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Research article

Wetland monitoring technification for the Ecuadorian Andean region based on a multi-agent framework

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ABSTRACT

Remote sensing using satellites and unmanned aerial vehicles (UAVs) has become an important tool for wetland delimitation and saturation assessment since they enable patterns identification and wetland saturation data collection in an agile and optimum way. However, their deployment and operative costs limit their implementation in harsh environments, such as the ones presented in the high Andean wetlands. In this context, this work presents a framework to monitor cost-effectively high Andean wetlands using a multi-agent approach based on: field testing, UAV orthomosaics, and satellite imagery. The method developed comprises two stages: i) definition of the monitoring agent (field testing, satellite, UAV) and ii) image processing. For these stages, semi-empirical and statistical models, which were developed in previous works are incorporated in an open-source framework to tailor each monitoring approach accordingly to the seasonality of a representative Andean wetland. The application of the method and its results highlight the suitability of using visual spectrum low-cost remote sensing approach to compute wetlands saturation percentage. In addition, the methodology proposed allowed the development of a temporal monitoring scheme, where the viability of each monitoring agent is examined. In order to validate the method, field data and multispectral imagery were employed using as case of study the Pugllohuma wetland located in the Antisana Reserve. Thus, the main contribution of this work lies in establishing a technified monitoring framework for the Ecuadorian high Andean wetlands, which can be scaled up and extrapolated to other wetlands with similar harsh environmental conditions, helping to their management and protection policies decision-making.

1. Introduction

High Andean wetlands are amongst the most diverse ecosystem in the world since they provide vital services such as water supply, flow regulation, and carbon storage [1] [2]. Furthermore, they support a unique diversity of high mountain plants and an extensive camelid (Llama, alpaca, vicuña) pastoralism all over the region. They act as a water supply allowing the formation of Andean basins and hydrographic systems, that flow towards the amazon basin and the Pacific and Caribbean shores; supplying fresh water to millions of inhabitants from the main cities of Central and South America [3]. These reasons supported the declaration of high Andean wetlands, as strategic ecosystems for the region [4]. Notwithstanding, these ecosystems are under great threat and vulnerability, due to the expansion of the agricultural frontier and climate change [5]. Several climate models have predicted that the warming rate in the lower troposphere will rise along with altitude, which means that high altitude ecosystems such as Andean Wetlands will be affected more than those at low elevation [6, 7].

In Ecuador, High Andean Wetlands play a key role in the ecological balance and the lives of millions of people. For instance, Quito (capital city of Ecuador) with 3 million inhabitants requires paramo surface water for 85% of its supply (7.4 m^3/s), having Papallacta, Mi-

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cacocha catchment, and Rio Pita as main intakes, all of them located in the Andean cordillera between 3200 and 3900 MASL [8]. Andean wetland importance for the Ecuadorian water management and protection program has encouraged the development of wetland conservation and management practices by several environmental agencies, such as: FONAG (*Water protection fund*), EPMAPS (*Metropolitan Public Company of Potable Water and Sanitation, Quito*), and MAE (*Environment Ministry of Ecuador*). Those agencies are in charge of developing conservation and repairing strategies for affected wetlands, based on their regular state and periodical changes. Nevertheless, monitoring techniques are limited to field testing measurements and sporadic UAV deployment, this latter is mainly related to isolated site visual recognition. In-situ measurements through field testing are costly and applicable only for small areas, whereas UAV monitoring is not significantly useful without a proper remote monitoring scheme. Hence, the data that was recently obtained presents limited coverage with uncertain accuracy and low periodicity, which limits their use for the development of prospective models to enhance wetland protection and management protocols. As it is well known, wetlands monitoring is not an easy task, since they are large interconnected hydrological networks, that need to be continuously and accurately monitored to support environmental policies.

1.1. Wetlands remote sensing platforms

To perform periodic wetlands monitoring, remote sensing has become an essential tool, as it is shown in references [9] [10]. Over the years, remote sensing platforms have been successfully tested for this application, from satellites [11] to UAVs [12] [13] .However, every remote sensing technique presents different constraints depending on the operating conditions, in the case of high altitude wetlands (Andean), there are many limitations for their implementation due to the cloudiness, accessibility, and wind gusts of the region.

In the case of satellites, their main advantage is the coverage area, since an image can cover hundreds of thousands of square kilometers. Nevertheless, the resolution offered by open-access satellite imagery is limited for certain applications, such as species identification and precise wetland delimitation [14]. Although private satellites could provide high-resolution images, their acquisition cost is relatively high, limiting their application in the current methodology. Some related research on this topic has been carried out using free satellite imagery (Landsat 8) in the central region of Ecuador for wetlands monitoring, where the images captured were processed through a CART algorithm to identify alterations of the pedogenesis of paramo soil [15]. Another study in the Andean region corresponds to the use of Landsat 7 images and supervised classification to classify snow, rock, grassland, and wetland, in order to set the distribution of animals in the region [16]. These two works are the only references dealing with monitoring through remote sensing in the Andean region and although they make a comprehensive case of the benefits of satellite imagery, the works lack a proper framework to set a periodical and accurate monitoring, which is needed for the development of conservation/preservation theories. In addition, the Coriolis acceleration of the equatorial region contributes to persistent cloudiness during the whole year, which limits the use of visual sensors and highlights the necessity of implementing other monitoring agents, which can tackle the meteorological conditions of the region during the year.

The suitability of UAVs for wetland monitoring has been documented by several studies, [17, 18, 19, 20] concluding that, UAV imagery acquired can significantly enhance wetland delineation and classification [21]. Fixed-wing UAVs offer similar endurance rates compared to manned aircraft, due to the lift provided by the aerodynamic surfaces, which multi-copters lack and limit their autonomy. The increased endurance and payload capacity offered by fixed-wing UAVs results in a larger area covered per flight, providing ultra-high resolution imagery. Besides, a high level of automation can be achieved at a low operational cost by using small electric UAVs. Notwithstanding, as is shown in [22, 23], the harsh operating conditions in high Andean ecosystems, such as low temperatures, strong wind gusts, and low air density; must be considered, when tailoring a commercial UAV for wetland monitoring. For instance, strong wind-gusts affect maneuverability and stability, reducing endurance dramatically, as the UAV needs to drain more energy from the battery to keep the aircraft within the planned path. Similarly, at high altitude conditions, low air density, and low temperatures affect the aircraft propulsion system performance [24], shortening its endurance compared to missions at sea level.

1.2. Software and sensors

Remote sensors, either satellites or UAVs require to process the gathered images in specialized software. Therefore, it is important to consider this component when developing a low-cost monitoring scheme. Among the most popular commercial software alternatives are Pix4Dmapper, Agisoft Metashape, and DroneDeploy. They are user-friendly software and include extra features to manage multispectral data. Yet, they are often restricted by expensive licenses and require high-performance hardware to be executed properly [25, 26]. Although several open-source alternatives are available including MicMac [27], VisualSFM [28], Python Photogrammetry Toolbox [29], and Open Drone Map [30], these are not complete solutions and a high level of expertise is required for their use. Another crucial component to consider for remote sensing applications is the cost associated with the camera type used as the payload. The cost of these cameras depends on their features, resolution, number of sensors, among others. For instance, when comparing multispectral cameras with the common visual spectrum (RGB) cameras, the maintenance and operation expenses increase the cost of multispectral imagery by a factor of ten compared to its RGB counterpart [23], making its continuous deployment almost prohibitive for the current application. These aspects have encouraged many institutions to develop their own image processing platforms tailored for RGB images [31, 32, 33].

