Linking critical points to the Flash Flood Indicator

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ABSTRACT

This paper addresses the issue of refining the estimation of flash flood hazard by modifying the Flash Flood Indicator (FFI) application, which is used by the flood forecasting service of the Czech Hydrometeorological Institute (CHMI). The existing FFI approach was based primarily on hazard assessment determined by comparing the runoff response with threshold values derived from theoretical discharge rates with a given return period, while exposure and vulnerability were considered only implicitly. The article proposes extending the methodology by explicit consideration of these factors by means of two main approaches: (i) adjusting the threshold values for hazardous runoff depending on the degree of urbanisation of the area, and (ii) incorporating critical points (locations where concentrated runoff may enter urban areas) and their contributing catchment areas in the FFI calculations.

Based on analysis of selected rainfall events from 2023–2024, it was found that lowering the threshold values in urban areas leads to a more realistic estimate of the risk of localised flooding, particularly within built-up areas of municipalities. At the same time, it was shown that the inclusion of critical points – defined as locations of concentrated runoff at the interface between built-up and non-built-up areas – significantly improves the identification of locations with an increased risk that are not adequately captured by the 3 × 3 km polygon grid. The results also confirm the crucial influence of the quality of meteorological data input – particularly radar precipitation estimates – on the accuracy of the resulting risk assessment. The proposed modifications represent a shift from assessing the hazard itself to a more comprehensive expression of actual risk, which takes into account the spatial variability of exposure and vulnerability. The article also identifies the main limitations of the current approach and gives recommendations for further development of the FFI system, particularly in terms of refining meteorological input and adaptive setting of threshold values.

INTRODUCTION

Flash floods can cause significant material damage and loss of life. They occur as a result of rapid water runoff triggered by intense rainfall, usually confined to a small area. Precipitation over an area typically up to a few km^2, lasting a matter of minutes, does not usually trigger a flash flood, but merely leads to rapidly forming surface runoff from the surrounding land. This can cause localised flooding of low-lying areas and buildings. However, if torrential rainfall persists for a longer period and affects a larger area, surface runoff concentrates in the valleys of permanent watercourses; and if several catchment areas of smaller watercourses are affected simultaneously, this leads to flash flooding at their confluence, which may also affect settlements situated further downstream.

The media has been focusing on the occurrence of flash floods in various parts of the world and their catastrophic consequences. In Europe, notable examples include the floods of July 2021 in Germany on the River Ahr (180 fatalities) and those of October 2024 near Valencia in Spain in the Turia river basin (232 fatalities). The high death toll of the flooding in Germany was due to local underestimation of the situation: despite the weather forecasts being more or less accurate, the hydrological response was not adequately assessed, which resulted in a lack of essential warnings of extreme flooding [1]. In Spain, the main problem arose from late warnings by local authorities and, more generally, the overall lack of preparedness of the emergency response system, infrastructure and the population [2].

In the Czech Republic (CR), torrential flooding of significant geographical extent and severity has also recently occurred, for example on the evening of 7th June 2020 in the Uničov region and parts of the Šumperk region [3], and on the evening of 29th June 2022 in the Pošumaví region in the Blanice catchment area on the Zlatý potok watercourse [4]. The peak flows of both floods reached a return period of approximately 50 years.

Early warning of flash flooding is often very difficult. Neither the resolution of meteorological models, nor the complex physics of the atmosphere during convective storms allow for a precise determination of the location of rainfall of hazardous intensity. The probability of a successful forecast is higher for extreme rainfall over a larger geographical area. However, meteorological models predict levels for certain parameters (e.g. CAPE – convective available potential energy), from which it is possible to deduce a general risk of torrential rainfall occurring in a given (larger) area. Forecast uncertainty often persists even on the day of the expected event. The variability of individual outputs from forecast models is high, which complicates spatial precision of meteorological or hydrological warnings. Soil saturation from previous rainfall is one of the key factors affecting runoff; i.e. higher levels of soil saturation lower the threshold for potentially hazardous intensity of rainfall.

For a more accurate prediction of flash flooding, it is therefore necessary to use data from meteorological radars. Based on the current development of water-bearing clouds in time and space, the propagation of these clouds is calculated over a time frame of approximately 30 minutes to an hour. This short-term forecast, which calculates the subsequent position of these rain clouds within a given time based on their movement and upper-air flow over the most recent time interval, is known as nowcasting. The nowcasting method currently used by the CHMI projects the movement of water-bearing clouds forward in time without any change to their structure (rain intensity), which is currently the greatest limitation of this short-term forecasting method.

Information on current soil moisture levels and the latest developments in water-bearing cloud cover is utilised by the Flash Flood Indicator (FFI), which is used for short-term prediction of the risk of localised flooding and the occurrence of flash floods. This tool has been in use within the CHMI forecasting service for several years and has undergone significant development since 2017 [5]. Experience gained from the operation of the FFI in 2022, and to some extent in 2023, is analysed and discussed in this article [4].

