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Flood Forecasting

“Everything should be made as simple as possible, but no simpler.”
Albert Einstein

One of the EUSDR PA5 targets[1] is to provide and enhance continuous support to the implementation of the Danube Flood Risk Management Plan – adopted in 2015 in line with the EU Floods Directive – aiming to achieve significant reductions of flood risk events, while also taking into account potential impacts of climate change and adaption strategies. The target is based on the assessment that there is no uniform specialised training on flood management in the Danube region (DR) and that the lack of knowledge in this domain constrains in many ways the implementation of both the EU Flood Directive and the Danube Flood Risk Management Plan (DFRMP). Noting that there is a need to harmonise flood risk management methodologies in the region, it has also been established that, in general, the Civil engineering curricula at various universities in the region does not put adequate emphasis on flood management issues.

Based on the above premise, the main objective of the project – *International Postgraduate Course on Flood Management* funded by the Danube Strategic Project Fund (DSPF) – is to develop a harmonised international postgraduate course on flood and flood risk management. The course is intended to integrate knowledge and expertise of the participating partners and professionals in the Danube region; the whole project is expected to result in a comprehensive flood management curriculum that offers the possibility for professional development of practicing civil engineers and flood managers throughout the region. The main goal is to offer a possibility for uniform education in this domain in the Danube region based on the EU directives and the EUSDR PA5 targets as well as on the DFRMP needs, state-of-the-art research results and extensive operative experience of the selected lecturers.

Flood forecasting – Scope of the course

Within the context of the overall curriculum, the course material on flood forecasting presented in the text below provides an overview of the following main issues and topics in this field:

- flood phenomena and flooding
- flood forecasting
- the role flood forecasting plays in flood management
- flood forecasting and warning systems (FFWS)

[1] For more information see www.danubeenvironmentalrisks.eu/eusdr-pa5-targets

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- key components of a dependable real time FFWS
- concepts and methods used for modelling of river flow and runoff processes in a river basin and real time flood forecasting
- latest trends and developments in establishing FFWS

In preparing the teaching material the authors, apart from using their own experience, relied on recognised sources and publications in the field of hydrology and hydrological forecasting, including the technical manuals, guides and specialised publications of the World Meteorological Organization (WMO) and UNESCO. Whenever deemed necessary and of interest for better understanding of the lecture material, it will be illustrated with real world examples, primarily focusing on the examples from Europe and the Danube region.

Floods and flooding

Floods are without doubt the most devastating natural disasters, striking numerous regions in the world each year. During the last decades, the trend in flood damages has been growing exponentially. This is a consequence of the increasing frequency of heavy rain, changes in upstream land use and a continuously increasing concentration of population and assets in flood prone areas. In general, all countries in the world are vulnerable to floods, causing damages that significantly affect the national GDP. In the Danube River Basin, important initiatives have and are being devoted to implementing appropriate countermeasures, both structural and non-structural, to alleviate the threats of water-related disasters. The worldwide impact of flooding is alarming and the UNESCO World Water Assessment Programme provides a clear evidence to this effect. Figure 1 shows the significance of flooding in the context of all water-based natural hazards.

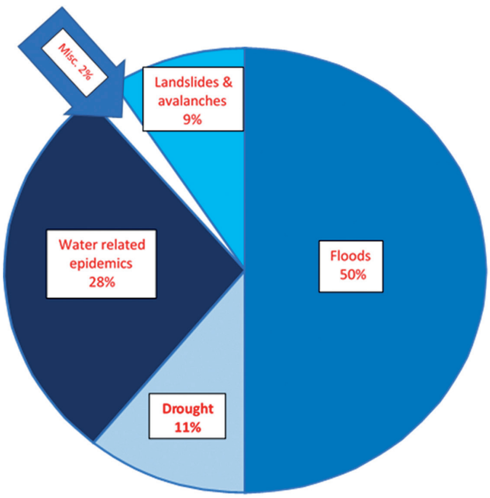


Figure 1. Types of water-related natural disasters, 1990–2001 (adapted from [24])

Floods account for more than 15% of all deaths related to natural disasters; for example, between 1987 and 1997, 44% of all flood disasters affected Asia, claiming 228,000 lives (roughly 93% of all flood-related deaths worldwide). Economic losses for this region totalled US$ 136 billion.

Many deaths have been caused by floods in the European countries as well. The 2002 floods in Europe claimed 100 lives and caused circa US$ 20 billion in damage. Over 12% of the population of the United Kingdom of Great Britain and Northern Ireland lives in fluvial flood plains or areas identified as being subject to the risk of coastal flooding while about half the population of the Netherlands lives below mean sea level.

With respect to the Danube Region, it has been estimated that close to 15% of all the population in the region lives on the flood plains of the River Danube and its tributaries. Memories are still fresh of the disastrous floods that hit the Sava River Basin in May 2014. By volume, the Sava River is the largest Danube tributary, with an average discharge of about 1,700 m^3/s, which accounts for almost 30% of the Danube's total discharge at the confluence of the two rivers in Belgrade.

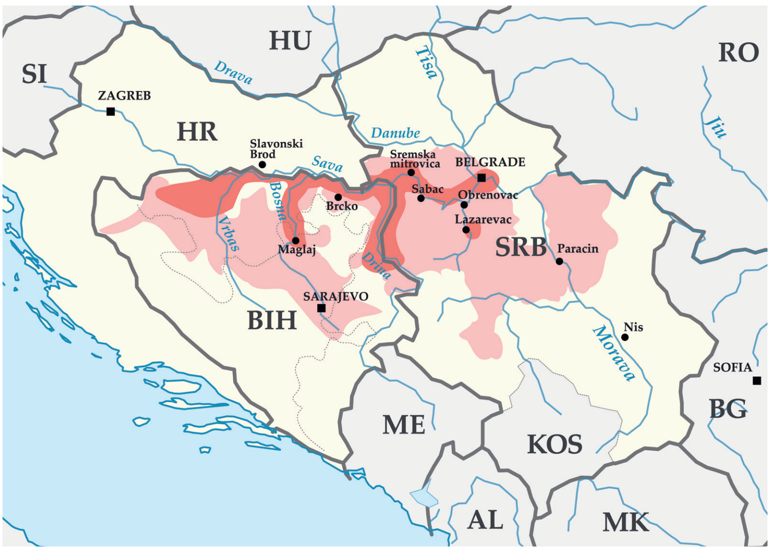


Figure 2. Areas in Croatia (HR) Bosnia and Hercegovina (BIH) and Serbia (SRB) affected by the May 2014 floods (2014 Southeast Europe floods; https://en.wikipedia.org)

The May 2014 floods in the Sava region affected large areas in Croatia, Bosnia and Hercegovina and Serbia along the Sava river and its tributaries (Figure 2). It resulted in 79 casualties and substantial economic damage in the three countries, assessed in the range of 3.0–3.8 billion Euros.

With the frequency and variability of extreme floods changing because of urbanisation, along with population growth in flood-prone areas, land use changes, climate change and a rise in sea levels, the number of people vulnerable to devastating floods is expected to rise. Adequate flood management and flood risk reduction actions are increasingly required to build up the capacity necessary to cope with floods. Flood Forecasting forms an important tool in reducing vulnerabilities and flood risk, and forms an important ingredient of the strategy to "live with floods", thereby contributing to national sustainable development.

Types of floods

There are quite a few definitions in use for the term "floods"; for consistency and to avoid possible confusion, we will use WMO/UNESCO International Glossary of Hydrology [25]. This widely recognised Glossary represents an informal world standard, in which all terms are defined in several international languages.

The Glossary defines "flood" as follows:

1. Rise, usually brief, in the water level in a stream to a peak from which the water level recedes at a slower rate.
2. Relatively high flow as measured by stage height/water level or discharge.
3. Rising tide.

Note that, unlike in some other languages, in English the term "flooding" signifies the effects of a flood as distinct from the flood itself, i.e. "flooding" is defined as "overflowing by water, due to flood, of the normal confines of a stream or other body of water, or accumulation of water by drainage over areas that are not normally submerged".

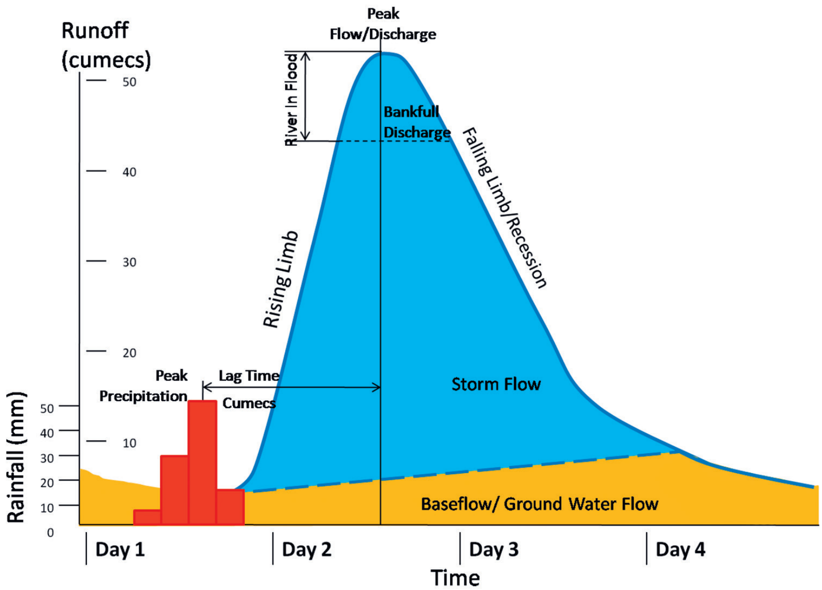


Figure 3. Illustration of a typical flood hydrograph overflowing river banks and causing flooding (https://mappedmusings.wordpress.com/tag/hydrograph/)

The Glossary gives definitions of a wide range of terms used in relation to floods and flooding; there is no need to catalogue them all here, but only to highlight the main features of different flood types.

Flash floods. These floods are frequently associated with violent convection storms or thunderstorms of a short duration falling over a small area. Flash flooding can occur in almost any area where there are steep slopes; it is common in mountainous regions subject to frequent severe thunderstorms. Flash floods are often caused by heavy rain of short duration. Flooding caused by flash floods frequently washes away houses, roads and bridges over small streams and has a critical impact on communities living in these often-remote areas.

Fluvial floods. This type of floods, causing fluvial flooding, occurs over a wide range of river basins. Floods in river valleys occur mostly on flood plains as a result of flow exceeding the capacity of the steam channels and spilling over the natural banks or erected embankments. Compared to fluvial floods, flash floods are often more damaging, occurring in narrow, steep and confined valleys, characterised as the name implies by the rapidity of formation and high flow velocities, which makes them particularly dangerous to human life.

Single event floods. This is the most common type of floods and flooding; widespread heavy rains over a drainage basin – lasting several hours to a few days – result in severe floods. Typically, these heavy rains are associated with cyclonic disturbance, depressions and storms with well-marked largescale frontal cloud systems.

Multiple event floods. These result from heavy rainfall associated with successive weather disturbances following closely after each other. On the largest scale, they often include floods in the large river plains in central Indian regions often caused by the passage of a series of low-pressure areas of depressions from the Bay of Bengal. This type of floods can also affect large basins in mid-latitude areas in winter, for example over the western Europe and also in the Danube region.

Seasonal floods. These floods occur with general regularity as a result of major seasonal rainfall activity, and mainly affects the areas with a monsoonal type of climate. As such they do not affect Europe and the Danube region (mentioned just for completeness).

Coastal floods. Storm surges and high winds coinciding with high tides are the most frequent case of coastal flooding. The surge itself is the result of the rising sea levels due to low atmospheric pressure. In a particular configuration, such as large estuaries or confined sea areas, the rising water level is amplified by a combination of factors (such as shallowing off the seabed and retarding of return flow). This type of floods affects major deltas such as the Mississippi, Ganges, Irrawaddy and also the Danube delta.

Tsunamis, resulting from sub-seabed earthquakes are a very specific cause of occasionally severe coastal flooding.

Urban floods. Urban flooding occurs when intense rainfall within towns and cities creates rapid runoff from paved and built-up areas, exceeding the capacity of storm drainage systems. In low-lying areas within cities, the formation of ponds from runoff occurs not only because of high rainfall rates but also due to drainage obstructions caused by debris blocking drainage culverts and outlets, often because of lack of maintenance.

