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TESTING RADAR AND PRESSURE SENSOR METHODS FOR DIRECT STREAMFLOW MEASUREMENT AND PREDICTION IN FORESTED WATERSHEDS: A CASE STUDY IN BRAȘOV AREA

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Abstract: *Accurate measurement of streamflow in small mountain basins is critical for flood forecasting and water resource management, yet it remains challenging due to harsh conditions and lack of infrastructure. This study evaluates two modern direct discharge monitoring methods – a non-contact radar sensor and a submersible pressure transducer – in forested headwater catchments of the Carpathian Mountains in Romania. The radar device (Sommer RQ-30) and the pressure sensor (METER Hydros 21) were installed in comparable small basins to continuously record water level and discharge. We describe the measurement principles, field installations, and operational advantages and limitations of each system. Two representative flood events were analysed: a summer flash flood (peak discharge ~4.6 m³/s) monitored by the radar sensor in a 14 km² basin, and a spring snowmelt-driven flood (peak ~1.4 m³/s) captured by the pressure sensor in a 0.87 km² basin. The radar sensor provided real-time hydrographs with clearly defined peaks and minimal signal noise, while the pressure sensor (paired with a V-notch weir) yielded accurate discharge estimates but required data filtering and maintenance. Overall, the radar method performed better in capturing rapid flood dynamics and operational reliability in remote sites, whereas the pressure sensor method offered cost-effective accuracy for moderate flows and baseflow calibration. Key findings highlight the complementarity of these techniques for small mountain basins: the radar sensor ensures safety and continuity under extreme events, and the pressure sensor remains valuable for detailed low-flow measurements. The paper also discusses the comparative performance under field conditions and provides recommendations for integrating both technologies in monitoring networks.*

Key words: *streamflow measurement, radar discharge sensor, pressure transducer, small catchment, mountain hydrology, flood monitoring.*

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1. Introduction

Accurate hydrological measurements in forested watersheds are essential for understanding water resources and managing flood risks. Headwater streams in mountainous forests typically make up the majority of a river network, constituting 60-80% of the total channel length and draining 70-80% of the basin area [16]. These small upland catchments are critical sources of water for downstream ecosystems and human use [10]. At the same time, their steep terrain and concentrated runoff make them prone to flash floods and debris flows [9]. Capturing reliable discharge data from such basins is thus vitally important for flood forecasting, watershed management, and ecological studies [4]. Continuous streamflow records enable the calibration of hydrological models and inform early warning systems [14]. In short, improving measurement accuracy in rugged forested catchments can greatly enhance predictive hydrology and risk prevention in these areas.

Monitoring stream discharge in small forestry watersheds is challenging; mountain streams often have highly variable flows and complex channel conditions that complicate conventional gauging methods [27]. During intense rainstorms, headwater streams can rise and fall rapidly, with flood peaks lasting only a short time [6]. The rugged topography yields steep, narrow channels with heterogeneous cross-sections, making it difficult to establish stable stage-discharge relationships [12]. The standard method of inferring flow from water level – such as stage-discharge rating curves – becomes unreliable if the channel cross-section shifts or if turbulent, non-uniform flow conditions occur [26]. Furthermore, mountain stream channels may be periodically obstructed by wood debris or sediment movement, and their stage readings can be affected by backwater from channel constrictions [15].

As a result, obtaining continuous and accurate discharge measurements in such environments requires instruments and methods that can handle flashy flows, rough channels, and remote locations. Traditionally, streamflow in headwaters has been monitored by measuring water level and converting it to discharge via an empirical rating curve. Usually, at the national level, thousands of gaging stations are operating and computing discharge from water level using station-specific stage-discharge relationships [13].

The accuracy of the water level measurement is vital, since any error propagates directly into discharge estimates [30]. Conventional gauging installations often involve stilling wells, weirs, or flumes to stabilise flow conditions for measurement, but such structures are costly to build in remote mountain areas and can be impractical or environmentally disruptive. Maintaining reliable stage-discharge ratings in flashy small streams is an ongoing challenge [18]. Despite the high demand for data, many mountainous catchments remain poorly gauged, and large temporal gaps in discharge records are common due to equipment failure or inaccessibility [36].

Electronic pressure transducers are popular, inexpensive, compact tools for measuring stream stage (water level) via hydrostatic pressure [11]. A major advantage is their robustness, as they are largely unaffected by weather and reliably measure data when properly maintained. They are favoured in remote settings for their low power consumption and ease of installation. However, the main drawbacks arise from being submerged; they are prone to fouling (clogging by sediment/algae) and damage from debris, requiring regular maintenance [19]. Readings can also drift with temperature or age, necessitating frequent calibration checks, and converting the stage measurement to discharge (flow rate) requires a separate, re-calibratable stage-discharge relationship that can be invalidated if the streambed geometry changes [28].

