmuse XT2)

The ESRI Survey123 template that was used is in Attachment 1.

4.4 Equipment used – hardware, software

Two drones were used: DJI Phantom 4Pro with its in-built 20MP visible spectrum (red, green, blue, RGB) sensor (camera) and the DJI Matrice 200 with the Zenmuse XT2 dual visual and thermal sensors (camera) made by Flir. Both drones are quadcopters, capable of slow image capture that avoids blur, and results in representative ground images. The hardware equipment was discussed in detail in deliverables 1 and 2.

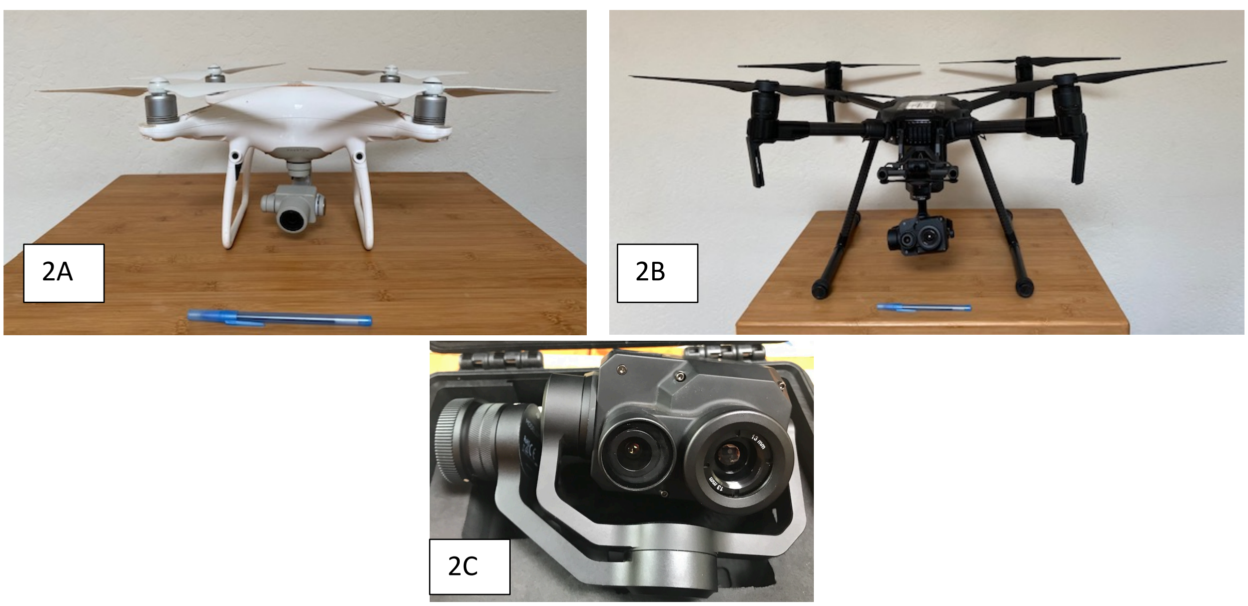


Figure 2A. DJI Phantom 4Pro with its 20-MP, high resolution visible light (RGB sensor) camera (pen for scale), Figure 2B. DJI Matrice 200 with ZenMuse XT2 dual lens camera (visible light, 12-MP, RGB sensor and 13mm thermal sensor), and Figure 2C, close-up view of the XT2: visual (left) and thermal (right). The XT2 captures images with both sensors at the same time, making it possible to identify locations with thermal anomalies on the ground during and post-flight. Image source: ManageWaterConsulting.com, 2020.

Several different software applications were used to capture and process the aerial imagery from both drones. The DJI Phantom 4 Pro (P4P) works with a remote controller (RC) and an iPad tablet. For manual flights the DJIGo4 application was used. For autonomous flights, Pix4D Capture software was used. The 20-MP, high resolution, visible light (RGB sensor) camera is attached to the P4P on a gimbal, making the camera very stable for capturing clear and high-quality images. The P4P was used for reconnaissance flights and initial aerial surveys. The images from the aerial surveys were 'stitched' together using Pix4D Mapper software to develop orthomosaic maps. These orthomosaic site maps had much higher resolution than the base map (Landsat, Google Earth maps), enabling close-up inspection of small areas of interest.

The Zenmuse XT2 dual lens camera is also fixed to the DJI Matrice 200 on a gimbal that is integrated with the drone for high quality thermal image capture. The visual XT2 lens is 12 MP. The 'Tau 2' thermal XT2 sensor is made by Flir, known for its high-quality sensors. The XT2 thermal sensor has a 13mm lens with 336/256 resolution. This thermal sensor detects the temperature (emissivity) of the ground surface. The spectral band detected is: 7.5 – 13.5 micrometers (um).

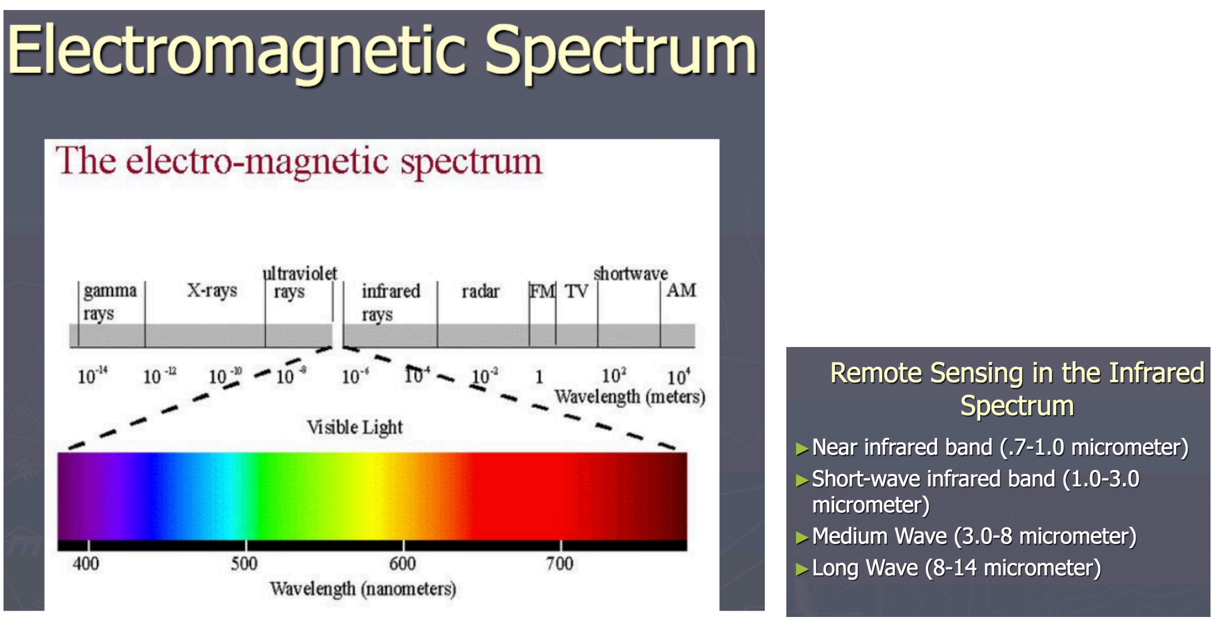


Figure 3. The XT2 sensors (cameras) detect visible and infrared parts of the electro-magnetic spectrum. The thermal sensor detects spectral bands between 7.5 – 13.5 um (micrometers). The visible light sensor detects spectral bands between 0.4 to 0.7 um. Source: Flir.com.

Emissivity is the ground's (or any material's) effectiveness in emitting energy as thermal radiation. Thermal radiation is electromagnetic radiation and it may include both visible radiation (visible light) and infrared radiation, which is not visible to human eyes, but is picked up by the XT2 thermal sensor. The XT2 visible light sensor records images as JPGs, while the thermal sensor records the infrared radiation (recorded as temperature) in every pixel as RJPGs (Radiometric JPGs). The value of the RJPGs is that the recorded temperature in images can be analyzed after the flight. During flight, the captured images are saved on the XT2 SD cards.

For planning manual and autonomous flights to capture images with the DJI Matrice 200 and XT2 sensors, the DJI Pilot application was used with a Samsung tablet connected to the drone's RC. The DJI Pilot application provides real-time information about the ground surface temperatures and guides the Pilot in Command to locations with thermal anomalies. Two settings – MSX and PIP – were typically used during flight to identify ground temperature contrasts. The MSX feature provides a thermal image that is superimposed on a visual image, making it easier to identify objects with high and low temperatures during flights. Contrasting color palettes representing temperature gradients in the DJI Pilot flight software helped identify contrasting temperatures during flights.

4.5 Collecting thermal aerial data

In this project we conducted *qualitative* analysis of ground temperatures using the drone aerial imagery and thermal data from the five sites. The images from the M200 aerial surveys permit spatial analysis and recognition of thermal patterns on the ground. Compared to dry areas, wet areas are subject to latent heat exchange with the atmosphere, resulting in cooling of the ground surface. The difference in dry vs. wet ground surface areas showed up as temperature anomalies in the reflectance index maps. The XT2 thermal sensor recorded the ground temperature for every pixel in each image.

Aside from the hardware and software, a variety of conditions can affect the aerial data collection. Site conditions that are most conducive for capturing representative thermal images to detect water leaks, include:

- no wind (for a steady flight to avoid image blur),
- clear and uniform visibility (e.g., no clouds, smoke, rain, low humidity),
- bare ground (no paving, minimal vegetation),
- underground pipeline depth < 5 feet, and
- large temperature contrast, large ΔT, between the water source and ground surface.

Geology also influences the transfer of temperature from leaking pipes or through levees. If the subsurface geology creates an effective barrier, such as a caliche layer (hardpan layers that act like a concrete barrier), leaking water temperature may not transfer and affect the ground surface temperature. Also, in sandy areas, leaked water may travel down rather than spread upwards toward the ground surface. Under such conditions, the ΔT on the ground would not be sufficient for the XT2 thermal sensor to detect an anomaly.

In contrast, alluvial soils and silty/clayey soils appear to transfer water temperatures more readily to the surface, resulting in detectable temperatures anomalies.

A long rainy season in 2019 and challenges with logistics, prevented us from schedule all flights in optimal environmental conditions. In 2019, the rainy season in California lasted into early June. Some of the initial flights were conducted too soon after rain events, resulting in insufficient temperature contrast and ΔT between the ground surface and source water, in order to capture consistent temperature anomaly patterns. For example, flights in March 2019 at the MPWD1 site did not detect significant ΔTs due to ground coverage by moist green grass. Subsequently, the majority of flights were scheduled starting in mid-July, well after the rainy season stopped. The travel logistics for fieldwork at LVVWA1 and LVVWA2 delayed the second field visit, so additional flights occurred in late October.

Initially, aerial surveys were conducted during morning, early afternoon, and late afternoon/early evenings to identify the time of day with the best conditions for obtaining thermal anomalies. Dr. Stark's guidance led us to more rigorous environmental data collection. To bracket times of day with highest ΔTs between source water and the ground surface, MW collected hourly temperatures for air, source water, and the ground surface. In addition, relative humidity was measured hourly, since high humidity negatively impacts the XT2 sensor's capture of accurate ground temperatures.

MW developed a 'daily thermal profile' to identify the best times of the day to capture the largest ΔTs that may detect thermal anomalies.

MW used the temperature and humidity measurements to develop a 'daily thermal profile' that identifies the best times to capture the highest ΔTs to detect thermal anomalies. We developed the daily thermal profile for UCM1 and UCM2 sites in mid-July 2019. This profile illustrates that the best time of day for thermal data collection was mid-afternoon, when the greatest temperature differences exist between the source water (low temperature) and ground (high temperature) and humidity is also at its lowest (Figure 4).

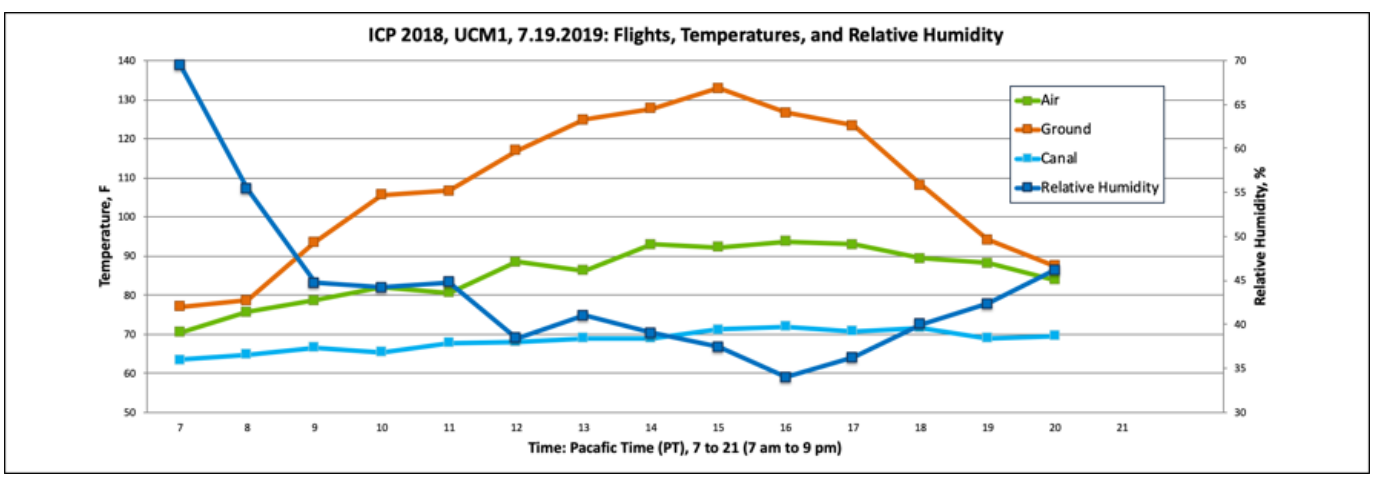


Figure 4. Hourly temperature and relative humidity data illustrate the 'daily thermal profile' for UCM1 and UCM2 sites – relationships between air, ground, and nearly constant temperature of source water. Note the largest temperature difference between the ground (high temperature) and canal water (low temperature) occurs between 2 and 4pm. Afternoons exhibited best conditions to collect aerial data for identifying thermal anomalies, because of the large ΔT (approximately 63F at peak difference). During this timeframe the high ground temperatures of up to 133F contrasted with the source water temperature of approximately 70F. Additionally, the low humidity benefits accuracy of the thermal image capture.

