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STRENGTH

D.2.1.2
Report on flood hazard

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2. Executive Summary

This deliverable presents the development of an Early Warning System (EWS) for torrential flow and flash flood risk in the City of Kaštela, with a focus on a representative torrential catchment draining from the southern slopes of Kozjak Mountain toward the urbanized coastal zone. The study addresses the increasing exposure of densely populated and rapidly urbanizing areas to short-duration, high-intensity rainfall events that can generate hazardous runoff, channel overflow, and local flooding.

The methodology combines hydrological, geomorphological, hydrogeological, and hydraulic analyses using modern geospatial datasets and engineering modelling tools. Catchment characteristics were derived from high-resolution LiDAR terrain data, digital elevation models, and Sentinel-2 satellite imagery. These datasets were used for watershed delineation, land-cover classification, slope and flow-path analysis, and estimation of hydrological response parameters. The study confirms that the selected catchment, with an area of approximately 3.23 km², exhibits steep topography, short concentration times, and conditions favourable for rapid runoff generation during intense storms.

For rainfall–runoff transformation, the widely applied SCS-CN (Soil Conservation Service – Curve Number) method was adopted. This approach is particularly suitable for small catchments with ephemeral surface flows, where infiltration capacity, antecedent soil moisture, and land use strongly influence runoff generation. Several Curve Number scenarios were analysed to represent changing wetness conditions before storm events. Based on these simulations, synthetic hydrographs and peak discharges were produced for warning purposes.

The hydraulic assessment focused on the downstream control section where the torrential flow enters a concrete channel. Using field geometry obtained from LiDAR surveys and the Manning–Strickler equation, channel conveyance capacity and overflow thresholds were determined. The results define the critical discharge above which overtopping and flooding become likely, providing the physical basis for warning levels and operational triggers within the EWS.

A key component of the system is the calibration and validation of model performance using surveillance camera recordings from real rainfall events. Observed flow behaviour and overflow conditions were compared with modelled responses, allowing refinement of thresholds and increasing confidence in operational reliability. Additional verification was carried out using significant events recorded in December 2025 and January 2026.

The final outcome is a practical, science-based warning framework that links observed or forecast rainfall with expected hydrological response and flood hazard levels. The proposed EWS supports municipal authorities, civil protection services, and infrastructure managers in taking timely preventive actions, reducing risk to residents and property, and improving climate resilience in the City of Kaštela.

3. Introduction

Hydrological analysis of a torrential catchment can be highly demanding. A key challenge is always to determine the appropriate balance between catchment parameterization and the complexity of the mathematical model. One of the fundamental methods widely used in engineering practice is the SCS method. The SCS (Soil Conservation Service of the U.S. Department of Agriculture) method, originally developed several decades ago, has become even more applicable through the integration of modern tools such as remote sensing, particularly for small catchments that generate temporary surface flows during intense rainfall events.

The analysed torrential stream has a relatively small catchment area of 3.22 km^2 (322.64 ha), and the SCS method is therefore considered an appropriate approach for deriving the direct runoff hydrograph during recorded rainfall events. The meteorological station Marjan, operated by Croatian Meteorological and Hydrological Service (DHMZ), is located only 9.0 km in a straight line from the study area; therefore, the recorded rainfall data from this station, together with the corresponding IDF curves registered for the same station, can be considered representative and reliable for the analysed location.

4. Methodology

Small catchments during intense rainfall events are characterized by the fact that cumulative rainfall gradually becomes equal to the total volume of generated surface runoff due to soil saturation processes and the complete filling of subsurface storage capacities. The SCS method is fundamentally based on this concept, relying on the difference between effective rainfall and cumulative rainfall. The difference between cumulative rainfall **P** and runoff **Pe** at a given moment represents the excess rainfall stored in the catchment's subsurface retention of limited capacity. The maximum subsurface retention capacity is denoted by **S**. Considering the presented input parameter nomenclature, the ratio between the difference of gross and effective rainfall and the available subsurface storage capacity is equal to the ratio between effective and gross rainfall, and can be expressed as follows:

$$\frac{(P - Pe)}{S} = \frac{Pe}{P}$$

where:

- **P − Pe**: currently filled retention capacity
- **S**: maximum retention capacity
- **Pe**: current cumulative effective rainfall
- **P**: current cumulative gross rainfall

This relationship is valid at any moment in time in the case where no initial abstraction exists within the subsurface retention. If the initial abstraction (**Ia**) is taken into account, the relationship takes the following form:

$$\frac{(P - Ia - Pe)}{S} = \frac{Pe}{(P - Ia)}$$

Empirically, the initial abstraction can be assumed to equal **20% of the maximum retention capacity**:

$$Ia = 0.2S$$

This parameter is not constant, but depends on antecedent rainfall conditions (soil moisture conditions). There is no continuous relationship between parameter **S** and antecedent soil moisture conditions, which are commonly classified into three levels: **low (I), medium (II), and high (III)**.
According to the previous expression, effective rainfall can be calculated as:

$$Pe = \frac{(P - Ia)^2}{P - Ia + S}$$

In the expression for effective rainfall **Pe**, the **CN (Curve Number)** parameter, i.e. the runoff curve number or hydrological land-cover complex, is used instead of parameter **S**.
The relationship between parameters **CN** and **S** is defined by the following expression, where **S** is given in inches:

$$S = \frac{1000}{CN} - 10$$

Satellite imagery of the area of interest is used to determine the land-cover complex. Different satellite datasets are combined in order to obtain complete information about the analysed catchment (Figure 1).

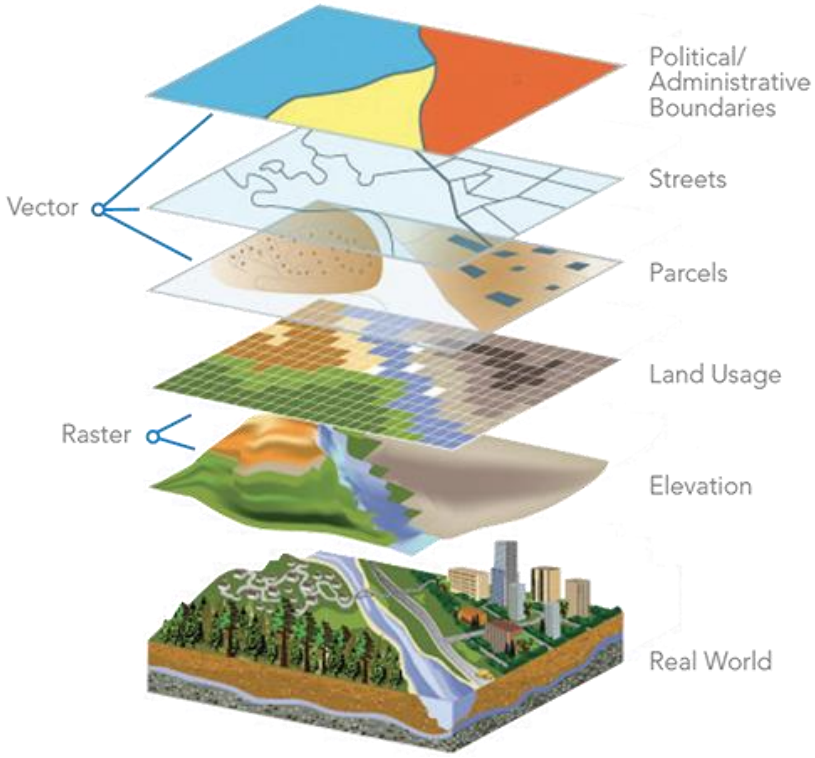

Figure 1: Overview of the information layers used for hydrological analysis

5. Hydrological, Geomorphological and Hydrogeological Characteristics of the Catchment

In the present case, land cover was determined using satellite imagery acquired by the Sentinel-2 satellite. Sentinel-2 is a multispectral satellite that records data in 13 spectral bands, covering the visible, near-infrared, and shortwave infrared regions, with a spatial resolution ranging from 10 to 60 metres.

Land-cover classification was performed using a supervised classification method. Four classes present within the study area were defined: coniferous forest, low vegetation, sparsely vegetated rock surfaces, and built-up areas. Reference spectral signatures were determined for each of these classes (Figures 2 and 3).

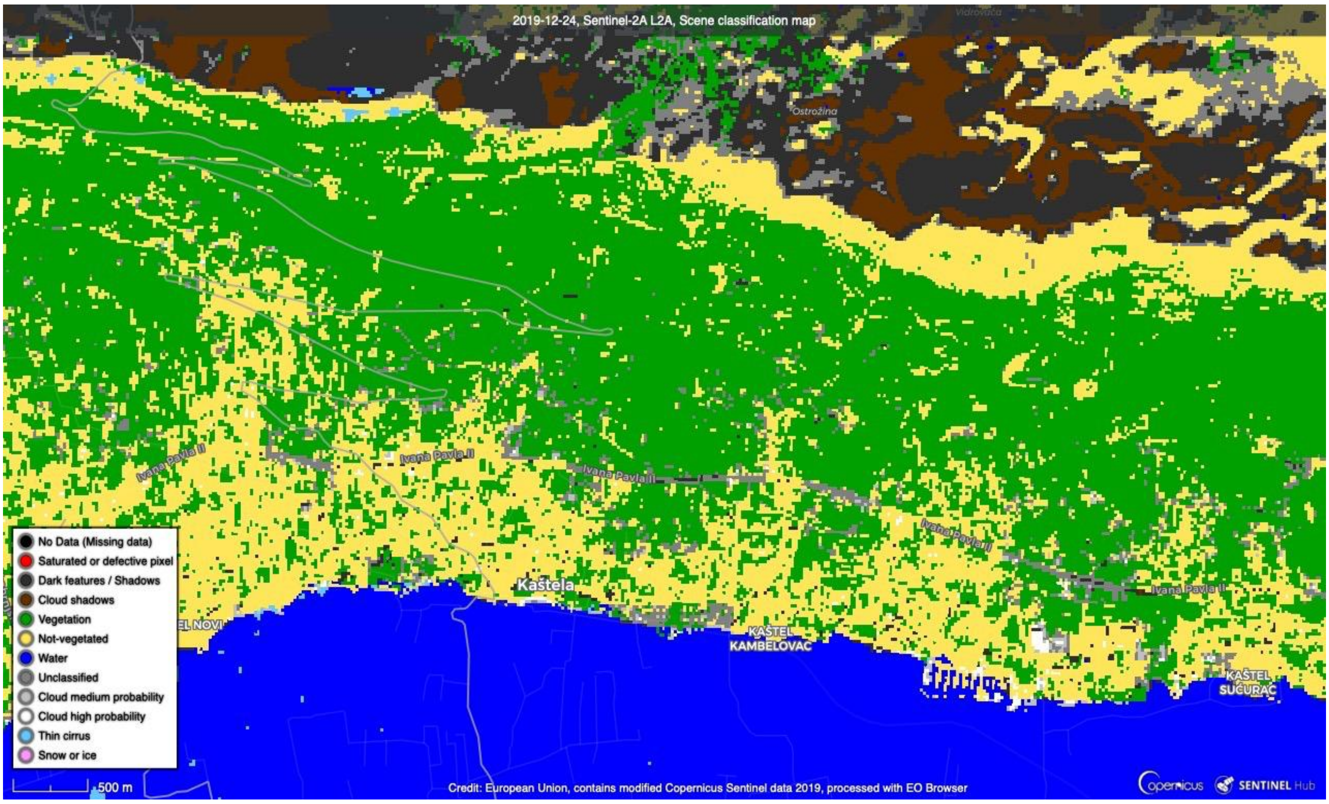

Figure 2. Land cover derived from the Sentinel multispectral satellite image acquired on 2019-12-24 (EU Copernicus Sentinel)

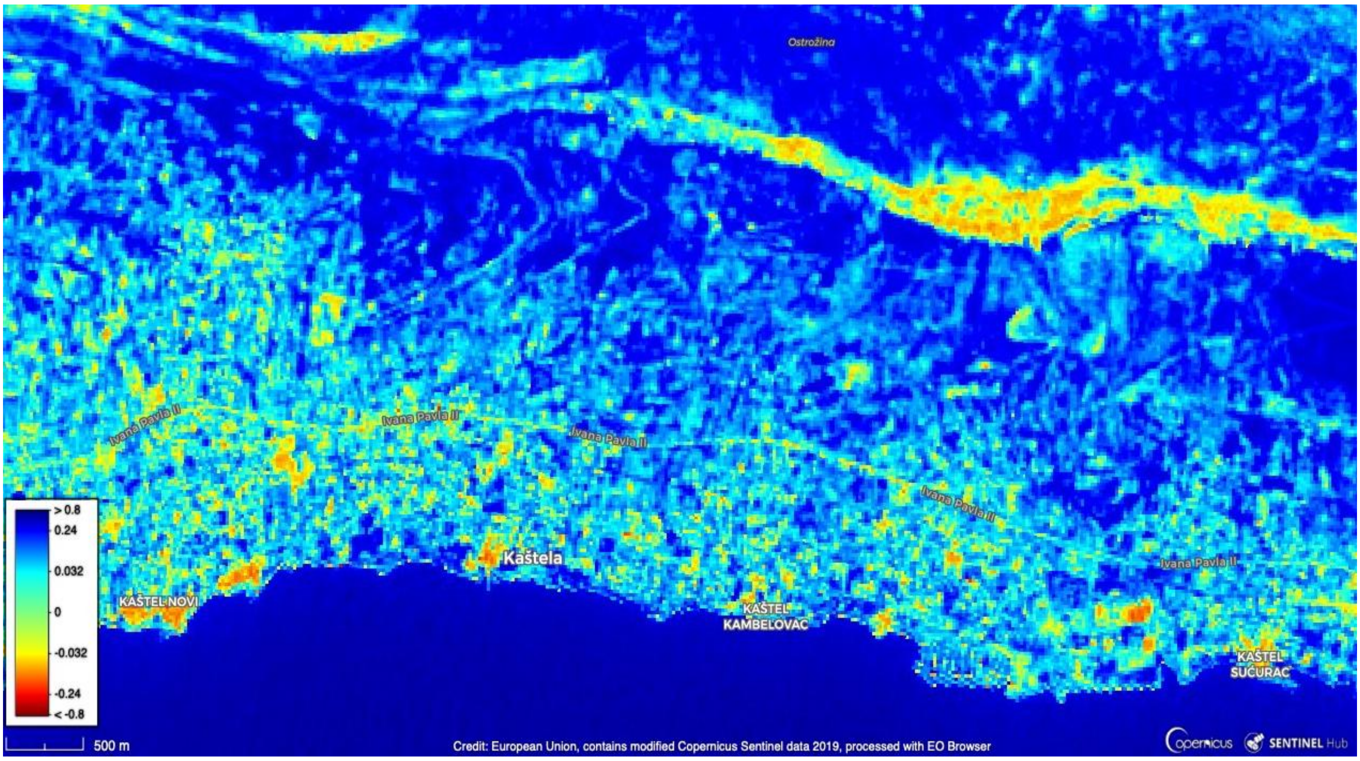

Figure 3: Soil moisture derived from the Sentinel multispectral satellite image (EU Copernicus Sentinel) during the rainy period

The thematic land-cover map was produced using the spectral angle mapping method applied to bands from the visible and near-infrared spectrum. The digital elevation model (DEM) used for the topographic analysis of the catchment is a subset of the DTM derived from LiDAR data provided by the Croatian State Geodetic Administration (DGU), resampled to a 5 × 5 m resolution.

