Digitizing end-to-end water asset monitoring and forecast

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ABSTRACT: Climate change affects water asset management, causing uncertainty around water availability and decision-making during critical times. Successful adaptation to climate change risks requires access to high quality datasets, accurate forecasts, and support tools that provide decision makers with knowledge and forecast capabilities, enabling informed and effective actions. In regions where water availability is critical, business as usual is no longer an option. Canal Isabel II and Divirod Inc. have partnered to demonstrate how an end-to-end monitoring and datasets of snow, precipitation, and water levels provide a unique path to forecasting and asset management in times of uncertainty. The proprietary sensing technology used in this demonstration offers unparalleled measurement accuracy, self-calibrated and standardized collection instrumentation, and cloud-based algorithms and delivery services to support real-time management possibilities. The sensing technology was deployed very rapidly and did not require any scheduled maintenance or calibration. Using just one type of sensors the authors obtained real-time series of water insights, including snow, precipitation, and water levels with millimeter accuracy. The demonstration was conducted in the *Lozoya* river watershed (Spain), a critical water asset that provides 40% of the water consumed in Madrid. With one sensing unit per reservoir and three units at strategic locations in the mountains, insightful data has been effectively collected 24/7 from the watershed. The new datasets have provided Canal Isabel II with unique and comparable water insights (labeled data) for modeling and forecasting. This paper presents the operational results, provided advantages, and a performance data comparison against previously existing state-of-the-art instrumentation. The fundamentals and benefits of the sensing technology are also presented.

1 INTRODUCTION

1.1 *Background*

Canal de Isabel II partnered with Divirod Inc. to deploy and evaluate a novel end-to-end monitoring solution in one of their managed watersheds. The solution provides access to data of unparalleled accuracy and drastically reduces the operational expenses related to managing an in-house measurement infrastructure.

The watershed of *Rio Lozoya*, north of Madrid, Spain, that supplies drinking water to approximately 40% of Madrid's population, was selected for the evaluation. Since 2021 reliable snow, water, and precipitation data are being captured at remote locations in the mountains of *Sierra de Guadarrama* and reservoirs along the *Lozoya* river with an uptime greater than 99.8%. The results obtained have been compared with data from already existing instrumentation and in-situ measurements, and showed an unparalleled accuracy and also the continuous capture of snowpack at strategic and remote locations normally not accessible due to weather conditions. Furthermore, the team demonstrated the ability to obtain precipitation rates using the same sensing technology.

This paper provides a comprehensive overview of the solution implemented, the results obtained, a data comparison from existing instrumentation as well as third-party data, and additional capabilities such as precipitation and forecast. This paper also provides conclusions and recommendations from the experience gained during this contract.

1.2 *Data vs Hardware*

Traditionally, managing water has entailed significant operational challenges including the purchase and deployment of sensing instrumentation that is located at remote places. The expense is not just limited to having someone knowledgeable on staff who babysits the technology performance, but also having dedicated operators to access remote places, often hazardous and affected by weather, to collect data and/or perform periodic scheduled maintenance. Furthermore, most of the instrumentation in the market is not self-sufficient nor ready to report measured data automatically to a digital system and requires additional equipment, service contracts, and associated operational expenses to bring the data back home.

For Canal Isabel II, having access to reliable data is the most important element for managing water efficiently and informing the decision making process. The means to gain access to such data becomes irrelevant and could be considered an unnecessary overhead. The work presented in this paper demonstrates that using a novel approach provides an efficient way to tackle water management and reduces the burden and expense of the scenario described above.

2 DATA-CENTRIC END-TO-END MONITORING TECHNOLOGY SOLUTION

2.1 *Data collection sensing technology*

The inherent limitations of traditional sensing technologies used for hydrological measurements do not permit scale deployments without paying a high price on related operational activities. The novel technology solution used in this work circumvents those limitations and enables continuous data collection without interruption of water insights in different forms: water levels, snow and ice accumulation, precipitation, soil moisture, as well as tides and waves if installed by the ocean. All data types are delivered using the same sensor design, which represents a tremendous advantage.