However, the inverse was true for LVVWA1 and LVVWA2 sites in late October 2019, when the greatest ΔT was in early mornings, with the ground temperature colder than the source water temperature (Figure 5).

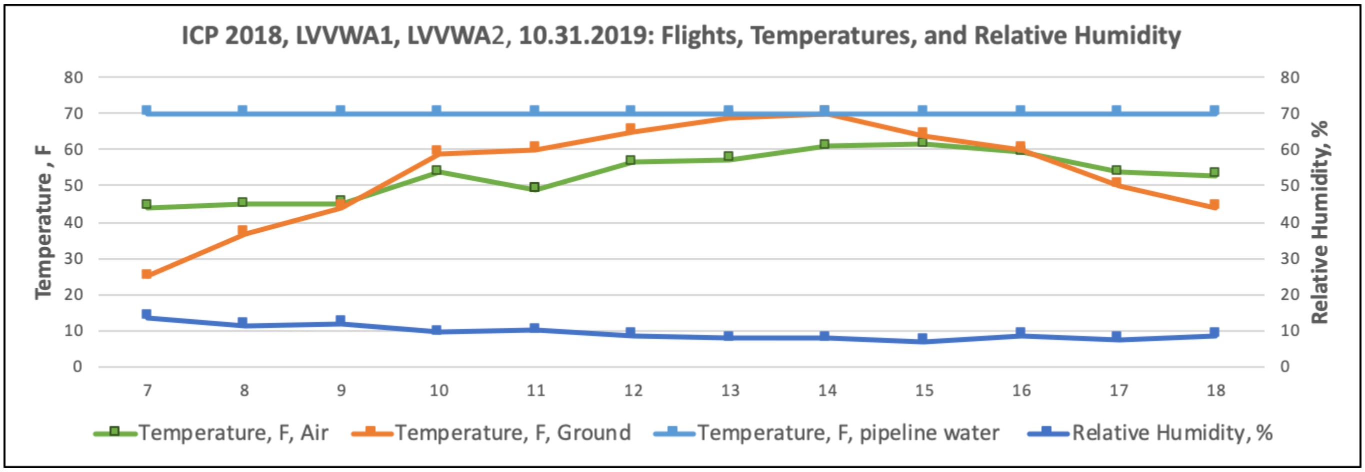


Figure 5. Hourly temperature and relative humidity data illustrate the 'daily thermal profile' for LVVWA1 and LVVWA2 sites – relationships between air, ground, and source water temperatures. Note the largest ΔT between the ground (low temperature) and pipeline water (high temperature) occurs between 7 and 8am. Mornings exhibited best conditions to collect thermal aerial data because of greatest ΔT (approximately 45F at peak difference). During this timeframe the low ground temperatures, at approximately 25F, contrasted with the source water temperature of approximately 70F. The humidity remained low throughout the day benefitting accuracy of the thermal image capture. Seasonal temperature differences impact the size of the ΔT. At the LVVWA sites, in the fall and winter the largest ΔT is in the morning, in contrast to the summer, when the largest ΔT is in the afternoon.

To detect representative ground temperatures, thermal flights typically ranged between 80 and 150 feet above ground level (AGL). Ground temperatures were recorded before flights using a hand-held infrared thermometer. Additionally, flights were conducted slowly, on clear days, during low winds (<5mph, to the extent possible) to avoid shadows and blurring of the images.

To capture representative temperature data, the following settings were specified for the XT2 sensors:

- Scene: outdoor setting, landscape
- Color palette: typically set at 'rainbow', but 'ironbow', and 'fusion' were also used.
- The temperature settings were between 25F and 150F, taking into account the source water and variability of ground temperatures. Source waters ranged from 60-76F and ground temperatures ranged from 25F to more than 130F.
- Camera frontal image overlap was set at 80 to 85%
- Camera side image overlap was set at 75 to 80%

Due to site access, environmental conditions, and other logistics, it was not possible to complete all the flights during the optimal ΔTs between the ground and source water.

4.6 Data processing, analysis, identification of temperature anomalies

Except for one site, the specific 'leak' source locations were unknown to MW's Pilot in Command.

Pix4D Mapper was used to process the thermal images into 'reflectance index maps' that were analyzed for temperature patterns and anomalies. The images from areas with apparent thermal anomalies in the reflectance index maps were downloaded and reviewed individually using Flir Tools software. Flir Tools software enables pixel-by-pixel temperature analyses of the aerial thermal imagery, since each pixel on each image records a temperature (radiometric) value. Various color palettes were used during analysis to identify the ground area with highest temperature contrasts and to determine if spatial patterns exist that suggest temperature anomalies due to water flow or leaks (that are not artifacts). The XT2 thermal images were compared to the visual images to identify specific locations on the ground. Currently, the review of the thermal images is manual and quite tedious.

Compared to dry areas, wet areas are subject to latent heat exchange with the atmosphere, resulting in a cooling of the surface. During the summer for MPWD1, UCM1, UCM2, LVVWA1, and LVVWA2 sites with ΔTs of >25F, we expected the surface ground area underlain by significant water leaks would appear consistently cooler by about 10F than the surrounding ground, but also warmer than the source water by > 10F (since leaked water would be heated by the surrounding hot ground). During fall and cooler weather at LVVWA1 and LVVWA2 sites, we expected the surface ground area underlain by significant water leaks would appear consistently warmer than the surrounding colder ground, but also cooler than the source water (since leaked water would be cooled by the surrounding cold ground).

For the subsurface pipelines, the surface ground temperature change was expected to be subtle and not show up as a continuous 'plume' connected to the leak source. The local geology impacts the temperature transfer of temperature from water leaks. If the water has to travel through heterogeneous or differentially compacted materials, non-uniform flow that is subject to differential warming or cooling by the ambient ground temperature, will result. However, some concentrated patchy lower or higher temperatures than the surrounding ground (temperature anomalies) were expected in the vicinity of large ongoing leak 'sources'.

Causes for potential temperature artifacts/ false thermal anomalies

Shadows and vegetation are known to cause false temperature anomalies. Such 'false' temperatures were commonly observed in the thermal images and require careful review to avoid misinterpretation. In thermal images vegetation appears as lower temperature during warm weather and higher temperature during cooler weather. Also, surface material differences exhibit different emissivity values due to different effectiveness in emitting energy as thermal radiation. In our fieldwork, differences in ground surface composition showed up in aerial images as temperature differences that, in some cases, appeared as temperature anomalies due to water leaks.

4.7 Data management

Voluminous aerial data was collected using the P4P and M200 drones. Hundreds of images were typically captured during each flight. The images from the drones were saved on SD cards during flights and transferred post-flight to local storage on a laptop. The visual data from the P4P was processed using Pix4D Mapper software on the desktop and in the cloud. Both the P4P and M200 images were 'stitched' together and visual orthomosaic and thermal reflectance index maps were developed.

The reflectance index map provides an overall view of temperature distribution and, if present, temperature patterns are easier to see than on the individual images. However, inspection of the individual images using Flir Tools is necessary to verify specific temperature values. The management of data involved five software applications as shown in the workflow below (Figure 6.)

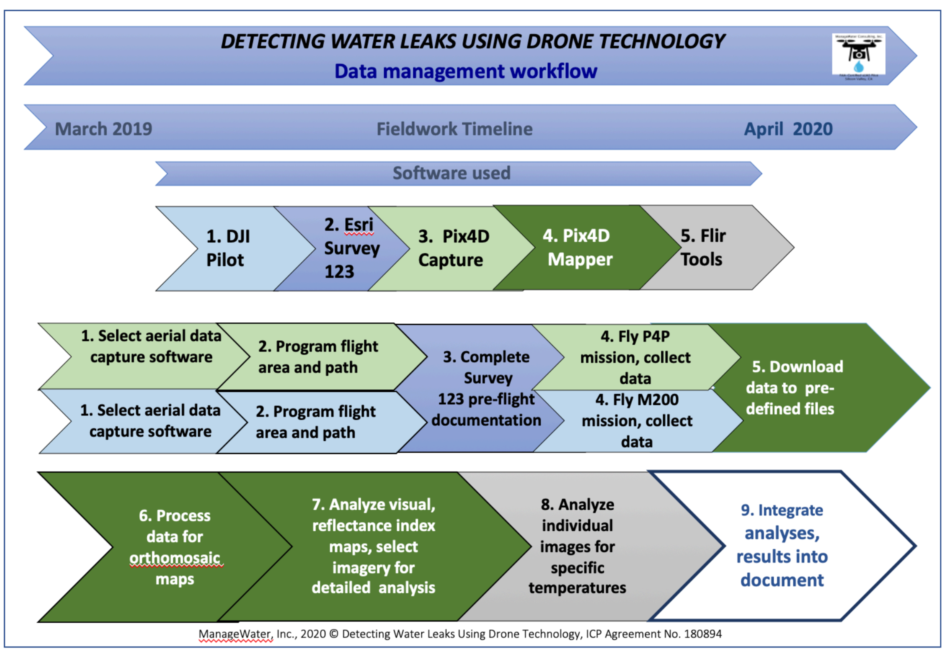


Figure 6. Five software applications were used to integrate the planning, data capture, processing, and analysis of the aerial imagery prior to presenting the information in this report.

Management of the voluminous aerial imagery requires a systematic protocol. To facilitate tracking and retrieval of images, the file identification system MW used includes site name, drone used, and date and time of data collection. For each site the data were stored in separate e-folders: 1. Images – aerial images from flights and 2. Projects – processed orthomosaic visual and reflectance index maps.

4.8 Reports for field sites

A 'Site Summary' is presented for the five field sites based on data collected in ESRI Survey123. Key information about each site includes, reason for site selection, geo-location, infrastructure containing source water (material type), date and time of flight, FAA airspace and other requirements (if needed), site-specific environmental and access conditions, drones used, flight altitude, results from the flights: examples of P4P drone aerial and M200 reflectance index maps, and challenges, if they were encountered. Field reports for all sites are in Section 5 with a section on 'results' and specific areas of temperature anomalies, if they were detected. Section 6 presents the project summary that includes findings, and conclusions that include 'next steps'.

5. Field Reports

5.1 Site: UCM1 – Grand canal

Reason site was included in study

Canals and levees are major water conveyance systems for irrigation in agricultural areas as well as conveyance systems for water from northern to southern California for urban uses. Although significant focus for canal maintenance is to mitigate flood risk, canals that leak through levees lose water and are inefficient, especially during droughts when water supplies are restricted.

Inspections and maintenance of canals and levees can increase water delivery efficiency and reduce flood risk. Traditional aerial methods to inspect canals include helicopters or airplanes that are expensive and typically fly at higher altitudes. By comparison, drone technology provides a relatively inexpensive and repeatable method to inspect such infrastructure for leakage. Drones fly at low altitudes and produce high image resolution. Additionally, the data from drone inspections can be processed fast and provide timely and valuable information to act on.

The UCM1 And UCM2 sites are located on the Grand Canal at the UC Merced (UCM) campus and are in FAA uncontrolled airspace (G). The sites are easily accessible (with permission from UCM) and safe to fly. This canal levees have several seeps and leaks that present a good opportunity for testing leak detection methods using drone and thermal technology. Dr. Brandon Stark at UCM is the main contact for this project. Dr. Stark also serves as the Director of the Center of Excellence for Unmanned Aircraft Systems Safety at UCM and for all UC campuses and has been an invaluable technical advisor for this project.

UCM1 Site Summary and Results

Latitude: 37.3675182229256 N ***Longitude***: 120.420371862241 W

Water source temperature: Lake Yosemite: 69F; Canal: 75F

Water infrastructure flown/inspected: canal and levee

Infrastructure material: earthen surface canal and levee berm, leak expected by UCM

Suspected leak rate: leak suspected at unknown gallons per minute.

Water pressure: atmospheric PSI, 14.696 psi, open water channel; variable with seasonal water demand.

FAA airspace: G

FAA/other restrictions: None

Site access permission from: Dr. Brandon Stark, UCM.