Until now, the hazard of flash floods and localised flooding has not been closely linked to 'risk' within the FFI system, which, in addition to hazard, also includes elements of exposure and vulnerability. One of the objectives of the research project, on which this article is based, was to incorporate elements of exposure and vulnerability in the FFI system, in particular by utilising the location of newly identified "critical points" and their contributing areas throughout the Czech Republic. Critical points (CP), defined as intersections of concentrated runoff paths and boundaries of built-up areas, represent locations where the effects of hazard posed by torrential rainfall are concentrated. At the same time, we can speak of risk (damage, loss of life and harm to population health) within urban areas.

This article demonstrates the current capabilities of the FFI system in predicting torrential flooding, using selected flood events as examples. In the case of localised flooding, the article examines options for adjusting parameters to determine critical thresholds for hazardous runoff and the use of critical points to emphasize factors of vulnerability and exposure within FFI calculations. Through re-simulation of selected events, the inclusion of adjusted critical runoff thresholds and a layer of critical points is evaluated.

METHODOLOGY

Risk estimation in the Flash Flood Indicator

Risk is most commonly expressed as the probability of an undesirable event occurring, and of adverse impact on life, health, property or the environment. Generally, such risk arises from the interaction of hazard, vulnerability and exposure, i.e. the duration for which the hazard is present.

$$R = f\,(\text{Hazard, Vulnerability, Exposure}) \qquad (1)$$

The longer the duration of exposure – that is, the longer the period during which an object is exposed to a hazard and the greater its vulnerability – the greater the overall risk.

From a perspective of probability, risk is defined as an n-tuple of vectors [6]:

$$R_i \equiv (Sc_i, P_i, D_i),\ i = 1, \ldots, n \qquad (2)$$

where:

Sc	is	hazard scenario
P		the probability of the hazard scenario occurring
D	are	the consequences (damage, loss), expressed in appropriate units

All these quantities are time-dependent, as the hazard scenario, the probability of its occurrence and the damage may all change over time. In accordance with the general definition given above, risk can be defined as a continuous function according to the following equation:

$$R(D) = \int_0^\infty (D(\mathrm{u}|O) \cdot g(\mathrm{u}) \cdot du) \qquad (3)$$

where:

D(u|*O*)	is	the risk function
u		an event quantifier dependent on the vector of measures and decisions
O		the height of the protective embankment along the watercourse, the capacity of the spillway, timely evacuation, etc., which influence the consequences of an extreme event.

The function *g(u)* represents the probability density of the occurrence of an event (hazard scenario) with consequences.

A simple conceptual model based on the equation described above (1) was applied to express risk within the tool – the Flash Flood Indicator. In the context of flash floods and to enhance the clarity of the text, individual components of risk are defined as follows:

— **Hazard**: a condition (threat or phenomenon) with the potential to cause undesirable consequences. In the context under consideration, this refers to flash floods or localised flooding resulting primarily from very heavy rainfall, or the breach of a reservoir dam (exceptional floods). These phenomena can cause flooding, damage buildings and infrastructure, and endanger lives.

The Flash Flood Index (FFI) calculates the probable runoff response to past, current or expected precipitation, namely:

- within a system of catchment areas and river sections, where, in each sub-catchment area, the temporal progression of the runoff response is derived at the location of the outlet profile; the output is an estimate of hazard characteristics, i.e. flash floods, for so-called "obce s rozšířenou působností" – ORPs (= municipalities with extended competence),
- in a regular 3 × 3 km polygon grid, where the magnitude of the maximum specific runoff in a given polygon is derived; the output is an estimate of the hazard characteristics of localised flooding for ORPs.

By combining the characteristics of both hazard components – localised flooding and flash floods – the extent of so-called 'aggregate' flash flood hazard is derived.

The peak discharge or maximum specific runoff is compared with the theoretical value of the discharge (specific runoff) corresponding to a 100-year return period, and, based on established threshold values, the hazard level of flash-flooding (within the catchment system) and localised flooding (within the polygon grid) is determined. The hazard level is classified according to the theoretical return period of the given event, regardless of the location where it occurs. The result is an expression of the event's hazard level on a four-point scale {0, 1, 2, 3}.

— **Exposure**: describes the extent to which (or for how long) people, infrastructure, property or other valuable assets are exposed to hazard. This includes residents, buildings, roads, infrastructure or agricultural land located in areas exposed to flash flood inundation or localised flooding. For example, buildings near watercourses where there are insufficient flood defences, or low-lying areas in settlements without adequate drainage systems, are more exposed to such a hazard.

