Evaluation of stream and wetlands restoration using UAS-based thermal infrared mapping

Mark Harvey 1, *, Danielle Hare 1, Alex Hackman 2, Glorianna Davenport 3, Adam Haynes 1, Ashley Helton 1, John W. Lane Jr. 4, and Martin Briggs 4

1 Department of Natural Resources and the Environment, Center for Environmental Sciences and Engineering, University of Connecticut, Storrs, CT, USA; ashley.helton@uconn.edu (A.Hel.);
danielle.hare@uconn.edu (D.H.); adam.haynes@uconn.edu (A.Hay.)
2 Massachusetts Division of Ecological Restoration, 251 Causeway Street, Suite 400, Boston, MA 02114;
alex.hackman@mass.gov (A.Hac.)
3 The Living Observatory, 139 Bartlett Rd, Plymouth, MA 02360; gid@media.mit.edu (G.D.)
4 U. S. Geological Survey, ESPD Hydrogeophysics Branch, 11 Sherman Place, Unit 5015, Storrs, CT 06269;
mbriggs@usgs.gov (M.B.), jwlane@usgs.gov (J.L.)

* Correspondence: mark.harvey@uconn.edu; Tel.: +1-860-798-9482

Received: date; Accepted: date; Published: date

Abstract: Unoccupied aerial systems (UAS) are now routinely used for collecting aerial imagery and creating digital surface models (DSM). Lightweight thermal infrared (TIR) sensors provide another payload option for generation of sub-meter resolution aerial TIR orthophotos. This technology allows for the rapid and safe survey of groundwater discharge areas, often present in inaccessible or dangerous terrain. Aerial TIR water-surface data were collected March 2019 at Tidmarsh Farms, a former commercial cranberry bog located in coastal Massachusetts, USA (41°54’17.6”N 70°34’17.4”W), where stream and wetland restoration actions were completed in 2016. Here we present a 0.4 km² georeferenced, temperature calibrated TIR orthophoto of the area. The image represents a mosaic of nearly 900 TIR images captured by UAS in a single morning with a total flight time of 36 minutes, and is supported by a DSM derived from UAS visible imagery. The survey was conducted in winter to maximize temperature contrast between relatively warm groundwater and colder ambient surface environment; lower-density groundwater rises above cool surface waters and thus can be imaged by a UAS. The resulting TIR orthomosaic shows fine detail of seepage distribution and downstream influence along the several restored channel forms, which was an objective of the ecological restoration design. The restored stream channel has increased connectivity to peatland groundwater discharge, reducing the ecosystem thermal stressors. Such aerial techniques can be used to guide ecological restoration design and assess post-restoration outcomes, especially in settings where ecosystem structure and function is governed by groundwater and surface water interaction.

Keywords: ecological restoration; wetlands; seepage; groundwater; springs; thermal; drone
1. Introduction

At temperate latitudes, cold water anomalies in summer and warm water anomalies in winter can indicate zones of spatially preferential groundwater discharge that can be mapped with ground-based TIR at high spatial resolution compared to more traditional groundwater discharge-characterization methodology (Briggs & Hare, 2018). Unoccupied aircraft systems (UAS) are now routinely used for collecting visible-light aerial imagery and creating digital surface models (DSM) of surface water-related features (Briggs et al., 2018; Pai et al., 2017; Woodget et al., 2015). Lightweight thermal infrared (TIR) sensors provide another remotely sensed data type that can be used to generate high-resolution (< 1 m) TIR orthophotos (e.g. Harvey et al., 2016). However, the use of TIR equipped UAS is relatively novel, only recently finding environmental and hydrological applications (Abolt et al., 2018; Briggs et al., 2018; Dugdale, 2016; Dugdale et al., 2019; Harvey et al., 2016; Fitch et al., 2018; Isokangas et al., 2019). Examples include environmental monitoring of natural geothermal systems (Harvey et al., 2016), and distinguishing sewer and stormflow discharges from groundwater based on characteristic temperatures (Fitch et al., 2018). In engineered peatlands UAS TIR was used to guide water isotopic sampling for a similar goal of parsing groundwater discharge endmembers (Isokangas et al., 2019).

