SCOPING STUDY
EXISTING APPROACHES AND METHODS FOR HEAVY RAIN MODELLING, MAPPING AND RISK ASSESSMENT

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D T1.1.1 Scoping Study

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Contents

1. Context and goals of this study

1.1. Project context

Heavy rain events are a major environmental risk in Europe: they can hit any location with only very short warning time. Every year people die, thousands lose their homes, and environmental damages like water pollution occur. And the risks of heavy rain events are increasing all over Europe. In the project RAINMAN, partners from 6 countries have joined to develop and test innovative methods and tools for the integrated management of heavy rain risks by local, regional & national public authorities. These will be included in the RAINMAN-Toolbox, a set of five transferable tools and methods for municipalities and regional stakeholders.

One of these tools is a guidance tool to assess and map heavy rain hazards and risks. In a first step, the partnership will develop methods to assess heavy rain risks under different categorised physical conditions and land uses of areas in Central Europe. Thus, e.g. adapted methods for urban and rural land uses in mountainous and low land will be specified.

The other tools support e.g. in finding, selecting and implementing suitable risk reduction measures as well as warning and emergency response systems. Furthermore, a catalogue of good-practice examples from all partner countries for the integrated reduction of heavy rain risks will be set-up.

1.2. Goals

The present document comprises the scoping study on existing approaches and methods for heavy rain modelling, hazard assessment and mapping. It represents one of the first results of the RAINMAN project. Therewith the scoping study functions as a basis for further documents and guidelines that will be developed in the scope of RAINMAN.

The goal of this scoping study is to

a) provide an overview on the main existing methods and hence provide a common knowledge basis within the project partnership. Methods described cannot be exhaustive.

b) Set the starting point for the development of a joint method framework for the guidance tool to assess and map heavy rain risks respectively, which will in turn be an integral part of the RAINMAN toolbox.

c) Set the frame for a guidance document addressing the demands for the assessment and mapping methods of heavy rain risks.

1.3. Approach

The study consists primarily of a collection of methods used in different European countries to identify regions at risk and to develop hazard maps for pluvial floods. Around 40 different documents from 9 countries were summarized in this scoping study. Mainly documents available in English, German, and Dutch were included; further information regarding Czech, Polish, Croatian, and Hungarian approaches was provided by our project partners. Due to the fact that the RAINMAN toolbox aims at local and regional authorities, the scoping took only methods in consideration that are used in practice, with a focus on good practice or the “state of the art”. Experimental or strictly scientific methods were not considered.

Also the results of a Scoping Workshop **with external experts on risk assessment and mapping** were included. The workshop focused on good practice examples on heavy rain risk assessment and mapping as well as on discussions of several pilot approaches with the participating experts. The experts presented various approaches and scenarios for heavy rain risk mapping from different countries within the EU. Approaches differ in type of maps, data, effort and target.

The content chapters of the study are organised as follows: Chapter 3 focusses on design precipitation, used for general hydraulic modelling tasks. It includes also methods that focus on previous events to designate areas at risk. Chapter 4 describes GIS-based methods developed in different countries including the widely used rolling ball (D8) analysis. Chapter 5 focusses on modelling; both surface flow modelling and sewer system modelling are included. Chapter 6 on hazard maps comprises available hazard maps for pluvial floods; the corresponding methods are discussed in the previous chapters. Summary and conclusions are given in Chapter 7.

In the annex, the interested reader can find a non-exhaustive list of current surface flood and sewer flood models.

2. Overview on assessment and mapping of pluvial floods in Europe

2.1. Survey of EU-COM „Working Group Floods“ 2016

2.1.1. Background and challenges

Already in 2016, the EU-COM Working Group Floods has conducted a survey among the member states to create an overview on the approaches and the state of the art in assessing, mapping and risk mitigation regarding pluvial floods and risks of heavy rain events. Questions with regard to pluvial flooding and heavy rain events as type of flood in the preliminary flood risk assessment (PFRA) and risk mapping as well as respective mitigation measures in flood risk management planning were topics of the questionnaire. The organisational, legal and financial frameworks for these tasks were also evaluated to create a better picture on the approaches in the member states.

28 questionnaires from 23 member states were completed and submitted. The results are given in the following two subchapters, and are deliberately given as original citations, in order to give the reader the unbiased picture from the WG F (text in square brackets by author).

2.1.2. Assessment

“As a major challenge reported in the questionnaires the MSs mentioned the availability of data of pluvial flood events and of information on consequences of these events. Guidance on how to collect and record flood event data appears to be necessary due to difficulties in collecting and merging existing data and a high level of interaction between different stakeholders is needed. So far this kind of guidance is only available in about half of the responding MS. Another critical aspect is the accuracy of information covering large proportions of the relevant territories in terms of digital elevation/surface models, land use, soil types, rainfall gauges etc.; Those MSs undertaking PFRA [Preliminary Flood Risk Assessment] and identifying APSFR [Areas of Potentially Significant Flood Risk] for pluvial flooding mostly refer to expert judgement and only to a smaller extent to modelling.“
(Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2017:10)

2.1.3. Mapping

“Key findings are:

Flood hazard and risk maps for pluvial flooding have been prepared by 9 out of 26 respondents in the first cycle and will be prepared by another 8 in the second cycle. If maps have been prepared during the first cycle, then integrated FHRM for pluvial and fluvial flooding have been the most frequent solution, but separate approaches are gaining ground in the second cycle. Most commonly, pluvial FHRM have been and are going to be elaborated for both urban and rural areas, and in other cases maps are prepared for selected regions, hot spots or pilot areas.

A majority of respondents (13) neither uses nor intends to use fixed return periods for pluvial flooding, nine did use them in the first cycle and two intend to do so in the second. However the challenge and problems to define return periods for PF has been commented by many MSs.

Pluvial mapping in the first cycle (where done) was mainly based on 2D modelling, also using the analysis of historic pluvial events. Some did GIS-based hydraulic analysis, which seem to gain ground during the second cycle.

With respect to communication, the publication of pluvial FHRM on the internet is the most popular approach, followed by the presentation to local authorities and on public events. Their regular incorporation into spatial planning and land use decision making is less common.

Those respondents, who are already working with pluvial FHRM, rather tend to consider them a reliable basis for FRMan planning and spatial planning decisions. Even the possibility to determine the return period of a pluvial flood event is seen positive by a majority of those respondents who already prepared the maps.

Résumé: The main challenges are adequate pluvial mapping methods and sufficient accuracy to use the results for further planning steps.”
(Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2017:15–16)

2.2. RAINMAN online survey on heavy rain risk management in pilot / partner regions (2018)

2.2.1. Background

In 2018, an online survey was jointly developed by the project partners before developing the toolbox (RAINMAN project activity T.4.1.1, January 2018 – December 2018). With the survey, information regarding two important inputs for the conception of the toolbox is gathered. On the one hand experiences with heavy rain in different regions are evaluated, on the other hand the stakeholders indicate their wishes and demands to improve heavy rain risk management. The results serve as a basis for the concept of the RAINMAN toolbox and its comprising methods and tools. The survey is structured in different thematic parts. One thematic block contains questions regarding “assessment and mapping of heavy rain hazards and risks”.

With the survey the RAINMAN partnership also involves the target group in the tool development process for the RAINMAN toolbox regarding tools and methods for the assessment and mapping of heavy rain risk. 75 % of the answers came from the main targets groups which are local public administration or local government and regional public administration.

322 questionnaires from the six RAINMAN partner countries were completed. The analysis of the results of the online survey is still ongoing. First results regarding the tools and methods for assessment and mapping of heavy rain risks are summarised in the next chapters. Additionally in the report of the online survey (D.T.4.1.1, forthcoming), the results will be analysed and considered against the background of the findings of the scoping study on available methods and approaches as well as demands.

2.2.2. Results on assessment and mapping

For the assessment of heavy rain risks a variety of methods is available and applied. A clear distinction between important / non important methods is not possible. The three most common methods used are “analysis of the drainage system”, “systematic documentation of heavy rain events”, and “analysis of the topographic conditions”. More detailed, the key findings regarding different analysis applied to assess heavy rain risks are:

- **Systematic documentation of heavy rain events** is applied in most partner countries and seems to be the easiest way of assessing heavy rain risks.
- In all partner regions the most frequently named historic data for the **risk assessment based on historic data** are rain measurements, time series and event databases.
- The most common **analysis of topographic conditions** that the respondents / their institutions have done is by identification of surface flow path. The results regarding other options (identification of area depressions, identification of flood channels, and identification of inflow from neighbouring areas) do not give a consistent impression.
- The source for the **analysis of precipitation data** is in most cases station data. Around 28 % of the respondents use radar data and only few base their analysis on satellite data.
- The **analysis of the drainage system** is a conventional task for the design of urban drainage systems. The integration of the assessment of heavy rain risks seem to be useful. No clear trend is visible when it comes to the analysis of the drainage system (weak spots).
- The **analysis of the building structure and infrastructure** is rarely used to assess heavy rain risks compared to the other types of analysis. In most cases the availability of free spaces is the main focus of the analysis.
- Modelling: The **development of hazard and risks maps** in the institutions of the respondents is especially build on GIS analysis or 2D-modelling.

Although most participants are aware of heavy rain risks, more than 40 % have not conducted any heavy rain risk assessment yet. According to the results of the online survey the main reasons are a lack of experiences and a lack of financial or personnel resources.

Reversely, this means (and is also confirmed by the results) that from the respondents’ perspective the provision of knowledge, data and financial resources would help to start mapping and assessing heavy rain risks. Out of 297 respondents, 250 respondents agree / partly agree to personally want / need guidance and methodology for the assessments and mapping of heavy rain risks for their institution or region.

3. Design Precipitation

Hydrographic data is the basis for design precipitations which are being used for different water management tasks and measures across Europe. In this chapter the findings related to the definitions and use of design precipitation values are summarised, with a focus on the purpose of pluvial flood modelling.

3.1. Country examples

3.1.1. Austria

Since the formation of the hydrographic office in 1893, hydrographic data is being collected and interpreted in Austria. As regards the observation network for precipitation / air temperature / evaporation, in 2014 there were ca. 1220 measurement stations, which makes with the Austrian area of ca. 84.000 km^2 a medium density of approx. 1 station per 70 km^2 (cf. Figure 1).

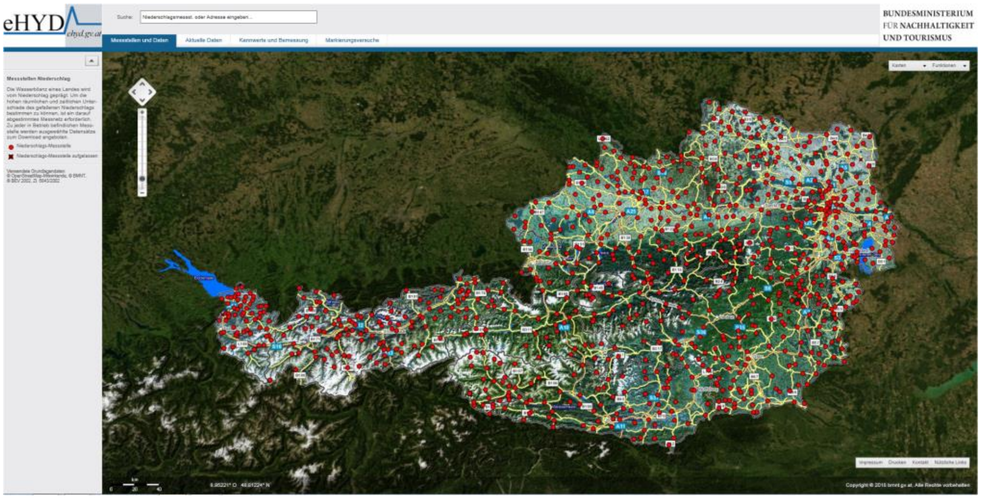
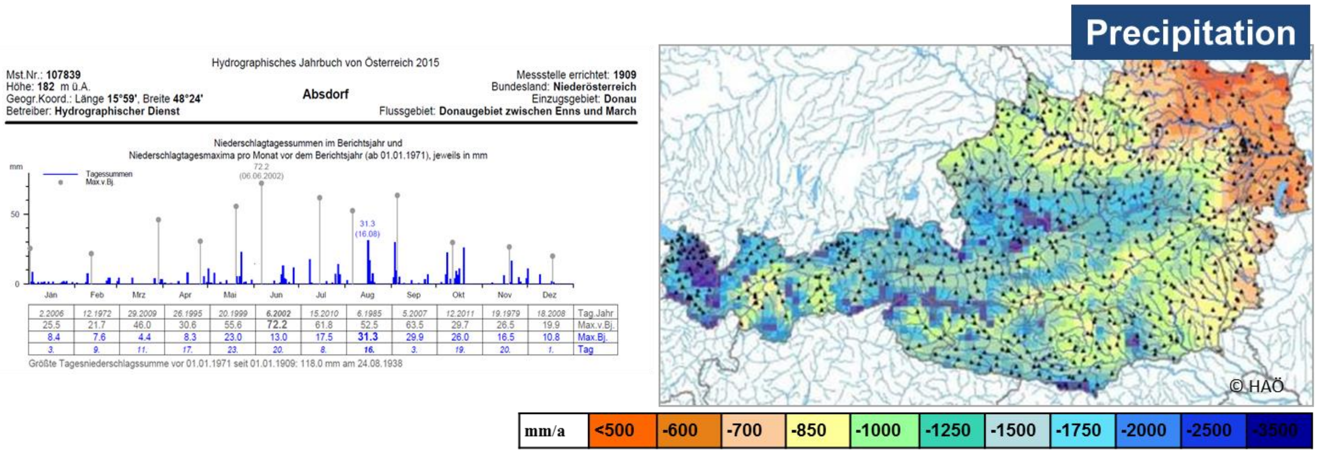


Figure 1: **Measurement Stations for precipitation / Air temperature / evaporation** (Source: screeenshot from Bundesministerium für Nachhaltigkeit und Tourismus, 2018b, 01.06.2018)

At these stations, precipitation data is being collected at least on a daily basis, and statistical interpretations are being made, see Figure 2, on a measurement station basis and on a national basis.