The resolution was further refined using appropriate algorithms in order to obtain accurate locations and flow directions of surface runoff (FLOW ACCUMULATION), as well as reliable catchment delineation (Figure 4).

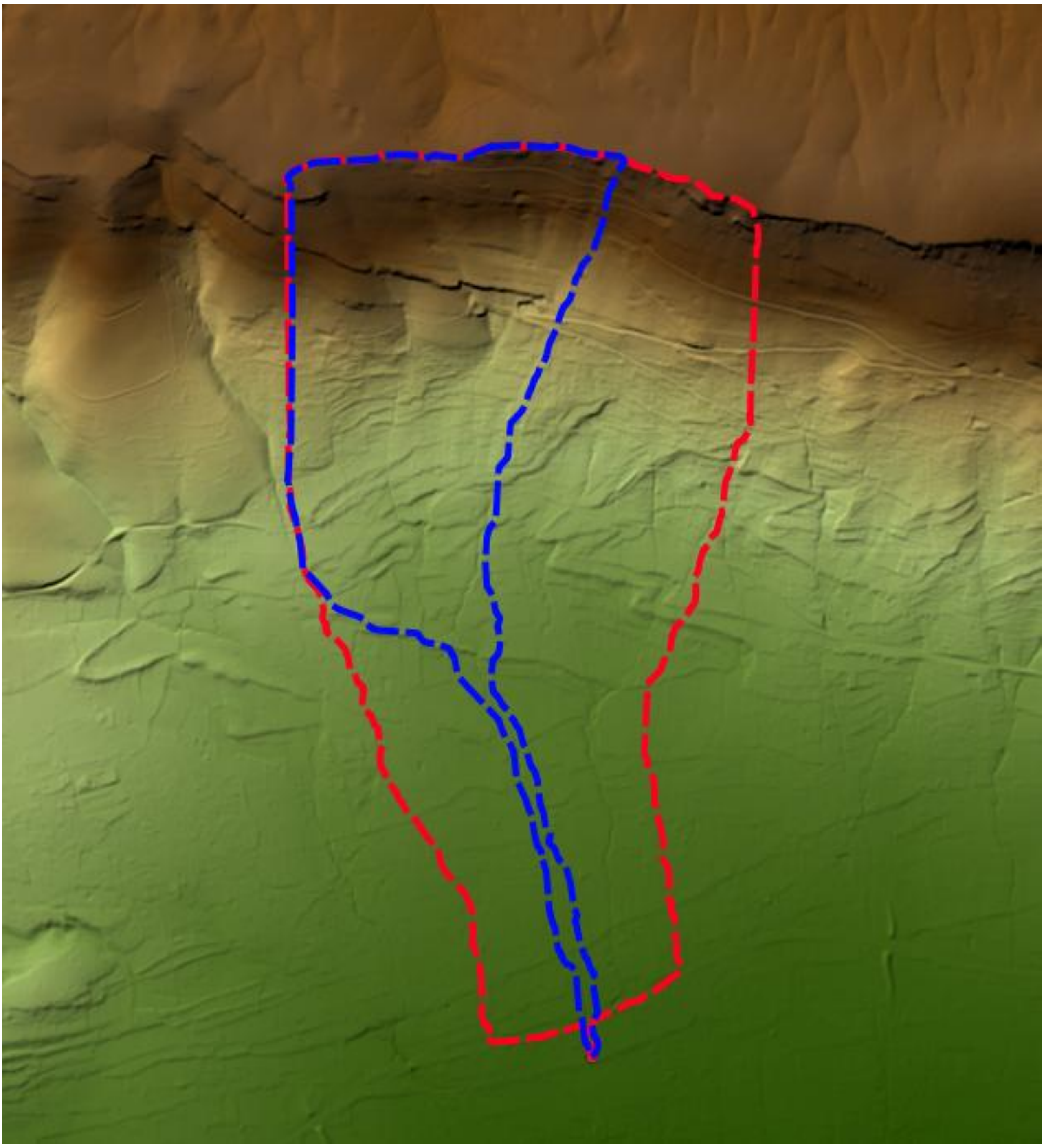

Figure 4. Catchment delineation on the DEM (LiDAR–DGU) for resolutions of 5 × 5 m (red dashed polygon) and 10 × 10 m (blue dashed polygon)

Catchment Delineation Based on a Digital Terrain Model (DTM) Derived from LiDAR Data at Different Spatial Resolutions

Catchment delineation represents a key step in hydrological modelling, as it defines the area within which precipitation runoff is collected and concentrated toward the selected outlet point. In this case, delineation was carried out using a digital terrain model (DEM) derived from LiDAR data provided by the Croatian State Geodetic Administration (DGU) at two different spatial resolutions: 5 × 5 m and 10 × 10 m. The difference in resolution has a direct impact on the accuracy of topographic parameter estimation and on the final catchment area.

The results show that the higher-resolution DTM (5 × 5 m) produced a larger catchment area compared with the lower-resolution model (10 × 10 m). The reason is that finer resolution allows the flow-direction algorithm to more accurately detect local slope variations and micro-topographic features that control water movement between neighbouring pixels. This improved precision is particularly important in areas near roads, filled or modified terrain, boundary zones between adjacent catchments, and microlocations where overflow or flow diversion from neighbouring basins may occur. In the 10 × 10 m DEM, such fine structures are often lost or generalized, which leads to an underestimation of the true contributing area.

In the present case, the catchment derived from the higher-resolution DEM is shown by the red dashed line (Figure 5) and includes additional micro-areas that were not recognized as part of the drainage system in the lower-resolution model. This confirms that the finer model captures all relevant topographic features more effectively, including roadside flow paths and overflow zones that influence the hydraulic and hydrological behaviour of the basin.

Considering its greater reliability and more realistic spatial representation, the larger catchment obtained from the 5 × 5 m DTM was adopted as the final delineation for further development of the hydrological model.

Hypsometric Curve

The hypsometric curve is determined by analysing the relationship between elevation and cumulative catchment area, and it represents one of the fundamental morphometric indicators describing the distribution of terrain elevations within a drainage basin. The procedure begins with the digital terrain model (DTM), from which the elevation and associated area are extracted for each pixel. The data are then grouped into elevation classes, and for each class the cumulative area located above a given elevation is calculated.

The resulting set of value pairs (cumulative area fraction – elevation) is plotted as a diagram, producing the hypsometric curve. This curve provides insight into the vertical structure of the catchment, the degree of erosional development, and the relative distribution of terrain mass. The shape of the curve may indicate the dominant geomorphological processes acting within the basin, while characteristic parameters such as the mean catchment elevation further support the interpretation of hydrological and geomorphological features of the area (Figure 5).

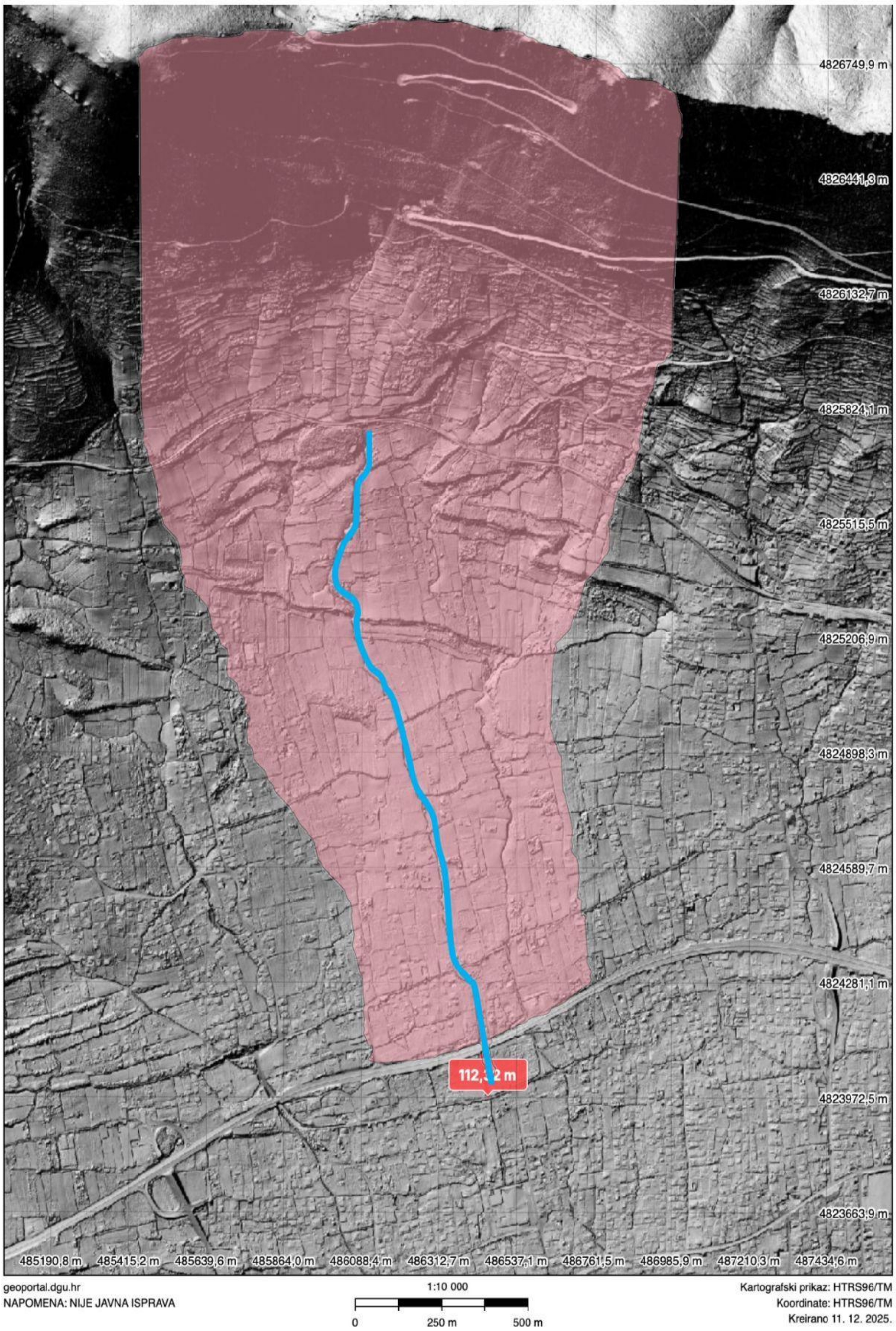

Figure 5. Catchment delineation on the DEM (LiDAR–DGU) for resolutions of 5 × 5 m and 10 × 10 m with an extended view of the LiDAR data.

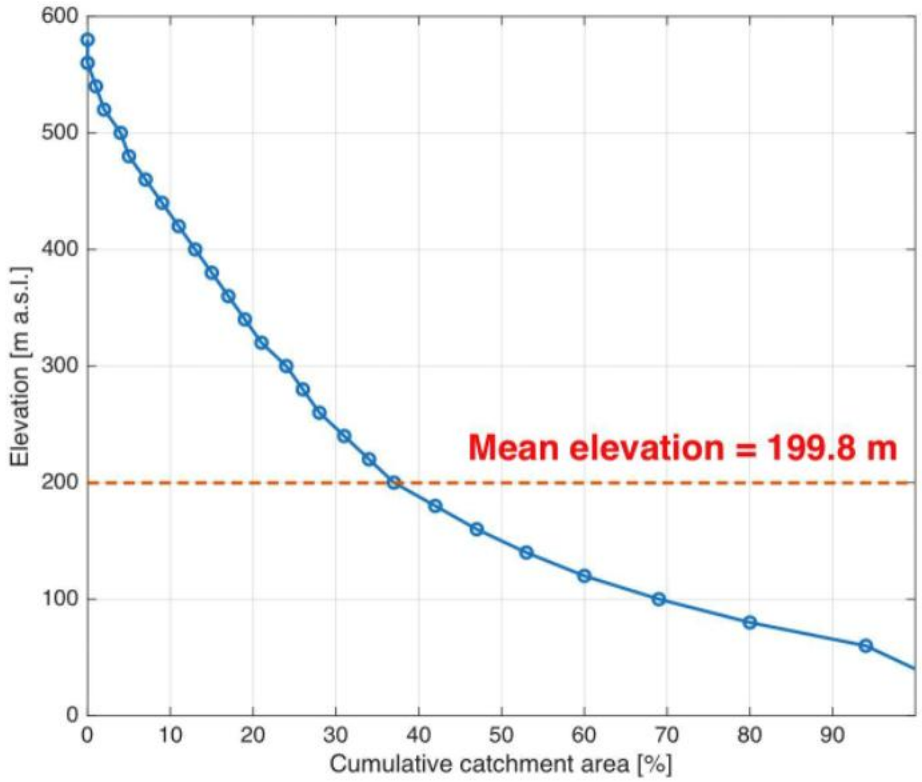

Figure 6. Hypsometric curve with the indicated mean catchment elevation of 199.8 m a.s.l.