Non-contact radar sensors are a modern alternative for stream monitoring, eliminating the need for in-stream equipment. Radar stage sensors measure water level by timing microwave pulses from above [24]. The main advantage is that mounting them high above the flow prevents sensor damage or loss from high flows, debris or sediment, significantly reducing maintenance and allowing them to operate during extreme floods [22]. Newer devices, like the Sommer RQ-30, combine a level meter with a Doppler surface velocimeter to measure both stage and surface velocity [35]. This velocity-area method continuously calculates discharge in real-time [25]. This approach reduces reliance on fixed rating curves and measures actual flow velocity for more accurate high-discharge estimates, the system's above-water placement protects it from damage, and it operates well in harsh weather [34].

Despite the promise of these new methods, a notable knowledge gap has remained: direct field comparisons between traditional contact sensors and modern radar systems in small, forested basins are scarce. Many studies have focused on testing one type of sensor at a time, for example, validating a radar gauge against an established rating curve, or assessing the accuracy of a pressure transducer in the lab, and few projects have deployed both sensor types side by side under the same real-world conditions to evaluate their performance differences [33].

In mountain forest catchments, where access is difficult and each method has trade-offs, such comparative data are especially valuable. This study addresses that gap by providing a direct field evaluation of a radar discharge sensor versus a pressure sensor in two forested catchments. The research objective is to compare the performance and reliability of a Sommer RQ-30 radar flow meter and a Hydros 21 submersible pressure transducer for measuring stream discharge in small mountainous basins. Through this comparative field study, we aim to identify the advantages and limitations of each method in a steep, forested watershed context.

2. Materials and Methods

2.1. Study Sites and Monitoring Setup

The comparative study was conducted in two small mountainous catchments in central Romania. The Valea Tigăi basin (Tigăi Valley) is a 14.01 km² forested watershed located in the Brasov region (Figure 1). About 89% of the basin is covered by mixed conifer (spruce, fir) and beech forests [37]. Elevations range from 854 m at the outlet (confluence with the Doftana river) up to 1,699 m at the ridge (Vf. Tigăile), with an average elevation of ~1,276 m. The basin has steep slopes and predominantly forest land cover, characteristic of Carpathian headwaters. The Valea Băii basin (Băii Valley) is a much smaller neighbouring catchment (0.867 km² or 86.66 ha) situated on the western slopes of the Piatra Mare massif. It is located entirely within forest land (fir, spruce, beech) and drains into the Timișu Mic valley to the south-east.

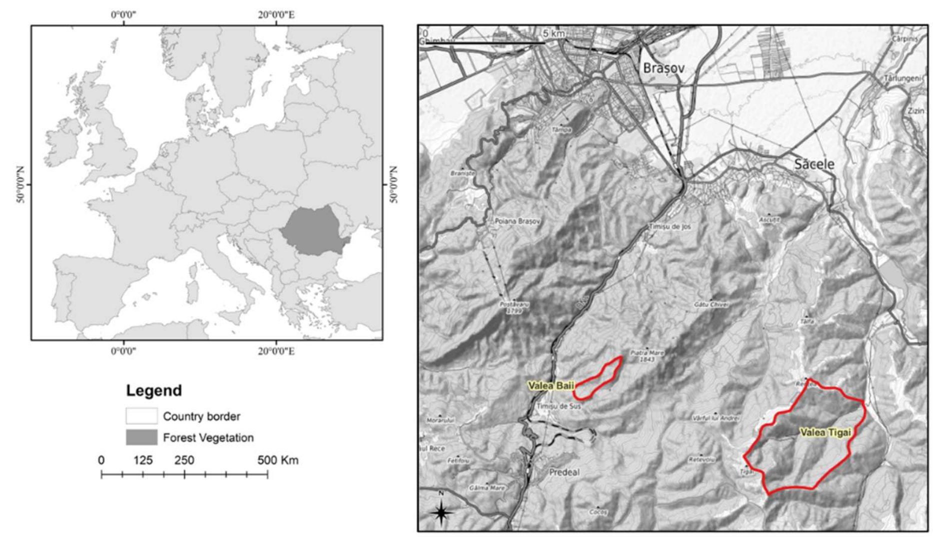

Fig. 1. *Valea Băii and Valea Tigăi watersheds limits (red) selected for study*

Both basins are ungauged, torrential streams that lacked permanent hydrometric stations prior to this study. They were selected for their similar mountainous character and to represent typical small, forested watersheds where new monitoring techniques are urgently needed to address data scarcity in headwater regions.

