

Application of k-means clustering on flood episodes in small catchments in Croatia

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This study presents an application of the k-means clustering method to the analysis of historical flood episodes in small catchments across the Republic of Croatia for the period 1998–2018. A total of 845 flood events with reliable and complete information were selected and described using three key parameters: flood duration, the size of affected area, and the portion of arable land within the flooded area. The results indicate that flood events in small catchments of the Danube River basin can be classified into five distinct clusters, while those in the Adriatic Sea basin are more uniform and can be grouped into two clusters. The identified clusters reveal significant differences in flood characteristics, allowing for the identification of flood types that require priority attention in flood risk management. The study demonstrates that multivariate clustering is a valuable tool for characterizing and regionalizing floods in small catchments, thereby supporting decision-making processes in flood risk management in Croatia.

KEY WORDS: floods, k-means clustering, small catchments, Croatia

Introduction

Anthropogenic and climate change-induced floods have been the focus of hydrologists for more than two decades. Intensities and frequencies of floods increase in many parts of Europe and other continents as well. Research on historical floods indicates that changes in their intensity and frequency have occurred over the last 60 years (Alifu et al., 2022). Analysis of streamflow and climate observations from 1960 to 2010 in Europe reveals that shifts in flood generation processes contribute more to the occurrence of regional flood anomalies than changes in extreme rainfall (Tarasova et al., 2023).

Due to the complex genesis of floods and their high dependence on regional geographical features, it is impossible to create a consistent flood characterization on a large scale. However, small catchments are specific in hydrological sense and they have different landscape parameters than large ones. Usually they have lower variability of precipitation (Paulíková et al., 2024). So, it increases possibility to establish flood regionalization on a smaller scale, such as in Europe (Blöschl et al., 2019). Another frequently raised question concerns the magnitude of floods and the varying sizes of catchments. In other words, are floods more frequent in small and medium catchments or in the large catchments? Results show different regional trends in Eastern, North-western, and Southern Europe (Bertola et al., 2020). The second regionalization of floods was related to flood drivers; according to the results, in north-western Europe, extreme precipitation has been the main cause of changes

in flood events over the past 50 years. In southern Europe, extreme precipitation, combined with antecedent soil moisture, contributes to changes in flood patterns. In Eastern Europe, the most significant drivers are changes in snowmelt (Bertola et al., 2021). There are certain changes in the timing of flood events, as earlier snowmelt causes larger floods to occur earlier, particularly in regions such as the Alpine, Northern, and Continental European areas (Fang et al., 2025). Additionally, analysis of the annual flood peaks from 1965 to 2005 reveals that more significant trends are detected in flood frequency than in flood magnitude (Mangini et al., 2018).

However, changes in river flood occurrence must have implications for future flood protection structures, measures, and the redefinition of flood risk areas (Blöschl et al., 2019). Another flood analysis confirms that much more attention has been given to the hydrological, hydraulic, and water management aspects of flood protection than to the socio-economic aspects of the problem related to flood consequences (Merz et al., 2010). Research on flood exposure in 37 European countries since 1870 indicates an increase in the annually inundated area and the number of persons affected, but flood fatalities have substantially decreased (Paprotny et al., 2018). The fact is that areas in the vicinity of water have always been densely populated, which now reveals the necessity of rethinking the territory to assess future events due to changes in the magnitude, frequency, and timing of river floods (Blöschl et al., 2017; Blöschl et al., 2019). Historical data on mega floods that occurred in European rivers,

collected from over 8,000 gauging stations, confirm that almost all of them (95.5%) fall within the envelope values estimated from previous floods in other similar places on the continent (Bertola et al., 2023). In other words, research on historical floods can teach us a great deal, despite the changes that have occurred over longer periods.

Floods can be analysed from several aspects, and the characterization of floods as small or large can be based on different parameters. In this work, we aim to identify floods in Croatia that exhibit similar behaviour and specific characteristics with respect to several criteria (Pappada et al., 2018). Generally, cluster analysis is a multivariate statistical method that connects and extracts useful information from large datasets. It can be very useful in water and groundwater quality classifications (Javadi et al., 2017; Bu et al., 2020; Aytaç, 2020; Li et al., 2025a).

