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Report on elaboration (enhancement) of the forecasting conditions

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1 Introduction

Enhancement of the conditions of hydrological forecasting generally depends on improving the quantity and quality of several types of data: meteorological and hydrological data, ice data, channel morphology etc. and accuracy of meteorological forecasts. Hydrological and meteorological services maintain monitoring systems and development of weather and hydrological forecasting models. Improvements in meteorological forecasts have an impact on improving hydrological forecasts. The organizational structure of hydrological and meteorological services by countries of the Danube River Basin is different as shown in Evaluation report on flood and ice forecasting systems and methodologies in the Danube countries (WP3 output 3.1). Increased flood risk in the Danube River Basin should be directed to the improvement of forecasting capabilities on basin-wide scale.

2 Monitoring and data

In-situ monitoring of meteorological and hydrological variables from data providers are particularly crucial for reliable hydrological forecast. Additionally, reliable data flow, data control and data processing are extremely important for efficient data management. Countries use different transmission techniques in data flow and different software for data control and data processing. The improvement of forecasting capabilities on basin-wide scale is the most cost-effective non-structural tangible solution, which highly reflects the solidarity principle. Therefore, the strong cooperation between countries in the region is necessary.

2.1 Meteorological data

Meteorological observations are an essential part of flood and ice warning and forecasting system. Generally, within the meteorological networks various data is collected. The most important variables are precipitation, air temperature, air humidity, wind speed, air pressure, solar radiation, sunshine duration, evaporation, soil moisture, snow depth and snow water equivalent.

We have to emphasize that actual measurements of evaporation and transpiration are performed only in some countries at few meteorological stations. Furthermore, potential evaporation is measured only at some places (see Evaluation report on flood and ice forecasting systems and methodologies in the Danube countries (WP3 output 3.1)). In addition, soil moisture measurements are hardly taken. Furthermore, composite weather radar imagery to be used in hydrological models are not available in all countries.

The floods in the Danube river basin are mainly generated in mountainous areas in combination with snowmelt. In most countries, there are no systematic measurements of snow water equivalent or its spatial distribution.

The availability and access to data is different across the Danube River Basin countries. Furthermore, not all of the data are free of charge in individual countries. Availability of meteorological data, terms of use for the countries involved in the DAREFFORT project and the number of on-line meteorological stations operated in the Danube River basin is shown in Table 1 and information about the type of data provided on the public website is presented in Table 2.

Table 1: Availability of meteorological data and terms of use in individual countries and the number of on-line meteorological stations operated in the Danube River basin (DRB) (information from national reports)

Country	Data availability and access	Terms of use	No. of on-line meteorological stations operated in DRB
Austria	www.ehyd.gv.at	All data is free of charge and can be used for research purposes as well for commercial purposes. Reference to the data source is required.	NA
Bulgaria	www.meteo.bg	Data access is limited and use of data is not free of charge.	116
Croatia	http://www.meteo.hr/	Archive data is not charged for scientific research use whereas for commercial use a fee is charged according to the price list of services and products.	12
The Czech Republic	www.chmi.cz	Operational data is available for public on the CHMI website. Verified data are not available on the website and only provided as a paid service.	90
Germany	https://m.hnd.bayern.de/ https://www.gkd.bayern.de/ https://opendata.dwd.de	The DWD does not give any guarantees for availability and service for its open data service. If a high level of data integrity and continuity is required there is a secured access in the so-called Geodata Service (Geodaten-Serverdienst). The use of this service is fee-based and serves the same data as the Open Data Service.	414
Hungary	www.met.hu	The data is provided for a fee, but basic data is free of charge.	appr. 300
Moldova	http://old.meteo.md/ http://www.meteo.md/index.php/meteo/	NA	6
Romania	http://www.meteoromania.ro/	NA	160
Serbia	http://www.hidmet.gov.rs/	The data that is published on the web site, both in real time and yearbooks, as well as the data provided to state institutions, are	28

		free of charge. Data issued on request are charged.	
Slovakia	http://www.shmu.sk/	To the bodies of state and public administration, to the court and the National Council of the Slovak Republic, the data is provided free of charge for exercise of their powers. In other cases, meteorological products are provided for remuneration.	271
Slovenia	http://meteo.arso.gov.si/met/en/	All the data are free of charge and can be used for research purposes as well for commercial purposes. A source of data is required.	113
Ukraine	https://meteo.gov.ua/	Data is provided to government agencies free of charge. In other cases, the data is charged.	0

NA indicates that this information is not available (not provided in the country reports)

Table 2: Information about the type of data provided on the public website (from national reports)

Country / Region	**Type of data provided on the public website** (air temp., humidity, precipitation, precip. type, snow cover, air quality, other)						
Austria (Lower Austria)	air temp.	humidity	precipitation				
Bulgaria			precipitation	precip. type	snow cover		
Croatia	air temp.	humidity	precipitation		snow cover		
Czech Republic	air temp.	humidity	precipitation		snow cover	air quality	
Germany	air temp.	humidity	precipitation		snow cover		wind, global radiation, air pressure
Hungary	air temp.	humidity	precipitation	precip. type	snow cover	air quality	wind
Moldova	air temp.	humidity	precipitation		snow cover	air quality	air pressure, wind speed, wind direct.
Serbia	air temp.	humidity	precipitation		snow cover		
Slovakia	air temp.	humidity	precipitation		snow cover	air quality	air pressure, wind speed, wind direct.
Slovenia	air temp.	humidity	precipitation	precip. type	snow cover		
Ukraine	air temp.		precipitation	precip. type	snow cover		

2.2 Hydrological data

In the frame of hydrological monitoring all countries collect data on hydrological parameters, i.e. water level, discharge and water temperature. Some of them collect also information about sediments and ice and there are practically no systematic measurements of water flow velocity. Bed load transport is hardly ever measured. There are also no systematic measurements of channel morphology, with the exception of navigable waterways along the Danube and its tributaries.

Measurements of river stages, and indirectly river discharges, are well developed in all hydrological services. However, the number of observation stations has unfortunately decreased over recent decades and we lost valuable information regarding the heterogeneity and dynamics of the phenomena measured. Furthermore, digitalisation of historical data is lacking in all services.

The problem of hydrological as well as meteorological services is also the lack of financing and frequently reduced allocations of budgetary resources of individual countries. Consequently, the number of gauging stations in some countries is lower than several decades ago. Thus, the reduction of funds for operation of hydrological as well as meteorological services have forced the services to improve their budgets by selling data. Commercialisation of hydrological data brings more harm than benefits for the society. Services are closing down and hiding data, which are expensive, but valuable for users, and nevertheless without a specific market value. The lack of funds makes it difficult to introduce new measurement technologies. In some countries digitisation and automation have been introduced into all observations and in others only partially.