A number of major cities situated in delta areas, such as for instance New Orleans, Dhaka and Bangkok, are protected by embankments and pumped drainage systems. When rainfall rates exceed the pumping capacity, the rapid accumulation of storm runoff results in extensive urban flooding.

Snowmelt floods. In upland and high-latitude areas where extensive snow accumulates over winter, the spring thaw produces meltwater runoff. If temperature rises are rapid, the rate of melting may produce floods, which can extend to lower parts of river systems. This type of floods occurs regularly in the Danube region.

The severity of meltwater floods will increase if the thaw is accompanied by heavy rainfall and can further be exacerbated if the subsoil remains frozen or is already saturated to its full field capacity. Although a seasonal occurrence where major snow fields exist in headwaters, which may produce beneficial flooding in downstream areas, severe effects can occur on smaller scales, especially in areas subject to changes between cold and warmer rainy winter weather.

Ice- and debris-jam floods. In areas that experience seasonal melting, if this is rapid, ice floes can accumulate in rivers, forming constrictions and damming flows, causing river levels to rise upstream of the ice jam. A sudden release of the "ice jam" can cause a flood wave similar to that caused by a dam break to move downstream. This type of flood occurs occasionally in the Danube region as well.

Both meltwater and heavy rainfall in steep areas can cause landslips, landslides and debris flows. As these move downstream, major constrictions can build up. When these collapse or are breached, severe flooding can result. Both of these phenomena are very difficult to predict.

Types of basins, processes and flood response

There is a wide range of river basins and systems all of which react in a specific manner to heavy rain, storms, or combined effects of sea and inland meteorological and hydrological/hydraulic conditions. In general, it is possible to define six main types of basins according to their temporal and spatial response to the hydrometeorological event, as follows:

1. Urban basins, densely populated with a high proportion of impermeable surfaces (small, up to a few square km); they respond in one or two hours and can overwhelm the capacity of the urban drainage network.
2. Upper watersheds and small to medium catchments, of an area between 10 and 500 km^2, which will respond in a few hours. The catchments located in upland areas with steep slopes react quickly causing flash floods.
3. Medium-sized rivers (with an area between 500 and 10000 km^2); they are characterised by relatively long-distance flow propagation with varying contribution of tributaries. In these basins flood can take days to affect the lower reaches.
4. Large river basins with an area of over 10,000 km^2 are characterised by long distance flow propagation for which flood response is in terms of weeks and reflects major seasonal meteorological conditions.

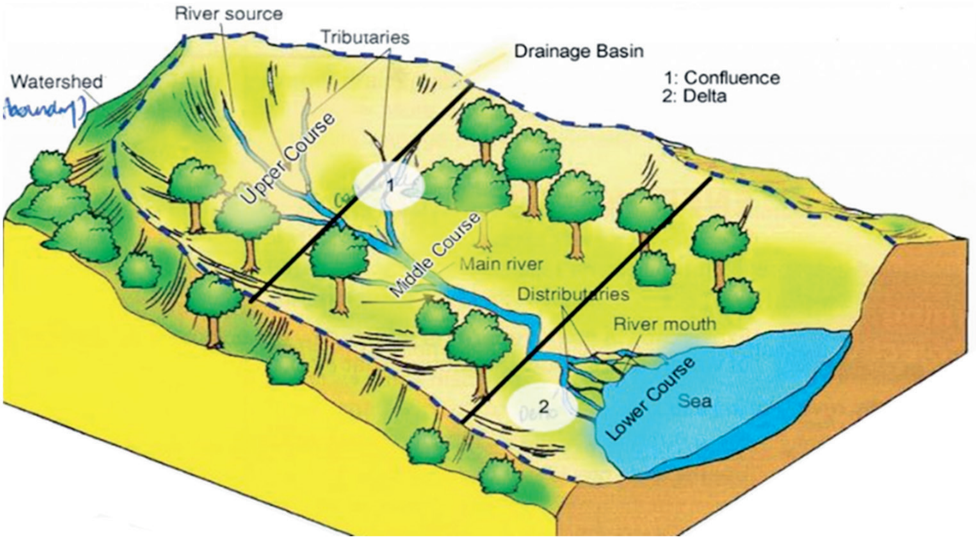


Figure 4. Illustration of a typical large river basin with its parts (adapted from https://teamgeographygcse.weebly.com/)

5. The very specific domain of river deltas and estuaries, which are under combined influence of maritime storm surge, tide effects and upstream incoming flood.
6. Groundwater-controlled river systems, subject to long periodic fluctuations of the water table.

Any forecasting service is above all dependant on the types of flood causing physical processes in the basin. Table 1 illustrates interaction between the basin size, the relevant physical processes/events and their effect on flood response.

Table 1. Interaction between basin size, physical processes/events and their effect on flood response [29]

Type of basin	**Physical process**						
	Wind	Infiltration	Rainfall intensity	Runoff	Propagation	Tide and surge	Water table
Urban		X	XXX	XXX	X		
Upper basin		XX	XX	XXX	X		
Long/large river	X		X	XX	XXX		X
Estuary	XXX				XX	XXX	
Aquifer	X			X		X	XXX

Legend: xxx – dominant effect; xx – normal effect; x – minor effect

The main processes in both the upper and urban catchment areas refer to interaction of infiltration and runoff that combine to produce high flow concentration in lower river reaches and low-lying basin areas. When it comes to long, large rivers, which by their very nature have large sub-basin areas, the combination of sub-basin floods and the way they combine along the main river – whether their flood peaks occur at different times or coincide, i.e. occur almost synchronously – will affect the way a flood propagates towards the lower reaches.

The Danube River Basin

Almost everything is known about the Danube, the largest river in the European Union; yet, it may be of interest to repeat a few basic facts and highlight issues related to floods and flood risks in the Danube River Basin.

The Danube River (Donau in German, Dunaj in Slovak, Duna in Hungarian, Dunav in Serbo-Croatian and Bulgarian, Dunărea in Romanian, Dunay in Ukrainian) with a total basin area of 801,463 km² is the second largest in Europe (after the Volga river). It rises in the Black Forest mountains of Germany and flows for some 2,850 km to its mouth at the Black Sea – with an average discharge at the mouth of 6,500 m^3/s. Along its course, it passes through 10 countries – Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Romania, Moldova and Ukraine – whilst more than 80 million people from 19 countries share the Danube catchment area, making it also the world's most international river basin.

It is usually divided into three major sub-regions – the Upper, Middle and Lower Basins (the latter including the Danube Delta). The Upper Basin extends from the source in Germany to Bratislava in Slovakia. The Middle Basin is the largest of the three and extends from Bratislava to the dams of the Iron Gate Gorge on the border between Serbia and Romania. The lowlands, plateaus and mountains of Romania and Bulgaria form the Lower Basin of the River Danube. Before reaching the Black Sea, the river divides into three main branches, forming the Danube Delta, which covers an area of about 6,750 km².

Flooding is the most common and most costly natural disaster in Europe; as evident from Figure 5, the Danube basin is no exception. In fact, large areas throughout the Danube basin are exposed to flood risks, and every type of flood outlined in the previous section can occur.

The increasing regularity of dangerous hydrological and meteorological phenomena in the basin has become a major cause for concern in Europe. Scenarios of the European Environmental Agency[2] predict that flood damage and the number of people affected by flooding will rise substantially by 2100 as a result of climate change, with one scenario estimating a rise in flood damage by some 40% and an increase in the number of people affected around 242,000, i.e. by about 11%.

From historical records and written chronicles, there is evidence about 78 significant floods that occurred along the Danube over the last nine centuries while 23 of them took place in the 18th century before extensive flood protection works were started.

[2] For more information see www.eea.europa.eu

Figure 5. The Danube River Basin and its major flood hazard areas – catchments > 4,000 km² (www.danubegis.org/maps)

Recent years saw an increase of flood frequency, and high-water marks have set records three times since August 2002 whilst five of the most significant floods in history have occurred in the last 10 years. Multi-annual averages of precipitation have been exceeded by 1.5 to 2.0 times recently, a maximum that was never before observed since systematic meteorological measurements have been available. Cognizant of the worsening situation, the EU eventually formalised flood management in 2007 through its Flood Directive. The International Commission for the Protection of the Danube River (ICPDR) established three years earlier, i.e. in 2004, its own long-term action programme for sustainable flood prevention in the basin, which was instigated by the disastrous floods that occurred in August 2002 in the Danube River Basin. The ICPDR also coordinates the implementation of the EU Flood Directive in the Danube Basin.

The role of flood forecasting in flood management

The need for flood forecasting and warning systems comes as a consequence of the limitations of structural flood protection systems. Due to the existence of settlements in flood-prone areas and to the need to meet community safety and protection of assets, the provision of an adequate flood forecasting and warning service is a necessity. Forecasting and warning services are, in most cases, provided by national state agencies; their main goal is to deliver reliable and timely information to the flood managers, civil protection agencies as well as to the general public. This should be accomplished with long enough lead time of forecast to allow people to take measures to protect themselves from flooding or take appropriate actions.

As no preventive or flood defence measures can ever be completely effective, flood forecasting constitutes a crucial part of flood management. The reality of economic limits to the provision of a flood defence system, together with the possibility that the capacity of defence systems may be exceeded, or may fail, require that other measures should be in place.

This is the reason why flood forecasting forms a part of flood management planning and development strategies, which recognise that there are occupied flood plain areas where non-structural measures can be effective. Flood management requires a variable degree of response from the water management agency, local or municipal authorities, transport and communications operations and emergency services. Flood forecasting has to provide information to these users both for preparation and response: at the most extreme level, flood forecasting is part of the wider disaster management capacity, which devolves from the highest level of government.

The precise role of flood forecasting varies depending on the circumstances dictated by both the hydrological and meteorological conditions and the built infrastructure, i.e. the flood risk areas in question. Cities present different problems from rural areas. Location of flood risk areas in relation to rivers, coasts or mountain ranges has a significant bearing on the types of flood forecasting required. The nature and type of floods and flooding events is also important, particularly whether floods are regular in occurrence (as for example in a highly predictable seasonal climate, such as monsoon or hurricane seasons) or highly irregular, such as violent thunderstorms.

No less important is to note the vital role that the flood forecasting and streamflow forecasting in general play in management and optimal operation of reservoirs and river flow regulation.

There is no design carved in stone for a flood forecasting system. The balance between particular components of the system, such as for example meteorological input and hydrological forecasts, scale and timing, have to be adapted to circumstances. Within a given country, a number of different flood types are usually encountered, and each will require a different forecasting approach. Headwater areas may require a system concentrating on flash floods, whereas flood plain areas may need a system to be focused on the slow build-up of flooding and inundation.

The nature of flood risks and impacts

Flood risks are related to hydrological uncertainties, which are also linked to social, economic and political uncertainties. In characterising future flood risks, the biggest and most unpredictable changes are expected to result from population growth and economic activity. This can be demonstrated by the historical development of coping with flooding, where the initial resilience of a largely rural population is lost by more complex societies. Flood risk management consists of systematic actions in a cycle of preparedness, response and recovery and should form a part of Integrated Water Resources Management (IWRM). Risk management calls for the identification, assessment and minimisation of risk, or the elimination of unacceptable risks through appropriate policies and practices.

Flood forecasting and warning activities are largely designed to deal with certain design limits of flooding. For example, depending on a range of probabilities of harmful damage, and available monitoring facilities, modelling and operational forecast systems can be set up in relation to known risks and impacts. In particular, these will focus on areas of population, key communications and infrastructure and the need to operate effective responses to flood. The magnitude of flood events and hence impacts are variable, so flood forecasting and warning has to operate over a range of event magnitudes. These vary from localised, low impact flooding, which can be countered by relatively simple measures, such as installing temporary defences, closing flood gates and barriers, to larger scale flooding, where property damage and losses occur, road and rail closures arise and evacuation of areas at risk takes place. Defence and remedial measures are designed or planned to operate up to a particular severity of flooding, which may be designated as having a particular probability. The measures are related to an economic decision relating costs against losses. Typical design criteria are 100 years (an event that is considered to have a 1% chance of occurring in any given year) for urban areas with key infrastructure, 50 years (2%) for lesser population centres and transport facilities, 20 years (5%) for rural areas and minor protection structures.