Flood regionalization and identifying previous floods risk together with predicting future flood events are essential for understanding the changing patterns in flood occurrence (Lai et al., 2020). Apart from k-means clustering methods, the most common methods used for flood regionalization are other clustering methods such as Agglomerative hierarchical clustering (AHC), Univariate clustering or Fuzzy k-means clustering. They are based on criteria that are used for determining whether two or more data sets are similar or dissimilar (Rokach and Maimon, 2005). Recently, machine learning models such as Random Forest and CatBoost are recognized as a tool of superior accuracy in defining spatially coherent and applicable maps of flash floods (Ke et al., 2026). For example, combination of Graph Neural Network (GNN) method, Dink-Net, and Shapley Additive exPlanations (SHAP) was successfully applied for flash flood regionalization (Li et al., 2025b). Also, combination of hydrological clustering and machine learning in flood risk assessment is one of the possible approaches for better understanding flood regionalization (Scorzini et al., 2026).

Specifically, in flood management, clustering is very useful tool. For example, clustering can help identify significant rain gauge stations for flood forecasting (Mehta et al., 2023). Alternatively, cluster analysis can group areas with similar characteristics in terms of vulnerability and create vulnerability classes (Fernandez et al., 2016). Another study divides the European territory into regions of similar projected climate changes using k-means clustering, simulating daily total precipitation and other meteorological parameters, and reveals overall similar regions of change (Carvalho et al., 2016). It was also utilized as an algorithm to assess urban flood risk (Xu et al., 2018). The most recent investigation of floods in Croatia are dealing with floods in urban or partially urban catchments (Krvavica and Rubinić, 2020; Nimac et al., 2022; Krvavica et al., 2023). Another field of interest is related to coastal flooding (Marić et al., 2024; Ljubenkov et al., 2024). This fact clearly shows the most vulnerable aspect of flood protection in Croatia strongly exposed to climate change impacts.

In this case study, the k-means clustering method has been applied to flood episodes that occurred in Croatia

between 1998 and 2018. The initial database has over 1000 flood events that occurred in small catchment areas. The database does not contain floods that occurred on large rivers, such as the Danube, Drava, and Sava rivers. According to EU Directive 2007/60/EC (2007) on the assessment and the management of flood risks, Croatian water authorities created „Register of flood events” (Hrvatske vode, 2019) in order to identify common patterns of flood dynamics. In particular, each flood event has been considered as a multivariate object characterized by a number of physical variables: source of flooding (fluvial, pluvial, groundwater or coastal and failure of artificial water bearing structure); flood duration in days; affected area in km², return period, characterisation of damages caused by floods (number of inhabitants, adverse effects on population and heritage and economy affected), type of economic activity and vegetation cover of the affected area (agricultural area, forests, industry, infrastructure etc.). Floods caused by the sewerage system are not included. However, many of these flood characteristics are not available or not reliable, so parameters included in further statistical analysis has to be reduced.

The primary objective of this paper is to categorize historical floods into classes based on similar characteristics through multivariate clustering, thereby highlighting the most affected flooding areas and defining priorities for flood protection development.

Materials and methods

The study area encompasses the entire territory of the Republic of Croatia (56 594 km², excluding the Adriatic Sea). Its area belongs to the Danube River basin by 62% and to the Adriatic Sea basin by 38%. The largest and international rivers, such as the Drava and Sava rivers and their sub-catchments, belong to the Danube River Basin. Fig. 1 presents 34 flood protection units corresponding to small catchment areas – 20 in the Danube River basin and 14 in the Adriatic Sea basin. They belong to larger management areas designated in different colours and presented in the Table 1. Flood management in Croatia has a long history, and this flood protection system has been established decades ago.

The major division is related to the Danube River basin and the Adriatic Sea Basin and these two basins have significant differences in vegetation cover, climate, slope, relief and hydrological and geological characteristics.

The Danube River Basin

The Croatian part of the Danube River Basin is mostly alluvial lowland with an altitude between 80 and 1656 m a.s.l. Land cover mostly consists of agricultural fields, app. 33% and forests (49%) (Hrvatske vode, 2009).

The average annual precipitation for the entire Croatia is shown in Fig. 2. for the observed period of 1981–2022, precipitation ranges from 600 to 2000 mm. When observing only the territory of the Croatian part of