The availability and access to hydrological data is different across the Danube River Basin countries. Furthermore, not all of the data are free of charge in individual countries. Availability of hydrological data and terms of use for the countries involved in the DAREFFORT project is shown in Table 3 and the type of the data provided on the public website in Table 4.

Table 3: Availability of hydrological data, terms of use in individual countries and the number of automatic on-line hydrological stations operated in Danube River Basin (DRB)

Country	Data availability and access	Terms of use	No. of on-line hydrological stations operated in DRB
Austria	www.ehyd.gv.at	All data is free of charge and can be used for research purposes as well for commercial purposes. Reference to the data source is required.	NA
Bulgaria	www.hydro.bg	The access to the data is limited. The use of data is not free of charge.	25
Croatia	http://hidro.dhz.hr	Archive data are not charged for scientific research use whereas for commercial use a fee is charged according to the price list of services and products.	172

The Czech Republic	http://hydro.chmi.cz/hpps/	Verified hydrological data (time series, daily averages, monthly averages etc.) is charged and available upon request.	153
Germany	https://m.hnd.bayern.de/ https://www.gkd.bayern.de/	Data for water levels, discharge, water temperature and sediments can be requested for single stations.	488
Hungary	www.vizugy.hu www.hydroinfo.hu	Data can be provided for a certain fee or free of charge.	350
Moldova	http://www.meteo.md/index.php/hidrologie/	Hydrological data and forecasts for representative stations are public available.	12
Romania	http://www.inhga.ro/ http://www.rowater.ro/	Hydrological data and forecasts for representative stations on the Danube and national rivers are public available, on the daily national reports elaborated by the National Hydrological Forecast Centre.	NA
Serbia	http://www.hidmet.gov.rs/	Data published on the web site, both in real time and yearbooks, as well as the data provided to state institutions, is free of charge. Data issued on request is charged.	96
Slovakia	http://www.shmu.sk/	To the bodies of state and public administration, to the court and the National Council of the Slovak Republic, data is provided free of charge for exercise of their powers. In other cases, hydrological products are provided for remuneration.	306
Slovenia	http://www.arso.gov.si/vode/podatki/	All data is free of charge and can be used for research purposes as well for commercial purposes. Reference to the data source is required.	139
Ukraine	https://meteo.gov.ua/	The data is provided free of charge to government authorities. In other cases, hydrological data is charged.	2

Information from national reports

NA indicates that this information is not available (not provided in the country reports)

Table 4: Information about the type of data provided on the public website (from national reports)

Country / Region	**Type of the data provided on the public website** (water level, discharge, water temperature, water quality, sediment transport, ice cover)					
Austria (Lower Austria)	water level	discharge	water temperature			
Bosnia and Herzegovina	water level					
Bulgaria	water level	discharge				

Croatia	water level	discharge				
Czech Republic	water level	discharge	water temperature			
Germany	water level	discharge	water temperature	water quality	sediment transport	
Hungary	water level	discharge	water temperature			ice cover
Moldova	water level	discharge				ice cover
Romania	water level	discharge				ice cover
Serbia	water level	discharge	water temperature			ice cover
Slovakia	water level	discharge	water temperature			ice cover
Slovenia	water level	discharge	water temperature		sediment transport	
Ukraine	water level		water temperature			

2.3 Ice data

Ice measurements are conducted along the Danube River's main flow and its navigable tributaries, based on the recommendation adopted by the Danube Commission. In other water bodies there are some ice measurements or observations. Because of the frequent problems with ice and historical floods, these services are best organised in Hungary. A review of the problems related to ice on the Danube is provided in the report "Die Donau und ihr Einzugsgebiet - Eine hydrologische Monographie, Folgeband II, Temperatur- und Eisregime der Donau und ihrer wichtigeren Zubringer", published in 1993.

In hilly headwater parts of the basin the ice build-up in the channel does not cause significant back water effect or particular problems during floods. Ice events are dangerous because in combination with rainfall can cause catastrophic floods. Currently the combinations of extremely rare events the so-called compound events, such as ice and rainfall, snow cover and rainfall, are not covered adequately enough by hydrological models or forecasting protocols.

Table 5: Information about ice data in individual countries (from national reports)

Country / Region	**Ice events reports**	**Information provided concerning ice events** (% of surface covered by ice, thickness of ice cover, duration of ice cover, other)			
Austria (Lower Austria)	No			duration of ice cover	
Bosnia and Herzegovina	Yes	% of surface covered by ice			

Bulgaria	Yes				Type of ice event
Croatia	Yes		thickness of ice cover	duration of ice cover	
Czech Republic	No			duration of ice cover	
Germany	Yes			duration of ice cover	
Hungary	Yes	% of surface covered by ice	thickness of ice cover	duration of ice cover	
Moldova	Yes		thickness of ice cover	duration of ice cover	Type of ice event
Romania	Yes	% of surface covered by ice	thickness of ice cover	duration of ice cover	
Serbia	Yes	% of surface covered by ice	thickness of ice cover	duration of ice cover	
Slovakia	Yes	% of surface covered by ice	thickness of ice cover		
Slovenia	No				
Ukraine	Yes	% of surface covered by ice	thickness of ice cover	duration of ice cover	

2.4 Recommendation for development

Most countries in the Danube River Basin have made a significant progress in the modernization of the meteorological and hydrological measuring networks. The modern networks provide high quality data used in warning procedures, forecasting systems and other data processing. The access to data is not uniformly regulated across the river basin countries.

National meteorological and hydrological services are obliged to meet national needs for meteorological, hydrological and related data and services, as well as to maintain networks, equipment and other supporting infrastructure. Furthermore, they need to cover the international obligations and initiatives. They also provide services to varied end-user needs.

Based on national reports, the recommendations to meteorological and hydrological services are as follows:

- The Danube river basin countries should consider the need to improve the measuring network in terms of the stations density and the inclusion of measurements of additional variables such as evapotranspiration, soil moisture, water equivalent in snowpack, bed and suspended load, periodical cross-section morphology, water velocity measurements, parameters of ice measurements, etc.
- In relation to the project scope, free open access to meteorological and hydrological data and information for the national hydrological forecasting services in the Danube catchment for their official duty.

- Standardized data exchange for sharing hydrological data.
- Development of meteorological and hydrological products at regional level, e.g. hydrological study of common river basins, development of composite weather radar outputs at regional level, etc.
- Collection of historical data records, digitization and storage in a database. Data is important for water resources management and modelling, climate change assessment, flood modelling and other hydrological analysis.
- Providing strong arguments for obtaining sufficient financial, technical and human resources to operate the services.

