Unmanned Aerial Systems in Hydrogeology

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Contributor: Mercedes Vélez-Nicolás

In less than two decades, UASs (unmanned aerial systems) have revolutionized the field of hydrology, bridging the gap between traditional satellite observations and ground-based measurements and allowing the limitations of manned aircraft to be overcome. With unparalleled spatial and temporal resolutions and product-tailoring possibilities, UAS are contributing to the acquisition of large volumes of data on water bodies, submerged parameters and their interactions in different hydrological contexts and in inaccessible or hazardous locations.

Keywords: drone applications ; groundwater ; Remote sensing

1. Background

Sustainable water management has become a major concern over the past decades; as water demand increases with socioeconomic development and population growth, the availability of freshwater resources shrinks due to climate change, aquatic ecosystem degradation and anthropogenic impacts. According to UNESCO [1], water use has been increasing 1% annually worldwide since the 1980s and the global demand for water is expected to keep a similar trend until 2050. This would account for an increase of 20% to 30% above the current level of water use. Under these circumstances, ensuring water in adequate quantity and quality to meet food security, environmental targets, public health requirements and the production of energy, services and other goods remains one of the greatest challenges for water managers in coming years. This is especially critical in regions such as sub-Saharan Africa, central and southwest Asia, which are affected by persistent multi-year droughts, or the Mediterranean basin, where water resources are unevenly distributed and present severe deficiencies in its southern and eastern parts. On the other side of the coin, extreme precipitation events and alterations in flood frequency and duration are affecting an increasing number of countries globally, causing loss of lives, health-related issues and multiple social and economic damages. These extreme hydrological phenomena are likely to be exacerbated as a result of climate change, with increases in their frequency according to the Fifth Assessment Report of the IPCC [2]. Likewise, water quality issues are becoming a major concern. Numerous aquatic systems have undergone severe pollution processes linked to agricultural, domestic and industrial activities and waste disposal, situation that compromises the supply of clean potable water and have deleterious effects on the ecosystem functioning and biota.

This scenario demands effective management and intervention in catchments, which necessarily involves gaining further knowledge of hydrological systems and filling current information gaps. In this regard, unmanned aerial systems (UAS) also known as unmanned aerial vehicles (UAVs), remotely piloted aircraft systems (RPAS) or drones, have recently emerged as new allies in environmental monitoring and management. UAS have not only made bird's eye observation a reality, but also offer a vast range of applications that is continually growing as technology advances. Although initially devised to support military operations, the civilian and scientific applications of UAS have attracted increasing attention in recent years, experiencing an exponential growth in their commercial, governmental and amateur use. The advances in fabrication, remote control capabilities and power systems along with the improvements in sensing technologies installed onboard, have led to the development of a wide range of UAS that can be used to obtain valuable information in different contexts. Numerous advantages of UASs over other systems can be cited; they are portable and enable the retrieval of data with very-high spatial resolutions and unprecedent temporal coverage. They also enable engagement with areas that would otherwise be inaccessible or cost-prohibitive, especially if compared with methods such as airborne campaigns. Moreover, these platforms are easy to deploy, can be flown in small enclosed areas [3] and their imagery might constitute systematic and permanent data that can be used by other individuals and organizations [4]. Regarding the latter aspect, it should be noted that there is still a long way to go in terms of standardization of the methods and available information. To date, UASs have been implemented in a wide range of fields, such as wildlife research and monitoring [5][6] forestry [7][8], precision agriculture [9], architecture, engineering and construction [10][11], disaster management [12] and social research just to name a few.

The need for monitoring the elements of the hydrological cycle is a widely recognized issue. Although in the last decades the field of hydrology has witnessed tremendous advances that have resulted in an increasing number of papers on the subject, as McCabe et al. [13] pointed out, there are still significant gaps in our hydrological knowledge and analysis capabilities such as the estimation of water and mass transport processes across aquatic–terrestrial interfaces, groundwater depth and storage, deep soil moisture, evaporation or snow water equivalent, among others. In this regard, the emergence of UAS is leading to improvements in the understanding of hydrological processes and the management of water resources [14].

