

Methodology of the Use of Meteorological Radar MMR50 and Other Meteorological Systems for Purpose Determination Risk of Flash Floods

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Abstract: - This article aims to determine the resulting risk of flash floods on the basis of outputs of meteorological radar MMR50, numerical weather prediction model GFS, aerological radiosonde Prostejov, Flash Flood Guidance and Integrated Warning Service System of Czech Hydrometeorological Institute. This methodology is used for the emergency management of individual municipalities with extended powers of the Zlín Region. This article also includes a description of the basic principles of radar rainfall measurements and all radar products that are part of software equipment of the meteorological radar MMR50. The first chapter focuses on basic description of meteorological radar, the principle of transfer of radar reflectivity on the intensity of precipitation, including a description of radar outputs. Use of radar outputs for measurement and prediction of convective precipitation is demonstrated on historical weather conditions of July 24, 2015, when local flash floods were in the central part of the Zlín region. In the last chapter, the theory of methodology is described with use of meteorological sources for measuring and predicting thunderstorms. The theory is verified in the same situation as in the previous case study. Outputs of methodology are compared with the station and other meteorological data in the Zlin Region.

Key-Words: - Radar meteorology; flash floods; thunderstorms; convective precipitation; crisis management; meteorological systems; numerical weather prediction models.

1 Introduction

The Zlin Region is one of the regions of the Czech Republic, which have been strongly affected by the impacts of local flash floods in the past decade. Three extensive flooding caused by persistent and intensive precipitation occurred in 1997-2006 (145 billion of material damages and the death toll of 88). This type of flooding is a specific with large expanse of the affected area. In contrast, flash floods have occurred regularly since 2007 until present (35 billion in material damages and the death toll of 41). This type of flooding affects the area of the very small size in the order of several km². Material damages are caused by not only torrential rainfall but also other hazardous atmospheric phenomena such as hail, strong wind gusts, tornadoes and atmospheric electrical discharges. Although, flash floods have not caused flood damage to the same extent as the second type of the flood, they occur at a substantially higher frequency.

In addition, current possibilities forecasting of torrential rainfall and other hazardous atmospheric phenomena are very limited. One of the main

problem of current meteorology is forecasting place and time of occurrence of convective precipitation. Forecasting of torrential rainfall and other hazardous atmospheric phenomena has been dealt with NWP models [1], nowcasting systems [2], [3], [4], [5], [6] and expert meteorological systems [7], [8], [9]. Both prediction methods achieve relatively low success rate, up to about 50%. Consequently, the Zlin Region has decided to actively solve this problem by creating the Information, Notification and Warning System of the Zlin Region. This system is formed by the backbone of information and communication infrastructure of the Zlin Region. The essence is its own internal network made of fiber optic cable, whose users are independent from the Internet and other external sources. The central unit is a server located on the regional managing workplace of the Crisis Staff of the Zlin Region. Information is distributed from this department to another 11 municipalities with extended powers. The main advantage is the efficient communication between the authorities of Crisis Management and the Integrated Rescue System of the Czech Republic before the

occurrence and during extraordinary events [10], [23], [24].

Information, Notification and Warning System of the Zlin Region consist of many components, such as central dispatching, warning information systems, video conferencing systems, municipal camera surveillance systems, sensors and meteorological stations, chemical detection elements, substitute energy sources and the mobile meteorological radar (MMR50). This meteorological radar is a major tool intended for monitoring the current precipitation situation and very short-term forecasts for 30-60 minutes. The purpose of the device is to provide timely and relevant information on the weather situation, which may arise from a flash flood [11].

The main objective of this article is to describe the methodology of monitoring and forecasting of dangerous weather phenomena by using the MMR50 meteorological radar and other meteorological systems such as NWP models, aerological radiosonde, Flash Flood Guidance and Integrated Warning Service System by Czech Hydrometeorological Institute.

2 Radar precipitation measurements

The mobile meteorological radar (MMR50) is a device intended for:

- Precipitation clouds detection,
- The intensity of precipitation estimation and
- The 3D information obtaining about the distribution of precipitation in the atmosphere.

2.1 Principle of radar precipitation measurement

The mobile meteorological radar (MMR50) consists of an antenna, which generates a narrow beam of high-energy pulses. When the beam encounters a particle of cloud, it is partially absorbed and then dispersed in all directions. Scattered rays are captured by the antenna where are subsequently amplified and detected by the radar receiver. The receiver calculates power of rays and the time from the pulse. The analog signal is digitized and processed by the special software. The resulting information is displayed to end users in the form of an image with radar reflections on a map [12], [13], [14].

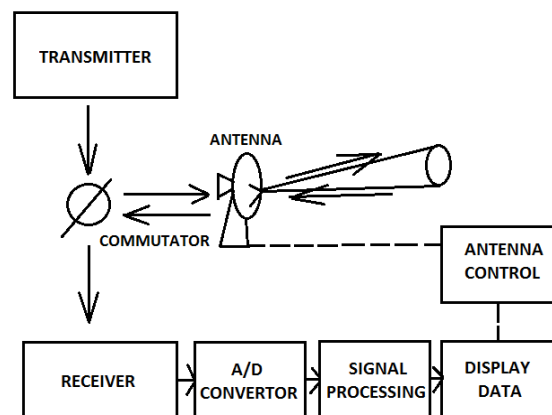


Fig. 1. Scheme of the meteorological radar MMR50 [6].

The mobile meteorological radar (MMR50) also consists of other components such as radar units, elevation and azimuth drive including sensors, heating and cooling system, and power source part and the control computer [10].

Table 1. Parameters of the MMR50 meteorological radar [16].