Table 1. Hypsometric values in tabular form

Area (m^2)	Cumulativa area (m^2)	Area (%)	H (m a.s. l.)
468	468	0%	580
7257	7725	0%	560
15447	23172	1%	540
42090	65262	2%	520
48578	113840	4%	500
61091	174931	5%	480
57594	232525	7%	460
58925	291450	9%	440
57148	348598	11%	420
59941	408539	13%	400
65741	474280	15%	380
68507	542787	17%	360

69240	612027	19%	340
75717	687744	21%	320
75741	763485	24%	300
68383	831868	26%	280
75289	907157	28%	260
80856	988013	31%	240
97636	1085649	34%	220
122931	1208580	37%	200
138966	1347546	42%	180
168870	1516416	47%	160
192474	1708890	53%	140
237170	1946060	60%	120
272169	2218229	69%	100
364280	2582509	80%	80
453475	3035984	94%	60
190394	3226378	100%	40

6. Geological and Hydrogeological Characteristics of the Catchment

The fundamental geological and hydrogeological characteristics of the Kaštela torrential catchment can be defined on the basis of results presented in the Hydrogeological Study of the Municipality of Split (Geological Survey Zagreb, 1979), as well as according to the interpretation of the Basic Geological Map of the former SFRY, Split Sheet 1:100,000 (Marinčić S.; Magaš N.; Borović I., 1969, Institute for Geological Research Zagreb), and the Basic Hydrogeological Map of the Republic of Croatia, Split Sheet 1:100,000 (Fritz F.; Kapelj J.; Renić A., 1998, Croatian Geological Institute).

According to the general information from the referenced studies, the morphological features of the analysed area are strongly influenced by the prominent mountain massifs of Opor (maximum elevation approximately 650 m a.s.l.) and Kozjak (780 m a.s.l.), located only a few kilometres from the coastline. The southern slopes of these mountains are predominantly composed of marly deposits of Eocene flysch, within which a series of intermittent and short-duration surface flows typical of torrential systems develop.

The coastal zone is highly urbanized, while the lower parts of the catchment (Kaštela Field) are predominantly agricultural land, although in recent years they have been subjected to intensive urban expansion. Higher elevations are covered by dense coniferous forests, which influence infiltration processes and the spatial distribution of surface runoff.

The geological structure of most of the analysed area consists of Eocene flysch deposits (units $E_{2,3}$), composed of limestone breccias, breccia-conglomerates, calcirudites, calcarenites, sandstones, biocalcarenites, calcsiltites, and marls. These deposits are characterized by pronounced rhythmic sedimentation and lateral lithological alternations. In the lower part of the profile, limestone breccias and breccia-conglomerates dominate, whereas marls prevail in the upper parts. The estimated total thickness of the flysch sequence is approximately 800 m.

Near the surface, these deposits are locally moderately permeable, enabling the occurrence of intermittent or permanent springs, although generally of very low yield. Overall, due to their lithological composition and structure, flysch deposits represent a low- to impermeable hydrogeological complex, which strongly controls the formation and dynamics of surface runoff and the development of torrential flows.

Above the flysch formations, breccias, conglomerates, limestones, and marls locally occur on some parts of the Kozjak slopes. These deposits also show rhythmic alternation and are hydrogeologically classified as partially permeable rocks, which may allow infiltration and occasional drainage toward deeper layers, but to a much more limited extent than highly fractured carbonate systems.

The northern marginal part of the analysed area is composed of Upper Cretaceous deposits (K_2–K_3), represented by thick-bedded to massive dolomites, overlain by bedded limestones with occasional lenses of stratified limestones and shaly marly varieties. The younger Upper Cretaceous member (K_{32}) consists of thick-bedded, locally massive limestones, while dolomites mainly occur as interbeds. These carbonate deposits are characterized by a well-developed fractured and often karstified structure, making them hydrogeologically highly permeable and important zones of potential subsurface infiltration and drainage.

Overall, the Kaštela torrential catchment has developed on a complex geological and hydrogeological setting in which permeable carbonate formations alternate with low-permeability flysch complexes. Flysch dominates in the surface parts of the basin and directly controls the concentration of torrential flows, limited infiltration capacity, and the intensity of surface runoff. This lithological and hydrogeological heterogeneity is crucial for understanding the origin, behaviour, and potential hazard of torrential flows forming in this area.

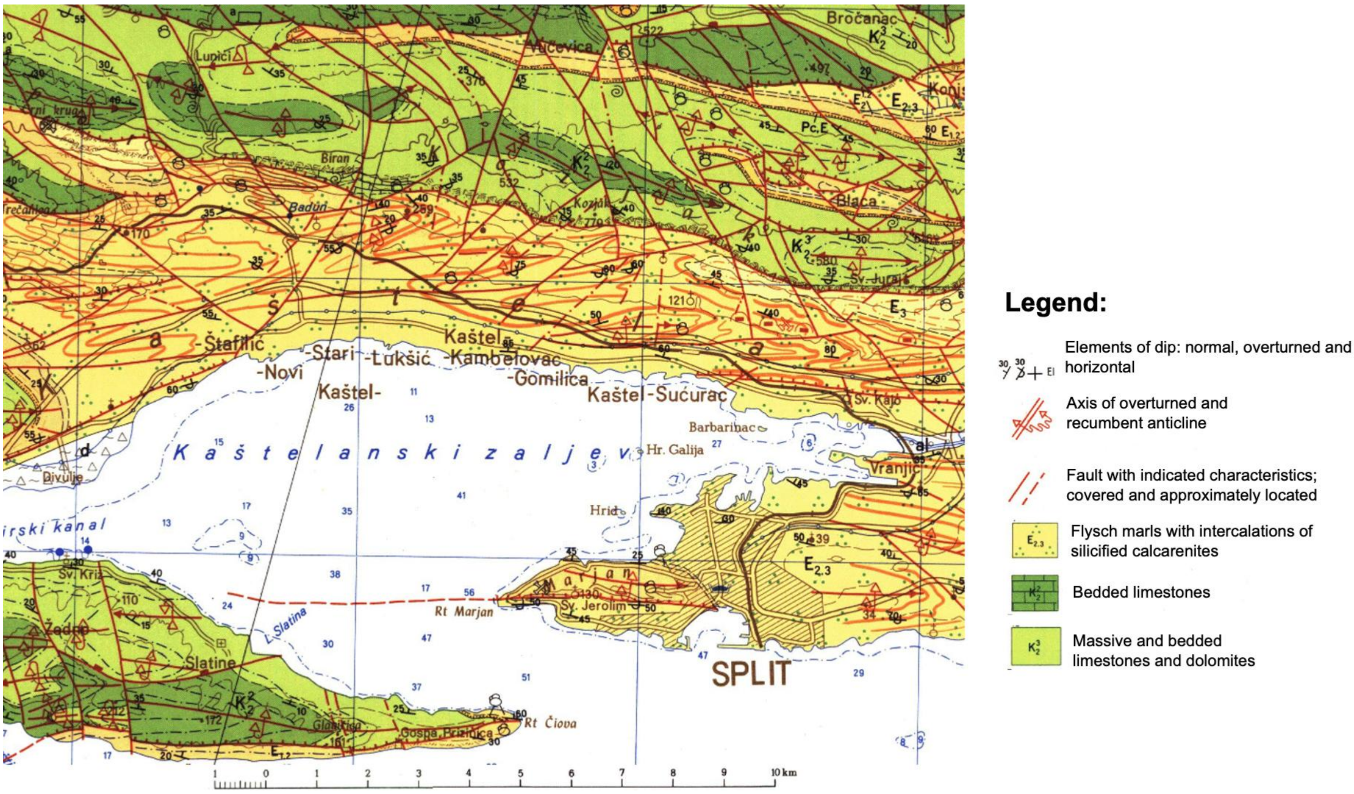

Figure 7. Geological map of the study area, partially modified after the Basic Geological Map of the former SFRY, Split Sheet 1:100,000 (Marinčić S.; Magaš N.; Borović I., 1969, Institute for Geological Research, Zagreb)

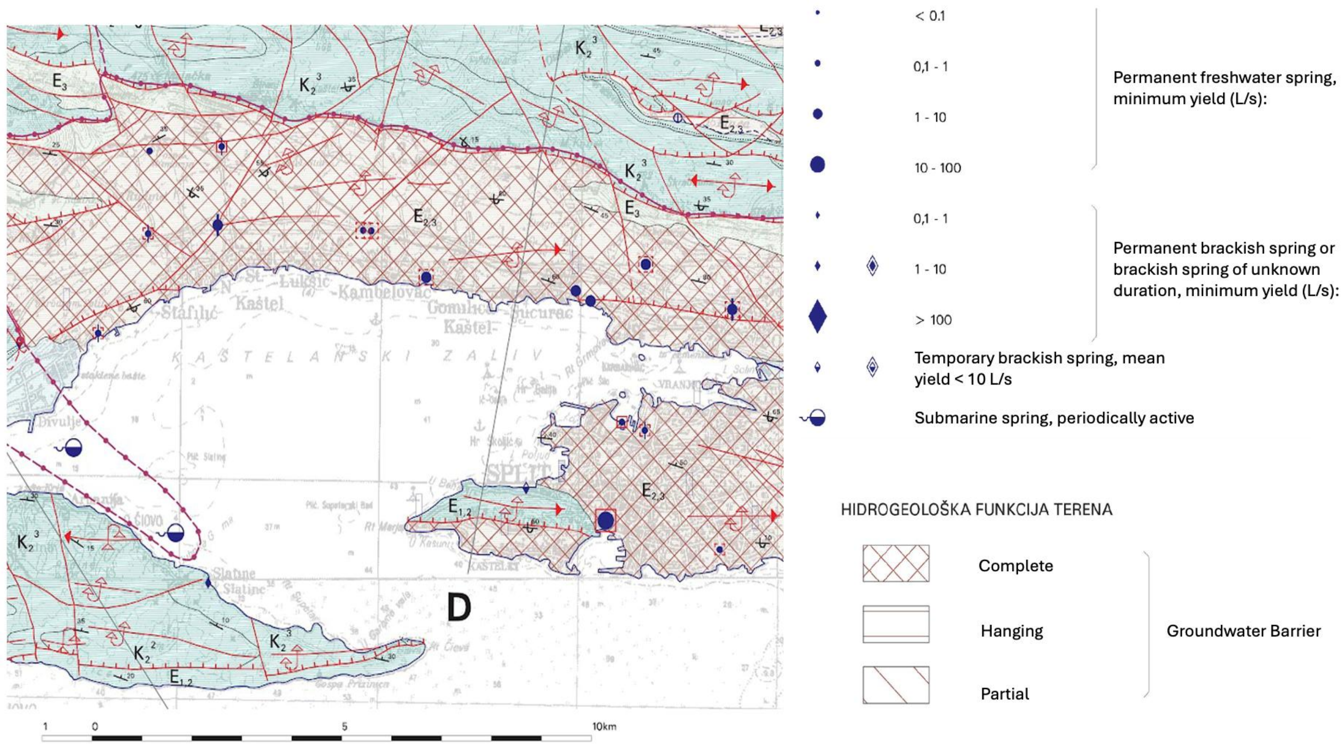

Figure 8. Hydrogeological map of the study area, partially modified after the Basic Hydrogeological Map of the Republic of Croatia, Split Sheet 1:100,000 (Fritz F.; Kapelj J.; Renić A., 1998, Croatian Geological Institute)

7. Calculation of Physical Catchment Characteristics

All data used for the purpose of catchment modelling were processed in the ESRI ArcGIS software package.

Each digital processing workflow applied for the development of a hydrological model incorporates secondary topographic attributes in order to derive the primary attributes required by the model. Specifically, algorithms that perform functions on the DEM dataset, such as FLOW ACCUMULATION (flow accumulation), ASPECT (slope orientation and gradient intensity), WATERSHED (watershed boundary), and CENTROID (centroid), generate the attributes that are interpreted through digital catchment maps containing the input parameters for the hydrological model.

All parameters required for model development were derived from the computational model of catchment geomorphology and torrential flow. Land cover, together with moisture conditions in the surface soil layer, determines runoff behaviour and consequently the ratio between generated runoff and total rainfall.

The torrential catchment is the area from which surface runoff is first generated, followed by concentrated torrential flow through the formed channel up to the regulated concrete section. Along the concrete section, additional lateral inflows of surface runoff are also present. The line separating two adjacent catchments is called the watershed divide.

Due to the high flow velocities and the large flow energy caused by steep terrain slopes, concentrated torrential flow has the capacity to transport significant quantities of eroded material, both as bed load and suspended sediment.

