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Estimating critical rainfall for flash flood warning systems using integrated hydrologic-hydrodynamic modelling

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Introduction

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- The model and the applied methodology are implemented in the **Lelandas River** Basin in Euboea for a relatively large number of rainfall **scenarios** combined with initial soil moisture conditions.
- The objectives are:
    - The determination of **input hydrographs**, which are used as boundary conditions in the hydrodynamic model.
    - The calculation of the **distribution** of the "**critical hazard**" in the cells of the two-dimensional (2D) computational domain, defined by combining the main hydrodynamic characteristics, which are depth and flow velocity.
- Finally, based on the calculated "critical risk," an estimate of the critical rainfall values for the selected study area is made, and an example of the operation of the applied **flood warning system** is presented.
- **Uncertainty** in rainfall estimation can lead to the underestimation or overestimation of a flood event.
- The longer the time frame given for a warning, the **less accurate** the prediction tends to be.
- On the other hand, delays in issuing a warning can result in **catastrophic losses of human lives and property**.

Study area
Hydrological and Geospatial Data

The Unit Hydrograph (UH) of the study area was obtained from Mandravelos (2022), who estimated it using the method of **isochronal curves**.

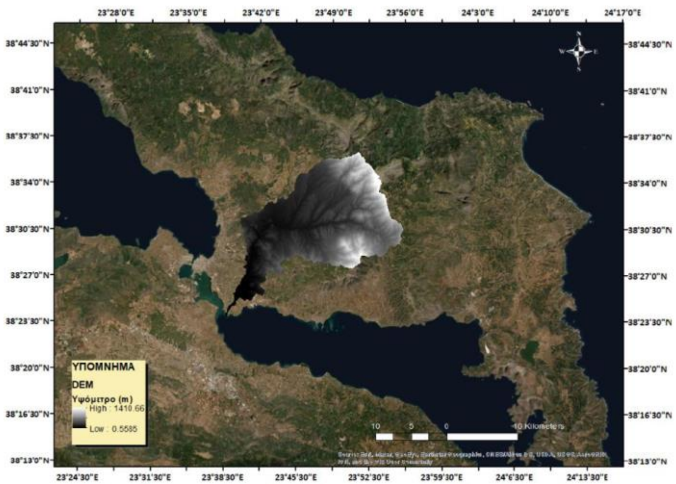

Fig. 1: Digital Elevation Model (DEM) of the Lelandas River Basin (Mandravelos, 2022).

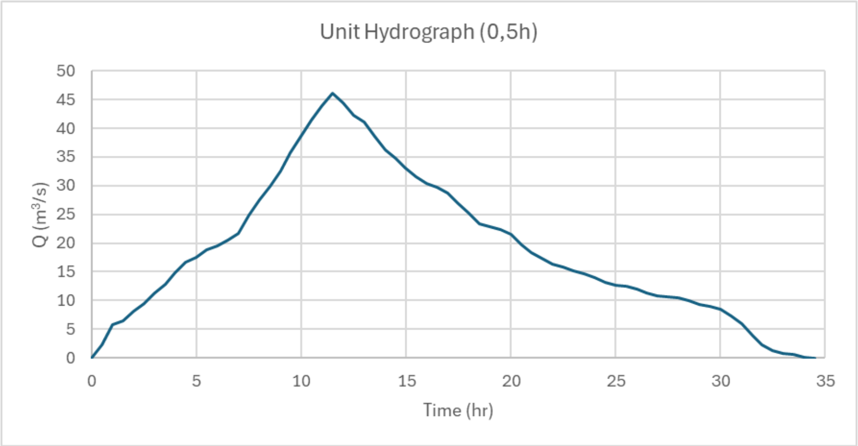

Fig. 2: The Unit Hydrograph of the Lelandas River Basin (Mandravelos, 2022).

Geospatial data (DEM) of the examined river basin, as well as the wider study area, were provided by the Hellenic Cadastre (Ktimatologio S.A.) with a resolution of 5 x 5 meters.

Regarding the formation of the **rainfall curve** for the study area, data were obtained from the KATO STENI station, which was considered **representative** of the entire river basin, as it is located at its center.