The sensing technology used here forms a global footprint microwave radar that levers on the GNSS-reflectometry technique (Martin-Neira 1993). Existing in-orbit satellite constellations act as signal emitters, while the sensing instrumentation acts as passive receivers of such radar. The sensor unit is installed at a certain height in front of the area of interest (reservoir, river, mountains, ocean, etc.) and collects simultaneously 10+ reflections that scan such area. All measured reflections are transmitted via the cellular network to the cloud for further processing and classification into different water data types. The result is a map of water content information across a large area in front of the sensor. The final datasets deliver provided to the user are highly accurate and contain valuable information of existing water around each receiving sensor.

The receiver unit is shown in Figure 1. It consists of an external antenna (10 cm diameter) and electronic unit (20 x 9 x 8 cm) that contains the receiver, power, and communication modules. The unit consumes 0.25W at 5V and can be powered using solar or from the grid using a transformer.

Thanks to the use of transmitted signals from highly precise satellites and proprietary design elements, all sensing units count with a continuous internal self-calibration. This unique feature eliminates the typical drift errors observed in other technologies. In addition, the robust design of the sensing units eliminates the need of periodic maintenance. Both design aspects together reduce the operational need, expenses, and potential risk of field personnel attending the units.

The sensing technology is also environmentally friendly. First, the sensing technology is passive. In an already crowded electromagnetic spectrum the only emissions required are those arising from the cellular transmission to the cloud, which are similar those emitted from a regular cell phone. Furthermore, since the technology levers on existing satellite constellations, no additional spacecrafts need to be placed in orbit for the application.

Another green advantage is that the instruments are not in the water, which eliminates potential pollutants resulting from corrosion of sensor materials. Instead, the instrumentation is installed at a certain height on existing infrastructure, such as poles, masts, rooftops, etc, close to the body of water and also away from the reach of people. The installation is easy and can be completed in less than 30 minutes. Furthermore, the footprint of the sensors is very small and does not introduce visual impacts to the environment. Finally, the design complies with strict regulations and certifications for outdoor environmental protection and waste reduction.

2.2 *Data delivery and access*

The most relevant aspect for users is data access. Users at Canal Isabel II can securely access their data via a user ID and password-protected dashboards, which provide information at both watershed and individual reservoirs levels. These dashboards were designed to be accessed via a computer, tablet, and/or smartphone, and to include the relevant parameters for effective watershed decision making.

The aggregated dashboard (see Figure 2, top) provides information on total volume of water at each of the 5 reservoirs, as well as volume change every 5 minutes, individual volumes, levels, and rate of change. In addition, it also provides snowpack levels during the winter season. The individual dashboards (see Figure 2, middle) provide information on water levels and volume over time, current values, and weekly trends, as well as time series of measured precipitation. The time series of snow data for each location at the mountains is also provided in separate dashboards (see Figure 2, bottom).

Figure 1. Sensing instrumentation consisting of an external antenna and electronics unit.