Beyond the limits of designed flood management and particularly for catastrophic events, for example dam or embankment failure, some aspects of flood forecasting and warning provisions may not be fully effective. However, it is important that in these cases monitoring facilities are sufficiently robust, as some continuing observations will be of vital assistance to emergency response and relief activities. In this respect, resilience of monitoring instruments, their structure and telemetry, are of considerable importance, especially as on-the-ground reporting may become impossible.

Flood forecasting systems: Main aspects

To avoid possible confusion, before entering into discussion about hydrological forecasting systems, there is a need to clarify the meaning of forecasting as other terms are also frequently used for the same pursuit. Quite often the term hydrological prediction is used as a synonym for hydrological forecasting even though they signify two completely different concepts [16].

What does forecasting really mean?

Classical definition of hydrological forecasting [28] reads as follows: a hydrological forecast is the estimation of future states of hydrological phenomena. In its revised and expanded version it reads [24]: a hydrological forecast is an estimate of the future state of some hydrological phenomenon, such as flow rate, cumulative volume, stage level, area of inundation or mean flow velocity, at a particular geographical location or channel section.

Both definitions are talking about point estimate without dealing with uncertainty (and hence risk!) that is unavoidable in making forecasts. The question asked in this context is: How much and when? For instance, in the case of a single event forecast one asks the question: how much will the maximum peak flow and/or peak water level be and when in time that maximum will occur? As another example, the relevant question in the case of continuous forecasting is as follows: How much will the flow and/or water level be one time step ahead from now on, two steps ahead, three steps ahead and so on? In this example, the time variable is not changing but is fixed and is incremental in an equidistant fashion and, in fact, one is seeking to forecast expected values of the entire future hydrograph at an ordered set of discrete time intervals. Therefore, one can state the following: the sequence of expected future values is a series of point estimates. These point estimates are the continuation of the past and present history of the hydrograph into the future.

The same principle applies to hydrological variables as to any other dynamic phenomena that is changing in time: the past and the present condition the future. Therefore, the best estimate of the expected value of the future outcome of a dynamic process (be it hydrological or any other) is the conditional mean (providing the related uncertainties are Gaussian).

As much as the conditional means may be smart, they say nothing about the associated uncertainties in the future that, in turn, characterise the reliability of future forecasts. Intuitively, however, one feels that as the lead time of forecast increases so does the level of uncertainty, i.e. the longer the lead time, the less reliable forecasts are.

The question is how can this uncertainty be reflected in the definition of forecast? The answer is relatively straightforward and points to the probabilistic analysis of forecast errors for there are evidently errors in our forecasts one step ahead, two steps ahead, and so on. These forecast errors scatter around the conditional means and they have their own statistical distribution; so if we are able to measure somehow what those scattering deviations are, we are equally able to estimate how reliable our forecasts are. So, providing that the forecasting errors have Gaussian (normal) distribution, which is a fairly reasonable assumption, the first and the second statistical moment – i.e. the mean and the variance (or its square root, the standard deviation) – are sufficient to characterise error distribution. Now, using the same arguments that were applied in arriving at the conditional mean as best linear unbiased estimate, the best estimate for the variance of the error sequence for a given lead time of forecast is the conditional variance. To conclude, if we need to establish the best forecast s-steps ahead, along with finding the measure of the corresponding forecasting uncertainty, we have to determine the conditional probability distribution of the hydrograph s-steps ahead, conditioned by the past and present information about that hydrograph.

In view of the above considerations, we can now revise the above classical definition of hydrological forecasting to read as follows [16]: Hydrological forecasting is the identification of the expected occurrence of a hydrological event specified with respect to its actual time of occurrence, its quantitative measure and its reliability (i.e. measure of uncertainty) as conditioned by available past and present information about the event.

So instead of asking in this context – How much and when? – our question on hydrological forecasting would in essence be this: How much, when and how certainly?

Having come this far, we can now ask what the hydrological prediction is then. The question that one asks in this context is this: How much and how often? Note that this is an entirely different question, and opens up the domain of hydrological frequency analysis, that is an entirely different concept from the one applied in real-time hydrological forecasting.

Type of forecast service

The processes occurring in the catchment can be monitored and forecasted by a combination of observations, measurements and modelling. It is necessary to design a flood forecasting and warning service based on a given type of catchment, physical processes and their effect on flood occurrence. Apparently, upland and urban catchments require different type of service and approach to monitoring and modelling than the large catchment areas. The former catchments present particular challenges in assuring flood forecasts with sufficient lead time for taking timely mitigation measures. Here, the emphasis must be on effective continuous real-time monitoring and rapid transmission and processing of data rather than modelling.

In large basins the lead time of forecast may not be so critical so that data sampling may only be necessary at intervals of several hours. In these basins more emphasis need to be placed on identifying distribution and patterns of rainfall that occur, and on observation of the hydrological response in the contributing sub-basins. To be noted that some large catchments have also problems with drainage congestion, which can arise when water level in the main river is high thus ‘congesting’ incoming floods from the smaller sub-catchments and causing flooding of the adjacent low-lying areas.

The most advanced form of forecasting and warning service that can be provided deals with forecasts of water levels and discharges together with information on the associated inundation extent and depth. However, such a high level of service is easy to offer even in the most developed countries, and is usually restricted to limited areas of high economic importance and highly populated districts. The level of service is largely dictated by the cost of instrumentation, monitoring network, high resolution mapping as well as by the complexity of modelling.

The type and level of forecasting and warning service that can be provided usually represent a balance between the technical feasibility to forecast the flood hazards and the economic justification for protecting vulnerable populations, important areas and infrastructure. Different types of forecasting services – from basic minimal levels to those of high quality and sophistication – can be summarised as follows:

Simple threshold-based flood alert: this basic service relies on real-time hydrological measurements along rivers. It does not deal with quantitative forecasting but qualitative estimation of the increase of river flow or water level. No hydrological or hydrodynamic model is required as hydrograph trends are extrapolated based on experience to estimate if and when critical threshold levels may be reached.

Flood forecasting: this higher-level service is based on the use of simulation tools and modelling. The tools can include simple methods such as statistical curves, level-to-level correlations or flood time-of-travel relationships; they allow a quantified and time-based forecast of water level to provide flood warning to an acceptable degree of reliability (i.e. the measure of uncertainty). Whether this simple approach is used, or a more sophisticated one – through models that integrate and replicate the behaviour of rivers throughout the basin – the simulation tools must be calibrated beforehand by using historical data from recorded floods. The simulation methods also need regular updating to ensure that catchment relations remain properly identified. The information delivered by a warning service is not confined to station locations, as in the flood alert, but can be focused on specified locations at risk.

Vigilance mapping: one step up service compared to the flood forecasting above. Flood forecasting and warning services produce a map-based visualisation (i.e. 'vigilance map') as an Internet service. The maps provide information on the levels of risk derived from observations and models, and are characterised with a colour code (e.g. green, yellow, orange, red) indicating the severity of the expected flood.

Inundation forecasting: This is the most sophisticated service that can be delivered to the public. It requires the combination of a hydrological or hydrodynamic level-and-flow model, that also deals with forecast uncertainty, with digital representation of the flood plain land surface. The level of detail and accuracy of the terrain model depends on the nature of the area at risk. The greatest level of complexity should be applied to sensitive areas of flood plain, where flood extent is dictated by minor relief, and to urban areas. Such models do have the ability to predict flooding to very precise locations, for example, housing areas or critical infrastructure locations such as power stations and road or rail bridges. The development of this approach also requires an in-depth knowledge of inundated areas from previous severe events.

Forecast lead time

The lead time of a hydrological forecast [24] is the period from the time of making the forecast (that is, the time origin of the forecast) to the future point in time for which the forecast applies. Definitions of categories of lead time are subjective, depending on the size and type of the catchment within a particular region or even country. In addition, it also depends on the type of flood, processes in the catchment that cause floods, real time information available, and capability of hydrological and meteorological models used.

However, the basic principle for assessing forecast lead time requirements is the minimum period of advance warning necessary for the preparatory action and for the flood mitigation measures to be taken effectively. This will depend on the needs of the target community or area. Individual householders and businesses may require from one to two hours to move vulnerable items to upper storeys or put sandbags or small barriers in place. Protection of larger infrastructure, setting up of road diversions and movement of farm animals to a place of safety may require lead times of several hours. On large rivers with a long lead time but major potential impact, the lead time for evacuating populations at risk may be in the order of days. Thus, the concept of forecast lead time has to be flexible and the minimum time may be entirely dependent on the catchment characteristics and the forecasting and warning system facilities. For small and urbanised catchments, flood response time may be so short that it is extremely difficult to provide an effective warning. If a high-risk, high impact situation exists, then the problem of short lead times has to be addressed by sophisticated automated alarm systems linked to real-time hydrological and hydraulic modelling.

The situations presented below illustrate some of the issues affecting forecast lead time:

In situations where only forecasts available are based on historical water level records, extrapolation of the water level graph over a period of a few hours is possible (hence, the forecast lead time equals a few hours), depending on the catchment characteristics and nature of the causative event.

In the case that telemetric rain gauge data or radar rainfall information are available, these can provide additional advance warning. In this case, an experienced forecaster using subjective judgement can estimate the likely flood response time. In a more sophisticated procedure, data can be used as input into a hydrological forecast model, thus extending the forecast lead time.

Further to the situation described above, forecast lead time can further be increased if a rainfall forecast is available, from a meteorological service based on numerical weather prediction (NWP) models. If this forecast can be presented as input to the catchment forecast model, several hours may be added to the flow-forecast lead time. This presumes a high level of cooperation between the meteorological service provider and the flood forecasting and warning service, i.e. if these two services are institutionally separated and independent of each other as is the case in some countries in the Danube basin and elsewhere.

Data and technical requirements

Precise details concerned with data and technical requirements depend on the particular nature of a flood forecasting and warning system and its objectives. In general, the overall technical requirements of an advanced reliable flood forecasting system are as follows:

- A real-time data collection subsystem that includes meteorological information, discharge data at the appropriate gauged sections of the river, or water levels and rating curves, and also soil moisture measurements when required. The subsystem may have manual or automatic recording gauges, data collection platforms, radars, satellites, airborne sensors and extensive use of GIS for presenting available information in a useful format.
- Access to the outputs of a numerical meteorological forecasting subsystem, i.e. numerical weather prediction (NWP) models to serve as meteorological forecasting inputs, such as the quantitative precipitation forecast (QPF) during the required lead time of the flood forecasting model.
- A subsystem to combine data from various sources and to provide a feedback mechanism for recalibration of measuring tools and techniques, and initialisation of model error correction.
- A catchment model subsystem, with a user friendly interface, to calculate discharge at the catchment outlet at required time intervals, along with a corresponding estimate of uncertainty.
- A subsystem comprising of a hydrodynamic or a hydrological channel routing model to calculate movement of the flood wave along the channel, the water levels, the effects of dyke breaches and reservoir operation, and the interaction with the flood plain and flooded areas, giving a flood inundation forecast.
- An error correction subsystem with an algorithm for improving the estimates of discharge based on the latest feedback from observed river-gauge data.
- A subsystem for tide or estuary modelling in case of backwater effects influencing the flood flow regime.
- Appropriate communications, GIS networks and decision support systems, producing forecast details at various levels and map forecasts showing flood inundation in real time.

Among all technical requirements given above, a need for adequate data represents a fundamental prerequisite for establishing and operating any flood forecasting system. A short overview of the main data types of a flood forecasting system is given further in the text.

Hydrological data essentially relate to measurement of river flow and water level, and the monitoring instruments should be able to record accurately peak values of both. A network of stream gauges is required for flood forecasting while the nature and composition of the network is determined by required lead time of forecast, forecast accuracy as well as the location of forecast profiles. The forecast profiles usually coincide with a location of hydrological station, as the most convenient solution for modelling river flow, model calibration and verification as well as for operational verification of the issued forecasts. At each such hydrological station, an accurate stage-discharge relationship (also called rating curve) should be established and maintained. Moreover, these stations should be equipped with telemetry links to the operational forecast centre.

However, forecast points can and need also to be designated to a specific reach of a river where flood impact is potentially high, for example near towns, important industrial facilities or agricultural areas.

Meteorological data. Rainfall intensity and duration, quantitative precipitation forecasts and historical precipitation data (for calibration of rainfall-runoff models) are all necessary prerequisites to develop and operate a successful flood forecasting and warning system. Meteorological data and forecasts are required in real time to maximise the lead time for flood forecasts and warnings. The principal item of meteorological data used is rainfall and this is required from a network of rain gauges or radar coverage. These data will provide a best estimate of rainfall over the area modelled, whether over a grid or to obtain a basin average.