It is important to notice that many of the aforementioned studies focus on high-income countries, which can afford expensive operating costs for periodic monitoring. This is not the case for developing countries, such as those located in the Andean cordillera, where the lack of funding for environmental initiatives, limits the implementation of many of the aforesaid technologies for wetland monitoring [34]. Thus, in the last decade, the development of a low-cost multi-agent monitoring system for wetland assessment has become a research priority, since this will support the decision-making process for the preservation, restoration, and conservation of these unique ecosystems.

2. Methodology

Based on the requirement for a multi-agent wetland monitoring methodology to enhance current techniques of conservation and management, this work develops a framework for optimal use of remote sensing platforms and their related products. For this purpose, the method developed in this work focuses on wetland periodic monitoring, by using photogrammetry techniques and RGB image processing algorithms, in order to enable accurate and low-cost monitoring.

2.1. Case of study - Pugllohuma paramo wetland

The Wetland considered as a case of study is part of the Antisana Water Conservation Area (ACHA), an important wetland complex in the Andean paramo. Fig. 1 shows the wetland location (43 km southeast of Quito), which covers a total of 22 hectares at an altitude of 4100 MASL. The selected wetland is known as Pugllohuma and has been the subject of several studies due to its relevance for the water supply to the capital city. Since 2016, FONAG acquired the wetland and the adjacent territories for testing and monitoring several restoration techniques. They have installed 18 hydrological wells to measure the

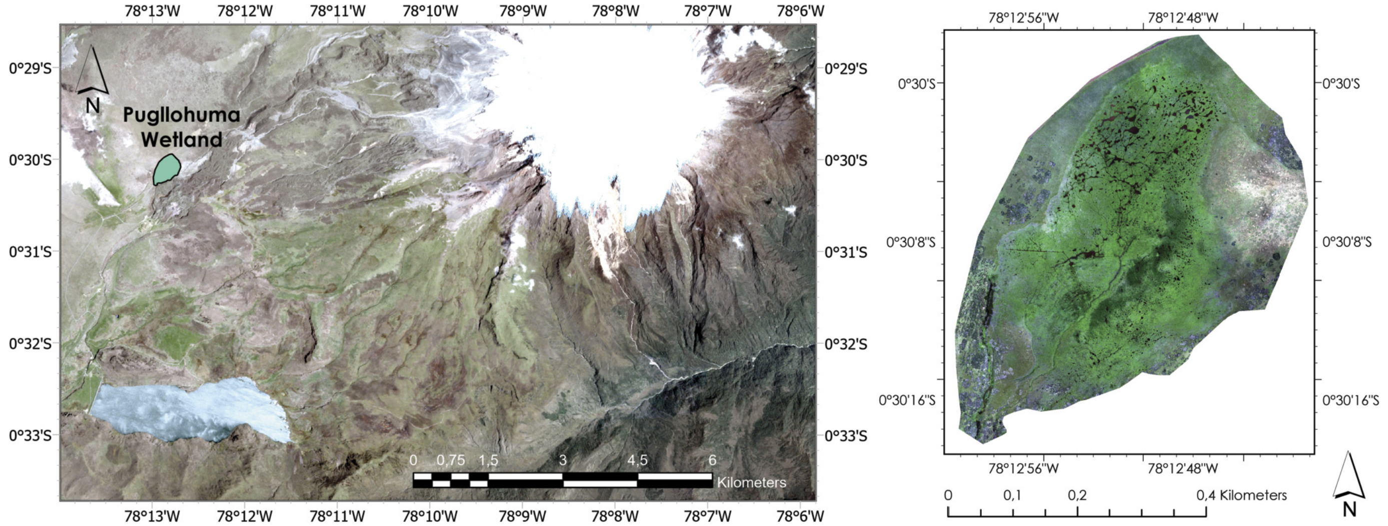


Fig. 1. Study area, Pugllohuma wetland location.

Table 1. Climatic conditions in the study area.

Parameter	Value	Observations
Average Temperature	5 °C	Lowest Record: -6 °C /Highest Record: 15 °C
Relative Humidity	> 86%	Average annual value
Wind Gusts Speed	> 12,20 m/s	Average maximum values
Precipitation	> 1600 mm	Annual value

phreatic level and to assess remediation techniques [17, 35, 36] potential for restoration of different coverages, such as herbaceous paramo, pads and scrubland. The historical data and representative thermodynamic conditions compared with other high Andean wetlands, made the Pugllohuma wetland the best option for the case of study to validate the current methodology. In addition, the complex operating conditions in this zone in terms of rain and wind gusts allowed to test the UAV tailoring for similar harsh conditions, which is ultimately useful to assess techno-economically the feasibility of UAVs in the multi-agent framework.

The seasonality of the Pugllohuma wetland is characterized by periods of long duration and low-intensity rainfall distributed throughout the year. Based on the historical reports from the National Institute of Meteorology and Hydrology (INAMHI) [37], the periods from March to June are the months with the highest rates of rainfall, lowest temperatures, and strongest wind gust [37, 38]. Table 1 summarizes the most relevant features regarding the weather conditions in the study area.

2.2. Multi-agent monitoring framework

The proposed framework is based on three monitoring agents: field testing, satellite platforms, and UAV imagery. Fig. 2 depicts the multi-agent approach implemented for the data gathering and post-processing phase. In this framework, two main tasks required for wetland assessment are defined: monitoring and identification. The first one refers to periodical measurements to assess the physical processes that take place, and the second task focuses on defining its boundaries by using digital mapping and image post-processing algorithms. The diagram is structured using periodicity and temporal axes, which distribute the agents accordingly to their usability. The periodicity axis refers to the expected temporal monitoring for each agent, while the accuracy level is related to the spatial resolution of the products obtained. The specific features for each agent are described in the next sections.

2.2.1. Satellite platforms

Although private satellites could provide high to ultra-high-resolution images, their acquisition cost is relatively high. In order to compare the quality and cost of both alternatives, a Free-access (Sentinel-2A S-2A) and a private platform (Planet Scope Scene-4 PSS-4) are selected in this work. The RGB orthomosaic and the NDWI index map are obtained for both satellites through the image processing software. Table 2, compares the features and prices for both satellites.

Table 2. Sentinel-2A and Planet Scope Scene-4 features and price comparison.

Platform	Sentinel - 2A	Planet Scope Scene-4
Access	Free	Private
RGB Resolution	10 m	3 m
Bands	13	4
Pixel depth	16 bit RAW	16 bit RAW
Coverage area	10,000 km^2	250 km^2
Processed level	2A	3A
Price	0.00 USD	600.00 USD

2.2.2. UAV platform

Since the performance capabilities of the UAV define various monitoring aspects, such as maximum area of coverage, image resolution, operating costs and initial inversion; parametric and semi-empirical tools for aircraft design and mission deployment are included in the remote monitoring framework. The implementation of these modules in the proposed methodology enables to tailor the UAV features to the demanded mission, some of the systems that can be sized with the aforesaid aircraft design tools are propulsion, energy system, aerodynamics, and telecommunications. In this way, the UAV can be optimized for higher endurance and better performance at low temperatures and strong wind-gusts [39].