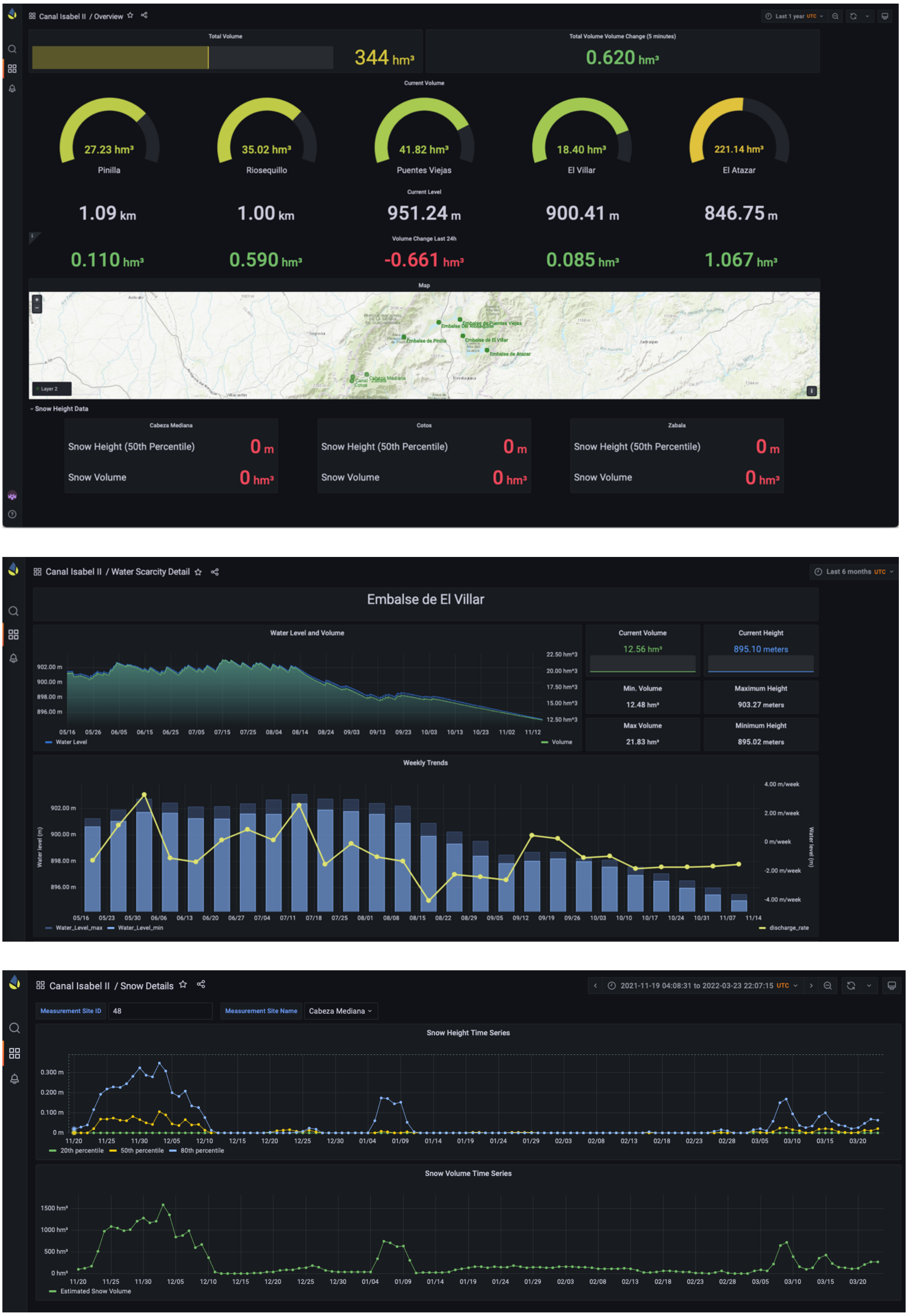

Figure 2. Watershed overview (top), detailed reservoir (middle), and snow (bottom) dashboards.

3 MAPPING THE WATERSHED

3.1 *Watershed localization*

The *Lozoya* river watershed is marked by heavy precipitation and extends from the *Sierra de Guadarrama* to the *Atazar* Dam which supplies drinking water to Madrid, Spain. Snow and rain collect high in the mountains and drain to the *Lozoya* River, which is interrupted by five reservoirs. As a consequence of climate change, rapid snowmelt and heavy rain episodes are shocking the area and raising vulnerabilities of the river courses. The deployed sensor network (Figure 3) track strategic snow-packed areas and reservoirs so Canal de Isabel II can increase the hydrological knowledge of these interdependent areas and optimize water management in this region.

3.2 *Mountains*

Sensing units were installed at the strategic locations in the *Parque Sierra de Guadarrama* (see Table 1). These units were co-located with other existing monitoring devices that provide meteorological services to the *Parque* (Figure 4, left). The new sensing units map the level and volume of snowpack every over the entire season providing a continuous recording of snow precipitation in the area that leads to snow melt events.

Snow measurements in high, remote places are manually conducted by field personnel. Clearly, this manual task cannot be performed on a daily basis, and even periodic field trips are interrupted by weather events that make the trip hazardous and risky. Therefore, the continuous snow data gathered by the Divirod sensing units has completely changed the way predictions can be performed and increased the knowledge of the snowpack as part of the watershed.

Table 1. Installation at *Parque de Guadarrama*.