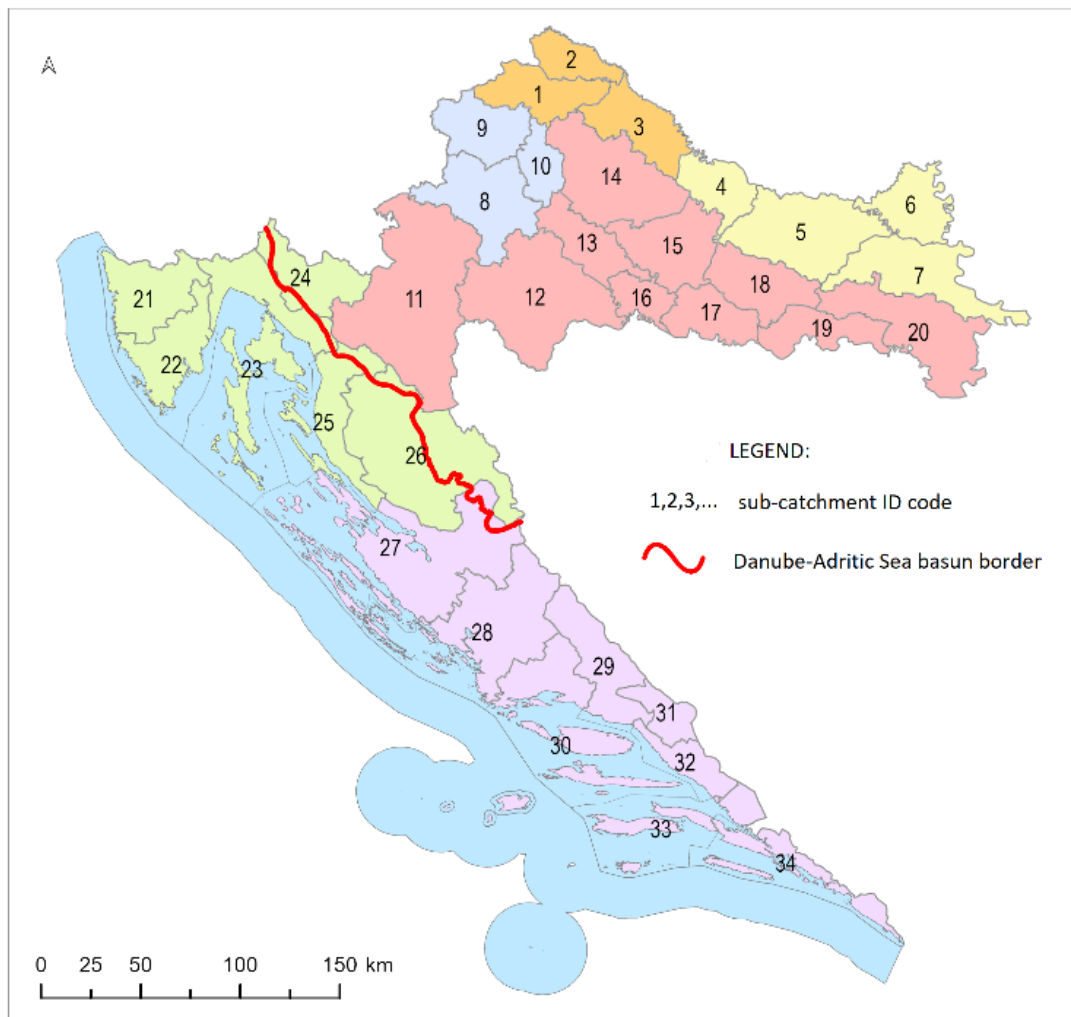


Fig. 1. Small catchments of Croatia with designated basin border (Geoportal Hrvatskih voda, 2019).

the Danube River Basin, precipitation ranges from 600 to 1000 mm, with the exception of hilly areas, where values are higher. The network of natural and artificial watercourses is of high density. Their main characteristics are small slopes and significant meandering liable to frequent flooding as it is presented in Fig. 2.

During the observed period, over 700 flood episodes were detected in 34 small catchments (Fig. 1), which predominantly belong to either the Danube River basin (Fig. 2). Fig. 3 presents the total number of flood episodes in small catchments of these the Danube River sub-catchments and their frequencies.

In the Danube River basin (the continental part of Croatia), most floods occurred in 2014, which corresponds to the recorded precipitation. For that year, precipitation was recorded at 20 to 85% above the mean annual values of the period 1981–2022, especially in the central part of Croatia and 152 flood episodes were recorded (Fig. 4b). In the 2010, (Fig. 4a), all meteorological stations recorded annual precipitation values higher than mean annual ones (15 to 79%), but

the highest precipitations during this year were recorded in the eastern part of the Croatia and on Istrian peninsula (The Adriatic Sea basin). To total number of recorded events is 147. In the 2015, there were 90 flood episodes and recorded precipitation was less than 24% above the mean annual values of the observed period.

