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REVIEW PAPER

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A catalogue of the flood forecasting practices in the Danube River Basin

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Abstract

Floods are one of the most devastating natural disasters that can cause large economic damage and endanger human lives. Flood forecasting is one of the flood risk mitigation measures serving to protect human lives and social estate. The Danube River Basin (DRB) is the world's most international river basin, flowing through the territory of 19 countries, covering more than 800,000 km^2. The frequency of floods in the DRB increased in the last decades, urging the need for a more effective and harmonized regional and cross-border cooperation in the field of flood forecasting. Reliable and comprehensive hydrologic data are the basis of flood forecasting. This paper provides an overview of the national flood forecasting systems in the DRB. Detailed information about meteorological and hydrological measurements, flood modelling, forecasting, and flood warnings is provided for 12 countries that cover almost 95% of the total DRB area. Notably, significant differences exist among the countries in terms of the measuring network density, the models used as well as forecasting and warnings methodology. These differences can be attributed to the geographical and climatological setting, political situation, historical forecasting development, etc. It can be seen that there is still much room left for improvements of measurement networks (e.g., density, measured parameters) and models used that could be improved to enhance the flood forecasting in the DRB.

KEYWORDS
Danube River Basin, data, flood forecasting, hydrology, models, monitoring

1 | INTRODUCTION

Floods are one of the most devastating natural disasters that can lead to significant economic damage and even loss of lives (Adikari & Yoshitani, 2009). For example, in 2013, flooding caused almost half of all global natural disaster-related losses (Adams & Pagano, 2016). Moreover, in the period from 1900 until 2006 floods caused more than 19% of fatalities related to natural disasters and more than 48% of the affected people due to natural disasters are related to floods (Adikari & Yoshitani, 2009; Jain et al., 2018). Furthermore, as the consequence of climatic variability and changes in extreme precipitation, an increase of the frequency of floods could be expected in different parts of the world in the future (Adikari & Yoshitani, 2009; Blöschl et al., 2019; Hannaford, 2015; Šraj et al., 2016; Trenberth et al., 2003; Vogel et al., 2011; Wilcox et al., 2018). The frequency of floods increased in the Danube River Basin (DRB) in the last decades as well (e.g., major floods in 2002, 2005, 2006, 2009, 2010, 2013, and 2014) (ICPDR, 2019; Morlot et al., 2019). Therefore, effective flood forecasting is needed to warn vulnerable people living in the endangered areas, since none of the current flood risk mitigation measures is enough to avoid catastrophes (WMO, 2011). Nowadays, there have been numerous methods and models developed and used for flood forecasting around the world; however, it should be noted that flood forecasting requires a good understanding of both meteorological and hydrological conditions of the particular country or region (WMO, 2011). A book entitled Flood Forecasting: A Global Perspective (Adams & Pagano, 2016) provides a comprehensive overview of flood forecasting systems in several countries: Australia (Pagano et al., 2016), Brazil (Fan et al., 2016), China (Liu, 2016), Columbia (Werner et al., 2016), Germany (Demuth & Rademacher, 2016), Great Britain (Pilling et al., 2016), Israel (Givati et al., 2016), Russia (Borsch & Simonov, 2016), and United States (Adams, 2016). In addition, Jain et al. (2018) provide an overview of flood forecasting systems in some other countries such as Nepal, India, Pakistan. Besides national or regional flood forecasting systems, the aforementioned book (Adams & Pagano, 2016) also discusses continental systems such as the European Flood Awareness System (EFAS) (Smith et al., 2016). A recent paper by Kauffeldt et al. (2016) also evaluates large-scale hydrological models (Kauffeldt et al., 2016). Even though flood forecasting systems are often developed by national or regional environmental agencies or similar organizations that do not report about their established systems in scientific journals, a search in the Scopus database using the search term 'flood forecasting' yielded almost 9,500 search hits at the end of September 2020, which indicates that the topic is of interest also for the researchers.