Recently, there has been a movement to better incorporate ecological services and functions into stream and wetland restoration projects (Hester & Gooseff, 2010). Hydrological processed-based wetland restoration requires understanding site-wide hydrodynamics, which often involves scaling-up measurements from discrete physical sampling points to the square-km scale (Grand-Clement et al., 2013). A fundamental challenge to point scale measurement upscaling is that wetland subsurface materials often exhibit strongly heterogeneous and anisotropic properties and preferential flow paths; traditional groundwater discharge characterization methods are often inadequate for representing system-scale dynamics (Hunt & Krabbenhoft, 1997). In contrast, spatially distributed thermal methods (i.e. ground-based thermal infrared and fiber-optic sensing) have shown great promise for the comprehensive mapping of preferential seepage processes in across wetlands (Hare et al., 2015; Lowery et al., 2007), though work is hindered by boggy terrain and vegetation. The use of spatially extensive thermal investigations to identify groundwater seepages could potentially improve restoration design and evaluation, particularly if deployed from a UAS platform. TIR-equipped UAS provides such an opportunity for developing effective and transferable methods to produce spatially contiguous and extensive groundwater seepage maps.

UAS-based imaging offers the potential to plan and evaluate process-based wetland restoration projects efficiently, with the combined collection of visible, DSM, and TIR data. However, the approach requires sufficient contrast between the temperature of the surface environment, and groundwater temperature; enough to allow the TIR sensor to resolve the groundwater as relatively warm (winter), or cool (summer). The use of TIR-equipped UAS to map high-temperature geothermal springs was previously demonstrated (Harvey et al., 2016), but imaging lower-temperature groundwater is more challenging, as temperature contrasts are much less. Further, relatively cold groundwater discharge often plunges in slow flowing surface waters in summer when most field work is conducted, reducing the surface expression of groundwater discharge zones (Hare et al., 2015). Thermal images collected during winter may provide the best opportunity to explore the potential of the method to evaluate wetland restoration design and implementation.

The objectives of the study were to evaluate i) the ability of TIR-equipped UAS for identifying groundwater discharges, and ii) the usefulness of TIR-equipped UAS as a tool for validating thermal refugia goals of process-based restoration.
2. Tidmarsh Farms Site Description

The study area, Tidmarsh Farms, is a former 2.5 square-km cranberry bog that underwent a process-based restoration in coastal Massachusetts, USA (41°54'17.6"N 70°34'17.4"W). The cranberry farm, through which the restored stream channel flows, was built on a series of smaller peat filled kettle holes located in Manomet Village in Plymouth, Massachusetts. The original stream channel, sometimes known as Beaver Dam Brook, was dammed in the early 1880s, forming an early version of what became known as Beaver Dam Pond. For the next 120 years water structures were built, maintained (including a perimeter ditch and lateral ditches), and covered with sand. In 2008, the owners of Tidmarsh Farms decided to take the farm out of production in order to ecologically restore and protect the area. In 2017, having completed the largest freshwater wetland restoration in Massachusetts, the property was purchased by the Massachusetts Audubon Society who in 2018 opened the Tidmarsh Wildlife Sanctuary to the public.

The Tidmarsh Farms restoration project used a ‘process-based’ approach (Beechie et al., 2010), which considers the underlying physical drivers of wetland and stream systems. The process-based approach identifies limiting factors to wetland recovery, with the goal of reducing ecological stressors and encouraging site rejuvenation. Focusing on the natural movement and storage of water on the land, the project team identified legacy agricultural impacts that affected site hydrology. The three primary issues were i) an anthropogenic sand layer placed during farming over native peatland soils that impacted water storage in the upper layer (~1 m), ii) dams and water control structures that interrupted the movement of water, and iii) physical simplification including channel straightening, ditching, and bog platform maintenance that reduced water retention. The ecological restoration approach developed to mitigate these impacts included ditch plugging, bog surface roughening, dam and water control structure removal, steam channel reconstruction (5.6 km), and large wood addition (~3,000 pieces). Collectively, these actions were intended to help increase hydrologic residence time on site and improve ecological services within the restored wetlands.