The catchment of every torrent, including the analysed one in Kaštel Gomilica, can be divided into three geomorphological zones:

- **Upper reach** – Torrent formation zone; area of denudation and erosion processes
- **Middle reach** – Transit zone (maximum longitudinal slopes), where the torrent reaches the highest flow velocities
- **Lower reach** – Accumulation zone; area of intensive deposition and sediment accumulation

An important factor affecting runoff generation within the catchment is the soil moisture level, which—considering rainfall on the day of flooding of the analysed site as well as on the preceding day—approached full saturation of the surface soil layer. One of the parameters that can be used in model calibration is the Antecedent Precipitation Index (API).

Table 2. Geomorphological and hydrological parameters of the catchment

Parameter	Symbol	Value	Unit
Catchment area	A	32.264	km²

Catchment perimeter	O	7.994	km
Distance to centroid	U	1.924	km
Mean catchment elevation	Hsr	199.8	m
Outlet profile elevation	H	19.68	m

For different CN values, different parameters of the unit hydrograph are obtained. The table below presents the parameters for several CN values that increase in accordance with rainfall amounts recorded on the previous day.

The initial CN value was determined based on the degree of catchment development, geological and hydrogeological characteristics of the basin, and the recommendations of the SCS method related to antecedent soil moisture conditions (CN reference tables).

Table 3. Hydrological parameters of the catchment

Parameter	Symbol	CN 75	CN 77	CN 80	CN 83	CN 85
Concentration coefficient	K	0.418923	0.418923	0.418923	0.418923	0.418923
Equivalent length (km)	L	3.486.081	3.486.081	3.486.081	3.486.081	3.486.081
Equivalent width (km)	Lw	0.923673	0.923673	0.923673	0.923673	0.923673
Mean catchment slope (%)	J	1.033.826	1.033.826	1.033.826	1.033.826	1.033.826
Hydraulic flow length (m)	l	4.357.601	4.357.601	4.357.601	4.357.601	4.357.601
Lag time (h)	Tl	0.964111	0.909504	0.830231	0.753670	0.703891
Time of concentration (h)	Tc	1.607.173	1.516.144	1.383.995	1.256.368	1.173.387
Rainfall duration (h)	D	0.213754	0.201647	0.184071	0.167097	0.156060

Hydrograph rise time (h)	Tp	1.070.988	1.010.328	0.922267	0.837218	0.781922

8. Hydraulic Analysis

For the purposes of the hydraulic analysis, the dimensions of the downstream terminal section of the torrent—channelized into a concrete canal—were determined using a LiDAR scanner. A point-cloud representation is shown below.

Based on these data, the channel geometry and bed slope at the final section (schematic view) were determined in order to establish the overflow level and the onset of flooding at the observed profile.

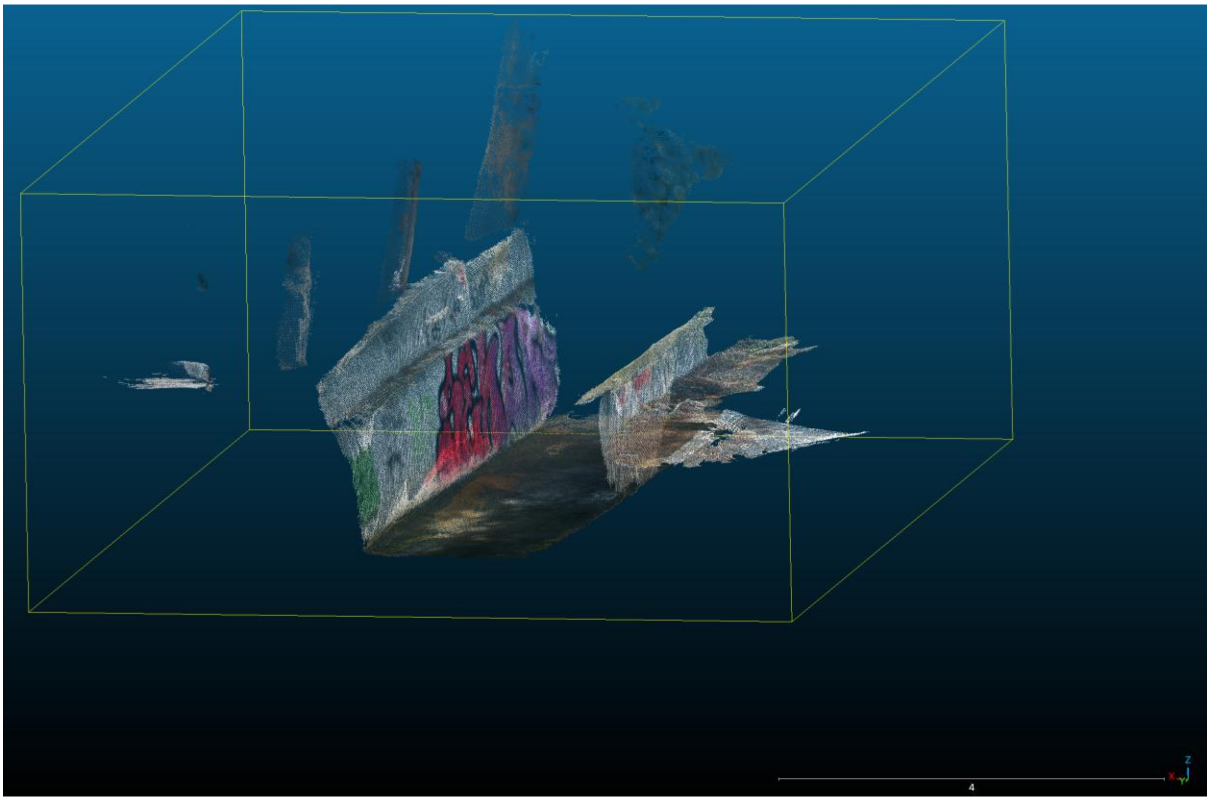

Figure 9. Outlet profile (point cloud data acquired by LiDAR scanning)

The point cloud data were used to derive the dimensions of the outlet profile, which are shown in the following figure:

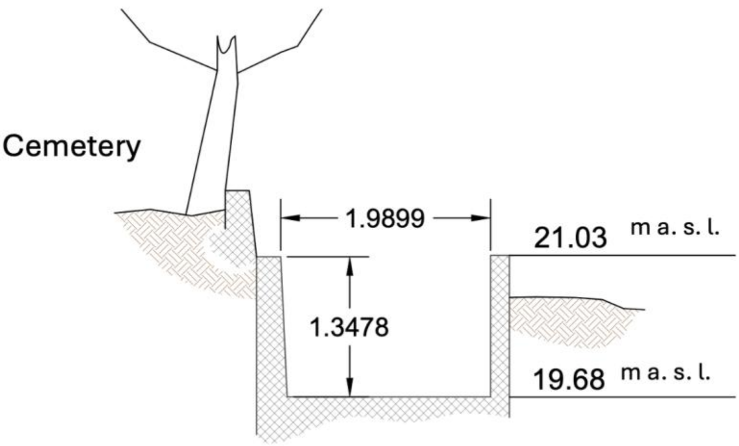

Figure 10. Sketch of the outlet profile, geometry derived from LiDAR scanning

For the purpose of assessing the flow conveyance capacity of the torrential watercourse and determining the onset of overtopping across the rigid channel boundaries, a hydraulic analysis was carried out based on the empirical–theoretical Manning–Strickler equation. The analysis includes two characteristic channel sections:

- **Natural torrent channel,** with a length of 3.5 km, an average longitudinal slope of 10.4%, developed in low-permeability flysch deposits, with vegetation present and an irregular cross-section.
- **Concrete rectangular channel**, with a length of 100 m, bottom width b = 2.00 m, sidewall height h = 1.35 m, and a minimum longitudinal slope of 1%, representing the final control section of the watercourse.

The main objectives of the analysis are to:

- determine the normal flow depth in both channel sections for the design discharge,
- analyse the hydraulic flow characteristics (flow area, hydraulic radius, velocity, Froude number),
- determine the maximum discharge that can be conveyed by the concrete channel before overtopping occurs (critical overflow discharge).

For the description of uniform flow in open channels, the well-known equation in the following form is used:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

where:

- Q – discharge $[m^3/s]$
- n – Manning roughness coefficient *(Strickler coefficient $k = 1/n$)*
- A – flow area $[m^2]$
- R = A/P – hydraulic radius $[m]$
- P – wetted perimeter $[m]$
- S – longitudinal bed slope $[-]$

For a rectangular cross-section (concrete channel):

$$A = b\,y, \qquad P = b + 2y, \qquad R = \frac{b\,y}{b + 2y}$$

where:

- b – bottom width $[m]$
- y – flow depth $[m]$
-

The normal flow depth y_n is determined as the solution of the governing equation.

$$A = by_n, \qquad V = \frac{Q}{A}, \qquad Fr = \frac{V}{\sqrt{g\,y_n}}$$

For a known overtopping depth of $y_{overflow} = 1.36\,m$, the maximum discharge that the concrete channel can safely convey can be directly calculated:

$$Q_{\max} = \frac{1}{n} A(y_{\text{overflow}}) \left(\frac{A(y_{\text{overflow}})}{P(y_{\text{overflow}})} \right)^{2/3} S^{1/2}$$

where the corresponding hydraulic parameters are evaluated for the overflow condition.

$$A(y) = b\,y, \qquad P(y) = b + 2y$$

If the actual discharge exceeds Q_{max}, overflow is unavoidable.

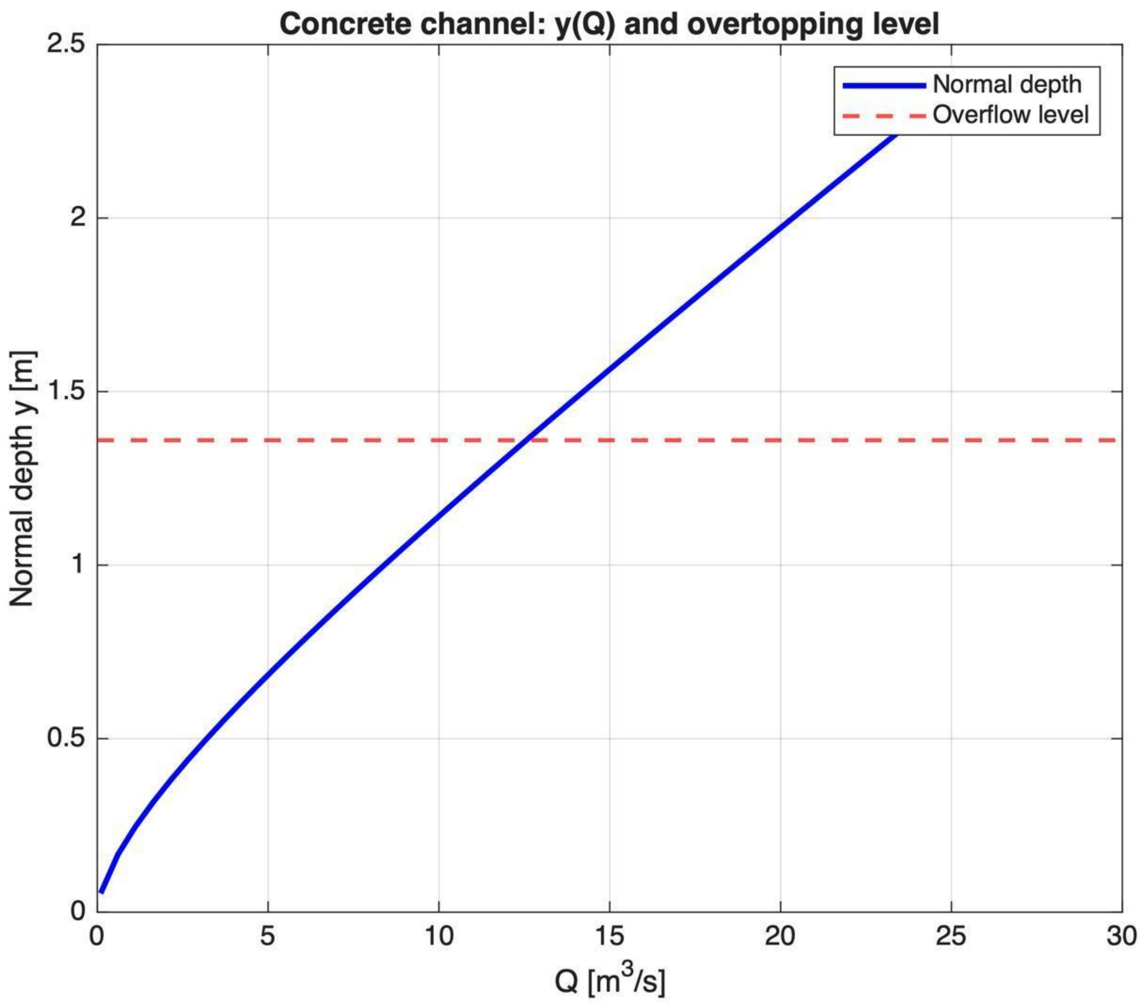

Figure 11. Relationship between overtopping and discharge at the outlet profile of the torrent

9. Hydrological Analysis

The Curve Number (CN) value is determined on the basis of three factors derived from satellite imagery and available background information: vegetation cover, land-use / surface treatment, and soil type. According to the SCS method, the following four hydrologic soil groups are used in engineering practice:

- **Type A**: poorest runoff conditions (very high infiltration capacity) – highly permeable deposits
- **Type B**: slightly better runoff conditions than Type A (high infiltration capacity) – partially impermeable deposits
- **Type C**: good runoff conditions (moderate infiltration capacity) – partially permeable deposits
- **Type D**: highest runoff potential (low infiltration capacity) – impermeable deposits

Table 4. Empirical CN values for different land covers and soil types, SCS Curve Number Table (Source: TR-55 NRCS, 1986)

Cover description: Cover type and hydrologic condition	Average percent impervious area [2]	Curve numbers for hydrologic soil group: A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

The mean CN value for the entire catchment is determined by weighted averaging. If the CN value is used in the expression for Pe instead of parameter S, the final equation for effective rainfall becomes:

$$Pe = 25.4\frac{(0.03937P - 200/CN + 2)^2}{(0.03937P + 800/CN - 8)} - 10$$

The SCS method is then used to derive the hydrograph of the analysed catchment for different return periods, which define the amount of gross rainfall. A hydrograph is a graphical representation of discharge Q (m^3/s) of a watercourse as a function of time.