2. UAS Applications in Hydrogeology

The number of papers documenting the application of UAS to groundwater (GW) and aquifer research is rather scarce, especially if compared with the extensive literature dealing with their use in riverine and oceanic environments. The reasons are the inherent limitations of remote sensing and the very early stage in which the technological developments in this field are currently. The major constraint in GW detection and mapping is related to the insufficient penetration capacity that remote sensing offers, only enabling the acquisition of data at the ground surface or within shallow subsurface layers a few meters deep. Apart from geophysical techniques, ground-penetrating radar (GPR) is the only technology that can survey depths of several meters. However, at present, owing to the mass, size and very high costs of these sensors, radars onboard UAS are still uncommon, and most experiences are restricted to applications such as landmine detection. Currently, some technological advances such as the Frequency Domain Electromagnetic (FDEM) method allow to perform geophysical surveys from UASs. These are aimed at the detection of underground properties such as magnetism and resistivity, which can be subsequently related with the presence of groundwater and its characteristics (e.g., salinity). Nevertheless, this field is still to be developed in scientific terms.

On the other hand, the thermal inertia of groundwater emergence in coastal areas (SGD) and fluvial systems has been recently exploited to generate temperature maps and monitor warm plumes by means of TIR-equipped UAS yielding promising results. Current available research on UASs applications in hydrogeology includes studies on surface-groundwater (SW–GW) exchange flow, submarine groundwater discharge (SGD), piezometric level delimitation and subsidence processes associated to groundwater withdrawals.

2.1. Surface Water–Groundwater (SW–GW) Interactions

Surface water–groundwater (SW–GW) interactions are critical to calculate water balances and sustainable levels of water extraction. These interactions have been traditionally studied through an array of methods (e.g., differential gauging, seepage meters, tracer injection experiments, monitoring of piezometric heads or satellite remote sensing) whose selection depend on the temporal and spatial scale, limitations and uncertainties inherent to each technique. Recently, UAS have been implemented in SW–GW research since they are the only tools that enable indirect observations of these processes with a sufficiently high spatial resolution.

As several experiences have demonstrated, UAS-derived TIR imagery can provide useful information on the size and extent of groundwater plumes emerging from springs and near streambanks, especially when the temperature contrast between SW and GW is marked. Abolt et al. [15] mapped thermal refugia associated with groundwater discharge in Devil´s river (Texas) using a small UAS equipped with an inexpensive uncooled microbolometer and proposed a method for stabilizing the resulting image mosaic and compensating the pixel bias. This low-cost platform produced more consistent results than those obtained from a more expensive TIR camera system and allowed to generate high quality maps of surface temperature in riparian ecosystems.

TIR imagery has also been supported by optical products; Harvey et al. [16] evaluated the suitability of UAS equipped with lightweight TIR sensors to identify groundwater discharges and validate thermal refugia goals in a hydrological restored peatland. TIR, visible, and DSM products were compared to evaluate the landscape forms and thermal signature of groundwater inflows. The authors detected substantial inflows of warm groundwater that were visible along the restored channel, along with seepage areas, discrete seeps and thermally stable pools of ecological importance (Figure 9). This work emphasizes the usefulness of UAS-based TIR for mapping groundwater seeps in wetlands with a spatial coverage that is unimpeded by site-access considerations. However, the approach presents several limitations: Firstly, while the method proved to be effective in a continental climate with cold winter conditions, it is less effective when applied in spring, autumn or in temperate to tropical climates as the temperature contrast between SW–GW is less evident and becomes quickly lost by surface mixing. Secondly, TIR sensors cannot penetrate vegetation, meaning that surface waters may not always be visible because of foliage. Thirdly, shallow groundwater temperature can be similar to the mean annual surface temperature, weakening the TIR images contrast. Casas-Mulet et al. [17] generated high-resolution TIR and RGB orthomosaics to characterize cold water patches associated with groundwater inputs over a 95 km-long river section using simultaneous UAS flights. This method allowed to identify riverscape spatial patterns of temperature and to detect and classify these patches. Finally, UAS-based TIR has also been applied in the field of mining by Rautio et al. [18]. The authors combined airborne and UAS TIR imagery to identify SW–GW interactions for the planning and siting of mining facilities in order to prevent potential acid mine drainage pollution.

