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Efficient hydrogeological characterization of remote stream corridors using drones

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1 OVERVIEW

This project demonstrates the successful use of small unoccupied aircraft system (sUASs) for hydrogeological characterization of a remote stream reach in a rugged mountain terrain. Thermal infrared, visual imagery, and derived digital surface models are used to inform conceptual models of groundwater/surface-water exchange and efficiently geolocate zones of preferential groundwater discharge that can be quantified using various ground-based methodology.

2 DESCRIPTION

Reactive processes and aquatic habitat throughout river corridors are controlled in part by the hydrodynamic template of groundwater/surface-water exchange (Harvey & Gooseff, 2015). Hydraulic pressure differentials induced by stream and valley geomorphology create a spectrum of nested hyporheic and groundwater flowpaths (Buffington & Tonina, 2009), whereas variations in sediment and rock permeability preferentially focus flowpaths and exchange zones (Winter, Harvey, Franke, & Alley, 1998). Such exchange zones, particularly those of groundwater discharge, can now be located with a variety of hand-held remote sensing tools (Briggs & Hare, 2018). Specifically, thermal infrared (TIR) sensing at times of surface-water and groundwater temperature contrast can yield unprecedented detail regarding nonsubmerged preferential discharge on the scale of centimetres to watersheds (Dugdale, 2016; Fullerton et al., 2018; Lee et al., 2016). Sufficient thermal contrast for the identification of discharge typically exists away from the equator in summer and winter, in late afternoon or early morning, respectively. Shallow preferential flow between surface-water features can also be inferred from discrete linear zones of greener, taller vegetation in water-limited landscapes as indicated by multispectral imagery (Pai et al., 2017). However, TIR and multispectral data collected by hand are practically constrained in spatial coverage and are typically collected at relatively low angle. This low imaging angle can often complicate analysis due to confounding process such as water surface reflection of infrared radiation from other sources (Dugdale, 2016). TIR and multispectral data are collected from various satellite platforms, but the typical 10-m+ spatial resolution is not suitable to define stream reach-scale process heterogeneity.

Numerical groundwater flow models are increasingly used to predict stream reach-scale (hundreds of metres) surface-water and groundwater exchange dynamics. Simulated exchange patterns are highly sensitive to relatively modest changes in bed and bank elevations, such as those found around large woody debris and small dams (Lautz, Siegel, & Bauer, 2006). High spatial resolution topographic light detection and ranging (lidar) data collected with manned aircraft are commonly used for topographic reconstructions but are not available for many remote watersheds; even when available, previously collected lidar may not reflect more recent morphologic changes driven by high flow events and resultant channel reworking. Small unoccupied aircraft systems (sUASs) are now effectively bridging the ground-based and manned aircraft to satellite remote sensing spatial scales. Typically flying at heights less than 120 m above ground surface in the United States, various sensors including visible light, TIR, and multispectral/hyperspectral can be flown simultaneously or sequentially to quickly create complementary geospatial datasets. Pai et al. (2017) recently demonstrated the potential for using structure from motion (SfM) techniques applied to sUAS visual imagery to derive subtle hydraulic gradients (<0.003) across floodplain meander bends. We build on that recent application in a remote stream corridor by adding georeferenced TIR video and radiometric still data regarding thermal heterogeneity caused by small beaver diversions and preferential groundwater discharge zones.

As part of their Watershed Function Scientific Focus Area (SFA), Berkeley Lab and its collaborating institutions (e.g., U.S. Geological Survey) have established a “Community Watershed” in the headwaters of the East River near Crested Butte, Colorado (USA), designed to quantify processes impacting the ability of mountainous systems to retain and release water, nutrients, carbon, and metals. The ongoing research spans a range of scales from hillslope to catena to catchment to basin, with surface water and groundwater linking multiple geomorphic compartments. A major goal of this SFA research is to generate transferrable understanding of mountain hillslope to river dissolved nutrient, carbon, and metals transport, integrating extensive and novel field observations with fully coupled numerical models.