Drone flight equipment used: DJI P4P, DJI M200 Zenmuse XT2

Flight altitude AGL *(Above Ground Level, feet)*: P4P: 60 – 390, M200: 130-180

Any site areas not flown: None

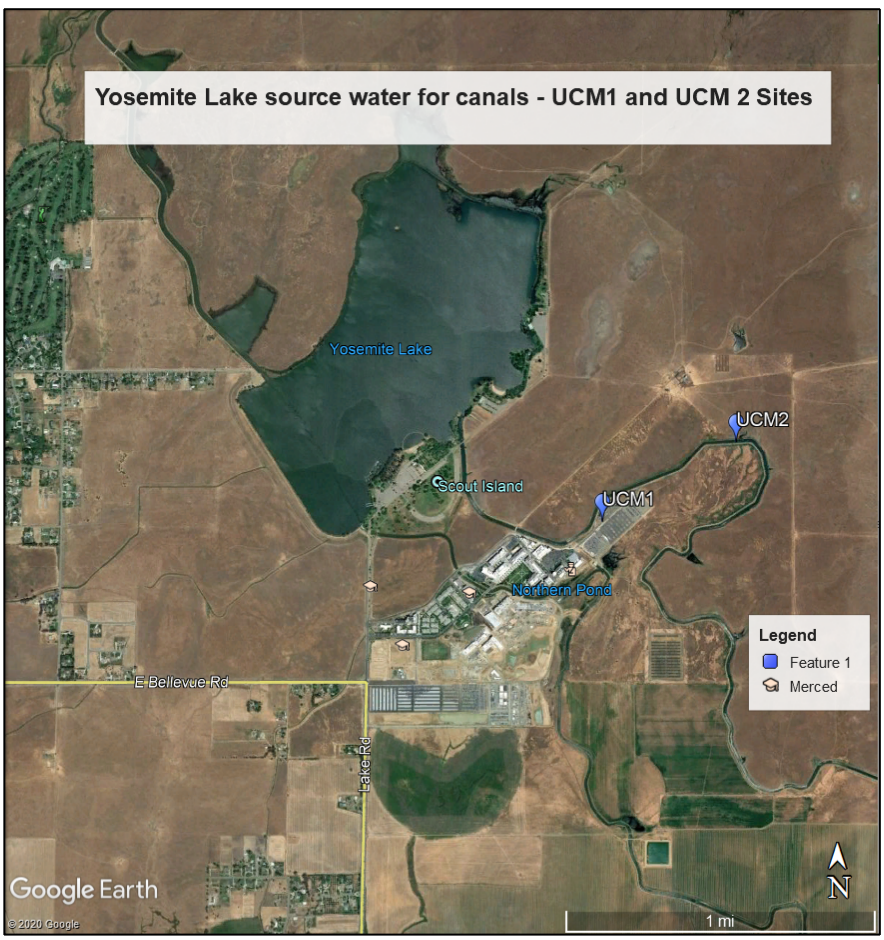


Figure 7. Google Earth satellite map showing Yosemite Lake, the source water for the canals at UC Merced and UCM1 and UCM2 field sites.

Figure 8. Orthomosaic map of UCM1 field site, generated using DJI P4P drone and Pix4D image Capture and Mapper processing software (lighter area). Surrounding area image uses Google Earth satellite view. Note the much higher resolution of the drone image, since it has a ground sampling distance (GSD) of approximately 1 inch and the satellite view has a nominal GSD of 50 feet.

Dates and times of site visits to UCM1 with drone flights:

1. 4/26/19, 11AM - 12PM

Drone(s): P4PM200, M200

Flight AGL: 150FT

Visibility: >3 miles

Canal water temperature: 11:30AM: 69F

Air temperature: 81F

Ground temperature: NA

Wind: 0 - 2.3MPH

Relative humidity: 82.4%

2. 4/26/19, 7 - 8PM*

Drone(s): M200

Flight AGL: 150FT

Visibility: >3 miles

Canal water temperature: 66F

Air temperature: 7PM: 76.7F
Ground temperature: NA
Wind: 0 – 0.9 MPH
Relative humidity: 7PM: 54.3%

3. 7/19/19, 10AM - 12PM
Drone(s): P4P, M200
Flight AGL: 150FT
Visibility: >3 miles
Canal water temperature: 10AM: 65.4F, 11AM: 67.8F, 12PM: 68F
Air temperature: 10AM: 81.9F 11AM: 80.6F, 12PM: 88.5F
Ground temperature: 10AM: 105.6F, 11AM: 106.7F, 12PM: 117F
Wind: 0 – 3 MPH
Relative humidity: 10AM: NA, 11AM: 44.8%, 12PM: 38.4%

4. 7/19/19, 7 - 8PM*
Drone(s): M200
Flight AGL: 150FT
Visibility: clear
Canal water temperature: 7PM: 68.9F, 8PM: 69.5F
Air temperature: 7PM: 88.2F, 8PM: 83.8F
Ground temperature: 7PM: 94.1F, 8PM: 87.4F
Wind: 0 – 3 MPH
Relative humidity: 7PM: 42.3%, 8PM: 46.2%

5. 7/20/19, 8 - 9PM
Drone(s): M200
Flight AGL: 150FT
Visibility: clear
Canal water temperature: 8PM: 68.4F, 9PM: 68.4F
Air temperature: 8PM: 83F, 9PM: 76.7F
Ground temperature: 8PM: 84.7F, 9PM: 83F
Wind: 0 – 4 MPH
Relative humidity: 8PM: 48.4%, 9PM: 49%

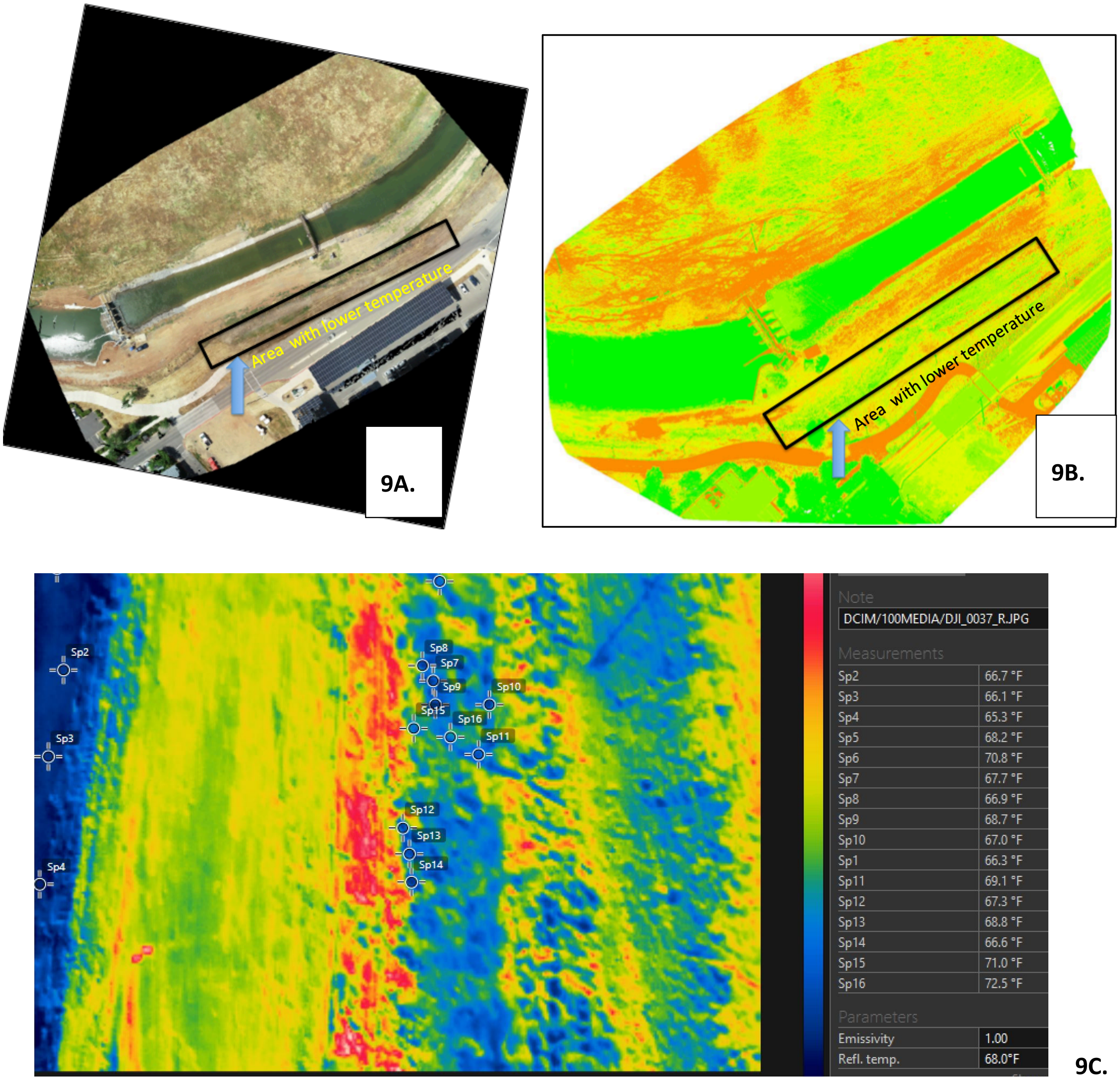
6. 8/31/19 – 12PM – 1:45 PM
Drone(s): P4P, M200
Flight AGL: 150FT
Visibility: >3 miles
    Canal water temperature: 12PM: 67F
    Air temperature: 92F
    Ground temperature: 122F
    Wind: 0 – 1.7 MPH
    Relative humidity: 28.8%

*Night flight using UCM and ManageWater Consulting, Inc., FAA waiver for daylight flight, 14CFR Part 107.29.

Results

At the UCM1 site, the earthen canal has several seeps through the earthen levee. The levee is mostly composed of native soil and rocky material. The canal water surface was approximately 4 feet below the top of the levee. Vegetation can be an indicator for water leaks. Grass and shrubs were visible on the campus site (Figure 8A), approximately 5 feet below the levee top. Clearly, this vegetation had access to water compared with adjacent vegetated areas that are dry. Lower temperatures were also observed in this area in the thermal images (Figure 8B).

The green vegetation below the levee, in contrast to dry surrounding areas, is an indicator for potential water leaks (Figure 9A). Since vegetation takes time to establish, the area where it is growing was interpreted to have an on-going water leak through the levee. The canal water is interpreted to migrate in the subsurface through the levee and leak out on the road-facing side. The orthomosaic and reflectance index maps (Figures 9B, 9C) were developed from aerial data collected at the end of August 2019. The large contrast in temperatures between the ground (122F) and canal (67F; 55F difference) and low humidity (28.8%) presented excellent conditions for the thermal sensor. The corresponding thermal anomaly showed up strongly on the levee surface (Figure 9C. green - cool, orange- hot).



9C.

Figure 9A. Vegetation can be an indicator of water leaks, as seen in this orthomosaic map generated using P4P, with Pix4D Capture and Mapper. Grass and shrubs are visible on the levee side facing the road, approximately 5 feet below the levee top (box area). The orthomosaic map shows an area that corresponds to thermal anomalies shown in the reflectance index map, figure 9B. The area in the box exhibited lower temperatures (green) than the bare ground on the top and side of the levee (orange) and is interpreted as a leak. In Figure 9C, the blue area on the far left is the canal (cooler temperature points Sp2, Sp3, Sp4,), the green and yellow area is the levee top (warm), and the red-yellow area is the levee side (warmest). Below this area, the area shown in dark blue patches is interpreted to be the area of water leakage (e.g., temperature points Sp5, Sp7, Sp8).

Night flight to capture thermal images

The flights during hot, late afternoons when air temperature was above 90F and ground temperature exceeded 115F posed several technical and operational challenges. The high temperatures reduced the battery life for the M200, so the flights had to be much shorter. Consequently, more flights and batteries were needed to cover the site, and additional time had to be spent in the field.

Using MW's FAA waiver to conduct drone night flights, we collected thermal data with the M200 and Zenmuse XT2 sensors. The goal of the night flight was to determine if thermal anomalies could be captured after sunset. Night flights were scheduled when the ground surface was expected to be still warm and more than 20F higher than the canal water. The preliminary results indicate that night flight, especially soon after sunset may be a viable option. MW is continuing to test the thermal sensor at night to investigate applicable methods for detecting water leaks.

5.2 Site: UCM2 – Barn site

Reason site was included in study

UCM 2 was chosen for the same reasons as UCM1, namely: this site has several water seeps and leaks through its levees that present a good opportunity for testing drone and thermal sensor technology.