The shape of the hydrograph depends on the topographic and physical characteristics of the catchment area (infiltration capacity, geological and soil composition, catchment shape, size, and slope), as well as on the duration, intensity, and temporal distribution of rainfall over the basin.

A distinction is made between:

- Natural hydrographs, obtained directly from field measurements, and
- Synthetic hydrographs, derived as outputs of hydrological models.

A synthetic hydrograph may also be a unit hydrograph, i.e. a hydrograph representing direct runoff generated by a unit rainfall excess. The unit hydrograph is based on the assumption that the catchment behaves as a linear and stationary system, for which the principles of proportionality and superposition apply.

According to unit hydrograph theory, for a given catchment, storm events of equal duration produce hydrographs with:

- approximately equal time bases, regardless of rainfall intensity,
- ordinates proportional to the volume of effective rainfall Pe,
- runoff time distribution (shape) independent of previous and future storms.

In the SCS method, the unit hydrograph of Victor Mockus (1957) is used, developed from empirical investigations of a large number of different catchments (Figure 12).

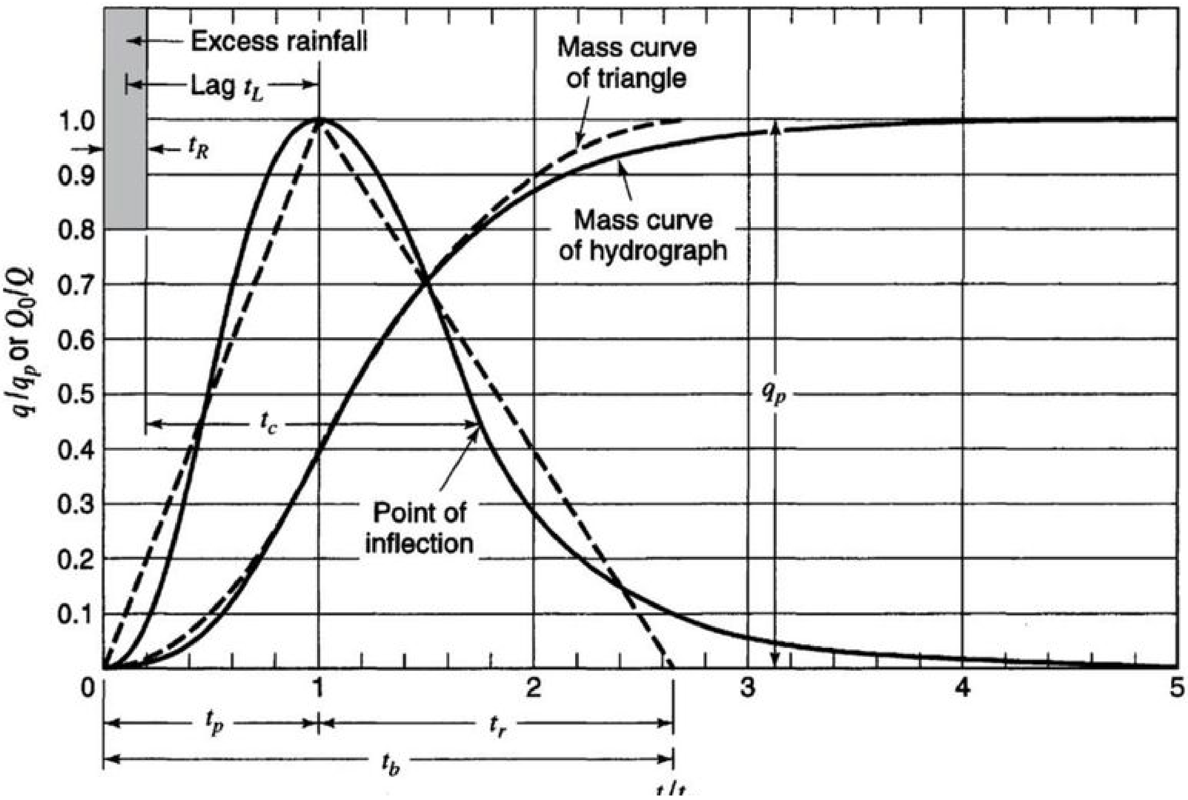

Figure 12. SCS curvilinear and triangular dimensionless unit hydrograph

The Victor Mockus dimensionless unit hydrograph used in the SCS method can be approximated by an equivalent triangular hydrograph (Figure 9), which has the same units for time and discharge, and therefore the same proportion of 37.5% of the total volume occurring within the rising limb time Tp. By applying the geometry of a triangle, the following relationships are obtained:

Base time of the triangular hydrograph:

$$T_b = \frac{1}{0.375} = 2.67$$

(time units)
Recession time of the hydrograph:

$$T_r = T_b - T_p = 1.67$$

(time units)
or:

$$T_r = 1.67T_p$$

I
f Qp denotes the peak discharge, the volume of the triangular hydrograph is:

$$V = \frac{Q_p}{2}(T_p + T_r)$$

The peak of the triangular hydrograph is:

$$Q_p = \frac{2V}{T_p(1 + T_r/T_p)}$$

Assuming that the unit excess rainfall is 1 mm, and the catchment area is A in km², the total volume of the unit hydrograph can also be expressed as:

$$V = 10^3 \cdot A \cdot P_e$$

where:

- V – hydrograph volume (m³)
- A – catchment area (km²)
- Pe – effective rainfall of 1 mm

Considering that the integral of the unit hydrograph, i.e. the area under the hydrograph, is equal to the catchment area, the expression for peak discharge becomes:

$$Q_p = \frac{2 \cdot 10^3 \cdot A}{3600(2.67T_p)} = 0.208\frac{A}{T_p}(m^3/s/mm)$$

where:

- Tp – hydrograph rise time (h)
- A – catchment area (km²)

The rise time of the unit hydrograph (Figure 8), Tp, is the time from the origin to the peak discharge, and in relation to rainfall excess duration D, it can be expressed as:

$$T_p = \frac{D}{2} + LAG$$

LAG is the lag time (TL), measured from the centroid of excess rainfall to the hydrograph peak, expressed in hours. According to the SCS method, lag time is calculated as:

$$LAG = 0.001362 \cdot L^{0.8}(S + 1)^{0.7}J^{-0.5}$$

where:

- L – hydraulic flow length (m)
- J – mean terrain slope (%)
- S – soil retention capacity

The most commonly used relationship between lag time and time of concentration is:

$$LAG = 0.6T_c$$

The time of concentration T_c can be defined in two ways:

- The time required for surface runoff water to travel from the most distant point of the catchment to the outlet profile.
- The time from the end of effective rainfall to the inflection point of the unit hydrograph, equal to 1.7 time units.

Therefore, considering the geometry of the triangular dimensionless unit hydrograph (Figure 8), the time of concentration can be expressed as:

$$T_c = 1.7T_p - D$$

The following useful relationships can be derived from the prescribed hydrograph geometry and the previous equations:

$$D = 0.2T_p$$
$$T_c + D = 1.7T_p$$
$$\frac{D}{2} + 0.6T_c = T_p$$
$$D = 0.133T_c$$

The unit rainfall duration D should be approximately 1/5 of Tp or 1/7.5 of Tc in order to reliably define the shape of the unit hydrograph. Small variations are acceptable, but according to Mitchell (1956), D must not exceed 0.25 Tp.

Fundamental hydrological parameters such as the time of concentration, hydrograph shape, and specific peak discharges strongly depend on catchment area, shape, and slope. Therefore, it is necessary to construct an equivalent rectangular catchment having the same concentration coefficient, the same area, and the same perimeter as the real catchment (Figure 10). It should be emphasized that the equivalent rectangular basin must have the same area as the actual catchment.

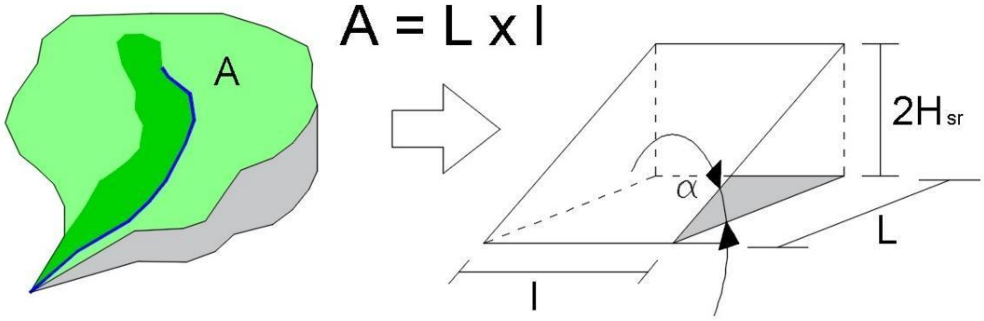

Figure 13. Schematic representation of the transformation of the real catchment into an equivalent rectangular catchment

The catchment concentration coefficient K, and the length and width of the equivalent rectangular catchment, L and l, are calculated using the following expressions:

$$K = \frac{2A}{OU}$$

$$L = \sqrt{\frac{A(2-K)}{K}}$$

$$l = \sqrt{\frac{AK}{2-K}}$$

where:

- K – catchment concentration coefficient (dimensionless)
- A – catchment area (km²)
- O – catchment perimeter (km)
- U – distance from the catchment centroid to the outlet profile (km)
- L – length of the equivalent rectangular catchment (km)
- l – width of the equivalent rectangular catchment (km)

The mean catchment slope (Figure 9), where $\tan\alpha = J$, is calculated as:

$$J = \frac{2(H_{sr} - H)}{L}$$

where:

- Hsr – mean catchment elevation determined from the DEM elevation histogram (hypsometric curve)
- H – elevation of the outlet profile

The hydraulic flow length l_w is calculated for alluvial terrain as the length of the equivalent catchment L increased by 25%. In the case of karst terrain, a karstification coefficient f_k is introduced, representing the ratio of karstified catchment area to total catchment area. The following expressions are then used:

$$f_k = \frac{A_k}{A}$$

$$l_w = 1.25L$$

$$l_w = (1.25 + 1.75f_k)L$$

where:

- fk – karstification coefficient (dimensionless, ranging from 0 to 1)
- A – catchment area (km²)
- Ak – karstified catchment area (km²)
- lw – hydraulic flow length (km)
- L – length of the equivalent rectangular catchment (km)

By the process of discrete convolution of rainfall excess duration D and the unit hydrograph, the hydrograph of direct runoff for the analysed catchment is obtained.

10. Precipitation

Precipitation represents the fundamental input parameter in the SCS (Soil Conservation Service) runoff model and largely determines the dynamic response of the catchment to rainfall events. Within the framework of this study, precipitation data were obtained from the Croatian Meteorological and Hydrological Service (DHMZ), from the reference meteorological station Marjan (Split), which is characterized by long-term, continuous, and high-quality measurements. The reliability and representativeness of this station are of key importance for the proper parameterization of SCS model inputs, particularly considering the pronounced spatio-temporal variability of precipitation in the Adriatic karst coastal region.

Based on the multi-year data series from the Marjan station, a family of Intensity–Duration–Return period (IDF) curves was developed, enabling the estimation of rainfall intensities for different storm durations and return periods. These curves were constructed using the Generalized Extreme Value (GEV) distribution, which, due to its flexibility and ability to adapt to different tail behaviours of the distribution, is particularly suitable for modelling extreme precipitation events.

The GEV distribution provided a statistically robust estimation of maximum rainfall amounts and corresponding intensities, which is essential for defining SCS model inputs in design scenarios and in the analysis of torrential catchment response.

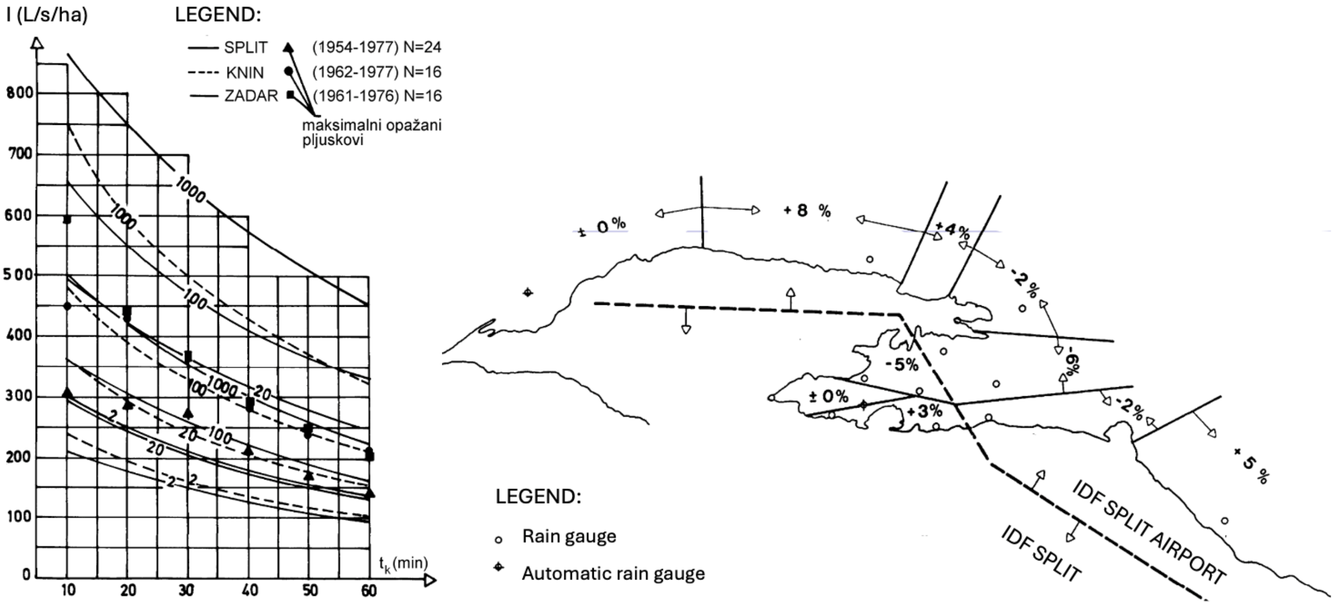

Figure 14. IDF curve and regional correction

The derived IDF curves represent a key hydrometeorological tool, as they enable the generation of synthetic rainfall hyetographs used as input to the SCS model for surface runoff simulation. This ensures that the model applies hydrometeorological data consistent with local climatic conditions, thereby increasing the reliability of the results and enabling an appropriate assessment of design discharges, rainfall contribution to torrential flows, and flood risk.