Regarding the payload of the UAV, an RGB camera was selected as the main payload sensor. This strategy is less time-consuming and constitutes a cost-effective approach. In addition, for the purpose of validation, an index-based analysis using a five-band multispectral camera is used as a payload for the same UAV. In this sense, the 20.1 MP RGB Sony camera with an APS-C sensor and the five bands MicaSense RedEdge-MX multispectral camera were selected for this study. Table 3 shows a brief comparison between the two sensors.

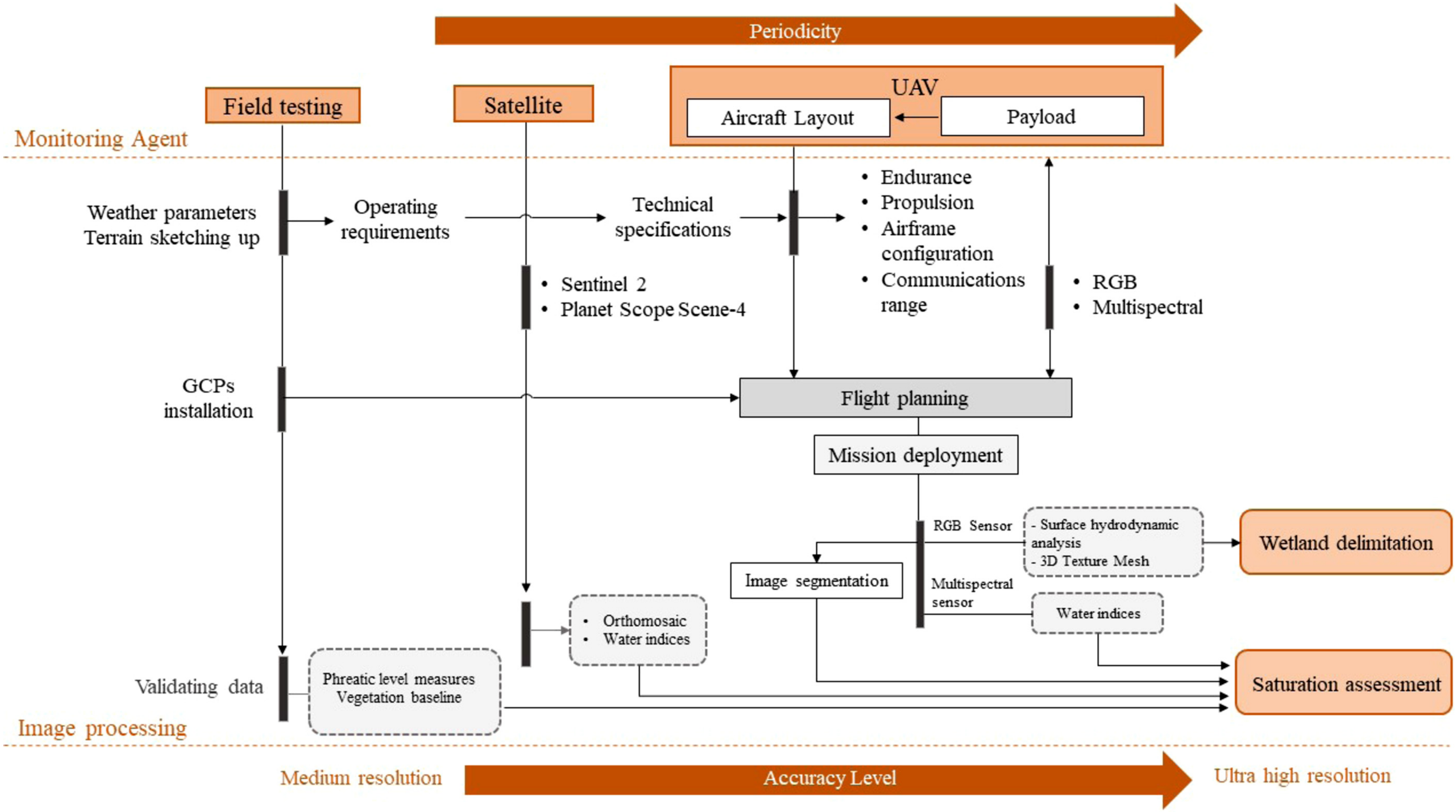


Fig. 2. Wetland assessment through multi-agent monitoring methodology.

Table 3. Comparison between the RGB camera and the multispectral sensor.

Sensor	Sony UMC-R10C	Micasense RedEdge-MX
Spectral bands	3 (Blue, Green, Red,)	5 (Blue, Green, Red, Red edge, NIR)
Weight	266 g	231.9 g
Resolution GSD	2.5 cm/ pixel (120 m AGL)	8 cm/ pixel (120 m AGL)
Focal length of lens	20 mm	5.4 mm
Geo-reference system	PPK compatible	DLS 2.0
Image resolution	5456 * 3632 pixels	1280 * 960 pixels
Megapixels	20.1 MP	1.2MP
Cost	1,499.00 USD	5699.00 USD

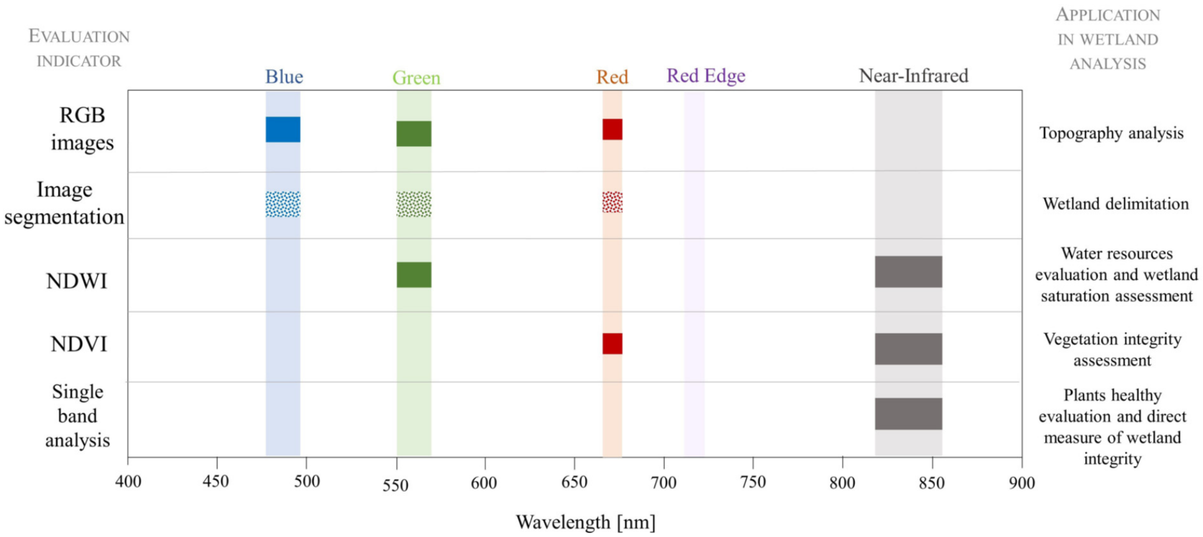


Fig. 3. Categorization of applications based on spectral bands for RGB and multispectral payloads.