— **Vulnerability**: refers to conditions determined by physical, social, economic and environmental factors or processes that increase the susceptibility of individuals, communities, physical assets or systems to the impact of a hazard. In the case of floods, vulnerability may mean:

- buildings that are not sufficiently resistant to the effects of (flowing) water,
- a lack of, or inadequate, flood prevention plans or measures,

— inadequate function of drainage systems in built-up areas, e.g. low capacity of bridges, culverts or sewers,
— insufficient awareness among residents of potential threats or current risks.

Within the Flash Flood Indicator tool, the characteristics of the area determined by exposure and vulnerability are key to distinguishing between built-up and non-built-up areas. For both exposure classification and vulnerability, a two-tier scale is applied [0, 1], based on the following logic:

Exposure: *Built-up areas* {1}
Non-built-up areas {0}
(4)
Vulnerability: *Built-up areas* {1}
Non-built-up areas {0}

Built-up areas (intravilan) are therefore classified at the highest level in the FFI system. Risk thus becomes a function of the hazard itself, with exposure and vulnerability being treated as (non-zero) constants. In this case, the following therefore applies:

$$R = f\,(\text{Hazard}) \tag{5}$$

The hazard level, and thus the risk, increases with the return period of the event; for example, a flood with a return period of 100 years poses a greater hazard than a flood with N = 10 years. However, it has become apparent that the hazard level must be assessed differently in built-up and non-built-up areas. In areas with a higher proportion of urbanised land, the volume of runoff from precipitation increases proportionally; that is, potentially hazardous runoff occurs with greater frequency. At the same time, the probability of greater exposure and vulnerability increases significantly, and therefore the potential hazard posed by a 100-year flood in rural areas, occurs with greater frequency in built-up areas.

It is clear from the above that there remains a need to refine vulnerability or exposure for specific locations in sufficient detail to enable all parameters to be set precisely for each specific catchment, river section or polygon within the FFI system. A simple principle has therefore been proposed for the assessment of risk of localised flooding, which takes into account the proportion of urban areas in determining the level of risk, by setting lower threshold values in relation to the magnitude of specific runoff:

$$\mathrm{T_u} = \mathrm{T_{100}} + (\mathrm{T_0} - \mathrm{T_{100}}) \cdot (1 - \mathrm{u_p})^2 \tag{6}$$

where:

u_p is the proportion of urban area
T_{100} the threshold value relative to the 100-year specific runoff within the built-up area
T_0 the threshold value relative to the 100-year specific runoff outside built-up areas

By applying this principle, the hazard classification – and thus the flood risk value – is adjusted; see *Equation (5)*.

Critical points and the Flash Flood Indicator

Critical points – in relation to flood hazard – are locations at the boundary between built-up and non-built-up areas where, during torrential rainfall, concentrated runoff may occur from what is known as the contributing area, i.e. rural land. The contributing area is the watershed which ends at the profile of the critical point. Concentrated runoff therefore poses an immediate danger to the municipality in question and, under certain circumstances, a significant risk to the property and lives of the municipality's inhabitants. Determination of critical points is based on a modified methodology [7], in which, in addition to the size of the respective contributing area, the key parameters include the average slope, the proportion of arable land and the value of the CN parameter (runoff curve number), which is used to express the overall characteristics of the so-called critical conditions index (F).

Within the assessment of risk arising from localised flooding or flash floods for the FFI, the original intention was to include the contributing catchment areas in the calculation of the flash flood risk estimate; in other words, to calculate the risk within a system of interconnected catchments and river sections. However, from the perspective of actual assessment of the hazard arising from the potential occurrence of torrential rainfall in the catchments of critical points, it was decided to incorporate the catchments associated with critical points (CPs) in the assessment of the localised flooding hazard, as the nature of runoff response is more like a pluvial flood than a fluvial (river) flood. The contributing layers of CPs therefore function within the FFI system as a separate GIS input layer with calculated physical-geographical characteristics and specified threshold values to assess the level of localised flooding risk.

The integration of critical points and their characteristics in the FFI system was tested using data derived from a previous project in 2009 (a total of 9,261 CPs and their contributing areas). The system is gradually being adjusted to layers of critical points updated in 2026. The classification of critical point catchments for risk assessment was based on a modified approach (see Section Risk estimation in the Flash Flood Indicator), which, in addition to the hazard level increasing proportionally with the increasing return period of the peak discharge, also assumes that exposure and vulnerability will increase proportionally with an increasing degree of urbanisation within the catchment area. Given that critical points, such as outlet profiles of contributing catchment areas, lie on the boundaries of built-up areas, the threshold values for determining the hazard level were considered for a degree of urbanisation corresponding to 100 per cent.

The FFI calculation procedure, used to derive the hazard (and risk) level of local flooding caused by torrential rainfall, has been modified so that, in addition to determining runoff within a 3 × 3 km grid, the risk of hazardous runoff from the catchment to critical points is also calculated. The affiliation of individual catchment areas of critical points to an ORP is determined by the catchment's outlet profile and its position relative to the ORP. The resulting risk level arising from local flooding is considered as the less favourable of the two calculations: over the 3 × 3 km grid and for the catchment areas leading to critical points.