Nevertheless, a similar Scopus database search using the search term 'flood forecasting Danube' yielded only 41 hits at the end of September 2020. Therefore, it is clear that not much information about the flood forecasting systems in use in different Danube River countries is available in the scientific literature and is often not known to the public. With the support of the International Hydrological Programme, biennial Conferences of the Danubian Countries have been held since 1961; the first one took place in Budapest (Brilly, 2010), while the most recent one, the 28th Danube Conference, was held in 2019 in Kyiv, Ukraine. Outputs of these conferences are often proceedings, nowadays published on conference websites, but without an effective outreach to the global scientific community. Moreover, several research projects such as GLOWA-Danube (Mauser & Prasch, 2016) were launched in recent decades in relation to flood forecasting. To enhance the flood forecasting in the DRB, the Danube River Basin Enhanced Flood Forecasting Cooperation (DAREFFORT) project was launched (DAREFFORT, 2019). This project provides an overview of the status of the national flood forecasting systems in the Danube River countries.

The main aim of this paper is to present an overview of the various aspects of the national flood forecasting systems in the DRB. Thus, the main idea of this paper is to provide valuable information about flood forecasting in the DRB countries, which would otherwise not be available to the research community.

2 | METHODOLOGY

The data collected in the scope of the DAREFFORT project (DAREFFORT, 2019) provide a synthesis of the collected data and support the evaluation of national flood forecasting systems. The data were collected using a questionnaire, where the contact persons (i.e., members of the national hydrological or meteorological service; in most cases also co-authors of this paper) from individual Danube River countries were invited to answer several questions related to hydrological and meteorological monitoring as well as ice and flood forecasting. The questionnaire was divided into three main parts (i.e., hydrological data, meteorological data, and the national hydrological forecasting service). Each of these contained a set of questions regarding the topic (with a total of 116 questions). Different types of questions were used such as yes/no, multiple choice, and short answer. The part about hydrological data included questions related to the hydrological network (e.g., how many hydrological stations are in operation); flood data (e.g., are maps with flood contour lines available); ice data (e.g., are ice maps available); geographic information system (GIS) (e.g., what attributes are used to describe catchments); data management and data formats (e.g., what kind of a database is used); data exchange (e.g., are procedures for national data exchange available); and data availability (e.g., are data freely available). The part about meteorological data covered the following topics: meteorological network (e.g., how many meteorological stations are in operation); meteorological data information (e.g., are data available as gridded data); GIS system (e.g., which software is used); data management and data formats (e.g., what is the frequency of data updating); data exchange (e.g., are procedures for national data exchange available). The third part of the questionnaire included questions related to the national hydrological forecasting service topics as dissemination of forecasts and warnings (e.g., is forecast efficiency estimated); the process of hydrological forecasting (e.g., how many models are in use); relation with stakeholders (e.g., are reports for stakeholders generated); perspective and development (e.g., what are the future plans).

In addition, each country prepared a national report, providing additional information about the ice and flood forecasting system. These national reports covered the following main topics: monitoring and data inventory; national hydrological forecasting service; perspective in developments. Thus, the idea was to collect additional information about these aspects of flood forecasting, which could not be gathered by the questionnaire. A template of the report with examples was provided to illustrate what is expected to be included in different subchapters of the national reports.

The collected questionnaire responses and national reports were then systematically analysed and evaluated. This means that all the information was gathered and merged into one document, which synthesized all the provided information collected by the questionnaires and national reports. The final document was reviewed by all project members to identify possible errors. It should be noted that the aforementioned reports and the questionnaire were also completed by the Copernicus EFAS and the International Sava River Basin Commission (ISRBC). Nevertheless, this review will mainly focus on the national flood forecasting perspective. Therefore, this paper presents the flood forecasting status in the Danube River countries according to the submitted national reports and questionnaires.