2.2006	12.1972	29.2009	26.1995	20.1999	6.2002	15.2010	6.1985	5.2007	12.2011	19.1979	18.2008	Tag.Jahr
25.5	21.7	46.0	30.6	55.6	72.2	61.8	52.5	63.5	29.7	26.5	19.9	Max.v.Bj.
8.4	7.6	4.4	8.3	23.0	13.0	17.5	31.3	29.9	26.0	16.5	10.8	Max.Bj.
3.	9.	11.	17.	23.	20.	8.	16.	3.	19.	20.	1.	Tag

Figure 2: **Annual statistics for precipitation at one measurement station**
(Source left: screenshot from Bundesministerium für Nachhaltigkeit und Tourismus, 01.06.2018) and
mean annual precipitation characteristics
(Source right: Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (BMLFUW), Abteilung Wasserhaushalt, 2005)

In Austria there are currently three different types of precipitation datasets for durations between 5 min and 6 days and annual probabilities up to 1/100 years, which can be used for design tasks. These are:

- Maximised model precipitations (MaxModN)
- Interpolated ÖKOSTRA - gauging station evaluations (Austrian-wide coordinated heavy rain regionalization and –evaluation)
- The design precipitations as combination of both evaluations

Through the MaxModN Values (most probably „too high“) and the ÖKOSTRA-values (most probably „too low“) the bandwidth of possible design precipitations is limited (Figure 3). However, it cannot be excluded that the design values can lie outside this fluctuation range in particular cases.

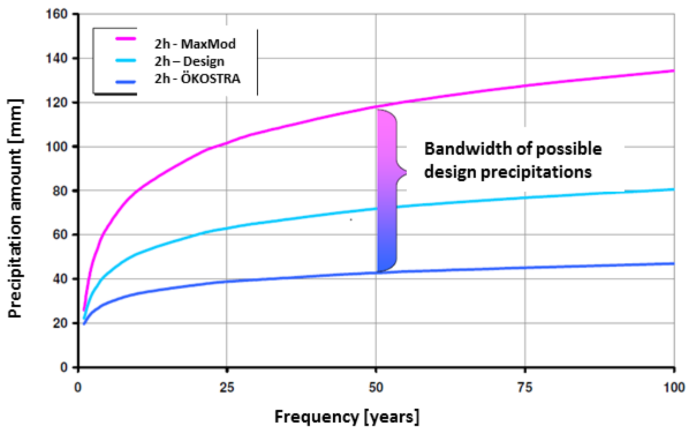


Figure 3: **Model data of a discrete grid point for the duration 2h**
(Source: Bundesministerium für Nachhaltigkeit und Tourismus, 2018a:4, translations by author)

Generally, for design tasks it is recommended to use the design precipitation values as a first approximation. However, for a detailed design of water management measures those (basic) design precipitations are to be compared with today's evaluation results (if available) of e.g. extreme value statistical gauging station evaluations (ÖKOSTRA-evaluations) and – if necessary – need to be adapted. The hydrographic federal states offices can be contacted for more information and additional data. The specification of the design precipitation for a certain design task lies solely in the responsibility of the person in charge for the design [BMNT, 2017]. All data are available on a 6 km * 6 km raster, have last been published in 2008 and are electronically available on http://ehyd.gv.at/.

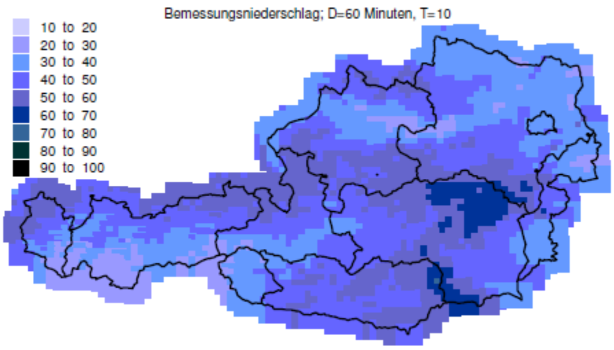


Figure 4: **Design precipitation (in mm) for 10 year probability and 1 h duration** (Source: Bundesministerium für Nachhaltigkeit und Tourismus, 2018a:7)

Also heavy rain is a topic of interest; data on statistics and historical events are available (Figure 5). To the author's knowledge, first discussions regarding design values for pluvial flooding have been started.

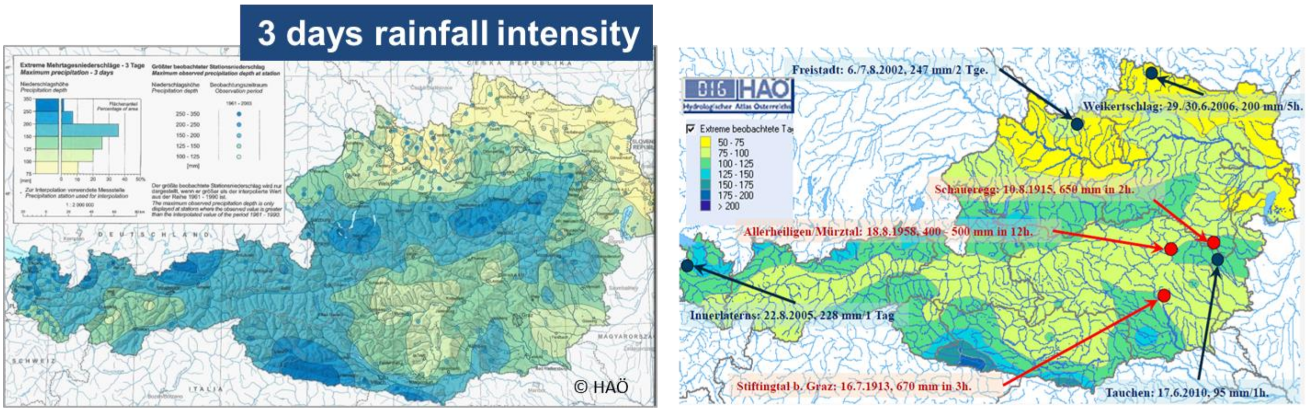


Figure 5: **3 days rainfall intensity pattern** (left) and **past heavy rain events** (right) (Source both: Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (BMLFUW), Abteilung Wasserhaushalt, 2005)

In the frame of the rural development funding programme 2017, municipalities were funded to investigate the consequences of pluvial floods. The design values were taken from eHYD as block precipitation with T10, T30, T100 with 30 min duration for the municipality area.

3.1.2. Croatia

At the moment no country wide approach for design storms for pluvial floods is available. In the scope of the RAINMAN Interreg project statistical analysis on precipitation data will be performed for the Croatian pilot areas. The statistical analysis will comprise of the following methods:

- Analyses of the homogeneity of data series about short-lasting heavy rainfall with the Wilcoxon test
- Trend analysis with the Mann-Kendall test
- Probability analyses for short-lasting heavy rainfall (GEV/Jenkinson theoretic distribution function)
- Analysis of IDF curves for precipitation durations of up to 24 h
- Analyses of "design storm" forms using the average variability of rainfall intensity

With the results from the statistical analysis maps showing the spatial distribution of heavy rainfall with the selected probabilities of occurrence will be produced.

3.1.3. Flanders / Belgium

For Flanders (Belgium) a guideline for the "best practice" in designing sewer system was released in 2012, including a chapter on design precipitation. The Intensity-Duration-Frequency relations (IDF-relations) with 10-minute data from the meteorological station Ukkel, between 1967-1993 were established and used from 1996 onwards. Research shows that in comparison with the 100 (1898-2007) year time series, there are differences in the extreme precipitation that could influence the design of sewer systems. Therefore in 2012 an update was carried out to include the entire time series in the IDF-relations. The IDF-relations are representative for the whole of Flanders, due to the low variability in topography and the relatively small area. Precipitation statistics cover rainfall intensities for T2, T5 and T20 for durations between 10 min and 15 days. (Coördinatiecommissie Intergraal Waterbeleid, 2012)

Trend analysis shows an oscillating pattern of extreme precipitation over multiple decennia, which can be explained by both natural oscillations and climate change (Willems, 2013).

No recommendations were found regarding the application to pluvial floods modelling.

3.1.4. England and Wales

England and Wales are two of the very few countries where design values for pluvial floods were found for a national approach: here, precipitation events with return periods of 30, 100, 1000 years and durations of 1, 3 and 6 h are used as input for the hydraulic surface flood modelling. (Environment Agency, 2018)

3.1.5. Germany

For Germany a regionalised design precipitation is available in KOSTRA-DWD-2010 (Deutscher Wetterdienst, 2015), which is based on data from 1951 to 2010. For durations between 5 min and 12 h, data from precipitation measurements between May and September were used. For durations between 24 and 72 h the daily precipitation height in a 1 km grid was used. The probabilities displayed in the tables and maps lie between 1 and 100 years. The regionalised design precipitation is displayed on maps with a raster size of 67 km^{2}. An example is given below in Figure 6.

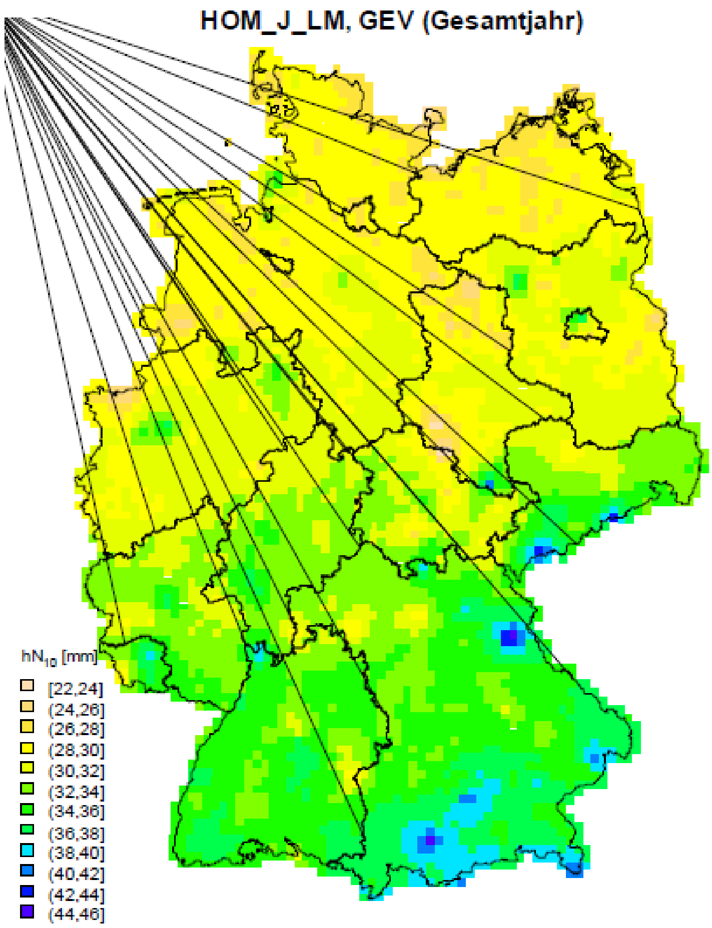


Figure 6: **Regionalised design precipitation for a storm duration of 1 hour and a probability of 10 years** (Source: Deutscher Wetterdienst, 2015:22)

In the frame of the project “radarclimatology”, the German Weather Service derived design precipitation values on the basis of calibrated radar data on a regular grid of 1 km² cell size for Germany. As the dataset comprises only 16 years of radar observations, the results are not considered to be statistically significant. However, this radar derived dataset reveals deficiencies compared to only rain gauge based analyses (i.e. KOSTRA-DWD-2010), especially for high precipitation intensities as it could be seen in Figure 7 (Winterrath et al., 2017).