RESULTS

Adjustment of threshold values for hazardous runoff

The *Equation (6)* was tested on selected significant rainfall events between 2023–2024 which had caused localised flooding, primarily within urban areas. In addition to rainfall data, the selection of episodes was based on fire brigade call-out data, which the CHMI holds for internal use, as well as photographs and videos from the affected areas.

In some cases, lowering the threshold values logically led to estimates of a higher degree of risk of localised flooding in polygons where the actual risk, based on actual consequences, was greater than the risk estimate based on the original threshold values (*Tab. 1*).

Tab. 1. Selected tested events with occurrence of torrential rainfall

Date of calculation	Tested ORP	Original maximum risk	New maximum risk
16th August 2023, 18:50	Prague	1	2
13th September 2023, 22:20	Opava	1	1
6th June 2024, 20:05	Brno	0	0
19th June 2024, 21:35	Ostrava	0	1
18th August 2024, 17:35	Prague	2	3

Three selected episodes are described in more detail below, in which changes to the threshold settings succeeded in bringing the FFI outputs closer to reality in the affected areas. These are the dates 16th August 2023, 19th June 2024 and 18th August 2024. In the remaining two cases, in Opava and Brno, changing the parameters did not alter the calculated risk level. The figure on the left shows the location of water-related fire brigade call-outs (black dots) and the highest risk values for individual ORPs, where the colour coding corresponds to risk levels 0–3, as shown in *Tab. 1*. The figure on the right shows the distribution and amount of rainfall during selected episodes.

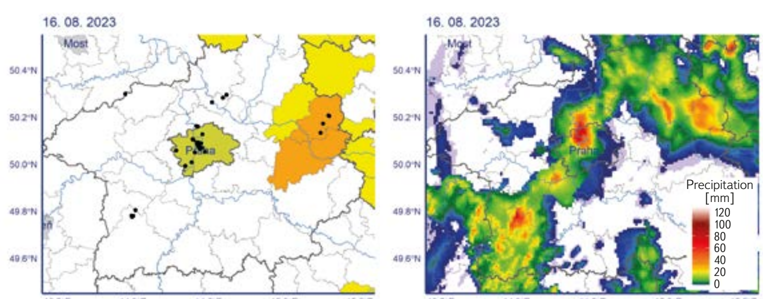

Fig. 1 a, b. General flash flood risk and precipitation total (MERGE) from 16th August 2023

On 16th August 2023, localised and very intense rainfall moved over the centre of Prague from the north and progressed very slowly (*Fig. 1b*). It therefore remained in a single location for an extended period, with 40 to 50 mm falling in approximately one hour (e.g. 44.5 mm at the Praha-Střešovice station). Judging by the high number of fire brigade call-outs, reports directly from the field and the volume of photos and videos on social media, relatively large parts of central Prague were affected. Although normal traffic and business were almost brought to a standstill for a short time, two consecutive FFI calculations in the early evening identified only the lowest risk of localised flooding (*Tab. 1*), which also corresponded to the lowest level of aggregate risk (*Fig. 1a*). Following changes to the threshold settings according to the *Equation (6)* and a subsequent re-simulation, the second level of local flooding risk was calculated for the centre of Prague, which represents at least an approximation of the actual impact of this situation on the centre of Prague.

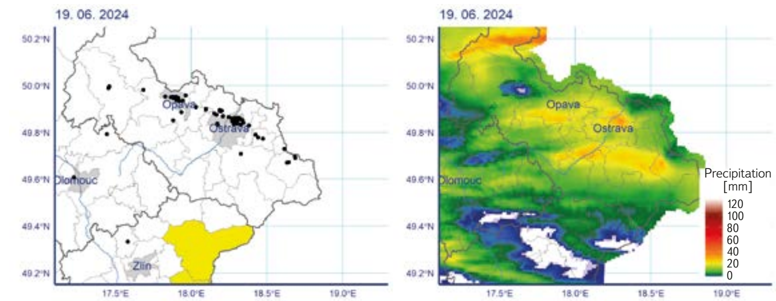

Fig. 2 a, b. General flash flood risk and precipitation total (MERGE) from 19th June 2024

From the FFI's perspective, the rainfall event in the Ostrava region on 19th June 2024 (*Fig. 2*) was a relatively complex situation, as the passage of intense rainfall over Ostrava was very rapid, while the FFI compares potential high-risk rainfall with actual rainfall over a period of at least one hour. In Ostrava, approximately 30 mm of rainfall occurred in some places over roughly 30 minutes, or even a shorter period, and radar estimates of rainfall tended to underestimate the actual amounts. In this case, the FFI was unable to respond adequately, and not even the lowest risk level was calculated. After a change to the parameters and a re-simulation, at least the lowest risk level for localised flooding was calculated for some parts of Ostrava.