The world is rapidly changing and the meteorological and hydrological services need to follow the developments in science and technology and to response to new challenges.

3 Hydrological forecasting methods and models

The national hydrological and the meteorological forecasting services of the Danube River countries mostly operate within the same institution, on a door-to-door principle (Table 6). In such case, the hydrological services have access to the meteorological data and predictions free of charge, daily consultations with meteorologists are practice and usually both services prepare joint warning product as well. On the contrary, the hydrological services that operate separately from the meteorological service have fee-based access to the meteorological data and predictions, limited consultation options and independent warning products. Since the hydrological phenomena depend on the weather conditions, it is strongly recommended to maintain the relationship with the responsible meteorological service on a high level: the formal collaboration protocols should be continuously subjected to improvements and the meteorological products and services development followed.

Table 6: Collaboration between the national hydrological and meteorological forecasting services in different Danube River countries and organizations (Information from national reports)

Country / Region	Relation with meteo service	Consultation with meteorologists	Meteorological data and predictions availability	Joint warning products
Austria	Separated	NA	Yes, payment-based	No
Bulgaria	Door-to-door	Daily	Yes, free of charge (internal IS)	Yes
Croatia	Door-to-door	Daily	Yes, free of charge (ftp, dBase)	Yes
Czech Republic	Door-to-door	Daily	Yes, free of charge (internal IS)	Yes
Germany (Bavaria)	Separated	Contact person available	Open data service + fee-based service (ftp, web)	No
Hungary	Separated	NA	Yes, free + payment based data (ftp, dBase)	NA
Moldova	Door-to-door	NA	Yes, free of charge (dBase)	NA
Romania	Separated	Daily	Yes, free of charge (internal IS)	No
Serbia	Door-to-door	Daily	Yes, free of charge (internal IS)	Yes
Slovakia	Door-to-door	Daily	Yes, free of charge (internal IS)	No

Slovenia	Door-to-door	Daily	Yes, free of charge (internal IS)	No
Ukraine	Door-to-door	Daily	Yes, free of charge (internal IS)	Yes

NA indicates that this information is not available (not provided in the reports)

The type and manner of hydrological forecasting are subject to regional natural conditions. In the upper and high slope river reaches, the discharges mostly depend on the local precipitation type and its intensity. In such regions, monitoring systems with as short as possible data transfer time steps are strongly advised for forecasting since the hydrological conditions are prone to rapid changes. The stages of the lower and low slope river reaches are strongly influenced by the drainage from the upper catchments with significant snow melt impact and the local river channel conditions. Here, the hydrological conditions are maintained for longer periods. The river icing plays an important role as well since river transport is strongly affected by the icing phenomenon.

The hydrological forecasting processes are nowadays supported by various hydrological and hydrodynamic modelling systems that mostly rely on observed precipitation and air temperature data, gauged or remotely sensed (weather radar and satellite imagery), as well as on forecasts from various numerical weather prediction models. Tables 7a and 7b present an overview of different hydrological and hydraulic models, respectively, that are used in the Danube River basin countries and the two organizations, namely the European Flood Awareness System (EFAS) and the International Sava River Basin Commission (ISRBC). One can notice large diversity among the Danube River countries in terms of hydrological and hydraulic models used and the number of models applied. Among the hydrological models, the deterministic/conceptual/lumped model type predominates over the deterministic/physically based/distributed model type. The lumped models are often used in semi-distributed manner by catchment division into subcatchments and/or elevation zones. The hydrological models used in more than one country (organisation) are listed in the first three rows of Table 7a. Those are DHI NAM, HBV/HBV-light and HEC-HMS. Among the hydraulic/routing models the dynamic wave – hydraulic routing model type predominates over the hydrologic routing model type. The routing models used in more than one country (organisation) are listed in the first two rows of Table 7b. Those are DHI MIKE 1D and HEC-RAS. Nevertheless, it does not mean that the mostly used hydrological or hydraulic models are recommended for general use in the Danube River basin. The choice of appropriate model/model type for application in a certain catchment is rather complex process. The recommendations about this process are given at the end of the chapter.

Table 7a: An overview of hydrological models used in different Danube River countries and organizations

Hydrological model	Country / Organization	Model Type
DHI NAM	Austria, Bulgaria, Croatia, Slovenia, ISRBC	Lumped/semi-distributed (deterministic, conceptual)
HBV/HBV-light	Austria, Serbia, Slovakia, ISRBC	Lumped/semi-distributed (deterministic, conceptual)
HEC-HMS	Bulgaria, Czech, Slovakia, ISRBC	Lumped/semi-distributed or distributed (deterministic, conceptual)

LISFLOOD	EFAS	Distributed (deterministic, semi-physical, semi-conceptual)
WFLOW	ISRBC	Distributed (deterministic, conceptual)
TOPKAPI	Bulgaria	Distributed (deterministic, physically based)
ANN	Bulgaria	Lumped (deterministic, empirical)
SWAT	Bulgaria	Semi-distributed (deterministic, physically based)
ISBA-TOPMODEL	Bulgaria	Distributed (deterministic, physically based)
HYDROG	Czech Republic	Lumped/semi-distributed (deterministic, conceptual)
LARSIM	Germany	Lumped/semi-distributed or distributed (deterministic, conceptual)
TAPI	Hungary	Lumped/semi-distributed (deterministic, conceptual)
SAC-SMA	Romania	Lumped/semi-distributed (deterministic, conceptual)
NOAH-R	Romania	Distributed (deterministic, physically based)
MANS	Serbia	Lumped (deterministic, conceptual)
Regression models	Serbia	Lumped (deterministic, empirical)

Table 8b: Overview of hydraulic models used in different Danube River countries and organizations

Hydraulic model/routing model	**Country / Organization**	**Model Type**
DHI MIKE 1D	Austria, Bulgaria, Croatia, Slovenia, ISRBC	Hydraulic routing (dynamic wave)
HEC-RAS	Slovakia, ISRBC	Hydraulic routing (dynamic wave)
HYDROG	Czech republic	Hydrologic routing (kinematic wave)
FluxFloris	Germany	Hydraulic routing (dynamic wave)
WAVOS	Germany	Hydraulic routing (dynamic wave)
DLCM	Hungary	Hydrologic routing
Lag&K, Muskingum	Romania	Hydrologic routing
LISFLOOD	EFAS	Hydrologic routing (kinematic wave)

The hydrological and hydrodynamic modelling system uncertainty is further weighted with the uncertainty from the meteorological forecasts. Therefore, the hydrological services tend to issue descriptive forecasts rather than quantitative ones originating from the modelling systems. Thus, experienced hydrological forecasters hold a key role in the critical evaluation of the modelling system results as well as within the decision making processes of the hydrological forecasting service. However, with the advent of new technologies and the decline of the old ones, continuous capacity building of the hydrological forecasting services is strongly recommended. The list of available public websites with information about hydrological forecasts is shown in Table 8.