3 | HYDROMETEOROLOGICAL MONITORING AND DATA

3.1 | DRB and hydrometeorological services

The DRB is one of the largest river basins in Europe. The total catchment area of the DRB is more than 800,000 km^2. It extends over the territory of 19 countries, and the entire river length is more than 2,800 km (ICPDR, 2019) (Figure 1). Some of the countries, such as Poland, Italy, Switzerland, Albania, and North Macedonia, cover only a small part of the DRB (ICPDR, 2019). Table S1 lists an overview of the countries included in the DRB. Twelve of the nineteen DRB countries are included in this review and these countries cover a total of 94.3% of the entire DRB area (Table S1), which means that almost all countries within the significant part of the territory in the DRB are included (except Bosnia and Herzegovina due to its political situation). Nevertheless, some information was also obtained for Bosnia and Herzegovina (DAREFFORT, 2019). Detailed information about many DRB characteristics such as climate (i.e., rainfall, air temperature, evapotranspiration), land use, vegetation, lakes, water engineering measures, or history of the DRB is available in the Hydrological Processes of the DRB book (Brilly, 2010). Furthermore, comprehensive

FIGURE 1 Location of the Danube River Basin (green shaded area) in Europe [Color figure can be viewed at wileyonlinelibrary.com]

analyses of the results about the flood regimes of rivers in the DRB are presented in the monograph, prepared by 30 scientists from 11 countries of the DRB (Pekárová & Miklánek, 2019).

National hydrological and meteorological services are generally responsible for monitoring hydrometeorological processes, data processing and collection, analyses of the collected data, forecasting, etc. Table S2 presents the organizational structure of the national hydrological and meteorological services in different DRB countries. It shows that in some countries (e.g., Bulgaria, Croatia, Czech Republic) hydrological and meteorological services are part of the same institution, while in other countries such as Austria, Germany, and Hungary, these two services are separated. In addition, for example in Germany, each federal state has its own hydrological service and organizational structure.

It should be noted that in the case of some countries such as Bulgaria, data cannot be obtained for free. In most other countries, at least some of the products are provided free of charge. For example, in Austria and Croatia, data are free of charge for research purpose, while for commercial use, this is not the case. In Table 1, it can be seen that there are relatively significant differences in meteorological station density, which is an issue that should be improved in the future. Moreover, Table 2 gives an overview of the number of stations where pan evapotranspiration and parameters for calculating potential evapotranspiration, snowfall, and the snow-water equivalent are measured. Similarly, as in the case of meteorological stations, we can see significant differences among different DRB countries.

3.2 | Meteorological measurements

This section provides an overview of the meteorological measurements in different DRB countries included in the review (Table 1). Meteorological measurements and data collection have a long history in all countries (of more than 100 years). Generally, regular networks of meteorological stations started to develop in the 19th century. Nowadays almost all DRB countries provide a modern network of meteorological stations to ensure real-time data acquisition. The most important parameters measured within the meteorological network are precipitation, air temperature, wind speed, relative humidity, air pressure, solar radiation, and sunshine duration. Different types of meteorological stations are in use in the DRB countries (i.e., synoptic meteorological, automatic weather, climatological, and manual precipitation stations).

3.3 | Hydrological measurements

As with meteorological stations, networks of hydrological gauging stations in the DRB countries started to develop in the 19th century. All countries have made great progress in the field of monitoring, from the simple staff gauge (with values observed and noted only once a day), to continuously registering gauges (recording water level on paper), and finally to digitally measured values stored by data loggers and/or transmitted to a database directly from measuring points. Nowadays, in almost all DRB countries a modern network of hydrological stations is available to ensure real-time data acquisition used in forecasting and warning procedures. Mostly, the following variables are measured at the hydrological stations: water level, discharge (periodically), water temperature, sediments and, in some cases, ice measurements. The water level is measured continuously, while the

TABLE 1 Overview of the meteorological stations, weather radars, station density in the Danube River Basin (DRB) and data access links