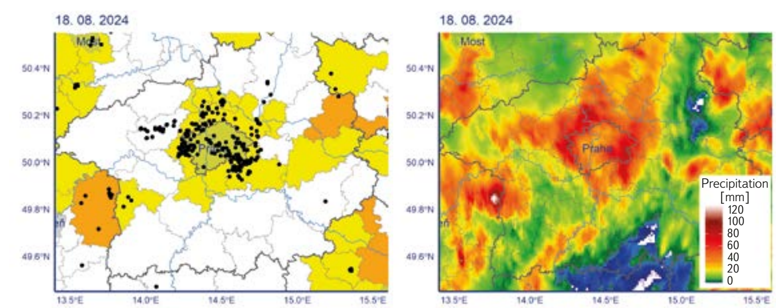

Fig. 3 a, b. General flash flood risk and precipitation total (MERGE) from 18th August 2024

The last episode tested was that of 18th August 2024, when Prague and the surrounding area were hit by very intense rainfall (*Fig. 3b*). At Prague-Ruzyně Airport, where rainfall was nearly 70 mm/hour, operations at the international airport had to be suspended because the runways (among other areas) were flooded. In many other places in and around Prague, the rainfall was so intense that it led to localised flooding or rapid runoff from the surrounding area. The FFI's operational calculations generated a Level 1 aggregate risk (shown in yellow in *Fig. 3a*), and only in exceptional cases was the risk of localised flooding at Level 2 (*Tab. 1*). Following changes to the threshold settings and a subsequent re-simulation, the highest level of localised flooding hazard was calculated for the Ruzyně Airport area, and in several locations localised flooding hazard was at the medium level 2.

Incorporation of critical points in the Flash Flood Indicator

The modified FFI procedures (see Section Critical points and the Flash Flood Indicator) were tested against past rainfall-runoff events from previous years, prioritising three selected flood events. Specifically, these were the flash flood of 2nd June 2024 in Štěnovice in the Plzeň region and the flash floods of 27th June 2024 in Blížejov in the Domažlice region and in Šišma near Lipník nad Bečvou.

Fig. 4 shows an example from the testing of a flash flood in Blížejov in the Domažlice region on 27th June 2024, specifically from the simulation run at 12:20 UTC, when significant localised flooding caused by torrential rainfall was recorded in the village of Blížejov. The upper part of the figure shows the distribution of rainfall (combined radar estimate – MERGE) and indicates the direction of inflow into the village of Blížejov. It is evident that two contributing areas of critical points were affected. The figure at the bottom left (*4b*) shows the original version of the calculation without critical points, while the figure on the right (*4c*) shows the result with CPs included. The heaviest rainfall occurred precisely on the catchment area with the defined critical points to the northwest of the village, which significantly influenced the estimate of actual risk of local flooding in the village of Blížejov. While calculations for the 3 × 3 km grid cell alone indicated only a low to medium risk (yellow), a very high risk (red) was recorded in the catchment area around the critical points. Furthermore, the unnamed watercourse in the village is culverted, and further downstream the channel leads into a railway culvert with limited capacity, which also contributed to the worsening of the drainage situation in the village.

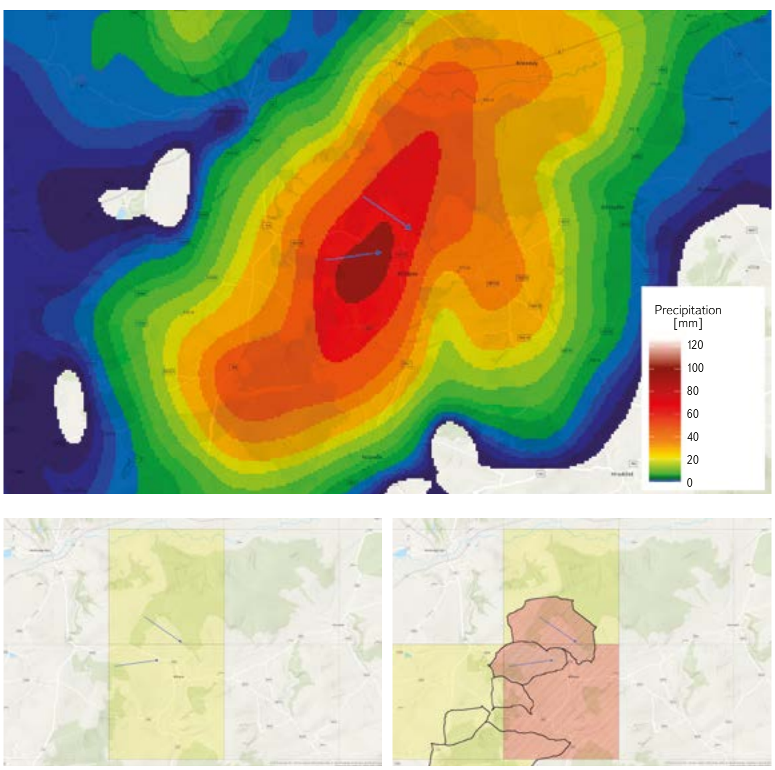

Fig. 4 a, b, c. Testing of calculations for the flash flood situation in Blížejov in the Domažlice region on 27th June 2024, 12:20 UTC. The upper image shows 24-hour precipitation total up to 28th June 2024, 06:00 UTC. On the left is the FFI calculation version without critical points; on the right is the new FFI calculation version including them

