

Statistical, Quantitative Probability and Nowcasting Forecasting Methods of Severe Convective Storms

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Abstract: - This paper deals with the comparison of the statistical, quantitative and nowcasting method of prediction of convective precipitation and the risk of flood floods, which are the main outputs calculated by the Algorithm of Storm Prediction. The evaluation of the success of these outputs was carried out on the basis of verified 63 thunderstorms and three floods that affected the Zlín Region between 2015 and 2017. The first part of the article focuses on the description and evaluation of the predictive outputs of the quantitative prediction of the probability of the occurrence and the intensity of convective precipitation computed from NWP models. At the same time, these outcomes are compared with the outputs of the statistical and nowcasting predictions of convective precipitation. The statistical prediction of convective precipitation is calculated on the selection of the predicted and historical situation from the statistics database. The nowcasting prediction works with the outputs of the MMR50 X-band meteorological radar of the Zlín Region. The second part explores the use of track storms for statistical prediction, which is intended as an indicative and complementary forecast for the method of quantitative prediction of precipitation. The conclusion of the two chapters is a comparison of the success of the predicted outputs of methods, which can be used and put into practice in particular for the prediction of convective precipitation and the risk of floods for purposes of warning and meteorological services and crisis management.

Key-Words: - Weather forecasting; convective storm; statistics; flash floods; meteorological radars; crisis management; NWP models.

1 Introduction

The prediction of convective precipitation and dangerous phenomena is the current problem of meteorology and hydrology regarding its social impact. The formation of these extreme weather phenomena is closely related to the formation of convective precipitation with an area of several square kilometers, and occasionally to hundreds km², the duration of several minutes or hours. Moreover, this characteristic of convective precipitation is a fundamental problem of current forecasting systems [1, 2, 3, 26, 27].

The prediction of convective precipitation is realized by numerical weather prediction (NWP) models and nowcasting methods using meteorological radars or a distance measurement of rainfall and clouds, such as meteorological satellites and aerological radiosondes, where we can obtain a forecast lead time with a maximum of two hours [4, 5, 6]. At present, nowcasting methods have been complemented by statistical and probabilistic prediction of situation. This approach integrated with principles of nowcasting has been studied in

many studies [7, 8, 9]. The second approach is based on a quantitative evaluation of conditions of convective precipitation clouds using NWP models and statistics historical situations. The quantitative assessment focuses on the estimation of future weather developments for a longer forecast lead time, ranging from 6 to 24 hours [10, 11, 12]. This approach has also been developed in the Algorithm of Storm Prediction, which implements the prediction of convective precipitation and dangerous phenomena. The primary aim of this article is to compare the accuracy of predictive convective precipitation methods to 63 storm situations and three flood events in the years 2015 - 2017. Verified plans are part of the statistical and quantitative prediction of convective precipitation using the Algorithm of Storm Prediction and the very short casting forecasts by Nowcast TITAN X-band of the meteorological radar of the Zlín Region. At the same time, the outputs of these methods are compared with the measured data from ground meteorological stations in the Zlín Region. The purpose is to provide information on the

accuracy of the different ways used for verification of the predicted situations and to forecast the intense convective precipitation.

2 Methods

The evaluation of the accuracy of forecasting convective precipitation is realized by these forecasting tools and methods:

1. Algorithm of Storm Prediction (statistical and quantitative forecast of convective precipitation).
2. X-band meteorological radar of the Zlín Region (Nowcast TITAN product).

The predictions were verified by data from a network of stations of the Czech Hydrometeorological Institute.

2.1. Algorithm of Storm Prediction

The Algorithm of Storm Prediction is an application developed to forecast convective precipitation and dangerous accompanying phenomena that may cause floods. This algorithm calculates seven outputs for each 3-hour interval particularly regarding predictions:

- precipitation occurrence for territory of the municipality of extended powers (MPE) and its regions,
- time occurrence of convective precipitation and
- forecast lead time of 6 - 24 hours [3, 13].

This algorithm generates a report of outputs which is computed on ten phases shown in Table 1:

Table 1. Forecast's phases and outputs of the algorithm [3]

Forecast phases	Forecast outputs
1. Time intervals	Time occurrence of precipitation, Occurrence of precipitation
2. General characteristic	A general characteristic of the predicted situation
3. Air mass of conditions	Atmosphere instability, Trigger a Support mechanism of convection, Deep Layer Shear 0-6 km, Dangerous phenomena, Organization and Propagation of storms
4. Local conditions	Temperature, Moisture, Wind and Orographic conditions in the ground level of atmosphere
5. Storm intensity	Storm intensity (3. phase)
6. Dangerous phenomena	Torrential rainfall, Hail, Strong wind gusts, Tornadoes
7. Phases summary	The probability of occurrence and rainfall intensity, Risk of dangerous phenomena, Risk of flash floods

8. Statistical forecast	Historical situation + Storm tracks
9. Forecast report	Summarization a visualization of algorithm outputs

Outputs of the algorithm called "the probability of precipitation occurrence (7th phase) and the statistical forecast (8th phase)" are evaluation subject of their accuracy compared to nowcasting output. These outputs are calculated on data from publicly available NWP models [3, 13].