Other studies focused on SW–GW interactions rely on the combination of ground-based measurements, UAS photogrammetry and hydrologic modeling. Pai et al. [19] quantified sinuosity-driven GW-SW exchange in a river employing a suite of UAS-derived products (water surface elevation, normalized difference vegetation index (NDVI) maps and vegetation-top elevation distribution along meanders) and distributed in situ temperature measurements. S*f*M photogrammetry was used to generate a DSM that allowed to estimate the river gradient, the hydraulic gradient across the meander necks, river-reach topography, and vegetation-top elevations. Compared with the surveyed ground control points, the modeled surface presented a 3.8 cm mean absolute error (less than aerial LiDAR) and a precision of 2.5 cm. The NDVI maps obtained presented a resolution better than 10 cm, enabling to document even individual plants. The combination of topographic analysis with low-cost multispectral imaging enabled to identify GW shortcutting, which occurred through the necks of the meander bends, where hydraulic gradients were found to be larger. Bandini et al. [20] evaluated the potential of spatially-distributed UASs observations for improving hydrological models and in particular, estimates of GW-SW exchange flow. The authors simulated a river and its catchment using an integrated hydrological model that was calibrated through 2 methods; first, against river discharge retrieved by in situ stations and the piezometric head of the aquifers and second, against dense spatially distributed water level observations obtained with UASs. After calibration, the sharpness of the estimates of GW–SW time series improved by 50% using UASs and the root mean square error decreased by R75% compared with the values provided by the model calibrated against discharge only. Tang et al., [21] simulated a flood event with the groundwater model HydroGeosphere to study the spatial and temporal variability of riverbed topography and hydraulic conductivity on SW–GW exchange and groundwater heads. The authors combined several state-of-the-art techniques; UAS-based photogrammetry, physically based measurements and the ensemble Kalman Filter. This combination resulted in substantially improved hydrological predictions and enabled the estimation of river-aquifer fluxes. Briggs et al. [22] combined remote sensing with ground- and drone-based measurements to characterize the enhancement of SW–GW interactions and changes in water chemistry induced by beaver activity along two alluvial mountain streams in USA. Several UAS were deployed to map the river corridor and beaver ponds and S*f*M techniques were applied to generate time-specific digital elevation models of floodplain structure and channel geomorphology. The UAS information was complemented with historical imagery, TIR data from handheld cameras and measurements of water quality (metals) and seepage associated to beaver pond return flows. The authors reported a multi-seasonal enhancement of the floodplain hydrologic connectivity and an increase in groundwater storage associated with beaver activity. Furlan et al. [23] combined electrical resistivity tomography with UAS photogrammetry to map the topography, internal morphology, water storage and hydrologic flow paths in a savanna wetland in Brazil. The authors used a fixed-wing UAS with a RGB sensor to obtain very high-resolution images and create an orthomosaic and a DSM for the relief analysis. The wetland was compartmentalized and the area and volume of each sector calculated for the subsequent hydrological modeling. On the other hand, the geophysical surveys provided information about groundwater behavior and infiltration zone architecture and enabled to produce a 2D inversion and a pseudo-3D model to visualize the subsurface geologic structure and hydrologic flow paths. The combined application of very high resolution UAS images and electrical surveys allowed the authors to propose a broader hydrologic interpretation of the wetland functioning and to complete surface and subsurface imaging of the system.