The Adriatic Sea Basin

The Adriatic Sea Basin is situated along the coastline, with part of it located in Bosnia and Herzegovina. The Croatian islands also belong to this basin. This region is primarily a karst region, famous for its distinctive karst formations. Watercourses in this basin have large slopes, some of them with characteristics of torrents. Altitudes vary between 0 and 1831 m a.s.l. The land cover is typical Mediterranean, consisting mostly of poor vegetation, pastures, and barren land. A portion of agricultural land is less than 11%, but approximately 40% of the territory is still covered by forests (Hrvatske vode, 2009).

Table 1. Structure of Croatian flood protection system

River Basin	Sub-catchment	ID Code	Name
The Danube River Basin	The Mura and Upper Drava river	1	Plitvica-Bednja
		2	Trnava
		3	Bistra
	The Lower Drava and the Danube River	4	Županijski kanal
		5	Karašica-Vučica
		6	Baranja
		7	Vuka
	The Upper Sava River	8	Zagrebačko prisavlje
		9	Krapina-Sutla
		10	Zelina-Lonja
	The Middle and Lower Sava River	11	Kupa
		12	Banovina
		13	Lonja-Trebež
		14	Česma-Glogovnica
		15	Ilova-Pakra
		16	Subocka-Strug
		17	Šumetlica-Crnac
		18	Orljava-Londža
		19	Brodsko Posavina
		20	Biđ-Bosut
The Adriatic Sea Basin	The Northern Adriatic Sea	21	Mirna-Dragonja
		22	Raša-Boljunčica
		23	Kvarnersko primorje i otoci
		24	Gorski Kotar
		25	Podvelebitsko primorje i otoci
		26	Lika
	The Southern Adriatic Sea	27	Zrmanja-Zadarsko primorje
		28	Krka-Šibensko primorje
		29	Cetina
		30	Srednjo-dalmatinsko primorje i otoci
		31	Vrljika
		32	Matica
		33	Neretva-Korčula
		34	Dubrovačko primorje

The average annual precipitation on the islands is less than 1000 mm, but the inland area has an average annual precipitation of between 1000 and 2000 mm (observed period: 1981–2022). This basin has been divided into two smaller catchments: the northern part of the Croatian coast with islands (green colour in Fig. 1) and the Dalmatian sub-catchments with islands (pink colour in Fig. 1).

Most of the floods occurred in 2014, when many meteorological stations recorded extreme annual precipitation, exceeding 40% of the mean annual values for the period 1981–2022, as shown in Fig. 4b.

Fig. 5 presents the total number of flood episodes in small catchments of these the Danube River sub-catchments and their frequencies.

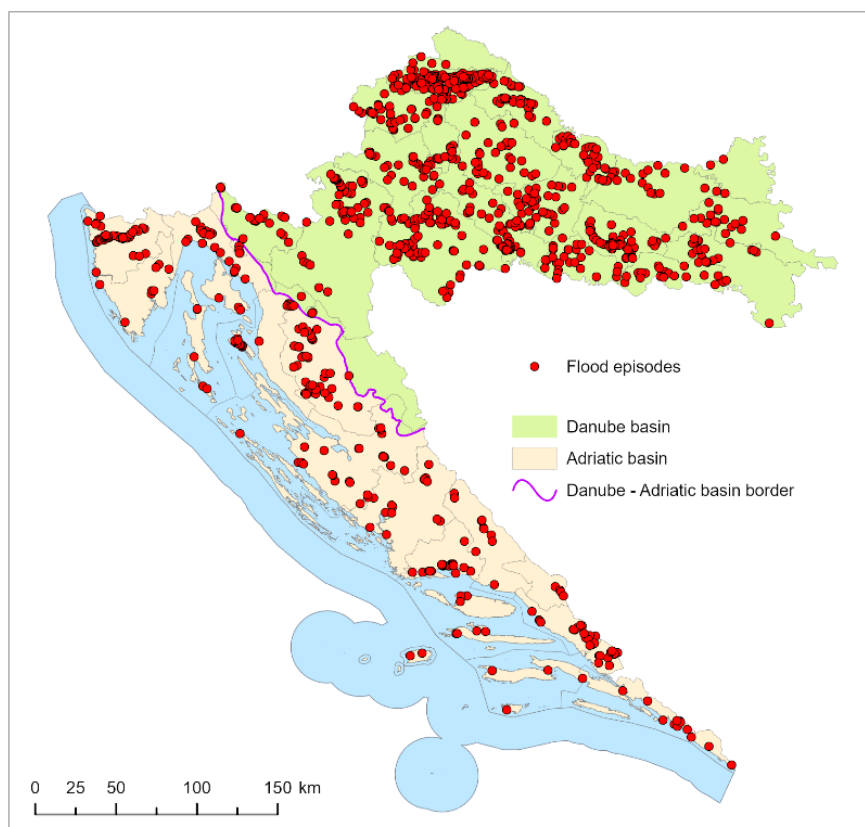


Fig. 2. Flood events in the Danube River and the Adriatic Coast catchments (1998–2018) (Geoportal Hrvatskih voda, 2019).