Country	Number of meteorological stations operated in DRB	Number of weather radars	Density of stations [per 10^3 km^2]	Data access
Austria	130	5	1.6	www.ehyd.gv.at http://www.noel.gv.at/wasserstand/#/de/Messstellen
Bulgaria	141	2	3.0	www.meteo.bg
Croatia	226	3	6.5	http://www.meteo.hr/ http://vrijeme.hr/hrvatska1_n.xml
Czech Republic	90	2	4.1	www.chmi.cz
Germany	414	17	7.4	https://m.hnd.bayern.de/ https://www.gkd.bayern.de/ https://opendata.dwd.de
Hungary	Approx. 300	4	Approx. 3.2	www.met.hu
Moldova	6	0	0.5	http://old.meteo.md/ http://www.meteo.md/index.php/meteo/
Romania	160	7	0.7	http://www.meteoromania.ro/
Serbia	300	16	3.7	http://www.hidmet.gov.rs/
Slovakia	851	4	18.1	http://www.shmu.sk/
Slovenia	295	2	18.0	http://meteo.arso.gov.si/met/en/
Ukraine	17	2	0.6	https://meteo.gov.ua/

TABLE 2 Overview of the number of stations with measurements of pan and potential evapotranspiration (i.e., parameters for the calculation), snowfall and snow water equivalent

Country	Number of meteorological stations with measurements			
	Pan evapotranspiration	Potential evapotranspiration	Snowfall	Snow water equivalent
Austria (Lower Austria)	0	0	120	120
Bulgaria	2	20	367	4
Croatia	10	0	12	9
Czech Republic	0	10	80	80
Germany	0	0	82	82
Hungary	0	0	125	0
Moldova	0	2	6	6
Serbia	0	Calculated for 28 stations	300	28
Slovakia	23	23	229	183
Slovenia	0	Calculated for 70 stations	141	6
Ukraine	0	0	17	7

TABLE 3 Overview of the hydrological stations, station density in the Danube River Basin (DRB) and data access links

Country	Number of hydrological stations operated in DRB	Density of stations [per 10^3 km^2]	Data access
Austria	150	1.9	www.ehyd.gv.at, http://www.noel.gv.at/wasserstand/#/de/Messstellen
Bosnia and Hercegovina	82	2.2	www.voda.ba/vodostaj
Bulgaria	66	1.4	www.hydro.bg, https://maritsa.meteo.bg/, https://arda.hydro.bg/
Croatia	284	8.1	http://hidro.dhz.hr, http://vodostaji.voda.hr/
Czech Republic	153	7.1	hydro.chmi.cz
Germany	488	8.7	https://m.hnd.bayern.de/, https://www.gkd.bayern.de/
Hungary	Approx. 2,850	Approx. 30.6	www.vizugy.hu, www.hydroinfo.hu
Moldova	17	1.3	http://www.meteo.md/index.php/hidrologie/
Romania	972	4.2	http://www.inhga.ro/, http://www.rowater.ro/
Serbia	183	2.2	http://www.hidmet.gov.rs/
Slovakia	366	7.8	http://www.shmu.sk/
Slovenia	149	9.1	http://www.arso.gov.si/vode/podatki/
Ukraine	51	1.7	https://meteo.gov.ua/

discharge is generally derived from the rating curve—the relationship between water level and discharge. Rating curves are based on regular discharge measurements.

Similarly, there are substantial differences in the number of hydrological stations, their density as well as data availability (Table 3). For example, in Bulgaria, the data are not provided free of charge. In some countries, such as the Czech Republic, only verified data are charged. All countries in the DRB also prepare flood reports where they summarize the main characteristics of flood events. In addition, some countries (i.e., Bosnia and Herzegovina, Bulgaria, Croatia, Germany, Hungary, Moldova, Romania, Serbia, Slovakia, and Ukraine) also prepare ice event reports. These reports mostly provide information about the percentage of the surface covered by ice and ice cover duration.