Table 2. Outputs classification [3]

Coefficients	Probability of precipitation occurrence and statistics	Radar reflectivity (dBZ)/ rainfall intensity (mm/hr.)	Colour of radar reflectivity
0	0 - 0,24	<52 (<48)	Yellow
1	0,25 -0,49	52 (65)	Red
2	0,50 -0,74	56 (115)	Dark Red
3	0,75 - 1	=>60 (200)	Grey

Classification of forecasting outputs, including outputs from the meteorological radar Zlín Region (product Nowcast TITAN) is listed in Table 2.

Verification outputs are performed by the Accuracy verification criterion, calculated as the ratio of all favorable situations to the total number of all cases [3, 13].

2.1.1 Forecast of occurrence and intensity rainfall

This output is one of the leading prediction algorithm outputs that are calculated by the following formula:

$$P_{prec}(A) = P(SI) + P(LC), \quad (1)$$

where $P(SI)$ is the probability of storm intensity (comparable to CHMI alerts) and $P(LC)$ is the probability of local conditions influencing the initiation of atmospheric convection, which are thermal, humidity, wind and orographic conditions [3, 13].

2.1.2 Statistical forecast of convective precipitation

The statistical forecast is a part of the 8th stage of the algorithm, which contains two partial outputs with the prediction of the occurrence and intensity convective precipitation for:

- historical convective rainfall situation and
- storm tracks.

The historic selection of the predicted situation is based on criteria such as the direction of rainfall, temperature, humidity, wind direction and velocity at 1000-300 hPa and local conditions. The aim is to determine the correlation dependence between criteria using the Pearson correlation coefficient:

$$\rho_{X,Y} = \frac{E(XY) - E(X)E(Y)}{\sqrt{E(X^2) - E^2(X)}\sqrt{E(Y^2) - E^2(Y)}}, \quad (2)$$

where random variables $X = E(X2)$ and $Y = E(Y2)$ represent the criteria of the historical and predicted situation. The correlation coefficient takes values from -1 to 1, with the positive correlation dependence, is defined for a range of 0.5 to 1 for the eighth phase algorithm output. The output is the probability of occurrence and intensity convective precipitation as well as the first evaluated output.

The storm track is determined by the prediction of the probability of the precipitation occurrence for which the statistic is associated with frequency precipitation according to the direction of rainfall movement [3, 13].

2.1.2.1 Statistical forecast using storm tracks

The main objective is to provide predictive information on the frequency and intensity of convective precipitation, which includes a set of averaged parameters for smaller areas as municipalities of extended powers (MEP) and their regions than the whole territory of the Zlín Region [3].

The prediction parameters for the determination of the storm tracks are:

1. air mass analysis:
 - a. significant convection indices and meteorological elements
 - b. thermal, humidity and wind conditions of the air mass
 - c. characteristics of the weather situation
 - d. triggering and supporting convection mechanisms
 - e. typing of pressure units
2. spatial distribution of convective precipitation according to:
 - a. places of occurrence and intensity of convective precipitation
 - b. potential trigger mechanisms of convection in the ground and boundary layers of the atmosphere:
 - i. orographic effects of the terrain

- ii. thermal conditions
- iii. humidity conditions
- iv. wind conditions of the Earth's surface (wind speed in the 10 metres above the terrain)

3. statistic of direction of the air flow and storm track
4. risk of flash flood [3].

Input data of the air mass analysis are data from aerological measurements in Prague and Prostějov [14] and Browsers of Current Aerological Probes [15]. Other data are obtained from the GFS model [16]. The weather characteristics of the situation are predominantly data on predictive warning information on severe storm phenomena [17], METEOALARM [18] and ESTOFEX [19]. The data of the synoptic forecasts are gained from the CHMI portal [20].

Summary statistics of the flow direction or storm tracks was calculated on the radar measurement of precipitation [21, 22], including potential triggers atmospheric convection for the Zlín region [23]. Storm tracks were calculated for eight directions of air flow (average wind directions at 700, 600 and 500 hPa). These were, in particular, the following directions of flow and their storm tracks:

- Southwest - tracks JZ1 West and center, SW2 East and center
- South - tracks J1, J2 East and center
- Southeast - tracks JV1 West and center, JV2 East and center
- Northeast - tracks SV1 North and center, SV2 South.
- West - tracks Z1, Z2 center and south.
- North [3].

At the same time, the largest share of flash floods was in these directions in the Zlín Region. The same outputs were calculated for each storm track as for aggregate flow direction statistics using basic frequency, average, median, and standard deviation methods.

Finally, for each flow direction or storm track, the resulting rate of flash flood risk for is calculated on the basis of the following criteria:

- probability of convective precipitation,
- intensity of storms,
- degree of soil saturation,
- speed of precipitation movement.