Parameters	Values
Operating frequency	X-band (9410 MHz)
Transmitter Power Peak	50 kW
Antenna Elevation	-1° to +90°
Pulse Repetition Frequency	500 Hz
Maximum range	100 km

As can be seen in Table 1, The mobile meteorological radar (MMR50) operates at X-band with a wavelength of 3 cm. The advantage of this feature is higher detection sensitivity of intense precipitation but with a significantly higher attenuation, lower repetition frequency and maximum range than meteorological radars from the Czech Radar Network.

2.2 Radar estimation of the rainfall intensity

Fundamental radar parameter is the radar reflectivity. Radar reflectivity is the amount of energy reflected from precipitation of cloud particles, where $N(D)$ denotes the spectrum of particle sizes and D_i represents the diameter of a droplet [12]:

$$Z = \sum D_i^6 = \int N(D) D^6 dD. \quad (1)$$

Measured radar reflectivity is reported as $10 \log Z_e$ [mm^6/m^3] in the unit of dBz.

Rainfall intensity I is dependent on the radar reflectivity Z determined using the Marshall-Palmer formula:

$$Z = aI^b \quad (2)$$

where a and b are experimentally determined constants ($a = 200, b = 1.6$). Rainfall intensity I is calculated by the following formula [12], [13], [14]:

$$I = 10(Z - 10 \log(a)) / 10b. \quad (3)$$

Table 2. The exponential dependence of radar reflectivity and intensity of precipitation [15].

Z [dBz]	I [mm/hr]	Meteorological targets
7	0,1	Weak rain
23	1	Moderate rain
39	10	Intensive rain
48	37	Intensive convective precipitation
52	65	Torrential rainfall
56	100	Intensive torrential rainfall
60	200	Hail, tornadoes

Table 2 shows that the radar reflectivity Z is changing exponentially dependent on the change of rainfall intensity.

2.3 3D information of the MMR50 meteorological radar

The mobile meteorological radar (MMR50) processes the input data into materials for analyzing and forecasting meteorological radar maps, and the subsequent distribution of documents to the Information, Notification and Warning System of the Zlin Region

3D radar information consists of the original volume of the radar data stored in Spherical coordinates which are converted into Cartesian coordinates. The result is product of radar reflectivity:

- PPI (Plan Position Indicator) is the field of radar reflectivity measured at various elevation angles. The algorithm is based on bilinear interpolation for each pixel separately.
- CAPPI (Constant Altitude Plan Position Indicator) the field of radar reflectivity calculated for a given altitude.
- ColumnMax (Composite Reflexivity) is the maximum radar reflectivity in a vertical column of the atmosphere.

- RHI (Range Height Indicator) is a vertical sectional view of the atmosphere where the main parameter is the azimuth. RHI algorithm is calculated as with the PPI.
- Max Z the maximum field of radar reflectivity with side projections representing a vertical column of the atmosphere.
- ECHOTOPS provides information on cloud altitude, with a maximum radar reflectivity.
- VIL (Vertically Integrated Liquid) is a vertically integrated liquid water content determined by assuming the Marshall-Palmer distribution; VIL value is determined by the following formula:

$$VIL = 3,44 \cdot 10^{-6} \int_{hz}^{ht} Z^{A/7} dh, \quad (4)$$

where Z [$\text{mm}^6.\text{m}^{-3}$] radar reflectivity, hz [m] height of the cloud base and ht [m] is the height of the cloud top. Summation over different levels of PPI is performed each surface element [12], [16].

These radar products (results) are used to specify the radar information in real time. The main objective is to obtain current information on the rainfall intensity and a probable occurrence of dangerous atmospheric phenomena.

3 Methodology of the measurement and forecasting of intensive convection precipitation

Radar results of the mobile meteorological radar (MMR50) provide us with information about the current state of the occurrence of precipitation in the atmosphere. One of the software components is an application Nowcast TITAN that provides predictive information about the intensity of precipitation equal or higher than 37 mm / hr. However, this predictive information is insufficient to assess the future occurrence of flash floods. Each meteorologist must have information on the conditions of air masses, satellite, aerological, station and other data.

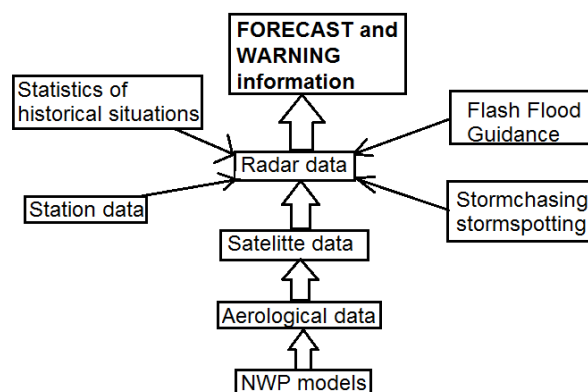


Fig. 2. Scheme of the forecast and warning of the flash flood.

Complex intense convective precipitation forecast includes data from:

- NWP models an aerological radiosonde (indices of convection, meteorological elements).
- Satellite data (Infra-Red image and IR image in the thermal spectrum)
- Radar data (outputs of the 6 radar products, statistics of historical situations, station data, the degree of the soil saturation and data from observations of thunderstorms).

3.1. Radar precipitation measurement

Analysis of the current rainfall situation contains the following information:

Table 3. Radar measurement intensive convective precipitation [17].

Radar products	Limits of measurement	Dangerous atmospheric phenomena
ColumnMax, Max Z	52 dBz	Moderate torrential rainfall
	56 dBz	Intensive torrential rainfall
	60 dBz	Hail, tornadoes
CAPPI	2 km	Torrential rainfall
RHI	2-4 km	Tornadoes
ECHOTOP	above 10 km	Torrential rainfall, hail, tornadoes
VIL	above 30 kg/m ²	Torrential rainfall, hail,

Probability prediction of the occurrence of dangerous accompanying phenomena should be combined with the outputs of NWP models, aerological, satellite and station measurements.