The traditional techniques for rainfall forecasting (often referred to as nowcasting), based upon ground-based telemetric rain gauges and meteorological radars, are still widely used. This is because networks have been progressively developed from conventional and broad-based hydrometeorological networks and for this reason are deemed cost-effective. With respect to radars, the use of radar data is warranted for they are available in real time, provide a finer spatial resolution of the precipitation field and have the ability to track approaching storms even before they reach the boundary of the catchment of interest. Radar has some advantages where rain gauges are sparse and the storms are localised, but are of limited value if storms cover large areas simultaneously covering the sites of many rain gauges. In such cases the gauges tend to produce more accurate estimates of rainfall than radar data even though it will still give a better indication of the spatial distribution than that achieved by the use of classical methods, i.e. Thiessen polygons or Kriging interpolation.

With the rapid development of space technology, increased capabilities of the meteorological satellites represent nowadays another option besides radar-based information. There are available open source algorithms which can calculate precipitation from both visual (during the day) and infra-red (during the night) satellite data (e.g. Meteosat). This way useful estimates of precipitation fields/images – with a resolution of 2.5 x 2.5 km up to 1 x 1 km depending on the location – can be established. These satellite-based estimates of precipitation fields have a frequency of 15 minutes and are available within 15 minutes after observation. What is more, these data can also be mixed and matched with radar data if available to arrive at more reliable estimates.

Last but not least, as already mentioned, numerical weather prediction models may be utilised, where available, to provide single and/or ensemble meteorological forecasts (of precipitation, temperature, humidity, etc.) that can be used as inputs into flood forecasting models.

Topographic data are increasingly required for development of flood forecasting systems, as a result of increasing demand for models that can produce realistic estimates of spatial flooding. To this effect, distinction is to be made between conventional topographic information, which can be obtained from classical maps and used to delineate catchment areas, and more detailed information available from digital elevation model

(DEM) data. A new breed of the high-resolution digital maps, obtained through use of LIDAR surveying technology, is now available and being increasingly used in a wide range of applications, including hydrology, hydraulics and flood forecasting. LIDAR high resolution DEM data provide much more accurate information of flood plain and channel capacity for hydraulic models and can be linked to a GIS to provide visualisation of flood inundation extent and flood plain infrastructure.

Other information and data. It is necessary to consider how to use other available data and information as part of the flood forecasting and warning system. Physical catchment data, such as geology, soil type, vegetation and land use data are used to estimate hydrological model parameters as part of the model calibration. Other useful data and information may include:

- population and demographic data as an indication of settlements at risk from flooding
- reservoir and flood protection infrastructure associated with control rules
- inventories of properties at risk
- location of key transport, power and water supply infrastructure
- systematic post-flood damage assessments

Flood Forecasting and Warning System (FFWS): Key Components

Flood forecasting and flood warning systems are closely linked and usually considered a unique system; nonetheless, they essentially comprise of two systems, each with its own specific components, role and responsibility.

Flood Forecasting System (FFS)

As already highlighted, the FFSs can in considerable manner defer from each other; however, there are several key components that are basically the same or similar in each FFS. To establish an effective real-time flood forecasting system, at a bare minimum the following key components need to be in place and linked in an organised manner:

1. Outputs from the meteorological numerical weather-prediction (NWP) models, in particular the rainfall forecasts, including ensemble forecasts, dealing with both rainfall quantity and time of occurrence.
2. Network of manual or automatic hydrological stations, linked to a forecasting control centre by a reliable real-time telemetry.
3. Network of manual or automatic meteorological stations, linked to a forecasting control centre by a reliable real-time telemetry.
4. Availability at the forecasting control centre of a real-time hydrological information system (RT–HIS) for processing and management of a) telemetry data received from the network of hydrological stations; b) telemetry data received from the network of meteorological stations; c) products of NWP models and

rainfall fields/images, if available, based on analysis and processing of radar and/or satellite data; d) other non-real-time and GIS data (such as DEM data, geology, soil type, vegetation cover, land use, etc.).

5. An adequate flood forecasting model, calibrated and verified as appropriate, and linked to the RT–HIS and operating in real time.

Flood Warning System (FWS)

Flood warnings are based on, but distinct from flood forecasts. They are issued when an event is occurring, or is imminent, and must be issued to a range of users, with various motives. Key objectives among them are:

- to bring operational teams and emergency personnel to a state of readiness
- to warn the public of the timing and location of the flood event
- to warn as to the likely impacts on, for example, roads, dwellings and flood defence structures
- to give individuals and organisations time to take preparatory actions
- in extreme cases, to give warning to prepare for evacuation and emergency procedures

Early warning systems of a flood may save lives, livestock and property and invariably contributes to lessening of the overall negative flood impact. They motivate individuals and communities threatened by hazards to react effectively, i.e. in time and in an appropriate manner, so as to reduce the impacts and damages of the flood hazard. They are consequently essential in mitigating the effects of hazards. As an example, information-sharing for flood alerts is essential for both coastal areas and rivers. The disastrous 1953 coastal flood in Western Europe, for instance, showed the high water levels arriving in England more than six hours before they hit the French, Belgian and Dutch coasts.

Unfortunately, this information did not arrive at the other side of the North Sea coast on time. This information from the Met Office of the U.K. would have increased the sense of urgency in the Netherlands and would likely have saved lives.

To be effective and comprehensive, early flood warning systems, and hazard warning systems in general, should be composed of four inter-related elements:

1. Risk knowledge aimed at increasing knowledge about the risks that individuals and communities face.
2. Monitoring and warning service aimed at providing the necessary information. Warning services must have a sound scientific basis for predicting and forecasting, and must be reliable enough to operate continuously to ensure accurate warnings in time to allow action. Warning services for different hazards should be coordinated where possible to gain the benefit of shared institutional, procedural and communication networks.

3. Dissemination and communication aimed at informing individuals and communities about risks and actions. Warnings should contain clear, useful information leading to proper responses to reach the individuals and communities at risk. Communication channels and tools must be identified beforehand and established at regional, national and community levels.
4. Response capability aimed at ensuring that proper response and action is undertaken by the individuals and specialised emergency agencies.

Figure 6. Main inter-related steps of the flood forecasting and warning system chain [26]

Due to their very nature, flood warnings need to be understood quickly and clearly. For this reason considerable attention has to be given to how technical information, produced by forecasters within a flood forecasting system, is conveyed to non-specialists from different organisations, the public, the media and in some cases illiterate population groups.

Main components of a national FFWS

From the above considerations it can be summarised that the main components of a national flood forecasting and warning system are the following:

- collection of real-time data for the prediction of flood severity, including time of onset and extent and magnitude of flooding
- preparation of forecast information and warning messages, giving clear statements on what is happening, forecasts of what may happen and expected impact
- communication and dissemination of such messages, which can also include what action should be taken
- interpretation of the forecast and flood observations, in order to provide situation updates to determine possible impacts on communities and infrastructure
- response to the warnings by the agencies and communities involved
- review of the warning system and improvements to the system after flood events

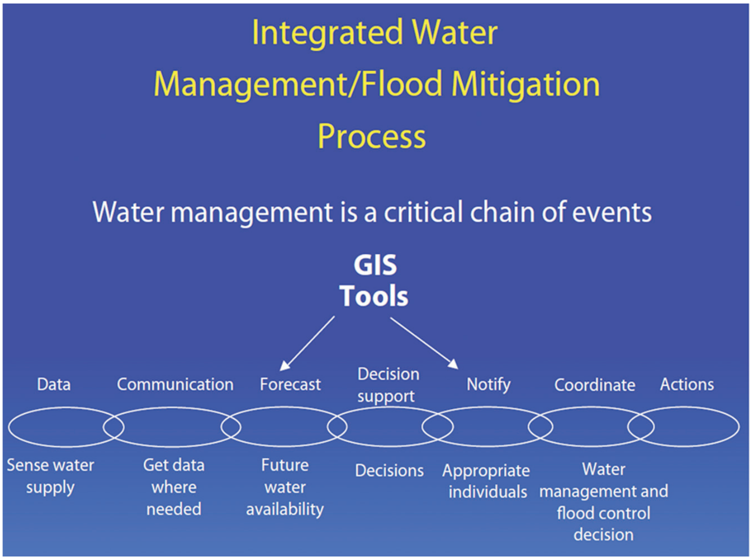


Figure 7. The linkages between the elements of FFWS and the application of GIS tools in integrated water/ flood management process [24]

There are a number of features common to all flood forecasting and warning systems, which are related to causes, impacts and risks. The following characteristics are to be well understood and are considered below in more details.

Features of different FFWS components

Meteorological phenomena. They are the prime natural causes of flooding, either as rainfall or snow and snowmelt. Clearly the ability to forecast critical events, in both time and space and also quantitatively, is of significant value in flood forecasting and warning. Meteorological knowledge associated with flood warning issues fall into two broad areas, namely the climatology behind flooding and the operational meteorology involved. The National Meteorological Service would be expected to be the best equipped to provide both, perhaps with the assistance of appropriate research organisations.

Climatology includes the understanding of rain bearing systems, their seasonality and the extremes of their behaviour. Understanding the types of weather systems from which flooding can originate will contribute largely to decisions about what sort of observational and forecast systems may be required. Thus in an arid zone, where flash floods are predominant, the observation and forecasting facilities must be geared towards rapid recognition of an event. The most effective means for this would be by satellite or radar, while broad scale, synoptic forecasting would be of limited value.

Understanding the seasonality of rain-bearing systems is very important operationally, as this will have a bearing on staff assignments and the organisation of alert and background working patterns. For areas in which the rainy season is well defined, for example Monsoon Asia, tropical Africa and Central America, attention needs to be paid to ensuring adequate staff cover to allow both regular situation updates and round-the-clock monitoring of severe conditions. In temperate and continental areas however, flood events are more random in their occurrence, so flexibility within organisations is required, so that staff can undertake flood warning duties as necessary, i.e. in states of emergency, though their routine tasks may be wider.

Hydrometeorological statistics (primarily rainfall, but also evaporation) are vital to flood forecasting and warning operations and they are usually dealt with separately from climatology data. The purpose of the data and statistics is to estimate the severity and probability of actual or predicted events and to place them in context. Long-term records are essential and this requires investment to install and maintain rain gauge networks (plus evaporation and/or climatological stations), to assure staff and facilities to process and analyse records and to maintain a flexible and accessible database.

Hydrometeorological data are also vitally required in real time for the provision of flood forecasts and warnings. To this effect, it is essential that a representative proportion of the rain gauge network is linked to the forecasting and warning control centre by telemetry. This has a three-fold purpose:

1. To allow staff to monitor the situation in general terms.
2. To give warnings against indicator or trigger levels for rainfall intensity and/or accumulations.
3. To provide inputs into hydrological forecast models, in particular into rainfall-runoff models.

Hydrological inputs/component. The requirements concerning hydrological information for a flood forecasting and warning system are similar to those for meteorology, in that it is necessary to have an understanding of the overall flood characteristics of the area as well as having real-time hydrological information for operational purposes. Key observation and data requirements are for water levels in lakes and rivers, river discharge and in some cases groundwater levels.

The network of hydrological observing stations have a dual role – to provide 1. hydrological non-real time data for long-term statistics; and 2. real time data through telemetry to a control/forecasting centre. Water level ranges at given points can be linked to various extents of flooding, so a series of thresholds can be set up to provide warning through telemetry.

The upstream–downstream relationship between water levels is also an important means of forecasting. Early flood warning systems, which are in use in some FFWS, depended on knowledge of the comparative levels from a point upstream to resulting levels at a point of interest at the flood risk site and the time taken from a peak at an upstream point to reach a lower one. These were presented as tables or graphs of level-to-level correlations and time of travel.

Developments in real-time flood modelling now provide the facility to provide more comprehensive information on forecasting of levels, discharges, timing and extent of flooding.