The degree of flash flood risk has a constant coefficient value for each flow direction and its storm track. In addition to the above criteria, the statistical frequency of severe storm phenomena is

also calculated, which can significantly support the emergence and development of a flash flood [3].

Table 3. Outputs classification of statistical forecast

Coefficients	Rainfall intensity (mm/3hr.)	Risk of flash flood
0	0-2	low
1	3-9	medium
2	10-29	high
3	>30	extremely high

Table 3 show the classification of statistical forecasts of rainfall intensity and the risk of flash floods. In practise, the high to extremely high risk is a real occurrence of a flash flood.

The main purpose of the storm tracks is to provide supplementary information on convective precipitation statistics, which is determined to be compared, in particular, with the algorithm prediction of convective precipitation computed by the Quantitative Probabilistic Prediction (QPF). These outputs are also intended as a backup output for prediction of convective precipitation in Algorithm in case of limitation of access to input data of NWP models (Internet failure) [3].

2.2. Meteorological radar of the Zlín Region

The very short forecast (nowcasting) was evaluated on outputs from the Nowcast TITAN, which is one of the products of the meteorological radar of the Zlín Region. This meteorological radar is part of the Information, Notification and Warning System of the Zlín Region, which provides an effective method of communication between municipalities with extended powers for crisis management, including warning of the population [25].

The primary physical variable is the radar reflectivity that is calculated by the Marshall-Palmer relation [24, 25]:

$$Z = aI^b \quad (3)$$

where a and b are experimentally constants ($a=200$, $b=1,6$). In practice, the radar reflectivity Z is recalculated to the rainfall intensity I according to the formula [24, 25]:

$$I = 10(Z-10\log(a))/10b \quad (4)$$

The Nowcast TITAN radar product provides information on the future distribution of the rainfall field with 60 minutes of the forecast lead time. Firstly, this product output is computed by selecting precipitation fields with the defined threshold of radar reflectivity. In the final phase, the predicted area of the precipitation occurrence is calculated by the length of arrows representing the measured moving speed of rainfall [24, 25].

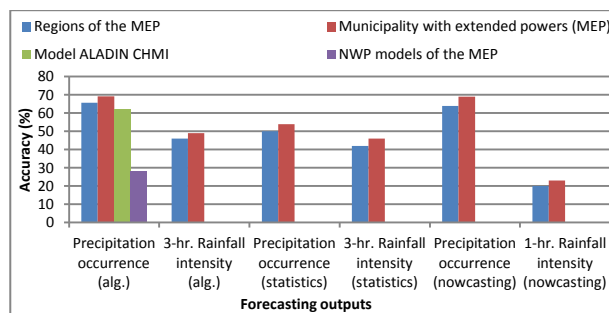
3 Success rate evaluation of convective precipitation forecast

The accuracy of predictive methods is compared with 63 situations and flash flood events that occurred in the Zlín Region in the years of 2015 - 2017:

- July 24, 2015,
- August 5, 2016,
- July 22, 2017.

3.1. A case study on July 24, 2015

Very intense convective precipitation hit the eastern part of the Czech Republic on July 24, 2015, accompanied by hail, strong wind gusts, and local torrential rainfall, which is occurred on the cold front in the afternoon and evening hours [3].



Graph 1. The accuracy of prediction method on July 24, 2015 [3]

Graph 1 state that the quantitative prediction achieved the highest accuracy. At the same time, the nowcasting forecast produced comparable results. However, the accuracy of the nowcasting rainfall intensity forecast was very low due to the considerable variation in the precipitation intensity over time. The statistical prediction had the most reasonable skill due to the small number of historical situations.

As can be seen in Table 3, the quantitative, numerical, statistical and nowcasting forecast of convective precipitation corresponded to the measured rainfall in the central part of the Zlín Region (Zlín station - 23 mm / 3 hours) [3].

Table 3. Verification of flash flood event on July 24, 2015 [3]

24. 7. 2015 (18-21:00)	Prediction	Prediction	Prediction	Real state
MEP of the Zlín region, reported flash flood event	Rainfall intensity (mm/3hr.) – Algorithm	Rainfall intensity (mm/3hr.) – statistical prediction - 11. 7. 2011)	Radar reflectance - Rainfall intensity (dBZ/mm/hr.)	Rainfall in mm (station)
Uherské Hradiště	0	3-9	56 (115)	7 - Staré Hutě
Otrokovice	3-9	3-9	0	0
Kroměříž	3-9	3-9	56 (115)	6 - Kroměříž
Holešov	3-9	3-9	56 (115)	6 - Holešov
Zlín	10-29	10-29	60 (200)	23 - Zlín
Bystřice	3-9	10-29	56 (115)	4 - Bystřice
Valašské Meziříčí	0	10-29	48 (37)	0
Rožnov	3-9	3-9	52 (65)	0
Vsetín	3-9	10-29	60 (200)	12 - Maruška
Vizovice	3-9	3-9	48 (37)	4 Vizovice
Valašské Klobouky	3-9	0	0	0
Luhačovice	3-9	3-9	48 (37)	0
Uherský Brod	0	0	48 (37)	0

