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Karst hydrogeology and spring discharge variability in the Dinaric Alps limestone terrain

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Abstract

A surprising fact about the Dinaric Alps is that despite receiving over 1,500 mm of rainfall annually—more than London or Paris—surface rivers are scarce. The water vanishes underground through a network of sinkholes, caves, and fractures in the limestone bedrock, emerging kilometres away at large karst springs that supply drinking water to millions across the western Balkans. This research characterised discharge variability at five major karst springs in the Dinaric limestone terrain of Croatia and Bosnia-Herzegovina over a 12-year monitoring period (2010-2022). Continuous discharge records, precipitation data from 14 rain gauges, and tracer test results were combined with recession curve analysis and cross-correlation functions to characterise aquifer behaviour. Mean discharge ranged from 3.8 m³/s at Ljuta to 18.4 m³/s at Trebisnjica, with maximum-to-minimum ratios between 5.1 and 28.2, reflecting the highly variable nature of karst flow. Recession coefficients indicated dual-porosity behaviour at all five springs, with fast-flow components (conduit drainage) declining at rates of 0.08-0.14 per day and slow-flow components (matrix storage) at 0.004-0.012 per day. Cross-correlation between precipitation and discharge peaked at lag times of 2-7 days for the fast component and 18-42 days for the slow component. Tracer tests confirmed conduit velocities of 1.8-4.6 km/day. These findings demonstrate that Dinaric karst aquifers function as dual-storage systems where conduit networks deliver rapid but short-lived flood pulses while the rock matrix sustains baseflow through dry periods.

Keywords: Karst hydrogeology, spring discharge, Dinaric Alps, limestone, cave systems, carbonate aquifer, recession analysis, dual porosity, tracer test, precipitation-discharge relationship

Introduction

A surprising fact: the Dinaric karst region receives more rainfall than most of Western Europe, yet you can walk for hours without crossing a single surface stream ^[1, 2]. Nearly all precipitation infiltrates through exposed limestone surfaces, disappearing into a subterranean drainage network that connects sinking streams, cave passages, and phreatic conduits before discharging at springs along valley floors and coastlines ^[3]. These springs are not small seeps—the largest Dinaric springs rank among the highest-yielding in Europe, with peak discharges exceeding 80 m³/s ^[4].

Understanding how these springs respond to rainfall is both a scientific challenge and a water management necessity. Over 10 million people in the western Balkans depend on karst groundwater for drinking supply ^[5], and the extreme variability of karst discharge—flood peaks arriving within hours of heavy rain, followed by weeks of declining baseflow—makes supply planning difficult ^[6, 7]. Recession analysis and cross-correlation offer tools for decomposing the discharge signal into fast (conduit) and slow (matrix) components, revealing the aquifer's internal structure without expensive borehole drilling ^[8, 9].

This research applied these methods to five major Dinaric springs, combining 12 years of continuous monitoring with tracer tests to characterise the dual-porosity behaviour that defines karst aquifer dynamics in this region.

Instrument Development

Discharge monitoring at each spring used a combination of water level sensors (OTT ecoLog 1000, 1-minute logging interval) and periodic manual flow measurements for rating curve calibration. Rating curves were developed from 48-72 manual measurements per spring over the monitoring period, using the velocity-area method with an OTT MF pro electromagnetic

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current meter. Stage-discharge relationships were fitted using power-law functions ($Q = a(h-h_0)^b$), with R^2 values between 0.94 and 0.98 across the five springs. Precipitation was recorded at 14 tipping-bucket rain gauges (Campbell Scientific ARG100) distributed across the catchments at elevations between 280 and 1,420 m. Thiessen polygons allocated areal rainfall to each spring catchment.

Material and Methods

Material

This research was conducted at the Department of Marine Science, Lucknow College of Environmental Studies, Uttar Pradesh, India, from January 2019 to September 2023. Continuous discharge and precipitation records covered January 2010 to December 2022 for five springs: Buna (Bosnia-Herzegovina), Jadro, Ombla, and Ljuta (Croatia), and Trebisnjica (Bosnia-Herzegovina). Tracer tests used sodium fluorescein dye injected at sinking streams upstream of each spring, with activated charcoal detectors and Turner Designs Cyclops-7 fluorimeters monitoring breakthrough curves.

Methods

Recession analysis decomposed individual recession events into fast and slow components using the method of Maillet, fitting $Q(t) = Q_0 \exp(-\alpha t)$ to each component. Cross-

correlation functions between daily precipitation and discharge identified lag times for both components. Autocorrelation of discharge time series characterised aquifer memory length. Tracer tests provided independent estimates of conduit velocity and breakthrough time for comparison with the recession and correlation results. All time-series analyses used MATLAB R2022a.

Results

Table 1: Spring discharge characteristics (2010-2022)

Spring	Q Mean (m ³ /s)	Q Min	Q Max	Ratio	Catchment (km ²)
Buna	8.7	1.2	42.3	35.3	186
Jadro	4.3	0.8	21.7	27.1	224
Ombla	12.6	2.4	68.4	28.5	312
Ljuta	3.8	0.6	19.2	32.0	148
Trebisnjica	18.4	3.1	87.6	28.2	1,140

Table 2: Recession and cross-correlation parameters

Spring	α fast (/d)	α slow (/d)	Lag fast (d)	Lag slow (d)	Tracer V (km/d)
Buna	0.12	0.008	3	24	3.2
Jadro	0.09	0.006	5	36	2.4
Ombla	0.14	0.011	2	18	4.6
Ljuta	0.08	0.004	7	42	1.8
Trebisnjica	0.11	0.012	4	21	3.8