By combining reliable DHMZ data, statistical analysis of extreme precipitation, and application of the SCS methodology, a consistent and accurate modelling of the hydrological response of the analysed catchment was achieved. This represents an important step in the further development of hydraulic calculations and in planning measures for the reduction of torrential flood risk.

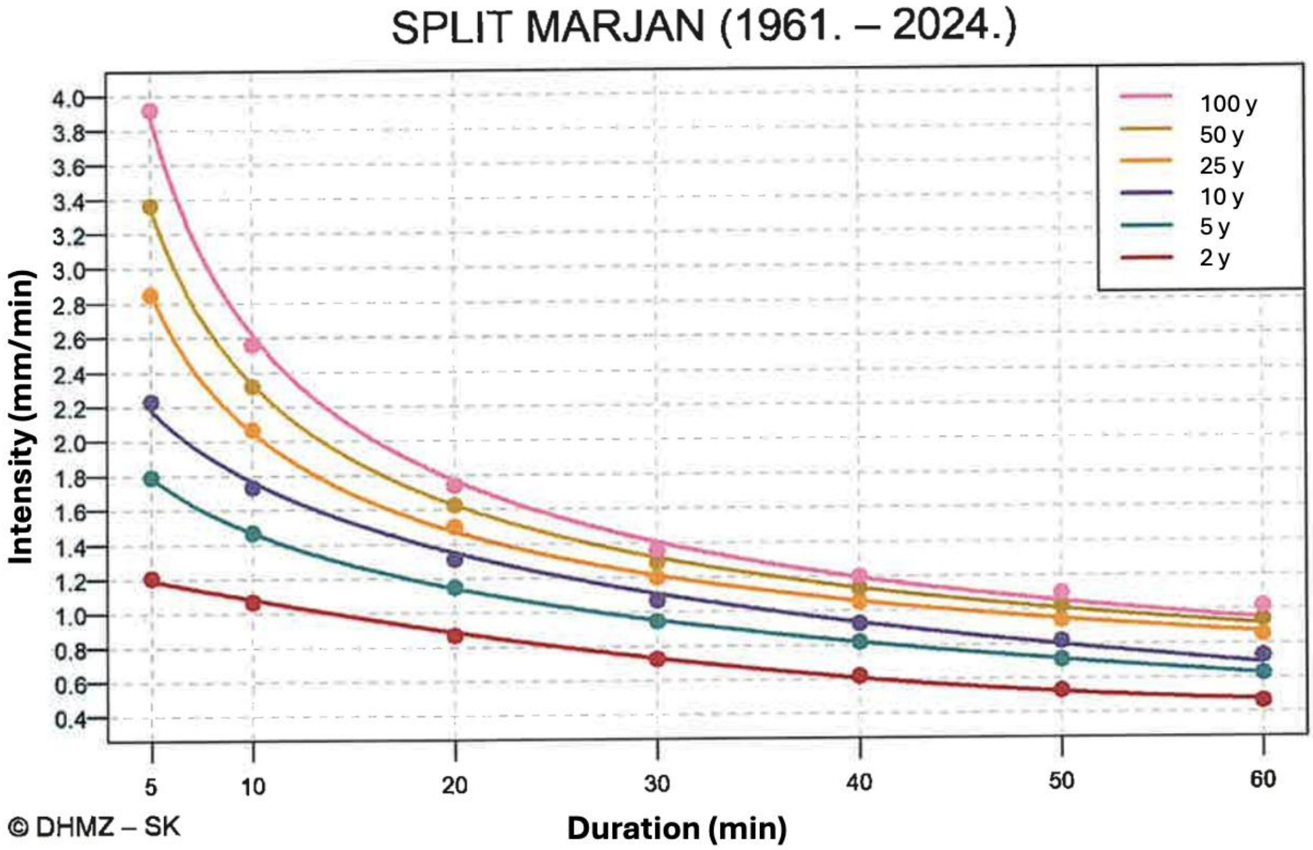

Figure 15a. IDF curves for return periods of 2, 5, 10, 25, 50, and 100 years for rainfall durations from 5 to 60 minutes. Circles indicate the estimated intensities for specific durations. Split–Marjan, period: 1961–2024.

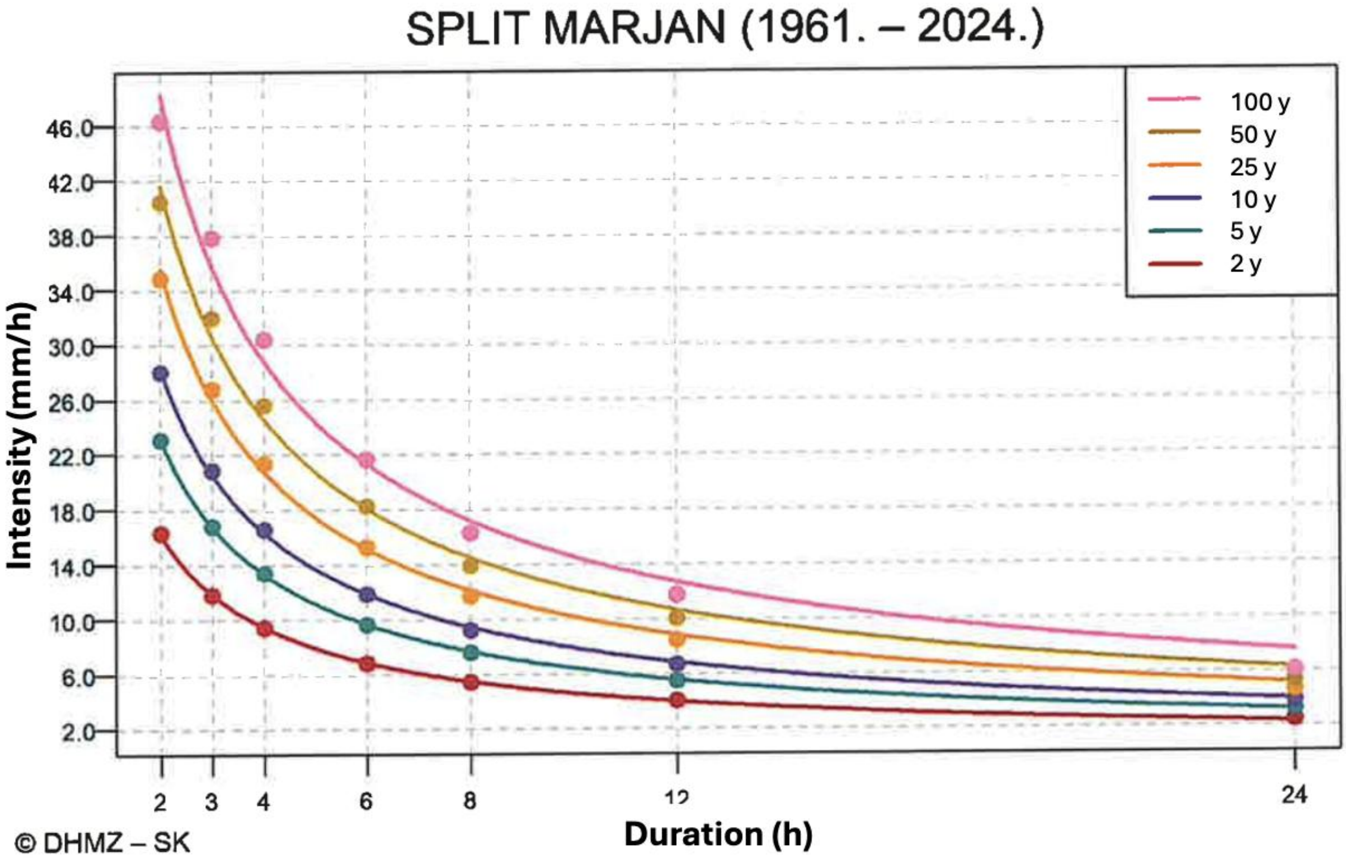

Figure 15b. IDF curves for return periods of 2, 5, 10, 25, 50, and 100 years for rainfall durations from 2 to 24 hours. Circles indicate the estimated intensities for specific durations. Split–Marjan, period: 1961–2024.

The Antecedent Precipitation Index (API) is a simple yet highly effective indicator of prior catchment wetness, widely used in hydrological modelling and runoff forecasting. API quantifies the accumulated effect of rainfall from previous days by combining the rainfall of the current day with a fraction of the index from the previous period. This fraction is reduced by a decay factor that represents soil drying processes, evapotranspiration, and groundwater percolation.

In this way, API provides a dynamic indicator of the catchment's "memory", i.e. the degree of saturation of the system prior to a new rainfall event. API values increase after intense or multi-day rainfall events, while during dry periods they gradually decrease. Owing to its simple formulation, limited input data requirements, and good correlation with catchment response, API is frequently applied in the estimation of antecedent moisture conditions and in the adjustment of hydrological model parameters.

$$API_t = P_t + k \cdot API_{t-1}$$

where:

- API_t = antecedent precipitation index for day *t*
- P_t = rainfall on day *t*
- k = decay factor (0.85–0.98) for daily time series data (rainfall memory factor)
- API_{t-1} = API value from the previous day

The API value acts as a weighting coefficient for increasing the mean CN value in the model. Therefore, it is important to account for all preceding rainfall events if the objective is to determine lag time and peak discharge as accurately as possible.

In the following section, discharge tables are developed for the analysed catchment under the assumption that the influence of the API parameter may increase the average catchment CN value from 75 CN to 80 CN for different rainfall intensities.

Table 4. Discharge for different rainfall intensities and CN75

CN	**75**						
i(mm/h)	30	35	40	45	50	60	80
t(h)	Q (m3/s)						
0	0	0	0	0	0	0	0
0,213754	0,024134	0,040732	0,054788	0,077567	0,103549	0,158927	0,285811
0,427508	0,114211	0,192761	0,259283	0,367081	0,49004	0,752114	1,352587
0,641262	0,307241	0,518548	0,697498	0,987487	1,318259	2,023266	3,638602
0,855016	0,593938	1,002422	1,348357	1,908945	2,548371	3,911244	7,033902
1,06877	0,91659	1,546979	2,080842	2,945964	3,932752	6,035995	10,85501
1,282524	1,189962	2,008365	2,701451	3,824595	5,105692	7,836225	14,09251
1,496278	1,342866	2,266429	3,048573	4,316036	5,761747	8,84314	15,90333
1,710032	1,334718	2,252678	3,030076	4,289848	5,726788	8,789484	15,80683
1,923785	1,18769	2,004531	2,696294	3,817294	5,095945	7,821266	14,06561
2,137539	0,969087	1,635581	2,20002	3,114691	4,157997	6,381701	11,47672
2,351293	0,749654	1,265232	1,701864	2,409424	3,216491	4,936676	8,878019

2,565047	0,565267	0,954032	1,283269	1,816795	2,425354	3,722437	6,694356
2,778801	0,422791	0,713567	0,959819	1,358869	1,81404	2,784192	5,007034
2,992555	0,315061	0,531745	0,71525	1,01262	1,35181	2,07476	3,731207
3,206309	0,235457	0,397394	0,534534	0,75677	1,01026	1,550548	2,788475
3,420063	0,176728	0,298274	0,401208	0,568013	0,758276	1,163804	2,092962
3,633817	0,132452	0,223546	0,300692	0,425706	0,568302	0,872231	1,568602
3,847571	0,100593	0,169777	0,228367	0,323312	0,431609	0,662435	1,191309
4,061325	0,076882	0,129757	0,174537	0,247101	0,329871	0,506286	0,910495
4,275079	0,058345	0,098471	0,132454	0,187522	0,250335	0,384215	0,690965
4,488833	0,0437	0,073755	0,099208	0,140454	0,1875	0,287776	0,517531
4,702587	0,032921	0,055563	0,074738	0,105811	0,141254	0,216797	0,389883
4,916341	0,024988	0,042174	0,056728	0,080312	0,107214	0,164552	0,295928
5,130095	0,01873	0,031611	0,04252	0,060198	0,080363	0,123341	0,221814
5,343849	0,014147	0,023877	0,032117	0,045469	0,0607	0,093162	0,167541
5,557603	0,009447	0,015945	0,021447	0,030364	0,040535	0,062214	0,111884
5,771356	0,005908	0,009971	0,013411	0,018987	0,025347	0,038903	0,069963
5,98511	0,003294	0,00556	0,007478	0,010587	0,014134	0,021692	0,039011
6,198864	0,001325	0,002236	0,003008	0,004258	0,005684	0,008724	0,01569
6,412618	0	0	0	0	0	0	0