3.2. A case study on August 5, 2016

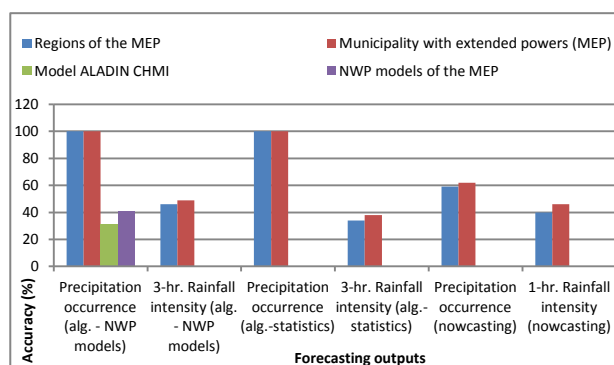
The local flash flood originated a combination of the repeated occurrence of intense convective precipitation and the extreme soil saturation in the south-eastern part of the Zlín Region in the town Valašské Klobouky. This intense rainfall occurred on a cold front, which slowly moved from south to north. The torrential rainfall caused local flooding on the Brumovka, including damage to municipal property and infrastructure within 60 min. [1].

As revealed by Table 4, the convective rainfall occurred across the whole territory of the Zlín Region. This flat occurrence of convective precipitation was also confirmed by all predictive methods, except for nowcasting meteorological radar outputs of the Zlín Region, which did not

predict rainfall in the western and northern parts of the Zlín Region. Convective precipitation with intensity above 20 mm was measured at the station Brumov Bylnice, including a consistent prediction of all methods.

Table 4. Verification of flash flood event on August 5, 2016 [3]

5. 8. 2016 (21-24:00)	Prediction	Prediction	Prediction	Real state
MEP of the Zlín region, reported flash flood event	Rainfall intensity (mm/3hr.) – Algorithm	Rainfall intensity (mm/3hr.) – statistical prediction - 27. 7. 2011)	Radar reflectance - Rainfall intensity (dBZ/mm/hr.)	Rainfall in mm (station)
Uh.Hradiště	10-29	10-29	48 (37)	11 - Staré Hutě
Otrokovice	3-9	10-29	0	8 - Košíky
Kroměříž	3-9	3-9	0	8 - Kroměříž
Holešov	3-9	nad 30	0	9 - Holešov
Zlín	3-9	10-29	48 (37)	6 - Zlín-Štúpa
Bystřice	10-29	10-29	52 (65)	9 - Bystřice
Valašské Meziříčí	3-9	3-9	0	7 - Valašské Meziříčí
Rožnov	3-9	nad 30	0	15 - Horní Bečva
Vsetín	10-29	10-29	52 (65)	24 - Val. Senice
Vizovice	0-3	3-9	52 (65)	9 - Vizovice
Valašské Klobouky	10-29	nad 30	52 (65)	21 - Brumov-Bylnice
Luhačovice	10-29	3-9	48 (37)	14 - Luhačovice
Uh. Brod	10-29	nad 30	48 (37)	14 - Strání



Graph 2. The accuracy of prediction method on August 5, 2016 [3].

Graph 2 demonstrate the very high success rate of the predicted convective precipitation for this event regarding quantitative and statistical prediction against NWP models. On the contrary, the nowcasting prediction was significantly lower due to the flat occurrence of rainfall from which it was not possible to determine precisely the future presence of convective precipitation.

3.3. A case study on July 22, 2017

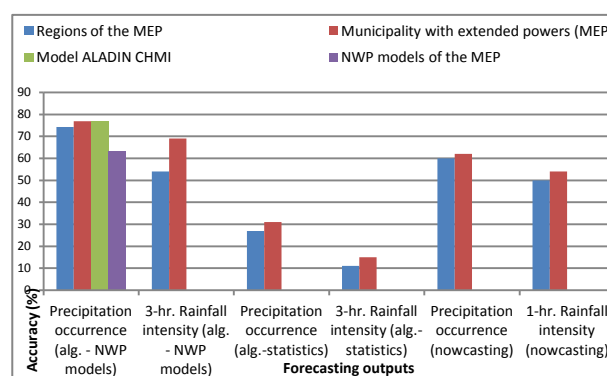
This case study is characterized by a very local precipitation with the intensity above 30 mm/hr, which occurred in the area of several square kilometres in the northern regions of Luhačovice. Local flash floods did not cause significant damage to the property of the population, because it occurred outside urbanized areas. Flood damage reached the order of several million crowns, especially in the case of damage to transport infrastructure and nearby meadows and fields. The formation of intense rainfall was significantly supported by the occluded front which remained in place for several hours [3].