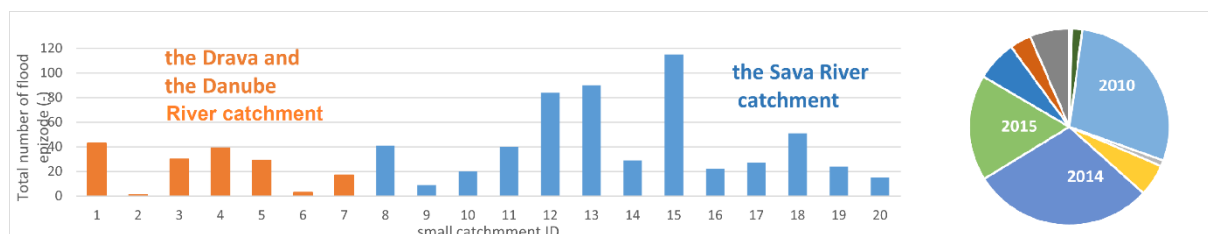


Fig. 3. Total number of flood episodes in small catchments of the Danube River basin and their frequencies.

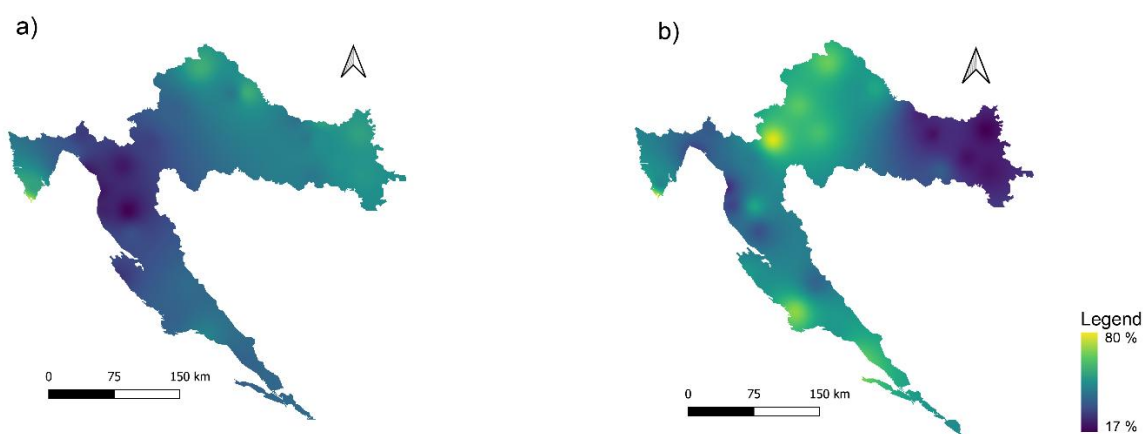


Fig. 4. Difference between average annual precipitation and a) precipitation that occurred in 2010 and b) precipitation that occurred in 2014 presented in %.

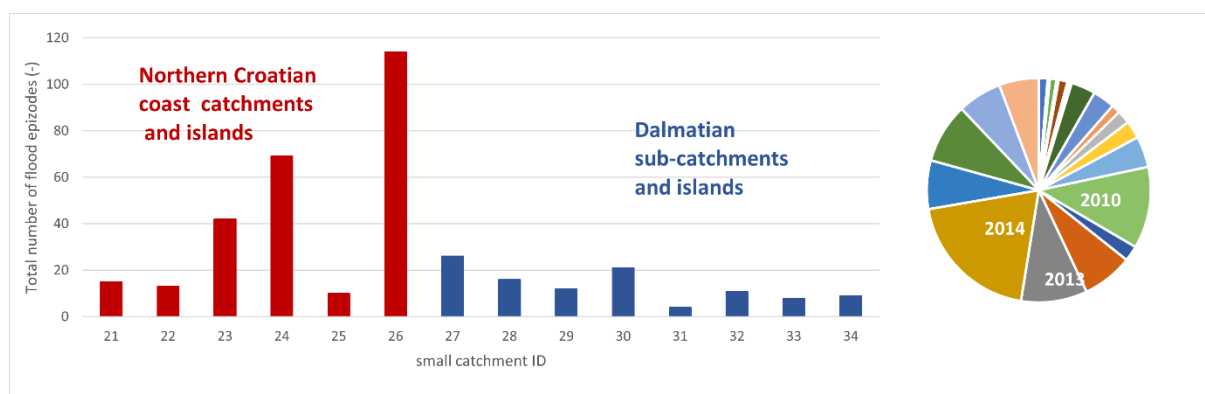


Fig. 5. Total number of flood episodes in small catchments of the Adriatic Sea basin and their frequencies.