Location	Latitude	Longitude	Sensor height (m)	Altitude (m)	Install date
Refugio Zabala	40.83715	-3.95853	10.0	2,080	15 Nov 2021
Puerto Cotos	40.82527	-3.96121	3.0	1,858	15 Nov 2021
Cabeza Mediana	40.84374	-3.90835	6.6	1,683	15 Nov 2021

In addition, the automatic data collection is performed over a large area in front of the sensor unit, ranging from one thousand to twelve thousand square meters. Snow height distribution data is collected over the entire area and volumes are calculated accordingly.

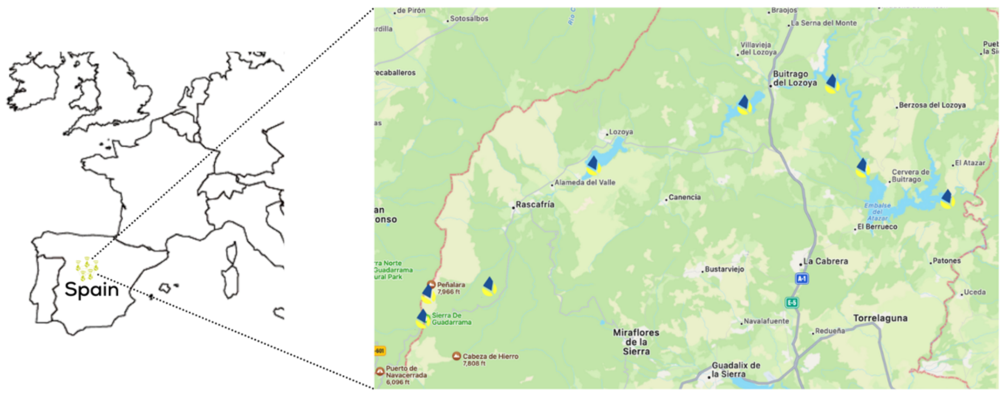

Figure 3. Location of installations along the *Lozoya* river watershed.

Figure 4. Mountain installation for snow monitoring (left), and reservoir (right).

3.3 *Reservoirs*

The sensing units were installed at the pump station of each reservoir (Table 2) and overlooking the body of the reservoirs (see Figure 4, right). These sensors scan over a large area of water similar to having hundreds of single point sensors, which increases the accuracy and reduces the errors due to waves. The data from all five reservoirs is referenced to the same vertical datum and comparable within one millimeter, a key condition to accurately model and intercompare regional data from multiple locations.

The data has been delivered every 5 minutes with an uptime greater than 99.1% with no periodic maintenance or calibration required. This feature offers a great advantage to the user since it eliminates the need of dedicated field personnel to travel and conduct scheduled maintenance and/or required calibrations.

Table 2. Installation at *Parque de Guadarrama*.

Reservoir	Latitude	Longitude	Datum	Install date
Pinilla	40.94507	-3.77436	1089.53	15 Nov 2021
Rio Sequillo	40.98519	-3.64924	1014.38	15 Nov 2021
Puentes Viejas	40.99278	-3.57237	954.45	15 Nov 2021
Villar	40.94820	-3.56301	906.40	15 Nov 2021
Atazar	40.90968	-3.47564	874.76	25 May 2021

4 ONE YEAR RESULTS

4.1 *Overview*

At the time of writing this paper, the solution has been operating flawlessly over 1+ year. The results presented herein illustrate the multiple data types benefits

4.2 *Snowfall*

Contrary to other single data point technologies, the adopted sensing technology collects heights across a large area in front of the sensor. The most efficient way to provide measurements is as a statistically distribution of the heights observed in such area.

Figure 5 shows snow height distribution collected across the respective areas from which accumulated volumes are calculated. During the 2021-22 winter season, there were repeated snow storms followed by higher temperatures leading to several cycles of snow accumulation and melting events. Note that a “normal” season would not have such swings in climate.

Using strategic locations in the mountains it is possible to extract very valuable information about water contribution to the watershed from snow melting events.