Table 9: Information about the availability of a public website to provide information about hydrological forecasts and URL of the website (from national reports)

Country / Region	Availability of a public website with hydrological forecasts	URL
Austria (Lower Austria)	Yes	NA
Bosnia and Herzegovina	Yes	www.rhmzrs.com
Bulgaria	Yes	http://hydro.bg/ https://arda.hydro.bg/ https://maritsa.meteo.bg/
Croatia	No	NA
Czech Republic	Yes	NA
Germany	Yes	https://www.hnd.bayern.de
Hungary	Yes	www.hydrionfo.hu www.vizugy.hu
Moldova	Yes	http://www.meteo.md/index.php/hidrologie/
Romania	Yes	www.inhga.ro
Serbia	Yes	https://www.hidmet.gov.rs
Slovakia	Yes	http://www.shmu.sk/sk/?page=1&id=hydro_vod_all
Slovenia	Yes	http://www.arso.gov.si/vode/napovedi/
Ukraine	Yes	https://meteo.gov.ua/ua/
Entire Danube river basin	Yes (near real time forecasts are restricted – archived are freely available)	www.efas.eu

NA indicates that this information is not available (not provided in the questionnaire)

Forecasting accuracy assessment is systematically undertaken only by some individual services, mostly on an occasional basis only, i.e. when looking for improvements in the service's operation or when introducing new technologies, measurements, data transfer, modelling, and similar. Systematic assessments of forecasts are only performed by the European Commission's Joint Research Centre (JRC) – for its EFAS forecasts, covering EU member states and associate members. In terms of forecasting accuracy assessment, the level of confidence into flash floods forecasting and forecasting of floods in the middle and lower river reaches cannot be assessed in the same way. The reason lies in the weak reliability of meteorological forecasts, even with only 24-hour lead-time.

Table 9 summarizes the short- and the long-term plans of the forecasting services. One can see that future plans are relatively similar and forecasting services will work on model development (e.g., better calibration, enhanced model structure), gauging networks improvements (e.g., new stations, modern equipment, denser network), forecasting system development (e.g., use of additional data, use of ensemble forecasts, flash-flood forecasting improvements) and warning process improvement. Moreover, some of the forecasting services also indicated that they will work on media relations (e.g., web-page development, data access, social media such as Twitter or Facebook).

Table 9: Overview of future plans of the Danube River forecasting services based on the provided national and organizational reports (from national reports)

Country / Organization	**Future plans**
Austria	IT system development
Bulgaria	Hydrological forecasting process development (new early warning system, model development), automatic hydrometric stations development (i.e. more stations))
Croatia	Models development, automatic hydrometric stations development (i.e. new modern stations (hydrological, meteorological, air quality, radar, oceanographic buoys,…))
Czech Republic	Models development, widening of the forecast portfolio, flash flood forecasting development, medium-term forecasts for drought events, optimization of gauging network (more stations, use of modern equipment)
Germany (Bavaria)	Use ensemble forecasts, use of supercomputer for hydrological modelling
Hungary	Hydrological forecasting system development (e.g., new 1D hydraulic model), ice-forecasting development
Moldova	Monitoring enhancement and forecasting development
Romania	Flash flood forecasting and warning development, development of snow water equivalent and rainfall grid data, use of ensemble forecasting, hydrological model development, hydraulic model development
Serbia	Hydrological modelling of additional catchment, hydraulic model development, hydrological and meteorological gauging network development (e.g., number of stations)
Slovakia	Forecasting system development (e.g., hydrological models development, use of probabilistic models)
Slovenia	Models development (e.g., Drava, Mura), warning process upgrade, enhanced communication with general public via social media, web-page development
Ukraine	Forecasting system development (use of ALADIN model for prediction, models development), use of meteorological radars, hydrological and meteorological gauging stations development
EFAS	Forecasting system development (e.g., use of additional data, better calibration, model development, use of grand ensemble forecast, better seasonal forecasting, better flash-flood forecasting, increase of spatial resolution), improvement of forecast data access for the EFAS partners
ISRBC	Meteorological data improvement (e.g., spatial coverage improvement, - increase temporal resolution, establish a nowcast,…), hydrological models development (e.g., calibrate models for low and high flows by using observed hydro- meteorological data of sufficiently long record, improvement of the reservoir operation models with real-time data,..), hydraulic model development (e.g., couple the hydraulic model to a hydrological model, calibrate the model for both high and low flows, flood mapping improvement), improvement of computational time taking into consideration also model quality

3.1 Recommendations for development

Based on the evaluation of the national reports and the completed questionnaires, the recommendations for development of hydrological forecasting methods and models are as follows:

- Hydrological forecasting systems for various catchments within the Danube River basin (micro, meso and macro scale) should be developed. Early establishment and capacity development of appropriate teams for development and management of the future forecasting system is strongly recommended.
- The catchment characteristics (size, topography, land cover, river network, slope, etc.), the river flow characteristics (floodplains, reservoirs, diversions, backwater effects, etc.), the hydro-climatic conditions, the forecasting purpose and the administrative conditions and constraints (organisational capability, computational resources, data and weather forecast availability) should be taken into account while making the choice on the appropriate hydrological/hydraulic model to be used. It is strongly suggested to follow the WMO Manual on flood forecasting and warning (2011), the guidelines of the WMO Flood forecasting initiative (Decision-Support for the Selection of Flood Forecasting Models, 2013) as well as the latest literature on flood forecasting techniques and their applications (examples: Jain et al., 2018; Kauffeldt et al., 2016; Adams and Pagano, 2016).
- Systematic forecasting accuracy assessment for the entire Danube River basin.
- Enhancement of the hydrological service relationship with the responsible meteorological service (e.g., data exchange, consultations, joint warnings).
- Improvement of cooperation among the hydrological services within the Danube River basin by organising regular expert meetings on flood forecasting, establishment of regional or bilateral agreements.
- Strengthening the IT support (skilled staff) and the IT capabilities (resources, tools, services) dedicated for flood forecasting in the individual forecasting services.
- Capacity building of the forecasting services on new technologies.
- Hydrological forecasting systems primarily use data from the observation network, which is maintained by the hydrological service. Data measured and collected by individual water users like hydroelectric power plants, water supply and irrigation systems and other users are not included in the forecast system. Therefore, it is recommended to collect all the water regime data in a single database, including data from private companies.
- Limited resources and lack of data limit the development of hydrological models. Furthermore, it is questionable using complex models if there is no data available for their use. Additionally, individual modelling methods were developed in different climates and some processes are treated in the model in more detail than the others are. Therefore,it is recommended to further develop the existing modelling methods and to use various models in the development of hydrological forecasts (ensemble forecasting).