Fig. 5 shows the situation in the vicinity of the village of Štěnovice in the Plzeň region on 2nd June 2024, when a major flash flood occurred, causing considerable damage to property and posing a threat to residents. The Losinský stream, where torrential rainfall occurred, is a right-side tributary to the river Úhlava which flows through Štěnovice. Downstream of the confluence, there is a gauging station on the Úhlava, which recorded the flood on the Losinský stream in the form of a distinct flow peak (*Fig. 6*). Based on the recorded hydrograph of the flood on the Úhlava, it can be deduced that an estimated 40–45 $m^3 \cdot s^{-1}$ ($Q_{100} \cong 20\ m^3 \cdot s^{-1}$) was flowing into the Úhlava river from the Losinský stream (11.6 km^2) at the peak of the flood.

Findings from amateur rainfall observations in Štěnovice and the village of Losiná conclude that there was relatively significant underestimation of radar rainfall estimates combined with rain gauges (using the MERGE method), which resulted in the FFI detecting only the lowest risk level (yellow) for the Losinský stream catchment. When considering the catchment area in relation to critical points, a level two (orange) risk was estimated north of Štěnovice, presumably due to slightly higher rainfall estimates that were, most likely, closer to reality.

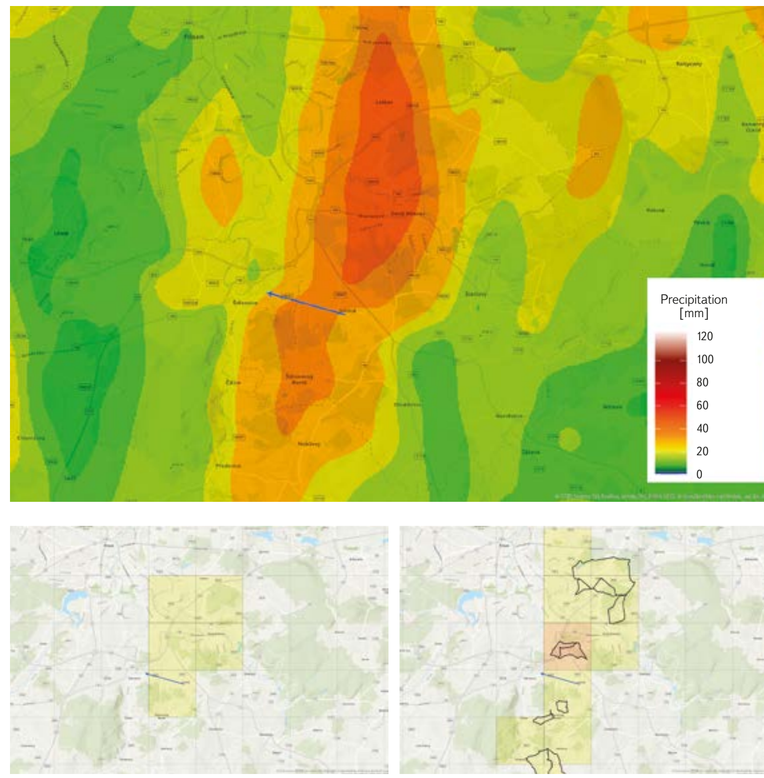

Fig. 5 a, b, c. Testing calculations for the flash flood situation in Štěnovice in the Plzeň region on 2nd June 2024 at 10:50 UTC. The upper image shows 24-hour precipitation total up to 3rd June 2024, 06:00 UTC. On the left is the FFI calculation version without critical points; on the right is the new FFI calculation version already including them