To monitor discharge, each basin was instrumented with a different sensor system. In the larger Tigăi catchment, a Sommer RQ-30 radar sensor was installed, while in the Băii catchment a METER Hydros 21 pressure sensor was deployed. The two sites were chosen to be broadly comparable in terms of channel morphology and flow regime (steep headwater streams), albeit at different scales. Both sensors were set up in late 2023 and recorded continuously through 2024, including several flood events described below.

2.2. The Radar Discharge Sensor (Sommer RQ-30)

The Sommer RQ-30 is a non-contact radar instrument designed for continuous discharge measurement in open channels (Figure 2). It was mounted above the stream on a bridge structure in the Valea Tigăi site. This location provided a fixed, stable support and a relatively stable cross-section, which is essential for accurate stage-discharge estimation [21]. The radar sensor was oriented to face the flow from above, at a distance of approximately 1-2 m above the maximum water surface. It operates by emitting electromagnetic waves toward the water surface and measuring the return time and Doppler shift of the reflected signals [8]. From the travel time, the sensor determines the instantaneous water level (stage), and from the Doppler frequency shift, it determines the surface velocity of the flowing water [5]. Internally, the RQ-30 combines these two measurements to compute discharge using a site-specific calibration curve or hydraulic model [7].

Fig. 2. *Non-contact radar discharge sensor (Sommer RQ-30) installed above the stream at the Tigăi catchment site* (Foto Mihalache A.)

The RQ-30 system in the Tigăi basin was configured to record at 5-10 minute intervals, providing high-resolution monitoring essential for capturing the rapid rise and fall of flash flood events common in steep terrain. To support continuous operation in this off-grid location, a small solar panel and a battery power supply were installed to ensure autonomous energy management. Data were logged locally and transmitted via a telemetry module (LoRaWAN/IoT) to a cloud platform, allowing for real-time access and remote system health monitoring.

In the Valea Băii basin, discharge was monitored using a Hydros 21 submersible pressure transducer (a CTD sensor) installed in a stilling well and paired with a custom compound weir (rectangular with a 90° V-notch insert). The compound design is critical for variable mountain streams: it ensures high sensitivity for low baseflows via the V-notch control while maintaining sufficient capacity for higher flood discharges through the rectangular section. The Hydros 21 uses a vented cable to measure the hydrostatic pressure head (stage) with approximately 1 mm resolution. The vented cable design physically compensates for barometric pressure changes, eliminating the need for a separate barometric sensor for correction.

The sensor was placed in a protected stilling well immediately upstream of the weir to measure the hydraulic head in the impoundment zone (Figure 3). While this setup offers high precision, limitations arise from the sensor being submerged. It is susceptible to sedimentation, biofouling, and damage from debris, requiring regular cleaning of the stilling well and weir notch to maintain data quality. Furthermore, accuracy can be compromised by sensor drift over time or changes in the weir structure, necessitating periodic inspections and calibration checks.

Fig. 3. *Hydros 21 submersible pressure transducer (a CTD sensor) in Valea Baii Catchment (Foto Niță M.D.)*

The Hydros 21 requires external power and logging, because it functions as part of an integrated monitoring ecosystem. In this study, data were recorded at 5-minute intervals by a data logger (METER ZL6) and transmitted via a cellular/LoRa telemetry system to the cloud. The lack of an internal battery in the sensor is mitigated by its low power draw and the centralised logger's solar charging capability.

To convert the recorded water levels into discharge, a stage-discharge rating curve was established for the hybrid weir. The theoretical discharge equations for triangular and rectangular sharp-crested weirs were applied in their respective ranges (Eq. (1)), following standard hydraulic protocols (e.g., ISO 1438 [23]). For the triangular (V-notch) portion (90° notch angle), the discharge was calculated using the Thompson equation [3]. This theoretical approach provides a robust baseline for discharge estimation in the absence of extensive field gauging, provided the weir geometry remains stable.

$$Q = C_d \cdot \frac{8}{15}\sqrt{2g}\tan\frac{\alpha}{2}\ H^{\frac{5}{2}} \qquad (1)$$

where:

α = 90° is the notch angle [°];

H – the head over the weir [m];

C_d – the discharge coefficient (experimentally around 0.59).

For a 90° notch, this simplifies to approximately $Q = 4.28\,H^{5/2}$ (in m³/s if H in m) for free flow. In our case, the coefficient was calibrated to yield $Q \approx 1.4\,H^{5/2}$ for the V-notch segment, reflecting site-specific energy losses.