Methodology

Calculation of concentration time (Giandotti method): t_c = 7.6h

Calculation of the IDF (rainfall-runoff) curve

Calculation of the block hyetographs (alternating block method)

Calculation of hydrological losses and effective rainfall:

- Use of the empirical SCS method with estimation of the CN (Curve Number) coefficient and use of the Ministry of Environment and Energy (ΥΠΕΝ) and CORINE tables (ArcGIS).
- This determination concerns the three states of soil moisture.
- The CN value of the examined catchment area has been estimated at 77.80, through a related analysis carried out using ArcGIS software.
- This study includes a sensitivity analysis for three additional CN scenarios, as presented below:

Scenarios / Conditions	i Dry	ii Normal	iii Wet	Change
CN_{real}	59.55	77.80	88.96	0%
CN1	54.33	73.91	86.69	-5%
CN2	65.20	81.69	91.12	+5%
CN3	71.37	85.58	93.17	+10%

Table 1: Scenarios and application of sensitivity analysis for the variation of the CN value from -5% to +10%.

Hazard Index

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Calculation of the Hazard Index (HI)

- In the current methodology, it is proposed to calculate the critical rainfall as an indicator for issuing a warning in the developing Flood Early Warning System (FEWS) (Huang et al., 2019).
- The critical rainfall is calculated through the Hazard Index (HI), which is derived from the results of the hydrodynamic model (Defra and Environment Agency, 2006; Huang et al., 2019).
- The Hazard Index, in addition to being used for calculating the critical rainfall, also serves as a determining factor for issuing a "pre-evacuation preparation" warning or an "immediate evacuation" order (Cao et al., 2010).

$$HI = h\,(U + 1.5) + DF$$

where:

- *HI* is the hazard index,
- *h* (m) is the flow depth,
- $U = \sqrt{u^2 + v^2}$ (m/s) is the flow velocity, and
- *DF* is the debris factor, which has characteristic values of 0, 1, and 2, depending on the likelihood that debris will lead to a significantly increased flood hazard.

Hazard Index

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Calculation of the Hazard Index (HI)

Considering that the presence of sediment load is a common condition in floods, a representative value of the sediment load index (DF) is set at 1.0. Therefore, the equation from which the hazard index is derived is simplified to the following for convenience (Huang et al., 2019):

$$HI = h\,(U + 1.5)$$

Where, as before, *HI* is the Hazard Index, *h* (m) is the flow depth, and *U* is the flow velocity.

For the flood warning system to be applied in this study, two risk levels are established, with two critical hazard index values (HI_c) defined:

- *HI_c = 0.5, corresponding to the "pre-evacuation preparation" (PE) level, and*
- *HI_c = 1.0, corresponding to the "immediate evacuation" (IE) level.*

Scenarios

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Scenarios of combinations of rainfall duration, total rainfall, and soil moisture

A total of 180 scenarios were examined based on:

- Rainfall duration,
- Total rainfall,
- Initial soil moisture conditions (dry, normal, wet).

Rainfall duration (h)	Total rainfall (mm)	Scenarios	Soil moisture
1	40, 50, 60, 70, 80, 90, 100, 110	8	Initial soil moisture conditions: dry, normal, wet
3	70, 85, 100, 115, 130, 145, 160, 175	8	
6	80, 100, 120, 140, 160, 180, 200, 220, 240	9	
8	90, 110, 130, 150, 170, 190, 210, 230, 250, 270, 290, 310	12	
12	120, 140, 160, 180, 200, 220, 240, 260, 280, 300	10	
24	150, 170, 190, 210, 230, 250, 270, 290, 310, 330, 350, 370, 390	13	

Table 2: The scenarios of combinations of rainfall duration, total rainfall, and soil moisture applied in this study.

The above scenarios were designed in such a way that they correspond to return periods ranging from 5 to at least 500 years.

Rainfall durations of up to 24 hours were selected for hydrological consistency, i.e., up to three times the concentration time (t_c = 7h).

Critical Rainfall

Calculation of Critical Rainfall

The goal of the methodology is to create a critical rainfall database for the examined catchment area.

More specifically, this database will be formed through the calculation of critical rainfall for all combinations of rainfall duration and initial soil moisture conditions (dry, normal, or wet).