Dissemination of forecasts and warnings. The effective dissemination of forecasts and warnings is very important. A balance has to be struck between information to the public and information to other bodies involved with flood management. Historically, this has resulted in a dichotomy for flood warning services, which have to partition support resources between the community and government. The subject has been the focus of severe criticism in the light of past failures at service delivery. Thus, the language used and the type of information passed on has to be carefully considered and structured. There has been a gradual evolution away from confining flood forecasting and warning information to authorities, that is, government, to a more direct involvement of the public. This has been helped by the growth in telecommunications, the computer, the IT revolution and increased ownership and coverage of media, such as radio and television. It is important, however, to maintain a broad spectrum for dissemination and not to be seduced by high-tech approaches. Even in technically advanced societies it is doubtful whether Internet communication of flood warning information can be entirely effective. The elderly and poor members of the community may not have the necessary facilities at home, and it may also be doubtful whether people will consult Websites when a dangerous situation is in place. It must also be remembered that these systems are dependent on telecommunications and power links that are themselves at risk of failure during flood events.

As a counter to over-sophistication and reliance on high-tech methods some alternative facilities need to be provided. In the past, in most parts of the world, emergency services (police, fire service, civil defence) have been closely involved in flood relief activities. Their role may change with changing technology but they still need to be involved in communicating flood warnings and rescue. Other general warning systems, such as flood wardens and alarm sirens should not be abandoned without careful consideration of the consequences.

Institutional aspects. A flood forecasting and warning system needs to have clearly defined roles and responsibilities. These are wide ranging, covering, inter alia, data collection, formulation and dissemination, uncertainty of outputs and any legal or liability requirements. Whatever the functional and operational responsibilities of the separate agencies involved in flood forecasting and warning, there is a fundamental responsibility through central government for public safety and emergency management. There may not be, however, a general statutory duty of the government to protect land or property against flooding, but the government recognises the need for action to be taken to safeguard the wider social and economic well-being of the country.

Operating authorities may have permissive powers but not a statutory duty to carry out or maintain flood defence works in the public interest. However, such responsibilities may be incorporated through legislation within acts and regulations under which different government departments operate. When legislation is set up or amended, it is therefore extremely important that interfaces between the duties and obligations of affected departments are carefully considered before statutory instruments are introduced.

The institutional structure and responsibility may become complicated for the following reasons. Several ministries may carry separate responsibilities for activities related to flood forecasting and warning. Furthermore, within implementing organisations, flood forecasting and warning duties may represent only a fraction of their overall responsibilities.

Some countries have a combined hydrological and meteorological service, for example Russia, Iceland, some eastern European countries. This theoretically eases issues over data collection, use and dissemination that arise when one organisation collects atmospheric data and the other provides rainfall and river data. In many cases rainfall data are collected by both the meteorological and hydrological agencies and the type of data is influenced by historical factors, or the primary requirement for rainfall data.

Flood forecasting and warning as a focused activity in the hydrometeorological sector is a relatively recent development. This may be evidence of the growing seriousness of flood impacts, both as a result of greater financial investment and pressure of population. Previously in the United Kingdom, France and other European countries, response mainly focused on flood defence and warning through the general meteorological forecasting of severe weather. However, the occurrence of a number of severe events from 1995 to 2003 led to the setting up of national flood forecasting and warning centres/services. This has provided the opportunity to enhance the development of monitoring networks specifically designed for flood forecasting and warning purposes. Hydrological networks consist of instruments that have electronic components for data storage and transmission (rain gauges and water level recorders) and meteorological effort has focused on collection and delivery of satellite and radar data.

Legal aspects. Any flood forecasting and warning system has to deal with uncertainty. This is inherent due to the nature of the meteorological and hydrological phenomena involved. To this has to be added the uncertainties involved with equipment and human error within an operational structure. Uncertainty may be dealt with in the design and planning processes, where a decision is made on the level of uncertainty, that is, the risk of failure that is acceptable. This then becomes a balance between the cost of safe design against that of the losses caused by damage. Except where "total protection" is provided for key installations such as national security locations and nuclear plants, aspects of uncertainty can be approached through probabilistic methods. The probabilistic approach is increasingly being used as part of risk analysis, where impact and consequence in human and economic terms are linked with the causative meteorological and hydrological characteristics.

Liability in strict legal terms is difficult to apply to the various activities in flood forecasting and warning. Whereas a contractor may face liability for the failure of a flood protection structure (for example a dam or a flood wall) or a manufacturer for a product not meeting specifications as to flood resistance or proofing, most national and international legal systems and codes regard floods and the causes thereof as "Acts of God". Liability in regard to flooding tends to operate in a "reverse" way, i.e. that compensation or redress for losses and damage may not be given if a case shows that there has been some form of negligence in design or that guidelines have been ignored.

In many countries governments or international agencies can provide compensation or assistance in rebuilding, but there is no legal obligation. Insurance is increasingly fulfilling the role of government in recovery actions, particularly in developed countries where it is a commercial arrangement. The increasing use of insurance has, however, meant that when events occur, the cost to insurance companies becomes larger, leading to rises in premiums. This situation also leads to insurance companies deciding on what is or is not a worthwhile risk, which often leads to properties in high flood risk areas being uninsurable.

Methods and models used for real-time flood forecasting

With recognition of the importance of flood forecasting and warning for flood management, the expectations from flood forecasts in terms of magnitude, reliability and forecast lead time have substantially increased, and there is no doubt this trend is only going to intensify in the future. Past methods of simple extrapolation of forecasts from gauged sites can no longer satisfy the requirements.

While the heart of any flow forecasting system is a hydrological model, it goes without saying that catchment modelling is just one of the crucial elements on which the effectiveness and efficiency of an integrated flood forecasting and warning system (FFWS) depends.

There exist a bewildering number of hydrological models in use in various parts of the world, including various procedures for their development, calibration and verification. As an example, Figure 8 illustrates typical procedures and steps needed in creating a suitable flood forecasting model [24].

As catchments respond to the hydrological cycle phenomena in a broadly similar manner, one might expect that modelling would be well focused, involving a fairly simple process of refinement to make the models more robust, versatile and sophisticated. Nonetheless, the fact is that a selected model can work quite well in some cases but poorly in others. For this reason, a modular approach to modelling is increasingly used, whereby each identifiable component of the runoff-generating process in the catchment (e.g. snowmelt, infiltration, groundwater, flood routing, etc.) can be represented as a separate module, which is then included into the overall model structure. Moreover, in a good model the forecast uncertainty – arising from data measurement error, model structural (physical) inadequacy and suboptimal parameter estimation – must be estimated and explicitly accounted for.

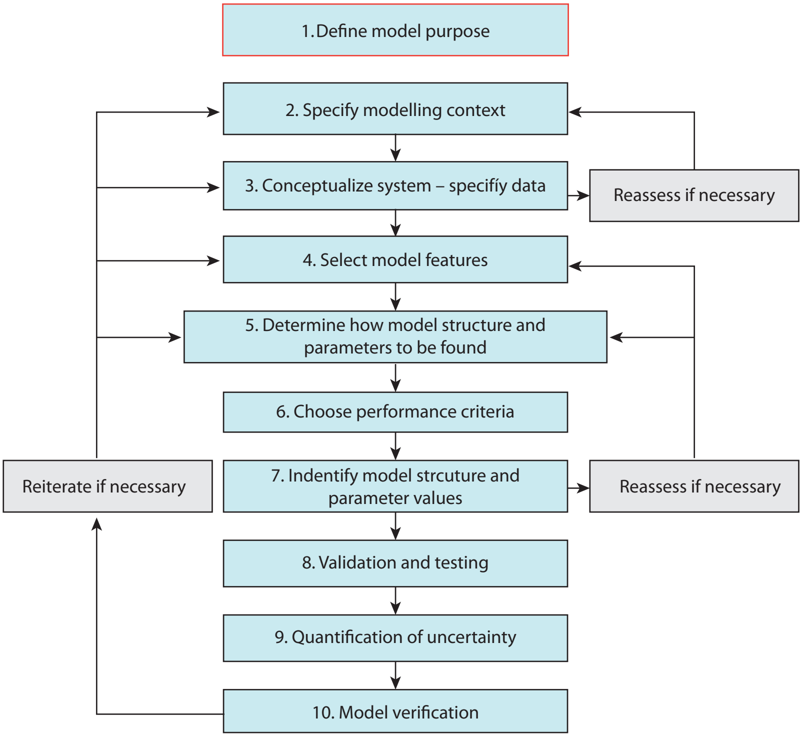


Figure 8. Typical steps and procedures required in creating a suitable flood forecasting model [24]

To be useful, the selected forecasting models must satisfy certain criteria, depending on the requirements of the stakeholders and the end-users of forecasts. On the other hand, the degree of model complexity should be consistent with the actual "information carrying capacity" [11] of the data available to calibrate and run them in operational mode. Increasing model complexity, in terms of the number of components and parameters involved, is not necessarily warranted or justifiable, and can actually be counterproductive. The best practice in developing and using FFWSs is evolving towards the use of more physically-based distributed models or at least an integrated suite of simplified models running simultaneously.

Prerequisites for a reliable real-time hydrological forecasting model

An ideal real-time, fully operational forecasting model should satisfy the following prerequisites [17], i.e. it must:

- account for the physical laws that govern the hydrological processes (i.e. rainfall-runoff in a catchment and streamflow along a main channel)
- explicitly account for forecasting uncertainties

- react, as quickly as possible, to changes that might occur in the watershed due to natural and human causes by modifying model parameters, i.e. must be adaptive while having parameters that are sensitive to such changes
- be rendered with long enough yet the most reliable forecast lead time
- specify and produce unbiased forecast errors
- be able to accommodate any changes in the observation network and the resulting additional information without changes in the model structure
- make data substitution possible through interpolation or finding analogies where there are missing measurements
- be numerically stable and without high demand of computer resources and time for computation
- express fast convergence for any numerical scheme in the model
- have a structure that makes it possible to include the model in operational systems of water management
- have recursive algorithms so that the model can be run on computers with limited memory capacity

It is safe to say that for the time being no universal, operative forecasting model exists, and most probably there will not be any in the near future. Yet, the generalisation of existing models should be accomplished, and an attempt made at the creation of new, ever more general models. The aim is to arrive at a model that would have modular structure and be as little site-specific as possible. To this effect, the MIKE SHE model[3] or Delft-FEWS platform may be considered good examples.

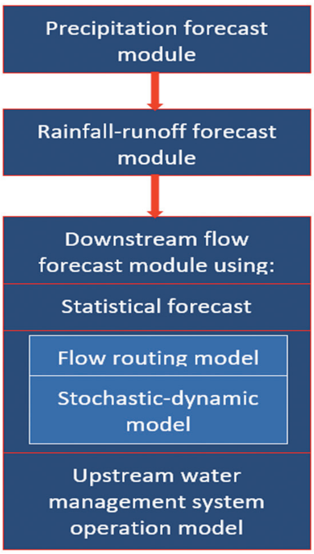


Figure 9. Modular structure of forecasting models (compiled by the authors based on [17])

[3] For more information see www.mikepoweredbydhi.com/products/mike-she

Such a modular structure is illustrated in Figure 9 above, where each module represents a sub-function within the complete task of hydrological forecasting [17].

Currently, a great number of hydrological models is in use in various parts of the world. Many models that were implemented in operational FFWSs decades ago are still in use, having undergone only occasional refinement or cosmetic interface updating, as the forecasts produced by them are still considered adequate by their end-users.

Describing such methods and models in detail, and the elaboration of their mathematical development is beyond the scope of these notes. Model development is a specialist undertaking and, regrettably, there is still a wide gap between developers and practitioners, including many specialists that are directly involved in operational flood forecasting. In the text that follows only the main categories or classes of models illustrated in the above Figure 9, and some representative examples, are presented.

Precipitation forecast module

Information about precipitation/rainfall distribution over a catchment represents a crucial forcing of any model used for modelling rainfall-runoff process in a catchment and forecasting of flow hygrogram at its outlet profile. The ability to forecast meteorological critical events quantitatively, such as rainfall and temperature in both time and space, is of significant value in flood forecasting and warning. Nowadays, such forecasts are produced by using numerical weather prediction (NWP) models and are available from National Meteorological and/or Hydrometeorological Services and, for Europe and hence the Danube basin, from the European Centre for Medium-Range Weather Forecast (ECMWF[4]). Apart from classical NWP products, the ECMWF is also producing ensemble forecasts;[5] all its real-time products are available to Member States[6] and Cooperating States[7] in real time who can use them either without modification or to prepare their own user-oriented specific forecasts for end users. The NWP products in general, in particular

4 For more information see www.ecmwf.int/

5 An ‘ensemble forecast’ consists of 51 separate meteorological numerical forecasts made by the same computer model, all activated from the same starting time. The starting conditions for each member of the ensemble are slightly different, and physical parameter values used also differ slightly. The differences between these ensemble members tend to grow as the forecasts progress, that is as the forecast lead time increases.