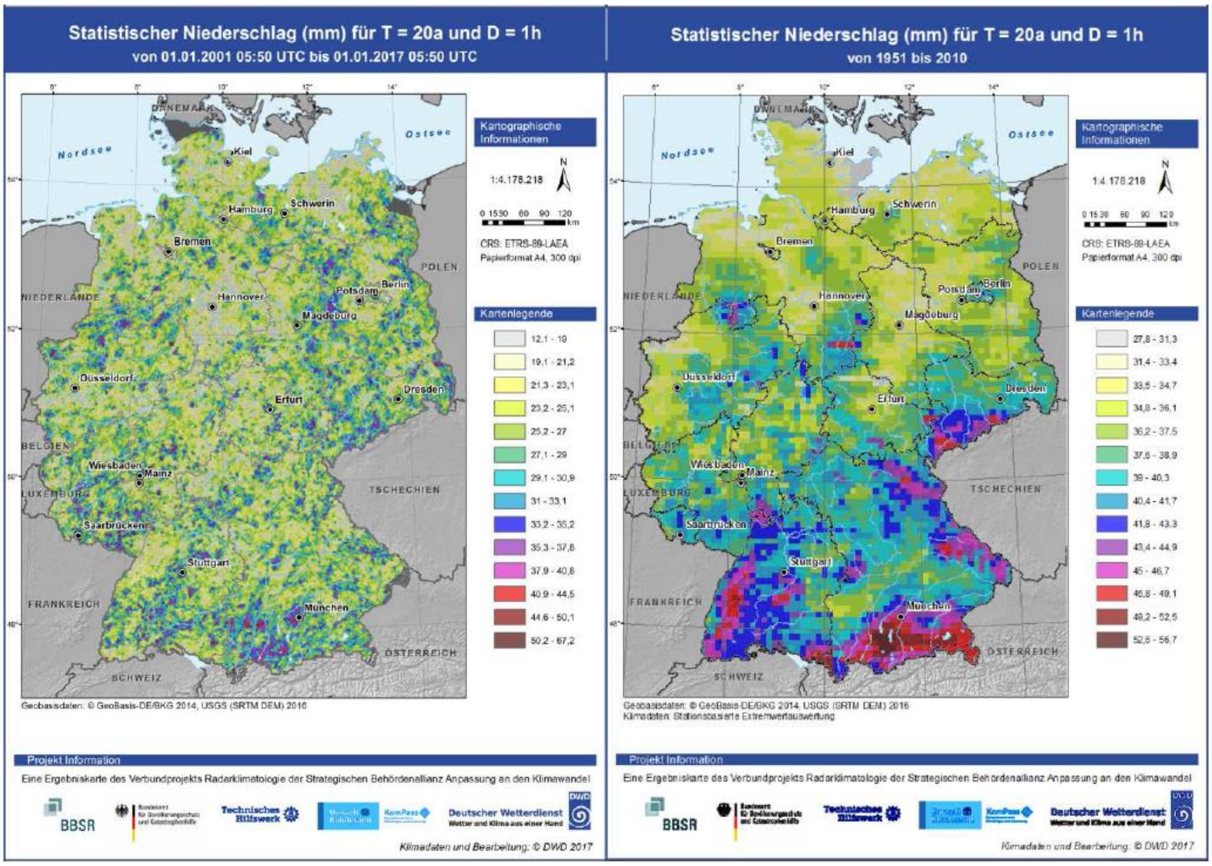


Figure 7: **Design precipitation for a 1 hour rainfall with a return interval of 20 years based on radar information** (left) and **based on long-term station records** (right) (Source both: Winterrath et al., 2017:53)

With regards to pluvial flood modelling, the following recommendations were found for the case of Baden-Wurttemberg: for return periods of 30, 100 and 1000 years an event with a duration of 1 h should be modelled. For the return periods of 30 and 100 years a regionalised value should be used. For the return period of 1000 years the amount of precipitation is 128 mm/h, for the entire region. (Landesanstalt für Umwelt Baden-Württemberg, 2016)

For the federal state of Bavaria the following recommendations are made: The modelling has to be done for at least the following precipitation probabilities: 30, 50 100 and 1000 years (Bayerisches Staatsministerium für Umwelt und Verbraucherschutz, 2017), and the choice of the storm duration and the precipitation distribution has to be justified for every individual case.

3.1.6. Hungary

There are two national standards in Hungary for designing precipitation discharges. One is for urban areas, and the other one is for rural areas.

According to the national standard, the duration of design storms is equal to the runoff time for urban areas. The value of the duration time of design storms is defined as 10 min. Design values for given return periods are given in Figure 8.

Return time (p) (year)	value of the 10 minutes intesity rainfall a_p	
	(mm/h)	(l/sha)
1	47,8	133
2	73,0	203
4	97,0	270
10	131	364
20	158	439
33	180	500
50	202	562
100	238	662

Figure 8: **Design precipitation intensity for a 10 minute rainfall in Hungary according to MI-10-455/2-1988** (national Standard)

For rural areas, no other definition for design precipitation was found. Depending on the kind of infrastructure to be build, a spatial design discharge (l/s * km^2) needs to be defined. For Hungary, this design discharge is the sum of the specific inland excess water discharge from rainfall and the specific inland excess water discharge from groundwater. On average areas the 10 % occurrence probability should be considered. 20-25 % occurrence probability should be considered on smaller than 10 km^2 catchments. Larger facilities (sluices, culverts, bridges) should be designed for 4-5 % occurrence probability. Special facilities (railway, motorway crossings) should be designed for 1-20 % probability (50-100 year return period). If the 10 % discharge is known, other probabilities can be calculated with multiplying factors given in the national standard.

3.1.7. The Netherlands

In the Netherlands there is a regionalised precipitation statistics based on hourly precipitation data from 1906 to onwards, which was updated for the actual climate in 2014 due to the already profound changes in the occurrence of heavy rain due to climate change, this is described in “New precipitation statistics for water management“ (Stichting Toegepast Onderzoek Waterbeheer, 2015). This precipitation statistics covers durations between 2 h and 8 days and shows a 10 % increase in the extent of heavy rainfall events in 2015 in comparison with the statistics for 2004-2014. For 2050 a further increase up to 15 % is expected. The data used for this guideline is the long term precipitation data from meteorological station “de Bilt”. In (Koninklijk Nederlands Meteorologisch Instituut, 2015) time series for KNMI’14 scenarios and statistics of heavy precipitation are contained. The time series for extreme precipitation are obtained by the generalised extreme value distribution. With this method the precipitation statistics can be derived for each year in the time series, in this case for 2014. The precipitation statistics are derived for the entire year, for summer and winter. Regional differences are included, with the Netherlands being divided in four categories for rainfall durations longer than 12 h, with the higher rainfall being situated in the western part of the Netherland and the lower Rainfall in the eastern part.

No recommendations were found regarding the application to pluvial floods modelling.

3.1.8. Poland

The “Atlas of extreme weather phenomena and synoptic situations in Poland” (Ustrnul et al., 2009) contains information on extreme weather phenomena between 1951 and 2006 and presents the synoptic situations over Europe which might have significantly influenced their formation. Examples of extremely high precipitation are presented as the daily total distribution in Poland with regards to the synoptic situation which prevailed over Europe at the time. The extreme values of daily precipitation totals defined by daily precipitation totals occurred with a probability 1 % (at over 10 stations) or even 0.1 % (at over 3 stations) are presented in tables. The Meteorological Hazard Atlas of Poland (Ustrnul et al., 2014) contains the maps of the daily maximum precipitation totals of a given probability and the maps of probability of precipitation totals exceeding 30 mm. Figure 10 presents the examples of maximal precipitation totals of probability of exceedance 10 %, 5 % and 1 % in three decades of August.

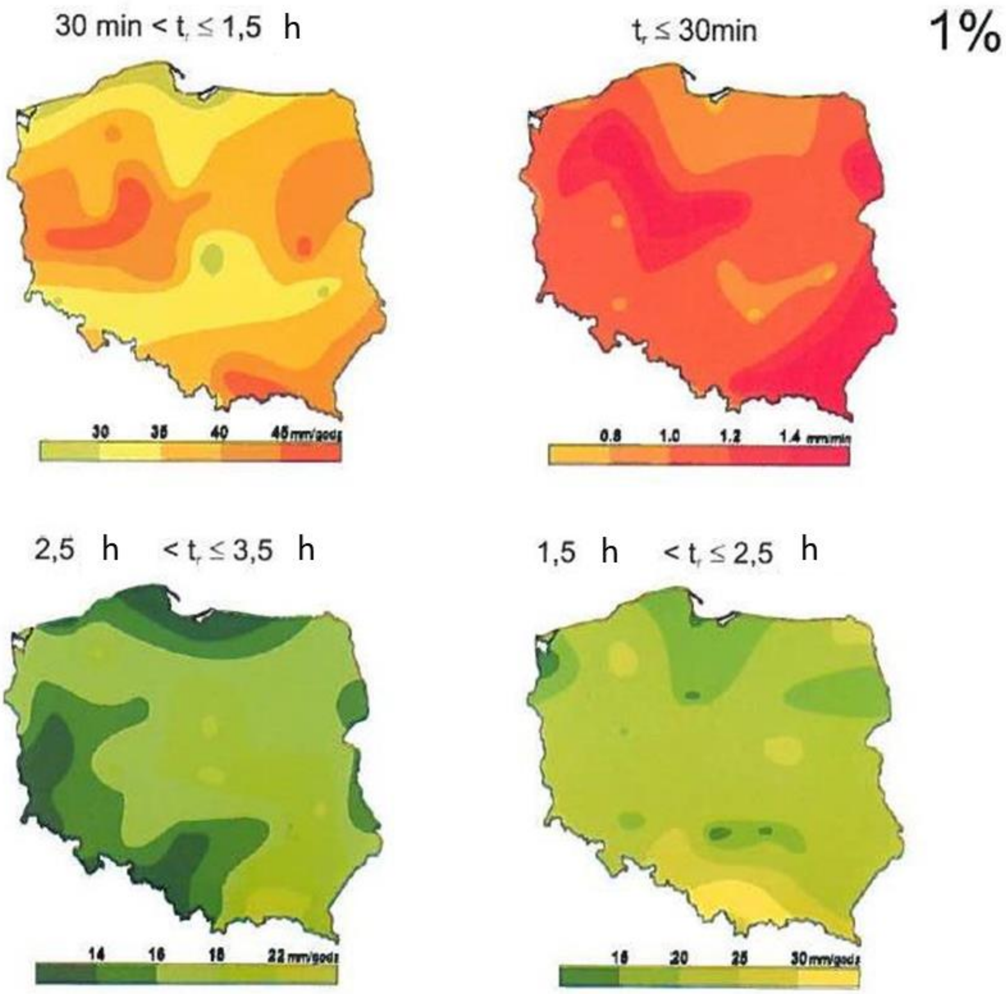


Figure 9: **Spatial distribution of maximal precipitation in Poland with probability of exceedance 1 % in selected classes of their duration**
(Source: Suligowski, 2004)

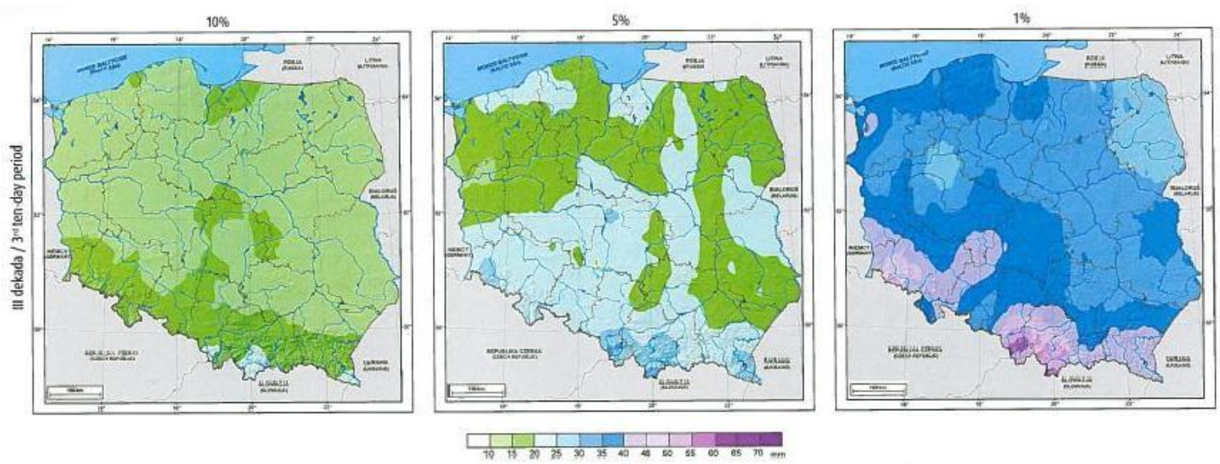


Figure 10: **Maximal precipitation totals of probability of exceedance 10 %, 5 % and 1 % in particular decades of August, on the basis of 1966-2010 data**
(Source: Ustrnul et al., 2014)

The analysis concerning temporal and spatial structure of the rainfall in Poland for hydrological purposes were carried out by R. Suligowski (2004). The study presents the formulas expressing the connection of rainfall characteristics: intensity, duration and frequency. Based on physical and statistical rainfall events analysis, three genetic types of rainfall have been specified. Classification of rainfall events due to genetic types is important to design hyetograph development. The spatial distribution of rainfall intensity-duration-frequency was presented on maps i.e. Figure 9. The formula/equation of rainfall intensity-duration-frequency for area of Poland was developed and the geographical regionalization of rainfall features related to the genetic types was carried out.

In Poland, the PANDa Project has been implemented since 2016, co-funding within the Program Smart Growth Operational Programme 2014-2020. The aim of the project is to develop and implement the Polish Atlas of Design Rainfall Intensities (Polski Atlas Natężeń Deszczów Miarodajnych, PANDa).

The digital PANDa platform is planned as an up-to-date and reliable source of information on design rainfall intensities, facilitating the designing systems for rainwater drainage and storage in Poland. The project involves preparing a database on rainfall over time and its statistical analysis in order to determine the intensities of design rainfall for 919 towns and cities across Poland. The rainfall intensities will be used to develop an online calculator for design rainfall intensity (www.retencja.pl/en/about-us/eu-projectspanda)

In Poland the precipitation model developed by Bogdanowicz and Stachy (1998) is commonly applied. The formula defines characteristics for precipitation as a probabilistic model of maximum totals

$h_{max} = 1.42 \cdot t^{0.33} + \alpha R,t \cdot -\ln p^{0.584}$

where:

- h_{max} – maximum rainfall totals (mm),
- t – rainfall duration t ϵ [5; 4320] (min),
- p – probability of precipitation exceedance: p ϵ (0;1],
- α – scale parameter dependent on region (R) of Poland and rainfall duration t,

In the central part of Poland including the lowlands of the province of Lower Silesia, the parameter α is calculated on the basis of the following formulas and depends on duration of rainfall (t):

- $\alpha = 4.693 \ln(t+1) - 1.249$; $t \epsilon [5; 120]$ (min),
- $\alpha = 2.223 \ln(t+1) + 10.639$; $t \epsilon [120; 720]$ (min),
- $\alpha = 9.472 \ln(t+1) - 37.032$; $t \epsilon [720; 4320]$ (min),

Now within the PAND-a Project a new source of information on design rainfall intensities is developed.