Methods

The total number of obtained flood episodes is 1086. However, some episodes lacked complete and reliable characterization, and the total number has been reduced to 845 flood episodes (531 from the Danube River basin and 314 from the Adriatic Sea basin). Each flood episode is described by its duration (in days), affected area (in km²), and percentage of arable land (including fields, orchards, etc.). These three flood characteristics are considered the most important and reliable for flood risk management.

There are two steps in processing these databases: normalization and k-means clustering.

The first step is the accurate preparation of your data, which is crucial for running a statistical model and accurately interpreting the results. In this case, normalization has been chosen as the most appropriate model for adjusting values measured on different scales to a common scale, because the data distribution is unknown. Among many normalization techniques, we applied simple min-max normalization.

$$X_{norm} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (1)$$

In the above formula, X_i represents the value of a specific feature, X_{min} denotes the feature's minimum value, and X_{max} denotes the feature's maximum value in the dataset (Ciaburro et al., 2018).

Principle of the k-means clustering

To identify similarities among a large dataset of flood episodes, the k-means clustering method has been employed. K-means clustering is an iterative method that converges on a solution. K-means clustering was introduced by MacQueen (1967). For the first iteration, a starting point is chosen that consists of associating the centre of the k clusters with k objects (either taken at random or not). Afterwards, the distance between the objects and the k centres is calculated, and the objects are assigned to the centres they are nearest to. Then, the centres are redefined based on the objects assigned

to the various clusters. The objects are then reassigned depending on their distances from the new centres until convergence is reached. Determination of number of clusters in k-means clustering method is very important step in its application. It can be done by using the elbow point or by calculation of silhouette coefficient. In this case the second one has been applied. The silhouette coefficient presents average value of “within” clusters dissimilarities and “between” clusters dissimilarities and it should be close to 1.0 (Batool and Hennig, 2019).

Correlation matrix

The correlation matrix is useful tool for multivariate descriptive statistics between two or more variables, in this case flood duration, the size of affected area, and the portion of arable land within the flooded area which are previously normalized (Vinod, 2014). It represents the interdependencies among variables, which can be negative values (between 0 and -1) and positive (between 0-1) and shows do they change in the opposite or the same direction.

Results and discussion

As previously explained, three basic characteristics of each flood episode were identified as the most reliable for multivariate clustering: flood duration, affected area, and percentage of arable land. For the 20 flood protection units located in the Danube River basin, the optimum number of clusters is 5, as defined by the mean cluster value (0.537). These five distinct groups of flood events are illustrated in Fig. 6 and detailed in Table 2.

As a result of k-means clustering, each cluster got multivariate characterisation (Table 2); however, it is possible to detect a dominant characteristic. In Cluster 1, the dominant characteristic is a large portion of arable land, although the areas are not very extensive, and the duration is medium. Cluster 2 groups floods of long duration, medium area, and a small portion of arable land. Cluster 3 groups floods of medium duration, small areas, and a small portion of arable land is flooded. Cluster 4 has catchments with a large portion of arable land, but

the duration of floods is very short. Cluster 5 is characterized by a moderate duration, large affected areas, and a medium portion of arable land that is flooded. Clusters 1, 2, and 5 require additional attention to develop priorities in flood protection measures.

For the 14 flood protection units located in the Adriatic Sea basin, the optimum number of clusters is 2, as defined by the mean cluster value. It means that only two different groups of flood events can be detected, what is presented in Fig. 7 and described in Table 3.

As a result of k-means clustering, each cluster got multivariate characterisation (Table 3); however, it is possible to detect a dominant characteristic. In Cluster 1, all three parameters exceed their maximum values: the

longest duration, the largest areas, and a high percentage of arable land. Cluster 2 groups flood episodes as less serious according to all parameters.

The situation in the Adriatic Sea is less complicated for decision-makers; prioritizing flood protection activities in this area is relatively straightforward.

The spatial distribution of the results is presented in Fig. 8.

Correlation between observed variables is very weak in the both basins.