Table 5. Verification of flash flood event on July 22, 2017 [3]

22.7.2017 (15-18:00)	Prediction	Prediction	Prediction	Real state
MEP of the Zlín region, reported flash flood event	Rainfall intensity (mm/3hr.) – Algorithm	Rainfall intensity (mm/3hr.) – statistical prediction(27.7.2016)	Radar reflectivity (dBZ/mm/hr.)	Rainfall in mm (station)
Uh.Hradiště	0	3-9	56 (115)	3 - Hluk
Otrokovice	0	0	0	0
Kroměříž	0	3-9	0	0
Holešov	0	3-9	0	0
Zlín	10-29	3-9	60 (200)	0
Bystřice	0	3-9	0	0
Valašské Meziříčí	0	3-9	0	0
Rožnov	0	10-29	0	0
Vsetín	3-9	10-29	0	3 - Val. Polanka
Vizovice	3-9	3-9	48 (37)	0
Valašské Klobouky	3-9	3-9	48 (37)	0

Luhačovice	30-49	3-9	60 (200)	36 - Horní Lhota
Uh. Brod	0	3-9	48 (37)	0

As described in Table 5, only the quantitative and nowcasting forecast of precipitation corresponded with the measured rainfall at Horní Lhota station (36 mm / hour). On the contrary, the statistical forecast reported the results for the entire territory of the Zlín Region and at the same time did not emphasize the future occurrence of intense precipitation in the MEP Luhačovice and Zlín. This fact was mainly due to the limited selection of the low number of historical situations as well as the first case study.

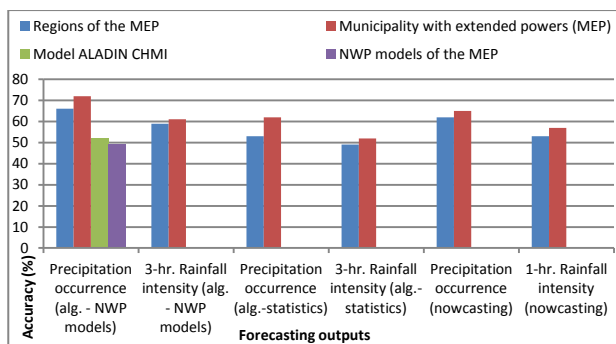


Graph 3. The accuracy of prediction method on July 22, 2017 [3]

Graph 3 illustrate that quantitative, numerical and nowcasting methods achieved the highest accuracy of convective precipitation predictions, in particular, the Algorithm of Storm Prediction with the more accurate forecast of intense precipitation for the MEP Luhačovice. The lowest accuracy was reported in the statistical forecasts of rainfall intensity where based on the selection of historical situations and situation similar to this flood event was not found.

3.4. The accuracy of prediction methods in years of 2015 – 2017

This chapter aims to present the results of the evaluation of the accuracy of the quantitative, numerical, statistical and nowcasting predictions of convective precipitation for 63 situations that were verified for the territory of the Zlín Region in the years 2015-2017.



Graph 4. The accuracy of a prediction method in years of 2015-2017 [3].

Graph 4 show that the highest accuracy of convective precipitation prediction was achieved with the quantitative prediction used in the Algorithm of Storm Prediction. Forecast computed from NWP models reached 20% lower than the quantitative prediction. The main reasons for this difference in the accuracy of both predictive methods were certain limitations of NWP models such as insufficient input data from ground meteorological stations, low horizontal resolution of models, and the use of a hydrostatic core model which is not primarily developed for atmospheric convection modeling. Nowcasting forecast had the second highest accuracy using radar precipitation measurements. The main limitation is the deficient forecast lead time - only for 60 minutes, which is insufficient for the realization of preventive flood protection measures of the Fire Rescue Service. On the other hand, the nowcasting prediction can be more accurate especially for very flat convective precipitation, which may affect areas of several tens to hundreds of square kilometers. The statistical forecast was the lowest accuracy due to the small number of historical situations.

4 Success rate evaluation of statistical forecast of convective precipitation

The success rate of statistical and numerical forecasting of the probability occurrence and the intensity of convective precipitation including the risk of flash flood computed by the Algorithm of Storm Prediction is compared by flood events that affected the Zlín Region in the years 2015-2017:

- July 24, 2015,
- August 5, 2016,
- July 22, 2017.

4.1. Case study on 24.7.2015

This case situation is part of the statistic database of the historical situation for the storm track NE1 North and central, used for statistical prediction of convective precipitation occurring in the northeast

airflow. This storm track is characteristic of the eastern and southeast anticyclonic situation where the cold air from the northeast penetrates the front of the anticyclone above northern Europe. Frontal thunderstorms usually occur on an occlusive or undulating cold front above southern Poland or western Slovakia. The formation of convective precipitation is supported by windward and leeward effects of Moravian-Silesian Beskydy and Hostýnsko-Vsetínská Highland combined with thermal influences of the valleys in the MEP of the Rožnov, Vsetín, Zlín, and Vizovice.