3.1.9. Switzerland

In Switzerland areas of risk for pluvial floods were established in 2018 for the entire country. As input for the modelling, a regionalised design storm with a return period of about 100 years and a duration of 1 h was chosen. The intensity of this specific storm varies regionally; the hydrograph has the same shape for all intensities (Bundesamt für Umwelt, 2018).

3.2. Chapter summary and conclusions

Design precipitations are available throughout Europe for general design tasks in water management (Table 1). Also, assessments of pluvial flood hazards, e.g. based on historical data are available. However, the definition of specific precipitation design values for pluvial flood modelling and more specific for the identification of pluvial flood extent could be found only for a few countries. Additionally, it is worth noting that these specifications have been made in Europe only since 2016.

The following issue shall be mentioned here: a meteorological precipitation event of a certain probability (e.g. T = 100 years) does not necessarily lead to a surface runoff event of the same probability. Therefore, discussions exist how a surface runoff event of a certain probability could be obtained, in order to have similar definitions for pluvial and fluvial flooding scenarios (fluvial flooding scenarios are defined according to the probability of the discharge in the river (i.e. the phenomenon on the surface)). Within the frame of the scoping study, only one approach was found in the German guideline DWA DIN EN 752 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., 2017).

Instead, the majority of the EU member states seem to take a pragmatic approach by defining a certain meteorological scenario (e.g. 3 probabilities, 1 storm duration). England and Wales make further investigations by assessing the worst case scenario out of 3 storm durations for each probability. Switzerland is the most pragmatic country by analysing only 1 scenario with only 1 storm duration.

Table 1: **Overview on design precipitation used in pluvial flood modelling**

Country	Probability	Duration	Intensity	Modelling software	Source
DE (Baden-Wurttem-berg)	30/ 100/ 1000 years	1 h	Regionalised (30/ 100 years); 128 mm (1000 years)	Not specified	LUBW (2016)
DE (Bavaria)	30/ 50/ 100/ 1000 years	Not specified	Not specified	Not specified	STUMV (2017)
GB (England, Wales)	30/ 100/ 1000 years	1, 3 and 6 h (worst case scenario)		JFlow+	Environment Agency (2016)
HU	1/ 2/ 4/ 10/ 20/ 33/ 50/ 100 years	10 min	Standardised for the whole country	HEC-RAS, HEC-HMS	National Standard
CH	100 years	1 h	Regionalised	FloodArea	BAFU (2018)
AT, Styria	10, 30, 100 years	30 min	Regionalised design values (eHYD)	FloodArea	Federal Office of the Styrian Government (2018), not published

4. GIS Based Methods

GIS methods can be suitable tools in order to identify potentially significant risk areas for pluvial flooding or potential hot spots. In this chapter, the findings for the application of GIS methods for surface flooding are being summarised.

4.1. Country Examples

4.1.1. Austria

In Austria, pluvial hazards can be analysed by using GIS analyses of flow paths based on digital terrain models (rolling ball analysis or D8). GIS analyses of flowpaths deliver the surface runoff paths classified according to the catchment size. Pluvial hazard maps based on flow path analyses are applied in the designation of hazard areas for floods and backwater through surface runoff (i.e. pluvial flooding), in the local spatial planning (zoning concepts, designated open land for surface runoff, protective measures) and as basis for building permissions and emergency management.

Overall, the GIS-based maps give good indications for hazard, are easy to read, deliver plausible results outside of settlements, and less representative results inside settlements. Plausibility checks and – if necessary corrections (e.g. bridges, inlets, culverts, small walls) - are obligatory before further use (cf. Haider, 2017).

The GIS analyses are easy to implement and cost-extensive (cf. Habersack et al., 2018).

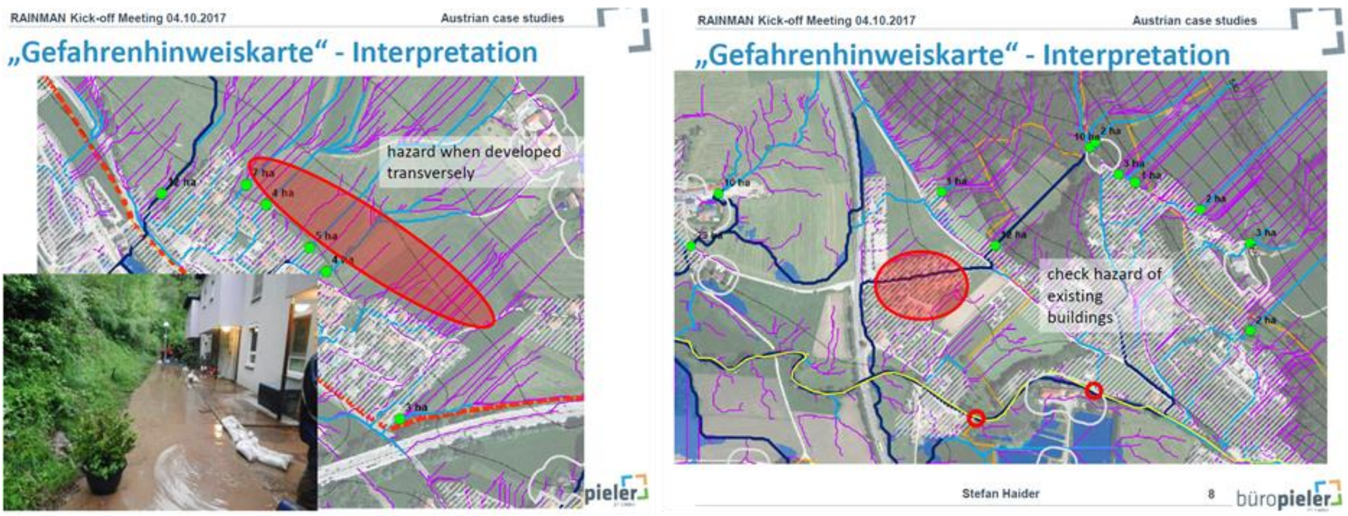


Figure 11: **Interpretation of indicative hazard maps** (Haider, 2017)

However, no general method specification (regulation or similar) for the identification and mapping of pluvial hazard areas exists yet in Austria. With regards to the Floods Directive implementation, pluvial floods were considered in the 1st cycle by way of a few significant past pluvial flood events. Since then, the awareness and records of pluvial flood events have increased, as well as the reliability and robustness of surface floods modelling tools have increased. Therefore, in the recent years pilot actions on national, regional and local levels were started in order to model and map pluvial flood risks (Chapter 5.1.1).

For the second cycle of the Floods Directive implementation it is agreed that pluvial floods are considered in the preliminary flood risk assessment and identification of areas of potentially significant flood risk. This is accomplished by providing hazard indication maps, generated by using

- generalised analyses based on 10 m * 10 m DEM for identifying significant pluvial catchments,
- and by providing detailed analyses based on 1 m * 1 m DEM for significant catchments,
- and by an indicator based on the catchment size and average slope.

This information serves as support for expert judgement in the frame of PFRA and APSFR designation for pluvial flood risk (cf. Pleschko, 2017).

4.1.2. Croatia

In the first cycle of the implementation of the Floods Directive, in the framework of the preliminary flood risk assessment, areas of potentially significant flood hazards for several flood sources were identified (Prethodna procjena ugroženosti od poplava [Preliminary assessment of flood risk], 2013). Based on data available, preliminary flash flood hazard assessment was made by geomorphological GIS analysis. It was based on ratios of basin area, flow length and average basin slope, with thresholds set by expert judgement.

4.1.3. Czech Republic

Pluvial floods (heavy rain floods) are caused by short-term intense rainfalls that hit a relatively small area. These floods therefore represent a local threat, but they may have catastrophic consequences for the affected site. Mostly local events occur mainly in sloping areas on small watercourses, but also outside the permanent river network. One of the main problems of pluvial floods is their prediction, which is practically impossible. Pluvial floods usually interfere with relatively small areas and are in most cases not recorded in time by the network of the Czech Hydrometeorological Institute (ČHMÚ) precipitation stations. Therefore, the warning information issued by the ČHMÚ can only be related to a much larger area, but not to such small localities that are potentially at risk of a flood due to the configuration of the terrain and other circumstances.

The aim of the methodology used in the Czech Republic (Štěpánková et al., 2017) is to propose a procedure for selecting small catchments where local torrential floods can occur and also to put these findings into practice and to propose appropriate measures to eliminate the consequences of floods.

In principal, the method uses a repeatable procedure of identification of decisive areas in terms of the creation of concentrated surface runoff, with the aim of defining so-called critical points (CP) within built-up areas as an auxiliary indicator of the threat of concentrated surface runoff and transport of solid matter by torrential rains. For each contributory area, a value is worked out as a so-called indicator of critical conditions for the occurrence of negative effects of torrential rain flooding.

For any specific CP contributory area, this indicator presents the combination of physical-geographical conditions, the form of land use, regional variations in landscape cover, and potential occurrence of extreme torrential rains (in relation to synoptic conditions):

$$F = P_{p,r} \cdot H_{m,r} \cdot (a_1 \cdot I_p + a_2 \cdot ORP + a_3 \cdot CNII)$$

where

F is the critical conditions indicator [-],
a is the weight vector [1.48876; 3.09204; 0.467171],

$P_{p,r}$ is the relative value of the size of the contributory area (considering a max. 10 km^2) [-],
I_p is the value of average slope of contributory area [%],
ORP is the proportion of arable land in the area [%],
CNII represents characteristic of surface in consideration of run-off [-],
$H_{m,r}$ is the relative value of total one day torrential rains with a repetition period of 100 years for territory within the Czech Republic [-]

The proposed method consists of four steps

- Determination of flow path
- Preliminary (spatial) identification of critical points (contributory area of critical point ≥ 0.3 km^2)
- Specification of geographical condition of contributory areas
- Final selection of critical points

There are four criteria to select a critical point:

- K1 size of contributory area (CA) 0.3 – 10.0 km2
- K2 average slope of CA ≥ 3.5 %
- K3 proportion of arable land ≥ 40 %
- K4 critical conditions indicator ≥ 1.85

On the basis of investigation using model catchment basins, where damage occurred even from areas with a proportion of arable land lower than 40 %, or completely forested areas, the selection carried out according to the conditions of criteria C1 - C4 was extended to include critical points with contributory areas of 1 km^2 and above, with an average slope of 5 % or more:

K1A - size of contributory area 1.0–10.0 km^2,

K2A - average slope of contributory area ≥ 5 %.

On the basis of parameters of combined criteria C1 to C4, or C1A and C2A, a total of 9,261 critical points were chosen for the whole Czech Republic which have a greater (unknown) probability of occurrence of negative impact of torrential rain flooding. The overall area of contributory areas of selected critical points in relation to built-up areas in CZ is 18,112.2 km^2, which represents 23 % of all land in the whole country. The results are available on the povis.cz portal.

4.1.4. Germany

In the City of Hamburg the Project RISA (RainInfraStructureAdaptation [RegenInfraStrukturAnpassung], Hamburger Stadtentwässerung, 2015) was carried out between 2009 and 2015. The objective of the project was to develop a strategy for water sensitive urban development. In the scope of this project an automated GIS method producing hazard maps for pluvial floods (Scheid et al., 2013) was developed. The aim of this particular research was to develop a method that could be implemented for the entire area of Hamburg with manageable efforts while obtaining a reliable quality of results. With this method two topographic assessment parameters are derived from the Digital Terrain Model. The first assessment parameter is the flow paths, the second parameter is the local sinks and depressions. A sensitivity analysis on the pre-screening for sinks, as especially in flat areas the influence of sinks and the threshold for the pre-screening can be quite substantial. The third parameter for the flood hazard assessment is based on the overflow frequency of manholes, where it is assumed that an overflowing manhole creates surface runoff towards the nearest sink. To determine the total potential flood hazard all assessment parameters are classified, where the sink obtained an additional charge due to influence of sewer overflows. The described method provides an automated, comprehensive initial analysis of pluvial flood hazards in urban areas.

In the German guideline DWA-M119 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., 2016) different methods to establish hazard maps are discussed. One of the proposed methods is the rolling ball analysis, discussed in the paragraph about Austria. The adapted GIS-method developed in the Project RISA is also proposed.

4.1.5. Hungary

"*Inland excess water is the surplus surface water forming due to the lack of runoff, insufficient absorption capability of soil or the upwelling of groundwater*" (Bozán et al., 2017:45), and it causes several problems in Hungary, with damages possibly affecting up to 1.8 million hectares, from which 60 % are located in the arable land (Bozán et al., 2017:45). Therefore, an inland excess water hazard map was developed for the flat lands in Hungary.

For modelling the complex process, effects of soil, (agro)geology, groundwater, land use, hydrometeorology, and relative frequency of inland water excess events were considered (for more details, please refer to Bozán et al., 2017). A multiple linear regression analysis (MLRA) was used for modelling the joint effect of the selected environmental factors on inundation, and the resulting map is illustrated in Figure 12.