6 Austria, Belgium, Croatia, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Serbia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

7 Bulgaria, the Czech Republic, Estonia, the former Yugoslav Republic of Macedonia, Hungary, Israel, Latvia, Lithuania, Montenegro, Morocco, Romania and Slovakia.

quantitative precipitation forecasts (QPF), are still fairly inaccurate and have inadequate spatial-temporal resolution in comparison with hydrological modelling requirements. Nevertheless, they are of great value and are regularly being used as input to hydrological models for flood forecasting.

The NWPs are not the only option for operational quantitative precipitation forecast. As already mentioned, for very short lead time of forecast, extrapolation of radar and/or satellite precipitation patterns, also called nowcasting by meteorologists, represent another possibility. Nowcasting methods capture the initial information very well, but as they do not include physics, the skill decreases rapidly with increase of lead time. (The NWPs, on the other hand, capture the physics of large systems very well, but lack local detail because of their limited spatial resolution). This option is especially valuable for severe weather conditions like the thunderstorms causing flash floods, as exact location and timing of these phenomena are difficult to predict without a radar/satellite nowcast.

It is important to stress at this point that the only way to improve either NWP or radar/satellite nowcasting products, QPFs in particular, is through appropriate calibration and verification of NWP models and radar/satellite images in a given catchment. There is no other way to achieve this, but through adequate spatial coverage of meteorological/precipitation telemetry network in the catchment that provides observed real-time meteorological data necessary for the purpose. At first glance it may look like a paradox, but the fact is that the evident contemporary achievements in meteorology cannot bear fruits without expanding rather than downsizing the telemetry network of meteorological stations.

Rainfall-runoff forecast module

Modelling of runoff processes in a catchment started in the first half of the 20th century, and coincides with the publication of L. K. Sherman's (1932) seminal paper on the unit hydrograph (UH). Sherman's theory described a dynamic link between effective precipitation and direct runoff by postulating a number of hypotheses that led to a linear construction (later called a dynamic linear system), which connected two quantities, input and output, changing in time. Direct runoff as output was calculated as a weighted sum of past effective precipitation inputs. The weights formed a function that was called 'unit hydrograph' (UH) that essentially was the response of a catchment to a unit volume input of effective rainfall spread uniformly over the catchment area during one time unit. The UH was not known a priori, but had to be identified from input–output records.

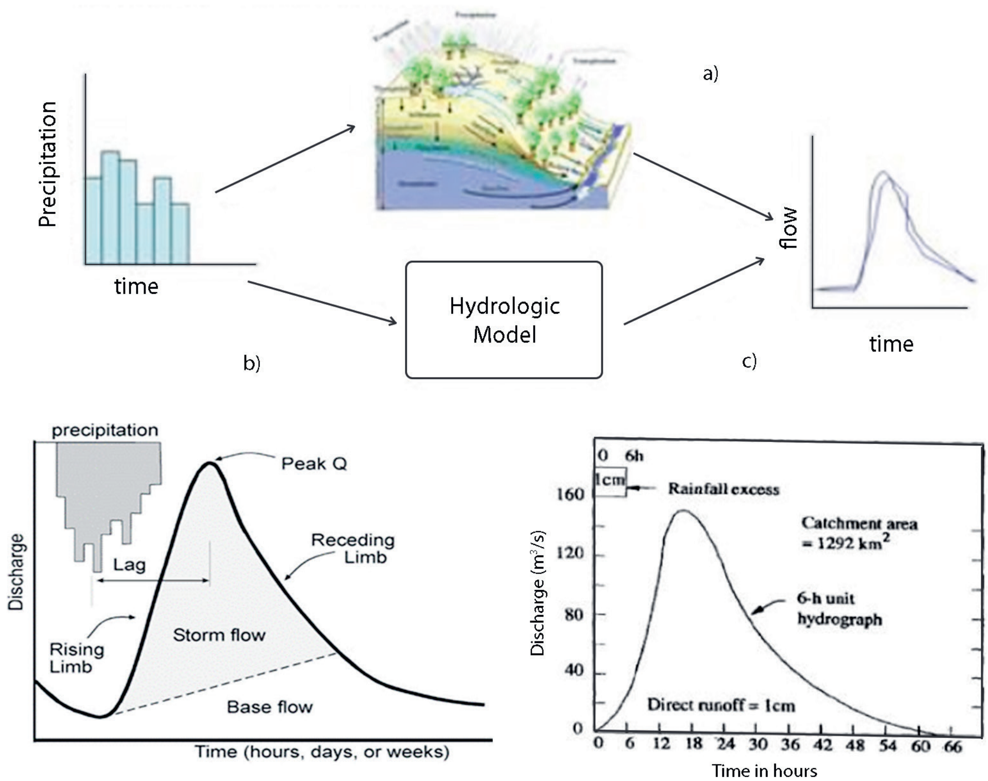


Figure 10. Illustration of a) rainfall-runoff processes in the catchment; b) typical flood hydrograph at the catchment outlet profile; and c) classical T-Unit Hydrograph (adapted by the authors based on [2])

The UH concept is still alive and well. It is being used in many models and engineering applications and thousands of papers have been published in scientific journals on the subject. Yet, the problem is that neither effective precipitation nor direct runoff exist in physical reality, and the concept epitomises vast oversimplification of the complex rainfall-runoff process. So hydrologists started using the UH concept, but also continued to rely upon the use of coaxial graphical procedures, the Antecedent Precipitation Index (API) rainfall-runoff charts and the like.

Things changed significantly with the advent of digital computing. It was recognised that the UH is in essence a black box, which cannot take into account physical processes in the whole land phase of the hydrological cycle, such as canopy storage, evapotranspiration, infiltration, soil moisture, groundwater flow, snow melt and flow routing. How can the human impacts such as land use changes, reservoirs and urbanisation be considered? How to go from external to internal modelling?

This led to the era of conceptual models – starting with the introduction of elementary linear reservoirs all the way to the complex Sacramento and Stanford-type watershed models and their numerous derivatives.

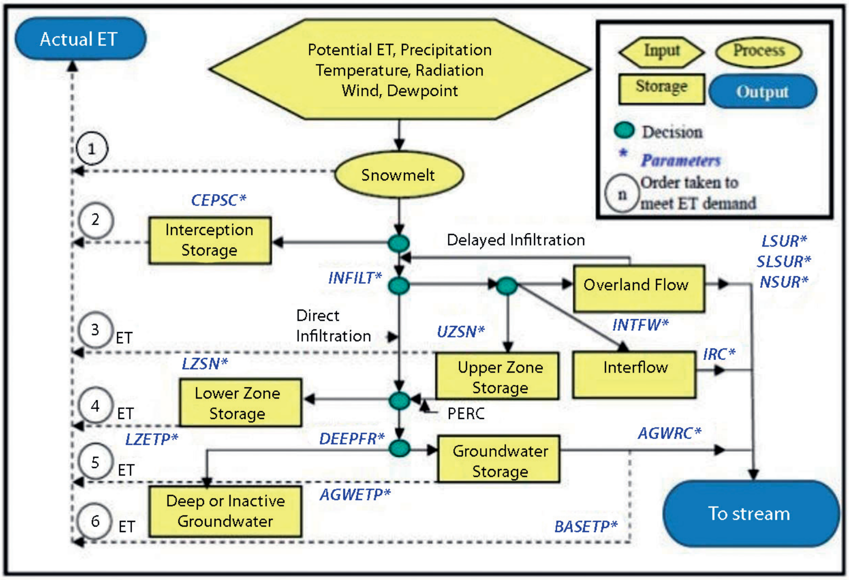


Figure 11. Stanford watershed conceptual model (adapted from [30])

Complex processes in the catchment that occur between catchment input and output have been gradually brought back to the stage in a digital framework. Between total precipitation and total river flow a deterministic structure has been conceptualised based on the physical understanding of the mechanisms and processes in the hydrological cycle.

Dynamic developments in this field led to introduction of a number of new concepts and approaches in modelling rainfall-runoff process. According to the model structure, the following type of models are being used:

- empirical (stochastic) data-driven rainfall-runoff models
- “physically inspired” lumped conceptual rainfall-runoff models
- physically or process-based distributed rainfall-runoff models
- hybrid physically-based/conceptual distributed models
- hybrid metric-conceptual models
- event-based versus continuous simulation
- simulation models versus forecasting models

Focusing on models that can be used for operational real-time flood forecasting, frequent problems in using distributed complex models – either the Sacramento/Stanford-type conceptual or the physically-based distributed models – arise from many parameters that have to be determined and, even more important, lack of adequate observed data for their calibration, verification and subsequent operational use.

Some of these parameters are measurable, such as for example the ratio of impervious areas in an urban catchment; other parameters, however, have to be calibrated from observed data, either manually or by applying some of the optimisation techniques.

As a result, they often lose their physical meaning in the process and eventually lead to disappointing model performance in spite of the model complexity.

Sometime this complexity is in the heart of the problem, in particular when it comes to using a model for operational flood forecasting. It has been argued that less complex, i.e. simplified conceptual models, consisting of elementary linear reservoirs and/or linear channels, contain very few control parameters and can easily be calibrated.

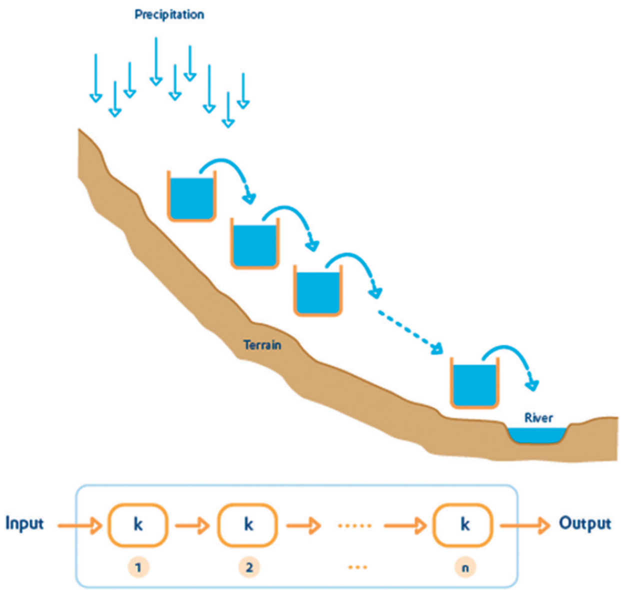


Figure 12. Kalinin–Milyukov–Nash (KMN) cascade conceptual model [16]

In spite of this simplification, they are usually capable of explaining a large portion of the catchment precipitation-runoff process. Very often simple linear reservoir cascade models could explain more than 90% of the total process variance. One such model is the Kalinin–Milyukov–Nash cascade[8] (Figure 12) – characterised by the Instantaneous Unit Hydrograph in analytical form controlled by two parameters only (the number of reservoirs/sub-reaches (n) and the residence time of reservoir/sub-reach, often referred

8 It is interesting to note two points regarding the KMN cascade: 1. Kalinin and Milyukov (1957) and Nash (1957) arrived independently at the same result, i.e. formulation of the Instantaneous Unit Hydrograph (IUH) by using a completely different approach; the former by serially linking sub-reaches of a river reach with one another and assuming that the flow out from a sub-reach (the so-called characteristic reach) is linearly proportional with the amount of water stored in that particular reach; the latter by assuming that overland flow in a catchment could be represented by a series of linked elementary reservoirs, where the outflow from one elementary reservoir is the inflow into the next one and is linearly proportional to the storage in the elementary reservoir. 2. In essence, Kalinin–Milyukov's IUH represents a linear flow-routing model; models of this type are well known, have been used in hydrology for quite some time for flood routing (better known as 'hydrological flow-routing models') and could all be derived from the kinematic wave equation, representing the first-order approximation, i.e. 'the bare bone structure', of the full hydrodynamic Saint-Venant equations that govern one-dimensional, unsteady, gradually varying flow in open-channel.

to as storage coefficient). With some adjustments and modifications, the KMN cascade model is a good candidate to fulfil the requirements of an operational real-time hydrological forecasting. For this purpose, it needs to be a) converted from a time continuous model into an adequate discrete time model; b) transformed into a form that allows easy updating; and c) able to deal with the inherent forecast and other uncertainties, such as those in the processes involved as well as in their measurement. Model simplification (by using the kinematic wave equation as first-order approximation of the Saint-Venant equations) inevitably yields increased model uncertainty, so it is important to handle this type of simplification-imposed randomness as well. Note that, as a matter of fact, the discrete version of the KMN cascade represents a discrete linear cascade model (DLCM), the term that is usually used for this class of models.