When water level exceeds 0.50 m, the rectangular weir section (width equal to channel width) begins to pass flow. In that regime, the additional discharge is calculated with the rectangular weir formula $Q_{\text{rect}} = C_d{}' \cdot L\sqrt{2g}\ h^{3/2}$, where L

is the horizontal crest length and h is the head above the rectangular crest (i.e., above 0.50 m). The combined discharge for heads above 0.50 m is the sum of the triangular weir flow (up to 0.50 m) plus the rectangular flow for the excess head. During the study, we did not record any event that exceeded the capacity of the compound weir; the peak stage observed was 0.53 m (just into the rectangular regime), for which the rating curve was well-calibrated. The rating curve was verified by in situ flow measurements at low and moderate flows, ensuring its accuracy across the range.

2.3. Calibrating Model for Discharge Prediction

The distributed hydrological model for the Tigăi basin was constructed within the MIKE SHE framework (integrated into the MIKE Zero platform) by defining a 50x50m computational grid based on the DTM and configuring spatially distributed inputs for topography, land use, and soil properties via shapefiles and converted grids. Key hydrological processes, including overland flow, unsaturated zone infiltration utilising Van Genuchten relationships, groundwater recharge, and Thornthwaite-based evapotranspiration, were coupled with the 1D MIKE HYDRO River network and forced using precipitation and temperature time series distributed via Thiessen polygons. Following variable time-step simulations (1-hour for surface flow, 6-hours for subsurface), the model was calibrated and validated against observed discharge data from the outlet sensor by adjusting parameters such as surface roughness (Manning M) and soil hydraulic conductivity to optimise hydrograph agreement.

The workflow (Figure 4) began with the processing of geospatial data (DTM, land use, soil types), continued with the generation of time series (climate and hydrometric variables), and culminated in the configuration of the MIKE SHE model and its coupling with the 1D network component (MIKE Hydro River).

For calibration, a period in July 2024 was selected, using detailed data provided by the Sommer RQ-30 radar sensor (water level and flow velocity in the control section). The derived continuous discharge series (1-minute resolution) served as the reference. The model simulation was carried out with an hourly time step, with data extracted synchronously for direct comparison with the measurements.

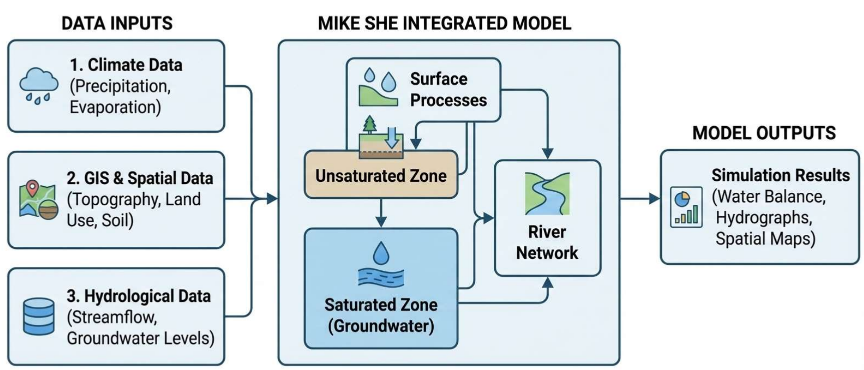

Fig. 4. *Workflow used for calibration*

3. Results

3.1. Hydrological Event Captured by the Radar Sensor

On 21 July 2024, the RQ-30 radar captured a sudden torrential flood in the 14 km² Tigăi catchment. Antecedent rainfall of ~26 mm on 20 July saturated the soil, and an intense storm in the early hours of 21 July (≈18 mm after 03:00) triggered a sharp runoff response. The radar's 10-minute interval recording clearly delineated the flood hydrograph (Figure 5).

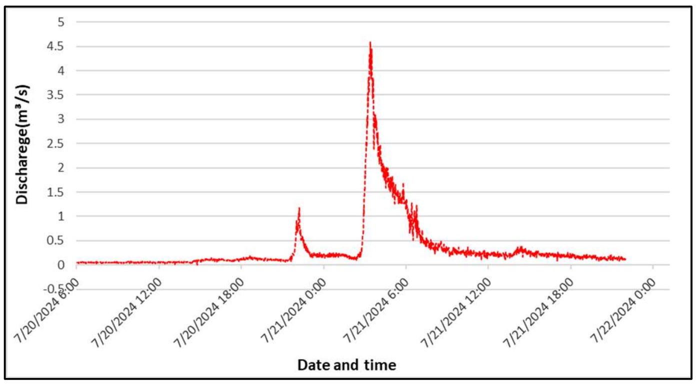

Fig. 5. *Flood hydrograph recorded by the radar sensor (RQ-30) in Tigăi basin on 21 July 2024: note the sharp peak at 03:22 and the fast rise/fall typical of a flash flood*