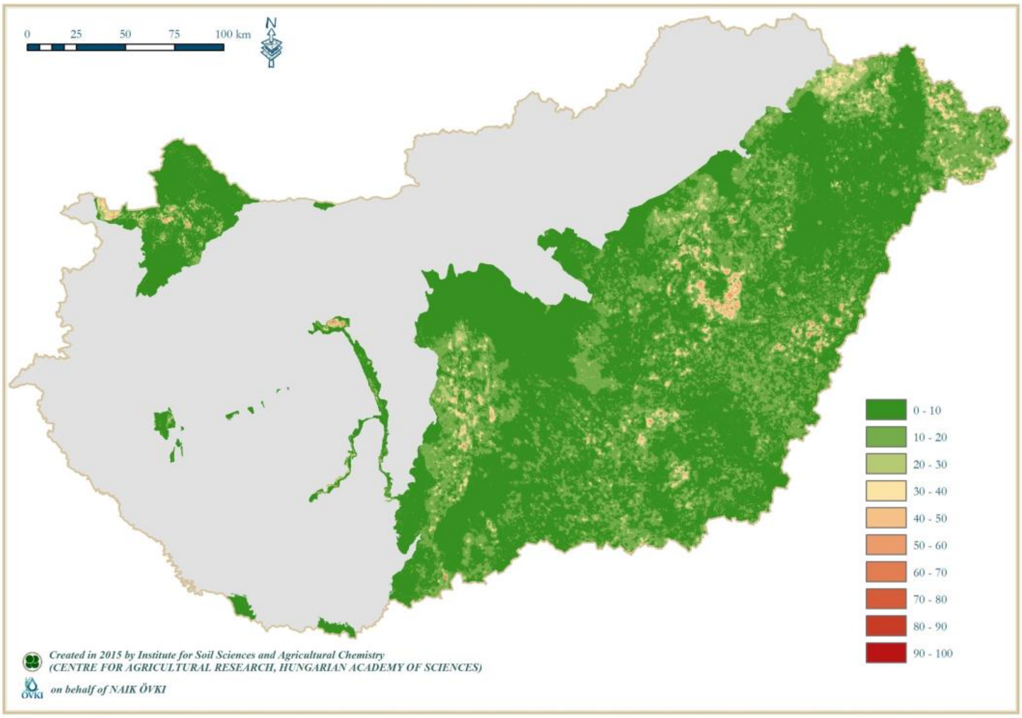


Figure 12: **Complex excess water hazard map** (Source: Bozán et al., 2017:47)

4.1.6. Poland

The review of the literature shows that in the context of flash flood hazards, the following physiographic factors can be crucial: oval shape of the basin, significant terrain and riverbeds inclination, concentric structure of rivers course, large surface covered by synthetic materials, high humidity and vulnerability to mass movements (Pociask-Karteczka and Żychowski, 2014). The increase in flood hazards in the recent years is among other things connected with constant changes – mainly related to the reduction in natural water retention, intensification of urbanization processes and not sufficient control over their environmental results (synthetic surface). They cause disadvantageous changes in water discharge structure in the basins (Romanowicz et al., 2014). The research showed that in the mountain areas (Carpathian region) flash floods caused by intensive and short-lasting precipitations are predominant in the basins smaller than 40 km^2 (Bryndal, 2014).

For the Carpathian region the areas vulnerable to flash flood occurrence were selected among others with the use of Terrain Vulnerability Index (Wpt). The basins were given ranks depending on their vulnerability to sudden water level increase (Bryndal, 2015). In the process of the identification of the basins that are the most vulnerable to flash floods, numerous aspects were considered: impact of physiological parameters of the basin on sudden water level increase, transformation of the precipitation into effective precipitation and reaction of the basin to the precipitation (Bryndal, 2014). A higher value of the Wpt means a higher vulnerability of the region to the occurrence of flash floods.

$$\mathbf{Wpt = PrA \cdot 2 + PrB \cdot 1 + PrC \cdot 3}$$

with

PrA, PrB, PrC – percentage of the area (geographic regions, districts) covered by identified catchments types (catchments type A, B, C) prone to flash floods

1, 2, 3 – the ranks of the identified catchments types; ranks depending on vulnerability to formation of flash floods; higher rank means higher type of vulnerability to the occurrence of flash floods

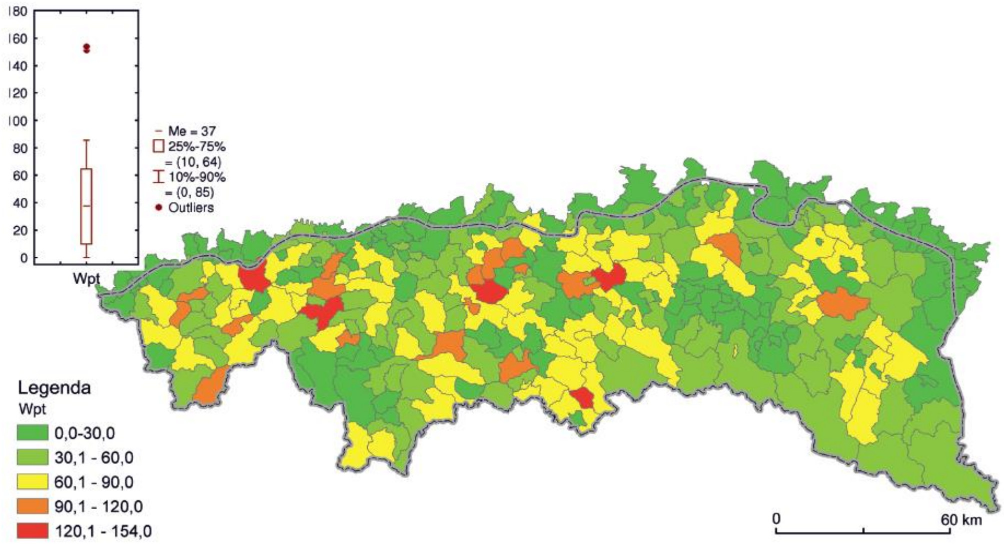


Figure 13: **Terrain Vulnerability Index (Wpt) in districts located in the Polish Carpathians**
(Source: Bryndal, 2014)

4.2. Chapter summary and conclusions

Several GIS methods have been explored and applied in different European countries regarding the identification of possible hazard areas to pluvial flooding (Table 2). Rolling ball or D8 analysis is one of them, others additionally use several characteristics of the basin for the identification of potentially significant hazard zones. In some countries expert judgement also enters the identification process.

Overall, even though this research field seems to be rather new (only a few years in broader consideration), applications are being done. In some countries, methods have been specified for administrative purposes.

Table 2: **GIS methods applied**

Method	Principles	Expert judgement	Application level	Application purpose and scale	Country
D8	Rolling ball	Yes	Catchments outside settlements	APSFR identification; national	AT
Critical points	Topgraphy land use	Yes	Catchments outside settlements	APSFR identification; national	CZ
RISA	D8 + sewer system overflow	-	Urban areas	Pilot areas	DE
Geostatistical kriging	Hydrometeorology, relief, soil, geology, groundwater, land use	Yes	Catchments outside settlements	Identification of hazardous areas, lowland areas (pilot)	HU
Terrain Vulnerability Index (Wpt)	physiographic parameters, land use, soil	-	Catchments, geographic regions, districts	Pilot areas	PL

5. Modelling

In this chapter, the findings regarding surface flood modelling tools and approaches are contained. Modelling is generally a very broad topic with quite a number of possible different approaches. Additionally, the applied starting conditions and boundary conditions are usually relevant for the obtained results.

5.1. Country Examples

5.1.1. Austria

In Austria, 2D hydrodynamic simulations (e.g. FloodArea, Hydro_AS-2D) are applied on pilot scales. While the results outside settlements are considered as reliable, the results inside settlements are considered as less reliable because of disregard of small structures (e.g. sidewalk curbstones, plinth walls, etc.) and of urban sewage systems. Therefore a respective detailed on-site assessment (bridges, culverts, garden walls, etc.) is required especially for settlements. The advantages of 2D simulations is in vivid images, delineation of flooded area and water depth, discharge rates and volumes, and the possibility of alternative flow paths (overflow) (Haider, 2017).

Figure 14: **2D hydrodynamic simulation results**
(left source: Büro Pieler ZT GmbH and hydrosim consulting, 2014 cited in Haider 2017) (right source: Gamerith et al., 2017)

The following examples for regional pilot applications were found:

- For Styria, in 2017 in the frame of the rural development funding programme, specifications for hydrodynamic simulations for municipalities were prescribed. Around 15 municipalities applied for the funding and conducted 2D hydrodynamic simulations (based on ArcGIS and FloodArea) with T10 (flooded areas in build-up areas), T30 (functioning of sensitive infrastructure), T100 (basis for emergency management plans) and 30 min duration. The relevant simulation time had to be determined. Further specifications related to the improvement of the DTM, requirements regarding the areas with overview / detailed modelling, starting and boundary conditions (runoff coefficients, roughness, erosion). The aim of the funding was to obtain a concept of measures for the municipalities with numerically assessed effectiveness.

- In the frame of the EU research project SWITCH-ON, a flash flood hazard map was developed for Upper Austria. Based on 2D hydrodynamic precipitation-surface flow simulations (DGM with 25 m raster width, without manual adaptations) with design precipitation values from eHYD with T100 and 1 h duration, the maximum water depths are displayed in a raster format in an interactive map (see Figure 15 and cf. http://ffrm.hangwasser.at/).
- Additionally, the software Visdom (www.visdom.at) is available, which combines visualization, simulation, and analysis techniques to assist decision making for protection, preparedness, and emergency management.

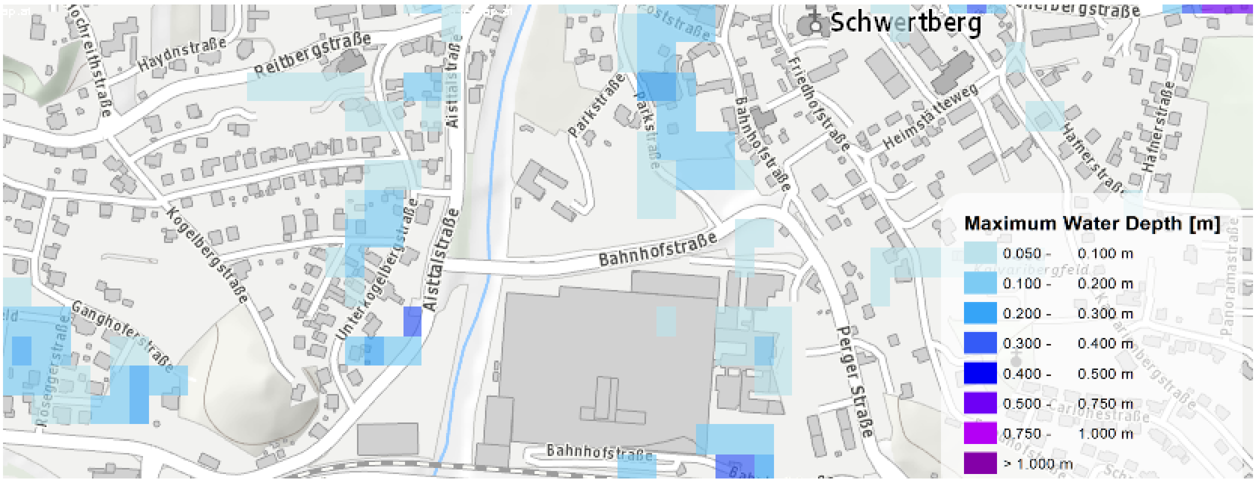


Figure 15: **Flash flood hazard map Upper Austria** (Starkregengefahrenkarte OÖ)
(Source: screenshot from Dipl.-Ing. Günter Humer GmbH, 01.06.2018)

However, with regards to the implementation of the EU Floods Directive, no regulation for hazard and risk modelling exists yet.