The site of the present study illustrated in the video is the mountain headwater Oh-Be-Joyful Creek located approximately 6 km north-west of the town of Crested Butte and a key tributary of the Slate River. The creek is generally incised into bedrock (predominantly Mancos Shale), and many steeper sections have little to no bed sediment. Banks range from bedrock walls to avalanche and rockslide deposits, and therefore, ground-based access is often difficult and dangerous. At an elevation of approximately 2,900 m a.s.l., the regional Peeler fault intersects Oh-Be-Joyful Creek from the south (Kimball, Runkel, Wanty, & Verplanck, 2010). Along the fault, rocks are brecciated hornfels cut by quartz veinlets (Ludington & Ellis, 1982), and the surface is covered in places by large boulders and stands of dense shrub vegetation. However, where the fault intersects Oh-Be-Joyful Creek, the forest canopy is relatively open over a few hundred metres of the stream corridor allowing sUAS-based data collection. Historic silver mining activities in Peeler Basin (Ludington & Ellis, 1982), and mining of sphalerite, pyrite, argentiferous galena, chalcopyrite, bornite, and molybdenum in the upper Redwell Basin to the east (Kimball et al., 2010), may continue to negatively impact groundwater that discharges in the fault zone. It is therefore of strong interest to SFA research to pinpoint any groundwater discharges that may be associated with the Peeler fault zone in the Oh-Be-Joyful corridor and sample for natural and produced metals. This research will enhance mechanistic insight into reactive processes at groundwater discharge interfaces in the context of surface-water quality.

We deployed a multirotor sUAS (3D Robotics Solo, 3D Robotics, Berkeley, CA) from the northern bank of Oh-Be-Joyful Creek, adjacent to the Peeler fault zone on August 17, 2017. The launch site is approximately 2.4 km from the lower parking area using a rough path that climbs approximately 130 m in elevation. All equipment used for this sUAS survey and the supporting ground-based data collection were easily backpacked in with one trip by two people. The survey took less than 45 min of total flight time and resulted in spatially referenced orthoimagery of several data types along the Peeler fault intersection zone of Oh-Be-Joyful Creek.

Visual imagery was collected with a GoPro HERO4 Black Camera (GoPro), and image stills from multiple flight lines were compiled automatically into a larger “stitched” image using Agisoft PhotoScan software. SfM techniques were then applied to this high-resolution visual imagery with PhotoScan to derive a time-specific digital elevation model (DEM). When precise spatial ground control points are deployed throughout the flight corridor (not done here), DEM precision can approach several centimetres depending on the height of the flight, camera type, and ground-based position control. The DEM layer can be directly incorporated into the structure of various numerical groundwater and channel flow models, although unlike some late-return lidar data, the SfM DEM generated from visual imagery incorporates the visible surface of vegetation and built structures into the surface model, only showing actual ground surface elevation where bare ground is visible from the aircraft. Pai et al. (2017) turned this potential limitation to an advantage, where preferential meander bend hyporheic flowpaths were indicated in part by relatively tall riparian shrub growth. Large woody debris in the channel is also incorporated into SfM-based DEMs. The focus of the current study is the identification of preferential groundwater discharge points, so the surface DEM was primarily used to qualitatively compare discharges indicated with thermal imagery to the fault zone surface morphology. For hyporheic exchange-based river corridor research where relatively subtle changes in water surface elevation can drive biogeochemically reactive downwelling of channel water, time-specific surface DEMs are likely to provide strong quantitative value. Woodget, Carbonneau, Visser, and Maddock (2015) also demonstrated the potential for UAS-based imagery in mapping stream bathymetry in shallow, clear water.