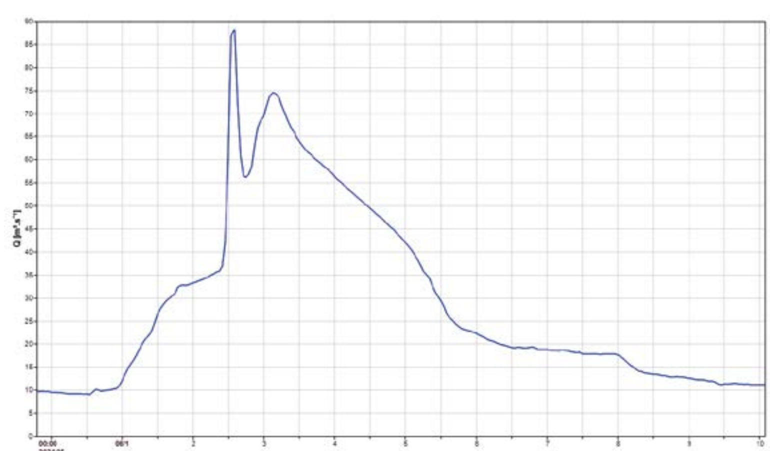

Fig. 6. Flood wave on the Úhlava river in Štěnovice at the beginning June 2024

The third event under consideration is the extreme flash flood of 27th June 2024 on the Šišemka (a tributary of the Moštěnka) in the Přerov region, where Šišma was the worst-affected village, although other villages were also affected. Flow conditions in Šišma were adversely affected by numerous footbridges over the Šišemka stream to individual properties. The peak flow rate in the villages of Šišma and Hradčany is estimated to have exceeded 30 $m^3 \cdot s^{-1}$ (more than Q_{100}), while in Prusy on the Moštěnka, the flow wave – which was apparently flatter, i.e. transformed – peaked at 18–20 $m^3 \cdot s^{-1}$.

Fig. 7 shows the situation around the village of Šišma and the combined radar precipitation estimates (MERGE), which were, unfortunately, significantly underestimated. An amateur rain gauge in the village of Šišma recorded more than 50 mm in roughly 30–40 minutes, yet the radar precipitation estimates for that location were only 10 mm. For this reason, the FFI also recorded the risk at only the lowest level (yellow), even when taking into account the catchment area contributing to critical points.

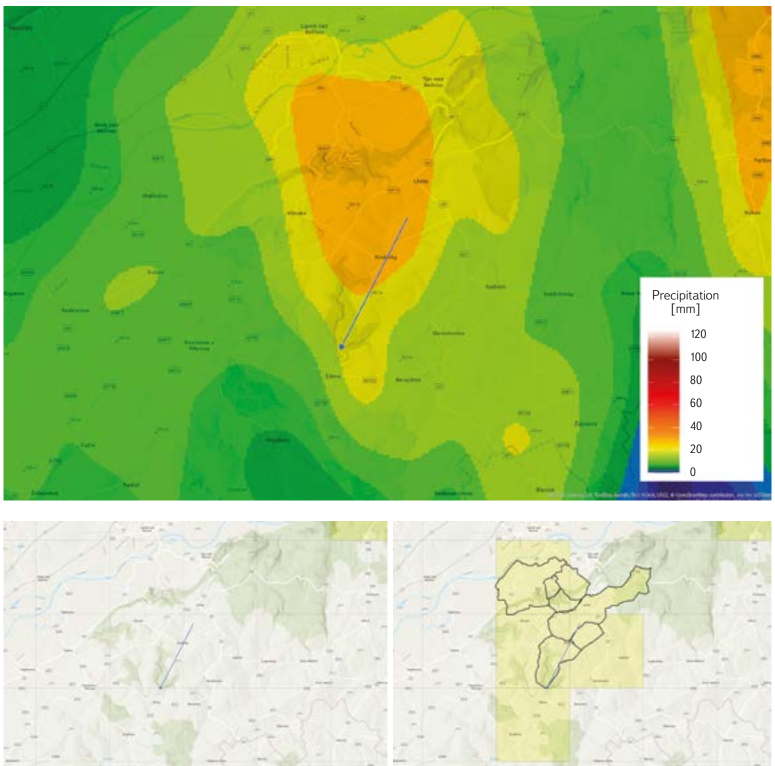

Fig. 7 a, b, c. Testing of calculations for the flash flood situation in Šišma near Lipník nad Bečvou on 27th June 2024, 15:35 UTC. The upper image shows the 24-hour precipitation total up to 28th June 2024, 06:00 UTC. On the left is the FFI calculation version without critical points; on the right is the new FFI calculation version including them

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Predicting flash floods remains one of the most complex tasks in the hydrometeorological forecasting service. The main reason for this difficulty lies in the significant spatial and temporal variability of convective precipitation, which fundamentally limits the reliability of the forecast. Numerical weather models, including those with high spatial resolution, generally provide only information on the increased probability of hazardous rainfall occurring in wider areas, but not on its precise location and intensity. Nowcasting enables short-term forecast refinement, the main benefit of which lies in extrapolating the current movement of precipitation. However, this approach is as yet largely unable to reliably capture rapid changes in the structure and intensity of convective cells, which are key to the development of flash floods. Furthermore, the resulting accuracy of flash flood predictions is significantly influenced by hydrological inputs, primarily the estimate of current soil saturation, as well as uncertainties in the estimation of both actual and forecast precipitation.