5.1.2. England and Wales

In England and Wales the Environment Agency conducted a project to obtain risk and hazard maps for pluvial floods by means of hydraulic modelling, which is described in Environment Agency, 2018. The following input precipitation was used: Occurrence changes of 1 in 30, 100 and 1000 years and storm durations of 1, 3 and 6 h. The storm durations are merged in a worst case scenario for each probability. The rainfall depth was determined for 5 km * 5 km tiles, which were divided in urban (more than 50 % man-made landscape) and rural squares (less than 50 % man-made landscape). A DTM for all of England and Wales with a resolution of 2 m was used as a basis for the hydraulic modelling. Building floors were raised by 0.3 m and roads were lowered by 0.125 m, bridges and other structures where added manually to ensure realistic flow paths. For the hydraulic modelling the commercial software JFlow+ 2D hydraulic model was used in 5 km * 5 km tiles, with a 500 m overlap to ensure no boundary problems were emerging. The model was validated in 3 pilot areas based on historical event and local modelling. Where compatible local models where available, they were merged into the national model. (Environment Agency, 2018) The outcomes of the model are hazards maps, which will be discussed in paragraph 6.1.5

In 2016 a guideline for the Lead Local Flood Authorities (LLFAs) was developed which describes the planned update for the flood maps produced in 2013. (Environment Agency, 2018) The Environment Agency encouraged the LLFAs to contribute their local model to the country wide model described in the previous paragraph. The guideline includes how LLFAs have to set up their local models to ensure compatibility with the national map. To be compatible and suitable for inclusion in the national map, locally produced information should, as a minimum:

- include a flooding scenario with 1 in 30, 1 in 100 and 1 in 1000 chance of occurring (in any year), calculated with the same model.
- include flood extent, depth, velocity, and flow direction data (wherever possible hazard data should also be included)
- take into account the deflection effect of buildings and sub-surface drainage
- use a model grid size no larger than 5 m
- provide the best representation of flood risk within the LLFA area (compared with historic flooding information)
- have an equal or higher confidence score than the existing mapping

A detailed description of the needed data and the required formats is given. (see Environment Agency, 2018)

5.1.3. Germany

In the German federal state of Baden-Wurttemberg a guideline for risk and hazard mapping for pluvial floods was developed by the local government: "Leitfaden Kommunales Starkregenrisikomanagement in Baden-Württemberg" (Landesanstalt für Umwelt Baden-Württemberg, 2016). Municipalities in Baden-Wurttemberg are encouraged to develop risk and hazard maps by means of hydraulic modelling, at a funding rate of 70 %. It is recommended that a 2D hydraulic model is used to produce the risk maps for pluvial floods, where the modelled area (watershed) can be maximum 5 km^2. From 2001 to 2004 a Laserscan campaign was conducted by the "Landesamt für Geoinformation und Landentwicklung Baden-Württemberg" which formed the basis for the state-wide hydraulically modified digital terrain model HydTERRAIN. HydTERRAIN can be used as a basis for the hydraulic model, but it has to be adapted to the local situation. The guideline describes which input data has to be used and which scenarios should be calculated (rare, extraordinary, and extreme). Is it recommended to calculate the model for 5-minute intervals with a storm duration of 1 h and a time lag of 1 h. No recommendations are given towards the software that can be used for the hydraulic modelling. The results of the modelling are used to produce risk and hazard maps, see paragraph 6.1.6.

In the federal state of Bavaria a similar guideline to assess the hazards and risks from flash floods was developed. (Bayerisches Staatsministerium für Umwelt und Verbraucherschutz, 2017) The guideline also includes chapters on vulnerability and measures, however in the present scoping study only the chapter on hazard maps is discussed. The requirements for the hydraulic modelling are listed below:

- The modelling has to be done for at least the following precipitation probabilities: 30, 50, 100 and 1000 years.
- 2D hydraulic modelling on the basis of a 1 m DTM
- The initial situation with respect to the soil moisture should be adapted to the precipitation scenario.
- The roughness should be adapted according to the water depth.
- The model should be adapted with respect to sewer systems, urban planning etc.
- For each precipitation scenario a map with water depth and flow velocities should be made.

- For each scenario an animation in 5 minute intervals should be made.

Municipalities in Bavaria are encouraged to develop risk and hazard maps by means of hydraulic modelling and can apply for funding.

In the Federal State of Bremen the project KLAS with a focus on climate adjustment ("Klimaanpassungsstrategie") was started in 2011. The focus of the project was to prepare the city of Bremen for extreme precipitation events. Three areas of interest were defined:

- Flood protection and risk management,
- Water and climate sensitive urban development and
- Improving the self-provision of land owners.

One of the outcomes of the KLAS project was a guideline on hydrodynamic modelling of pluvial floods (Hochschule Bremen, 2017). The guideline discusses three different kinds of models:

- Sewer system models,
- Surface models and
- Combined sewer system and surface models.

For each of the three model categories the uncoupled as well as the coupled version are compared to each other in terms of required data, recommended application and output. Because this guideline is used as a basis for almost all other German guidelines, with respect to hydraulic modelling, the six different possible model configurations will be elaborated in Table 3 below.

Table 3: **Summary of model configurations described in the KLAS guideline** (Hochschule Bremen, 2017, translated from German)

	Uncoupled calculation			coupled calculation		
	Sewer system model	Surface model	combined model	Sewer system model	Surface model	coupled model
Summary	Discharge is calculated by sewer system model. Overflow is virtually buffered until there is enough discharge capacity in the sewer system	Discharge is calculated by surface model.	Two runs of surface model: one with overflow from the sewer system and one without. Overflow from sewer system are represented by wells in the surface model. Volume is calculated by stand-alone sewer system model.	In case of overflow of the sewer system, the flow is calculated by the surface model. Excess water can flow back in the sewer system	Discharge is calculated by surface model. The sewer system model functions as transport and storage medium. Water can flow from the sewer system back into the surface model.	Discharges are represented by both the sewer system and surface flow model. There is constant interaction between both models
Precipitated areas	Effective precipitation flows in sewer system	Each model element in every time step	Each model element in every time step	Effective precipitation flows in sewer system	Each model element in every time step	Each model element in every time step
Results	Flow velocity and water levels in	Flow velocity and	Flow velocity and water levels at the	Flow velocity and water	Flow velocity and water levels in	Flow velocity and water levels in

	sewer system Overflow volumes	water levels at the surface	surface	levels in sewer system and at the surface Overflow volumes influenced by surface flow	sewer system and at the surface Overflow volumes influenced by surface flow	sewer system and at the surface Overflow volumes influenced by surface flow
Notes	Possible overestimation of discharge in sewer system Estimation of water levels at the surface only possible with overflow volumes	In areas where the sewer system has an influence on the flooding processes, the flooding probability might be under or over estimated	The overlaying of the results tends to overestimate the overland flow	Possible overestimation of discharge in sewer system Flooding results only from overflow from the sewer system	Because the discharge is calculated in the surface model, the discharge on the surface might be overestimated and the discharge in the sewer system under estimated	Due to the spatially distributed approach, the results are closest to the real situation Large data and calculation requirements
Applicati on	Design of sewer systems Mapping of flooding processes not possible	Display of flooding processes in case no sewer system model is available	Display of flooding processes in case the area is too big for a coupled sewer system model and information about overflow volumes are available	Display of flooding processes for small to medium catchments	Display of flooding processes for small to medium catchments	Display of flooding processes for small to medium catchments

This guideline includes a sensitivity analysis, which describes the influence of sidewalks, walls, the height of man holes and raster size of the DTM on water levels. The general conclusion of the sensitivity analysis is that walls have the biggest influence on the water levels. For each application a trade-off between accuracy and investment has to be made. The key points of the different models are summarised in the table below.

The KLAS guideline also includes a chapter on deciding which kind of model to use. The flowchart below displays the decision tree.

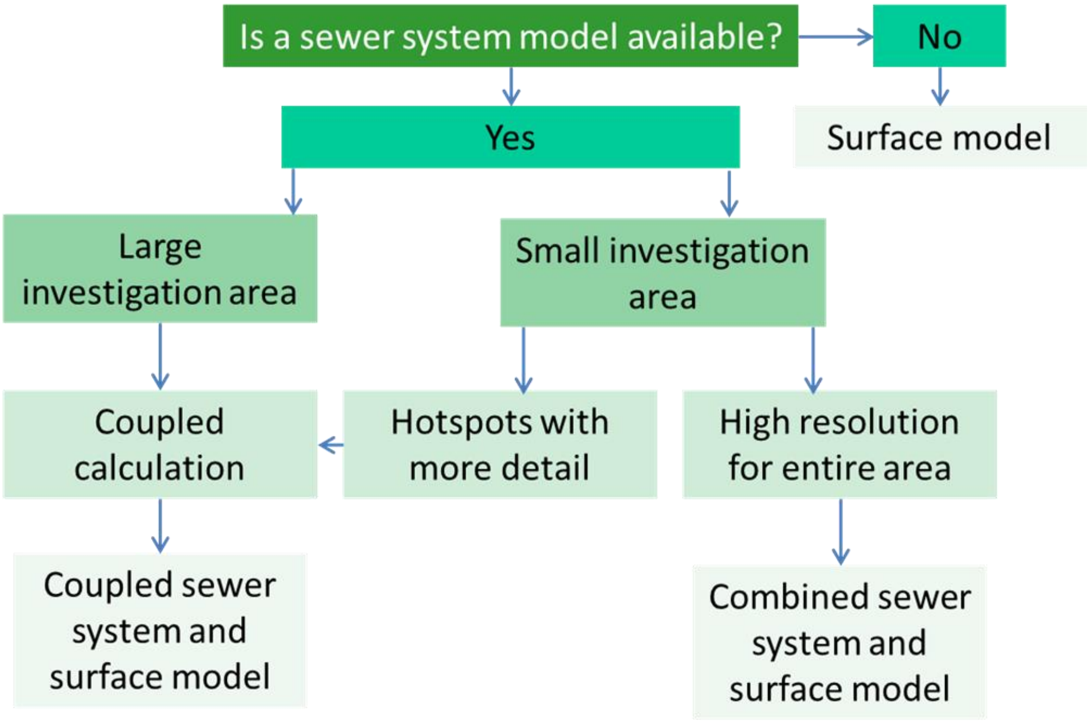


Figure 16: **Decision tree from the KLAS guideline**
(Hochschule Bremen, 2017:5, translated from German)

In the German guideline DWA-M119 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., 2016) different methods to establish hazard maps are discussed. Regarding modelling 4 different methods are proposed.

- The first method is the hydraulic simulation of the sewer system and the overflow volumes associated with heavy rain events.
- The second method builds on the rolling ball analysis and is called "static volume assessment". In this approach the depressions in the terrain are filled up with surface run-off from a design storm. The transfer of excess water in case a depression is fully filled is not considered. With this method the water level along the flow paths cannot be defined. It is also possible to use the overflow volumes from the sewer system in a spicific depression to calculate the water level in the depression. The result of this method is a layout of flooded areas for a specific design storm with corresponding water levels.
- The third method is the "street transect method" in which the discharge in the streets is calculated. The results of the rolling-ball analysis and information on street profiles are necessary. The results of this method consist of critical points were water from the street enters buildings or sites.
- The fourth and last method consists of different variations on 2D hydraulic simulations, which are described in the paragraph on the KLAS project in more detail.

The methods described above can also be found in "Starkregen und urbane Sturzfluten– Praxisleitfaden zur Überflutungsvorsorge" (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., 2013) and „LAWA-Strategie für ein effektives Starkregenrisikomanagement" (Bund/Länder-Arbeitsgemeinschaft Wasser, 2018).

5.1.4. Hungary

According to the information provided by the Hungarian partners, the HEC-RAS software is used for 2D runoff modelling in Hungary.

5.1.5. The Netherlands

In the Dutch city of Noordwijk a comparison between different modelling techniques in areas with a different topographic profile was carried out. The GIS flow path (rolling ball) technique was compared with a coupled 1D-2D model. The modelled storm was 60 mm for 1 h, for the GIS model it is assumed that the sewer system has a capacity of 20 mm/h. Three different areas were selected, an old city centre in the dunes, a living area in the transitional area and a flat living area. In the old city centre, both the GIS-model and the coupled 1D-2D model predict flooding for most of the known vulnerable locations. In the transitional area the flooding predicted by the GIS-model is lower than with the 1D-2D simulations. Also the vulnerable locations are not detected with the GIS-model. In the flat living area, both model outcomes are very comparable and the vulnerable locations are detected by both models. This case study shows that the used GIS-technique is suitable to conduct quick scans for urban pluvial flooding in most situations.

5.1.6. Poland

In Poland, hydrological models (e.g. HEC-RAS, MIKE 11, MIKE 21) are applied for simulation of the flooded area. Examples of application:

- 1-dimensional (1D) models were applied to simulate a pluvial flood event in an ungauged basin. The 1D hydrological models were used for determining the flood hazard areas e.g. in the Stobnica river basin (Walega, 2013) and in the area of the Upper Vistula River basin (Gądek and Bodziony, 2015).
- A 1-dimensional (1D) model was applied for simulation of the impact of afforestation on the runoff from the catchment and reduction of flood risk by increasing the retention in the catchment (Bogusz and Tokarczyk, 2016),
- In the frame of the ISOK Project (IT System of the Country’s protection against extreme hazards), (www.isok.gov.pl) 2D hydrodynamic simulations (e.g. MIKE 21) were applied for certain conditions, especially for urban areas (simulation of water movement and water depth in the floodplain). A 2D model was applied also for the simulation of the flood in the Nysa Łużycka river basin in August 2010 (Banasiak, 2012).

5.1.7. Switzerland

In Switzerland a country wide hazard map for pluvial flood is currently being developed, using the software FloodArea, which is a GIS-based 2D hydraulic model. (Bundesamt für Umwelt, 2018)

5.2. Chapter summary and conclusions

Modelling approaches for pluvial flooding were found in several countries (Table 4). While some countries have already delivered national or federal approaches fixed in guidelines (England, Wales, several Federal States in Germany, elaborated approximately since 2010), other countries like Austria or the Netherlands have made pilot activities in order to investigate which methods (GIS versus hydraulic simulation) deliver results with reliable quality and with affordable effort (digital terrain model resolution, manual adaptations of DTM?) in individual situations (terrain or catchment characteristics, soil saturation, roughness coefficients, existence of sewer systems). Also the quality of the simulation programs seems still to be a topic of interest, as codes have improved over the past years. Depending on the complexity of the situation and on the requirements regarding the result quality, simulations range from GIS models over hydraulic surface flow modelling to coupled surface / sewer models.