TIR data were collected using a gimbal-mounted FLIR VUE Pro R 13 mm camera (FLIR Systems, Wilsonville, OR) that can store colour video relative to a colourbar scale or radiometric still images of apparent temperature that can be manipulated in postprocessing (Dawson, Holmquist-Johnson, & Briggs, 2018). Radiometric data allow for colourbar ranges to be adjusted for consistency during surveys collected in “autoscale” colourbar mode (observed apparent minimum to maximum temperature sets colourbar range) and for certain temperature ranges to be better highlighted that may indicate processes such as groundwater discharge. Additionally, radiometric image data have greater potential for automated postprocessing and analysis methods. TIR stills can also be compiled to create an apparent time-lapse video along the river corridor, as shown recently by Fitch, Kelleher, Caldwell, and Joyce (2018). In actual video mode, the data stream of which is visible on the sUAS hand controller during flights, real-time imagery can be used to efficiently geolocate possible groundwater discharge zones when they are either the coldest or warmest features along the river corridor by observing changes in the automated colourbar range. During the afternoon of data collection in mid-August 2017, mixed stream temperatures approached 15°C, whereas discharge of groundwaters was expected to be less than approximately 8°C. With the video colourbar set to autoscale, we were able to observe potential seepage zones in real time during the flights (e.g., when the lower limit of the colourbar dropped to 8°C or less). The utility of thermal autoscale mode in identifying video frames that contain groundwater discharge points is however limited to situations when discharge temperature is a landscape surface temperature range end member. Video mode was also useful while the sUAS was hovering under manual control, a feature not available for fixed-wing sUAS, where dynamic mixing processes between groundwater discharge and stream water can be recorded over time. For this study, we used the TIR data primarily for the geolocation of preferential groundwater discharges and in-stream mixing zones. In another type of surface-water system, Harvey, Rowland, and Luketina (2016) demonstrated the potential of sUAS-based thermal data for the quantification of hydrothermal heat fluxes and it is likely that other creative applications of this data type will be developed for river corridor research.

We have compiled the various data from this study to demonstrate the realized utility of sUAS for remote river corridor hydrogeological characterization. The video begins with a continental-scale viewpoint using publicly available Google Earth imagery (Google). After zooming into the existing Google Earth imagery at the Peeler fault intersection zone, we show several still images of Oh-Be-Joyful Creek to demonstrate the rugged terrain and complicated depositional environment (e.g., abundant large woody debris and near-stream hillslope colluvium). Individual visible image stills collected by sUAS can be compiled into a time-lapse presentation of data collection along the stream corridor, as shown here, and in manual flight mode, flight path adjustments can be made in real time while viewing the imagery on the controller. Next, real-time TIR video collected while the sUAS was under manual control shows the take-off procedure from the north bank and mixing processes of cold groundwater and surface water along the south bank in the fault zone. Radiometric image stills are then compiled into a time-lapse viewpoint of TIR data along the stream corridor (greyscale).

The video then shows the automated flight pattern that was developed in the field over existing satellite-based imagery, followed by visible, DEM, and TIR orthoimages. Zooming into the TIR orthoimage reveals several focused points of preferential groundwater discharge and a mixing zone of surface water and groundwater along the main stream channel adjacent to the intersection with the Peeler fault. A direct comparison to the existing satellite-based imagery illustrates the enhanced surface detail that can be captured during sUAS surveys. Finally, the TIR orthoimage is again shown, followed by a version with a narrower colour scale, effectively highlighting hydrogeological processes of interest, such as preferential groundwater discharge initiation points, in-channel mixing, and upstream warming around small beaver dams.

UAS-based stream corridor characterization is likely to be done on the front-end of research and site characterization projects to guide additional or paired ground-based data collection, as shown recently with spatially extensive surface-water radon measurements by Kelly, Dulai, Glenn, and Lucey (2018). Although high-resolution elevation maps and thermal imagery can efficiently indicate zones of exposed preferential groundwater discharge, it is not typically possible to quantify exchange rates using UAS data alone. An exception to that would be if focused groundwater discharge were strong enough to measurably alter mixed stream temperature, to which thermal mixing models could be applied (e.g., Briggs, Lautz, & Mckenzie, 2012). Additionally, vertical hyporheic exchange, particularly downwelling, is not likely to be a tractable target for surface thermal mapping unless these bidirectional exchange processes measurably impact water surface temperatures. For this study, the abundant preferential groundwater discharge zones observed coincident with the Peeler fault motivated a direct dye injection to the stream to determine gross groundwater discharge based on channel dilution with distance. The dye experiment was conducted on the evening of August 1, 2018, and indicated that a substantial amount of groundwater enters the channel over approximately 75 m where the fault intersects the stream. Our video presentation ends with imagery of the fluorescein dye drip and mixed dye concentrations along the river corridor (Briggs, 2018). The combination of UAS-based imagery and more traditional physical and chemical measurements allows a comprehensive and quantitative understanding of groundwater discharge exchange process for this remote stream system.

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