4 Analysis of the flow of data and information and bottlenecks

In the following, the results of data availability mentioned in section 2 are analysed with respect to data exchange and improvement of forecasting conditions (section 3).

4.1 Information flow among neighbouring countries

Along the course of the Danube there are numerous border crossings. At these borders, it is particularly important to have a good exchange of data or even forecasts. If there is no good bilateral cooperation, this can be a bottleneck for a successful flood forecast for the entire Danube River basin. Many countries mentioned below already exchange their data via bilateral agreements.

Figure 1 shows the border crossings at which a flow of information should happen along the Danube and its tributaries. A comprehensive data transfer can lead to an improvement of the forecast results for each country. First, the border crossings along the course of the Danube (1) is analysed. From the origin of the Danube in Baden-Wurttemberg the Danube River flows to Bavaria. From there the first border to another country, Austria, is crossed. From Austria the Danube flows further to Slovakia and along the Slovakian, Hungarian border. Flow of information between these countries is based on bilateral agreement with respect to national data policies. From Hungary, the Danube flows along the border between Croatia and Serbia. As for the countries mentioned before an exchange of information and knowledge is recommendable. The Danube from Serbia flows along the border between Romania and Bulgaria and finally, it meets a triangle of Romania, Moldavia and Ukraine, where an information flow is also of high importance. The above mentioned countries are all involved in the DAREFFORT project, so the project could provide a good basis for a better flow of information and national cooperation. The border crossings of the larger tributaries of the Danube River are also shown in Figure 1, as they also have a considerable influence on the flood forecast. The Inn (2) originates in Switzerland and continues to flow into Austria and Bavaria. The exchange of Information between Switzerland and especially between Austria and Bavaria are of high importance for the flood forecasting for the Danube River. Between Austria and Bavaria there is already a well-established exchange and flow of information regarding flood forecasting. From Italy to Austria, from Austria to Slovenia, then along the Hungarian Slovenian border flows the Drava (3). It finally flows into the Danube in Romania. A good flow of information should take place between these countries, which are connected by the Drava. The Sava (4) flows from Slovenia to Croatia, then Bosnia and Herzegovina and Serbia. Information exchange between these countries is therefore also of high importance. For the Sava River there is already an established network of data exchange provided by SavaHIS. The Morava (5) flows from the Czech Republic along the border between Austria and Slovakia. The Tisza (6) flows from Ukraine along the border between Ukraine and Romania to Hungary and finally to Serbia, from where it flows into the Danube. The Prut (7) flows from Ukraine to Romania. These tributaries should also have a flow of information between the respective countries.

4.2 Bottleneck analysis of update frequencies for real time hydrological and meteorological exchange of data

Which data each country makes available and, above all, in what update frequency, differs greatly between countries along the Danube River. If a downstream forecasting centre works with national data with a higher frequency than an upstream country can deliver, this will be a bottleneck in cross-country data exchange. In this case, data from the upstream country cannot be used optimally by the downstream countries. Figures 2 and 3 show the variables foreseen to be transmitted in the DanubeHIS and their update frequency.

Figure 2 shows the hydrological variables, namely water level (h), discharge (Q) and water temperature (tw), their update frequency and marked possible bottlenecks in data transfer. The upper and middle course countries Germany, Czech Republic, Austria, Slovakia, Hungary, Slovenia, Croatia and Serbia all have an update frequency of one hour or less and provide water level, discharge and water temperature. Therefore, there should be no bottlenecks here. Romania supplies data once or twice a day, which is much rarer than the neighbouring country Serbia. Since Serbia is the upper-lying country, there is no bottleneck in the data flow in this case. Romania, Serbia and Ukraine all have an update frequency of one to two times per day, and the upper stream countries provide the data in equal or higher frequency, so there are no bottlenecks in data transfer in this case. Regarding exchange of the data with Bulgaria, the problem arises, since Bulgaria does not supply any water temperature, which can lead to a major bottleneck in the data exchange. Moldova has a higher update frequency (every 15 minutes) than the surrounding countries. However, since Moldova does not use flood forecasting model (see Figure 5) there is no direct bottleneck here either. However, if Moldova want to process the data of the surrounding countries in the future, the update frequency of the other countries is too low compared to their own frequency.

Regarding meteorological data (Figure 3), the bottlenecks look similar to those recognised for hydrological data. Germany, Czech Republic, Austria, Slovakia, Hungary, Slovenia, Croatia and Serbia all have an update frequency of one hour or less. There should be no problems with the exchange of information and data between these countries. However, individual countries provide different variables. The necessary variable needed in the frame of DAREFFORT project is precipitation, which is provided by all of the countries. At the border crossing between Croatia and Serbia there is a large difference between the update intervals of meteorological data. In Croatia, they are significantly higher comparing to Serbia. However, Croatia does not need data from Serbia with respect to flood forecasting, so there is no bottleneck here. Unlike hydrological data transfer, there is also no bottleneck between Bulgaria and Romania as both provide the required precipitation at the same frequency. On the other hand, Moldova has a higher update frequency of meteorological data than Serbia and Bulgaria. Here a bottleneck would arise, if Moldova would use a hydrological model for which they would need input variables from neighbouring countries. Ukraine also has a slightly higher update frequency of the meteorological data than Romania and Bulgaria, so the data frequency is too low for Ukraine and a bottleneck could appear.

The largest difference between the variables and the update frequency of the data is for ice data. These are shown in Figure 4. In some countries (e.g. Slovenia and Croatia) no ice data is recorded at all. In some countries ice data are recorded by an observer and in the others by automatic stations. Furthermore, the intervals vary strongly, namely from five minutes, over daily, up to only publishing the ice data in yearbooks. In addition, also measured variables vary strongly. All these differences can be a bottleneck for precise predictions.

The density of measuring stations and the frequency of data updates is crucial for the improvement of forecasting systems and the data exchange in the future. In general, we can conclude that a high temporal and spatial measurement density in the catchment area is important for a good flood forecast. This applies not only to the measurements in the country under consideration, but also to the upper reaches. Therefore, a high measuring frequency and a high station density is important to avoid bottlenecks.

Analysis demonstrates that currently the countries use very different hydrological and hydraulic models, which are presented in Figure 5. If we would like to have a Danube-wide forecast in the future, the measured variables of all of the countries, especially downstream countries are needed in a high frequency and density. An alternative way would be to exchange forecasting results. The forecast data of the border regions could then be passed on to the next country as an input data. However, in some countries, there are separate models for individual river basins and in the others, only one model for the entire country is available. However, some of the countries, such as Austria, Slovenia and Croatia, already use similar hydrological and hydraulic models. In order to make a common hydrological forecast for the entire Danube River basin possible, this would have to be further coordinated and expanded.