In the context of flash floods, the classification of areas as either built-up or non-built-up zones is essential. In urban areas, the catchment's runoff response is much faster and the volume of surface runoff increases, resulting in more frequent occurrence and higher intensity of local flooding, even during rainfall events with shorter return periods. The assessment of risk level in the FFI is linked to threshold values for hazardous runoff, which are derived from the discharge volume with a 100-year return period and remain the same regardless of the area's classification. However, values determined in this way may not reflect the actual level of hazard and risk in built-up and non-built-up areas.

A key element of exposure and vulnerability is critical points, defined as locations where concentrated surface runoff from the agricultural landscape enters the built-up area of a municipality. It is these locations that often represent the initiation points of flood damage during torrential rainfall. Including the catchment areas of these critical points in the FFI calculation significantly improves the accuracy of hazard and risk estimates [8], particularly in cases where the standard 3 × 3 km polygon grid is unable to adequately capture local runoff response and its impact on populated areas.

Despite these adjustments to the method of determining hazard and risk levels, the reliability of the input precipitation data remains a key source of uncertainty. An analysis of selected cases of significant downpours and floods, for example in Štěnovice on 2nd June 2024 and in Šišma on 27th June 2024, revealed a significant underestimation of radar precipitation forecast compared with the totals measured by amateur observers. This shortcoming had a direct impact on the FFI's ability to adequately assess the level of risk, even though the calculations included all available data on precipitation totals, intensity and critical points. These examples, along with other cases from previous years, emphasise that further improvements in the prediction and assessment of flash floods will necessarily depend not only on refining the FFI methodology, but also on further development and validation of radar precipitation products, which are undergoing gradual development [9].

Based on the modified approaches tested on real flood events, the following conclusions can be drawn:

The flood events tested demonstrated that adjusting the threshold values for hazardous runoff based on the proportion of urban areas within the calculation polygons allows for a more realistic estimate of the risk level within built-up areas. This leads to a better distinction between situations that may result in actual impacts within built-up areas and cases where increased runoff has less significant consequences. At the same time, however, it is important to bear in mind that reducing runoff thresholds may lead to an increase in the number of false alarms.

The inclusion of critical points in the FFI calculation represents a significant contribution to local risk assessment. Taking the catchment areas of critical points into account makes it possible to capture local runoff peaks which would otherwise be suppressed or completely overlooked within a standard polygon grid. This approach contributes in particular to a more accurate risk assessment in smaller settlements and in areas where concentrated surface runoff enters built-up areas and represents the main mechanism causing flood damage.

At the same time, it is confirmed that the successful prediction of flash floods is fundamentally dependent on the quality of meteorological inputs. Uncertainties in radar precipitation estimates and in short-term precipitation forecasts are directly reflected in the overall uncertainty of the FFI results and may lead to an underestimation of risk, even in cases where critical points and the degree of urbanisation of the area are taken into account. Despite these limitations, however, it can be stated that the FFI is gradually shifting from assessing the hazard level itself towards a more realistic estimate of flood risk.

Nevertheless, analysis of flood events continues to show that model estimates require further refinement, particularly in urban environments. Local terrain morphology, technical infrastructure and land use have a fundamental influence on the resulting level of risk and present a significant challenge for the further development of methodological approaches to the assessment and prediction of flash floods.

Based on the above conclusions, it is possible to formulate recommendations for the further development of the FFI, including towards more effective management of the risks associated with flash floods. These recommendations relate both to the technical development of FFI itself and to its practical integration into crisis management and directions for further research.

Further improvements to the processing of radar precipitation estimates appear to be key. Regular validation of radar data against a network of professional rain gauges should be a standard part of operations. In addition, the use of local rain gauges operated by local authorities or volunteers could also be considered [10]. Despite the awareness of possible systematic or random errors in these measurements, such data can provide valuable information on local extremes that radar estimates cannot always reliably capture. Another important step towards reducing the uncertainties in forecasts of convective precipitation—which is crucial for the development of flash floods—is to strengthen nowcasting methods, particularly by incorporating algorithms capable of modelling the development of convective cells over time, including changes in their structure and intensity. At the same time, the introduction of adaptive hazard and risk thresholds, differentiated according to the type of settlement, appears to be a promising approach. Urban, suburban and rural areas differ significantly in their runoff response, and uniform thresholds may therefore not correspond to the actual level of risk in a given area.

Alongside technical developments, it is essential to focus on better integration of risk assessment into the crisis management system. Critical points identified across the whole of the Czech Republic should be systematically utilised, for example, when updating local flood management plans. At the same time, it is advisable to improve communication of the risk to local residents, particularly in relation to areas where there is an increased concentration of surface runoff and localised flooding caused by inadequate drainage within the municipality. Raising awareness of these 'blind spots' can help to reduce damage and improve residents' preparedness. A further step could be to integrate the FFI indicator with municipalities' automated warning systems, such as smart sirens, SMS alerts or notifications via mobile apps. Such integration would enable faster and more targeted warnings in situations where the risk of localised flooding is rapidly increasing.

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