Storm track NE1 - North and central part

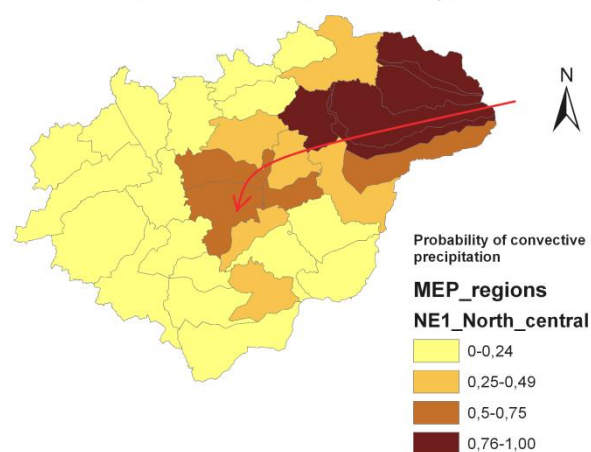


Fig. 1 Direction of precipitation movement for storm track NE1 – North and central

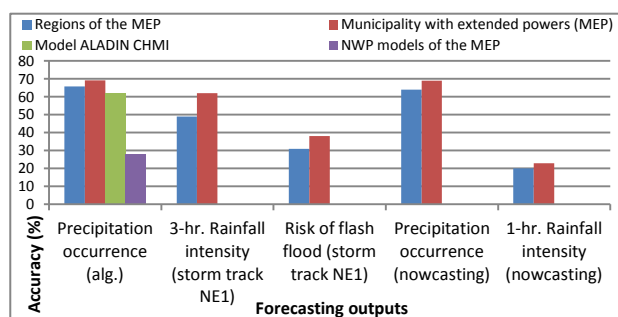
As can be seen in Fig. 1 that the most likely occurrence of convective precipitation is always in the northeast part of the Zlín Region in the MEP of the Rožnov and Vsetín. Consequently, convective precipitation moves and develops over the central parts of the Zlín Region.

Table 7. Statistical forecast outputs of Algorithm for the Zlín Region (24.7.2015) [3]

24.7.2015 (18-21:00)	Forecast	Forecast	Real state
MEP of the Zlín region, reported flash flood event	Rainfall intensity (mm/ 3hr.)	Risk of flash flood	Rainfall in mm (station measurement)
Uherské Hradiště	0-2	low	7 - Staré Hutě
Otrokovice	0-2	low	0
Kroměříž	0-2	low	6 -Kroměříž
Holešov	0-2	low	6 - Holešov

Zlín	10-29	high	23 - Zlín
Bystřice	0-2	medium	4 - Bystřice
Valašské Meziříčí	3-9	high	0
Rožnov	>=30	extremely high	0
Vsetín	>=30	high	12 - Maruška
Vizovice	10-29	high	4 Vizovice
Valašské Klobouky	0-2	high	0
Luhačovice	3-9	medium	0
Uherský Brod	0-2	low	0

Table 7 confirm that the most intense convective precipitation was predicted by NE 1 storm track statistics, including the prediction of high flood risk for the central part of the Zlín Region.



Graph 4 Verification of statistical forecast for the Zlín Region (24.7.2015) [3]

Graph 4 show the comparison of predictive outputs of NWP models, Algorithm and nowcasting methods. The success rate of the statistical forecast of rainfall intensity was comparable to the prediction of convective precipitation with NWP models and Algorithm. Statistical prediction of risk of flash flood is significantly lower due to the local occurrence of torrential rainfall in the MEP Zlín. For this reason, the risk of flash flood forecast is more accurate because it uses input data from NWP models and includes a wider range of predictive parameters with higher predictive success rate.

3.2. Case study on 5.8.2016

This case situation was also included in the convective precipitation statistics for the storm track of the SW 2 east and central. In the first case, convective precipitation was usually initiated on undulated cold fronts, which moves from Austria to Hungary via western Slovakia and affecting the eastern border of the Czech Republic. In the latter

case, convective precipitation occurs in the trough (meteorology) above Central Europe as local precipitation associated with orographic storms. The formation of convective precipitation is supported by the windward and leeward effects of the White Carpathians, Javorníky, Hostýnsko-Vsetínské Highland and Moravian-Silesian Beskyds in combination with the thermal effects of the valleys and lowlands in the MEP of the Uherský Brod, Vsetín and Rožnov.

Fig. 2 illustrate that the first occurrence of convective precipitation is presupposed in the south and southeast of the Zlín Region and then progressing eastwards and northeast. The highest probability of precipitation is in mountainous parts in the eastern and northeast regions of the Zlín region due to the most favorable conditions for the formation of torrential precipitation and floods.