The water level began rising around 02:45 AM on 21 July, from a base level of ~0.05 m, and peaked at 03:22 AM with a maximum stage of 0.35 m. The corresponding peak discharge was 4.6 m³/s, the highest observed by the radar to date. This flood peak is approximately seven times the long-term mean flow (~0.65 m³/s) for the basin. The radar also measured a peak surface velocity of 3.77 m/s, which interestingly occurred one minute before the discharge peak (at 03:21 AM). This slight lead of the velocity peak can be explained by the rapid expansion of the cross-sectional area at peak stage, causing discharge to continue increasing for a moment after velocity starts levelling off. Throughout the event, the velocity remained relatively high and steady (in the range 3.6-3.8 m/s during the rising limb), indicating a consistent flow regime (supercritical or torrent flow) despite stage changes (Figure 6).

After the peak, the flood subsided over several hours. By 04:22 AM (one-hour post-peak), the water level had fallen to ~0.17 m (half of the maximum), and discharge has dropped to 1.9 m³/s. Notably, the surface velocity showed only a modest decrease by that time (around 3.26 m/s, down from 3.7 m/s at the peak). This indicates that even as flow depth decreased, the stream maintained considerable kinetic energy (likely due to the steep channel slope). By 07:22 AM (four hours after the peak), the stream had largely returned to baseflow: stage was ~0.06 m and discharge 0.46 m³/s, roughly 10% of the peak value. Velocity at that time was 2.1 m/s, still above what one might expect for such a shallow depth, suggesting residual fast runoff in the channel.

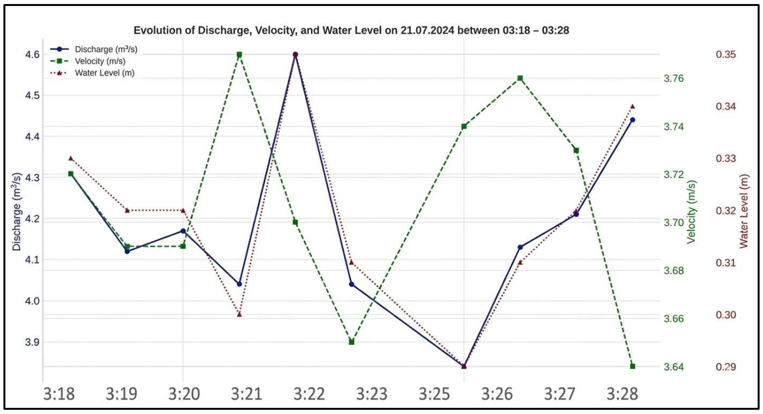

Fig. 6. Graph of the evolution of hydrometric parameters in the Tigăi river basin

Overall, the radar sensor captured the flood event in fine detail, with a well-defined, sharp rise and exponential-like recession. The hydrograph is characterised by a very steep rising limb (<40 minutes from near-baseflow to peak) and a more gradual recession (~4-5 hours to return close to baseflow). The precise timing of the peak and the high temporal resolution of the data demonstrate the radar's ability to monitor flashy floods in small basins. No data gaps or spikes were present, indicating the sensor remained fully functional and unperturbed by the high flow. The only minor irregularity was the slight plateau in velocity readings around the peak (as noted, velocity did not drop as quickly as stage), but this is a real hydrodynamic effect rather than sensor noise.

3.2. Hydrological Event Captured by the Pressure Sensor

The second event analysed occurred during the monitoring period from 1 October 1 to 15 October, 2025, in the 0.87 km² Valea Băii catchment, monitored by the Hydros 21 multi-parameter sensor (water level, temperature, and electrical conductivity) and compound weir. This significant flow event was driven by autumn rainfall. The water level began rising sharply early on 8 October, peaking later that afternoon at a maximum stage of approximately 70 cm (0.70 m), a substantial increase from the pre-event base levels, which fluctuated between 20 and 30 cm.

The sensor recorded the entire hydrograph showing a rapid rising limb characteristic of a rainfall runoff response in a small, steep catchment. Following the peak, water levels receded gradually over the next four to five days, returning toward baseflow conditions by 14 October (Figure 7). While explicit discharge values are not presented in this chart, a stage of 0.70 m represents a major hydrological event for the small Băii basin relative to its typical flows. Smaller hydrological pulses were also noted earlier in the month around 3 October, and during the recession limb around 11 October.