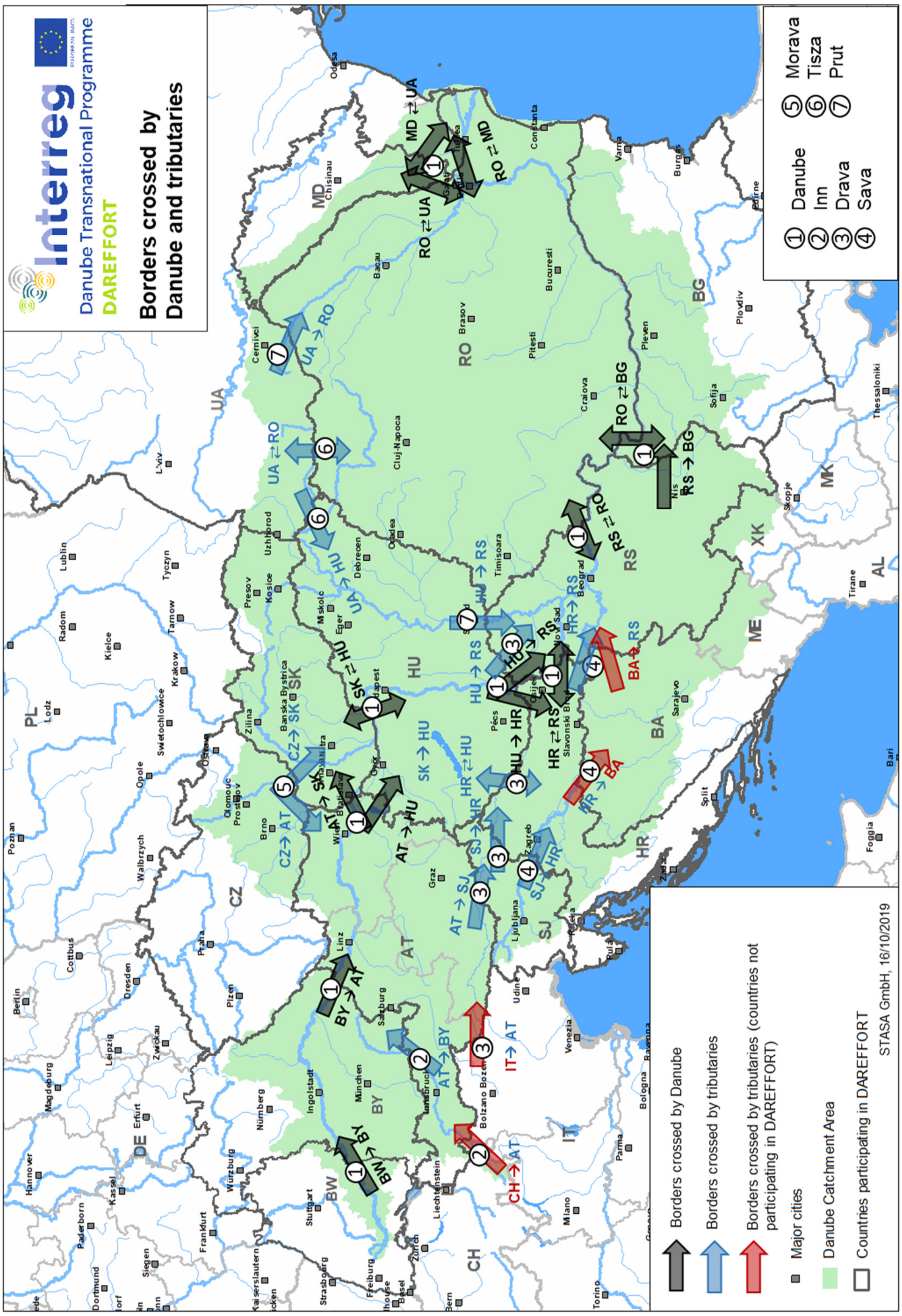

Figure 1: Information flow along Danube and its main tributaries

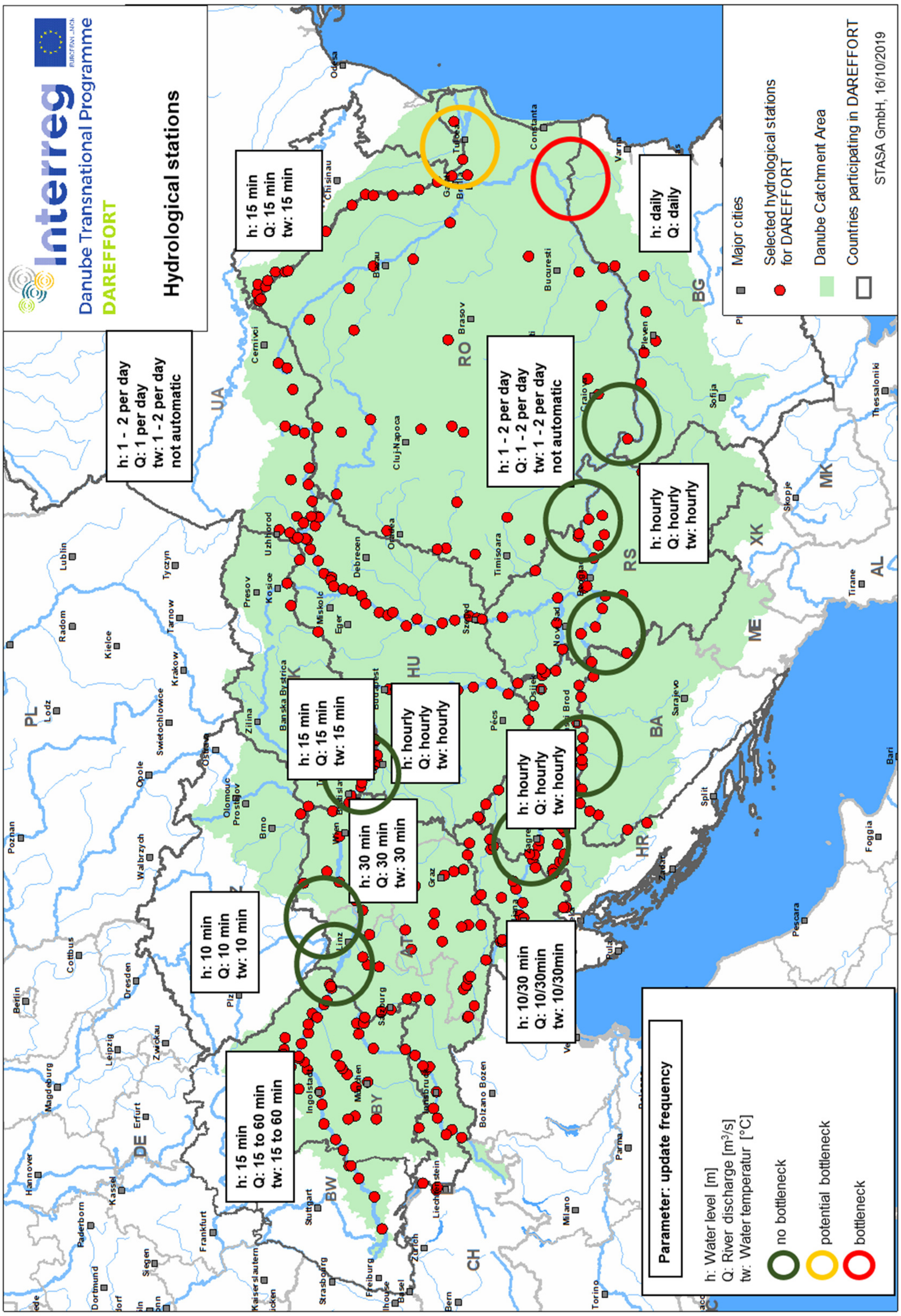

Figure 2: Update intervals for hydrological