The DLCM or discrete KMN cascade model types (deterministic component) coupled with a stochastic component within the unified deterministic-stochastic state-space model formulation are being successfully used for real-time streamflow and flood forecasting in the Danube basin, in particular Hungary where it is operational used in the whole country since 1984 [17], but also outside Hungary, i.e. in Germany, Thailand and Malaysia. This modelling approach, but using instead the Kalinin–Milyukov non-linear model formulation as deterministic component, has also been successfully tested in the Serbian part of the Danube river [2] [3] [4].

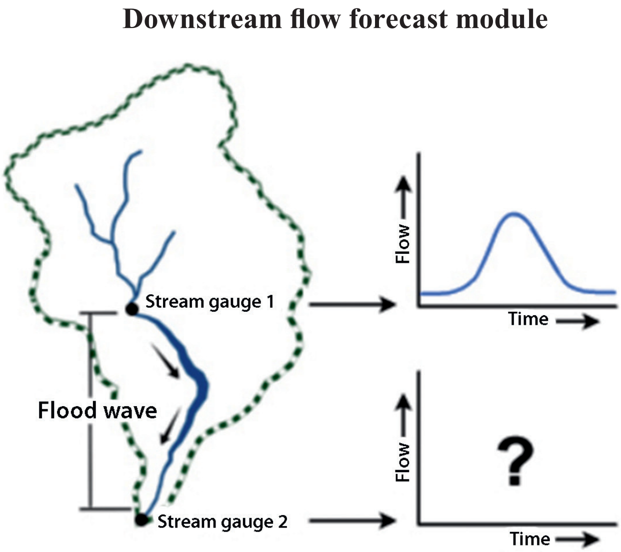


Figure 13. A catchment and river reach with upstream and downstream hydrological profiles [2]

Given the observed or forecasted flow hydrograph at the catchment's outlet profile upstream, this module deals with the dynamics of river flow with the main objective to come up with a model capable of real-time streamflow and flood forecasting at the downstream river reach or reservoir profile (Figure 13).

In general, the runoff-runoff phenomenon is addressed by various routing techniques that are broadly classified as either hydrological or hydraulic routing [24] as shown in Figure 14.

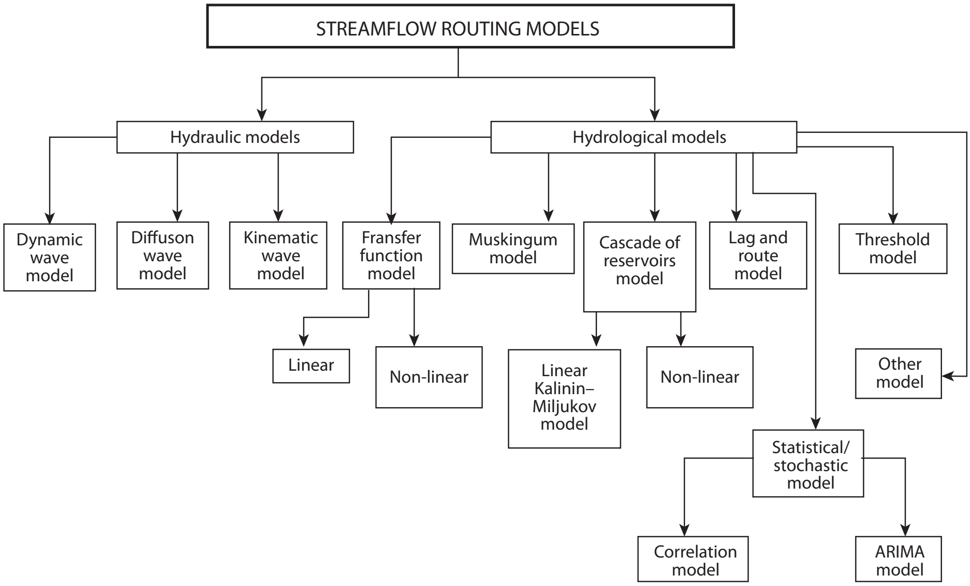


Figure 14. Classification of streamflow routing models [24]

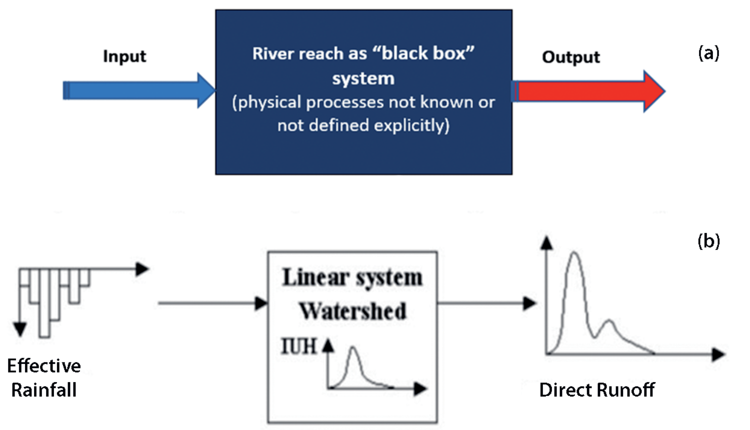
As in case of catchment models, there exists a number of different forms of routing models spanning a wide range of complexity and computational requirements. In comparison to hydrological routing, which focuses on the relationship between the hydrographs at the upstream and downstream sections of a channel reach, hydraulic routing provides a more physically-based description of the dynamics of flow, such as for example the velocity and depth as functions of space (distance) and time. Hydraulic routing using dynamic or diffusion wave model requires details of the channel sections and much greater computational effort; for this reason, in comparison with hydrological routing it is less used as a tool for real time forecasting. As noted earlier, the kinematic wave model represents a 'bare bone structure', of the full hydrodynamic Saint-Venant equations and is often considered hydrological rather than hydraulic routing model; as such, it is not too demanding in terms of data requirements, and is widely used in various forms for real-time streamflow forecasting. In general, the picture becomes pretty blurred when one attempts to make a clear cut classification of various models used in hydrology; this is also the case with the classification presented in Figure 14.

Without going into exhaustive details, a short account of the following three main approaches in modelling the runoff-runoff process is presented in the text below:

– stochastic black box approach
– deterministic (dynamic) streamflow routing methods
– coupled structural (dynamic) – stochastic models

1. *Stochastic approach.* The problem of flow forecasting many modellers are trying to solve by using a “black box” input–output approach, whereby the physics behind the streamflow (runoff-runoff) or the catchment (rainfall-runoff) process is not defined explicitly. Stochastic hydrologists essentially look at the unit hydrograph theory and consider input–output relation only, but with one major difference. It is assumed that both input and output are two stationary random time series connected by system ‘transfer function’.[9] The stochastic approach in modelling hydrological time series has its root in, and has decisively been influenced by a brilliant book written by the statisticians George Box and Gwilym Jenkins on time series analysis, forecasting and control [6]. Time series analysis became a popular tool in hydrological research and various identification techniques were used to estimate the system transfer function, or the stochastic IUH in hydrological parlance, from observed data.

Even though it is still being used, the approach performs poorly when used for real-time hydrological forecasting. However, it paved the way to a favourable marriage between the deterministic groom and the stochastic bride (or was it vice versa?). In the previous chapter, we have already touched on the benefits of this marriage for real-time hydrological forecasting, and a few more arguments in its favour will be discussed under the coupled structural– stochastic models later in this chapter.



$$Q(t) = \int_0^t i(\tau)u(t-\tau)d\tau$$

i(*t*): effective rainfall, *u*(*t*): instantaneous unit hydrograph, *Q*(*t*): direct runoff

Figure 15. Illustration of a) the stochastic black box approach in modelling runoff-runoff process; and b) unit hydrograph approach in modelling effective rainfall – direct runoff process (Adapted from [2])

[9] This function some hydrologists termed a Stochastic Instantaneous Unit Hydrograph (SIUH)! There is no doubt this is an incorrect term as the stochastic transfer functions simply transform input into output series without any consideration of physical processes involved.

2. *Dynamic streamflow routing.* All the hydraulic routing models (i.e. dynamic, diffusion and kinematic wave) and a few of the hydrological routing procedures (Muskingum, discrete linear cascade of reservoirs, and the Kalinin–Milyukov model) listed in Figure 14 above are to a lesser or greater degree deterministic physically-based models.[10]

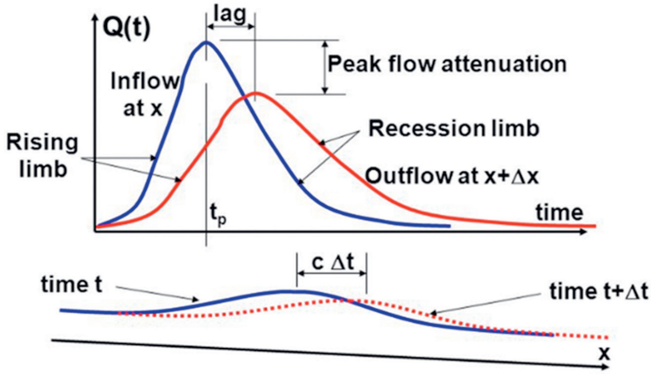


Figure 16. Dynamic flood routing: definition of key notions and variables (PPT – Flood Routing definitions PowerPoint Presentation, free download – ID:719053 slideserve.com)

All hydraulic routing models are nowadays being used in various forms for real-time flood forecasting as well as for delineation of flood risk areas.

3. *Structural (dynamic) – stochastic models.* As indicated in the foregoing text, the uncertainty is implicit in any human endeavour aimed at forecasting the future, and the hydrological forecasts are no exception to this dictum.

Broadly speaking, any hydrological model (either of the precipitation-runoff or the runoff-runoff type, or combined) used for real-time forecasting that has a modus operandi capable of assessing explicitly the probabilistic measure of uncertainty associated with each forecast as in Figure 17, belongs to this model category.

Uncertainty estimation is often carried out using a combination of numerical meteorological or hydrological models and statistical techniques. These techniques comprise of Monte Carlo analysis and statistical post-processing. Monte Carlo analysis is at the heart of ensemble techniques, where multiple plausible, equally probable initial conditions or model parameters are used as inputs to multiple model runs. Statistical post-processing aims to characterise the relation between forecasts and observations and, assuming that this relation is valid in the future as well, applies this relation to future forecasts.

Another and probably the best way to deal with uncertainty of forecasts is identical to many of the control systems applications in the sixties of the last century in rocket and

[10] Some pure hydraulicians might argue that none of the hydrological models for streamflow routing belongs to this category, but it has been demonstrated that a linear cascade model is discretely coincident with the hydraulic kinematic wave model. Similar reasoning applies for a variant of the original Muskingum, i.e. the Muskingum–Cunge model that has more physical/hydraulic basis.

communication engineering: forecasting the future trajectory of a dynamic system subject to random disturbances by minimising forecast error variance. Rudolph Kalman worked out his famous Kalman filter in 1960 for these types of problems. Back to hydrological forecasts, in essence the Kalman filter enables recursive estimate of conditional density functions (i.e. uncertainty) of our 'deterministic' dynamic hydrological forecasts. In fact, the Kalman filter gives the best estimation for linear dynamic systems and no better tool could be designed. (The trouble is that catchment processes cannot always be approximated by, and modelled as linear dynamic systems.)