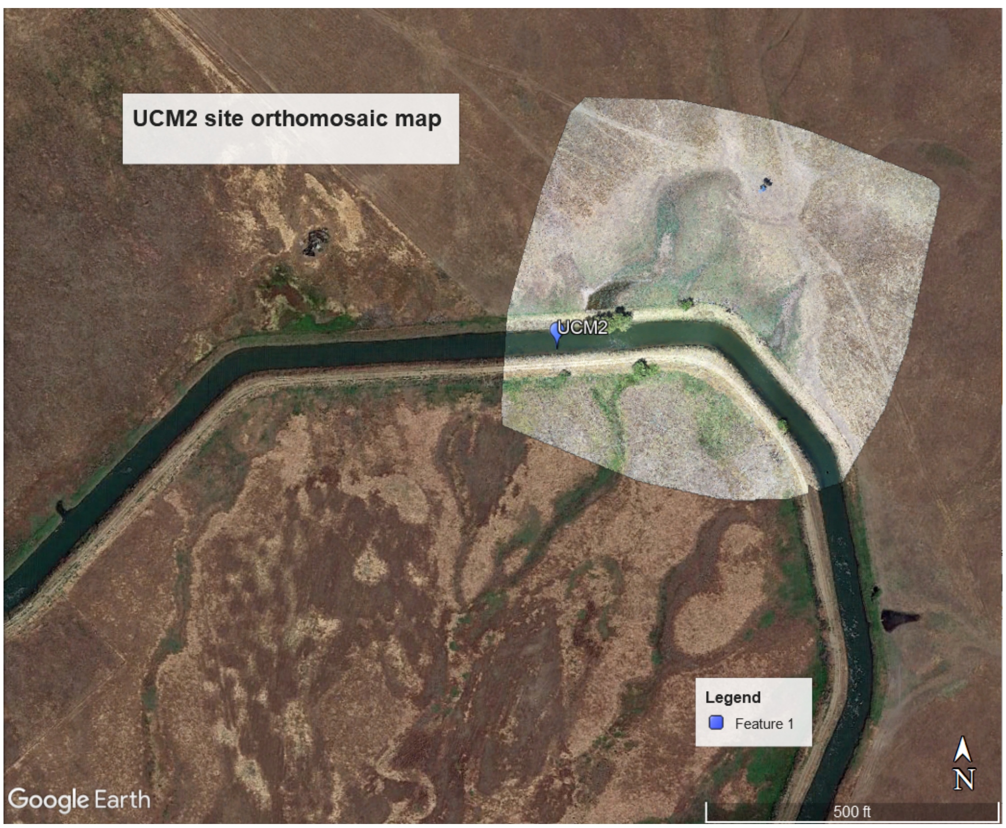


Figure 10. Map of UCM2 field site, generated using DJI P4P drone and Pix4D image Capture and Mapper processing software (lighter area). Surrounding area image uses Google Earth satellite view. Note the much higher resolution of the drone image, since it has a ground sampling distance (GSD) of approximately 1 inch and the satellite view has a nominal GSD of 50 feet.

This site is different from the UCM1 site because the area is hotter, more open, with shallow water ponded areas. The areas appear to be fed by leaking canal water. However, it was difficult to see specific leak locations from an on-the-ground perspective. The leak areas were more visible in visible light aerial surveys and even more apparent on the reflectance index maps.

UCM2 Site Summary and Results

Latitude: 37.3727814294746 N ***Longitud****e*: 120.411032913365 W

Water source temperature: Lake Yosemite: 69F; Canal: 72.9F

Water infrastructure flown/inspected: canal and levee

Infrastructure material: earthen surface canal and levee berm, leak suspected by UCM Suspected leak rate: leak suspected at unknown gallons per minute.

Water pressure: atmospheric PSI, 14.696 psi, open water channel; variable with seasonal water demand.

FAA airspace: G

FAA/other restrictions: None

Site access permission from: Dr. Brandon Stark, UCM

Drone flight equipment used: DJI P4P, DJI M200 Zenmuse XT2

Flight altitude AGL *(Above Ground Level, feet)*: P4P: 60 – 390, M200: 130-180 ft. AGL

Any site areas not flown: None

Dates and times of site visits to UCM2 with drone flights:

1. 4/27/19, 11AM - 12PM

Drone(s): P4P, M200 – flight failed battery voltage error due to excessive heat

Flight AGL: 150FT

Visibility: >3 miles

Canal water temperature: 69F

Air temperature: 88F

Ground temperature: 120F

Wind: 0 - 2.3MPH

Relative humidity: NA

2. 7/20/19, 10:25AM – 12:00PM

Drone(s): P4P, M200

Flight AGL: 150FT

Visibility 10AM-12PM: >3 miles

Canal water temperature: 10:30AM: 68.4F

Air temperature: 10:30AM: 87F

Ground temperature: 10:00AM: 108.3F, 11AM: 116.8F

Wind 10AM-12PM: 0 – 3 MPH

Relative humidity: 10AM: 44.2%, 11AM: 39%

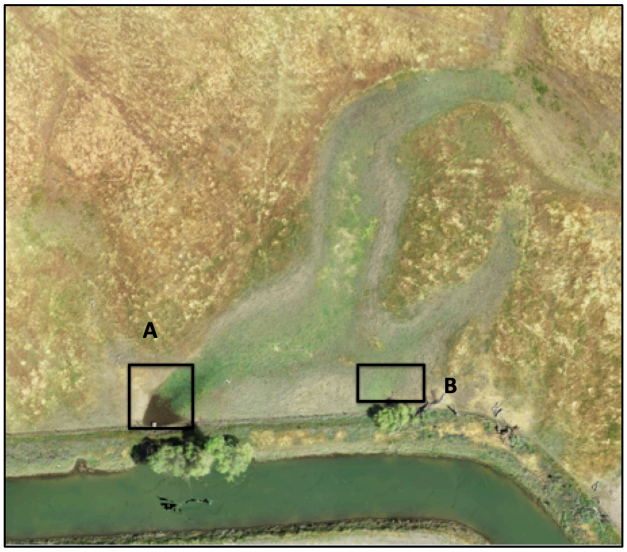
3. 7/20/19, 9 – 10:00PM*
Drone(s): M200
Flight AGL: 150FT
Visibility: Clear
Canal water temperature: 9PM: 68.4F
Air temperature: 9PM: 76.7F
Ground temperature: 9PM: 83F
Wind: 0 – 3 MPH
Relative humidity: 9PM: 49%

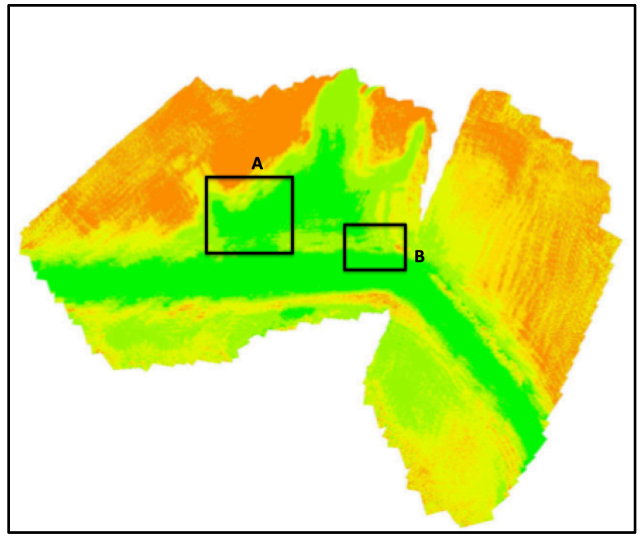
4. 8/30/19 – 1PM
Drone(s): P4P,
Flight AGL: 164FT
Visibility: Clear
Canal water temperature: 68F
Air temperature: 9PM: 91F
Ground temperature: 122F
Wind: 2.8 -6.2MPH
Relative humidity: 36.4%

*Night flight using UCM and ManageWater Consulting, Inc., FAA waiver for daylight flight, 14CFR Part 107.29.

Results

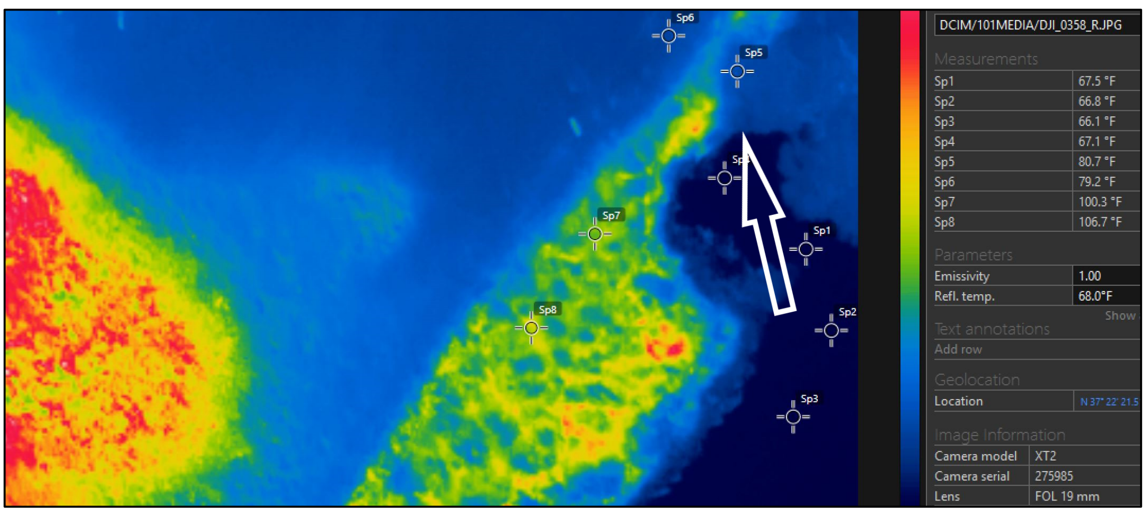
At the UCM2 site, two large outflows through the earthen levee were observed in both the orthomosaic and reflectance index maps. The canal water surface is approximately 5 feet below the top of the levee. The aerial map developed from P4P images (Figure 11A) shows two main water leaks (boxed areas: A, B) through the levee. The reflectance index map (Figure 11B) developed from the M200 images clearly shows the locations of lower temperature anomalies for the canal area (green) compared with the hotter ground (yellow - orange). The areas with boxes A and B are interpreted to be leak areas. Using Flir tools software, we reviewed temperatures on a pixel-detail level in the thermal image. The temperature anomaly is evident – the darkest blue area in Figure 11C identifies the specific area of leak in box A.





11A **11B.**

Figure 11A. Orthomosaic map developed using P4P drone illustrates 2 main areas of water flowing out of the canal (boxes: A, B). Figure 11B. Reflectance index map for UCM2 with thermal anomalies detected, reflecting the 2 main leaks areas (boxes: A, B).



11C.

Figure 11C. Close up thermal image of an area of low temperature in box A. Using Flir Tools software the image illustrates specific low temperature locations (dark blue area, Sp1 to Sp4) where water is interpreted to be flowing out through the levee. Green, yellow, orange, and red areas are warmer temperatures, e.g., Sp5 to Sp8).

Night flight to capture thermal imagery

The UCM2 site was at a lower elevation, warmer, and less breezy than the UCM1 site. The hot conditions at the site led us to schedule flights at night. Using MW's FAA waiver to conduct the drone night flights we collected data with the M200 and Zenmuse XT2 sensors. The preliminary results indicate that night flight, especially soon after sunset may be a viable option. MW plans to continue testing the thermal sensor to detect water leaks using night flights.

5.3 Site: MPWD1 – Hallmark tank site

Reason site was included in study

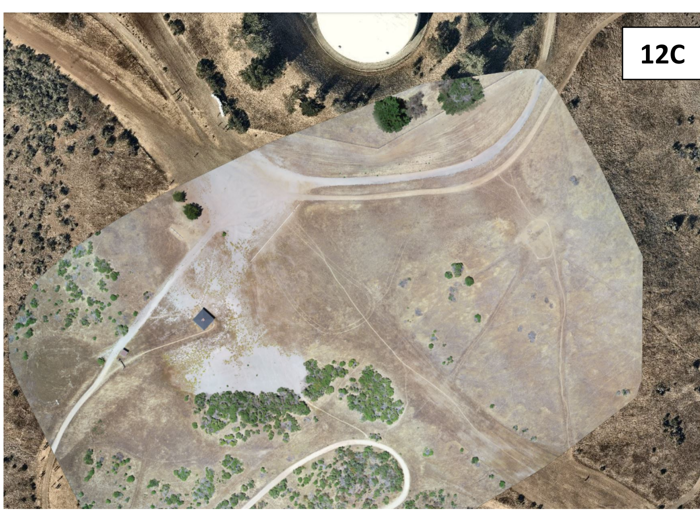
Throughout California pipelines convey treated water long distances in rural and urban areas. Inevitably, pipes leak due to age, environmental conditions, corrosion, and other reasons. Although, recent regulations (SB 555) require validated water loss audits on water distribution systems, traditional and current technologies (e.g., on-the-ground-inspections, traditional acoustic methods, line pressure loss, satellite imagery) for water leak identification typically can't identify specific locations on the ground for crews to investigate efficiently.

By comparison, drone technology could provide a relatively inexpensive and repeatable method to inspect such infrastructure for leakage. Additionally, the data from drone inspections can be processed fast and provide timely and valuable information to act on.

12A

Figure 12A. MPWD1 site location map. Google Earth satellite map.

12B.



12C

Figure 12B. Aerial views of MPWD1 site on March 19, 2019, with abundant grassy area due to recent and prolonged rainy season. The ground temperatures were too low due to the cooling effect of the green vegetation, resulting in insufficient contrast between the ground surface and water temperatures. The lack of contrasting ground to water temperatures resulted in no discernible temperature anomalies. Figure 12C. shows the aerial orthomosaic map for the MPWD1 site on July 26, 2019, almost two months after last rain event, with grassy areas dried out and ground temperatures (>100F) more than 40F higher than the water (60F). The orthomosaic map was developed using the P4P drone and Pix4D Capture and Mapper software.

The MPWD1 site is easily accessible (with permission from MPWD) and safe to fly. The MPWD1 site has a right-of-way with a 4-inch PVC conveyance pipeline that is buried less than 5 feet below the ground surface. The site is accessible on foot from a nearby access road in an area that is unpaved, open space with minor vegetation, and the soils are heterogeneous. The pipeline has had leaks in the past and for this study the MPWD staff simulated a leak on several occasions by opening a valve on the line in a subsurface valve box that is about 4.5 feet below ground surface. This simulation presented an excellent opportunity to test the drone and aerial thermal imagery and its capability to detect the subsurface water 'leak'.