stations and recognized bottlenecks in data transfer

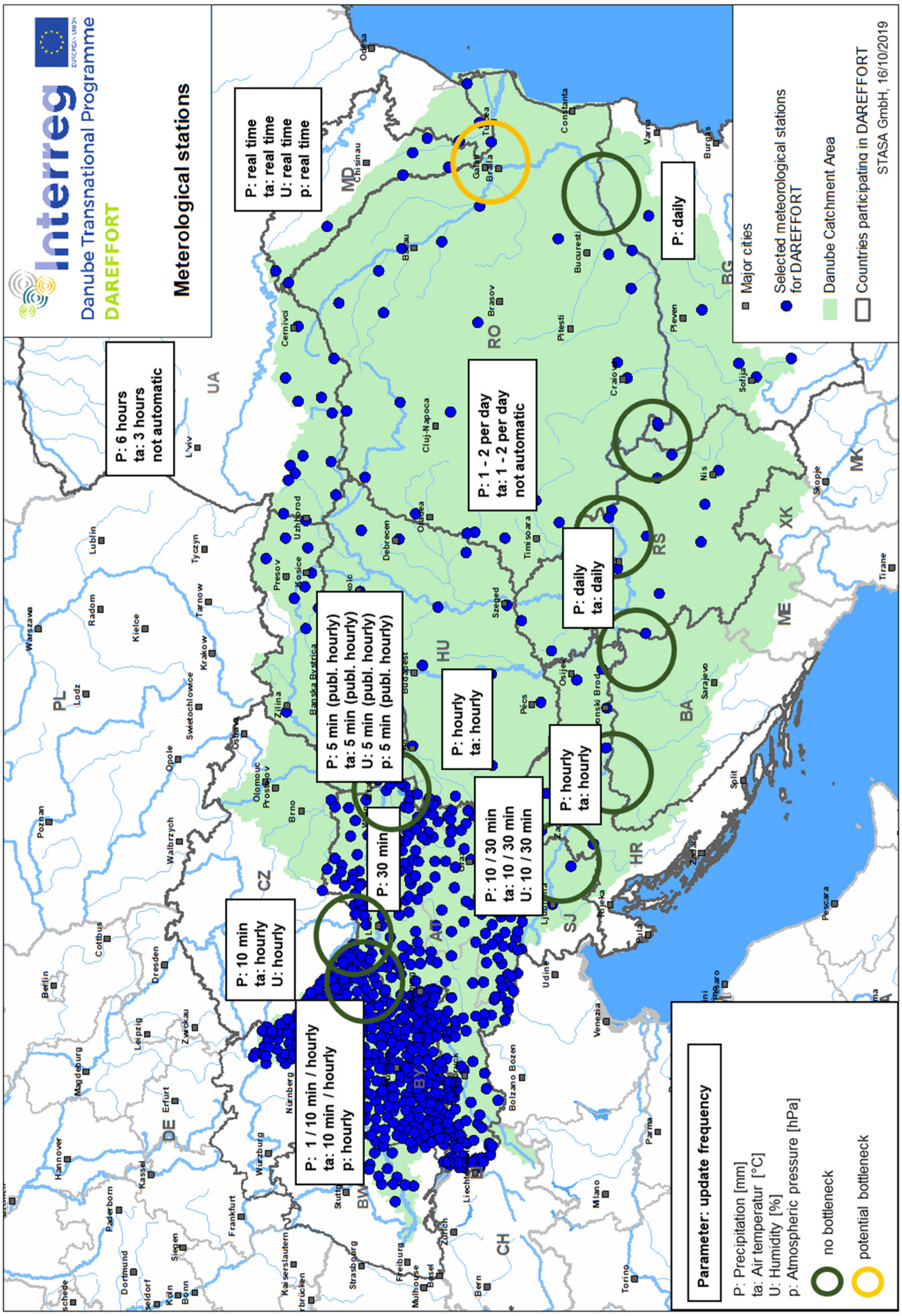

Figure 3 Update intervals for meteorological stations and recognized bottlenecks in data transfer

