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COMMENTARY
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Looking to the Skies: Realising the Combined Potential of Drones and Thermal Infrared Imagery to Advance Hydrological Process Understanding in Headwaters

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Key Points:

- Knowledge of headwater catchment dynamics is limited by point observations which are sub-optimal for hydrological process understanding
- Drone-based thermal infrared remote sensing can provide observations of headwater network dynamics across multiple space-time scales
- We call for the increased use of drone-based TIR in hydrology for improved understanding of headwater dynamics under future climate change

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Abstract In river systems, headwater networks contain the vast majority of the stream length. Thus, climate and land-use change in headwaters have disproportionate impacts on downstream ecosystems and societies that rely on them. Despite decades of hydrological research, difficulties in observing hydrological properties across scales means that scientific knowledge of processes driving streamflow in headwaters remains limited. However, the recent emergence of two complementary technologies, drones and thermal infrared (TIR) remote sensing, has potential to collect data at scales and resolutions needed to advance hydrological process understanding in headwaters. In this commentary, we explain how drone-based TIR can offer unique high-resolution observations of surface connectivity and headwater network dynamics across multiple spatio-temporal scales. We explore the current state-of-the-art of drones and TIR imaging in the hydrological sciences, highlighting the potential benefits but also steps that will need to be taken to release these technologies' full potential. We finish by contending that drone-based TIR is particularly well-placed to bridge the current gap between field (point) observations and model simulations to provide the improved hydrological understanding needed for a changing world.

1. The Challenge

Headwater streams compose ~90% of stream length (Downing et al., 2012) and maintain hydrological, biogeochemical and ecosystem integrity at regional scales (Freeman et al., 2007). Thus, climate and landscape changes in headwater catchments have disproportionate downstream impacts on water quantity and quality and, in turn, ecosystem health and society (Freeman et al., 2007). However, after decades of experimental and modeling research, hydrological understanding of headwater catchment dynamics (i.e., where water comes from, how long water takes to travel through headwater catchments, and how these combine to generate streamflow), remains incomplete (Blöschl et al., 2019; Hrachowitz et al., 2016; Ward & Packman, 2019). This knowledge gap stems largely from our inability to observe many hydrological properties at scales amenable to understanding underlying processes, and is a major barrier to developing more generalized understanding in the hydrological sciences (Beven et al., 2020). Hence, improving our ability to make meaningful hydrological observations is crucial for advancing hydrological understanding in an uncertain future under global change.

How streamflow is generated remains a key research question in hydrology. Answers are often envisaged in terms of the variable source area (VSA) concept, a hydrological theory that codifies how and when certain parts of (headwater) catchments contribute to streamflow by connecting to the stream network. These hydrologically-connected upstream areas are crucial in determining hydrological response (Gannon et al., 2014; Kiewiet et al., 2020; Zehe et al., 2007) and water quality (Ocampo et al., 2006). However, observing how and when different areas connect and contribute hydrologically is challenging. Previously, the community has relied largely on point-based monitoring (groundwater dynamics, e.g., Bonanno et al., 2021; Jencso et al., 2009; Pavlin et al., 2021; soil moisture, e.g., Ali & Roy, 2010; tracer applications, e.g., Kiewiet et al., 2020; Klaus et al., 2015; McGlynn & McDonnell, 2003), as past remote sensing approaches (e.g., Mengistu & Spence, 2016; Wagner et al., 2007) have often been too coarse to observe fine-scale hydrological processes in headwaters. Even when considering densely gridded point datasets (e.g., Western et al., 1998), inferring connectivity purely from point-based measures can be misleading (Klaus & Jackson, 2018). Progress in observing hydrological connectivity has been made by mapping stream network extension and contraction dynamics (Godsey & Kirchner, 2014) and observing patterns of surface saturation in the stream corridor (Glaser et al., 2018). However, these observation approaches are cumbersome