Table 4. Discharge for different rainfall intensities and CN80

CN	**80**						
i(mm/h)	25	35	40	45	50	60	80
t (h)	Q (m3/s)						
0	0	0	0	0	0	0	0
0,184071	0,016691	0,048623	0,073779	0,094183	0,126203	0,18877	0,325205
0,368143	0,078989	0,230105	0,349156	0,445717	0,59725	0,893345	1,539013
0,552214	0,21249	0,619007	0,939268	1,199027	1,606665	2,403194	4,14011
0,736286	0,410771	1,196623	1,81573	2,31788	3,105898	4,645694	8,003385
0,920357	0,63392	1,846679	2,80211	3,577049	4,793152	7,16943	12,35116
1,104428	0,822985	2,397449	3,637837	4,6439	6,222705	9,307706	16,03488
1,2885	0,928735	2,705509	4,105281	5,240618	7,022291	10,5037	18,09528
1,472571	0,9231	2,689094	4,080372	5,20882	6,979684	10,43997	17,98549
1,656643	0,821414	2,392873	3,630893	4,635035	6,210826	9,289937	16,00427
1,840714	0,670227	1,952446	2,962598	3,781921	5,067675	7,580052	13,05856
2,024785	0,518466	1,510349	2,29177	2,925571	3,920189	5,863682	10,10168

2,208857	0,390942	1,138859	1,72808	2,205989	2,955968	4,421434	7,617039
2,392928	0,292405	0,851808	1,292515	1,649966	2,210912	3,307005	5,697153
2,576999	0,217898	0,634761	0,963173	1,229544	1,647556	2,464357	4,245479
2,761071	0,162844	0,474382	0,719816	0,918885	1,231282	1,841709	3,17281
2,945142	0,122226	0,356059	0,540277	0,689693	0,924171	1,382342	2,381435
3,129214	0,091604	0,266854	0,404919	0,516901	0,692634	1,036017	1,784802
3,313285	0,069571	0,202668	0,307524	0,392572	0,526036	0,786826	1,355507
3,497356	0,053172	0,154896	0,235035	0,300035	0,402039	0,601357	1,035989
3,681428	0,040352	0,117549	0,178366	0,227694	0,305103	0,456363	0,786201
3,865499	0,030223	0,088043	0,133595	0,170542	0,228521	0,341814	0,588862
4,049571	0,022769	0,066328	0,100644	0,128478	0,172157	0,257507	0,44362
4,233642	0,017282	0,050344	0,076391	0,097517	0,13067	0,195452	0,336715
4,417713	0,012954	0,037735	0,057259	0,073094	0,097944	0,146502	0,252386
4,601785	0,009784	0,028502	0,043249	0,05521	0,073979	0,110656	0,190633
4,785856	0,006534	0,019034	0,028882	0,036869	0,049404	0,073896	0,127305
4,969928	0,004086	0,011902	0,01806	0,023055	0,030893	0,046209	0,079606
5,153999	0,002278	0,006637	0,01007	0,012855	0,017226	0,025766	0,044388
5,33807	0,000916	0,002669	0,00405	0,00517	0,006928	0,010363	0,017852
5,522142	0	0	0	0	0	0	0

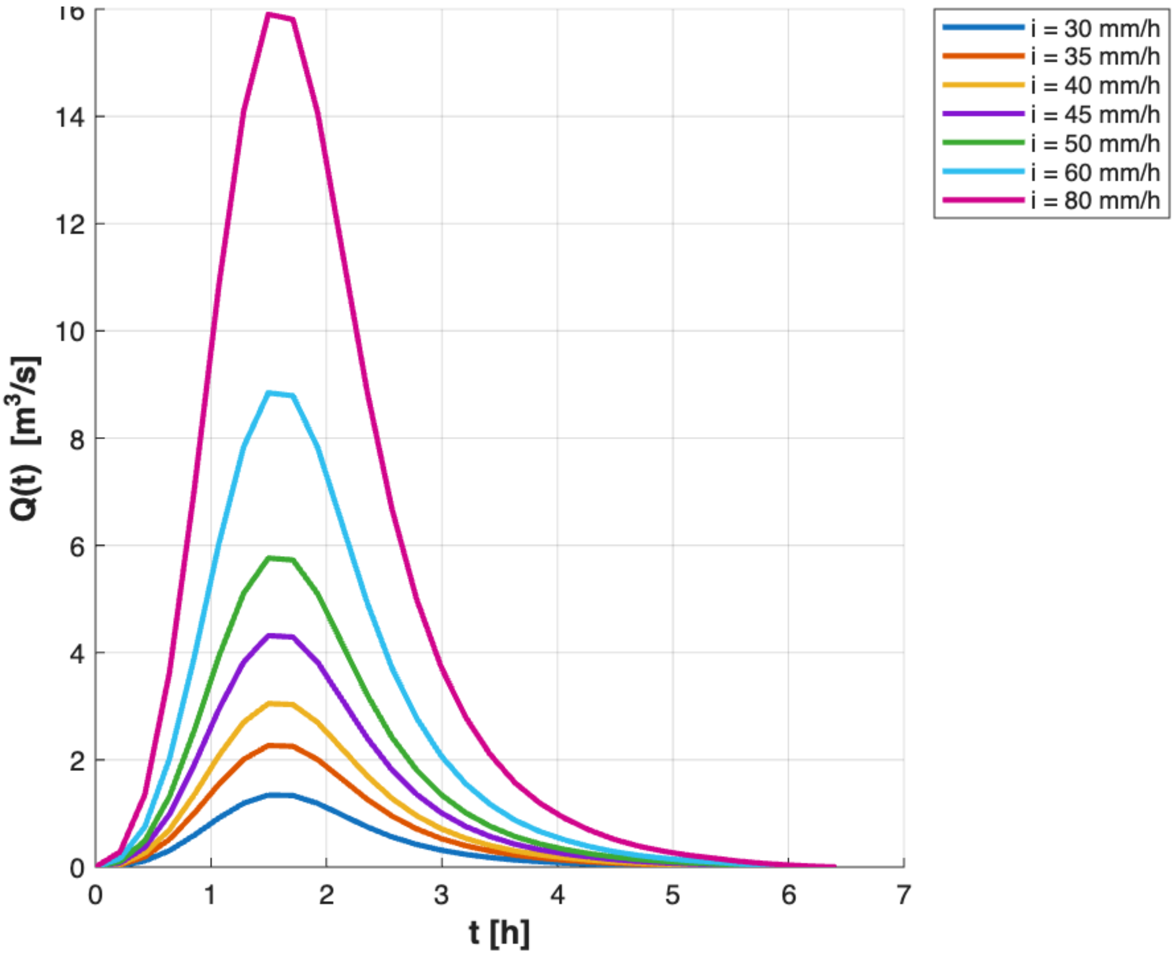

Figure 16. Direct runoff for different rainfall intensities and CN75

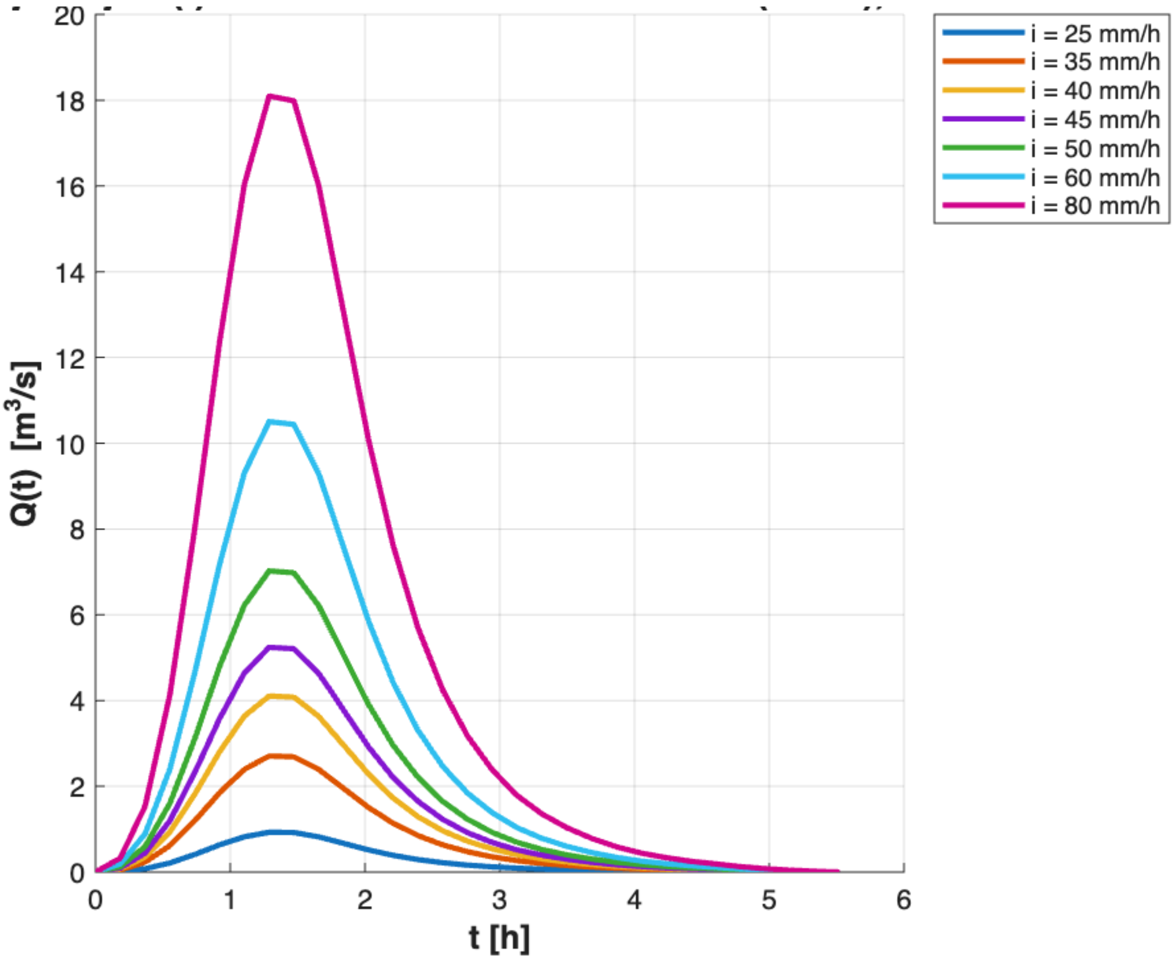

Figure 17. Direct runoff for different rainfall intensities and CN75

11. Early Warning System (EWS) Model

The critical overtopping discharge is:

$$Q_{krit} = 12\, m^3/s$$

For the Early Warning System (EWS), a safety factor of 2.0 is introduced, and the warning threshold is therefore defined as:

$$Q_{EWS} = \frac{Q_{krit}}{2} = 6\, m^3/s$$

The duration of the design rainfall event is:

$$\Delta t = 0.2\ h$$

Under dry conditions (without significant antecedent rainfall, CN = 75), for $\Delta t = 0.2\ h$, overtopping (≥ 6 m^3/s) is caused by rainfall intensities of:

- i = 60 mm/h
- i = 80 mm/h

Under wet conditions (at least 50% of the rainfall amount of the current day has fallen during the previous three days → CN = 80), the same effect is caused by:

- i = 50 mm/h
- i = 60 mm/h
- i = 80 mm/h

Algorithm Logic

The measured variable and direct input parameter of the system is 10-minute rainfall. Critical rainfall intensities for the warning system are:

Dry regime:

- 50 mm/h *(5 mm in 10 min)*

Wet regime:

- 40 mm/h *(4 mm in 10 min)*

A wet regime is assumed when the cumulative rainfall during the previous three days exceeds 50% of the cumulative rainfall on the day of observation.

Travel Time of the Flood Wave to the Outlet Profile After Warning Activation

Rainfall Intensity	10-min Rainfall	Time to Overtopping
80 mm/h	8 mm / 10 min	40 min
60 mm/h	6 mm / 10 min	55 min
50 mm/h	5 mm / 10 min	65 min
40 mm/h	4 mm / 10 min	80 min

Risk Levels for Dry Conditions

- 0 – Green: no danger
- 1 – Yellow: increased monitoring
- 2 – Orange: preparedness, possible flooding
- 3 – Red: high probability of overtopping (> 6 m^3/s)

Proposed Warning Activation Logic

- Warning activation is recommended if two consecutive measurements exceed the threshold for the corresponding regime (Level 1 – Yellow).
- If four measurements exceed the threshold within 1 hour for the corresponding regime (Level 2 – Orange).
- If six measurements exceed the threshold within 1 hour for the corresponding regime (Level 3 – Red).
- If an event is active and three consecutive measurements fall below 65% of the threshold, the system is reset and returns to its initial state.

Conclusion

The proposed Early Warning System (EWS) guidelines are based on the results of the hydraulic and hydrological modelling, which identified critical 10-minute rainfall thresholds and the corresponding rise times to overtopping at the outlet profile. This enabled the development of an operational logic relying exclusively on continuous rainfall measurements at a 10-minute time step, with differentiation between dry and wet regimes based on rainfall during the previous three days, and estimation of Time to Overtopping (TTO) updated with each new measurement.

However, reliable operation of the EWS requires further calibration and validation using real flood events, since the modelled thresholds and rise times depend on local catchment and channel conditions (initial soil moisture, losses, runoff routing, changes in roughness and channel geometry, culvert blockage, etc.).

The monitoring system can significantly improve the model and reduce forecast uncertainty through the introduction or strengthening of:

1. Continuous water level/discharge monitoring at the critical profile to confirm overtopping onset
2. Additional rain gauges within the catchment to improve spatial rainfall representativeness
3. Soil moisture data or proxy antecedent rainfall indicators
4. Periodic field inspections and surveys of channel geometry and structures (culverts, retention structures) for updating hydraulic parameters

In this way, the EWS evolves from a conceptual modelling solution into a reliable, locally calibrated operational system with clearly defined thresholds, warning levels, and time-relevant information for decision-making.