Thus, for each cell in the examined grid, 36 critical rainfall values can be derived, corresponding to the possible combinations of different rainfall durations (6), initial soil moisture conditions (3), and flood warning levels (2).

During the 2D hydrodynamic modeling process, after initially creating a grid, we extract the hydraulic characteristics of the flow (such as depth and velocity) for each cell, and then calculate the hazard index (HI) for all examined scenarios.

Critical Rainfall

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Calculation of Critical Rainfall

Next, we compare the critical hazard index HI_c, i.e., the values 0.5 and 1.0 corresponding to the two risk levels, with the maximum hazard indices HI that resulted from each examined scenario of rainfall intensity and duration, so that, ultimately, when these maximum hazard indices are arranged in ascending order, for two consecutive positions of these maximum values, the following holds:

$$(HI)_k < (HI)_C \leq (HI)_{k+1}$$

where k and k+1 are two consecutive positions. Let R_k and R_{k+1} be the rainfalls that produce the hazard indices $(HI)_k$ and $(HI)_{k+1}$ at the consecutive positions k and k+1, respectively. Then, the critical rainfall R_c is calculated through linear interpolation of the rainfalls R_k and R_{k+1}.

Flood Early Warning System

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Graphical representation of the applied Flood Early Warning System (FEWS)

In the applied Flood Early Warning System (FEWS), the steps followed during the process of issuing a flood warning are:

1. Determination of the rainfall duration, according to the relevant hydro-meteorological forecast.
2. Determination of the soil moisture category before the examined rainfall event, according to the cumulative rainfall amounts of the previous five days.
3. Based on the expected rainfall duration and the determined type of pre-existing soil moisture, the critical rainfall corresponding to this expected event is determined, a value that has already been calculated and is extracted from the database (of critical rainfalls).
4. Calculation of the cumulative rainfall at the decision time, r_d:

$$r_d = \sum_{t=0}^{t=t_d} r_o$$

Flood Early Warning System

Graphical representation of the applied Flood Early Warning System (FEWS)

And calculation of the cumulative rainfall at the warning time r_w:

$$r_w = r_p + r_d$$

The time steps for calculating r_d and r_w are 15 minutes for 1-hour rainfall duration, 30 minutes for rainfall durations of 3 hours or 6 hours, and 1 hour for rainfall durations of more than 6 hours.

5. Comparison of the rainfall at the warning time, r_w, and the critical rainfall, r_c. In the case where the following holds:

$$r_w > r_c$$

Then, a warning must be issued to the at-risk population.

Flood Early Warning System

Graphical representation of the applied Flood Early Warning System (FEWS)