2.2. Submarine Groundwater Discharge (SGD) Mapping

Submarine groundwater discharge has a suggested impact on marine environment and geochemical cycles, playing a key role in the transport of nutrients, contaminants, and other chemical substances to coastal water. Although neglected for many years owing to the intrinsic difficulty of its quantification and the poor understanding of the process, in the last decades there has been a sharp increase in the number of publications on this topic. SGD has been traditionally studied using geochemical tracers, geophysical techniques, piezometric levels, water budgets and hydrological modeling. These classical methods, however, have large uncertainties associated, are labor-intensive and difficult to implement over large areas. Most SGD research is based on the detection of groundwater discharge from temperature anomalies and the seasonal contrast between ocean and groundwater temperature. TIR imagery from manned aircraft, although costly, has proved to be useful in mapping SGD, especially in areas where temperature contrasts between groundwater and seawater are marked. Conversely, satellite monitoring suffers either from an inadequate spatial resolution for detailed studies, or it is restricted by established schedules (revisit times) that may not be adequate for the needs of each study. In this context, since the implementation of UAS in SGD research is still relatively new, only a few recent studies are available, highlighting UAS´s suitability as affordable alternatives to the aforementioned methods and to overcome limitations in terms of spatial resolution.

Siebert [24] studied what they termed as "sub-lake groundwater discharges" in the Dead Sea; off-shore springs that drained the surrounding mountain freshwater aquifers. The authors integrated data obtained from ground-truth measurements, high-precision and high-resolution bathymetric campaigns, side-scan sonar imaging from an USV and imagery of sea surface temperature from a TIR sensor mounted on an UAS. Their approach proved to be suitable for precisely mapping SGD locations from remotely sensed thermal anomalies and even led the authors to hypothesize that the anomaly size reflects discharge quantities.

In a pioneer work, Lee et al. [25] successfully characterized and quantified SGD in an island of the Korean Peninsula through UAS-based TIR mapping supplemented by ground-based observations. Thermal signatures of SGD plumes and their tidal-derived fluctuations were captured with great detail (Figure 10).This work evidenced that UASs offer better results in the study of SGD dynamics in small, localized target areas (0.01–1 km^2) than manned aircrafts, which are more adequate for regional characterizations. The drone-based methodology allows an easier control of the spatial resolution, more flexibility in field operations and lower costs compared to conventional aerial surveys, making it a powerful tool to study SGD and other coastal processes.

More recently, Mallast and Siebert [26] investigated variations in thermal radiation induced by focused and diffuse SGD in a sedimentary fan of the Dead Sea. The authors used a hoovering UAS equipped with a long-wave TIR camera and a radiometry module and assumed that thermally stable areas indicated focused SGD whereas highly variable areas indicated diffuse SGD. After applying specific subjective variance thresholds and spatio-temporal analysis, their results highlighted that the spatio-temporal behavior of a SGD-induced thermal radiation pattern can vary in size and over time by up to 155% in the case of focused SGDs and by up to 600% in the case of diffuse SGDs owing to underlying flow dynamics. The authors recommend the application of this approach prior any in situ sampling in order to identify adequate sampling locations and intervals.

2.3. Water Table Definition

The definition of the water table of an aquifer is usually carried out from observations at specific points in the territory with the subsequent application of the interpolation methods devised for this purpose (linear, polynomial, IDW, kriging, etc.). Direct observations are made by measuring water level depth with specific instruments (electrical probes, pressure transducers, radar, etc.) at observation points that reach the saturated zone (wells, boreholes, piezometers, pits, excavations). The piezometric level is inferred from the subtraction of water level depth from ground elevation with respect to datum. Photogrammetry carried out from UAS can provide high accuracy in the definition of the morphology of the terrain and is useful for levelling the observation points. Nevertheless, the determination of the level depth using UAS require certain exposure of the water sheet. Therefore, it is not possible to detect the piezometric level when the observation points are closed (installed boreholes or piezometers with covers) or when their geometric characteristics (diameter) do not favor inspection from air. That is why there are very few works in this field. The only applications described refer to peatlands and karst aquifers affected by large dissolution/collapse structures (cenotes).