3.2 Very short-time forecast via MMR50 meteorological radar

The very short-term forecast is performed through the application of Nowcast TITAN. The principle of this system is simple. The algorithm marked on the map, such precipitation fields that have reached the radar reflectivity ($Z=48$ dBz), determines the direction of movement based on previous

precipitation radar outputs and the red arrow indicates where the rainfall field will move during 30-60 minutes [10].

Comprehensive forecasting of flash floods is supplemented by information from:

- Statistics of historical weather situations.
- Degree of saturation of soils obtained from the Flash Flood Guidance.
- Observations of thunderstorms (Stormchasing and Stormspotting).

Statistics of historical weather events are intended to supplement the resulting predictions. The main selection criteria of historical weather situations is the direction of movement of precipitation (wind direction at 700 hPa), the synoptic situation and significant meteorological parameters (temperature, relative humidity at 2 meters above ground, wind direction and wind speed of 10 m above ground).

The degree of soil saturation is analyzed from the Flash Flood Guidance and demonstrates the probability of occurrence of flash floods by the permeability of the soil surface.

Observations from the terrain thunderstorms are supplementary information to nowcasting which can detect and confirm the presence of dangerous accompanying phenomena. Simultaneously, the purpose of the data is control and verification of radar precipitation measurements.

4 Case study on 24.7.2015

The methodology of measurements and predictions using the mobile meteorological radar (MMR50) was verified on a case study dated July 24, 2015. The central part of the Zlin Region was hit by local flash floods accompanied by hail and strong wind gusts.

The forecast of the weather situation was very complicated. Czech Hydrometeorological Institute did not deliver predictive warning information on the occurrence of the strong thunderstorms for this region.

The triggering mechanism of intensive convective precipitation was cold front on the western Slovakia, which had a tendency to go back to the east of the Czech Republic.

4.1. Outputs of radar precipitation measurement

Formation and development of intense convective precipitation were demonstrated at various radar products as ColumnMax, CAPPI 2km, Max Z, Range Height Indicator (RHI), ECHOTOP and

Vertically Integrated Liquid (VIL) in real time between 17: 18-18: 13. These radar results show certain qualities and character of intensive convective precipitation clouds.

4.1.1 Radar products ColumnMax and CAPPI 2 km

Column Max is radar product which provides information about the maximum intensity of precipitation in the vertical column of the atmosphere. However, this output does not inform us about the current state of rainfall, but that a certain level of atmospheric precipitation occurs with the maximal intensity. Hence, the probable occurrence of rainfall is measured using CAPPI 2 km.

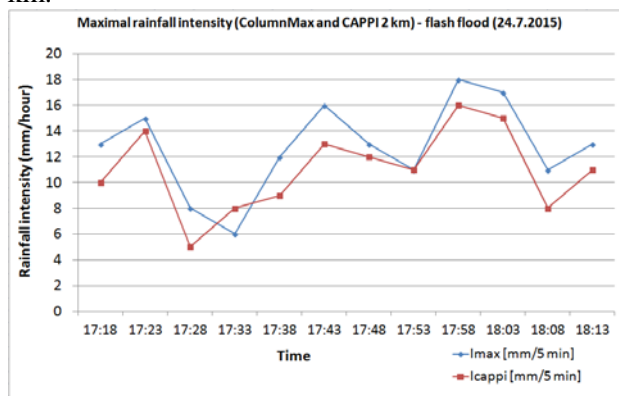


Fig. 3. The current maximal intensity of precipitation measured by means of products Column Max and CAPPI 2 km.

Rainfall in mm/5 minutes is calculated from hourly precipitation intensity, divided by 12. Hour period had three peaks with the most intense rainfall. Rainfall intensity by product CAPPI 2 km achieved lower values than in ColumnMax, which determines the maximum intensity of precipitation in the whole atmosphere.

4.1.2 Radar product Max Z

Radar product Max Z contains information about the maximal intensity of precipitation in the column as ColumnMax and in addition horizontal and vertical distribution of rainfall intensity in different height levels.

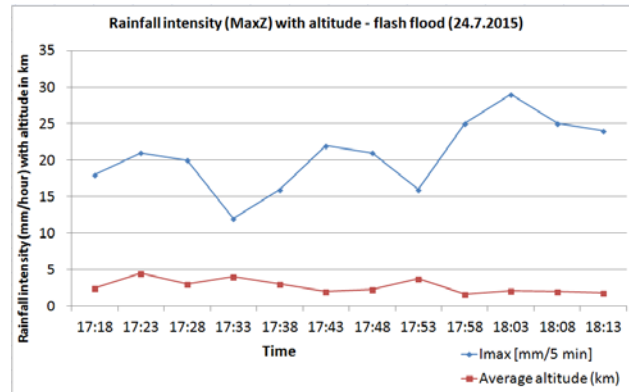


Fig. 4. The current maximal rainfall intensity in different height levels (radar product Max Z).

Formation and development of convective precipitation clouds was clearly demonstrated by the outputs of the product Max Z. Intense convective precipitation occurred at the altitude of 3-5 km in the initial stages of development of convective storms; the mature stage in the levels of 2-4 km and the dissipating stage under 2 km. The most intense rainfall occurred mainly in the mature and dissipating stage of convective storms.

4.1.3 Radar product Range Height Indicator (RHI)

Range Height Indicator RHI gives information about the vertical and horizontal spatial distribution of rainfall intensity in the azimuth. The main purpose is to detect the area of Bounded Weak Echo Region (BWER) and HOOK Echo at an altitude of 2-4 km, which indicates the presence of supercell storms accompanied by tornadoes.