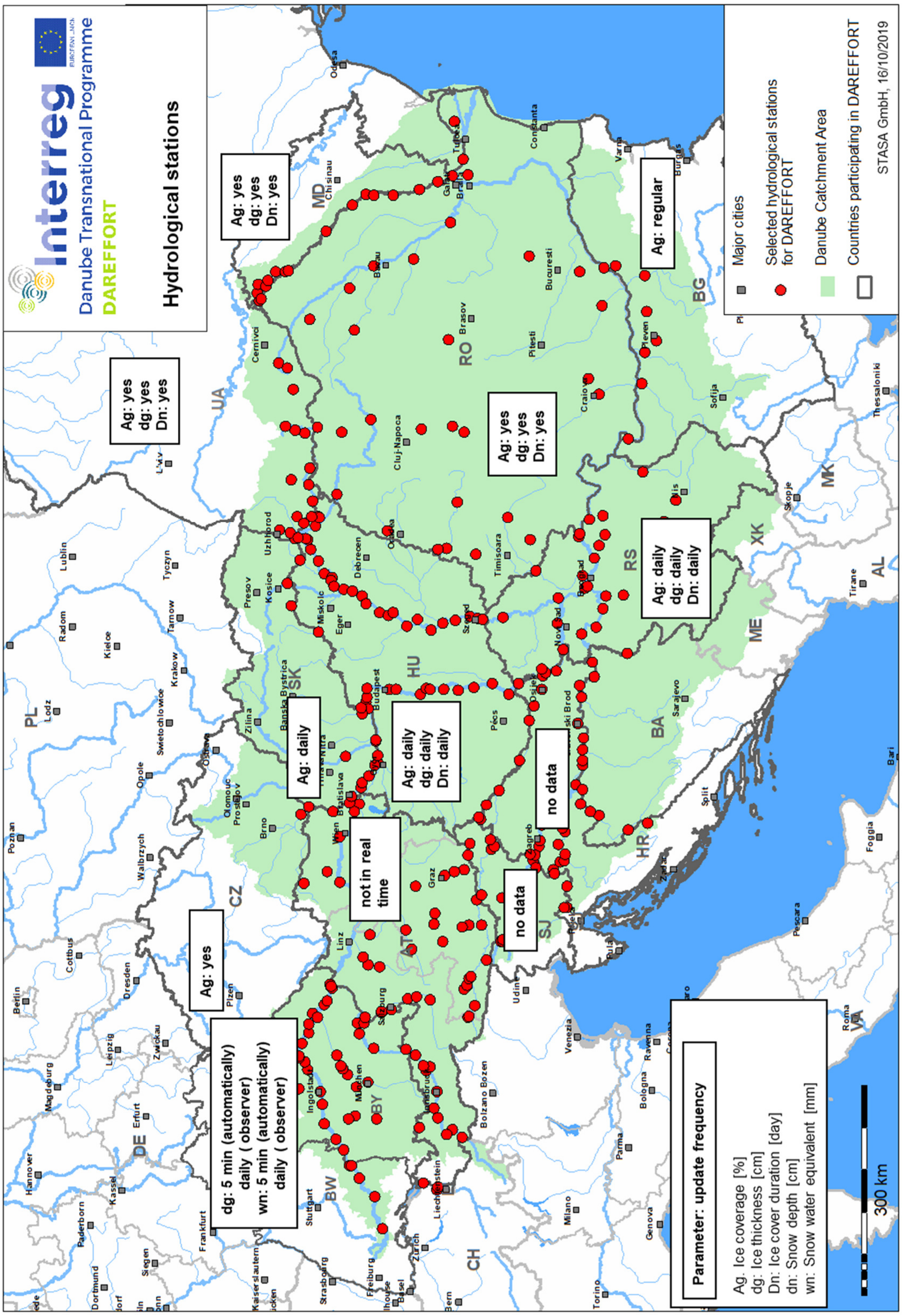

Figure 4: Update intervals of ice data at hydrological stations

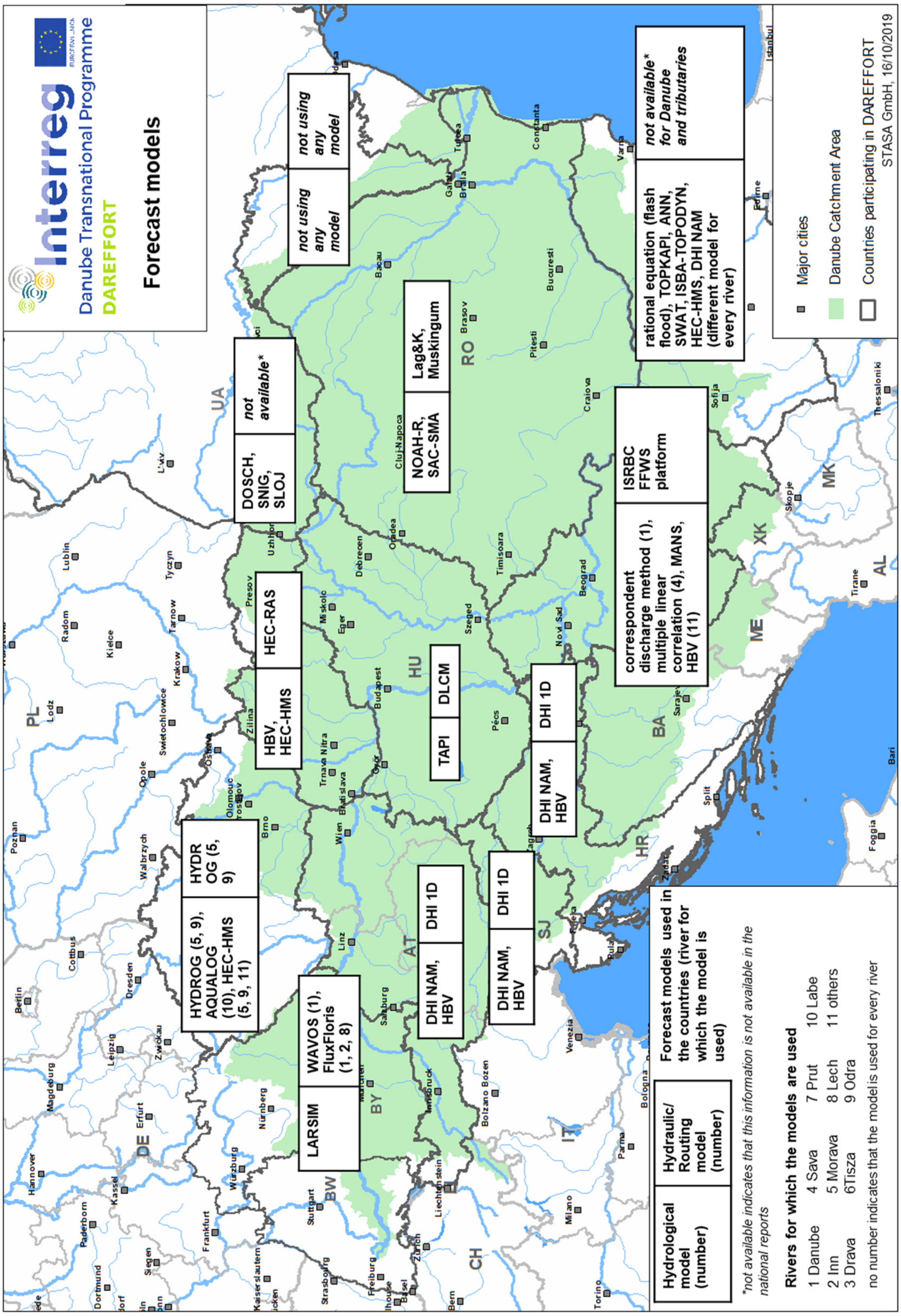

Figure 5: Forecast models used in individual countries