Storm track SW1 - East and central part

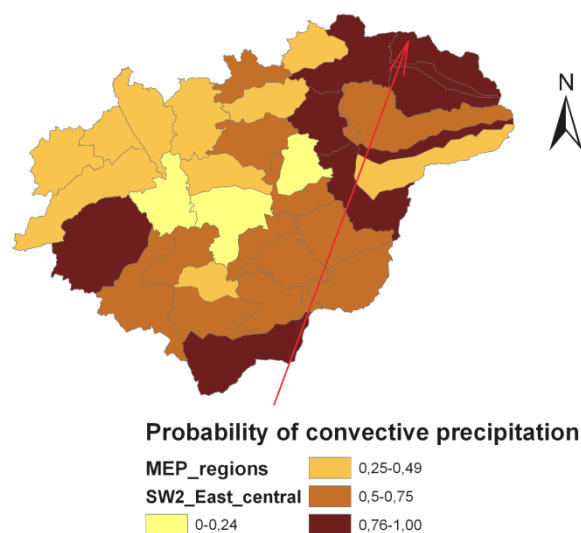


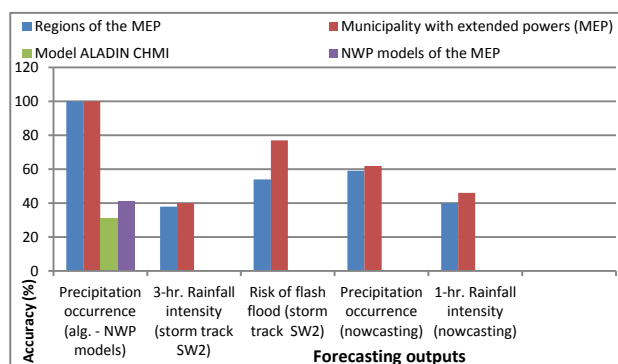
Fig. 1 Direction of precipitation movement for storm track SW 2 – East and central

Table 8. Statistical forecast outputs of Algorithm for the Zlín Region (5.8.2016) [3]

5.8.2016 (21-24:00)	Forecast	Forecast	Real state
MEP of the Zlín region, reported flash flood event	Rainfall intensity (mm/3hr.)	Risk of flash flood	Rainfall in mm (station measurement)

Uh.Hradiště	10-29	medium	11 - Staré Hutě
Otrokovice	0-2	low	8 - Košíky
Kroměříž	3-9	low	8 - Kroměříž
Holešov	3-9	low	9 - Holešov
Zlín (povodeň)	3-9	medium	6 - Zlín- Štípa
Bystřice	10-29	medium	9 - Bystřice
Valašské Meziříčí	10-29	high	7 -Valašské Meziříčí
Rožnov	>=30	high	15 - Horní Bečva
Vsetín	10-29	high	24 - Val. Senice
Vizovice	3-9	high	9 - Vizovice
Valašské Klobouky	10-29	high	21 -Brumov-Bylnice
Luhačovice	10-29	high	14 - Luhačovice
Uh. Brod	10-29	high	14 - Strání

Table 8 indicate that the most intense convective rainfall was predicted for those MEPs of the Valašské Klobouky, Luhačovice, Uherský Brod, Vsetín, Bystřice p. Hostýnem and Uherské Hradiště. It follows that the statistical prediction of convective precipitation and the risk of flash floods corresponded to the actual state. However, convective precipitation occurred in most of the area, and this fact paradoxically led to a decrease in the success rate of convective precipitation predictions according to Graph 5.



Graph 5 Verification of statistical forecast for the Zlín Region (5.8.2016) [3]

Graph 2 demonstrate the results of convective precipitation forecasts, which were lower especially in statistical predictions of rainfall intensity. The main reason was the flatness of precipitation. On the other hand, the statistical forecast of the risk of

flash floods has reached a relatively high level of success rate for the above reason.

3.3. Case study on 22.7.2017

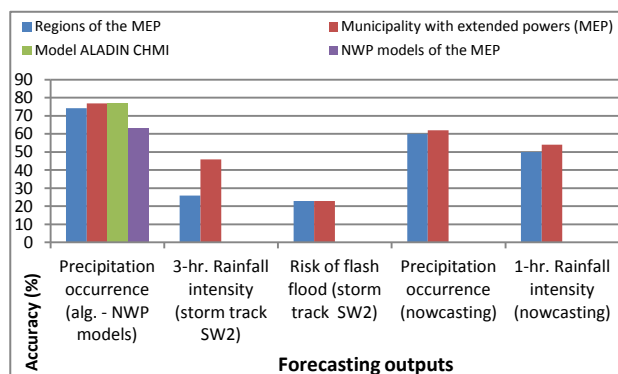
This case study was characterized by the same storm track as in the previous case study. Nevertheless, convective rainfall occurred in a different area compared to the situation of 5 August 2016. The occlusal front was the cause of the torrential precipitation, which moved from the southwest to the northeast part of this region. In spite of this minor difference, this situation had similar features, and the initiation conditions were fulfilled for convective precipitation and flash floods for the SW 2 - east and center storm track.

Table 9 show that both storm tracks predicted the occurrence of intense convective precipitation including a high flood risk for the MEP of the Luhačovice. However, the success rate of these outputs was very low according to Graph 6. The main reason for the very low success rate of the statistical forecast was the very local occurrence of torrential rainfall and flash floods in the MEP of the Luhačovice and a broader forecast for more MEPs, especially MEPs in the south, southeast, east and northeast of Zlín Region.