As observed in Table 3, the weight of both sensors is approximately the same, however, the focal length of the lenses and image resolution of each camera differ, which affects directly the mission planning phase. The flight plan is designed according to the GSD, overlap, sidelap requirements for the post-processing phase, and the expected mission endurance. In the case of the RGB Sony camera, as its image resolution is higher than the Micasense camera, it is possible to operate at higher altitudes. This latter allows a shorter flight time and a more extensive coverage area per flight, leading to lower operation costs. On the other hand, as the Micasense image resolution is lower, its flight height is limited by the ground resolution required in the post-processing phase, demanding more flights for the same monitoring area. Regarding the sidelap and overlap ranges expected, they must be the same for both cameras (60% to 80% recommended). Once the mission flights are performed, the method continues with the image processing phase, which is further described in the section below.

2.3. Image processing

Once the RGB orthomosaic is obtained from the UAV, the map is processed through an image segmentation model to identify wetland areas. The algorithms implemented in Python enable, the segmentation of the survey area in two parts: i) contour area (partially dry) and ii) wetland area (flooded or moist). Pixels corresponding to the boundary show areas with low moisture content such as the wetland boundaries elevated surfaces and altered or destructed spots. Whereas, pixels corresponding to the wetland show areas with higher water content, such as flat surfaces and main drains. Nevertheless, there are excluded pixels, which do not correspond to any of the segmentation areas. The excluded pixels number is accounted for in the algorithm and has to be below the 5% of the total pixels to reduce data loss. The presented model employs the HSV color range to categorize and segment properly [40]. In this way, Fig. 3 shows analysis applications for each tool implemented. As observed, wetland saturation and topography analysis can be achieved by RGB images through post-processing techniques like image segmentation [40] or object-based image analysis [41].

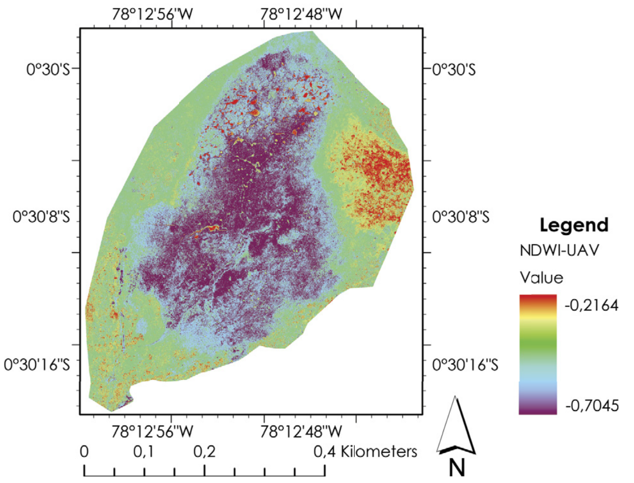
In order to validate the aforementioned algorithm, the multispectral sensor is used to assess the NIR band of the NDWI index for surface water characterization.

2.3.1. Field testing

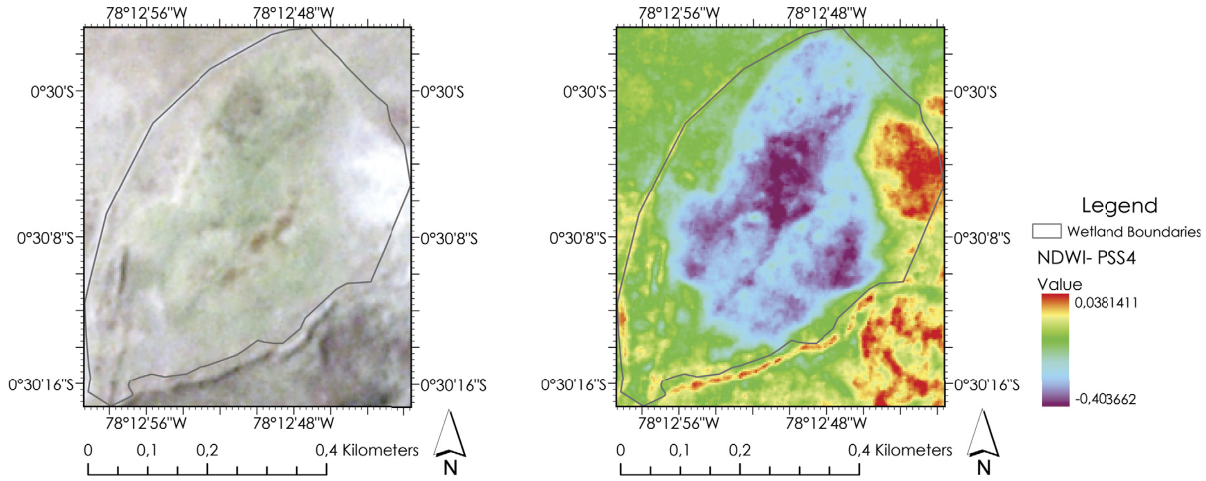
The in-situ survey is essential to obtain the baseline parameters of the aircraft layout and to provide validation data for the products of the remote sensing platforms. Regarding the data requirements to validate the remote sensing products, this methodology considers a digital elevation model (DEM) of the phreatic level of the wetland. The DEM is built up through the measurements taken in 18 hydrological wells installed in the survey area. The water table model is correlated with an image processing code developed in Python to define wetland saturation areas, using RGB segmentation and categorization indirectly.

3. Results and discussion

This section presents the results from implementing the three aforementioned monitoring agents in the area of interest ACHA. Then all the techniques are blended to describe the multi-agent temporal framework for wetland assessment. Firstly, the satellite imagery is processed and used for the assessment of wetlands, then the UAV layout was tailored for the operating environment, as well as the image acquisition processes. Afterward, multispectral imagery from UAVs and the satellite was captured to validate the image processing algorithm and assess their suitability for wetland assessment. Lastly, the field data (phreatic level) was correlated with the maps obtained previously from the segmentation model, topographic analysis and multispectral imagery. The results from each approach are further described in the following sections.

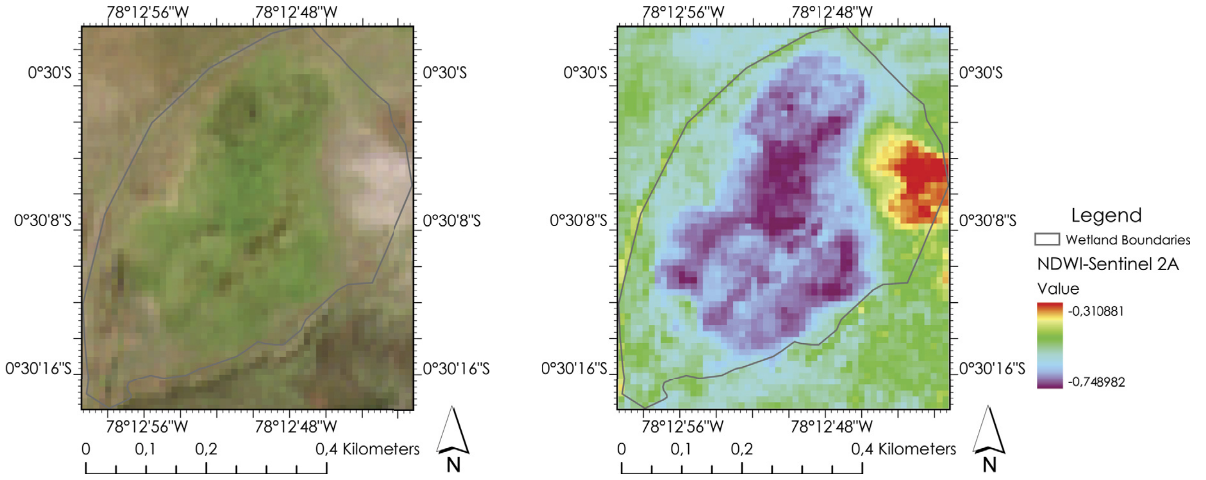


(a) Spectral index map NDWI obtained from the UAV mission



(b) RGB orthomosaic 3m spatial resolution, PSS4

(c) NDWI 3m spatial resolution, PSS4



(d) RGB orthomosaic 10m spatial resolution, S2A

(e) NDWI 10m spatial resolution, S2A

Fig. 4. Satellite imagery products.