MPWD1 Site Summary and Results

Latitude: 37.4546100106439 N ***Longitude***: 122.220580279941 W

Water source temperature: 60F

Water infrastructure flown/inspected: canal and levee

Infrastructure material: 4-inch diameter, PVC, leak simulated by MPWD Suspected leak rate: 5gpm

Water pressure: 33 PSI, at valve with simulated leak

FAA airspace: E5; 200FT AGL ceiling limit

FAA/other restrictions: None

Site access permission from: Ms. Tammy Ruddock, General Manager, Brent Chester, Supervisor, Mid-Peninsula Water District

Drone flight equipment used at MPWD1: DJI P4P, DJI M200 Zenmuse XT2

***Flight altitude AGL (Above Ground Level, feet*)**: P4P: 130 – 180, M200: 130-180 ft. AGL

Any site areas not flown: None

Dates and times of site visits to MPWD1 with drone flights:

1. 3/19/19, 9AM – 11:30AM. Leak simulated by MPWD: 5 gallons/minute.

Drone(s): P4P, M200

Flight AGL: 80FT

Visibility: >3 miles

Pipeline water temperature: 60F

Air temperature 10:30am: 55F

Ground temperature: NA

Wind: 0 - 1MPH

Relative humidity: NA

Note: Recent rains, ground covered with green grass - grass has cooling effect, lowering temperature contrast significantly.

2. 3/24/19, 8 - 10AM. Leak simulated by MPWD: 5 gallons/minute.

Drone(s): P4P, M200

Flight AGL: 190 FT

Visibility: >3 miles

Pipeline water temperature: 60F

Air temperature 10:30am: 55F

Ground temperature: NA

Wind: 0 - 1MPH

Relative humidity: 43%

Note: Recent rains, ground covered with green grass - grass has cooling effect, no thermal anomaly detected.

3. 7/26/19, 12PM - 4PM Leak simulated by MPWD: 5 gallons/minute.

Drone(s): P4P, M200

Flight AGL: 150FT

Visibility: >3 miles

Pipeline water temperature: 60F

Air temperature: 12PM: 74F

Ground temperature: 12PM: 118F

Wind: 0 – 3 MPH

Relative humidity: 12PM: 58.5%

4. 7/30/19, 12:48PM – 4PM Leak simulated by MPWD: 5 gallons/minute.

Drone(s): M200

Flight AGL: 147FT

Visibility: clear

Pipeline water temperature: 60F

Air temperature: 12:48PM: 75.4

Ground temperature: 12:48PM: 120F

Wind: 0.7 – 5MPH

Relative humidity: 12:48PM: 48.3%

5. 8/2/19, 1:05PM – 4PM. Leak simulated by MPWD: 5 gallons/minute.

Drone(s): M200

Flight AGL: 130FT

Visibility: clear

Pipeline water temperature: 60F

Air temperature: 82.4F

Ground temperature: 118F

Wind: 0 – 5MPH

Relative humidity: 48%

6. 8/22/19, 3:05PM – 6PM. Leak simulated by MPWD: 5 gallons/minute.
Drone(s): M200
Flight AGL: 147ft
Visibility: clear
Pipeline water temperature: 60F
Air temperature: 3:05PM: 83.9F
Ground temperature: 3:05PM: 120F, 5PM: 100F
Wind: 0.7 – 5MPH
Relative humidity: 42.1%

Results

At the MPWD1 site, MPWD staff simulated a 5 gpm leak by opening a subsurface valve in a concrete vault, approximately 4.5 ft below ground surface. The 'leak' is from the valve that is connected to a subsurface 4-inch PVC pipeline that containing domestic water at 60F. Knowing the infrastructure segment on the ground with the leak made it much easier to plan the flight mission and focus on the specific ground region of interest for further analysis.

The aerial orthomosaic map was developed from P4P images using Pix4D Capture and Mapper software (Figure 12C, 13A, 13C, 13D). Figure 13B illustrates a reflectance index map from the M200 Zenmuse XT2 thermal sensor using DJI Pilot software for the flight and images and Pix4D Mapper to combine them into the map. The reflectance index map (Figure 13B) shows the locations of a lower temperature anomaly at the valve box and to the left of it (green and mottled green) compared with the hotter ground (yellow - orange).

We used the reflectance index map to find the temperature patterns and anomalies. The area of the valve box (square: Figures 13A, 13B, and 13D), the lower temperature anomaly (diamond: Figures 13A, 13B, and 13D), and two vegetated areas (ovals: 13A, 13B) are outlined. Vegetation can be misinterpreted as a temperature anomaly due to leakage, but it is a result of cooling of the leaf surfaces from transpiration.

The reflectance index map view is best for initial review before further analysis using individual radiometric images (RJPGs). Figure 13F illustrates the level of detail captured in individual thermal images.

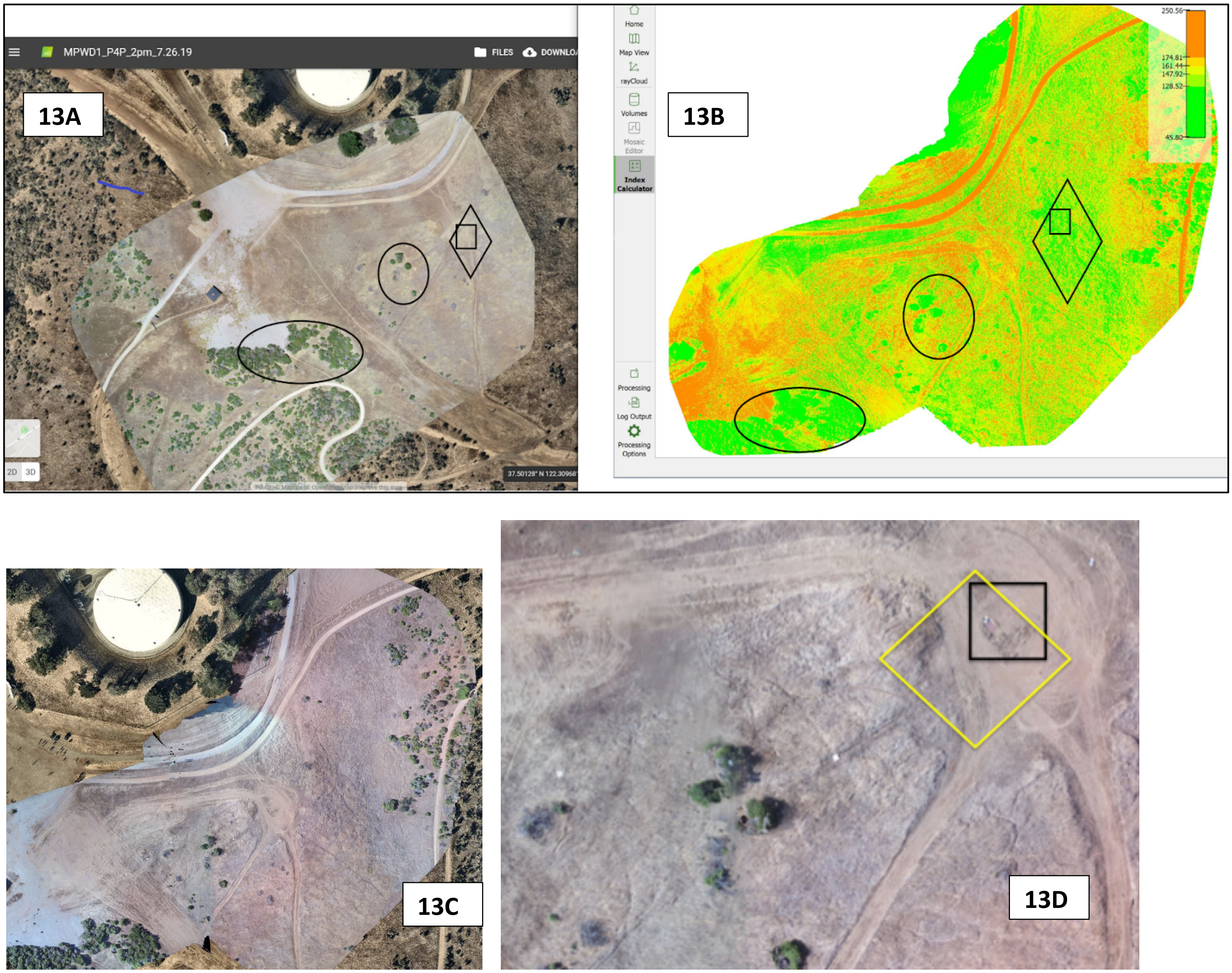
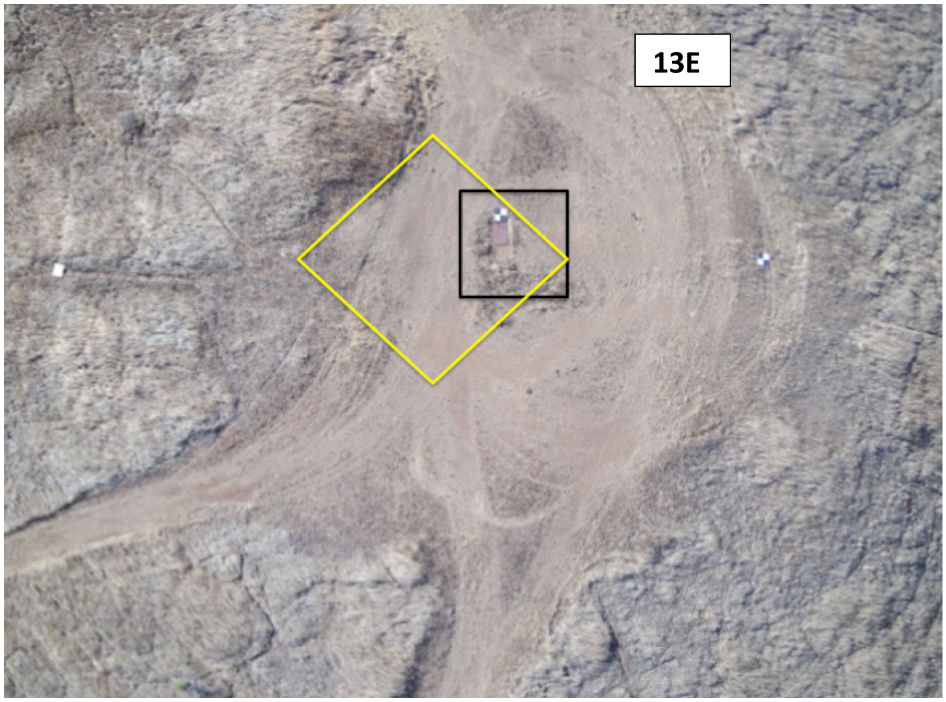
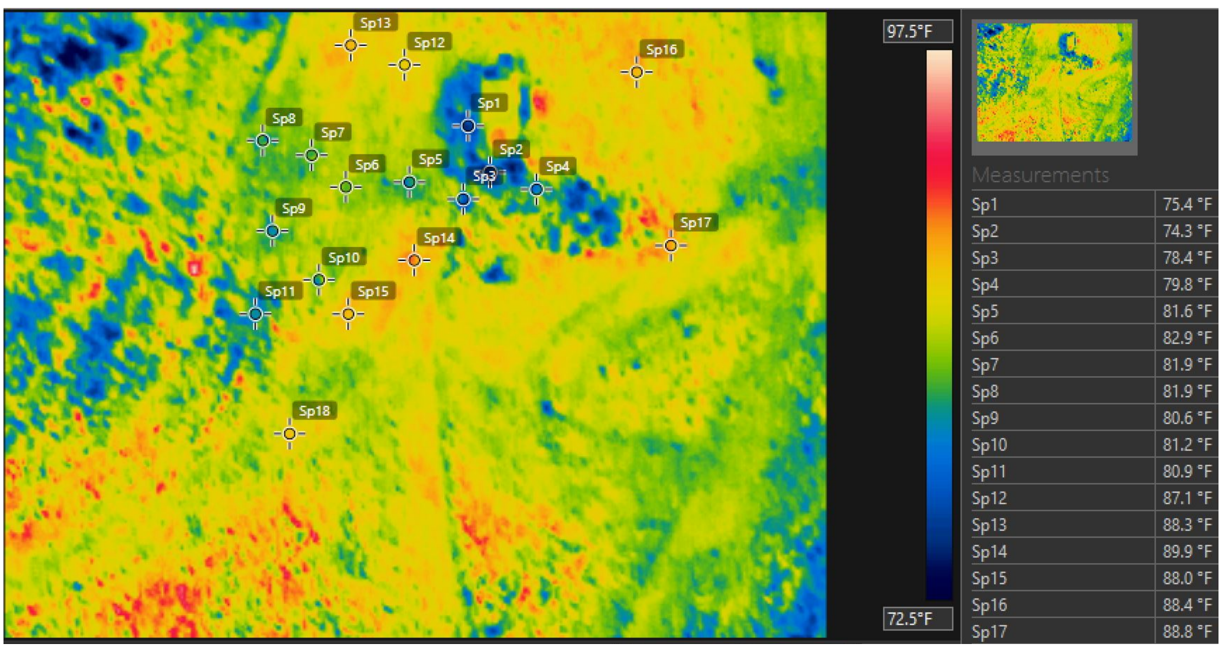


Figure 13A, B, C, D. Figure 13A. Visual (P4P) and Figure B reflectance (M200) aerial maps illustrate the MPWD1 site. The green areas in Figure 13B reflect cooler temperatures, while the yellow-orange areas reflect warmer temperatures. Figure 13 C shows the reference location for the enlarged view in Figure 13D. The square on Figures 13A, 13B, and 13D outlines the general area of the valve box (approximately 4.5 ft. subsurface) – the location of the simulated 'leak'; the diamond shows the general area with lower temperatures. This area is interpreted as: 'affected by the simulated leak' – with temperatures approximately 10F lower than the surrounding ground on the dirt road. By comparison, the ovals (13A, 13B) to the left show how vegetation appears as a temperature anomaly, an artifact on the reflectance map.