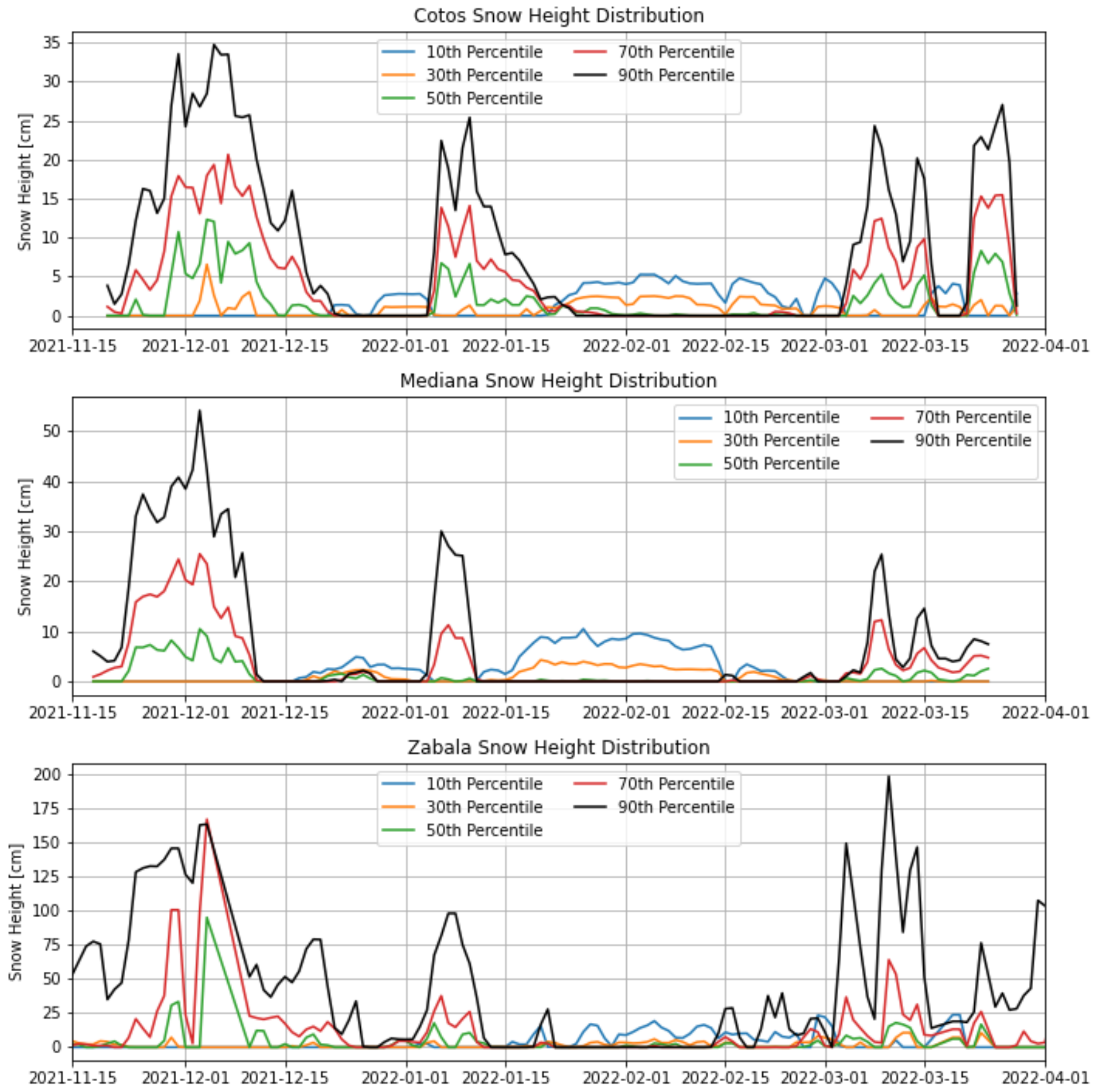

Figure 5. Measured snow height distribution over time.

4.3 *Reservoir levels*

Figure 6 below presents one year of data comparison between the new solution and that from previously existing instrumentation (point radar). The main differences between datasets are provided in Table 3.

Table 3. Main characteristics of water level datasets.

	Temporal resolution (mins)	Vertical Resolution (mm)
Reference Data	1,140	10.0
Divirod Data	5	1.0

The new datasets provide several advantages over the existing instrumentation. First, the system has run without interruption and physical intervention (scheduled maintenance or calibration) which reduces operational expenses. Second, the accuracy of the new data allows a 10 times tighter control on water availability. Taking as an example the *Atazar* reservoir with a surface area of 10.7 km^2, the water volume measurable increments can be reduced from to 0.01 hm^3. Having a tight accounting of water resources is becoming more important than ever as we witness the extremes of climate change effects: water availability affected by droughts and evaporation, and dam safety affected by torrential rain events.