Thus, Rahman et al. [27] proposed a methodology for mapping groundwater in a treed-bog peatland using orthophotography and photogrammetric point clouds acquired from an UAS. DSM and a DEM were used to obtain a canopy height model and open water objects were converted into a continuous surface. The elevations of the samples were interpolated to generate a water table surface, which was then subtracted from the DEM to obtain the depth to water surface. This method demonstrated great potential for measuring groundwater levels over large, complex and inaccessible areas, although its performance and effectiveness were hindered in densely vegetated areas. Bandini et al. [28] proposed a methodology based on the observation from UAS to define the water surface elevation (WSE) in cenotes in the calcareous aquifer of the Yucatán Peninsula (Mexico), which is useful to feed hydrological models and estimate hydraulic gradients and groundwater flow directions. WSE observations were retrieved using a radar and a global navigation satellite system on-board a multicopter platform. Moreover, water depth was measured using a tethered floating sonar controlled by the UAS. Later, these observations are transformed to orthometric water height above mean sea level and compared with the ground-truth observations retrieved by a GNSS rover station. The authors estimate an accuracy better than 5–7 cm in the WSE and they highlight that UASs allow monitoring of remote areas located in the jungle, which are difficult to access by human operators.

Other applications related to the detection of the saturated zone depth using UAS are focused on the identification of drainage systems in agricultural fields; Allred et al. [29] conducted UAS surveys to detect drainage pipes in a pilot agricultural field where documentation on the pipe network was available. The study was caried out using visible, NIR, and TIR images during the dry period. Under these field conditions, drainage pipes could not be detected with the VIS and NIR imagery. Conversely, the TIR image detected roughly 60% of the subsurface drainage infrastructure. Kratt et al. [30]

followed a similar approach and obtained better results with visible images than with the TIR sensor, which did not detect the phenomenon owing to thermal differences lower than the sensitivity of the instrument, a consequence of non-optimal environmental conditions.

2.4. Subsidence

Subsidence is a slow and gradual movement caused by tension-induced changes over natural terrains or built surfaces. This geological hazard can affect all types of terrains and is produced by a range of natural factors and human activities. With regards to the latter, groundwater extraction plays a significant role in the occurrence of land subsidence; pumping can lead to substantial drawdowns and water table depressions in the neighboring areas of boreholes, resulting higher water extraction costs and, in the worst-case scenario, to material and human damage.

This phenomenon has been extensively documented worldwide using different techniques like interferometry synthetic aperture radar (InSAR) from satellites or numerical models [31][32][33]. Nowadays, the implementation of UASs as complements or enhancing tools for conventional surveying and mapping of subsidence is drawing increasing attention among the scientific community, however, this discipline is still in its earlier stages of development.

Although works on the application of UASs in the study of subsidence linked to groundwater extraction are scarce, some pioneering attempts are worth mentioning. One of them was conducted in Arizona (USAEE.UU), where the central and southeastern regions present subsidence problems driven by groundwater pumping, leading to fissures and cracks caused by tensile failure of sediment and soil. These fissures have resulted in property damages and increase the risk of groundwater contamination from surface pollutants. To address this issue, the Arizona Geological Survey (AZGS) founded the earth fissure program in 2007 to systematically identify, map, and monitor earth fissures. In 2018 the AZGS incorporated the use of UAS-S*f*M for fissure monitoring and terrain mapping [34]. As a result, they produced accurate DSM of the areas affected by fissures, highlighted the diffuse nature of ground surface disturbance around fissure openings and proposed to extend the use of UASs to other zones of Arizona due to the better precision of the method. On the other hand, the effect of subsidence on groundwater levels has been studied by [35][36]. The authors used RGB images from a rotatory-wing UAS to extract subsided cultivated land in high-groundwater level coal mines. After calculating several vegetation indexes and applying a hierarchical extraction method to define subsided farmland, the comparison of the results of the UAS-based images (Kappa coefficient of 0.96) with a traditional method (Kappa coefficient of 0.86) demonstrated the highest accuracy of the former. However, the methodology displayed some weaknesses; although the remote sensing images obtained by UAS at low altitude had high spatial resolution, the amount of data was relatively large, slowing down data processing. In addition, the high energy demands of the rotary-wing UAS only allowed to conduct shorter flights, what hindered the obtention of data over larger areas, and the resolution of the images was affected by meteorological conditions (cloudiness and fog).

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