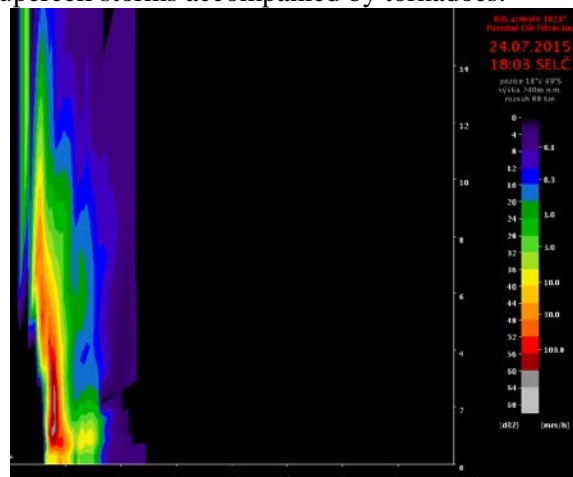


Fig. 5. Vertical and horizontal distribution of rainfall intensity in the azimuth 102° (radar product RHI).

Figure 5 illustrates the distribution of rainfall intensity in the process of dissipating of convective storms. The most intensive reflections in the form

of hail occurred at the level of 2 km and then below this level.

4.1.4 Radar product ECHOTOP

ECHOTOP radar product provides additional information about the occurrence of the maximum rainfall intensity at the highest altitude.

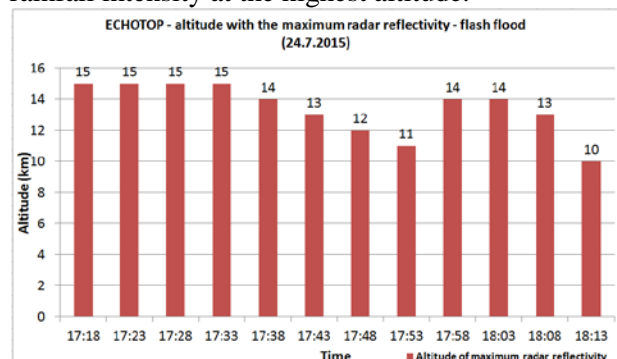


Fig. 6. The height of the maximum rainfall intensity (radar product ECHOTOP).

Figure 6 shows that rainfall maximum intensity was present at an altitude of 15 km in the initial development of convective cells. Height occurrence of intense precipitation has gradually decreased (14-10 km) due to loss precipitation in the process of dissipating of convective storms.

4.1.4 Radar product Vertically Integrated Liquid VIL

Radar product VIL gives information about the amount of liquid water contained in the cloud in kg per m². This product is very important for the prediction of torrential rainfall which can cause the flash flood.

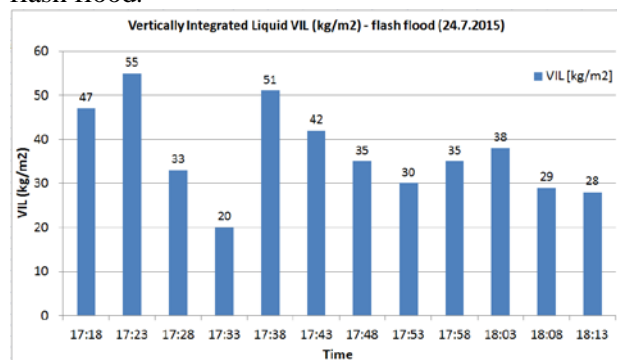


Fig. 7. The quantity of liquid water contained in the convective precipitation clouds.

Figure 7 demonstrates the greatest amount of liquid water which was presented in convective precipitation clouds in the initial stage of development and the mature stage of convective storms. Torrential rainfall was measured in the district Vsetin and Zlin between 17 and 18 hours.

Station precipitation measurements corresponded with radar outputs.

4.2. Outputs of forecasting precipitation using Nowcast TITAN

Very short-term forecast was implemented by software Nowcast TITAN. The output of was a graphical information about the current and future state of intense convective precipitation for 30-60 minutes in advance. Nowcast TITAN determines the area of municipalities with extended powers of the Zlin Region, for which it was calculated the forecast of precipitation locations and the direction of movement precipitation:

Table 4. Forecast precipitation of the Nowcast TITAN.

Time period	Measured precipitation on in locations	Predicted precipitation on in locations	Direction of precipitation on motion
17:18-17:33	Vsetín, Rožnov, Vizovice	Vsetín, Walachian Meziříčí, Bystřice	Southeast (SE)
17:38-17:48	Vsetín, Vizovice, Zlín	Vsetín, Walachian Meziříčí, Zlín	Southeast (SE)
17:53-18:18	Vsetín, Bystřice, Zlín	Bystřice, Zlín, Holešov	East (E)

4.3. Other forecasting outputs

Outputs of the Nowcast TITAN were supplemented by other information, which is very important for predicting probability of occurrence of flash floods:

- NWP models predict rainfall intensity 30-50 mm / hr for the phenomenon of "Strong thunderstorms".
- Satellite measurements were measured maximum temperature cloud top -60 °C, which is typical for vertically developed convective clouds.
- The anticipated rate of precipitation was confirmed by statistics of historical situations in the areas of Vsetin, Vizovice, Zlín and Bystřice in the days 7.11 and 8.07. 2011.
- The highest degree of soil saturation (the highest risk of flash floods) was computed from the area Roznov, Vsetin, Zlín and Bystrice.
- Amateur meteorologists have confirmed the occurrence of thunderstorms accompanied by

torrential rainfall and hailstorm in the municipalities Fryšták, Zlín-Štípa, Lukov, and Hrobice. Strong wind gusts were seen in Zlín-Malenovice which caused material damage to the roofs of houses.