All DRB countries included in this review have also established some kind of a bilateral agreement with their neighbouring countries for hydrological data exchange. This is mostly the case for border and cross-border watercourses. The harmonization of flows for border profiles is performed in accordance with pre-defined hydrological criteria and agreements. Neighbouring countries carry out joint measurements of discharge at the border sections, regularly or when necessary.

4 | HYDROLOGICAL FORECASTING

4.1 | Modelling

One can notice that many different models are used throughout the DRB (Table 4). In fact, more than 12 different models are in use in the 12 analysed countries. Furthermore, DRB countries use conceptual models such as Dansk Hydraulisk Institut (DHI), Nedbor Afstromnings Model (NAM) or Hydrologiska Byråns Vattenbalansavdelning (HBV) (e.g., Petan et al., 2015), physically based models such as TOPMODEL, and even empirical models such as the rational equation. Thus, it is clear that such empirical approaches could be replaced with more sophisticated models that better represent the rainfall-runoff process. One can also notice that some countries use different models for different parts of the country (i.e., a regional approach) or different catchments (i.e., a catchment-based approach). In contrast, other countries use the same model structure for the whole country. Moreover, different routing models such as DHI 1D, Discrete Linear Cascade Model, Hydrologic Engineering Centre—River Analysis System are used in the DRB countries. In the case of the hydraulic models, it seems that the DHI 1D model is the most commonly used. Moreover, all countries indicated that they cooperate with other DRB countries in the framework of hydrological modelling and forecasting to some extent. The use of different models could be explained by the different flood types that occur in the DRB, which require specific modelling techniques.

4.2 | Forecasting

The hydrological and hydraulic models described in Section 4.1 are then used for flood forecasting. As mentioned, flood forecasting requires a good understanding of both meteorological and hydrological conditions (WMO, 2011). Table 5 provides an overview of the collaboration between hydrological and meteorological services in the process of flood forecasting in the DRB countries. One can see that hydrological and meteorological services in most countries are operated door-to-door, while in some countries such as Austria, Germany, Hungary, and Romania these two services are separated. When both services are located together, the hydrological service has access to the meteorological data and forecasts without any fee. In some of these cases, the hydrological and meteorological services issue joint warning products (Table 5). However, in cases where services are

TABLE 4 Overview of the hydrological and hydraulic/routing models used in the Danube River Basin (DRB) countries

Country	Hydrological model	Hydraulic model/Routing model
Austria	DHI NAM, HBV	DHI 1D Hydrodynamic model
Bulgaria	Rational equations used for flash-flood forecasting, TOPKAPI (Ogosta River), ANN (Iskar River), SWAT (Vit River), ISBA-TOPODYN (Osam River), HEC-HMS (Yantra River), DHI NAM (Rusenski Lom River), DHI NAM (Maritsa and Tundzha Rivers), ISBA-TOPMODEL (Arda River)	DHI 1D Hydrodynamic model (Maritsa and Tundzha Rivers)
Croatia	DHI NAM (Sava and Danube River)	DHI 1D Hydrodynamic model (Sava and Danube River)
Czech Republic	HYDROG (Morava and Odra Rivers), AQUALOG (Labe River), HEC-HMS (Odra and upper Morava River and other Rivers)	HYDROG (Morava and Odra Rivers)
Germany (Bavaria)	LARSIM	FluxFloris (Inn, Lech and Danube Rivers), WAVOS (Danube and Main Rivers)
Hungary	Multiple modules are used: meteorological, snow, areal mean calculation, rainfall-runoff (TAPI), error correction, flow routing, back water effect	Discrete Linear Cascade Model (DLCM)
Moldova	Not using any model	Not using any model
Romania	NOAH-R, NWSRFS (SAC-SMA, Snow17)	NWSRFS(Lag&K,)custom Muskingum type routing models, HEC-RAS
Serbia	Correspondent discharge method (Danube River), Multiple linear correlation (Sava River), Nonlinear model of river runoff (MANS), HBV (small rivers)	ISRBC FFWS platform
Slovakia	HBV and HEC-HMS	HEC-RAS
Slovenia	DHI NAM	DHI 1D Hydrodynamic model
Ukraine	DOSCH, SNIG, SLOJ models	NA