During the assessment and design phase, a key question for the project team focused on where to locate the reconstructed stream channel within the broad valley. Project designers hoped to replace highly modified (wide, straight, shallow) agricultural channels with more geomorphically appropriate (narrow, sinuous) channels that also provided cool/cold-water habitat by intercepting groundwater discharge. Hare et al. TIR-equipped UAS Each identified discharge was characterized as a low-flux or high-flux zone by scaling up vertical flux measurements based on a subset of thermal flux profiles (~0.15 m/day, ~3 m/day, respectively) analyzed with 1DTempPro software (Koch et al., 2015). These locations were compared to the underlying peat depth and subsurface peat basin structure, determined by ground penetrating radar (GPR). The results of the pre-restoration assessment demonstrated that both high and low-flux seepage occurred along the margins of the peat surface, but high-flux preferential discharges also appeared within the peat surface interior (Figure 1a). No groundwater discharge was visible interior of these zones (Figure 1b), signaling an abrupt end to any groundwater input along the site edge. These interior preferential flow path discharges correlated with large increases in peat depth (high curvature) located on the upgradient side of the regional groundwater flow path, as well as in areas of general peat thinning (Figure 1c); it was theorized that the high curvature induced high seepage zones interior of where was expected due to the abrupt change in hydraulic conductivity (Hare et al., 2017). Therefore, the restoration design incorporated the observational theory (Hare et al., 2017), and the site’s interpolated peat depth, along with other site data, to place the new stream channel for maximize groundwater input.
Figure 1. Hand-held TIR images collected before the restoration (March 2014), along the relic cranberry bog drainage ditches. Images show: (a) natural groundwater discharge, (b) no discharge, (c) clustered centimeter-scale macropore discharge features, and (d) discrete discharge features observed after the restoration (March 2018) in similar locations to the pre-restoration period, indicating persistent subsurface hydrogeologic controls.

Figure 2. Data used to iteratively design new channel features: (a) LiDAR layered with notes from interview with the cranberry farmer, (b) feature layout, and (c) final engineering plan set by Inter-Fluve, Inc. Multiple data types allowed the project team to consider spring locations and potential intersections with the new channel.
3. Methods

3.1. Aerial Imaging Field Methods

UAS TIR imagery was collected during the early morning of March 19, 2019 using a DJI Matrice 100 quadcopter fitted with an ICI 9640 640x480 uncooled TIR sensor (spectral response 7-14µm) and automated image capture (ICI UAV module®). Imaging was performed before sunrise, when most of the bog surface was covered in frost (air temp was approximately -3 °C), but flowing channel features were not frozen.

The flight plan was developed using UgCS® software. The UgCS photogrammetry tool was utilised with the following parameters: forward and side overlap 80%, flight speed 8 m/s, and ground resolution 16 cm (equates to a flight altitude of 120m above ground level). The flight plan was then uploaded to the quadcopter’s flight controller via a Samsung S4 smartphone running Android and the UgCS® for DJI application. Accordingly, both in-flight navigation and image capture were autonomous. Ground control points were not deployed at the time of data collection.

Visible imagery was collected from aircraft approximately one-year prior (March, 2018) using a Ricoh GRII Camera (Ricoh Imaging Company, Ltd., Japan) when there was patchy snowpack over the land areas. Image stills were collected along multiple flight lines, with aircraft altitudes ranging approximately 90 – 120 m above ground level. Position of the aircraft was tracked by internal GPS. Ground control points were not deployed at the time of data collection. Additional detail of methodology for both TIR and visible data collection, including flight and photogrammetry processing parameters, is available from Harvey et al. (2019).

3.2. Image Processing and Analysis

TIR images were processed using Agisoft Photoscan® commercial photogrammetry software, running on a computer equipped with an i7 processor and 32 GB RAM. Georeferencing was improved within Agisoft Photoscan using ground control points, which were identified during post processing using Google Earth satellite imagery. The TIR orthophoto was then post-processed using QGIS open-source desktop geographic information system (GIS). This involved the conversion of the raw 32-bit pixel values to calibrated temperature values (°C) (Section 3.3).