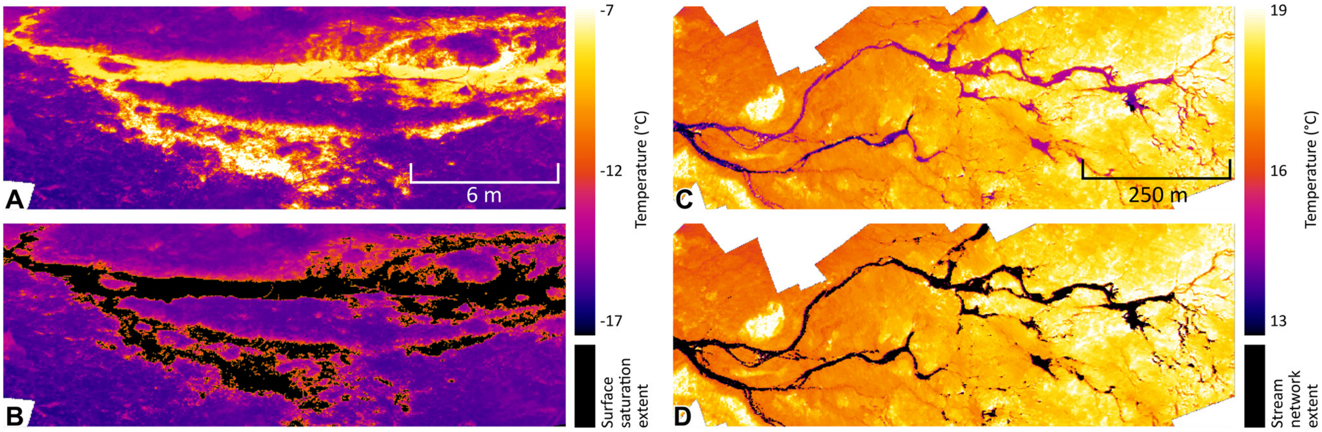

Figure 1. (a). Winter-time ground-based TIR monitoring of surface hydrology in the Weierbach catchment, a temperate forested headwater catchment in Luxembourg. (b) Surface saturation and stream network extent in the Weierbach clearly segmented from presence of pixels that are warmer than surroundings (courtesy of B. Glaser). (c) Summertime airborne TIR mosaic of headwater stream network in Nunavik, Canada (subarctic tundra landcover). (d) Stream network extension/connectedness clearly segmented via pixels that are cooler than surrounding areas. Drone-based TIR has potential to combine the multi-temporal monitoring of ground-based methods (a) with the spatial coverage of (c) airborne approaches.

and have been limited by their spatial extent, acquisition time, and/or revisit intervals. We therefore urgently need improved methods for monitoring hydrological processes in headwaters at fine spatio-temporal resolution. In this context, this commentary explores the potential of leveraging drone-based thermal infrared (TIR) technologies to advance hydrological understanding of sensitive headwater catchments.

2. Current State of the Art

At larger scales, remote sensing approaches have long been a valuable asset in hydrology (e.g., Junqueira et al., 2021; Lettenmaier et al., 2015; Matgen et al., 2006; Mengistu & Spence, 2016; Schmugge et al., 2002), but these (predominantly satellite-based) techniques have been largely incapable of mapping fine-scale headwater dynamics. More recently, a renewed interest in remote sensing, based on low-altitude, high-resolution methods, has emerged for the derivation of key hydrological states in upstream catchments. In particular, high resolution thermal infrared (TIR) imaging has been increasingly used to quantify hydrological states through the use of temperature as a "tracer" or "signature" for (near-) surface flow and saturation (Glaser et al., 2018). Hydrologists have used ground-based TIR for characterizing groundwater-surface water (GW-SW) interactions in 2D (e.g., Briggs et al., 2013; Deitchman & Loheide, 2009; Drake et al., 2010; Hare et al., 2015; Lu et al., 2020; Pandey et al., 2013; Schuetz & Weiler, 2011), describing hydraulic processes such as surface flow velocity or mixing across the stream channel (e.g., Antonelli et al., 2017; Puleo et al., 2012) and understanding surface water energy budgets or thermal heterogeneity (e.g., Baker et al., 2019; Cardenas et al., 2014; Marruedo Arricibita et al., 2018; Tonolla et al., 2010). Ground-based TIR has also been increasingly deployed for mapping surface saturation (e.g., Antonelli et al., 2020; Glaser et al., 2018; Glaser et al., 2020; Glaser et al., 2016; Pfister et al., 2010; Figures 1a and 1b). At the heart of these methodologies is the capacity of ground-based thermography to facilitate high-frequency measurements, a key consideration when understanding hydrological processes and dynamics through time. Although these techniques are useful at small scales, the narrow spatial extent of these ground-based TIR techniques has limited their applicability for understanding hydrological processes over larger domains, and there is a need for techniques capable of bridging the gap between coarse satellite- and fine resolution (but static) ground-based remote sensing.