Note: NA indicates that the information could not be obtained in the scope of the review.
Abbreviations: ANN, Artificial Neural Network; HEC-HMS, Hydrologic Engineering Center-Hydrologic Modeling System; HEC-RAS, Hydrologic Engineering Centre-River Analysis System; ISBA, Interactions between Soil, Biosphere, and Atmosphere; ISRBC FFWS, International Sava River Basin Commission Flood Forecasting and Warning System; LARSIM, Large Area Runoff Simulation Model; NOAH, National Centers for Environmental Prediction, Oregon State University, Air Force, Hydrology Lab; SAC-SMA, Sacramento Soil Moisture Accounting Model; SWAT, Soil & Water Assessment Tool; TOPKAPI, TOPographic Kinematic APproximation and Integration

TABLE 5 Overview of the collaboration between the hydrological and meteorological services in the scope of the flood forecasting

Country	Relation with meteorological service	Consultation with meteorologists	Meteorological data and predictions availability	Joint warning products
Austria	Separated	Before and during a flood event	Yes, payment-based	No
Bulgaria	Door-to-door	Daily	Yes, free of charge	Yes
Croatia	Door-to-door	Daily	Yes, free of charge	Yes
Czech Republic	Door-to-door	Daily	Yes, free of charge	Yes
Germany (Bavaria)	Separated	Contact person available	Open data service + fee-based service	No
Hungary	Separated	Intermittently, in emergencies	Yes, free + payment based data	No
Moldova	Door-to-door	NA	Yes, free of charge	NA
Romania	Separated	Daily	Yes, free of charge	No
Serbia	Door-to-door	Daily	Yes, free of charge	Yes
Slovakia	Door-to-door	Daily	Yes, free of charge	Yes
Slovenia	Door-to-door	Daily	Yes, free of charge	No
Ukraine	Door-to-door	Daily	Yes, free of charge	Yes

Note: NA indicates that the information could not be obtained in the scope of the review.

TABLE 6 Overview of the hydrological forecasting practices and systems in the Danube River Basin (DRB) countries

Country	Phenomena in focus	Available numerical weather predictions	Hydrological model forecast interval and updates
Austria	Riverine and flash floods	Long-term, short-term and nowcast forecasts	Up to +48 h (Danube), continuous operation
Bulgaria	Riverine and flash floods	Medium and short-range forecasts	Up to +96 h, updated daily (and on-demand)
Croatia	Riverine (forecast only) and flash floods (forecast and warning)	Medium and short-range forecasts	Up to +120 h, updated hourly
Czech Republic	Riverine and flash floods	Medium and short-range, nowcast and ensemble forecasts	Up to +66 h, updated hourly, twice a day manual runs
Germany (Bavaria)	Riverine and flash floods	Medium range and nowcast forecasts	Up to +96 h, updated hourly
Hungary	Riverine floods, hydrological drought, river icing	Medium and short-range forecasts	Up to +144 h, updated daily (and on-demand)
Moldova	Riverine floods, river icing	NWP model forecasts	NA
Romania	Riverine and flash floods	Long, medium and short-range forecasts	Between +2 and +7 days updated daily, FFG up to +6 h, updated every hour, up to 15 days using what-if scenarios in special situations
Serbia	Riverine and flash floods, river icing	Seasonal, monthly, medium and short-range, nowcast and ensemble forecasts	Between +2 and +5 days, updated daily
Slovakia	Riverine, flash and ice floods, river icing	Medium and short-range, nowcast and ensemble forecasts	Up to +48 h, updated on 6 h
Slovenia	Riverine, karstic and flash floods, hydrological droughts	Medium and short-range, nowcast and ensemble forecasts	Up to +144 h, updated hourly
Ukraine	Riverine and ice floods, mudflows, hydrological droughts	NWP model forecasts	Up to +48 h

Note: NA indicates that the information could not be obtained in the scope of the review.
Abbreviations: FFG, Flash Flood Guidance; NWP, Numerical Weather Prediction

separated, the hydrological service mostly does not have free access to the meteorological data and predictions. However, there are also some exceptions such as Romania (Table 5).