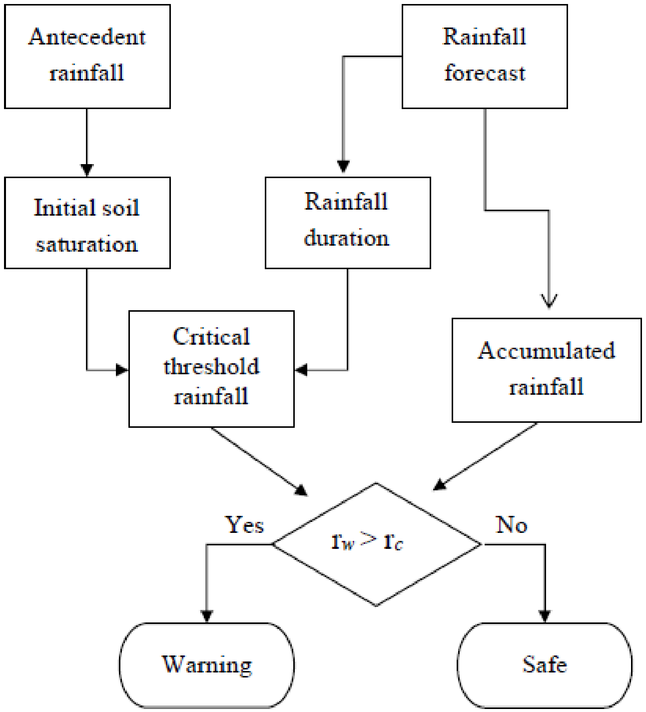
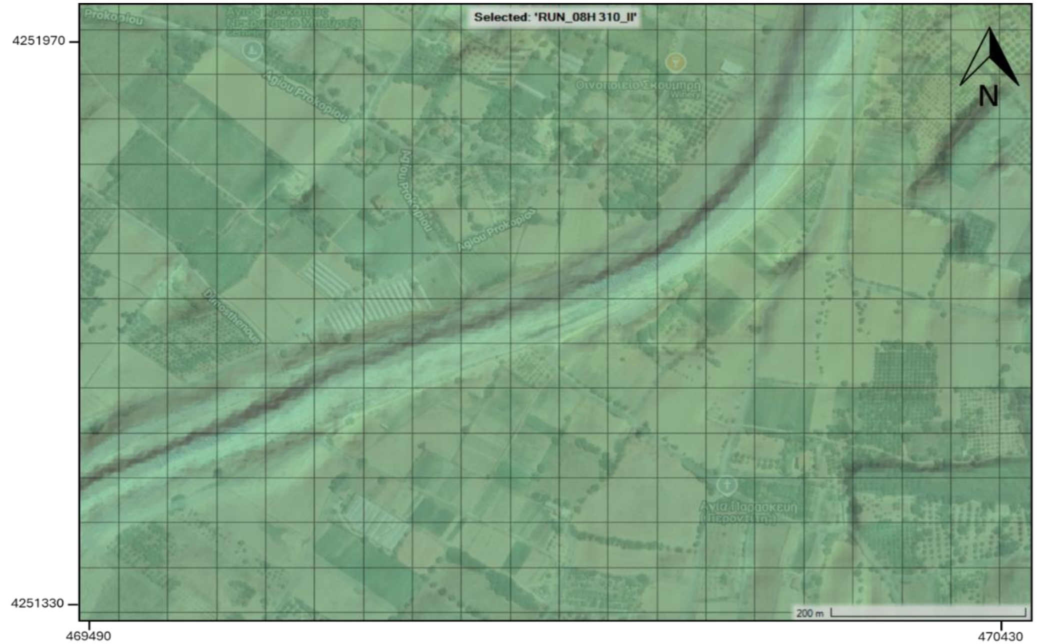


Table 3: Flowchart of the process followed for issuing or not issuing a flood risk warning for an examined study area (Huang et al., 2019, modified).

Computational tools

- Geographic Information Systems: ArcGIS
- Hydrological analysis: HEC-HMS
- Hydrodynamic analysis: HEC-RAS

Application of FEWS
With estimation of critical rainfall



Initially, it is necessary to calculate the value of the critical rainfall R_c for the two risk levels, through a derived quantity that results from the hydrodynamic analysis, the hazard index.

As presented earlier, the equation from which the hazard index is calculated at a certain location of the floodplain is:

$$HI = h\,(U + 1.5)$$

where:

- *HI* is the hazard index,
- *h* (m) is the flow depth, and
- $U = \sqrt{u^2 + v^2}$ (m/s) is the flow velocity