Results would be more reliable with a wider range of parameters, but at the moment, only data for three parameters are available all floods. There is a possibility of determining flooded areas by using remote sensing

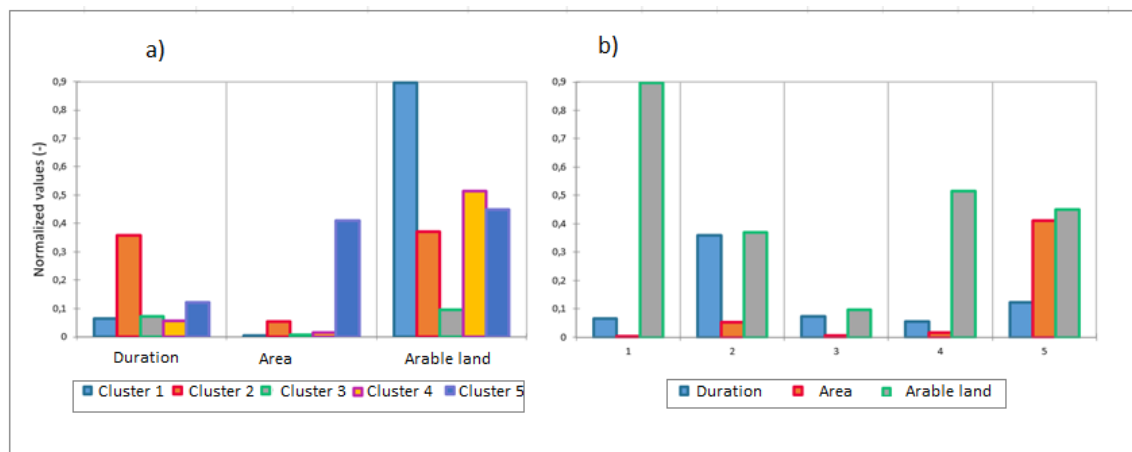


Fig. 6. Cluster characterisation of the 20 small catchments of the Danube River basin.

Table 2. Characteristics of clusters of the Danube River basin

	Duration [days]	Area [km ²]	Arable land [%]
Cluster 1	4–5	<0.14	50–90 (and more)
Cluster 2	9–23 (and more)	3–5	10–35
Cluster 3	5–6	0.14–1.2	<10
Cluster 4	<4	1.2–3.0	45–50
Cluster 5	6–9	5–10 (and more)	35–45