3.3. Temperature calibration of TIR images

Temperature calibration utilised aluminum trays filled with water of various temperatures recorded with a using a high-precision (0.01 °C) digital thermometer (Traceable Thermometer, Control Company, Friendswood, TX). Five distributed temperature measurements were made inside each try (each corner and center), while the UAV hovered (15 m above tray level) capturing TIR images (Figure 3a). The temperature probe was left to stabilize for 15 seconds before the temperature was recorded. In order to get the water surface skin temperature, the thermometer was placed in contact with the uppermost surface of the water.

The five values were averaged to give a best estimate of the water surface temperature of each tray. Average temperature measurements were regressed against average raw pixel values from the TIR images of the trays during the flight (plus two additional sites on rivers with known temperature at time of image capture) (Figure 3b). Temperature calibration was undertaken one week after the TIR flights at Tidmarsh Farm (March 35, 2019), with warmer ambient air temperature (5 °C versus -3 °C). Accordingly, temperature values in figure legends should be regarded as approximate. This uncertainty has no effect on the ability to detect groundwater seeps and does not affect the conclusions of the study.
4. Results and Discussion

4.1. Image Quality and Spatial Coverage

Results show the TIR-equipped UAS survey method has sufficient resolution and sensitivity to resolve subtle temperature contrasts presented by groundwater seeps in cold, temperate winter conditions. The UAS method can efficiently map large areas (i.e., 0.4 km² area captured in 36 minutes of flight), and is well suited for assessment of wetlands, both before and after restoration efforts.

We compared TIR, visible and DSM imagery to evaluate the landscape forms and thermal signature of groundwater inflows (Figure 5). Whereas the visible and DSM images show stream and pond morphology (Figure 5a, 5c and 5d), they provide no indication of groundwater input. However, the TIR image makes groundwater input obvious, and substantial inflows of warmer groundwater are visible along the restored channel (i.e., compared to other locations on the wetland platform) (Figure 5b). DSMs extracted from visible imagery (Figure 5c and 5d) provide an efficient method for mapping the restored channel forms (compared to ground-based surveys).

Figure 6 provides close-up views of the TIR imagery, with colors adjusted to provide more contrast at the warmer end of the temperature scale (more clearly shows groundwater input). Note i) warm groundwater discharge is clearly discernible from the relatively cooler surface waters (Figure 6a), ii) seepage zones distributed along the reconstructed stream channel (Figure 6b), and iii) discrete seeps within the stream channel are clearly identifiable (Figure 6c).

Before the restoration, ground-based TIR (Figure 1) showed that “wet areas”, long known by farmers (Figure 2), were due to groundwater seeps, likely due to the thin peat in this area (rather than ponding of meteoric water in topographic depressions). This led to the seeps being utilized during the restoration process and demonstrated the value of TIR to inform the restoration design (Hare et al., 2017); thermally stable pools and streams are important for ecological refugia, which are fundamental for successful ecological restoration (Lake et al., 2007). Based on our results, we expect UAS TIR imagery would be equally useful in the pre-restoration design phase.
One of the objectives of the restored stream channel was to strengthen the connection between groundwater and surface water, encouraging groundwater discharge. To meet this objective, the restored channel was located according to underlying hydrologic drivers of peatland groundwater outflows (Figure 7). Our post-restoration TIR imagery confirms this approach was successful; both diffuse and focused groundwater seepage is visible along the reconstructed channel (Figure 6b and 6c), showing greater groundwater connection than in the relic channel. The process-based design resulted in a lateral thermal profile typical of a groundwater-dominated stream, which demonstrates the success of the stream placement based on the restoration objective.

4.2. General Utility and Limitations of the Method in Wetlands

Here, we have successfully demonstrated the TIR-equipped UAS method, in a continental climate, during cold, winter conditions. The timing of the survey was intentional, to provide maximum temperature contrast. The same method would not be as effective when applied in the spring or autumn, or in temperate to tropical climates; in these cases, the temperature contrast between surface environment and groundwater could be too small to be resolved by our equipment. Similarly, vegetation coverage is at a minimum in the winter and this provided ideal conditions. In continental climates, surface waters may not be visible outside of winter because of foliage. In temperate/tropical climates streams may be partly or completely covered throughout the year.