5 Methodology of the use meteorological data for determination risk of flash flood

Official document “The methodology uses of meteorological radar of the Zlin Region for crisis management“ was created for the purpose of analysis, interpretation and prediction of torrential rainfall and other dangerous phenomena through meteorological radar MMR50, which is part of the Information, Notification and Warning System of the Zlín Region. The main objective is to determine the overall risk of flash floods, not only from radar outputs, but also of the outputs of numerical weather prediction model GFS, aerological radiosonde in Prostějov in the Czech Republic, Flash Flood Guidance, Integrated Warning Service System of Czech Hydrometeorological Institute and Algorithm of convective storm prediction. Crisis management personnel of the municipality with extended powers will primarily use this methodology primarily for decision support in terms of deployment of preventive measures against the occurrence of flash floods [17].

5.1. The main conditions of flash floods

The process of analysis, interpretation and prediction of radar data is determined by the sequence of the main conditions of flash floods:

1. Estimated precipitation intensity measured by product CAPPI 2 km.
2. The amount estimate of vertically integrated liquid measured by product VIL.
3. The forecast movement speed of convective precipitation via radar product CAPPI 2 km, MCS Propagation Vector and directional wind shear.
4. Analysis of soil saturation of Flash Flood Guidance.
5. The forecast intensity of storms on the Integrated Warning Service System of Czech Hydrometeorological Institute and Algorithm of convective storm prediction [17].

Firstly, the measured intensity of rainfall is derived by scale of radar reflectivity (product

CAPPI 2 km). Torrential rainfall is detected at levels of 48 dBZ and higher [17].

Table 5. The probability of flash floods based on thresholds of radar reflectivity (dBZ) [17], [18].

Colour spectrum of radar reflectivity	Radar reflectivity [dBz]	Rainfall intensity	Propability of flash floods (%)
	48	Weak torrential rainfall	0-25
	52	Strong torrential rainfall	25-50
	56	Heavy torrential rainfall	50-75
	60	Extremely strong torrential rainfall	75-100

Table 5 shows that weak torrential rainfall with intensity 37 mm / hr. (48 dBZ) may cause flash flood for the duration above 50 minutes in the area. Occurrence of hail and strong wind gusts is very unlikely.

Strong torrential rainfall with intensity 65 mm / hr. (52 dBZ) can cause a flash flood for the duration of 30 minutes in the area. Strong torrential rainfall threatened in combination with strong wind gusts.

Very strong torrential rainfall with intensity 115 mm / hr. (56 dBZ) could cause flash flood for the duration in excess of 20 minutes in the area. Strong gusts and hail threatened the occurrence of rainfall.

Extremely strong torrential rainfall with intensity above 200 mm / hr. (Over 60 dBZ) can trigger a flash flood for the duration of over 10 minutes in the area. The greatest danger are strong wind gusts, hail and in some cases even tornadoes [17].

The main hypothesis of flash floods is that the simultaneously occurring intense precipitation in combination with the presence of slow or static precipitation movement and severe, respectively very or extremely heavy soil saturation. An important fact is that the actual occurrence of heavy rainfall will not cause a flash flood [17].

Secondly, the scale of vertically integrated liquid determines estimation of quantities of liquid water in the cloud. The main objective is to determine the risk of torrential rainfall that can cause flash flood combined with static or slow

motion precipitation and very or extremely strong soil saturation [17].

Table 6. The probability of flash floods based on the intensity of torrential rainfall [17].





Colour spectrum of VIL	VIL [kg/m ²]	Intensity of torrential rainfall	Propability of torrential rainfall (%)
	0-29	Weak torrential rainfall	0-25
	30-49	Strong torrential rainfall	25-50
	50-69	Heavy torrential rainfall	50-75
	Nad 70	Extremely strong torrential rainfall	75-100

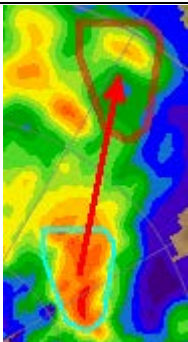
Table 6 provides information about the risks of torrential rainfall including its intensity and experimentally determined interval VIL.

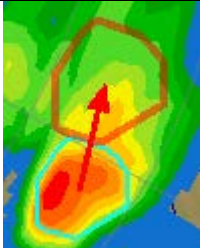
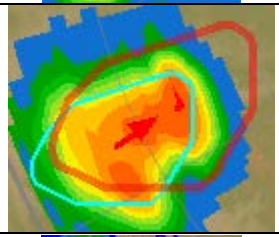
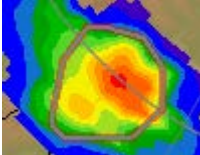
3. The risk of flash floods according to the rainfall velocity is calculated based on these conditions:

- A. Forecasts of direction and location of rainfall defined length of the red arrows of the product CAPPI 2 km or VIL.
- B. MCS Propagation Vector.
- C. Directional wind shear in the atmosphere [17].

Thirdly, the risk of flash floods is determined based on the predictions of speed movement of precipitation from radar products CAPPI 2 km and VIL:

Table 7. The probability of flash floods based on radar output product CAPPI 2 km [17], [18].

Radar output (product CAPPI 2 km)	Speed movement of precipitation	Propability of flash floods (%)
	Very fast movement (>50 km/hr.)	0-25

	Fast movement (30-50 km/hr.)	25-50
	Slow movement (10-30 km/hr.)	50-75
	Stationary movement (0-10 km/hr.)	75-100

Measured rainfall intensity (blue border) is not mutually overlapped with the predicted location (red border). The red arrow, characterizing very fast movement of precipitation, is very long. There is not threat of formation of flash floods.