Table 6 provides an overview of the hydrological forecasting practices in different DRB countries. The hydrological forecasting services operate in daily (7/365) mode. The daily operational practices are mostly performed during the morning shift. As a rule, the second shift or 24/7 operation is introduced during emergencies. Hydrological services are mostly responsible for riverine and flash floods forecasting.

Moreover, some of the countries focus on the icing phenomenon as well as on mudflows (i.e., debris flows), hydrological droughts, or karstic floods (Table 6). During the forecasting practices, the hydrological services mostly use country-specific information systems, visualization tools, etc. Some countries use international or regional platforms as well, such as the EFAS or the International Sava River Basin Commission Flood Forecasting and Warning System (ISRBC FFWS). Table 6 indicates that all services have access to the different types of numerical weather predictions (i.e., mostly to the short and medium-range ones). Moreover, almost half of the services use ensemble forecasts and nowcasts, but only some have access to long-term forecasts. The hydrological model forecast interval is mainly between 48 and 144 h, and in some cases even longer. In addition, hydrological models perform calculations multiple times per day (i.e., 2–4 times) or operate on an hourly basis. In some cases, manual model runs are also used (Table 6).

For the evaluation of the hydrological forecasting efficiency, different countries use multiple efficiency criteria. Among the most frequently used methods are the Nash-Sutcliffe efficiency, the root mean square error, the Pearson correlation coefficient (R^2), the absolute relative error, etc. Moreover, some countries are also using different types of efficiency criteria such as hit rate or false alarm ratio. Moreover, in the national reports, countries also included information about the efficiency of the forecasting. As expected, better performance is obtained for larger catchments than for the headwater catchments. In addition, forecasts for shorter lead-times (e.g., 12-h) are generally better than those for longer lead-times. Some countries also indicated improved forecasting performance in the last few years.

4.3 | Warning and dissemination

Flood warning and its dissemination to end users are crucial for efficient flood protection systems (Jain et al., 2018). The hydrological forecasting services in the DRB countries are responsible for issuing hydrological, flood, or flash flood warnings with their national early warning systems. Table 7 and Table S3 provide an overview of the daily operational and warning dissemination practices in the DRB countries. One can notice that most of the hydrological services publish daily reports, including forecasts. These are mostly published for a duration of up to a few days (i.e., 2–3), while only in some cases longer duration forecasts are issued. Some of the services automatically generate the forecast report, some other services also prepare seasonal forecasts (Table 7). In case of emergency, most of the countries use the 3-stage impact-oriented warning levels (Table 7). These forecasts and warnings are then disseminated to the national early warning system authorities (Table S3). These are mostly emergency services, civil protection, water management institutions, ministries, etc. (Table S3). In some countries, additional authorities such as local municipalities, navigation authorities, and downstream countries are also notified (Table S3). The forecasts and warnings that are dedicated for different authorities are mostly communicated using special channels that are different from those for the public (Table S3). The general public is mainly informed via the internet, social media, or broadcast services.