Groundwater temperature is also a factor. The northeastern USA has a typical continental geothermal gradient (Blackwell et al., 2011), with shallow groundwater temperature approximating the mean annual surface temperature. Less commonly, groundwater may be much warmer due to magmatism and/or geologic faults that allow deeply circulating groundwater to reach the surface (Harvey et al., 2016). Our results show how UAS-based aerial TIR can be applied to mapping groundwater seeps in wetlands. This approach provides a viable alternative to ground-based seep identification methods (i.e. ground-based TIR or direct temperature measurements), particularly at the scale of this survey. Depending on survey size, UAS may provide a less labor-intensive solution, with spatial coverage that is unimpeded by site-access considerations. For instance, the hand-held TIR survey conducted by Hare et al. (2017) took place over three days (2 in the summer and 1 in the winter) for ~2 hours each and was substantially more efficient than the weeks-long fiber optic distributed temperature sensing survey (Hare et al., 2015; Hare et al., 2017). The efficiency of UAS allows for repeat surveying, opening opportunities to conduct temporal thermal evaluations. More importantly, by using photogrammetry to combine images from a single flight, a complete landscape snap-shot-in-time image could be achieved, ensuring the entire area of interest was covered, including areas that would have been difficult to access by foot. Also, many wetland sites do not allow for direct foot access, due to active farms, waterlogged areas, or protected areas, making UAS TIR the only viable approach for a temperature survey.

Here we have demonstrated the UAS TIR method at Tidmarsh Farms, where groundwater flows are clearly large enough (i.e. compared to surface water flows) to be seen. In wetlands like Tidmarsh, the method will allow for more accurate and reproducible surface monitoring. In other wetland areas where groundwater inflows are relatively weak, or in river environments, groundwater inflows may be greatly diluted and the thermal signature quickly lost, even in the winter. In such areas, groundwater seeps may not be identified using TIR-equipped UAS, and the refugia potential would be similarly reduced. This remains to be tested in future studies.
Figure 4. Calibrated TIR orthophoto of the Tidmarsh study area overlaid on Google Earth imagery. Map Datum WGS84. Note: white square detail is shown in Figure 5 (a - c). Map Datum WGS84. Temperature values in figure legend should be regarded as approximate.
Figure 5. Comparison of winter UAS imagery showing: (a) visible light, (b) TIR, (c) and (d) digital surface models. Note: Only TIR shows both stream morphology and temperature. Area corresponds to white square in Figure 4. Map Datum WGS84. Temperature values in figure legend (b) should be regarded as approximate.
Figure 6. TIR imagery showing: (a) confluence of cool surface waters and warmer ground water, (b) diffuse seepage zones along reconstructed stream channel (white boxes), and (c) warm ground water seeping into the stream channel. Map Datum WGS84. Temperature values in figure legends should be regarded as approximate.
Figure 7. The restored channel was geolocated based in part on the conceptual model presented by Hare et al. (2017) that predicted preferential groundwater discharge upward through the peatland platform based on the underlying topography of the sand-peat aquifer interface.

5. Conclusions

A key question of the study was to determine if TIR-equipped UAS imaging would have sufficient resolution and sensitivity be able to resolve subtle temperature contrasts resulting from surface-groundwater connectivity. Our results confirm this, with focused and diffuse seeps clearly visible. The survey timing maximized temperature contrast between relatively warm groundwater and cooler surface waters (more equilibrated with air temperature), while minimizing vegetative cover that could obstruct the TIR sensor’s view from above. Further, we targeted a winter day when there was no snow on the bog platform and little ice on the surface water features. The same method would not be as effective during times of snow and deep freeze, or in summer when relatively cold, dense groundwater tends to plunge in slow flowing warmer surface water.