In this vein, airborne TIR has been adopted for mapping streams at larger scales, with conventional (i.e., piloted aircraft) airborne TIR remote sensing shown effective for characterizing stream temperature and discrete surface or groundwater inputs to rivers at whole-river longitudinal extents (e.g., Dole-Olivier et al., 2019; Handcock et al., 2006; Torgersen et al., 2001; Vatland et al., 2015) or laterally across wide channels or braid-plains (e.g., Mejia et al., 2020; Tonolla et al., 2012; Wawrzyniak et al., 2013). Indeed, airborne TIR is a sufficiently mature technique that it is used to map water temperature across entire watersheds or even regions (e.g., Dugdale et al., 2015; Fullerton et al., 2015; Fullerton et al., 2018). However, the cost associated with such airborne TIR acquisition means that it has not been taken-up for the characterization of hydrological processes outside of the main river stem, nor for detecting temporal change at high frequency - two aspects that are vital for understanding hydrological processes in headwater catchments (Glaser et al., 2020).

Recent advances in drone-based remote sensing offer a unique opportunity to bridge these space-time disparities, increasing the limited coverage associated with ground-based remote sensing while permitting data capture at relatively high frequency and in areas outside of the immediate stream corridor. While recent applications of drones have demonstrated potential for mapping surface saturation and connectivity via segmentation of standard (RGB) imagery (e.g., DeBell et al., 2015; Dominique & David., 2013; Reaney et al., 2019; Spence & Mengistu, 2016), newer drone-based thermal infrared solutions eliminate difficulties associated with the complexity of visible image classification (e.g., Carbonneau et al., 2020), offering both increased spatial coverage over more common ground-based TIR and facilitating low-cost multitemporal data capture needed for hydrological monitoring. Indeed, drone-based TIR has already started to see use in the hydrological sciences, with studies focusing on its use to identify GW-SW exchanges in a similar vein to earlier ground- and airborne-applications (e.g., Briggs et al., 2019; Harvey et al., 2019). However, the majority of recent applications in hydrology have, like conventional airborne TIR, focused on monitoring in-stream ecologically-relevant phenomena (such as the location of thermal refuges; Casas-Mulet et al., 2020) or hydraulic properties (e.g., geometry of thermal plumes; Caldwell et al., 2019; KarisAllen & Kurylyk, 2021). Conversely, drone-based TIR has as of yet not been deployed for monitoring properties such as the extension and contraction of the stream network or patterns of surface saturation (and related hydrological connectivity) outside of the channel and more broadly across headwater catchments, despite the fact that the approach appears to offer an ideal compromise between spatial coverage and repeat (high frequency) monitoring that is lacking in conventional (costly) airborne approaches. Drone-based TIR thus holds a high degree of promise for the quantification of headwater network/surface saturation dynamics at space-time scales amenable to understanding streamflow response at the catchment outlet.

This lack of uptake among the hydrology community may relate to well-publicized issues relating to sensor drift of miniaturized drone mounted TIR cameras (e.g., Abolt et al., 2018; Casas-Mulet et al., 2020; Dugdale et al., 2019) that can render the derivation of absolute temperature values difficult. However, we argue that for the quantification of key hydrological states (e.g., surface saturation, stream network extension, connectivity [from surface saturation]), the absolute accuracy of drone-based TIR is largely immaterial. When using temperature as a tracer, it is only necessary that wetted pixels are able to be clearly differentiated from their dry neighbors. Given that recent research in the agricultural and archeological sciences (e.g., Allred et al., 2018; Casana et al., 2017; Khanal et al., 2017) has demonstrated the ability of drone-based TIR to detect soil moisture patterns and that preliminary TIR images of stream network extension (Figures 1c and 1d) highlight its ability to clearly delineate the extension/length of the wetted parts of the headwater network, drone-based TIR is well placed to generate the space-time data necessary to unlock current barriers to understanding headwater network dynamics and hydrological processes.

3. Leveraging Drone-Based Technologies

Despite clear potential, drone-based TIR raises challenges that will need to be addressed by the hydrology and remote sensing communities. Many of these relate to legal and logistical considerations that are well-covered in previous reviews (e.g., DeBell et al., 2015; Vélez-Nicolás et al., 2021). However, some stumbling blocks are more specific to headwater hydrology data acquisition. For example, mapping headwater network extension and/or surface saturation dynamics at event-scales will require the acquisition of data during rainy conditions. While weatherproof drones do currently exist, we are only aware of a handful of models that are also capable of supporting TIR cameras (e.g., DJI Matrice 200/300 series), and there is limited information relating to the performance of TIR sensors during rainfall events and whether the resulting imagery will be biased by the presence of raindrops. We therefore urge further investigation to better understand the performance of drone-based remote sensing in varied meteorological conditions.