5 | CONCLUSIONS AND FURTHER DEVELOPMENT

Based on the presented review, it can be seen that significant differences exist in the flood forecasting system characteristics among the DRB countries, which can be related to the specific conditions in the countries (i.e., geographical and climatological setting, political situation, historical forecasting development). The improvement of forecasting capabilities on a basin-wide scale is the most effective tangible non-structural solution, which highly reflects the solidarity principle. Based on the conducted review and collected information, the following conclusion can be made from the perspective of the DRB flood forecasting system improvements:

- Enhancement of the hydrological and meteorological network in terms of the station density in the countries with a lower density of stations and the inclusion of measurements of additional variables such as evapotranspiration, soil moisture, sediment, and ice in the measuring network in the countries where these variables are not measured on a regular basis. Station density improvement is essential for better spatial and temporal representation of the hydro-meteorological processes generating flood events. For example, floods in the DRB are often generated in the headwater catchments, where hydrological data and snow measurements are sparse. Development of a composite radar product at a regional level would also be beneficial to have better coverage of the DRB since the density of radars differs significantly among the DRB countries.
- Enhancement of the relationship between meteorological and hydrological services as well as among neighbouring countries within the DRB (e.g., data exchange, consultations, joint warnings). Based on the presented overview it is clear that this cooperation could be improved.
- Development or upgrading of hydrological and hydraulic/routing models to reduce the forecasting uncertainty and improve performance for all parts of the DRB with a focus on the state-of-the-art techniques following the World Meteorological Organization (WMO) guidelines (WMO, 2011, 2013) as it is clear that some forecasting services still apply simple empirical approaches that do not always yield accurate forecasting predictions.
- Assessment of the forecasting accuracy and uncertainty estimation using state-of-the-art methods (e.g., Beven & Young, 2013; Seibert

TABLE 7 Overview of daily operational practices in the scope of the flood forecasting in the Danube River Basin (DRB) countries

Country	Output product with hydrological forecast	Warning classification (threshold definition)
Austria	Data and information on the water balance; runoff forecasts	Warning and 3 alert levels
Bulgaria	Daily report with 3-day forecast (text + maps), results from hydrological model forecasts (text+graphs)	3 levels (discharges, statistically derived)
Croatia	Daily hydrological bulletin	4 alert levels (water levels) according to National Flood Defense Plan
Czech Republic	Daily report with 3-day forecast + hydrological model forecasts (text + graphs + data tables)	3 levels (discharges, impact oriented)
Germany (Bavaria)	Hydrological status report; Automatic water level and discharge forecasts	4 alert levels (water levels, impact-oriented), 3 warning levels (according to alert levels)
Hungary	Daily hydrological report with water level forecast for next 6 days (shallow river section information, river ice reports and forecasts)	3 flood levels (water levels, impact-oriented), 3 ice conditions
Moldova	Daily hydrological report	4 flood levels
Romania	Daily hydrological report with 7 day (10 day on-demand) forecast; Monthly with next 3 months forecast	3 levels (water level thresholds, impact-oriented)
Serbia	Daily: Hydrological data and forecasts bulletins; Periodically: Weekly, monthly and seasonal bulletins with hydrological outlook and icing events forecasts	3 flood levels (water levels, impact-oriented), 3 ice conditions
Slovakia	Daily: Hydrological report and numerical 48-hour forecasts, hydrological drought map;seasonal: weekly snow (SWE) report	3 flood levels (water stage, impact-oriented), 2 ice conditions
Slovenia	Daily hydrological report with 3-day forecast(text + data tables)	3 levels (discharges, impact oriented)
Ukraine	Short-term forecasts (up to 15 days); Long-term forecasts and predictions (up to 60 days); Seasonal forecasts (up to 97 days)	3 flood levels (water levels)

et al., 2018), which should be systematically performed to detect catchments/rivers with poorer forecasting performance so that improvements could be made in these areas (e.g., additional stations, models modifications). In addition, forecasting efficiency evaluation should be done systematically at the regional level, which would allow the evaluation of how flood forecasting efficiency changes with forecasting methodology development or network density modifications.

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DATA AVAILABILITY STATEMENT

All the related data used to prepare this manuscript is available on the DAREFFORT project web-page (DAREFFORT, 2019).

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