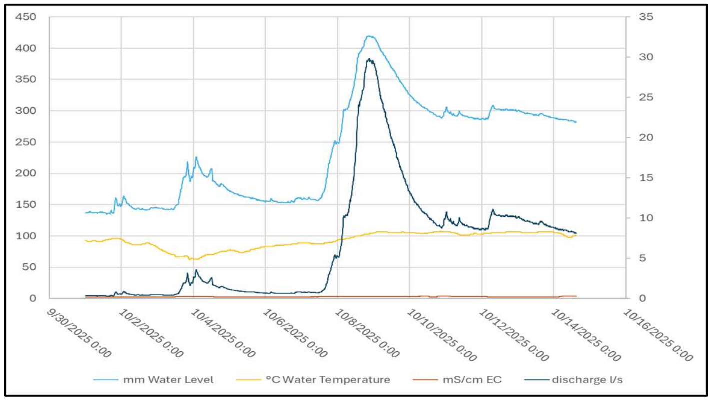

Fig. 7. *Multi-parameter hydrograph recorded by the Hydros 21 sensor in Băii basin during 1-15 October, 2025, showing Water Level (cm), Temperature (°C), and Electrical Conductivity (µS/cm)*

A significant advantage of the Hydros 21 sensor used in this deployment is the simultaneous capture of ancillary environmental data, which provides crucial context for the hydrological event. The figure clearly demonstrates the interplay between streamflow generation and water chemistry. Preceding the flood, electrical conductivity showed strong diurnal fluctuations generally ranging between 200 and 275 µS/cm. As the water level rose sharply on 8 October due to rainfall runoff, electrical conductivity exhibited a dramatic decrease, dropping to a minimum near 100 µS/cm during the flood peak. This is a classic illustration of the "dilution effect," where incoming precipitation, which has very low ionic content, dilutes the solute-rich groundwater baseflow. As water levels receded after 9 October, conductivity values gradually recovered toward pre-event levels.

Concurrently, water temperature also responded to the event. While generally showing diurnal variations between roughly 10 and 14°C, the temperature signal was dampened and depressed slightly during the peak runoff phase on 8 October, suggesting the input of cooler precipitation waters and reduced thermal influence from solar radiation during the storm event. The combined data successfully captured the physical and chemical dynamics of this autumn flood event without exceeding the measurement limits of the sensor or weir.

3.3. Hydrological Model Calibration Results

Calibration focused on adjusting the hydraulic roughness parameters (Manning's M), the infiltration coefficients, and the unsaturated zone parameters. Figure 8 presents the graphical comparison for the significant flood event of 21 July, 2024. The model reproduces the general shape of the flood wave well, but the peak timing is delayed by approximately 40 minutes, and the simulated recession curve is steeper, suggesting a slower basin response time in the model than in reality.

The model performed in simulating peak magnitude: the simulated maximum discharge (4.61 m^3/s) was practically identical to the observed one (4.60 m^3/s), with a deviation of only +0.2%.

However, due to the temporal delay of approx. 40 minutes (Figure 9), the statistical performance indicators (Table 1) were modest.

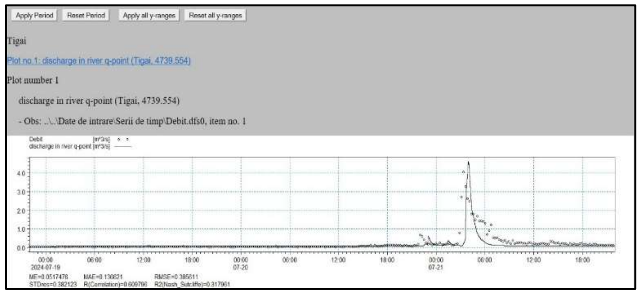

Fig. 8. *Comparison of simulated and observed discharge in the Tigăi basin (modelling results extracted from MikeSHE, for the period 19-21 July, 2024)*

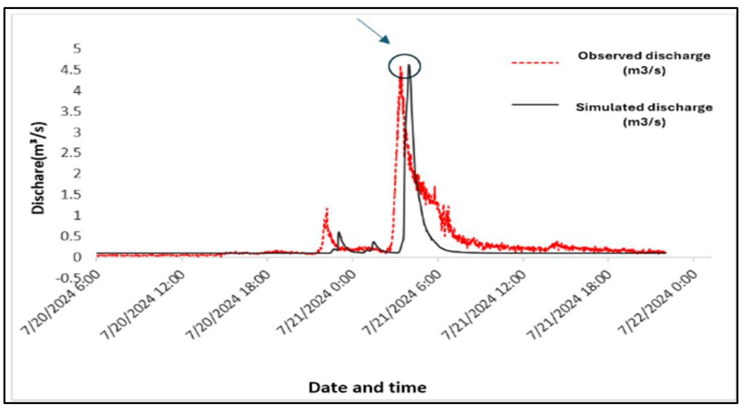

Fig. 9. *Observed versus simulated discharge*

Simulated versus observed indicators Table 1

Indicator	Simulated	Observed
Q	682.5	903.5
Water balance (wbl)	58972551.18	78058080.00
Water balance error (wbl%)	24.45%	-
Minimum	0.00	0.00
Maximum	4.61	4.60
Mean	0.16	0.21
R^2	0.75	-
Pearson Correlation Coefficient	0.87	-
	248.06	-
	942.05	-
NSE	0.74	-