Another key consideration is impact of land-cover on the ability to extract key hydrological metrics from drone imagery. While TIR has been demonstrated readily capable of identifying stream network extension in bare/unforested regions (such as those common in parts of Europe or high arctic locations), forested regions present a problem whereby dense tree canopies limit the ability of TIR sensors to resolve ground-level hydrological

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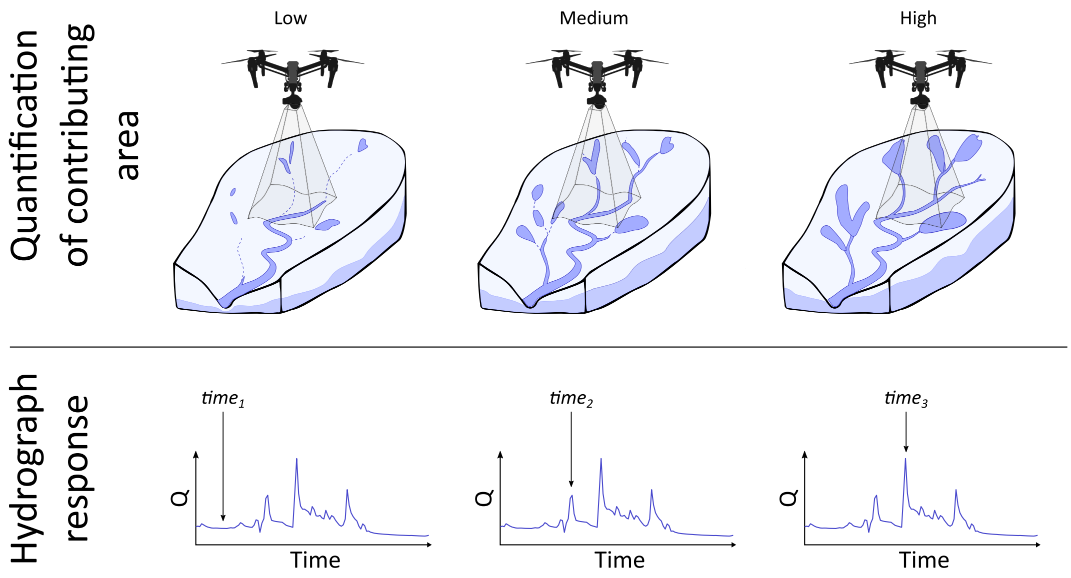

Figure 2. Schematic of drone-based TIR methodology to quantify links between hydrological connectivity and downstream runoff response. Drone-based TIR imagery of headwater catchment uses temperature as a tracer for headwater network/surface saturation extent, allowing for quantification of area contributing to streamflow.

properties, particularly in coniferous woodland where winter leaf loss does not occur. While understory drone acquisition flights are technically possible (e.g., Hyyppä et al., 2020; Wang et al., 2021), this introduces a substantial risk to both equipment and researchers and is unlikely to provide a universal solution. Research is therefore needed to understand the accuracy with which headwater network extension/surface saturation dynamics can be quantified as a function of varying forest density, as well as the potential for fusion of ground- and drone-based data to provide seamless coverage in areas of patchy forest.

Guidance is also needed concerning optimal spatio-temporal scales of data acquisition. Given the relatively low resolution of TIR sensors, it is possible that TIR flights may need to be conducted at lower altitude than normal to capture fine enough detail for deriving surface saturation or stream network extension while avoiding the phenomena of "mixed pixels" (e.g., Martí-Cardona et al., 2019; Wawrzyniak et al., 2012). With current technology, such campaigns would clearly generate high resolution TIR data (<10 cm resolution), but the flight time needed to collect such data, and the potential computation demands for georeferencing, mosaicking and storage of such information, will place limits on what might be realistically achievable with drone-based TIR. Thus, coverage of drone-based TIR surveys is likely to be limited to sub-catchments on the order of $\sim 10^0$ km^2. While such coverage is suitable for improving hydrological understanding in headwaters (through observing temperature patterns, deriving the extent of surface saturation and connectivity and thus linking this to streamflow response), it may nevertheless limit the ability to resolve scale-dependent processes that require the deployment of other coarser/higher coverage sensing methods. Similarly, further information is needed on appropriate temporal frequencies with which to conduct repeat imaging flights and thus capture the dynamic response of the headwater network as it connects in real-time to the catchment outlet to produce runoff (Figure 2). Data from ground-based TIR studies (e.g., Glaser et al., 2016; Glaser et al., 2018; Glaser et al., 2020) can provide useful a useful starting point to develop standardized acquisition methodologies in this regard, but further focus is required in terms of the practical/logistical issues surrounding rapid repeated drone surveys (i.e., battery requirements, drone reliability).