Table 4: **Overview of model assumptions and boundary conditions for national / regional approaches**

Case study	DTM resolution	Model time	Modelled area	Run-off coefficient	Model output
DE (Baden-Wurttem-berg)	0.8 p/m^2	Event + 1 h	< 5 km^2 catchments	Statistical analysis University Freiburg	Flooded area, water depth, flow velocity
DE (Bavaria)	1 m	Not specified	Not specified	Not specified	Flooded area, water depth, flow velocity
GB England/ Wales	2 m	Event + 3 h	5 km by 5 km tiles, 500 m overlap	Revitalised Flood Hydrograph, SERIES Hydrology, manning	Flooded area, water depth, flow velocity
HU	10 m * 10 m	Not specified	Not specified	Not specified	Flooded area, water depth, flow velocity
PL	1 km	1 h	Not specified	Not specified	Flooded area, water depth
CH (Kanton Luzern)	1 m	2 h	Between 50 km^2 and 160 km^2	Based on Rickli and Forster, (1997), modified with Scherrer & Naef (2003) and slope correction	Flooded area, water depth

6. Hazard Maps

Hazard mapping is a powerful communication means for several purposes, e.g. administrative purposes and for raising awareness with the broad public. This chapter summarises the findings related to pluvial flood hazard mapping. In this section, different approaches shall be accounted for:

- hazard mapping displaying flooded areas, water depths and/or velocities, and
- indicative hazard maps (flowpath)

This is due to the fact that both approaches deliver helpful information for administrative purposes and for awareness raising purposes. However, with respect to the Floods Directive implementation, the reporting of flood hazard maps requires flood extents, and, where appropriate, water depths and velocities.

6.1. Country Examples

6.1.1. Austria

In Austria, no nationally agreed method for the mapping of pluvial hazards exists yet. However, some federal countries have published indicative hazard maps:

- For the Federal State Lower Austria, indicative hazard maps based on GIS analyses are published with blanket coverage in the Lower Austria Atlas (http://atlas.noe.gv.at/webgisatlas//init.aspx?karte=atlas_hochwasser&cms=atlas_wasser).
- Also for the Federal State Styria, results of the GIS-analyses of flowpaths are publicly accessible in the Styrian Digital Atlas (http://gis2.stmk.gv.at/atlas//init.aspx?karte=gew&ks=das&cms=da). The city of Graz has also published a flowpath map (https://www.graz.at/cms/beitrag/10295894/8115447/Online_Karte_Fliesspfadkarte.html). With regards to the pluvial risk modelling done in 2017 in the frame of the rural development funding programme, map specifications were not standardised, and produced maps are not published, but remained with the municipalities.
- For the Federal State Burgenland, a registration is needed, before indications for pluvial floods are publicly visible in the Federal Web-GIS System. (cf. Habersack et al., 2018).
- Additionally, hazard maps covering the federal state Upper Austria and displaying flood extent and water depths were produced in the frame of the EU project SWITCH-ON (http://water-switch-on.eu/) and are publicly accessible (see Figure 15 and cf. http://ffrm.hangwasser.at/).

6.1.2. Belgium/Flanders

For Flanders the flood hazard map was updated in 2017. The hazard map is available to the public under the following link: http://www.waterinfo.be/default.aspx?path=NL/loketten/geoloket.

The hazard map shows the combined potential hazard for fluvial and pluvial flooding in the map layer “Overstromingsgevoelige gebieden 2017”. The potential flooding hazard is divided in two categories: effective flooding area and possible flooding area. There is also a map layer that shows the difference between the 2007 and the 2017 areas “Risicozones overstromingen 2017”. No information on the methods used to establish the hazard maps could be found.

6.1.3. Croatia

Croatia, in the framework of Flood Risk Management Plan, has provided flood hazard maps for the whole territory, covering fluvial and pluvial floods integrated on the same map with other flooding sources (http://korp.voda.hr). The main elements of methodology are based on hydraulic simulation for fluvial floods and developed in the EU Twinning project "Development of Flood Hazard Maps and Flood Risk Maps" finished in April 2014. However, depending on circumstances, flooding sources, flooding mechanisms and data available use of other more suitable approaches are allowed.

6.1.4. Czech Republic

Determination of Critical Point and their contributory areas (Chapter 4.1.3) for the whole territory of the Czech Republic is localisation of pluvial flood hazard. The resulting hazard map (Figure 17) is available on the povis.cz portal.

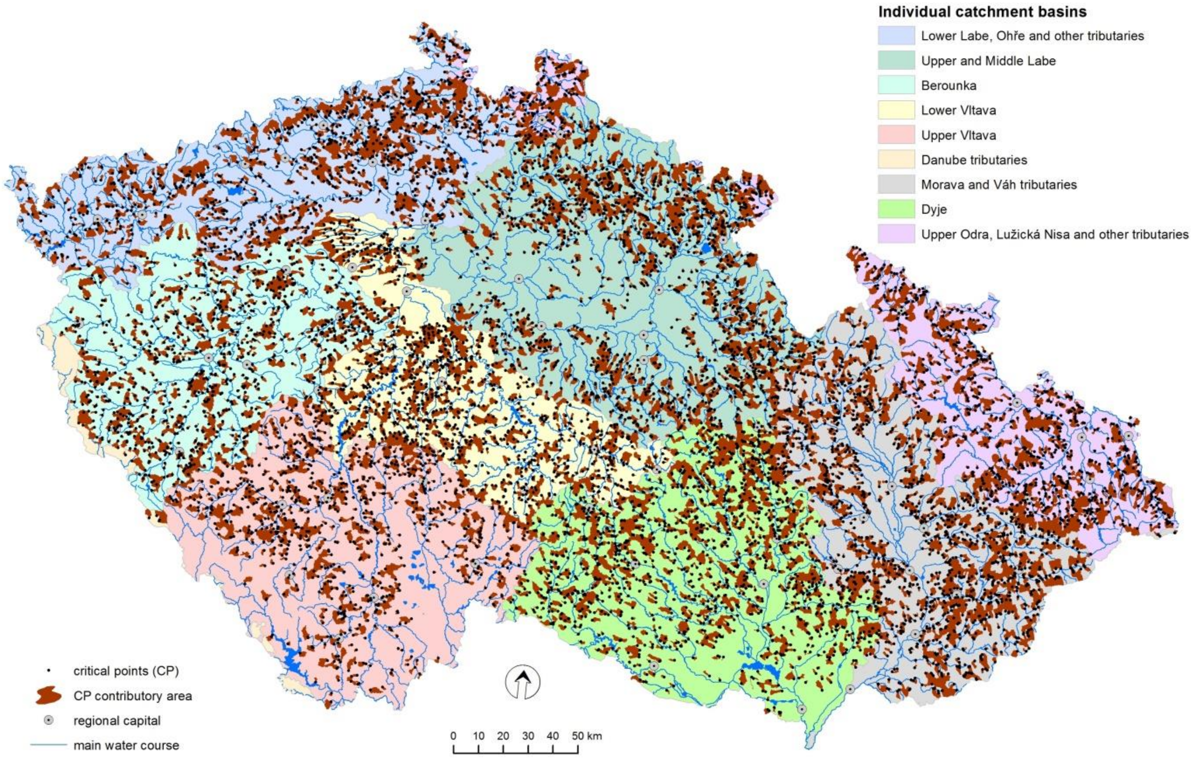


Figure 17: **Identified critical points and their contributory areas within CZ**
(Source: Povodňový informační system)

Information on the localization of individual critical points and their contributory areas is a useful basis for the proposal of complex land consolidation, or within landscape planning – i.e. on a "local level".

6.1.5. England and Wales

The output of the in 2013 conducted modelling for England and Wales can be found online under URL https://flood-warning-information.service.gov.uk/long-term-flood-risk/map. On this website the flood hazard maps for flood risk from rivers, surface water and reservoirs can be viewed. In a basic view of the surface floods, the flood extent is displayed in 4 categories (very low, low, medium and high). In a detailed view the flow velocity and water depth for low, medium and high flood risk can be viewed. The flow velocity is divided in two categories (below or above 0.25 m/s), the water depth is divided in three categories (below 300 mm, between 300 and 900 mm and over 900 mm).

6.1.6. Germany

In the guidelines for risk and hazard mapping for pluvial floods developed by the federal state of Baden-Wurttemberg (Landesanstalt für Umwelt Baden-Württemberg, 2016) and the federal state of Bavaria (Bayerisches Staatsministerium für Umwelt und Verbraucherschutz, 2017) also recommendations for hazard maps are given. Hazard maps should be made for all precipitation scenarios. Water depth should be represented in the following categories: 5-10 cm, 10-50 cm, 50-100 cm and > 100 cm. The flow velocity should be displayed in the following categories: 0.2-0.5 m/s, 0.5-2 m/s, > 2 m/s. In addition a map with the maximum flood extent should be made.

Yet, hazard maps are publicly available only for areas of limited geographical extent (mostly municipalities):

- City of Cologne in North Rhine-Westphalia
  http://www.hw-karten.de/index.html?Module=Starkregen
  Computer analysis based on a high resolution digital terrain model (1 m * 1 m) without consideration of subsurface structures. Water depths out of 3 different precipitation scenarios are simulated.
- City of Unna in North Rhine-Westphalia
  http://starkgegenstarkregen.de/starkregenkarte/
  Water depths were derived from a GIS based hydrodynamic model (FloodArea) with a precipitation load of 90 litres per hour.
- Glems Catchment in Baden-Wurttemberg
  http://www.starkregengefahr.de/glems/gefahrenkarten/starkregengefahrenkarten/
  Water depths derived from a GIS based hydrodynamic model (FloodArea) with 3 different precipitation scenarios (60, 120, 240 mm/h).

Apart from the local applications, the German Weather Service together with the German Insurance Association initiated a project to develop a country wide heavy rain risk map. The goal is to combine radar based precipitation analyses and topographic information (hazard) with damage data (vulnerability) to derive the heavy rain risk for each postal address in Germany (Gesamtverband der Deutschen Versicherungswirtschaft e. V., 2017). This information will be made available via the information system "ZÜRS public" under the URL http://www.kompass-naturgefahren.de for private house owners to inform themselves about their exposure towards natural hazards.

6.1.7. Hungary

Hungary has a nationally agreed method for the mapping of pluvial hazards (see Chapter 4.1.5 and https://www.vizugy.hu/index.php?module=vizstrat&programelemid=145)

6.1.8. Poland

The problem of heavy precipitation and pluvial flash flood hazards was one of the tasks realised in the project KLIMAT "Impact of climate change on environment, economy and society. Conclusions for science, engineering and spatial planning" (Instytut Meterologii I Gospodarki Wodnej Państwowy Instytut Badawczy, 2012). Within this project, activities concerning the presentation of flash flood events in GIS standard were undertaken. The base was the hydrographic map of Poland (MPHP). Catalogues of heavy rainfall and flash flood events were developed on the basis of hydro-meteorological data (1971-2010), media information and other sources. These catalogues and historical data were the basis for the map layers related to heavy precipitations and flash floods hazard in GIS standard (Figure 18). Maps illustrating the spatial distribution of flash floods in Poland for 1971-2010 were carried out (Figure 19). The regions characterised by the most frequent flash flood occurrence were shown in both basin and administrative structures (Ostrowski et al., 2012; Lorenc et al., 2012).

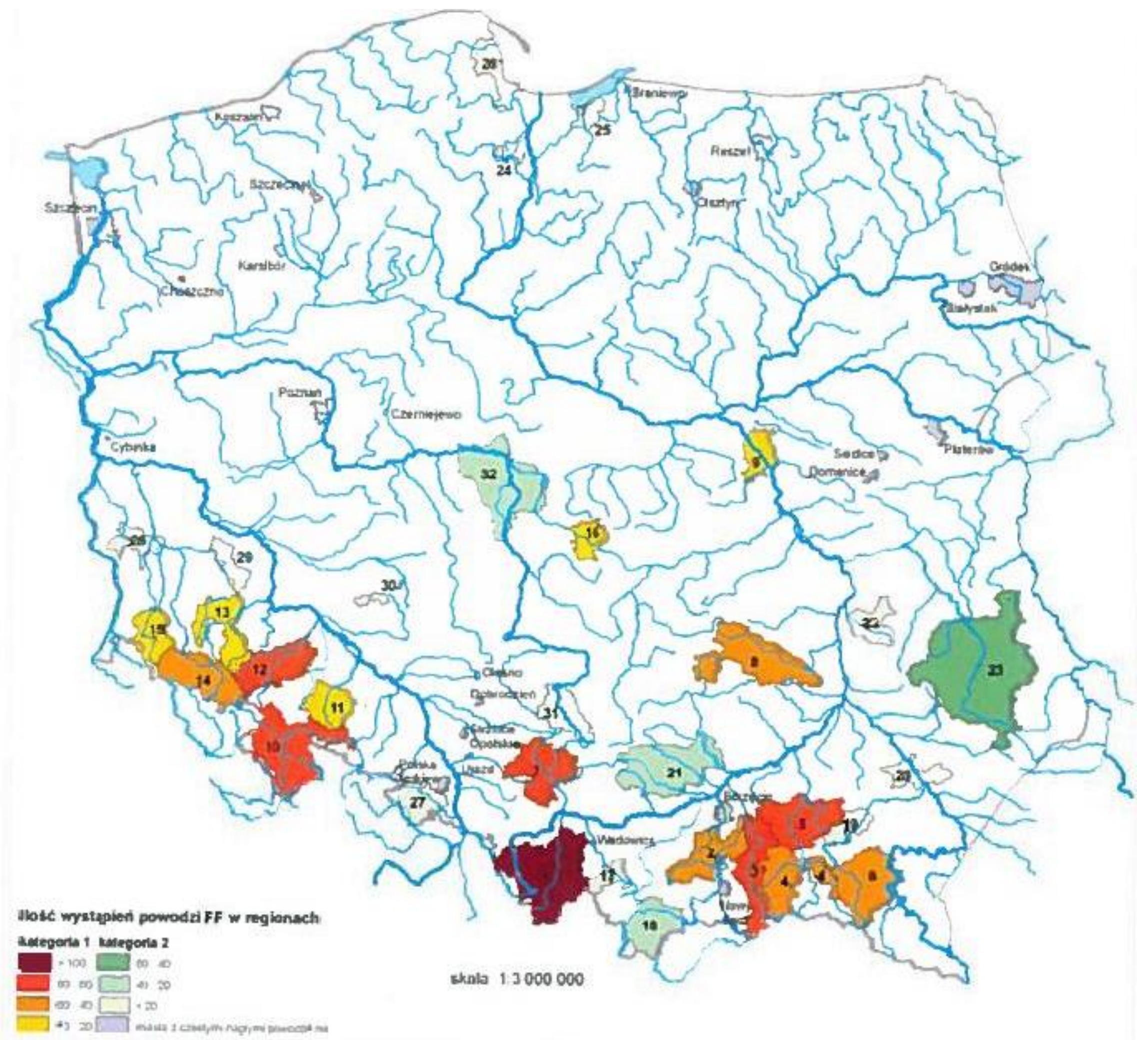


Figure 18: **Areas of the most frequent flash flood events in Poland in 1971-2010**
(Source: Ostrowski et al., 2012)