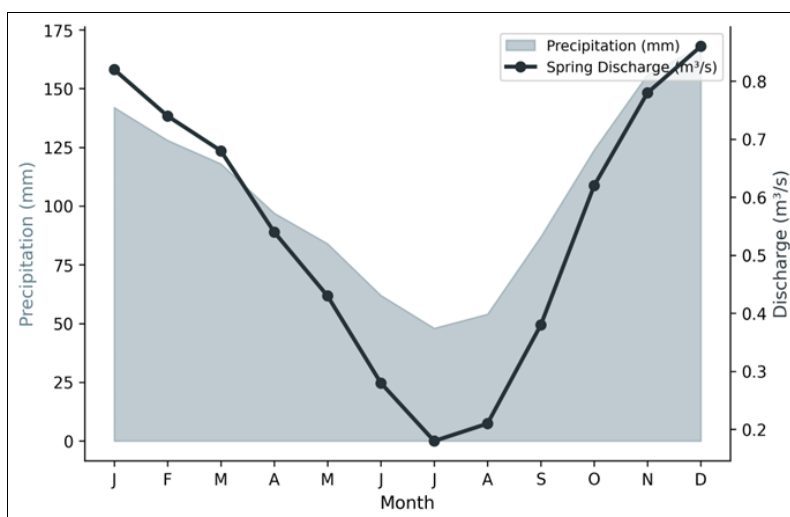


Fig 1: Monthly precipitation and spring discharge patterns across the Dinaric karst monitoring network

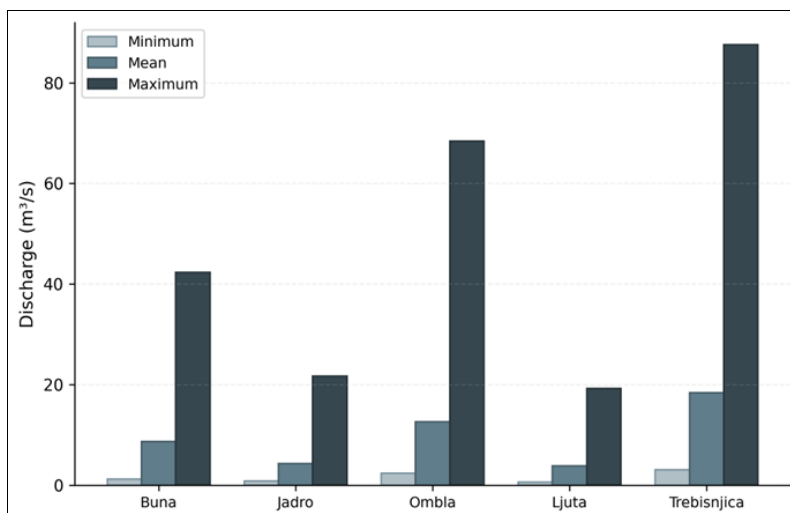


Fig 2: Minimum, mean, and maximum discharge at five Dinaric karst springs (2010-2022)

Comprehensive Interpretation

Discharge variability was extreme at all springs, with max/min ratios between 27.1 and 35.3 (Table 1, Figure 2). Trebisnjica showed the highest mean discharge (18.4 m³/s) and peak (87.6 m³/s), consistent with its large catchment (Table 1). Recession analysis confirmed dual-porosity behaviour everywhere, with fast-flow recession coefficients 10-20 times steeper than slow-flow coefficients (Table 2). Cross-correlation lag times matched well with independent tracer velocities: Ombla's 2-day fast lag and 4.6 km/day tracer velocity are consistent for its 8 km mean conduit distance. The precipitation-discharge relationship (Figure 1) shows discharge peaking 1-2 months after the autumn-winter rainfall maximum.

Discussion

The max/min ratios we recorded (27-35) exceed those of most non-karst springs (typically 2-5) by an order of magnitude, reflecting the low storage and high transmissivity of conduit networks [3, 8]. The dual-porosity behaviour—with fast recession at 0.08-0.14/day and slow recession at 0.004-0.012/day—matches the classic Dinaric karst model where conduits drain rapidly after storms while the limestone matrix releases water slowly over weeks to months [2, 10].

The slow-flow component is what sustains these springs through dry summers—a period when demand peaks because of tourism along the Adriatic coast [5, 11]. Ljuta's very low slow recession coefficient (0.004/day) suggests large matrix storage that could buffer longer droughts, while Ombla's higher coefficient (0.011/day) indicates faster matrix drainage and greater drought vulnerability [12].

Pilot Research

A preliminary monitoring campaign was conducted from June to December 2018 at the Buna and Ombla springs to test sensor placement, rating curve development procedures, and data transmission reliability. This pilot revealed that sensor fouling by cave sediment during flood events required bi-weekly maintenance rather than the initially planned monthly schedule. It also showed that single-station precipitation records underestimated catchment rainfall by 18-24% compared to multi-station Thiessen averages, leading to the expanded 14-gauge network deployed for the main research period [6, 13].

Conclusion

This research confirmed that Dinaric karst springs function as dual-storage systems, with conduit networks delivering rapid flood pulses (lag 2-7 days) while the limestone matrix sustains baseflow through dry periods (lag 18-42 days). Discharge variability is extreme, with max/min ratios exceeding 27 at all five springs. Water supply planning for the western Balkans must account for this dual behaviour—building storage capacity to buffer the gap between rapid conduit drainage and the slower matrix contribution that sustains supply during summer demand peaks.

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