3.1. Satellite imagery

Regarding the satellite imagery, the selected platforms were Sentinel 2-A (10 m spatial resolution) and Planet Scope Scene-4 (3 m spatial resolution), their features were previously described in Table 2.

Both satellites are implemented with multispectral sensors. The satellite images shown in Figs. 4b and 4d depict the private and open access RGB mosaics obtained through Planet Scope Scene-4 (PSS4) Platform and Sentinel-2A (S2A) platform respectively. Both images were captured on February 16th, 2019; since this date presented the lowest

Fig. 5. Mission planning parameters compared with different visual sensors.

percentage of cloud coverage for the entire year, approximately <38% in both cases. It is worth to mention, that it was not possible to verify or identify altered spots or water-saturated areas through the RGB mosaics, due to the low resolution of the images. In order to observe the suitability of using multispectral imagery from satellites, it was configured a similar analysis to the aforementioned through the use of the NDWI spectral index. Figs. 4c and 4e show the NDWI maps from the PSS4 Platform and S2A platform respectively. In both cases, the NDWI index highlighted the center of the wetland, denoting the lowest values, which represent the wet vegetation. These products present similar results to the NDWI map, previously obtained from the UAV mission; the difference lies in their resolutions, which for the case of satellites do not allow to visualize the open water areas or affected zones. Nevertheless, in the case of larger wetland complexes with greater open water areas, this could be feasible, as the obtained resolution could help in the identification of main trends regarding the state of wetlands.

3.2. UAV layout and mission deployment

The aircraft layout was developed using the operating conditions of the Pugllohuma wetland and the two payloads (RGB and multispectral camera). In this sense, an electrical fixed-wing drone was tailored to operate at high Andean wetland conditions using in-house aircraft design tools [17, 22], which enabled to determine: endurance, propulsion type, power supply, and airframe configuration. As a result, the UAV components were selected to achieve an endurance of 40 minutes at 4000 MASL, which were considered optimum for the harsh conditions of the zone (16 m/s wind gusts). The flight path was designed in the open software “Mission planner” [42], which enables autonomous flight mission design through waypoints for a predefined area [17]. Each mission requires to set the overlap, sidelap, flight speed and flight height, which for the present case were set depending on the type of camera (RGB or Multispectral). Fig. 5 shows the dependency of flight height, flight time, and ground resolution for the two payloads employed. As observed, the mission time for the same coverage area reduces when the flight altitude increases, at the same time, as the flight altitude increases, the GSD decreases (lower image resolution). From the results can be seen that 25% of additional autonomy can be obtained when using RGB sensors for the same GSD, this parameter is vital, as longer autonomy reduces the number of missions required and hence operating costs.

Based on the data from flight logs of test flights the different settings for the mission are tuned. Then the mission carrying the payload is deployed. From this verification, the mission is carried out for 40 minutes at a height of 80 m above ground level, which delivers images with a ground resolution of 6 cm/pixel, an overlap of 80% and a sidelap of 70%.

3.2.1. RGB post-processed image with in-house code

As described in Section 1, a significant milestone in the development of remote sensing in the Andean region is the capability of assessing wetland saturation with RGB sensors to reduce operational costs. For this aim an RGB image in-house Python algorithm [23] was applied to segment pixels through an HSV color model to define saturated and non-saturated zones. In Fig. 6 is observed both zones, where the non-saturated areas represent: boundaries of the wetland, altered spots, and wetland zones with higher altitudes. The saturated zones are located in the northeast part, which is adjacent to the main natural drainage areas. As observed in this figure the proposed image processing algorithm predicted a 36% saturated area with a 3% loss of pixels. This minimal loss of information and accurate definition of the saturated area highlights the potential opportunities of in-house codes for reducing operating costs for remote sensing activities.

3.2.2. Topographic analysis

In order to validate the RGB image processing algorithm and verify multispectral indices and field data, a micro-topographic analysis of the survey area was carried out. For this evaluation, four maps were developed. i) The digital surface model (DSM), Fig. 7a, depicts different altitudes within the terrain, obtaining an average height of 4117 MASL, and a maximum and a minimum altitude of 4130 MASL and 4096 MASL, respectively. ii) The contour lines in the map, Fig. 7b, were established every 2 meters in order to determine zones with low altitude gradients such as the areas covered between heights of 4112 m and 4118 m, which allowed to identify zones with higher capacity of water accumulation. iii) The wetland slope map, Fig. 7c, allows visualizing different slopes in a 2D model, and characterizing the terrain as a quasi flat surface [43] since the average slope of the wetland is 4,07°. iv) The wetland aspect map, Fig. 7d, shows slopes directions and how surface runoff points towards the center of the wetland. In this context, the north-center zone of the wetland is characterized by a quasi-flat surface with a low altitude gradient and a high capacity for water storage. As observed in this micro-topographic assessment, the main trends captured by the in-house segmentation model were corroborated, where the less saturated zone is located in the higher part of the Pugllohuma wetland.

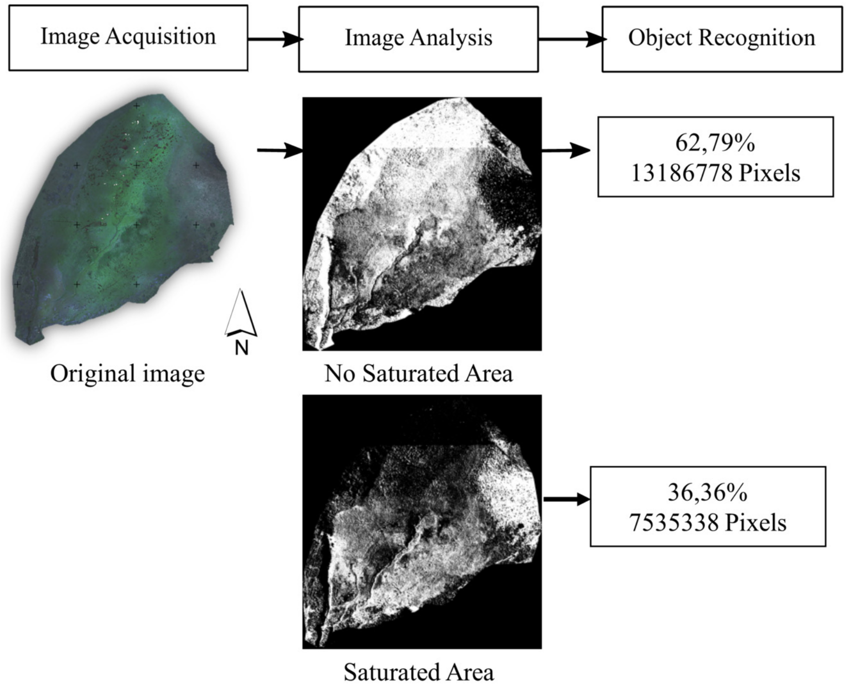


Fig. 6. Image segmentation applied to Pugllohuma wetland.