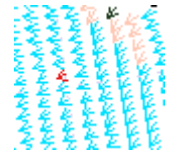
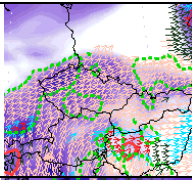
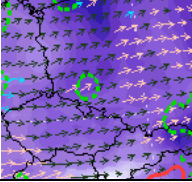
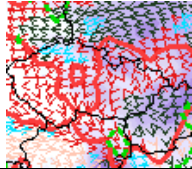
Fast motion of precipitation is characterized by moderately long red arrow, whereby the blue and red-bordered precipitation fields are not overlapping. If no precipitation is extremely intense and does not last for a prolonged period (over 50 minutes) over areas with extreme soil saturation (under 15 mm / hr.), then the probability of flash floods is low (25-50%).

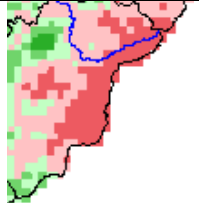
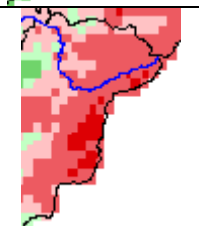
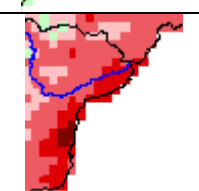
The slow movement of precipitation is shown by short arrow while blue and red-bordered fields precipitation are partially overlapping. In this case, there is a high risk of flash floods with strong or extremely strong intensity of precipitation with shorter duration of 30-50 minutes and a very high soil saturation (15-20 mm / hr.).

Stationary movement of precipitation is marked by merging of blue and red border of precipitation fields. This situation signifies very high risk of flash floods threatened with strong or extremely strong intensity of precipitation of a shorter duration than 30 minutes, and soil saturation (20-30 mm / hr.)

The resulting risk of flash floods based on the speed movement of precipitation is calculated by velocity predictions of NWP model GFS (MCS Propagation Vector) and radiosonde in Prostejov (directional wind shear) [17].

Table 8. The probability of flash floods based on MCS Propagation Vector and directional wind shear [17], [19], [20].

NWP model GFS (MCS Propagation Vector)	Radiosonde Prostějov (directional wind shear)	Speed movement of precipitation	Propability of flash floods (%)
	SW-SW (southwest surface wind – altitude wind)	Very fast forward movement (>50 km/hr.)	0-25
	SW-NW southwest-northwest	Fast sideward movement (30-50 km/hr.)	25-50
	SW-N southwest - north	Slow movement (10-30 km/hr.)	50-75
	SW-NE southwest - northeast	Neutral or backward movement (0-10 km/hr.)	75-100

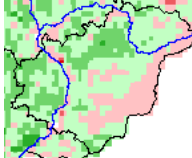
	Strong	20-30 mm (dark pink)	25-50
	Very strong	15-20 mm (red)	50-75
	Extremely strong	>15 mm (crimson red)	75-100

Sum of precipitation per 1 hour is potentially hazardous precipitation total over the duration of one hour, which is derived daily for 6 pm local time. Sum of precipitation is determined by precipitation-drainage model with a preset threshold value. Values represent rainfall for the territory of 3x3 km, which could potentially cause surface runoff from the territory with a return period of 2-5 years [17], [21]

Directional wind shear is determined based on wind directions in different height levels of the atmosphere. Just opposite wind directions from the northeast in the ground and southwest at an altitude represent the maximum directional wind shear. In practice, it means that precipitation will move very slowly or not at all, and the probability of flash floods will be very high [17].

Fourthly, soil saturation is another crucial predictive factor of flash floods. The data source is the Flash Flood Guidance from the Czech Hydrometeorological Institute. The risk of flash floods is determined based on the degree of soil saturation:

Table 9. The probability of flash floods based on the soil saturation [17], [21].

Flash Flood Guidance (soil stauration)	Degree of saturation	Sum of precipitation per 1 hour	Propability of flash floods (%)
	Very weak, weak	above 30 mm (other colours)	0-25

Fifthly, the forecast of storm intensity on the System of Integrated Warning Service from Czech Hydrometeorological Institute and algorithm prediction of storms:

Table 10. The classification of dangerous phenomenon "Storm" [17], [22].

Degree of storm intensity	Intensity of dangerous phenomena	Impact of dangerous phenomena	Propability of flash floods (%)
Weak storms	Rainfall >30 mm/ hr., Wind >15 m/s	Elektrical discharges	0-25
Strong storms	Rainfall = 30-50 mm/hr., Wind >20 m/s	Electrical discharges and torrential rain	25-50
Very strong storms	Rainfall = 50-90 mm/hr., Wind >25 m/s, Hail >=2 cm	Electrical discharges, torrential rain and hailstorm	50-75
Extremely strong	Rainfall = <90 mm/hr.,	Electrical discharges,	75-100

storms	Wind>30 m/s, Hail>=4 cm	torrential rain, hailstorm, tornadoes	
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Forecasting warning about the dangerous phenomenon of "Storm" provides us information about the rainfall intensity and dangerous accompanying phenomena (torrential rain, hail, strong wind gusts and tornadoes), which can cause a flash floods. In the future, the storm intensity will also be determined according to the algorithm of storm prediction. This algorithm is based on the penetration of the overall instability of the atmosphere, triggering and supporting convection indexes and deep layer shear in the atmosphere.

All limits of parameters have been studied by repeated measurement of several tens of situations [17].

5.2. Determination of overall risk of flash flood

The calculation of the resulting risk of flash floods is performed to the area in the Zlín Region which have been detected or measured high rainfall combined with high length of duration of rainfall and soil saturation.