Table 9. Statistical forecast outputs of Algorithm for the Zlín Region (22.7.2017) [3]

22.7.2017 (15-18:00)	Forecast	Forecast	Real state
MEP of the Zlín region, reported flash flood event	Rainfall intensity (mm/3hr.)	Risk of flash flood	Rainfall in mm (station measurement)
Uh.Hradiště	10-29	medium	3 - Hluk
Otrokovice	0-2	low	0
Kroměříž	3-9	low	0
Holešov	3-9	low	0
Zlín	3-9	medium	0
Bystřice	10-29	medium	0
Valašské Meziříčí	10-29	high	0
Rožnov	>=30	high	0
Vsetín	10-29	high	3 - Val. Polanka
Vizovice	3-9	high	0

Valašské Klobouky	10-29	high	0
Luhačovice	10-29	high	36 - Horní Lhota
Uh. Brod	10-29	high	0



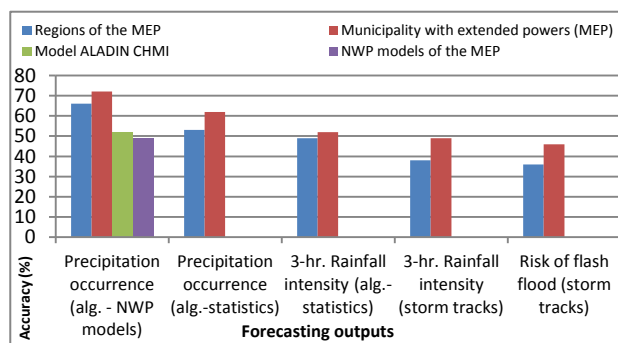
Graph 6 Verification of statistical forecast for the Zlín Region (22.7.2017) [3]

4.4. Comparison of the success rate of statistical forecast algorithm outputs

This chapter focuses on the comparison of the success rate of statistical predictions computed in Algorithm of Storm Prediction:

- convective precipitation according to historical situation statistics,
- intensity of convective precipitation according to the historical situations statistics,
- the intensity of convective precipitation according to the storm tracks
- the risk of flash floods by the storm tracks

The first two outcomes include the average success rate for 63 storm situations in the years of 2015-2017. The last two outputs provide the results of the average success rate of forecasts for the three flash floods that hit the Zlín Region between years of 2015 and 2017.



Graph 7 Comparison of the success rate of convective precipitation and risk of flash flood for statistics of the

historical situation, storm tracks, and NWP models for the Zlín Region for the years of 2015-2017 [3]

Figure 7 confirm the higher success rate of prediction of convective precipitation for NWP models compared to statistical predictions using a database of historical situations and storm tracks. NWP models provide predictive outputs with more accurate predictions than statistical predictions that express the statistical occurrence of convective precipitation. These statistics provide predictive information on the layout of convective precipitation, calculated for a large number of situations. However, convective precipitation usually occurs in every situation and in different areas. Consequently, the uneven occurrence of convective precipitation was one of the causes of lower predictive success. This fact was most evident in the occurrence of torrential rainfall that caused local flash floods in the Zlín Region between years of 2015 and 2017.

4 Conclusions

This article aimed to provide information on methods designed to predict intense convective precipitation that may cause flash floods. The accuracy of quantitative, numerical, statistical and nowcasting predictions is verified in three flash floods, including 63 events, which were recorded by stationary measurements in the Zlín Region between years of 2015 and 2017.

The quantitative prediction of convective precipitation used to compute all outputs in the Algorithm of Storm Prediction, which achieved the highest accuracy of the predicted occurrence and intensity rainfall for all situations, including flood events in the years of 2015-2017. This method is applicable in combination with nowcasting for the prediction of convective precipitation with the accuracy of 60-70 % for territory of municipalities with extended powers. Nowcasting prediction can provide more accurate information on the occurrence of convective rainfall; however, with a short forecasting lead time. The statistical prediction is usable for an orientation view of a given situation that is intended to be compared to other predictive methods or as a backup output in the case of restricting access to publicly available data from NWP models on the Internet. The statistical prediction of convective precipitation and flash floods using storm tracks is another complementary statistical predictive tool used in the Algorithm of Storm Prediction. The success rate of these forecast outputs is lower, as is the case for statistics of historical situations due to its flat and uneven occurrence of convective precipitation.

Therefore, these outputs are only for comparison with Algorithm outputs computed from NWP models rather than as the main prediction output.

The limitation of this study regarding the comparison of the evaluation results of the accuracy of the individual predictive methods is the low number of verified events. Future research will focus on ascertaining the quantitative prediction of tens to hundreds of events for the whole territory of the Czech Republic, including a comparison with these predictive methods. The primary goal will be to increase the accuracy of Algorithm of Storm Prediction by verification to offer the inclusion in the Czech Hydrometeorological Institute operating mode.

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