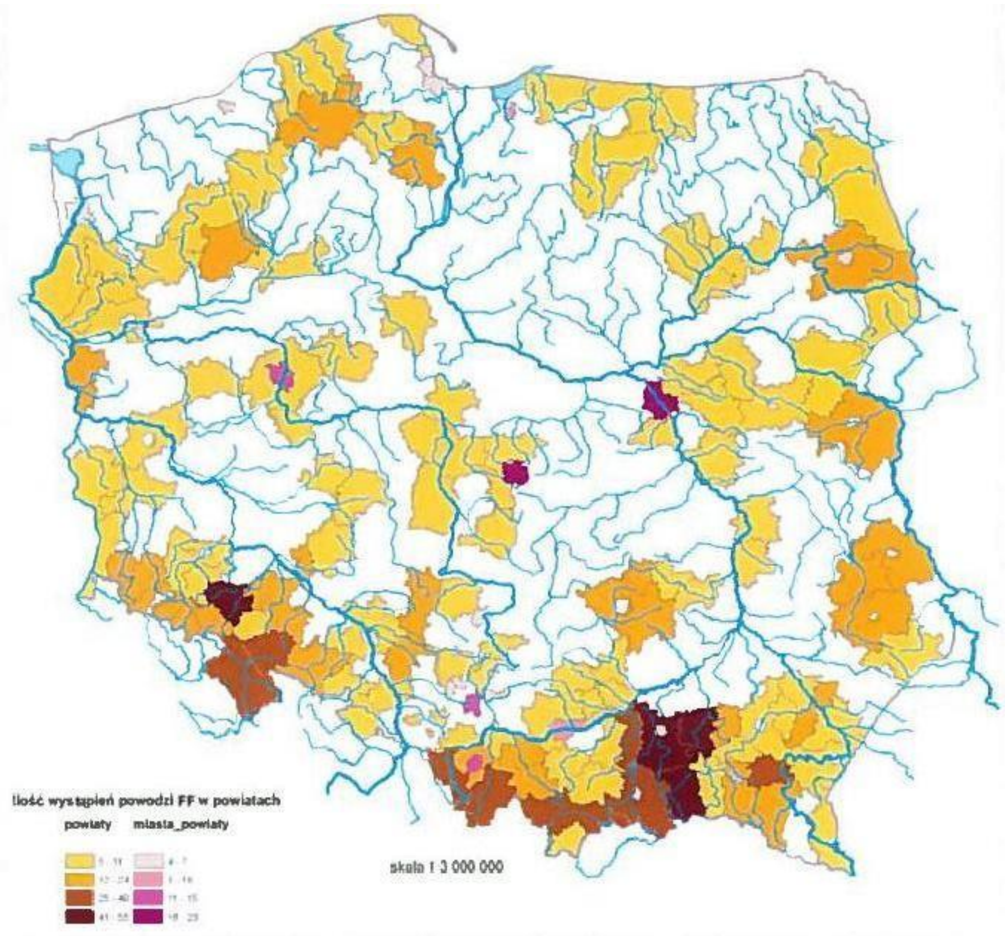


Figure 19: **Districts with the highest flash flood hazards in 1971-2010**
(Source: Ostrowski et al., 2012)

6.1.9. Switzerland

In Switzerland a country wide hazard map for pluvial flood is developed in 2018, but not yet published (as of 26.06.2018). Some information on content is already available on a page with general information about the topic. The maps will most likely be accessible from here: https://www.bafu.admin.ch/bafu/de/home/themen/naturgefahren/fachinformationen/naturgefahrensituation-und-raumnutzung/gefahrengrundlagen/oberflaechenabfluss.html, for the Kanton Luzern a map and further technical information is available here: https://www.geo.lu.ch/map/oberflaechenabfluss/.

6.2. Chapter summary and conclusions

Hazard maps are already available for pluvial flooding (Table 5). First countries have elaborated and published maps on national levels (England and Wales, Switzerland) with nationally agreed specifications, in other countries (e.g. Germany, Austria) maps can be elaborated based on regional approaches. Generally, mapping specifications seem to be an area of discussion still.

Table 5: **Hazard maps summary**

Map purpose	Map scale	Hazard information	Classes	Application scale	Countries
Awareness raising		Flood extent, water depth, velocity	Depth: 0-300 mm / 300-900 mm / > 900 mm, velocities: < 0.25 m/s, > 0.25 m/s	National	GB: England and Wales
Awareness raising		Flowpath: related catchment size; medium slope, …	Catchment sizes: 0.05-1 ha, 1-10 ha, 10-100 ha, > 100 ha	Regional, local	AT: NÖ, OÖ, Bgld., Graz
Awareness raising / insurance companies	Until 1:2,500	Flood extent	Effective flooding area/possible flooding area	Regional	BE: Flanders
Awareness raising	Until 1:12,500	Flood extent, water depth	Depth: < 0.10 m / 0.10 m - 0.25 m / >0.25 m	National	CH
Awareness raising /national legislation	Different	Flood extent, water depth, hazard	Effective flooding area/possible flooding area	Regional, hazardous area	HU
FRM, Awareness raising, self-provision	1:2,000 (Cologne), 1:5,000 (Glems)	flood extent, water depth	Depth: < 5 cm, 5 cm - 50 cm, 50 cm - 100 cm (Unna), < 6 cm, 6 cm - 60 cm, 60 cm - 100 cm, > 100 cm (Glems), low, moderate, high, very high (Cologne)	Local/regional	DE

7. Summary and conclusions

7.1. Discussion of approach

The most difficult part of the scoping study was to decide which documents and methods shall be included and which ones shall be left out. The chapters on design precipitation and detailed precipitation measurements were included because the results from both design storms and detailed precipitation measurements can be used to designate areas at risk or produce hazard maps. Furthermore the results can be used as input for either GIS-based methods or hydraulic modelling, therefore it was considered appropriate to include information on these two subjects. Especially in the field of modelling a lot of scientific case studies are available, these case studies were only included if they were used in guidelines or provided a comparison between different methods. When a method was found in multiple documents, the document in which the method was developed was described in detail, the other documents were not considered further.

7.2. Summary of available methods

Overall, the systematic approach from public administrations to the topic of pluvial floods is comparably new in most European countries. Few countries already provide nationally or federally agreed approaches which are fixed in guidelines. Other countries are still in an investigative phase. This scoping study shows that the topic of pluvial flooding is getting attention in administrations, however, the processes of establishing agreed methods seem to be at least in today’s discussion or already in progress. Therefore, the timing for this scoping study is considered to be very good in order to summarise the very recent activities in the European countries, and therefore this scoping study may help countries with less progress on the topic in finding good practice examples of pluvial floods modelling. An overview is given in the table below. Additionally, in the annex a list of simulation model descriptions (not exhaustive) is provided, which might be useful if countries investigate pluvial risk assessment and mapping possibilities.

Table 6: **Summary of available methods**

Method	Data requirements	Implementation effort	Application scale	Usage	Countries
Previous events	Low	Low	Regional, national	Regional, national	PL
Rolling ball (D8)	Low	Low	Regional	National	AT
Critical points	Medium	Low	National	National	CZ
RISA flood hazard assessment	Low-medium	Low-medium	Regional	Urban environments	DE
Static volume assessment	Low-medium	Low-medium	Regional		DE
Street transect method	Medium	Low-medium	Regional	Urban environments	DE
Sewer system modelling	Medium	Medium	Local	Urban environments	DE

Hydraulic modelling (surface)	High	High	Local	Regional, national	UK, DE, HU
Geostatistical kriging	Medium	Medium	National	National	HU
Coupled modelling	High	High	Local	Urban environments	Pilot areas

7.3. Conclusion for the guidance tool on assessment and mapping of heavy rain risk

Already in the WG F Workshop in 2016, the following content-related conclusions relevant for RAINMAN were made:

- *"… approaches and methods for urban and rural hazard and risk maps on pluvial flooding are not identical but build on the same basis. … Even if there are similarities the urban and rural specifications have a different scope and require a different level of detail. The adequate approaches reflect different conditions and local needs, also regarding the communication and emergency response. Availability of data is nevertheless a decisive factor for processing, accuracy and result. … importance of local expert knowledge and of the variation of the several parameters involved."*
(Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2017:20)
- *"… great care has to be taken to proper communication of the information. Communication of PF maps to the users of the maps is crucial, to avoid wrong interpretation and to raise attention and awareness of the recipients. Generally the way of communication of the findings from mapping, including the level of detail, depends on the audience targeted (e.g. national vs. local level, authorities vs. individuals). It was pointed out that different channels of information should be used and findings need to be well explained, with special emphasis on the consequences and actions resulting from the findings. For example, local authorities generally require more detailed mapping to use them for planning decisions, than the general public. The targeted explanation of the meaning of the maps and of the ideas expressed by them also helps to avoid misinterpretation and misunderstandings. …"*
(Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2017:20–21)
- *"… maps are also an important tool of emergency management, serving as a basis for community and private planning as well as for the communication between stakeholders (e.g. municipalities). Emergency management as target group of PFHRM should be considered in the mapping design and processing …."*
(Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2017:21)

RAINMAN will take up these issues and provide approaches in further deliverables and outputs. With regards to the RAINMAN Scoping Workshop in 2017 in Vienna, similar issues were concluded (Spira, 2017:6):

- *"What's good enough?*
One of the fundamental aspects the RAINMAN consortium needs to consider is the level of detail for the mapping. As simulations and models will never provide a 100 % correct map, the project partners need to agree on reasonable scale and level of detail."

- *"How to communicate uncertainties?*
  From the beginning on, communication activities have to be considered when developing project outputs. With regards to risk assessment and mapping, uncertainties will be a challenge that needs to be addressed in the toolbox."
- *"Which approach and scenario to take?*
  From the beginning on, communication activities have to be considered when developing project outputs. With regards to risk assessment and mapping, uncertainties will be a challenge that needs to be addressed in the toolbox."

Also these issues will be addressed in RAINMAN, possible approaches and best practice examples will be put together and published in further outputs and deliverables.

Overall, with a view to the RAINMAN Activity "Method development for assessment and mapping if risk zones for heavy rain risks" it can be concluded from this Scoping Study, that *"data availability and quality might differ very much in the different CE Member States, and the phenomenological characteristics of pluvial flooding might be just as manifold. Therefore, the approaches shall be suitable for the regionally available data and the regional specificities that have to be accounted for. Consequently, assessment methods shall be coordinated in RAINMAN rather than harmonized.*

With regards to mapping, the same approach shall hold; the approach chosen shall be suitable to the special regional characteristics and to the assessment methods they are based on."
(Spira, 2017 [unpublished])

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9. Annex – Model descriptions

For the reader's information, a short overview on existing models shall be given in Table 7. It is noted that this list is not exhaustive.

Table 7: **Overview of available software (not complete)**

Model	Dimensions	Surface /sewer?	Principles	Application
Automatic Overland Flow Delineation (AOFD) tool	Creates 1D model of the surface	Surface	Rolling and bouncing ball	Input files for hydraulic models Coupling with 1D sewer system models
SWMM	1D	Sewer	Physically based	Designing and sizing of drainage system components for flood control.
InfoWorks CS-2D/ ICM	1D-2D	Sewer and Surface	Physically based	Hydrological modelling of the complete urban water cycle
Sobek 2DFLOW	2D	surface	Physically based	Overland flow (compatible with Sobek-Urban)
Sobek 1DFLOW(Urban)	1D	Sewer and surface	Semi-distributed	Urban planning, real time modelling (compatible with Sobek 1DFLOW)
Multi-Hydro Open source Includes SWMM	1D-2D	Sewer and Surface	Fully-distributed physically based	Research
Mike Urban	1D-2D	Sewer and Surface	Fully-distributed physically based	Emergency response planning for urban flooding
TUFLOW	1D-2D/2D-3D	Sewer and Surface	Fully-distributed physically based	River flooding, urban flooding, pipe network modelling
Hydro_AS-2D	2D	Surface	Physically based	Surface flooding
JFlow+	2D	Surface	Fully-distributed physically based	River flooding, surface flooding
FloodArea	2D or 1D/2D	Surface	Grid based	ArcGIS application, surface flooding

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