Overall risk of flash floods is calculated by the following equation:

$$X_{flash\ flood} = (X_1 + X_2 + X_3 + X_4) / 4, \quad (5)$$

where X_1 is maximal probability (P_{max}) of flash flood based on measured rainfall intensity and vertically integrated liquid, X_2 is P_{max} speed movement of precipitation, X_3 is P_{max} soil saturation and X_4 is P_{max} storm intensity.

The probability of storm intensity is given by the following formula:

$$X_I = (X_A + X_B) / 2, \quad (6)$$

where X_A is P_{max} rainfall intensity based on radar product CAPPI 2 km and X_B is P_{max} intensity of torrential rainfall designated by product VIL.

Rainfall intensity is calculated as the product of the duration of one radar output (5 min) and intensity of precipitation measured at five minutes. The overall probability speed movement of precipitation is given by this formula:

$$X_2 = (X_C + X_D + X_E) / 3, \quad (7)$$

where X_C is P_{max} speed movement of precipitation based on radar products CAPPI or VIL, X_D is P_{max} MCS Propagation Vector and X_E is P_{max} directional wind shear.

The overall risk of flash flood is given by this table 11:

Table 11. The overall risk of flash flood [17].

Risk of flash floods (%)	Propability of flash floods (%)	The maximum risk (sub-conditions)	The minimum risk (main conditions)
Low	0-25	25	0
Moderate	25-50	50	25
High	50-75	75	50
Very high	75-100	100	75

5.3. Verification on case study (24.7.2015)

Methodics of use of meteorological data to determine the resulting risk of flash floods is verified on a case study dated July 24, 2015. The resulting risk of flash floods is compared with the measured data of meteorological radar MMR50 and the station data in the Zlín Region.

Firstly, major conditions of flash floods are analyzed. Finally, the resulting risk is calculated according to equations 6 and 7 and table 11th.

Major analyzed conditions of flash flood are :

First and second condition is rainfall intensity measured by product CAPPI 2 km and intensity of torrential rainfall by product VIL.

Table 12. Measured radar data of product CAPPI and VIL [18].

Location	Duration of storm (minutes)	Radar reflectivity - rainfall intensity (product CAPPI 2 km)	Vertically Integrated Liquid (product VIL)
Huslenky	20	52 dBZ – 20 mm/hr.	40
Hostalkova	15	56 dBZ – 30 mm/hr.	40
Lhota	10	56 dBZ – 20 mm/hr.	30
Stipa-Frystak	15	56 dBZ – 30 mm/hr.	40
Frystak-Lukov	25	56 dBZ – 50 mm/hr.	30

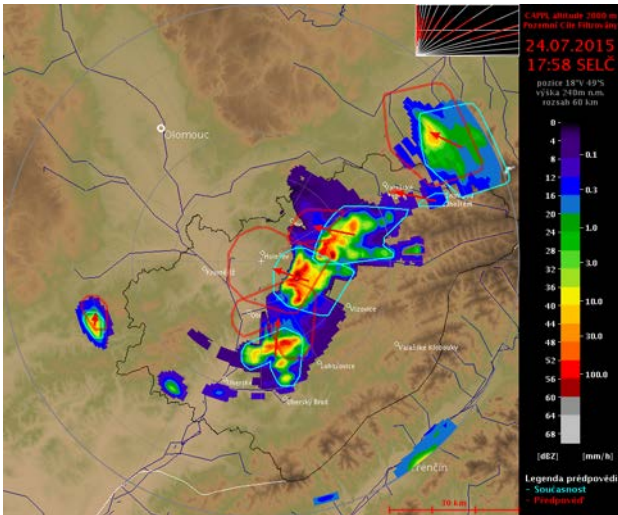


Fig. 8. The most intensive precipitation measured by product CAPPI 2 km on 24.7.2015.

Table 13. Probability of radar data (CAPPI 2 km and VIL).

Location	Maximum probability of rainfall intensity (product CAPPI 2 km)	Maximum probability of vertically integrated liquid (product VIL)	Average maximum probability of radar outputs
Huslenky	25	50	37.5
Hostalkova	50	50	50
Lhota	25	25	25
Stipa-Frystak	50	50	50
Frystak-Lukov	75	25	50

The highest risk of flash floods in terms of rainfall intensity was calculated for the municipality Frystak and Lukov in the central part of Zlin Region, which was confirmed by the measured maximum precipitation totals in this area.

Third condition is movement speed of convective precipitation estimated via radar product CAPPI 2 km, MCS Propagation Vector and directional wind shear.

Table 14. Measured data od speed movement of precipitation [18], [19], [20].

Location	Speed movement of precipitation (product CAPPI 2	MCS Propagation Vector (NWP model GFS)	Directional wind shear (radiosonde Prostějov, 12 hr.)
Huslenky	Slow motion	Pink arrow – fast motion	Northeast-southwest
Hostalkova	Slow motion	Pink arrow – fast motion	Northeast-southwest
Lhota	Slow motion	Pink arrow – fast motion	Northeast-southwest
Stipa-Frystak	Slow motion	Pink arrow – fast motion	Northeast-southwest
Frystak-Lukov	Slow motion	Pink arrow – fast motion	Northeast-southwest

	km)		
Huslenky	Slow motion	Pink arrow – fast motion	Northeast-southwest
Hostalkova	Slow motion	Pink arrow – fast motion	Northeast-southwest
Lhota	Slow motion	Pink arrow – fast motion	Northeast-southwest
Stipa-Frystak	Slow motion	Pink arrow – fast motion	Northeast-southwest
Frystak-Lukov	Slow motion	Pink arrow – fast motion	Northeast-southwest

Table 15. Probability of speed movement of precipitation forecast.