13F.

Figure 13E. M200 aerial visual image for reference to Figure 13F, showing the location of the valve box (square box) and approximate location of thermal image showing lower temperatures in figure 13F. This M200 aerial thermal image shows a closer view of the valve box with a metal cover (Sp1, upper center blue area) – the location of the subsurface simulated leak. The greenish mottled area, in the dirt road, to the left of the valve box is interpreted to be soil with lower temperature due to conductivity of the cooler water (Sp5 – Sp11). The adjacent road surface is 88 - 90F warmer (yellow – orange, Sp14, Sp15). The observed temperature gradient has to do with subsurface spreading of the leaked water, distance to the leak water source, and increased contact time with warmer soil.

5.4 Site: LVVWA1 – Church site

Reason site was included in study

The Las Vegas Valley Water Authority (LVVWA) manages miles of water distribution pipelines in areas that fit the study criteria discussed in Section 4 of this report. LVVWA staff took time to provide information and access to two field sites, LVVWA! And LVVWA2, (Figure 14) that could benefit from this technology.

The pipeline at the LVVWA1 is located in Searchlight, Nevada and was installed between 1992-1995. The pipe is made of 6-inch diameter asbestos cement and some PVC and buried between 1.5 and 4 feet below the ground surface. The LVVWA1 pipeline, also known as: 'S1' and 'Church site'. Water pressure in the pipeline ranges from 60 (high elevation) to 110 (low elevation) PSI. Groundwater is the water source and the temperature in the pipeline is about 70F. The site is easily accessible, but away from general public areas, and generally a very good site for this study.

Current methods to inspect the LVVWA lines for leakage include monitoring for pipeline water pressure changes, observation of constant 'use' during the middle of the night (such use is unlikely), on-the-ground visual inspections, traditional acoustic methods, and using spectral bands from satellite imagery. Except for on-the-ground-inspections, these methods typically can't identify specific leak locations on the ground for crews to investigate efficiently.

By comparison, drone technology provides a relatively inexpensive and repeatable method to inspect such infrastructure for leaks. Using drones, the data is captured and processed fast to provide timely and valuable information to act on. The segment of LVVWA1 that staff recommended for inspection had experienced several leaks and recently was repaired. Although LVVWA1 pipeline was not suspected to be leaking, it was a good field site to collect aerial data to see if the thermal sensors picked up temperature anomalies.

USING DRONES TO DETECT WATER LEAKS – LAS VEGAS VALLEY WATER AUTHORITY, SEARCHLIGHT SITES: LVVWA1 AND LVVWA2

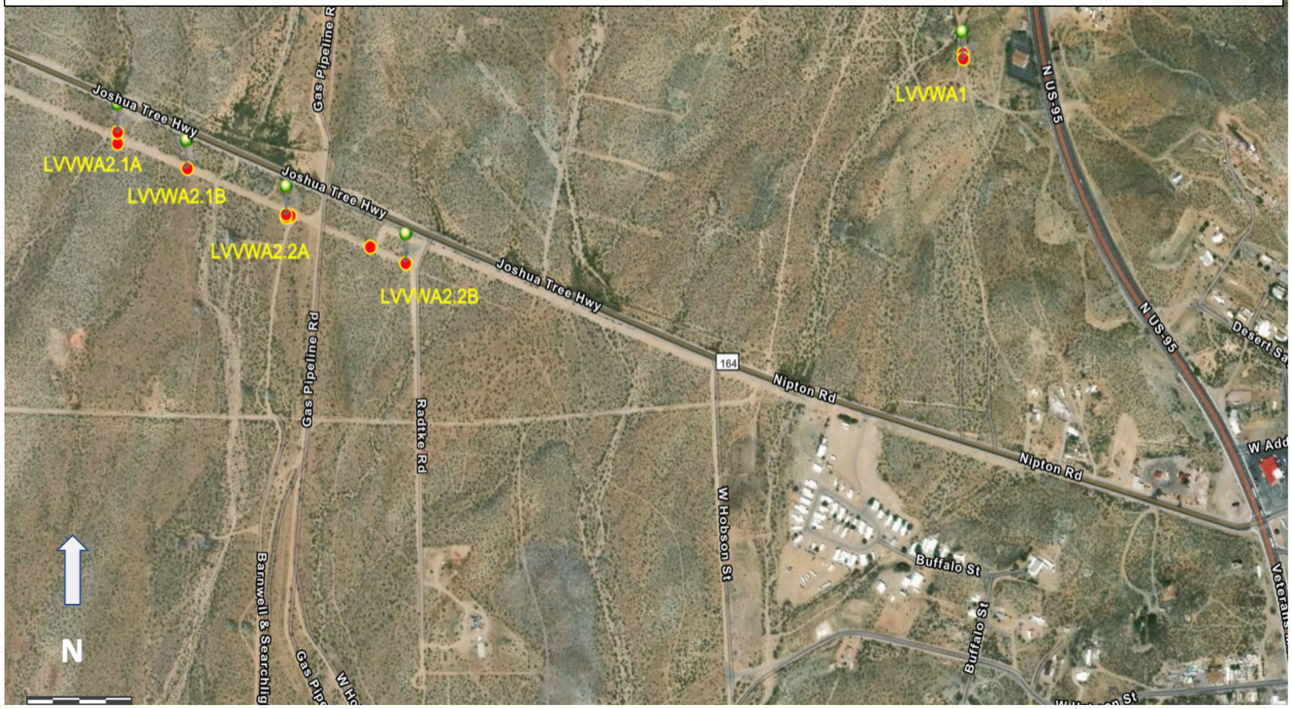


Figure 14. Map showing location of drone flights for LVVWA1 and LVVWA2, segments 1 and 2. The LVVWA1 site is west of Highway US 95 and the LVVWA2 site is adjacent to and south of Joshua Tree Highway, also called Nippon Road. To avoid interference from five high voltage power lines, the LVVWA2 site was flown in two segments: 2.1AB and 2.2AB. The red dots indicate multiple flights at each location.

LVVWA1 Site Summary and Results

Latitude: 35.4717932828101 N ***Longitude***: 114.925782708558 W

Water source temperature: 70F

Water infrastructure flown/inspected: 1.5 to 3-feet below ground surface, buried pipeline

Infrastructure material: 6-inch diameter asbestos cement and some PVC. Leak rate: 0gpm

Water pressure: ranges from 60 (high elevation) to 110 (low elevation) PSI.

FAA airspace: E5

FAA/other restrictions: None

Site access permission from: Mr. Derek Jackson, Small Systems' Superintendent, Las Vegas Valley Water Authority

Drone flight equipment used at MPWD1: DJI P4P, DJI M200 Zenmuse XT2

Flight altitude AGL (Above Ground Level, feet)**:** P4P: 100 – 150, M200: 60 -150 ft. AGL

Any site areas not flown: None

Dates and times of site visits to LVVWA1 with drone flights:

1. 5/26/2019 5:35AM – 9:35AM. No leak expected by LVVWA.
Drone(s): P4P, M200
Flight AGL: 80 - 164FT
Visibility: >3 miles

Pipeline water temperature: 70F
Air temperature: 53F
Ground temperature: NA
Wind: 0MPH
Relative humidity: NA

2. 5/28/19, 2:39PM – 5:15PM. No leak expected by LVVWA.
Drone(s): P4P, M200
Flight AGL: 150 FT
Visibility: >3 miles

Pipeline water temperature: 70F
Air temperature: 82.7F
Ground temperature: 105F
Wind: 1.2MPH
Relative humidity: 21%

3. 10/31/19, 2:39PM – 5:15PM. No leak expected by LVVWA staff.
Drone(s): P4P, M200
Flight AGL: 150 FT
Visibility: >3 miles

Pipeline water temperature: 70F
Air temperature: 59.3F
Ground temperature: 60F
Wind: 1.2 – 4.9MPH
Relative humidity: 8.7%

Results

The LVVWA1 site water pipeline is located on the west side of the dirt road that runs north-south (Figures 15A, 15B). According to LVVWA staff, this pipeline has had significant leaks in the past and recently a large line break was repaired on the north end. During the May and October 2019 fieldwork, hundreds of aerial images were collected during drone flights. The LVVWA1 site was revisited between October 29 and 31, 2019. At the time, the site representative indicated that no leaks were known on LVVWA1. During the first two days of the site visit the weather was unusually cold with gusty winds of more than 30 mph, so drone flights were not conducted until October 31. The goal of this visit was to complete aerial surveys to develop a reflectance index map and analyze it for thermal anomalies. No thermal anomalies were detected that could be interpreted as pipeline water leaks during fieldwork in May and October 2019.

Figure 16A. Flight map (lighter area), using sUAS DJI P4P and Pix4D Capture for LVVWA1.

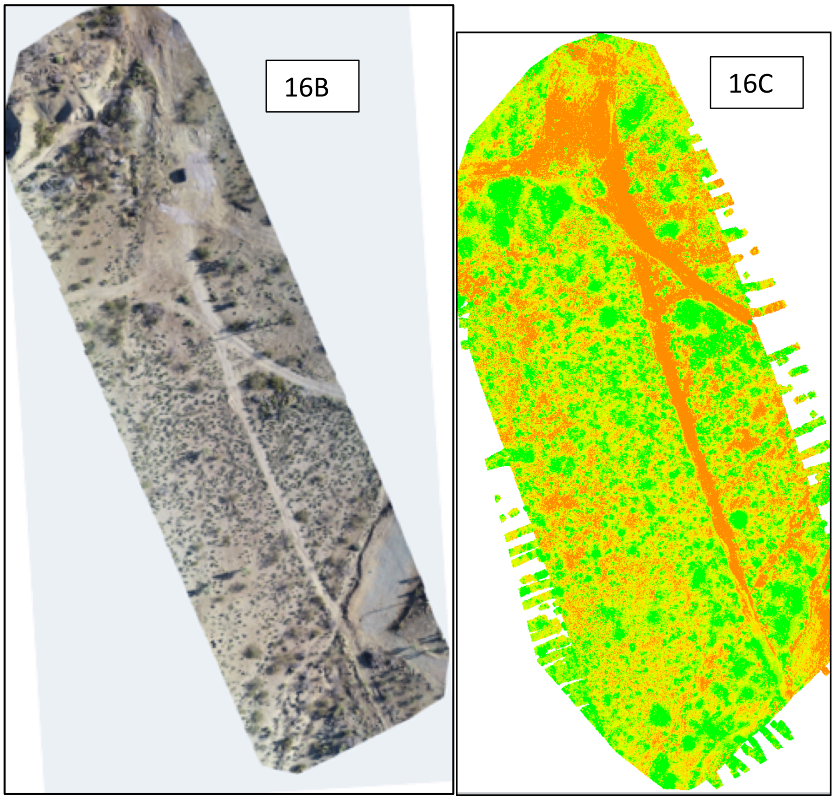


Figure 16B.
Aerial orthomosaic map of LVVWA1 using DJI P4P imagery and Pix4D Capture and Mapper software.
Figure 16C.
Reflectance index map images were collected in October 2019 using DJI Pilot software. Pix4D Mapper software was used to develop the reflectance index map (the orange depicts cooler ground surfaces and the green represents vegetation that reflects warmer temperature compared to the ground. The water pipeline runs north-south along the west side of the dirt road. (Image source: MW, 2019.)

5.5 Site: LVVWA2 – Transmission line site

Reason site was included in study

LVVWA2 was chosen for many of the same reasons as LVVWA1. LVVWA staff call this line the "the well collector line at S2" or "Transmission line S2". The stretch of LVVWA2 pipeline that staff recommended for inspection is buried deeper (5 to 8 feet below ground surface) and suspected to be leaking. In May 2019, LVVWA staff suspected a leak on this line because when they shut the wells off, (the water source) the water pressure dropped relatively quickly on a 3000-foot long segment of the line. This 8-inch PVC pipeline was installed in 1992 without sand bedding material, so it has been prone to punctures from rocks that surround it. In the aerial survey, the pipeline runs parallel to and south of Nipton Road (Highway 164), approximately 5 miles to the southeast of Searchlight, Nevada (Figure 14).

The LVVWA2 site was easily accessible, away from public areas, and generally (except for the high voltage power line corridor that was not flown) a good site for this study. The pipeline is deeper than the optimal depth of less than 5 feet below ground surface. Nonetheless, we wanted to test the ability of the thermal sensor to detect an assumed large amount of leaked water that was ongoing for "some time" prior to May 2019 site visit. Our thesis was that if a sufficient ΔT was present between the ground and pipeline water; the thermal sensor would detect thermal anomalies on the ground surface. Due to potentially large water losses, MW conducted eight aerial surveys to detect thermal anomalies indicative of leaks. Aerial data was collected in May and late October 2019.

LVVWA2 Site Summary and Results

Latitude: 335.4705343628633 N ***Longitude***: 114.942147620129 W

Water source temperature: 70F

Water infrastructure flown/inspected: 5 to 8-feet below ground surface, buried pipeline

Infrastructure material: 8-inch diameter PVC. Leak rate: 5 gpm (May 2019 site visit), 0 gpm (Pipeline shut off due to continued leak, so no water flowing in October 2019 site visit)

Water pressure: ranges from 60 (high elevation) to 110 (low elevation) PSI.