3.3. Multispectral analysis

The water index (NDWI) was calculated to establish baseline data for determining the accuracy of the proposed image processing methodology [44]. The spatial resolution of 6,92 cm/pixel allows visualization of open water areas, as shown in Fig. 4a. However, the values of these features are similar to those with dry vegetation or bare soil, as a result of high water turbidity values. Despite obtaining negative values for open water drainage, the vegetation near the drainage system presented the lowest values, which allowed to distinguish dry and wet areas. In this sense, open water areas and vegetation with the lowest NDWI values represent zones with higher water content. This result differs slightly from the in-house proposed methodology, which is within the expected range since multispectral imagery employs more spectral bands and allows a more accurate delimitation of the wetlands.

3.4. Field data

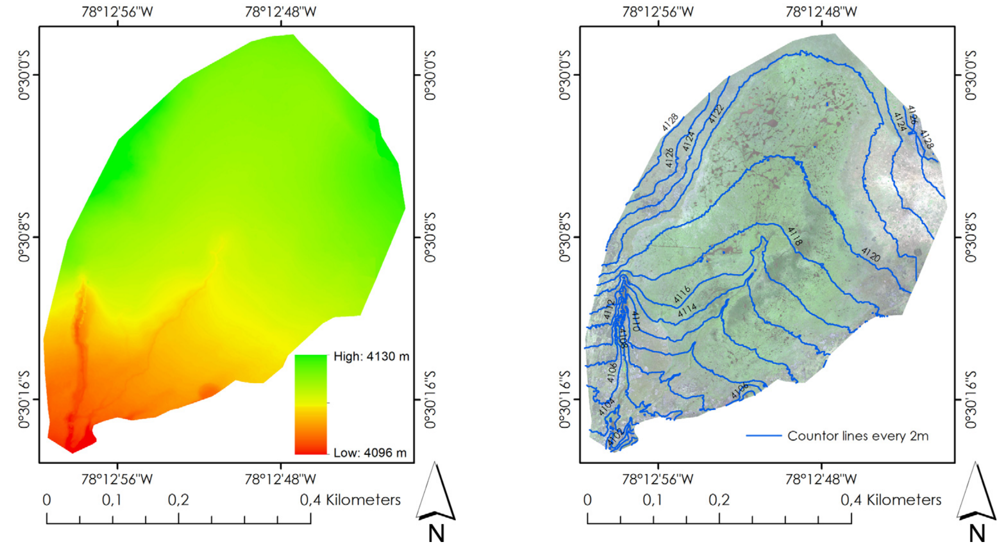
The phreatic level evaluation is used to validate the different maps for wetland saturation assessment. In this way, the DEM extent of the phreatic level map is adjusted to the center of the wetland system as the peripheries present higher altitudes and all the piezometers are located inside this boundary. The measurements of the phreatic level were obtained in November 2019 from 18 piezometers installed on the study zone by FONAG. The phreatic level was calculated by the interpolation method, Spline. This method presented the best results as it generated a smooth surface similar to the DSM of the wetland. In this context, the phreatic level parallel to or 20 cm below the terrain was overlapped with the 3D RGB model of the wetland to understand how the topography influences the water accumulation system (Supplementary Fig. S1). The aforementioned figure corroborates what was obtained with the NDWI indices for the multispectral imagery, where water accumulates in the middle zone of the wetland. The areas which contain the highest saturation of water follow the main natural drainage of the wetland. In this sense, Fig. 4a is used to determine the saturated zone of the wetland. From these results, the saturated zone is computed, which represents 39,27%. The latter value is significantly similar to the predicted with the in-house image processing code (36%), however, the delimited wetland areas differ to some extent, which is expected as RGB sensors capture fewer spectral bands, constraining the precision to accurately define the wetland boundaries. Fig. 8, depicts the obtained water-saturated area.

3.5. Multi-agent periodical framework

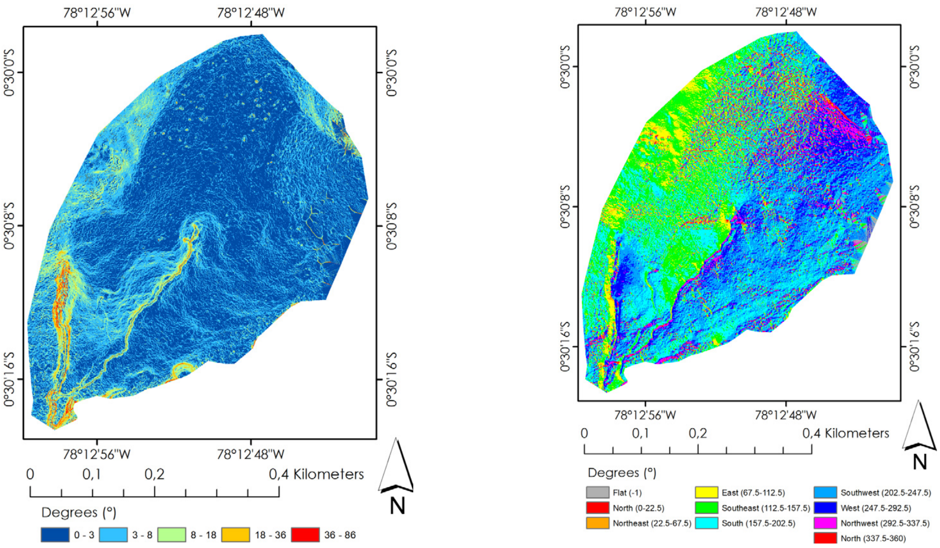
In order to deal with the complex weather conditions of the high Andean region, a periodicity variable is included in the analysis. The temporal framework settles the most suitable operating periods for each monitoring agent according to the seasonality and the different climatic features of the survey area (Supplementary Fig. S2), which is representative for the high Andean paramo wetlands. This multi-agent framework is pioneer for this region, due to the complex accessibility and limitations to deploy the different remote sensing techniques, as was previously highlighted. This first framework has used historical data from nearby meteorological stations, nevertheless part of the future work lies on refining the time-frames for each of the monitoring techniques by employing the current method for longer testing periods.

In the case of satellite platforms, the usefulness of the imagery obtained over the high Andean region depends largely on the cloudiness of the region. Therefore, during rainy months, which are usually very cloudy the imagery obtained will not be useful, as a lot of post-processing work is needed to remove cloud disturbances, which then contributes to image loss of information. In contrast, during the dry months, from July to October, the suitable periods for monitoring are longer since there is less cloud coverage.

For the UAV agent, suitable periods for data gathering are September to October (dry periods). In contrast, during the rainy season, the suitable periods are shorter and during March they are null. However, from the experimental flights, it is observed that UAVs can fly with moderate rain, which increases the potential use of these devices for longer monitoring periods. Nevertheless, due to the strong wind-gust in June and August, UAV deployment can be somehow limited to certain times during the day for monitoring. In the months of January and May, the wind levels are within the UAV's capacities, and when precipitation



(a) Wetland Digital Surface Model (DSM) (b) Countour Lines



(c) Wetland Slope (d) Wetland Aspect

Fig. 7. Topographic variables, Pugllohuma Wetland.