The Nash–Sutcliffe Efficiency (*NSE*) of 0.32 and the coefficient of determination (R^2) of 0.37 reflect unsatisfactory performance according to the criteria of Moriasi et al. [32], caused by the lack of synchronisation. Nevertheless, the RMSE had a low value (0.385 m^3/s, approx. 8.4% of the simulated peak), and the Pearson correlation coefficient (0.61) indicated a moderate correlation, with the model following the general trend.

The volumetric analysis (Figure 10) showed a water balance error (wbl%) of 24.85%. The total volumes (Vsim = 58.66 x 10^6 m^3 vs. Vobs = 78.06 x 10^6 m^3) indicate an underestimation of runoff by the model. This suggests that a portion of precipitation is excessively retained as infiltration or subsurface storage, possibly due to overestimated hydraulic conductivity in the unsaturated zone.

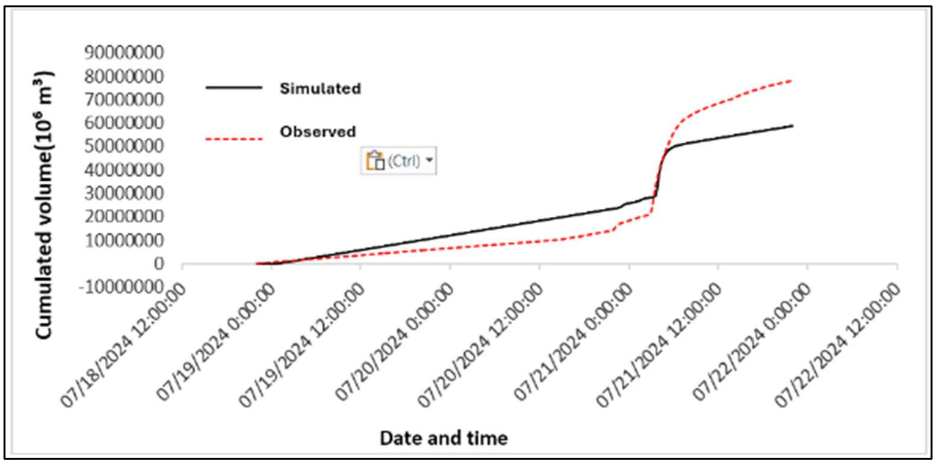

Fig. 10. *Comparison of cumulative observed and simulated volumes for the Tigăi hydrographic basin (period 18-22 July, 2024)*

4. Discussion

The outcomes of this comparative study highlight how emerging sensing technologies can be applied to improve hydrological measurements in ungauged, forested mountain basins. Obtaining reliable discharge data is crucial for flood risk management, model calibration, and water resource assessment in mountain hydrology [38]. Traditional methods face significant hurdles in these environments, such as steep terrain, flashy flows, and lack of infrastructure [1]. Our findings confirm that radar and pressure sensors offer modern, efficient, and scalable solutions for continuous monitoring in such settings [29]. Both sensor types captured everyday baseflow conditions and extreme events, providing high-resolution datasets needed for advanced hydrological analysis and early warning systems.

Regarding performance and suitability, the *radar sensor (RQ-30)* proved particularly suited for remote mountainous areas requiring autonomous operation. Its successful deployment in the Tigăi basin, an area without stable mains power or easy access, shows the practicality of a self-powered, telemetry-enabled radar unit. This aligns with other reports of radar stream gauges functioning well in hazard-prone, hard-to-reach locations [17].

The advantages of non-contact measurement were evident: no sensor outages due to debris impact or lightning occurred, and maintenance was minimal. These benefits come at a higher initial cost relative to simpler methods. However, considering the value of real-time data for flood forecasting, the investment can be justified. In our case, the RQ-30 delivered real-time discharge readings accessible instantly via the IoT network, a critical advantage in mountain flood warning [20, 31].

On the other hand, the *pressure sensor plus weir approach* underscores the viability of low-cost monitoring solutions for small streams and research applications. The Hydros 21 sensor is relatively inexpensive and was effectively combined with a modified weir to yield high-precision measurements, especially for low flows. This approach can be replicated in other small basins where a weir or flume can be installed.