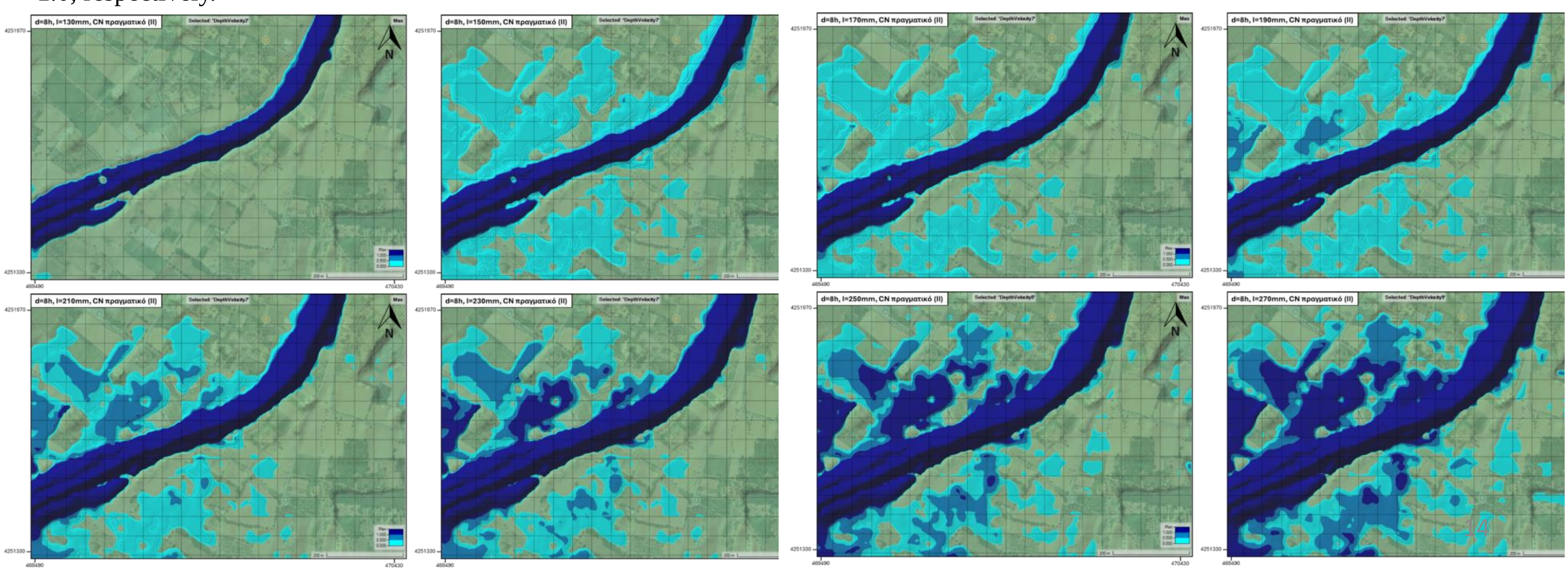
Application of FEWS
With estimation of critical rainfall

Furthermore, as mentioned earlier, for the flood warning system of this study, two risk levels are established, with two critical hazard indices HI_c defined:

- *HI_c = 0.5, corresponding to the "pre-evacuation preparation" (PE) level, and*
- *HI_c = 1.0, corresponding to the "immediate evacuation" (IE) level.*

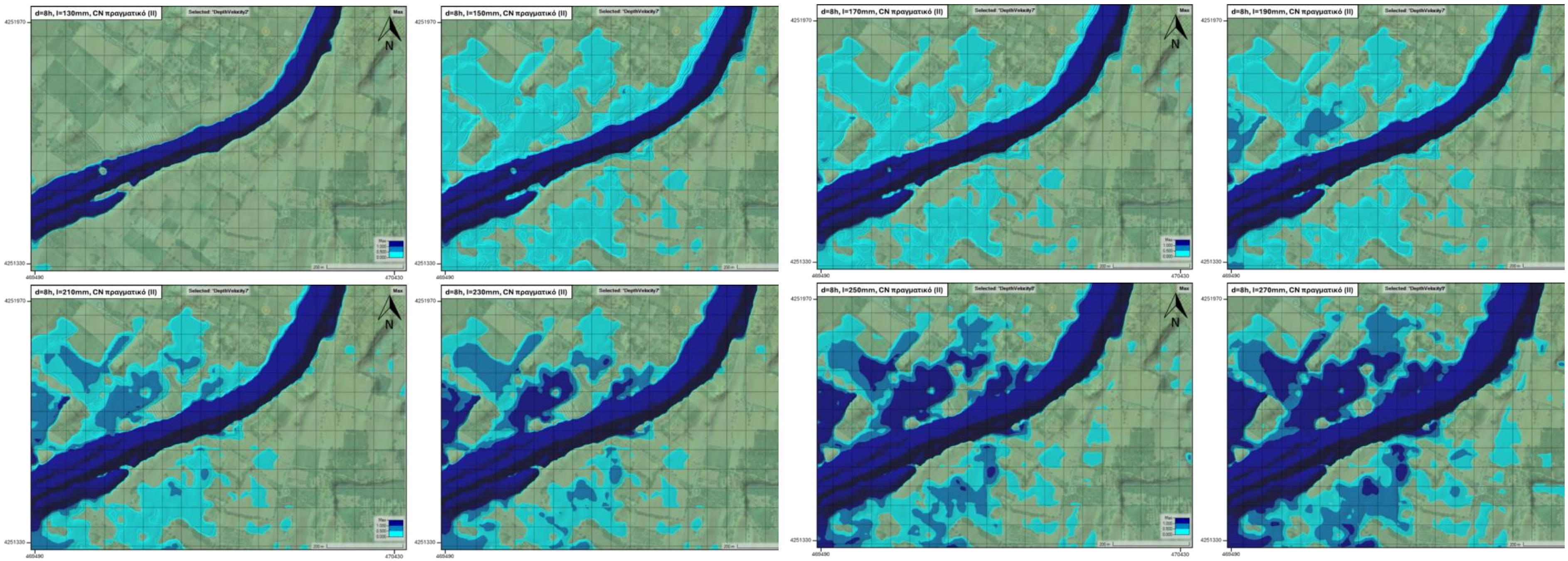
Having developed the hydrodynamic simulation scenarios using HEC-RAS for a rainfall duration of 8 hours and total rainfall of 90, 110, 130, 150, 170, 190, 210, 230, 250, 270, 290, and 310 mm, we are now able to calculate the critical rainfall (assuming normal soil moisture conditions prior to the event).