The primary objective of the study was to determine if the engineered stream channel at Tidmarsh Farms had successfully intercepted groundwater seepage, compared to relic farm channels. The TIR-equipped UAS was able to image the entirety of the restored channel area in a single morning. Results show the reconstructed stream channel is warmer along its entire length, indicating spatially contiguous groundwater connectivity. Therefore, the groundwater discharge ‘processed based’ restoration design was successful in this regard, and likely creates thermal refugia for aquatic habitats. Further, the DSM extracted from visible imagery was useful in efficiently mapping the restored channel forms (compared to ground-based surveys).

Our results show how TIR-equipped UAS can be applied to mapping groundwater seeps in wetlands. This approach provides a viable alternative to ground-based seep identification methods (i.e. ground-based TIR or direct temperature measurements), particularly at the scale of this survey. Depending on survey size, UAS may provide a less labor-intensive solution (<1 hr rather than multiple days), with far greater spatial coverage than ground-based methods, particularly when site access is limited. Temperature calibration and georeferencing of imagery provides the potential for more accurate and reproducible surface monitoring of wetland areas. This has potential applications in wetlands monitoring, wetlands restoration planning, post-restoration evaluation, and mapping thermal refugia. More generally the TIR imagery can be used as a base-map for planning any geochemical, geophysical or ecological sampling campaign; the high-resolution georeferenced TIR imagery allows individual seeps to be identified, located and sampled.
Supplementary Materials: The following are available online: //doi.org/10.5066/P9X8PBWN, georeferenced thermal and visible orthomosaic images (tif format).

Author Contributions: Conceptualization, M.B. and D.H.; methodology, M.H. and M.B.; validation, M.H; formal analysis, M.H., A.Hay.; investigation, M.H., M.B., A.Hay., D.H., A.Hac, A.Hay; resources, M.H.; data curation, M.H. and M.N.; writing—original draft preparation, M.H., D.H., A.Hac, A.Hay, G.D.; writing—review and editing, M.B., A.Hel. and J.L.; visualization, M.H., D.H., and A.Hac; supervision, M.B.; project administration, M.B.; funding acquisition, J.L., M.B. and A.Hel.

Funding: Funding for this methods development was provided by National Science Foundation Division of Earth Sciences award (#1824820), U.S. Department of Energy grant DE-SC0016412, and the U.S. Geological Survey (USGS) Toxic Substances Hydrology Program.

Acknowledgments: We thank the Audubon Society for site access and logistical support. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

Abolt, C., Caldwell, T., Wolaver, B., & Pai, H. (2018). Unmanned aerial vehicle-based monitoring of groundwater inputs to surface waters using an economical thermal infrared camera. Optical Engineering, 57(5), 053113.

Blackwell, D. D., Richards, M. C., Frone, Z. S., Batir, J. F., Williams, M. A., Ruzo, A. A., & Dingwall, R. K. (2011). SMU geothermal laboratory heat flow map of the conterminous United States, 2011. Supported by Google. org. Available at http://www. smu. edu/geothermal. Retrieved August 21, 2015.

Beechie, T. J., SEar, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., Roni, P., & Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. BioScience, 60 (3), 209-222.

Briggs, M. A., & Hare, D. K. (2018). Explicit consideration of preferential groundwater discharges as surface water ecosystem control points. Hydrological Processes. https://doi.org/10.1002/hyp.13178

Briggs, M. A., Dawson, C. B., Holmquist-Johnson, C. L., Williams, K. H., & Lane, J. W. (2018). Efficient hydrogeological characterization of remote stream corridors using drones. Hydrological Processes, (November), 1–4. https://doi.org/10.1002/hyp.13332.

Dugdale, S. J. (2016). A practitioner’s guide to thermal infrared remote sensing of rivers and streams: recent advances, precautions and considerations. Wiley Interdisciplinary Reviews: Water, 3(2), 251-268.

Fitch, K., Kelleher, C., Caldwell, S., & Joyce, I. (2018). Airborne Thermal Infrared Videography of Stream Temperature from a Small Unmanned Aerial System. HPEye. https://doi.org/10.1002/hyp.13218.