4.4 *Precipitation*

Precipitation rate is another data type recorded simultaneously by the same sensing units. The radar nature of the sensing technology permits to retrieve directional rain rate, which converts this sensing unit into a small passive rain radar with scanning dependent on the position of the satellites in the sky (see Figure 7).

Figure 8 shows all precipitation events collected over the rainy season at the *Atazar* reservoir. Data available from a local rain gauge (i.e. tipping bucket of small aperture) has been overlaid in the same plot. The data collected at a single location cannot be directly compared with that collected across a large area (rain radar like).

The next step for 2023 is to use the new datasets to convert precipitation across an area into a measure of effective water collected by the reservoir.

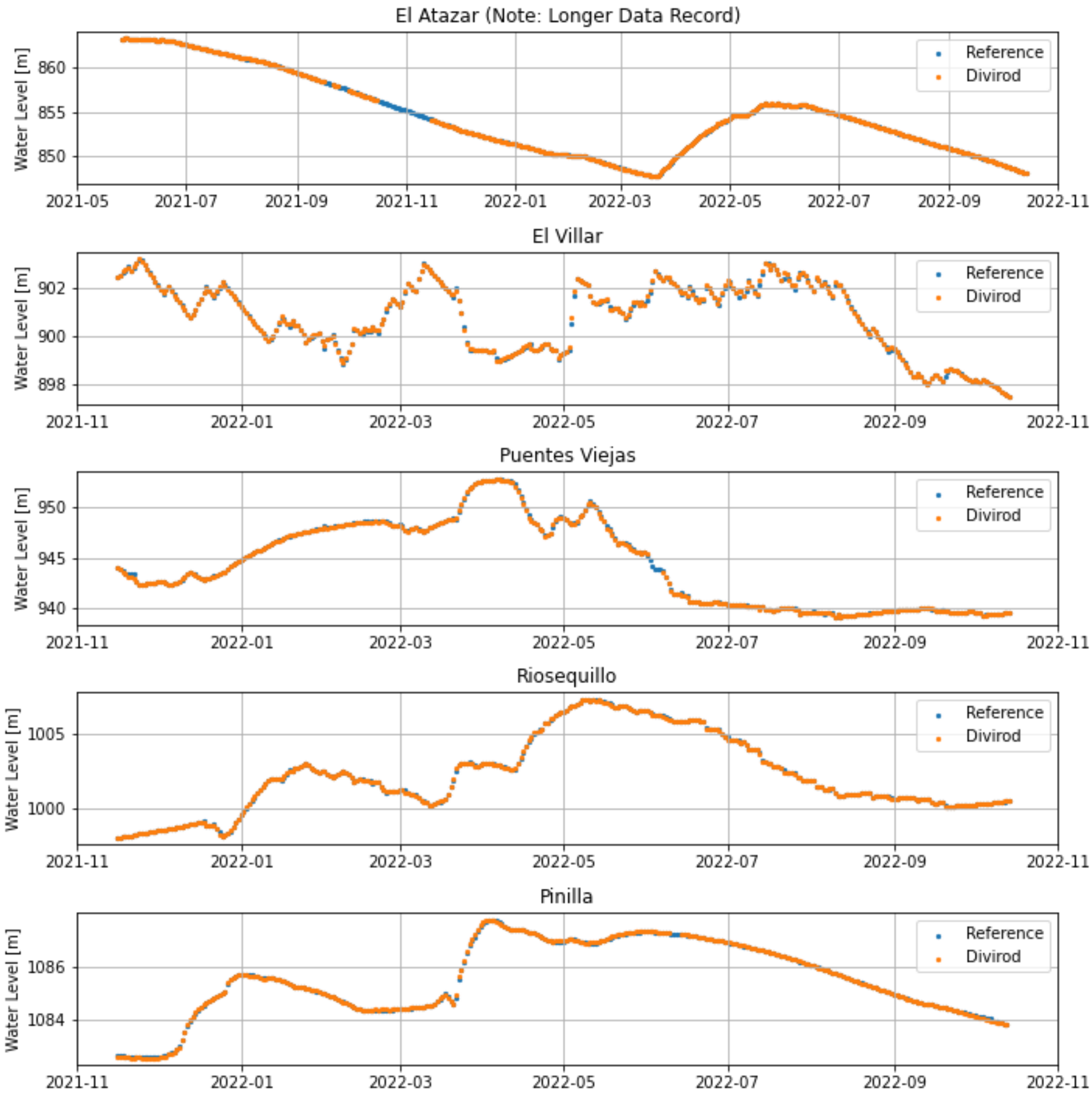