Location	Speed movement of precipitation (product CAPPI 2	MCS Propagation Vector (NWP model GFS)	Directional wind shear (radiosonde)	Average max. probability
Huslenky	75	50	100	75
Hostalkova	75	50	100	75
Lhota	75	50	100	75
Stipa-Frystak	75	50	100	75
Frystak-Lukov	75	50	100	75

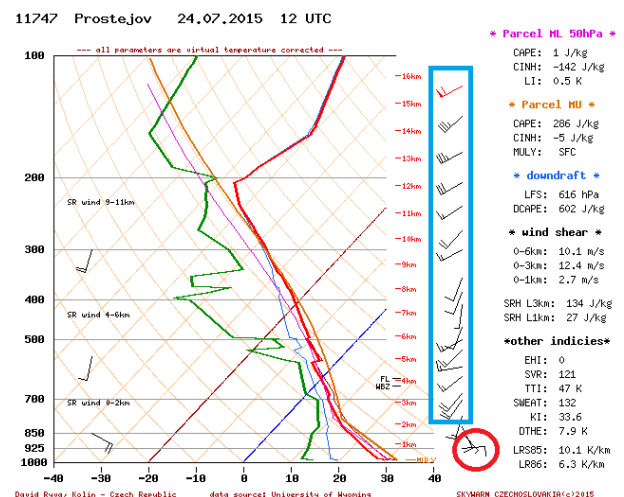


Fig. 9. Skew-T diagram of radiosonde Prostějov [20].

The resulting risk of torrential precipitation was high 50-75%, was as a consequence a significant change of wind direction in the atmosphere and overall slow movement storms.

Four condition is soil saturation of Flash Flood Guidance:

Table 16. Probability of soil saturation [21].

Location	Degree of soil saturation	Sum of precipitation per 1 hour	Average max. probability
Huslenky	Very weak, weak	above 30 mm/hr.	31.25
Hostalkova	Strong	20-30 mm/hr.	50
Lhota	Very weak, weak	above 30 mm/hr.	25
Stipa-Frystak	Strong	20-30 mm/hr.	50
Frystak-Lukov	Strong	20-30 mm/hr.	50

The risk of flash floods based on the soil saturation was quite low 0-25% in most areas of the Zlin region; the exception was nearby municipality Fryšták, Huslenky and Hostalkova and where risk combined with rainfall intensity was moderate risk 25-50%.

Five condition is intensity of storms on the Integrated Warning Service System of Czech Hydrometeorological Institute and algorithms for the convective storms prediction.

Table 17. Probability of storms intensity [22].

Degree of storm intensity	Intensity of dangerous phenomena	Impact of dangerous phenomena	Maximum probability of flash floods (%)
Weak storms	Rainfall >30 mm/ hr., Wind >15 m/s	Elektrical discharges	25

As can be seen in Table 17, Czech Hydrometeorological Institute did not deliver predictive warning information on dangerous phenomenon storm. Weak storms were predicted on July 24, 2015, but there were local flash floods in region.

At the conclusion of the resulting evaluation of the risk of flash floods is shown in the Zlín Region for each storm cores, where was supposed highest potential:

Table 18. Overall risk of flash flood.

Location	Huslenky	Lhota	Stipa-Frystak	Frystak-Lukov
Radar data (CAPPI+ VIL)	37.5	25	50	50
Speed movement	31.25	50	75	75
Soil saturation	31.25	50	50	50
Storm intensity	25	25	25	25
Probability of flash flood	42	38	50	50
Risk of flash flood	Low	Low	High	High

The highest values of the risks of flash floods was achieved in the nearby village of Stipa, Fryšták and Lukov and despite the main conditions (warning against storms and especially soil saturation), the risk was lowest. In this example, it was demonstrated that flash floods do not incur the action of one or two conditions, but on the formation of flash floods must operate with all conditions.

6 Conclusion

The aim of the article was to provide information about current possibilities of monitoring and predictions of intense convective precipitation in the Zlin Region, Czech Republic. Principles of the methodology of measurements and predictions via the mobile meteorological radar (MMR50) were verified on a case study of the July 24, 2015 when the Zlin Region was hit by flash floods.

The most intense precipitation was predicted for area district the Vsetín, Zlin and Bystrice using the software Nowcast TITAN, which is part of the meteorological radar equipment. Convective precipitation over 30 mm / hr. was measured in the Vsetín district (ground meteorological station Huslenky 33.8 mm and Hošťálková 33.1 mm) and Zlin (ground meteorological station Zlin-Stipa 42.8 mm). Station measurements showed the 80% success rate in predictions of locations of intense convective precipitation. In addition, the occurrence of hailstorms and strong wind gusts was confirmed by observations of amateur meteorologists in the central part of the Zlin Region. These dangerous atmospheric phenomena caused material losses of tens of millions of crowns.

Methodics of the use of meteorological data for determination risk of flash flood was shown in the

last chapter of this paper. The main goal was to determine overall risk of flash flood based on five basic conditions of formation of flash floods. The fact was that on the ground meteorological station Zlin - Stipa was measured at 24 mm / hr between 17 to 18 hours, which did not fulfill the criteria for issuing a warning to "Strong storms." It was a borderline situation where warning of Czech Hydrometeorological Institute has not been issued, yet local flash floods nearby the village Frystak occurred. At the same time, the outputs of meteorological radar MMR50 confirmed that the most intensive rainfall combined with slow motion and strong soil saturation were measured at ORP Zlin, specifically in the area of municipalities Stipa, Frystak and Lukov.

Future research will concentrate on the optimization of limits setting for individual radar products, the expansion of the database of historical weather events statistics and observation networks of amateur meteorologists. The main objective will be to ensure timely and quality information on the current and future state of intense convective precipitation, which may cause flash floods.

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