Using HEC-RAS and the RASter Calculator tool, for each of the above scenarios, maps were created that depict the hazard index *HI* of the two-dimensional (2D) computational domain, with a color gradient corresponding to the risk levels PE and IE, based on the values 0.5 and 1.0, respectively.



Application of FEWS

With estimation of critical rainfall



From the following images and according to the data generated by HEC-RAS, we observe that the hazard index in the area starts to reach the critical value HI_c = 0.5 (corresponding to the PE risk level) for *I* = 190mm, while it reaches the value HI_c = 1.0 (corresponding to the IE risk level) for *I* = 230mm. Based on the applied methodology, we define:

- Critical rainfall value (for normal soil moisture conditions) corresponding to the PE risk level is R_c = 180mm.
- Critical rainfall value (for normal soil moisture conditions) corresponding to the IE risk level is R_c = 220mm.

Application of FEWS

With estimation of critical rainfall

The example developed in this section is based on the following assumptions:

- Rainfall duration of 8 hours,
- Normal soil moisture conditions (II), and
- The 8-hour hourly rainfall forecast is shown in the table below.

Time	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
Decision time t_d (h)	0	1	2	3	4	5	6	7	8
Warning time t_w (h)	1	2	3	4	5	6	7	8	9
Forecasted rainfall r_p (mm) (t_k~t_{k+1})	30	40	60	40	20	15	20	5	0
Observed rainfall r_o (mm) (t_{k-1}~t_k)	0	34	41	62	36	21	7	19	3
Cumulative rainfall at decision time r_d (mm)	0	34	75	137	173	194	201	220	223
Cumulative rainfall at warning time $r_w = r_p + r_d$	30	74	135	177	193	209	221	225	223

Table 4: Table of information regarding the rainfall forecasting and assessment process.

For issuing a "pre-evacuation preparation" (PE) or "immediate evacuation" (IE) warning, the following procedure is followed:

1. Since the rainfall duration is 8 hours, we refer to the scenarios we have developed with an 8-hour rainfall duration.
2. As previously mentioned, the initial soil moisture conditions are normal, so from the set of scenarios in step 1, we select those that represent the normal soil condition (II).
3. In this case, from the critical rainfall database, we extract the values for the security levels PE and IE, which are R_c = 180mm and R_c = 220mm, respectively.
4. The cumulative rainfall at the warning time is calculated as shown in the table above.
5. At the decision time $t_d = t_5$ = 4h, the cumulative rainfall is 173mm, and the forecasted rainfall for the next hour is 20mm. Therefore, the cumulative rainfall at the warning time is 193mm. Assuming the rainfall is distributed uniformly over time, it will reach 180mm at t = 4.35h. Therefore, at t_w = 4h, a PE (pre-evacuation preparation) warning should be issued for the area.
6. In the same manner, the cumulative rainfall is expected to reach 220mm at t = 6.90h. Therefore, at t_w = 6h, an IE (immediate evacuation) warning should be issued for the study area.

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