12. Calibration Using Surveillance Camera Recordings

The following section provides instructions for the installed camera, which can be used to monitor water level and the hydrological regime at the outlet profile in real time:

Hikvision Camera Instructions:

- https://hik-partner.com/
- Log in with OneHikID Account
- hikvisionkamera@proton.me
- GQd8Xh!rH.sY
- Site & Device -> Location

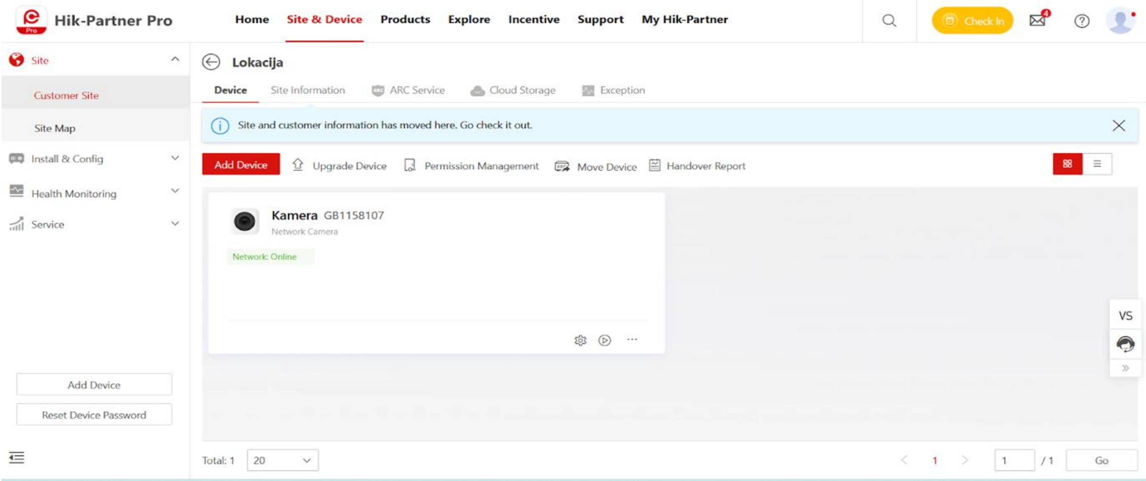

Figure 18. User interface

- Gear icon – camera settings menu
- Play – live camera view
  - when opening for the first time, the browser may request installation of Web Control or similar software – this should be allowed and installed
  - if a verification code / encryption password is required, enter: CZJKSY
- Three dots → Playback – review recorded camera footage

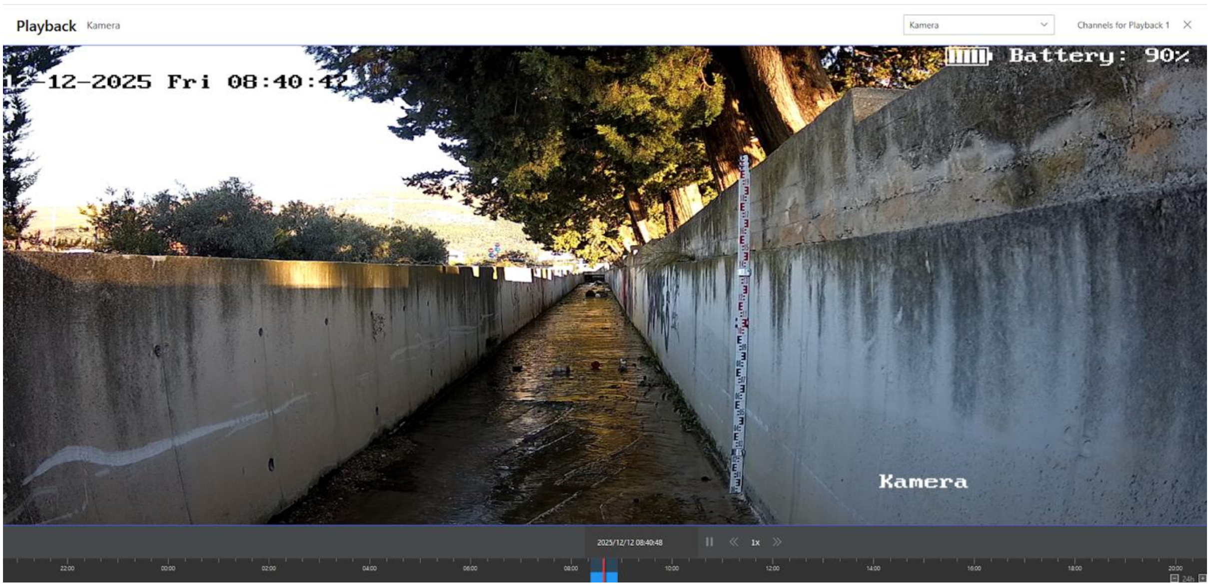

Figure 19. Camera recording

Figure 20. Photographs of mounted camera and installed gauge

13. EWS – Appendix – December 2025 and January 2026

The following section presents the measured rainfall data and the corresponding catchment response in the form of water level observations recorded using the installed camera.

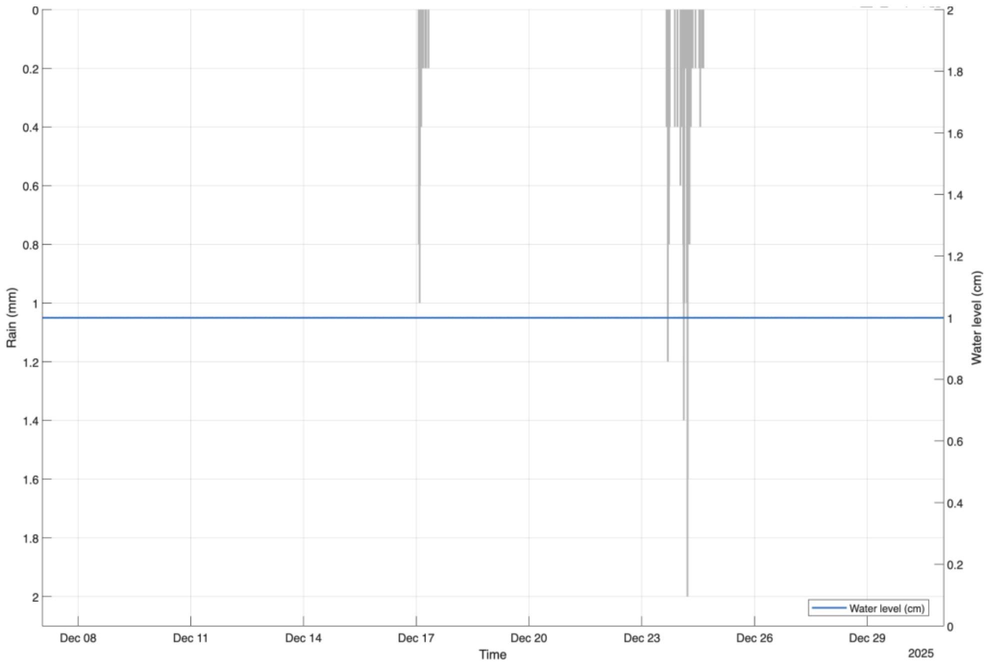

Figure 17a. Recorded water level at the control profile and precipitation within the catchment (December 2025).

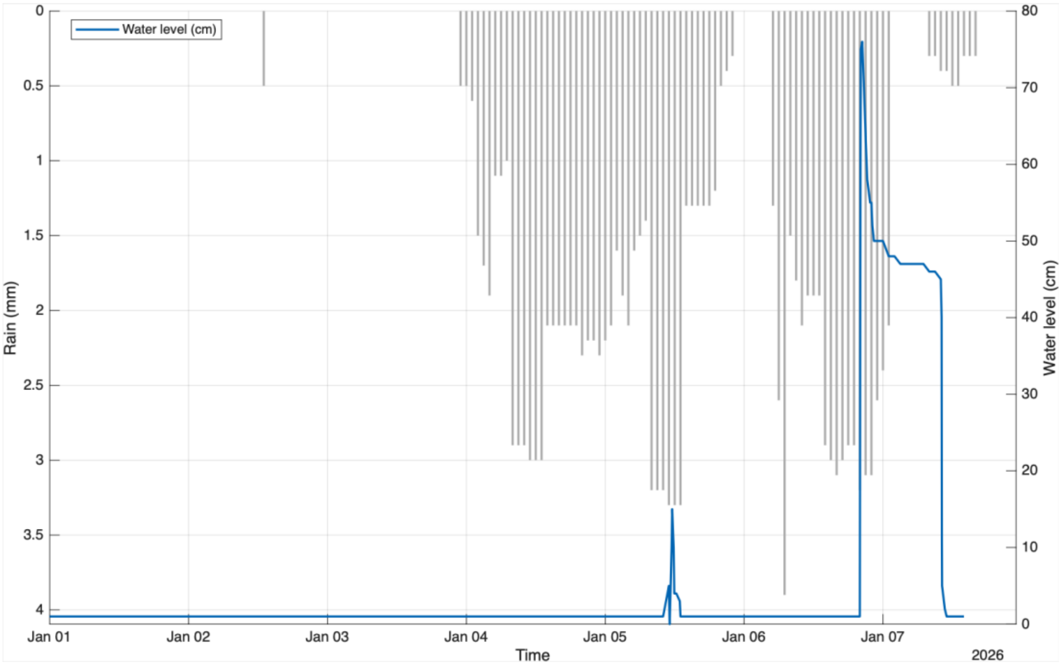

Figure 17b. Recorded water level at the control profile and precipitation within the catchment (January 2026).

Measurements from January provide additional insight into the functioning of the catchment and its response to rainfall forcing. By analysing Figure 17b, specific behavioural characteristics of the catchment can be identified.

(A) Without prior wetting (antecedent saturation), rainfall does not produce a measurable rise in water level.

During the beginning of January, several hours of rainfall with lower hourly intensities did not generate any water-level response until sufficient saturation had accumulated.

(B) After wetting of the catchment, even moderate intensities can generate a very strong response.

The second event (6–7 January) produced a maximum water level of approximately 76 cm, although hourly intensities were not extreme; the decisive factor was the API (Antecedent Precipitation Index / antecedent rainfall from previous days).

Therefore, the existing “dry/wet” differentiation should be upgraded to three moisture regimes with clear operational logic:

Regime R0 – DRY

- antecedent rainfall is low
- initial losses dominate (infiltration, epikarst/soil storage)
- rainfall often produces no response in the channel

Criterion (proxy measurement, recommended):

R48 < 20 mm or Dwet < 8 h

where R48 is cumulative rainfall over the previous 48 h, and Dwet is the number of hours with rainfall during the previous 48 h.

Regime R1 – WETTED

- losses are reduced, runoff generation begins
- response to moderate rainfall is possible

Criterion:

R48 ≥ 20 mm and Dwet ≥ 8 h

Regime R2 – SATURATED (critical state observed in January 2026)

- the catchment generates rapid direct runoff
- small additional rainfall impulses may cause large water-level rises

Criterion:

R48 ≥ 35 mm and Dwet ≥ 18 h

This state is consistent with observations from January: a preceding multi-day rainfall period was required for the subsequent rainfall to trigger a record rise in water level.

Note: These criteria can be calibrated later, but at present they are physically meaningful and directly supported by the January 2026 event.

Critical 10-min thresholds – Upgrade for three regimes

Existing thresholds:

- DRY: 50 mm/h (5 mm / 10 min)
- WET: 40 mm/h (4 mm / 10 min)

Upgraded thresholds according to three regimes:

Regime R0 – DRY

- Warning threshold (yellow): 5 mm / 10 min
- High danger threshold (red): 8 mm / 10 min

(remains consistent with the established hydrological model)

Regime R1 – WETTED

- Yellow: 4 mm / 10 min
- Orange: 5 mm / 10 min
- Red: 6 mm / 10 min

Regime R2 – SATURATED (based on January 2026 measurements)

1. Yellow: 3 mm / 10 min
2. Orange: 4 mm / 10 min
3. Red: 5 mm / 10 min

Extended activation logic

Input parameter:

- 10-min rainfall (primary trigger)

Recommended upgrade:

Introduce proxy moisture indicators (R48 and Dwet) calculated solely from the same rainfall time series, without additional sensors.
Alert activation:

Retain the logic of consecutive exceedances, but thresholds depend on the newly established regimes R0, R1, and R2:

- Level 1 (yellow): 2 consecutive measurements above the regime threshold
- Level 2 (orange): 4 measurements above threshold within 1 h
- Level 3 (red): 6 measurements above threshold within 1 h

Reset:

If an event is active and 3 consecutive measurements fall below 65% of the threshold → reset.

Conclusion After Collected Measurements

The proposed EWS guidelines are based on hydraulic and hydrological modelling that defined critical 10-min rainfall thresholds and corresponding rise times to overtopping at the outlet profile. The upgrade based on measurements from January 2026 confirms that the catchment behaves such that, without prior wetting, rainfall may not cause a rise in water level, whereas after saturation even moderate rainfall impulses can generate sudden and significant rises in the regulated channel.
For this reason, an operational differentiation into three moisture regimes (dry – wetted – saturated) is proposed, derived solely from rainfall data (R48 and Dwet), together with adjusted intensity thresholds and more conservative estimates of time to overtopping in the saturated regime.
Additionally, the introduction of feedback from measured water level (rapid rise Δh) as a secondary trigger is recommended, increasing system reliability under conditions of possible hydraulic controls (blockages, roughness changes, local geometry, culverts).

14. Annex

IDF curves for Town of Kaštela, 2025, Croatian Meteorological and hydrological service (DHMZ)