The trade-off is the need for regular oversight. The sensor must be checked for fouling, and the weir must be maintained. In heavily forested basins like Valea Băii, leaf litter and sediment are constant challenges, with the V-notch requiring frequent cleaning to prevent clogging. Thus, operational limitations include potential data gaps if maintenance is delayed or if extreme events damage the structure [19]. Nonetheless, pressure transducers remain very useful for establishing stage-discharge relations and for collecting multi-parameter data sets in streams, making them well-suited for research-focused deployments [28].

Regarding data quality and hydrological insights, the high-resolution data obtained in this study allow some hydrological interpretations. The flash flood in Tigăi exhibited a classic flashy response with a lag of only tens of minutes from rainfall to peak flow. The high velocity, even as discharge fell, suggests the flood wave was quickly flushed through the basin with little backwater or storage. The pressure sensor data from Băii provide insight into spring melt behaviour in a small basin, showing a prolonged recession likely sustained by groundwater release

These observations contribute to the sparse literature on hydrological response in Carpathian forest watersheds. By demonstrating the sensors' ability to capture these dynamics, the study supports their application in improving hydrological models. For instance, the radar data from Tigăi were used to calibrate a distributed hydrological model (MIKE SHE) in subsequent research, achieving Nash-Sutcliffe Efficiency ~0.74 for flood simulation. This underscores that better field data translate to better model performance, fulfilling one of the original motivations for the sensor deployment [28].

To further contextualise our findings, it is helpful to compare them with other studies and manufacturer specifications. Pressure transducers are known for their affordability and ease of integration, and are widely used in small catchment studies [19]. Our experience corroborates this advantage, as setting up the Hydros 21 was straightforward and low-cost. However, the limitations we encountered (immersion issues, clogging potential, calibration needs) are also commonly reported.

Radar gauges like the RQ-30 have been reported to provide reliable measurements in conditions where traditional gauges fail. Indeed, our results reflect extremely consistent performance from the radar during the extreme event, aligning with those reports. A limitation of radar systems is the requirement for a known cross-sectional profile to compute discharge [20]. In this study, that requirement was met by installing the radar at a stable bridge section and surveying the channel. In more dynamic channels, a radar alone might struggle unless paired with another sensor or method to update the cross-section.

The complementary strengths of the two sensors suggest that an integrated monitoring strategy could yield the best overall coverage [9]. For example, a small basin network might employ radar sensors at sites prone to violent floods or where maintenance access is limited, and pressure sensors in tributaries or for calibrating low-flow portions of the hydrograph.

Our results imply that a hybrid system – perhaps deploying both a radar and a pressure sensor at the same site – can provide cross-verification and fill gaps [2, 9]. A radar could capture flood peaks while a pressure sensor on a weir could refine low-flow measurements, ensuring accuracy across all flow ranges. Data from both can feed into hydrological models to improve spatial and temporal representation of runoff processes [13]. In contexts like the Carpathians, where many basins remain ungauged, deploying a combination of modern sensors is a promising path to greatly enhance data availability for flood forecasting and climate change impact assessment [37].

Finally, it is worth noting the importance of data transmission and real-time capabilities. Both systems were equipped with telemetry, which is increasingly standard. The radar's data were available in real-time, crucial for early warning, whereas the pressure sensor's data were also accessible remotely with slight delay due to post-processing needs. In practical terms, any sensor network in these basins should be coupled with robust communication to ensure data can be acted upon. IoT and LoRaWAN solutions make even remote forest sensors reachable, as demonstrated by integrating the devices into a cloud platform for visualisation. This digital integration is a critical aspect of modern hydrological monitoring, enabling data collection, automated alerts, and decision support.

5. Conclusions

This study demonstrated the effective application of modern sensing technologies to overcome the significant challenges of monitoring discharge in ungauged, steep forested mountain basins. The comparative field analysis revealed distinct operational advantages for each system: the non-contact radar sensor proved superior for capturing rapid flash floods in remote locations due to its robustness, real-time capability, and minimal maintenance requirements. Conversely, the submersible pressure sensor combined with a compound weir offered a cost-effective solution with high precision for baseflows and moderate events, though it demanded more intensive maintenance and data post-processing due to fouling and noise. Furthermore, the successful integration of high-resolution radar data to calibrate a distributed hydrological model (MIKE SHE) underscored the critical dependence of predictive modelling accuracy on reliable field observations. Ultimately, given their complementary strengths, a hybrid monitoring strategy utilising both radar and pressure sensors is recommended as the most effective approach for enhancing hydrological data coverage and improving flood risk management in rugged mountain environments.

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