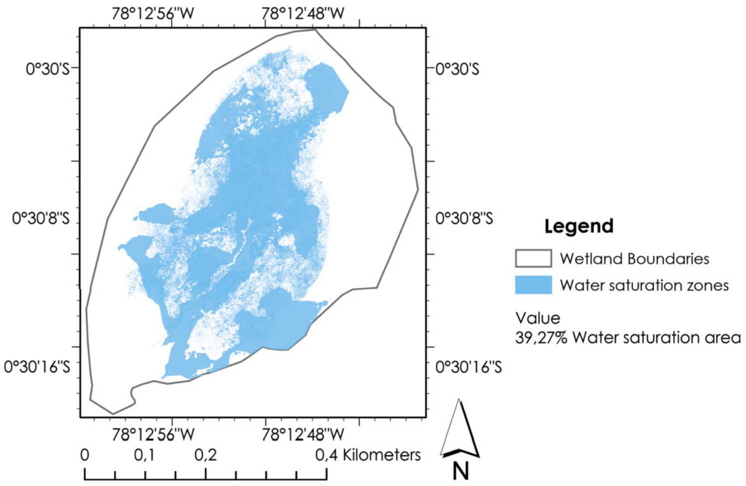


Fig. 8. Wetland saturation area.

rates are moderated, they can also be deployed to gather data. Since, the operational costs for UAVs increase during the rainy and windy periods (lower UAV autonomy and waterproofing needed), it has been defined that the optimum periodicity for this platform during the rainy months should be limited to one sample per month, which is enough based on the current periodicity of data collection (phreatic measurements in-situ collected).

To summarize, the products with the different monitoring agents provide an useful insight into the suitability of the method proposed for a technified monitoring of high Andean wetlands (Supplementary Fig. S3 depicts the comparison of the three monitoring agents). Since the periodicity of the data depends on the monitoring timeframe, the method presented has been tested for open collaboration with the community by creating the website platform HUMEGIS [45], where orthomosaics can be uploaded to the platform, for computing wetland saturation. In this way, the scalability of the model has been evaluated and has been highlighted its potential contribution for management and protection of wetland ecosystems (media and technological magazines have covered its potential benefits for hydric reservoir protection [46]). Finally, it is important to mention that at this stage the study focus on the development of the monitoring framework, and hence part of the future work is its refinements and implementation for longer time-frames, where theories relevant to conservation and management of wetlands can be developed.

4. Conclusion

A multi-agent temporal framework based on the integral use of remote sensors (satellite and UAVs) and field measurements has been developed and validated against experimental measurements (phreatic level model), topographic analysis, and multispectral indices, using the Pugllohuma wetland as a case of study. The monitoring scheme proposed implements an in-house image processing algorithm based on HSV for classifying and segmenting RGB visual imagery with a ground resolution of 6 cm/pixel (overlap of 80% and sidelap of 70%), which reduces importantly operating costs and offers a variety of possibilities for extrapolating the method to other high Andean wetlands. In addition, the potential of the method for periodical measurements offers important synergies with the efforts of wetland conservationist agencies and hydric resources management organizations.

From the validation process, it was found, that the method proposed differed by 4% in the definition of saturated areas when compared with multispectral and in-situ measurements, which is very promising and opens the possibility of its implementation for other similar wetlands. In this regard, the website platform HUMEGIS has been built to scale this initiative and enable open collaboration between different stakeholders, to increase the database of processed orthomosaics offering GIS layered maps to facilitate wetland management.

Finally, a periodic framework based on meteorological data from the region has been developed to evaluate which monitoring agent is adequate based on seasonality during the year. For the UAV, the suitable periods for the data are restricted by the precipitation and the wind speed which affect its operability, the most suitable months for its implementation are September to October, with short periods of use in December, February, April and July. For the case of the satellite agent, the most suitable timeframe is between July to September, with short periods of use during the months of December, February and April. Nevertheless, the main limitation of this latter agent is the low resolution of the imagery which can compromise certain types of analysis for wetland characterization. Regarding the temporal framework, it is important to highlight that the novelty of the method proposed limits the historical data available and hence constrains its accuracy. To tackle this, it is planned to gather more data related to the agents´ operation in the Pugllohuma region, so the algorithms can be calibrated properly enhancing the temporal framework model prediction.

5. Future work

At this stage, this work focused on developing a multi-agent monitoring framework suitable for wetland periodical data gathering, hence this work does not encompass the environmental theories required for their conservation/preservation. Thus part of the future work is related to implementing the validated methodology presented in this work to enhance wetland conservation practices. In addition, it is expected that the data acquired through this method will enable faster supervised and unsupervised classification of different ecosystems in the region. Furthermore, the collection of more data will help to enhance current models accuracy and improve the training of deep learning techniques to easy technified monitoring implementation for other wetlands.

Another aspect that is expected to be explored is the suitability of uncommon spectral indices for wetland monitoring to enhance their health assessment and delimitation.

Declarations

Author contribution statement

Esteban Valencia: Project director, conceived and designed the article.

Iván Changoluisa: Performed the experiments; Collaborated with the paper edition.

Kevin Palma, Patricio Cruz, Deyanira Valencia & Diego Quisi: Contributed agents, materials, analysis tools or data.

Paul Ayala, Victor Hidalgo & Diana Puga: Analyzed and interpreted the data.

Nelson Jara: Performed the experiments.

Collaborators contribution statement

Carlos Cevallos: Contact between EPN-FONAG.

Gabriela Espinel: Analyzed data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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References

[1] C. Ramsar, Los humedales altoandinos, in: Ramsar COP9 DOC, 2005.
[2] D.J. Cooper, E.C. Wolf, C. Colson, W. Vering, A. Granda, M. Meyer, Alpine peatlands of the Andes, Cajamarca, Peru, Arct. Antarct. Alp. Res. 42 (1) (2010) 19–33.
[3] C. Ramsar, Estrategia regional de conservación y uso sostenible de los humedales altoandinos, in: Ramsar COP9, in: DOC, vol. 26, 2008.
[4] C. Ramsar, Los humedales altoandinos como ecosistemas estratégicos, in: Ramsar COP8, in: DOC, vol. 8, 2002.

[5] M.E. Orúe, P. Laterra, F. Cabria, Expansión de la frontera agrícola en Argentina y erosión hídrica: mapas de riesgo utilizando el Modelo Usle con apoyo de sig, in: TELEDETECCIÓN_Hacia–Un Mayor Entendimiento de la Dinámica Global y Regional, 2007.

[6] R.S. Bradley, M. Vuille, H.F. Diaz, W. Vergara, Threats to water supplies in the tropical Andes, Science 312 (5781) (2006) 1755–1756.

[7] A. Coudrain, B. Francou, Z.W. Kundzewicz, Glacier shrinkage in the Andes and consequences for water resources, Hydrol. Sci. J. (2005).

[8] W. Buytaert, R. Célleri, B. De Bièvre, F. Cisneros, G. Wyseure, J. Deckers, R. Hofstede, Human impact on the hydrology of the Andean páramos, Earth-Sci. Rev. 79 (1–2) (2006) 53–72.