FAA airspace: E5

Site access permission from: Mr. Derek Jackson, Small Systems' Superintendent, Las Vegas Valley Water Authority

Drone flight equipment used at MPWD1: DJI P4P, DJI M200 Zenmuse XT2

***Flight altitude AGL (Above Ground Level, feet*)**: P4P: 100 – 150, M200: 60 -150 ft. AGL

Any site areas not flown? Yes – area where high voltage electrical transmission lines are present were not flown due to safety concerns (Figure 16A.)

Dates and times of site visits to LVVWA2 with drone flights:

1. 5/23/19 8:04AM – 11:35AM. Leak expected by LVVWA.

Drone(s): P4P, M200

Flight AGL: 80 - 150FT

Visibility: >3 miles

Pipeline water temperature: 70F
Air temperature: 54.7F
Ground temperature: NA
Wind: 3.4 - 4.4MPH
Relative humidity: 60.6%

2. 5/24/19 7:13AM – 10:35AM. Leak expected by LVVWA.

Drone(s): P4P, M200

Flight AGL: 150 FT

Visibility: >3 miles

Pipeline water temperature: 70F
Air temperature: 65F
Ground temperature: NA
Wind: 0 – 2.4MPH
Relative humidity: 42%

Note: 5/25/19: too windy (20-35mph) to fly.

3. 5/26/19 9:21AM – 12:35PM Leak expected by LVVWA.

Drone(s): P4P, M200

Flight AGL: 150 FT

Visibility: >3 miles

Pipeline water temperature: 70F

Air temperature: 53F

Ground temperature: NA

Wind: 0 – 1.4MPH

Relative humidity: 42%

4. 5/27/19 5:30AM – 9:15AM Leak expected by LVVWA.

Drone(s): P4P, M200

Flight AGL: 150 FT

Visibility: >3 miles

Pipeline water temperature: 70F

Air temperature: 47F

Ground temperature: 50F

Wind: 0.6 – 2.6 MPH

Relative humidity: 50%

5. 5/27/19 8:10AM – 11:20AM Leak expected by LVVWA.

Drone(s): P4P, M200

Flight AGL: 150 FT

Visibility: >3 miles

Pipeline water temperature: 70F

Air temperature: 64.5F

Ground temperature: 70F

Wind: 8.2MPH

Relative humidity: NA

6. 5/27/19 5:18AM – 9:20AM Leak expected by LVVWA.

Drone(s): P4P, M200

Flight AGL: 150 FT

Visibility: >3 miles

Pipeline water temperature: 70F

Air temperature: 48F

Ground temperature: 49F

Wind: 1 – 1.6MPH

Relative humidity: 50%

7. 5/28/19 8:45AM – 10:20AM Leak expected by LVVWA.

Drone(s): P4P, M200
Flight AGL: 150 FT
Visibility: >3 miles
Pipeline water temperature: 70F
Air temperature: 74F
Ground temperature: 82F
Wind: 1.4MPH
Relative humidity: 25%

8. 5/28/19 1:40PM – 4:20PM Leak expected by LVVWA.
Drone(s): P4P, M200
Flight AGL: 150 FT
Visibility: >3 miles
Pipeline water temperature: 70F
Air temperature: 75.7F
Ground temperature: 90F
Wind: 0.6 – 2.3MPH
Relative humidity: 24.2%

9. 10/31/19, 2:39PM – 5:15PM. No leak expected by LVVWA.
Drone(s): P4P, M200
Flight AGL: 150 FT
Visibility: >3 miles
Pipeline water temperature: 70F
Air temperature: 59.3F
Ground temperature: 60F
Wind: 1.2 – 4.9MPH
Relative humidity: 8.7%

Results

The LVVWA2 site water pipeline is located on the south side of the dirt road that runs north-west to south-east (Figure 17A). During the May site visit, LVVWA staff stated that this pipeline has a history of leaks and at the time of this site visit the pipeline was experiencing significant losses of pressure, likely due to water leaks.

The LVVWA2 site was flown eight times in two segments – 2.1AB and 2.2AB, as a safety precaution, because five high voltage power lines transected the site.

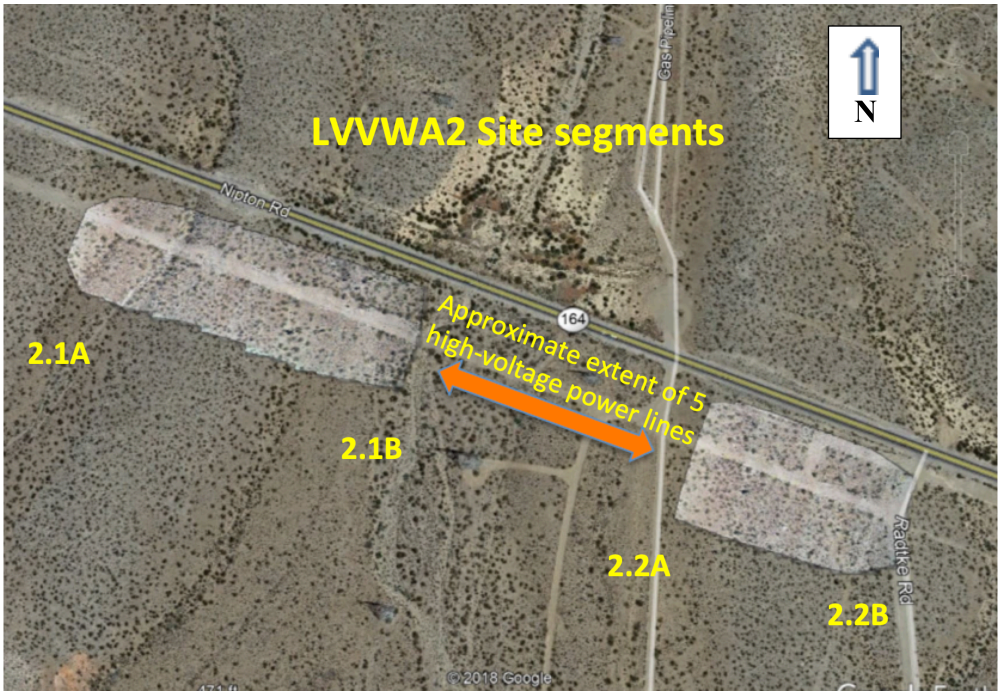


Figure 17A. The LVVWA2 site water pipeline was considered to have a leak due to pressure losses when wells were turned off. LVVWA2 was mapped using the P4P drone in two segments (light areas) to avoid flying in the area where high voltage power lines are located.

During the May 2019 fieldwork, hundreds of thermal images were collected from drone flights. On May 27 at 6:50 am, the aerial thermal sensor detected a pattern of apparent thermal anomalies. That morning was chilly, with ground temperature in the low to mid-50s F, while water temperature was about 70F. Near the north-west end of 2.1A (Figures 17A, 18A, 18B), the temperature increased consistently about 10F, to mid and high 60s F (Figures 18A, 18B). This apparent thermal anomaly was visible in this area for about 45 minutes.

17B. Aerial orthomosaic map, generated using DJI Phantom 4 Pro and Pix4D Mapper software, for LVVWA S2-1AB, S2-2AB. (Source: MW drone flight, 2019). The water pipeline runs parallel to the south side of the dirt road. Note: orange box shows the location of a thermal anomaly observed on May 27, 2019.

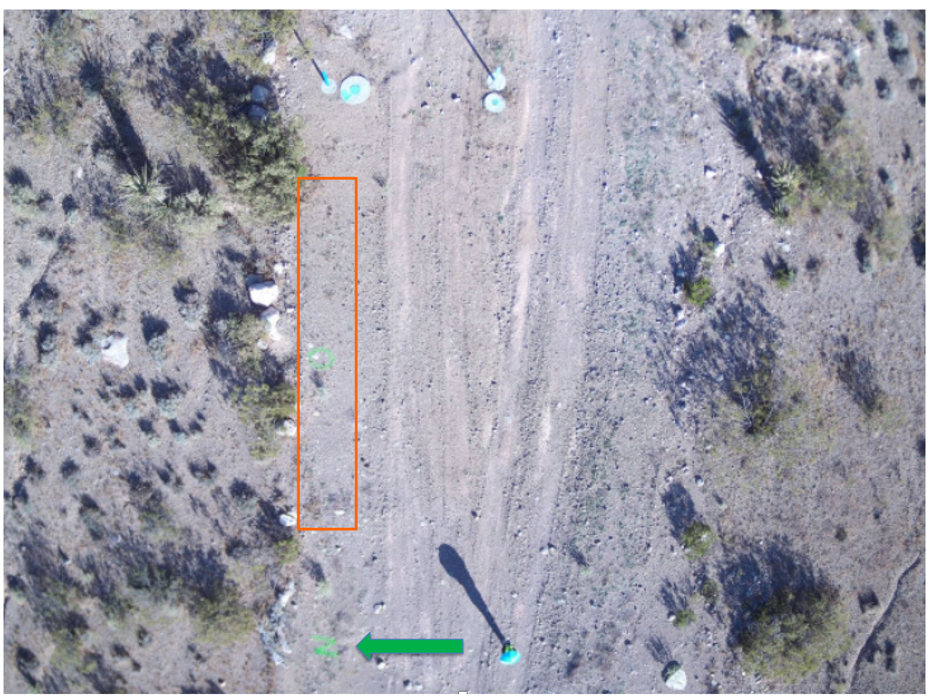


Figure 18A. Visual aerial image showing the location (orange box) of the temperature anomaly observed early morning on May 27, 2019. The water pipeline runs along the left side of dirt road, in the area of the orange box. The arrow points to the green "N" on the ground to help locate the area of interest in the visual and thermal images.

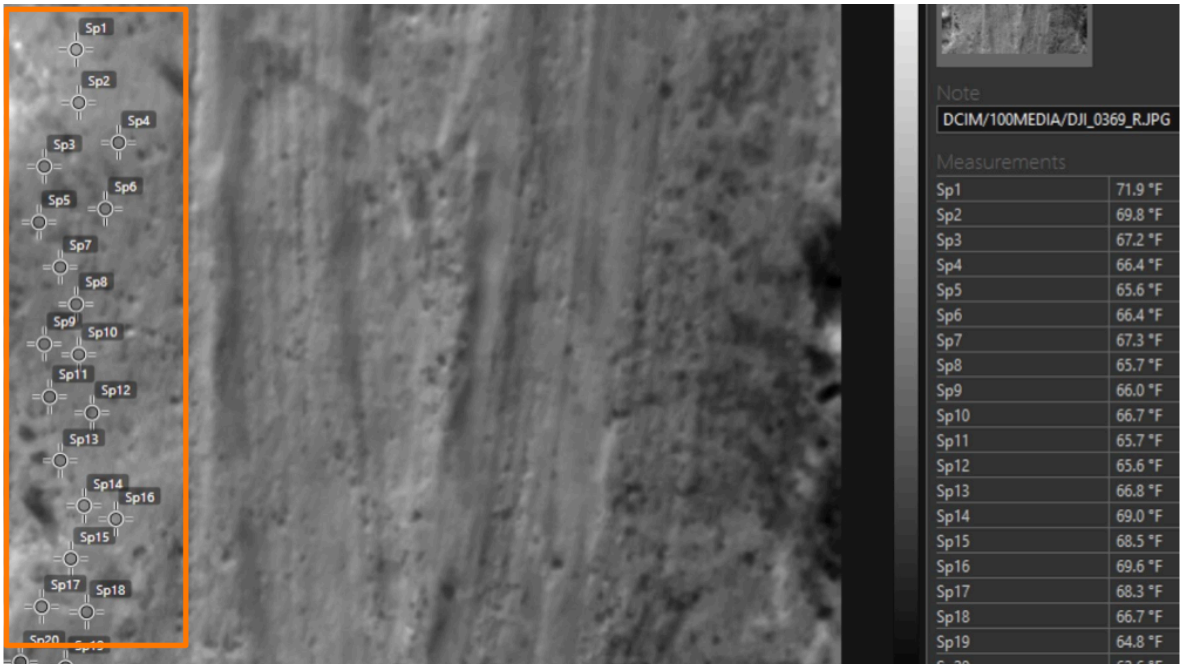


Figure 18B. Thermal aerial image showing the location (orange box) of the temperature anomaly observed early morning on May 27, 2019. The water pipeline runs along the left side of dirt road. The thermal images for LVVWA2 were generated using DJI Matrice 200 with Zenmuse XT2 sensor and DJI Pilot software. Flir Tools software was used to analyze the image and temperature values. As the flight proceeded along the pipeline, approaching the 'N' mark on the ground (Figure 17A. green letter on the ground, bottom center), the Pilot in Command observed temperatures that were consistently 10F higher than the previous leg of the flight. The contrast in temperature appeared as an anomaly due to the flight's early hour and lack of extended exposure to solar radiation.

The MW pilot in command contacted LVVWA staff, but the thermal anomaly in this area was no longer apparent later. The potential causes of the temporary anomaly and lack of clear visibility of the exiting leak(s) are discussed in the Summary and Findings sections below.