Grand-Clement, E., Anderson, K., Smith, D., Luscombe, D., Gatis, N., Ross, M., & Brazier, R. E. (2013). Evaluating ecosystem goods and services after restoration of marginal upland peatlands in South-West England. Journal of Applied Ecology, 50(2), 324-334.

Hare, D. K., Briggs, M. A., Rosenberry, D. O., Boutt, D. F., & Lane, J. W. (2015). A comparison of thermal infrared to fiber-optic distributed temperature sensing for evaluation of groundwater discharge to surface water. Journal of Hydrology, 530, 153-166.

Hare, D. K., Boutt, D. F., Clement, W. P., Hatch, C. E., Davenport, G., & Hackman, A. (2017). Hydrogeological controls on spatial patterns of groundwater discharge in peatlands. Hydrology & Earth System Sciences, 21(12).

Harvey, M. C., Rowland, J. V., & Luketina, K. M. (2016). Drone with thermal infrared camera provides high resolution georeferenced imagery of the Waikite geothermal area, New Zealand. Journal of Volcanology and Geothermal Research, 325(October 2017), 61–69. https://doi.org/10.1016/j.jvolgeores.2016.06.014.
Harvey, M., Briggs, M. A., Dawson, C. B., White, E. A., Haynes, A., Fosberg, D., & Moore, E. (2019). Thermal infrared and photogrammetric data collected by small unoccupied aircraft system for the evaluation of wetland restoration design at Tidmarsh Wildlife Sanctuary, Plymouth, MA. U.S. Geological Survey Public Data Release. https://doi.org/10.5066/P9X8PBWN.

Hester, E. T., & Gooseff, M. N. (2010). Moving beyond the banks: Hyporheic restoration is fundamental to restoring ecological services and functions of streams.

Hunt, R. J., Krabbenhoft, D. P., & Anderson, M. P. (1997). Assessing hydrogeochemical heterogeneity in natural and constructed wetlands. Biogeochemistry, 39(3), 271-293.

Isokangas, E., Davids, C., Kujala, K., Rauhala, A., & Ronkanen, A. (2019). Combining unmanned aerial vehicle-based remote sensing and stable water isotope analysis to monitor treatment peatlands of mining areas. Ecological Engineering, 133(July 2018), 137–147. https://doi.org/10.1016/j.ecoleng.2019.04.024

Kelly, J. L., Dulai, H., Glenn, C. R., & Lucey, P. G. (2018). Integration of aerial infrared thermography and in situ radon-222 to investigate submarine groundwater discharge to Pearl Harbor, USA. Limnology & Oceanography, 1–20. https://doi.org/10.1002/lno.11033

Koch, F.W., Voytek, E.B., Day-Lewis, F.D., Healy, R., Briggs, M.A., Werkema, D., and Lane, J.W., Jr., 2015, 1DTempPro: A program for analysis of vertical one-dimensional (1D) temperature profiles v2.0: U.S. Geological Survey Software Release, 23 July 2015, http://dx.doi.org/10.5066/F76T0JQS.

Lake, P. S., Bond, N., & Reich, P. (2007). Linking ecological theory with stream restoration. Freshwater biology, 52(4), 597-615.

Lowry, C. S., Walker, J. F., Hunt, R. J., & Anderson, M. P. (2007). Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor. Water resources research, 43(10).

Pai, H., Malenda, H. F., Briggs, M. A., Singh, K., González-Pinzón, R., Gooseff, M. N., & Tyler, S. W. (2017). Potential for Small Unmanned Aircraft Systems Applications for Identifying Groundwater-Surface Water Exchange in a Meandering River Reach. Geophysical Research Letters, 44(23). https://doi.org/10.1002/2017GL075836.

Ribeiro-Gomes, K., Hernández-López, D., Ortega, J., Ballesteros, R., Poblete, T., & Moreno, M. (2017). Uncooled thermal camera calibration and optimization of the photogrammetry process for UAV applications in agriculture. Sensors, 17(10), 2173.

Woodget, A. S., Carbonneau, P. E., Visser, F., & Maddock, I. P. (2015). Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. Earth Surface Processes and Landforms, 40(1), 47–64. https://doi.org/10.1002/esp.3613