Although this commentary focuses on drones and TIR for understanding headwater dynamics, we nonetheless recognize the potential that standard (RGB) visible drone imagery holds for improving process understanding of headwater hydrology. For example, the ability to resolve catchment microtopography from highly detailed digital surface models (DSMs, derived from structure from motion photogrammetry) has the potential to revolutionize the extraction of hydrological networks at a resolution several orders of magnitude higher definition than existing LiDAR datasets acquired by national mapping agencies (e.g., Scottish Government, 2012), as well as the derivation of water level/depth with centimetric precision (e.g., Dietrich, 2017; Kohv et al., 2017). Such advances hold promise for enhanced modeling of surface flows, although it is important to consider that large increases in resolution would also necessitate bulk improvements in computing power to avoid yielding prohibitively long model runtime. RGB imagery could help in the identification of correlates (e.g., depressions, water levels, land-use types) of surface saturation or stream network extension, extracted from TIR data. We therefore emphasize the complementary nature of drone-based TIR and RGB data, and call for the development of approaches that combine these approaches for improved understanding of headwater hydrology.

Aside from these more practical and conceptual issues, the acceptance of drone-based TIR methods within the hydrology community is reliant on them being demonstrated robust. Thorough and repeatable validation of drone-based measures of surface patterns (i.e., saturation) and derived surface connectivity must be considered a first step. Physical inspection of locations that show clear surface saturation (via the "squishy boot" method; Rinderer et al., 2012) as well as discrete monitoring via conventional techniques (i.e., point measurements) will need to be carried out in tandem with drone surveys to ensure that observations of connectivity are accurate. While this step has already been demonstrated for ground-based TIR, the increased spatial scale of drone-based surveys means that validation will be more field-intensive. Where ground validation cannot be easily achieved by means of conventional fieldwork owing to the difficulty of collecting data at spatio-temporal scales amenable to the drone data, the installation of high-density low-cost sensor networks (e.g., Mao et al., 2019), capable of relaying information in real time using LoRaWAN or 5G cellular connections, holds promise for the generation of rich validation datasets not previously possible using other means. Where disparities between conventional and drone-based observation methods are evident, advances in machine learning (e.g., Carbonneau et al., 2020) may provide solutions for more clearly segmenting wetted pixels from the TIR data (when combined with RGB imagery), further increasing the utility of extracted data. Indeed, the simultaneous collection of visible imagery (outlined above) and even drone- or ground-based LiDAR (e.g., Orlandini et al., 2012) data capable of revealing other catchment characteristics related to runoff generation (e.g., topography, land-use) holds potential for improved segmentation of TIR imagery, further improving the accuracy of extracted hydrological metrics.

4. Releasing the Opportunities for Catchment Hydrology

In light of the novel hydrological observation opportunities provided drone-based TIR, we call for its increasing involvement in hydrological process research. Its unprecedented potential for directly quantifying spatio-temporal dynamics in key hydrological states (e.g., surface saturation, headwater network expansion/contraction) in response to changing meteorology and antecedent conditions, and linking this to how catchments produce runoff, represents a powerful tool for supplementing classical point-based hydrometric measures. Data acquired through drone-based TIR approaches opens new opportunities for better observing spatial patterns at high temporal frequency, deriving hydrological connectivity across the land surface and monitoring stream network extension and contraction at scales needed for understanding and modeling of headwater response to future climate change (and understanding what parts of the landscape contribute to streamflow at specific times). By pairing this data with flow measurements collected at the catchment outlet via traditional gauging (Figure 2) or even via time-lapse thermal imagery of the outlet itself (e.g., outlet plume geometry; KarisAllen & Kurylyk, 2021), drone-based TIR is uniquely well-placed to provide a step-change in the variable source area concept, allowing direct observations on how runoff producing areas expand and connect in headwater catchments and thus govern water quality and quantity downstream (Figure 2). In this light, we argue that drone-based TIR has a key role to play in providing the key data streams necessary for combatting the "general decline of field hydrology relative to modeling" (Beven et al., 2020, p. 871) by providing a remote sensing "bridge" between field (point) observations and model simulations. Moreover, such data sets will be of high value in spatially distributed modeling approaches for predicting the "right response for the right reason" to advance hydrological science.

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