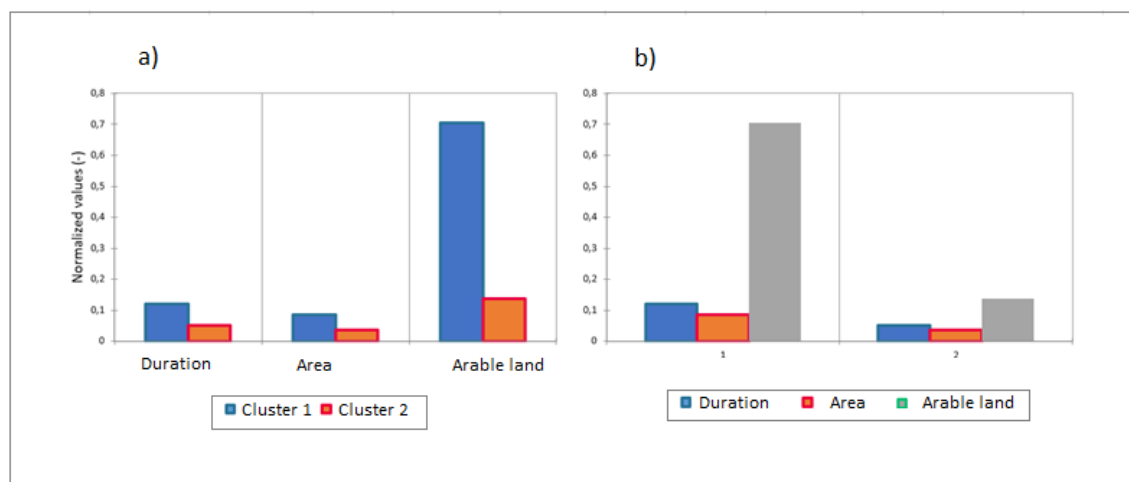
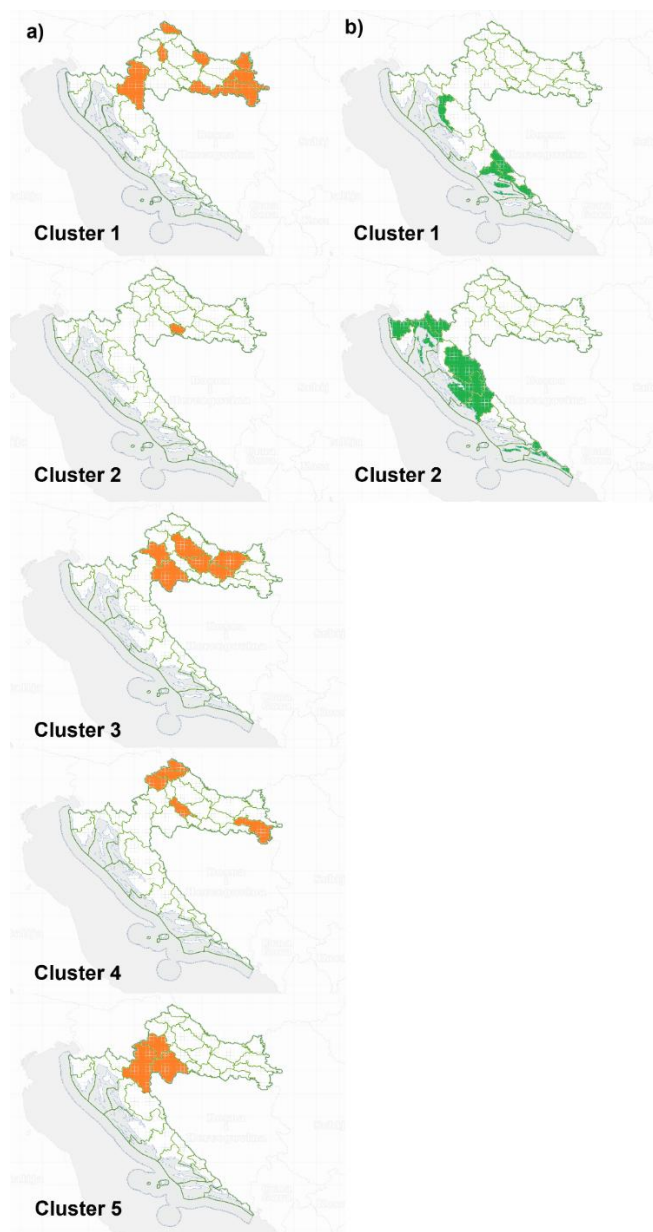


Fig. 7. Cluster characterisation of the 14 small catchments of the Adriatic Sea basin.

Table 3. Characteristics of clusters in the Adriatic Sea basin

	Duration [days]	Area [km ²]	Arable land [%]
Cluster 1	3–6 (and more)	1.5–3.5 (and more)	15–70 (and more)
Cluster 2	<3	<1.5	<15

**Fig. 8.** Clusters for a) the Danube River basin and b) the Adriatic Sea basin.

data obtained by Landsat and Sentinel satellites. In published papers, a good correspondence was shown between the areas and discharges flooded area and water discharges at hydrological stations located downstream (Vyshnevskiy and Shevchuk, 2024). In Croatia, there are also activities in this direction (Graf and Matić, 2025).

Conclusion

This work, inspired by the EU Directive 2007/60/EC

(2007) on the assessment and management of flood risks, presents research on the occurrence of flood episodes in Croatia to define common characteristics of floods in the period 1998–2018. In particular, each flood event has been considered a multivariate object characterized by three parameters: flood duration, size of affected area, and the portion of arable land within the total affected area. So far in Croatia there was no such research and the most of recent investigations were oriented to urban or coastal flooding.

The results obtained by k-means clustering show that floods in small catchments of the Danube River basin exhibit greater variability and can be grouped into five distinct clusters, several of which indicate flood types that require increased attention in future flood protection planning. In contrast, flood events in the Adriatic Sea basin are less complex and can be classified into two main clusters, making the prioritisation of flood protection measures in this area more straightforward.

The reliability and applicability of the results are strongly dependent on the quality and completeness of the input data. Therefore, continuous and systematic updates of the flood database are essential to ensure robust future analyses. In addition, future research should include more flood events on large rivers, such as the Danube, Drava and Sava, which were not considered in this study, but represent a significant component of flood risk at the national and international scale. Finally, the integration of new technologies, such as remote sensing data from satellite missions, or application of machine learning technologies would enable a more accurate determination of flooded areas and enhance the overall assessment of flood characteristics. Such an extended and integrated approach would contribute to a more comprehensive understanding of flood processes and support more effective flood risk management strategies in Croatia and help in defining priorities in flood protection system development.

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