Figure 6. Reservoir water levels over time.

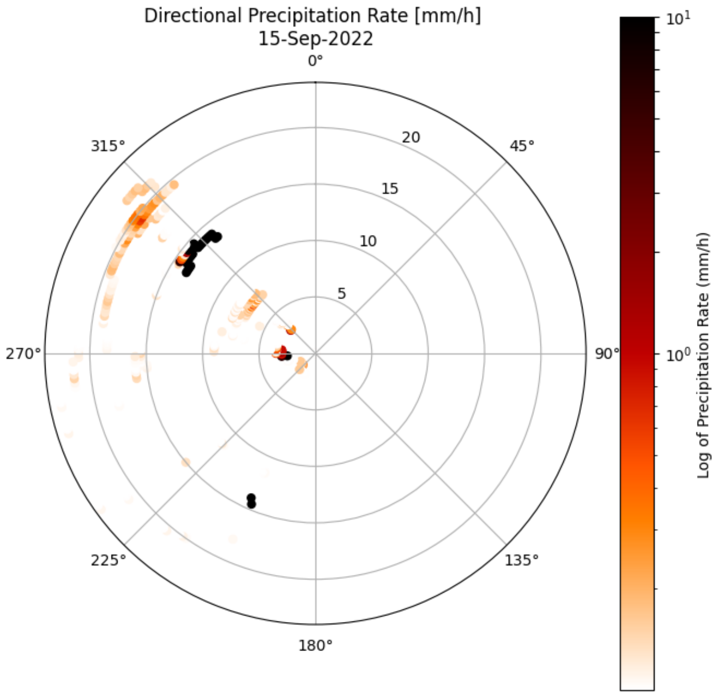

Figure 7. Precipitation rate at *Atazar* reservoir on September 15th, 2022. The precipitation rate is measured over time (radial axis) and using existing satellites in the sky (azimuth in polar axis).

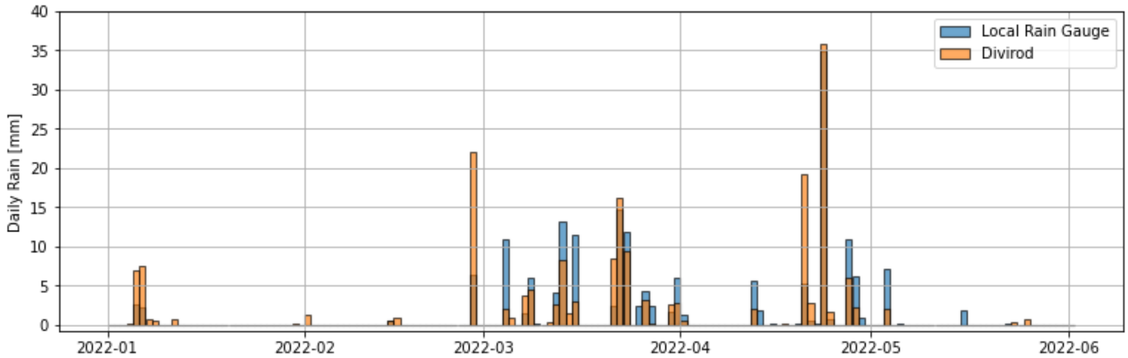

Figure 8. Daily precipitation at the *Atazar* reservoir during rainy season.

4.5 *Forecasts*

Water availability forecasts are very valuable for watershed management. In order to produce accurate forecasts, not only the right inputs have to be considered (e.g. accurate inputs of snow, rain, and demand) but also having enough data to account for seasonality patterns. The new snow datasets collected over time in the mountains together with millimeter precision water levels in the head reservoir were used to start training the forecast model.