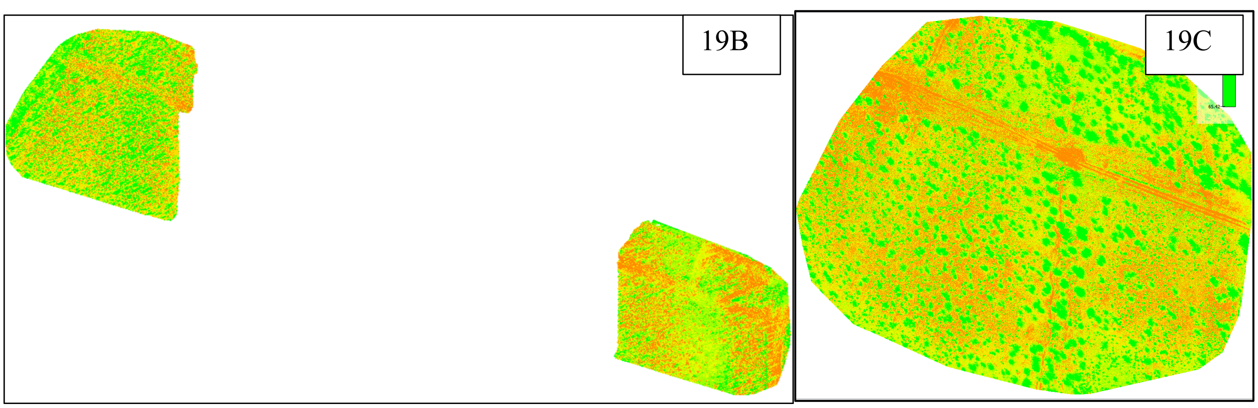
Data analyzed from aerial surveys in May 2019 at LVVWA2 did not exhibit thermal anomalies indicative of water leaks. Possible reasons for not detecting anomalies at LVVWA2 are:

- the pipeline is too deep for the leaked water temperature to affect the ground surface temperature,
- the leak(s) are located in an area not flown, such as the stretch between the power lines,
- the subsurface geology affects the spread of the leaked water laterally and vertically, such that the leak travels underground and does not affect the ground surface temperature,
- many small leaks comprise 'the leak', so they are too small to affect the ground surface temperature, and

- some combination of the above conditions affect the leaked water flow, resulting in no temperature transfer from the leaking water to the ground surface.

The LVVWA2 site was re-visited between October 29 and 31, 2019. The site representative indicated that the segment of pipeline with the suspected leak was shut down at this time. No other leaks were known. On October 29th and 30th the weather was unusually cold, rainy, and with wind gusts in excess of 30 MPH. Flights were suspended until environmental conditions were safe and suitable (no rain, wind <15mph). The goal of the visit was to develop a reflectance index map and analyze it for thermal anomalies.

Figure 19A. Aerial mapping using sUAS DJI M200 XT2 and DJI Pilot software for LVVWA2, sections 2.1A-B and 2.2A-B. The red dots represent the flight path and images taken during flight. (Source: MW, 2019).



Figures 19B, 19C. Reflectance index map from LVVWA2 flight on October 31, 2019, using sUAS DJI M200 with the XT2 sensor and DJI Pilot software. The reflectance index map from this flight illustrates the cooler ground surfaces (orange) and vegetation that indicated warmer temperature (green) compared to the adjacent ground. The reflectance index map on the left (19B) shows both sections 2.1A-B and 2.2A-B. The reflectance map on the right (19C) is from a later flight on October 31st of segment 2.1A-B. No thermal anomalies attributable to water leakage were observed during the flights or in the reflectance index maps. (Source: MW, 2019.)

6. Summary and Conclusions

6.1 Summary

In this project MW developed workflows to integrate drones and software applications – evolving, innovative technologies – to detect water leaks. The project's goal was to advance the field application of drones with visual and thermal sensors to detect specific locations of water leaks. To accomplish this, MW used two commercially available quadcopter drones – DJI Phantom 4 Pro (P4P) with a visible light sensor and DJI Matrice 200 (M200) with dual visible and medium long-wave infrared electromagnetic spectrum sensors (Zenmuse XT2). MW developed workflows to prepare for field work, conduct aerial surveys, and process and analyze the data.

Initially, MW identified the site and environmental conditions suitable to obtain representative thermal data. To select appropriate field sites and solicit participation in the project, MW sent Fact Sheets about the project with site selection criteria to 32 potential participants. The majority of contacts were water agencies in the San Francisco Bay Area. Universities in California and Nevada, as well as a water agency in southern Nevada were also contacted.

In the end, the five 'best fit' field sites included three sites at water agencies and two at a University of California campus. We collected data from the aerial surveys of the water conveyance infrastructure – subsurface pipelines and canals with levees – at the five sites. The sites at water agencies included the Mid-Peninsula Water District in Belmont, California (MPWD1) and Las Vegas Valley Water Authority (LVVWA1 and LVVWA2), close to Searchlight, southern Nevada. Two field sites were selected at the University of California at Merced (UCM1, UCM2), California. Of the five sites, three had known leaks – UCM1, UCM2, LVVWA2, one had a simulated leak – MPWD1, and one had no known leaks – LVVWA1.

Workflows were developed to systematically approach the integration of methods for managing processes, hardware, software, and data collection. ESRI's Survey123 application was used to manage site and environmental data. Before flights we documented site and environmental conditions, including the temperatures for water, ground, and air, as well as measuring the relative humidity. Ground temperatures and relative humidity affect the quality of thermal images. Pix4D Capture was used for flight design and image capture using the P4P drone. DJI Pilot software was used for flight design and image capture using the M200 drone. Pix4D Mapper was used for developing orthomosaic and reflectance index maps.

The orthomosaic maps from the P4P are high resolution and provide ground sampling distances of less than 1 inch. Using such high-resolution imagery with Pix4D Mapper software enables precise measurements. These maps provide visual details about objects on the ground that are helpful for locating water leaks. For example, even small plants are visible at UCM1 and can be used as 'indicators' for water leak areas.

The XT2 thermal sensor detects the ground surface temperature (as radiometric data) and records it in each pixel of each image. The recorded radiometric data in images (RJPGs) display specific areas with cooler or warmer temperatures that we evaluated for 'thermal anomalies' compared to the surrounding ground. Such thermal anomalies can reflect a 'leaking' water source. Larger differences in temperature (ΔT) between the source water and ground make it easier to detect and interpret the thermal anomalies. For example, at UCM2 the difference in leaking canal water temperature of 70F vs. the ground at 116F, provided an excellent temperature contrast, ΔT, and temperature anomaly.

Diurnal and seasonal temperature trends impact scheduling of drone surveys. To understand the temperature variability and ΔT, MW collected hourly temperature and humidity measurements to develop a 'daily thermal profile' for the UCM1, UCM2, LVVWA1, and LVVWA2 sites. This information was used to target best times for capturing the highest temperature contrasts in aerial thermal data. The contrasting temperatures reveal spatial temperature patterns on the ground. From the aerial thermal images MW developed aerial reflectance index maps. The reflectance index maps provide broad spatial views of temperature differences and patterns on the ground from which anomalies can be detected. The temperature anomalies are interpreted to identify locations with leaks. The UCM1 and UCM2 sites demonstrate that the drone and thermal technology works well to identify water leaks that rise near or to the ground surface.

Using this technology to identify leaks from subsurface pipelines is more challenging. However, knowing the *general* area or stretch of line considered to be leaking assists to identify the *specific* area in the reflectance index map and individual thermal images. At the MPWD1 site a lower temperature anomaly was present in the vicinity of the valve box with the simulated leak.

The LVVWA1 site was expected not to have a leak, given that a pipe break had recently been fixed. No thermal anomalies attributable to water leakage were detected at LVVWA1. At LVVWA2, a large leak was expected by LVVWA staff. MW detected a 10F thermal anomaly on May 27, 2019. However, with subsequent flights, the anomaly was not detected again. Possible explanation for not detecting the pipe leak at LVVWA2 include:

- the pipeline is too deep, so water temperature from the leak does not affect the ground surface temperature,
- the leak(s) are located in an area not flown, such as the stretch between the power lines,
- the subsurface geology affects the upward spread of the leaked water,
- many small leaks comprise 'the leak', which causes insufficient temperature transfer, and
- some combination of the above conditions affect the leaked water flow, resulting in no discernible temperature transfer from the leaking water to the ground surface.

Other temperature patterns were visible. Careful analysis of the spatial patterns led to is avoiding their misinterpretation. For example, at the MPWD1, LVVWA1, and LVVWA2 sites some areas appeared cooler than the surrounding ground. However, closer review of the visual orthomosaic and reflectance index maps shows that the cooler patterns matched the vegetation patterns.

6.2 Conclusions

Based on background research prior to the start of this project, MW expected that commercially available drone hardware and software would be capable of capturing and processing aerial visual and thermal data that can be used for detecting water leaks. This expectation proved true, although detailed workflows for field data collection and subsequent aerial image analysis had to be developed to integrate all elements of drone use and the data management process.

Drone hardware and software applications continue to evolve. Workflows to integrate the hardware with software and analytics are not streamlined. Therefore, MW developed workflows for:

1. Systematic site and environmental data collection,
2. Aerial image capture, and
3. Post-flight thermal data processing and analysis.

These three main workflow elements were key for improving the fieldwork processes and results for this project. Using ESRI Survey123 at each site, provided consistent capture of the environmental and site data, including geospatial tags, so it can be linked to GIS maps. Development of daily thermal profiles using measurements of hourly water, air, and ground temperatures and relative humidity assisted with timing of flights to obtain significant ΔT that facilitated analysis of thermal anomalies. The daily thermal profiles also demonstrated occurrence of changes in ΔT by season and geographic location. Once the images were available for post-processing, MW developed of reflectance index maps using Pix4D Mapper software and used them to review spatial temperature patterns on the ground. Once ground thermal patterns were identified, MW used Flir Tools software to analyze individual image temperatures to locate specific leak areas.

The high resolution of DJI P4P drone's visible light images, individually or as part of orthomosaic maps, provide detailed geospatial, visual relationships for items of interest on the ground. The P4P drone is an excellent tool for capturing visual digital imagery. The Pix4D Capture and Mapper software is relatively easy to use for developing high quality orthomosaic maps. Such maps provide visual geospatial relationships and allow measurements of areas of interest. The less than one-inch ground sampling distance (GSD)from the DJI P4P drone provide excellent resolution of objects on the ground compared with traditional nominal GSD of 50 feet in satellite remote sensing. The P4P orthomosaic maps were used to help identify locations that may be sources of water leaks.

Our work shows that, in unpaved areas with little to no vegetation, thermal anomalies can best be identified when the ΔT between source water and ground surface is at least 25F.

We used the M200 with the XT2 thermal sensor to detect ground surface temperature anomalies from the water infrastructure. Our work shows that, in unpaved areas with little to no vegetation, thermal anomalies can best be identified when the ΔT between source water and ground surface is at least 25F. Using thermal images, to develop reflectance index maps for the five field sites facilitated identification of spatial thermal patterns on the ground surface, thus aiding with identification of water leaks at three of the sites. The M200 with the Zenmuse XT2 dual sensors is a powerful tool for capturing aerial thermal images in relatively small areas (a few acres) due to limitations of battery life.

This project demonstrates that commercially available drone and sensor technologies, under certain conditions, can be used to detect water leaks. The relative low cost of the drone equipment, ability to repeat flights and collect data frequently, process the data rapidly, and access remote sites make drones a good resource for water managers. MW's fieldwork shows that by integrating drone hardware with various software applications one can collect and identify thermal anomalies from the aerial data. The thermal anomalies when combined with visual images can lead to precise local identification of the leaks.

Apart from the need to develop workflows, current drone hardware and software limitations exist. For field projects in hot summers when ΔTs are best between water sources and the ground surface, high temperatures limit the battery life for the M200 drone. The limited battery life increased the number of flights with the M200 and extend time in the field. Under high temperature conditions, night flights should be considered. Also, drones with much longer flight times, such as those that can take off and land vertically, using rotors, but fly as fixed wing airplanes, known as VTOLs (vertical take-off and landing) may be a viable solution, especially for surveying large areas.

The DJI Pilot software used with the M200 Zenmuse XT2 sensors continues to improve, although current flight time prediction inaccuracies and frequent firmware updates can interrupt image capture during fieldwork. Drone software and hardware integration with tools for automated analysis are needed in order for this technology to scale and be more broadly used by water managers.

What Next?

Currently, the review of the thermal images to detect water leaks is manual and quite tedious. Automating recognition of ground surface thermal patterns attributable to water leakage will facilitate development of a leak intensity index. A leak intensity index will enable real-time comparison of aerial images to reference leak images. Such pattern recognition will save time, make these tools smarter to help prioritize fixes, and make drone and thermal sensor technologies useful for water managers.

Drone and sensor technologies are viable additional tools to detect water leaks and manage water. MW is continuing to work with these technologies to advance their usefulness for water management.

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8. Attachments

8.1 Field template – ESRI Survey123

- Site name
- Today's date, starting time
- FAA airspace
- Other regulatory requirements
- Explain other regulatory or site requirements
- Weather, good for flying?
- Weather notes
- Air temperature, F
- Ground temperature, F
- Water temperature, F
- Relative humidity, percent
- Wind, mph
- Cloud cover, OKA
- Source water containment
- Explain other details about source water containment
- P4P used
- P4P image capture software
- P4P image capture software
- P4P Battery 1
- P4P Battery 2
- P4P Battery 3
- P4P Battery 4
- P4P Battery 5
- P4P Battery 6
- M200 used?
- M200 image capture software
- M200 A, A batteries
- M200 BB, BB batteries
- M200 CC, CC batteries
- M200 DD, DD batteries
- M200 EE, EE batteries
- Mavic 2 E
- Batteries notes
- P4P ft AGL
- M200 ft AGL
- End time
- Notes
- Site photo 1
- Site photo 2