[9] S. Rapinel, E. Fabre, S. Dufour, D. Arvor, C. Mony, L. Hubert-Moy, Mapping potential, existing and efficient wetlands using free remote sensing data, J. Environ. Manag. 247 (2019) 829–839.

[10] M. Boon, S. Tesfamichael, Wetland vegetation integrity assessment with low altitude multispectral UAV imagery, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 42 (2017) 55.

[11] M. Guo, J. Li, C. Sheng, J. Xu, L. Wu, A review of wetland remote sensing, Sensors 17 (4) (2017) 777.

[12] M.A. Boon, R. Greenfield, S. Tesfamichael, Wetland assessment using unmanned aerial vehicle (UAV) photogrammetry, in: ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLI-B1, 2016, pp. 781–788.

[13] J.V. Marcaccio, C.E. Markle, P. Chow-Fraser, Unmanned aerial vehicles produce high-resolution, seasonally-relevant imagery for classifying wetland vegetation, in: ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-1/W4, 2015, pp. 249–256.

[14] J.E. Colwell, Coarse-resolution satellite data for ecological surveys, Bioscience 36 (7) (1986) 468–475.

[15] V. García, C. Márquez, T. Isenhart, T. Rodríguez, S. Crespo, A. Cifuentes, Evaluating the conservation state of the páramo ecosystem: an object-based image analysis and CART algorithm approach for central Ecuador, Heliyon (2019).

[16] P. Moyota, C. Verdugo, C. Guadalupe, C. Jara, B. Vaca-Barahona, A. Villavicencio, B. McLaren, Caracterización ecológica de bofedales, hábitat de vicuñas aplicando metodologías de teledetección y sig estudio de caso: reserva de producción de fauna chimborazo, Eur. Sci. J. 12 (2016).

[17] E.A. Valencia, K.A. Palma, I.D. Changoluisa, V.H. Hidalgo, P.J. Cruz, C.E. Cevallos, P.J. Ayala, D.F. Quisi, N.G. Jara, Wetland monitoring through the deployment of an autonomous aerial platform, IOP Conf. Ser. Earth Environ. Sci. 432 (2020) 012002.

[18] J. Jiménez López, M. Mulero-Pázmány, Drones for conservation in protected areas: present and future, Drones 3 (1) (2019) 10.

[19] F. Nex, F. Remondino, UAV for 3D mapping applications: a review, Appl. Geomat. 6 (1) (2014) 1–15.

[20] E.R. Hunt, M. Cavigelli, C.S. Daughtry, J.E. Mcmurtrey, C.L. Walthall, Evaluation of digital photography from model aircraft for remote sensing of crop biomass and nitrogen status, Precis. Agric. 6 (4) (2005) 359–378.

[21] M.A. Boon, S. Tesfamichael, Wetland hydrological integrity assessment with unmanned aerial systems (UAS), in: ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII-3/W2, 2017, pp. 31–35.

[22] E.A. Valencia, M. Oña, D. Rodriguez, A. Oña, Experimental performance assessment of an electric uav with an alternative distributed propulsion configuration implemented for wetland monitoring, in: AIAA Propulsion and Energy 2019 Forum, 2019, p. 4461.

[23] E. Valencia, V. Alulema, D. Rodríguez, Wetland monitoring using unmanned aerial vehicles with electrical distributed propulsion systems, in: IntechOpen - Propulsion Systems, 2019, p. 22.

[24] E.A. Ranquist, M. Steiner, B. Argrow, J3.1 Exploring the Range of Weather Impacts on UAS Operations, University of Colorado Boulder, 2017.

[25] PIX4D, Pix4d system requirements: minimum and recommended computer specifications, https://support.pix4d.com/hc/en-us/articles/202557289-System-requirements-Minimum-and-recommended-computer-specifications, 2021.

[26] Agisoft, Agisoft system requirements: minimum and recommended computer specifications, https://www.agisoft.com/downloads/system-requirements/, 2021.

[27] E. Rupnik, M. Daakir, M.P. Deseilligny, Micmac–a free, open-source solution for photogrammetry, Open Geosp. Data Softw. Stand. 2 (1) (2017) 1–9.

[28] C. Wu, Visualsfm: a visual structure from motion system, http://ccwu.me/vsfm/doc.html, 2011.

[29] H. Rahaman, E. Champion, To 3D or not 3D: choosing a photogrammetry workflow for cultural heritage groups, Heritage 2 (3) (2019) 1835–1851.

[30] OpenDroneMap, Drone mapping software, https://www.opendronemap.org/, 2021.

[31] D. Popescu, L. Ichim, Aerial image segmentation by use of textural features, in: 2016 20th International Conference on System Theory, Control and Computing (ICSTCC), IEEE, 2016, pp. 721–726.

[32] A. Zeggada, F. Melgani, Y. Bazi, A deep learning approach to uav image multilabeling, IEEE Geosci. Remote Sens. Lett. 14 (5) (2017) 694–698.

[33] C.L. Doughty, K.C. Cavanaugh, Mapping coastal wetland biomass from high resolution unmanned aerial vehicle (uav) imagery, Remote Sens. 11 (5) (2019) 540.

[34] J. Acquatella, C.J. De Miguel, A. Bárcena Ibarra, Financing for sustainable development in Latin America and the Caribbean, in: Regional Preparatory Conference of Latin America and the Caribbean for the World Summit on Sustainable Development, 2001.

[35] A. Toapanta, Mapeo a detalle de las coberturas del suelo de los humedales jatunhuayco y Pugllohuma, 2019, unpublished.

[36] S. Sadeghian, J.M. Rivera, M.E. Gómez, Impacto de sistemas de ganadería sobre las características físicas, químicas y biológicas de suelos en los andes de colombia, Ing. Reg. 17 (2017) 1–12.

[37] Instituto Nacional de Meteorología e Hidrología - INAMHI, Reporte técnico de estaciones meteorológicas m5126 jatunhuyaco histórico, 2018, unpublished.

[38] Fondo para la Protección del Agua- FONAG, Anuario hidrometeorológico 2018, http://www.fonag.org.ec/web/wp-content/uploads/2019/09/Anuario2018-min.pdf, 2018.

[39] D.J. Vera, E.A. Valencia, E. Lopez, W.E. Banda, Modeling a propulsion system for the trajectory correction of weather balloons, in: AIAA Propulsion and Energy 2019 Forum, 2019, p. 4464.

[40] D. Puga, Desarrollo de un código de programación en lenguaje python para el estudio de zonas forestales, Master's thesis, Escuela Politécnica Nacional, Quito-Ecuador, 2019.

[41] I. Dronova, Object-based image analysis in wetland research: a review, Remote Sens. 7 (5) (2015) 6380–6413.

[42] M. Oborne, Mission planner GCS, http://ardupilot.org/planner/, 2019.

[43] R.v. Zuidam, Aerial photo-interpretation in terrain analysis and geomorphologic mapping, Tech. Rep., Smits Publishers, 1986.

[44] S.K. McFeeters, The use of the normalized difference water index (ndwi) in the delineation of open water features, Int. J. Remote Sens. 17 (7) (1996) 1425–1432.

[45] HUMEGIS, Plataforma de información de monitoreo de zonas de protección hídrica, https://hidrologia.cedia.org.ec/sitio/.

[46] Mit technology review 35 LATAM, http://www.technologyreview.es/innovadores-menores-35-latam-2020, Nov. 2020.