As expected, there is a strong correlation observed (see insert in Figure 9) between snow melt from different locations and the detailed increase of water level in the head reservoir. The goal of the model is to find the effective increase of water level from snow melt. The results in Figure 9 correspond to a 7-day forecast model, that uses limited, but accurate, snow information. The RMSE obtained with the trained model is 0.63 hm^3, and the actual records fall within the predicted range. As data collection continues, the authors will include additional seasonal observations to extend the forecast range (current target is 2 months) with a smaller RMSE.

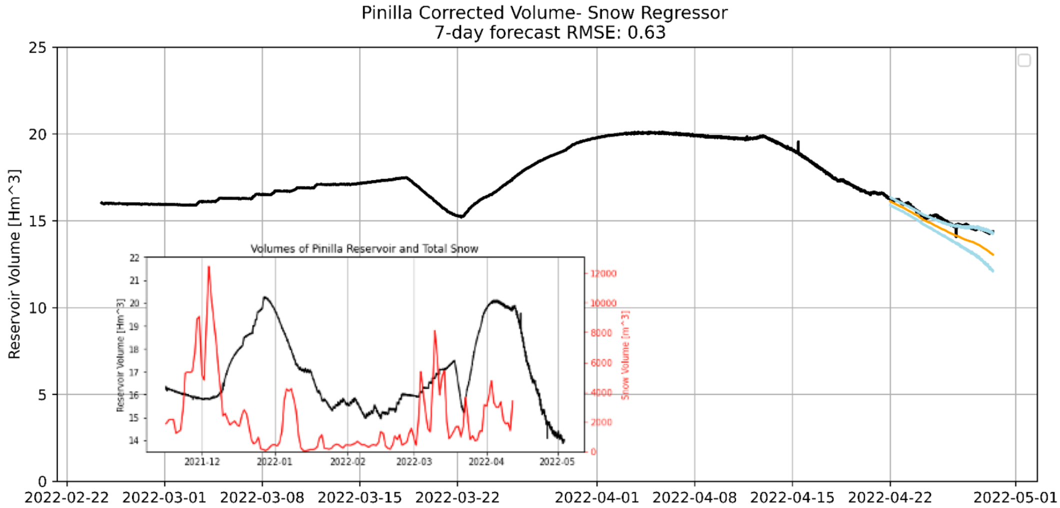

Figure 9. Water availability 7 day forecast at head reservoir, *Pinilla*. Time series of snow volume and water level of *Pinilla* reservoir (insert).

5 CONCLUSIONS

This paper has presented the data results of one year monitoring of the *Lozoya* river watershed using a new end-to-end monitoring and forecast system. Multiple water data types are retrieved with the same sensing instrumentation thanks to having access to an advanced global radar technology system.

In the case of reservoirs, the comparison with data from existing instrumentation has shown that the new approach offers a 10x improvement in water accounting. This factor is extremely important in view of the extreme situations caused by climate change. Having a permanent and accurate snow data collection in the mountains offers unique opportunities to forecasting water availability. The system also reduces the risk and hazards of field personnel accessing remote locations prone to adverse weather conditions. This use case is relevant for both watershed and hydroelectric management.

In addition, the results demonstrate the operational advantages of having an end-to-end and cost-effective solution for watershed management and decision making. The operational burden of procuring, installing, maintaining, and calibrating sensing instrumentation, is shifted from the watershed management entity to the supplier, which is only possible by using this type of scalable and robust technologies.

The high accuracy and inter-comparability of the data enable precise and accurate forecast of water availability using snow input from a set of strategic locations in the mountains. The high degree of accuracy of the measured data permits to establish very fine detail correlations between snow melting and the effective water level increase in the head reservoir. With this machine learning approach there is no need to completely map snow levels in the mountains but focus on a limited number of strategic locations, making the approach incredibly practical and cost efficient.

Lastly, the ease of data access through convenient online platforms has been commended from a user point of view. Improved user interfaces to interact with the data enables a rapid and informed decision-making process.

6 REFERENCES

Martin-Neira, M. 1993. A passive reflectometry and interferometry system (PARIS): Application to ocean altimetry. European Space Agency Journal, 17(4), 331–355.