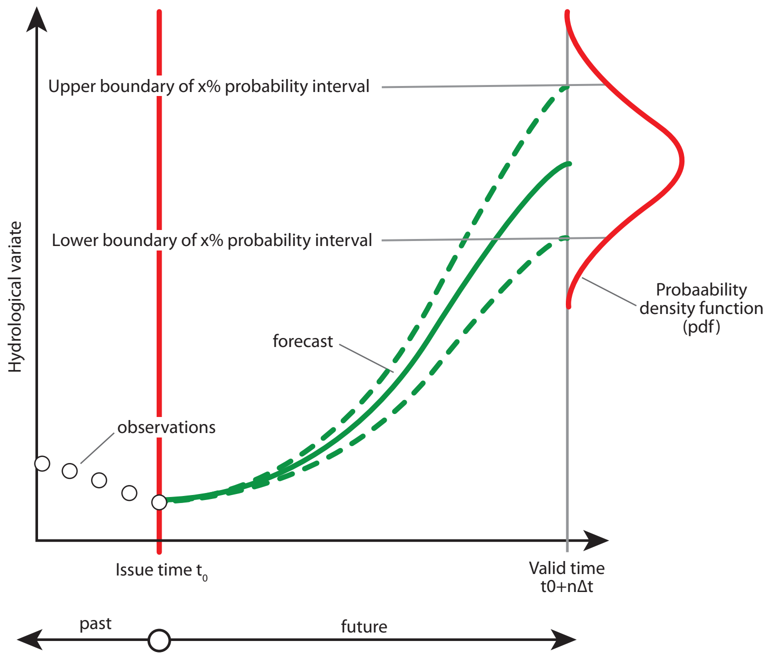


Figure 17. Illustration of a forecast with probabilistic measure of forecast uncertainty [16]

The above techniques aim to produce probabilistic forecasts that are reliable and as certain as possible. The very notion of reliability pertains to the probabilistic nature of the forecasts: predicted probabilities have to be matched by observed relative frequencies. Measure of uncertainty pertains to the width – or rather, the narrowness – of the predictive intervals (see Figure 17), i.e. the variance of the forecasting errors. Ideally, the variance should be as close to zero as possible, with the ultimate but unattainable goal of having zero value.

There are several procedures the hydrologists use nowadays in practice, but the discussions are still ongoing on what constitutes the most appropriate approach for estimating predictive uncertainty of hydrological forecasts.

Common procedures include, but are not restricted to:

Use of meteorological ensemble forecasts as input to a precipitation-runoff model (with subsequent flow routing downstream the river reach), thus producing a 'plume' of hydrological forecasts at each time step.

Multi-model approach whereby the ensemble of river flow forecasts of a number of rainfall-runoff or runoff-runoff models is used synchronously to produce a combined flow forecast at each time step, through aggregation of the results of available alternative model structures, thus avoiding reliance on a single model.

The multi-model approach can also be applied to the ensemble of forecasts obtained from alternative parameter sets of the same model, which produces near equal model efficiency. This approach is similar to that used in generating meteorological ensemble forecasts and may be considered a special category of multi-model forecasts. Using a single hydrological model, multiple numerical prediction are conducted using slightly different initial conditions that are all plausible given the past and current set of observations or measurements. Sometimes the ensemble of forecasts may use different forecast models for different members or formulations of a forecast model. The multiple simulations are conducted to account for the two sources of uncertainty in forecast models: first, the errors introduced by chaos or "sensitive dependence on the initial conditions"; second, the errors introduced because of imperfections in the model. Using the output from a number of forecasts or realisations, the relative frequency of events from the ensemble can be used directly to estimate the probability of a given flood event.[11]

Lastly, for tackling predictive uncertainty of real time hydrological forecasts, probably the best approach is to couple a suitable deterministic hydrological model with a stochastic component within a unified deterministic-stochastic state-space model formulation, thus enabling the use of the Kalman filtering techniques. This approach satisfies to a high degree the prerequisites for a reliable real-time hydrological forecasting model and has been extensively tested and operationally used in the Danube basin and elsewhere.

Before concluding the discussion on hydrological modelling, let us just reaffirm something what already seems logical and obvious: all the modules/models considered (see also Figure 9) – i.e. the precipitation forecast and the catchment rainfall-runoff – may each be used either standalone or combined in an integrated system for flood forecasting.

There are numerous examples of real-time forecasting and warning systems in use in the world. Some of them will be shortly summarised in the next section, focusing primarily on the systems in operational use in the Danube basin.

[11] Ensemble forecasts are more widely applied to NWP models than to hydrological models, with the probabilistic outcome to a number of NWP runs being used to provide the "most likely" scenario for input into a hydrological model. Applying ensemble approaches to both NWP and hydrological models would undoubtedly be prone to producing results with a wide range of uncertainty.

Examples of the FFWS in operation in the Danube basin

More than 40 rivers cross at least one border in Europe, with the most transnational river being the Danube, which is shared by 18 countries. In case of flooding, this means that different authorities involved in water resource management, civil protection and the organisation of aid must communicate, share data and information and, ideally, take concerted actions to reduce the impact of the flooding along the course of the river. There are a number of FFWSs in operation within the Danube basin, ranging from local, national and regional ones. There is also a unique pan-European system that also covers the Danube basin. In the text that follows, an outline is given about this European system, the newly developed regional Sava FFWS and the national Hungarian flood forecasting system.

European Flood Alert System[12]

Significant floods that occurred across Europe at the beginning of the 21st century led the European Commission (EC) to initiate the development of the European Flood Awareness System (EFAS). The objective of EFAS is to provide a pan-European medium-range streamflow forecast and early warning information in particular for large transnational river basins, in direct support to the national forecasting services. From 2003 to 2012, EFAS was developed and tested at the Joint Research Centre (JRC), the in-house science service of the EC, in close collaboration with various national hydrological and meteorological services across Europe, and other research institutes. In 2011 EFAS became part of the Copernicus Emergency Management Service (EMS)[13] in 2012 it was transferred from research to operational service, and over the past 10 years EFAS has become increasingly integrated into national and European flood risk management.

EFAS Structure. EFAS follows many operational hydrometeorological systems in generating forecast products based on the output of a hydrological model forced by numerical weather predictions (NWPs). For each forecast, the initial conditions of the hydrological model are derived using observed meteorological data. The forecast products are placed on a web platform available to the EFAS partners. These products are then analysed and, if necessary, the awareness of responsible authorities to the potential for upcoming flood events is raised.

The operational EFAS has been outsourced to four centres: 1. Hydrological data collection centre, which collects historic and real-time river discharge and water level

[12] For more information see www.efas.eu

[13] Copernicus Emergency Management Service (Copernicus EMS) provides information for emergency response in relation to different types of disasters, including meteorological hazards, geophysical hazards, deliberate and accidental man-made disasters and other humanitarian disasters as well as prevention, preparedness, response and recovery activities. The Copernicus EMS is composed of an on-demand mapping component providing rapid maps for emergency response and risk recovery maps for prevention and planning and of the early warning and monitoring component which includes systems for floods, droughts and forest fires (www.emergency.copernicus.eu).

data; 2. Meteorological data collection centre, which runs onsite at the JRC[14] and collects historic and real-time observed meteorological data; 3. Computational centre at the European Centre for Medium-Range Weather Forecasts (ECMWF), which collates NWPs, generates the forecast products and operates the EFAS Information System web platform; and 4. Dissemination centre, which analyses the results on a daily basis, assesses the situation, and disseminates information to the EFAS partners and to the EC.

Data acquisition. EFAS requires hydrological and meteorological data from in situ observations to calculate the initial hydrometeorological conditions and forecasting data to drive the flood forecasting system. Various meteorological and hydrological national services or river basin authorities, including a number or agencies from the Danube region, provide real-time and historic data to EFAS. For EFAS, the meteorological and hydrological data collection centres are in charge of managing the existing network of providers of observed data. The centres can also contact potential providers and negotiate standard data license agreements between the provider and the Copernicus services.

Data are collected on a 24/7 basis. Hydrological data collection provides real-time and historic in situ hydrological observed data. Real-time data are used in the generation of post-processed forecast products while the historic data are also used in model calibration. Currently, data are collected for over 800 sites. The meteorological data collection centre collates several variables from gauges including precipitation, temperature and wind speed, though not all variables are collected from all stations. Alongside the in situ observations HSAF[15] satellite-derived soil moisture and snow coverage products are also collated for visualisation purposes. Where the flood alerts issued by the national agencies are available, these are displayed in a common framework. For example, EFAS Information System (EFAS-IS) shows the warnings issued by the Swedish Hydrological Service to the public in the same way as it illustrates the warnings by the Bavarian water services. This provides a feedback loop from the officially issued warnings to the EFAS system.

Model components. Within EFAS, hydrological forecasts are generated by cascading an ensemble of meteorological forecasts through a deterministic hydrological model. This section briefly outlines both the models that provide meteorological forcing and the hydrological model LISFLOOD.

1. Meteorological Models: In order to capture some of the uncertainty in the weather predictions, EFAS has been designed to operate with several NWP systems capable of providing the required forcing for the LISFLOOD hydrological model. Currently, EFAS makes use of four NWP products, including two based on the ECMWF Integrated Forecasting System.

2. Hydrological Model LISFLOOD: LISFLOOD is a GIS-based spatially distributed hydrological rainfall-runoff model developed at the JRC for operational flood forecasting at pan-European scale. Driven by meteorological forcing data (precipitation, temperature, potential evapotranspiration, and evaporation rates for open water and bare soil surfaces),

[14] For more information see https://ec.europa.eu/jrc/en

[15] For more information see http://hsaf.meteoam.it

LISFLOOD calculates a complete water balance at a 6-hourly or daily time step and for every grid cell. Processes simulated for each grid cell include snowmelt, soil freezing, surface runoff, infiltration into the soil, preferential flow, redistribution of soil moisture within the soil profile, drainage of water to the groundwater system, groundwater storage and groundwater base flow (Figure 14.)

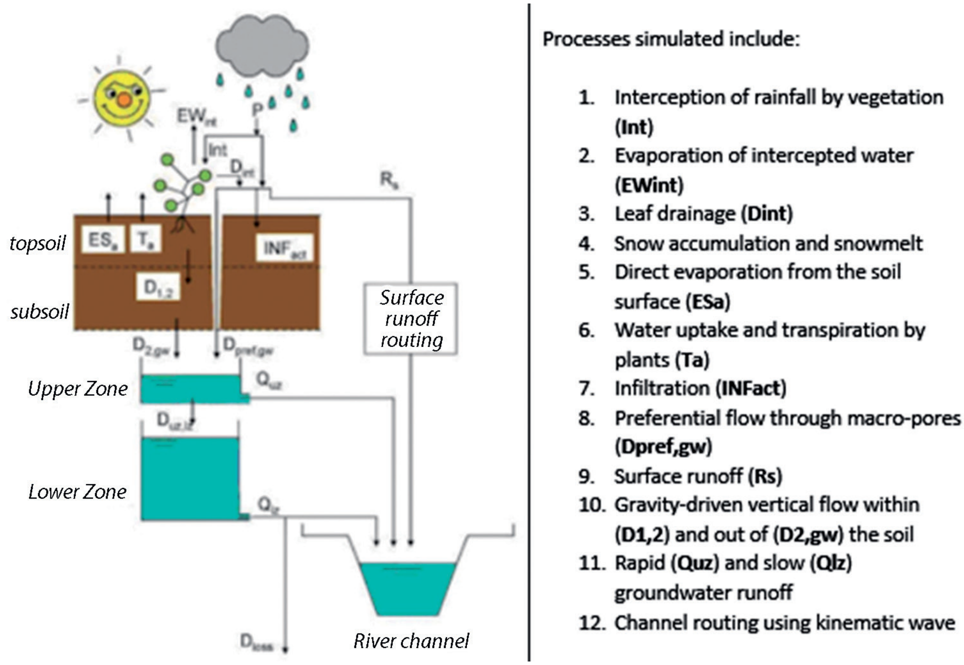


Figure 18. Schematic description of the hydrological LISFLOOD model used in EFAS (www.efas.eu/about-efas.html)

Runoff produced for every grid cell is routed through the river network using a kinematic wave approach. The pan-European set-up of LISFLOOD uses a 5 km grid on a Lambert Azimuthal Equal Area projection. Spatial data are obtained from various European databases with emphasis on having a homogeneous base for all over Europe.

Generation of forecasts. The generation of forecasts is the responsibility of the computational centre. The task can be subdivided into three main components: 1. collating all the necessary forcing and input data; 2. running LISFLOOD; and 3. preparing results for visualisation.

Full details about the EFAS – including model calibration, computer hardware and software, scheduling of execution, forecast products, flood alerts, post-processed forecasts, flash flood alerts, forecast dissemination, case studies and much more – interested students can find at the EFAS website and in numerous papers published about this system (e.g. [15]).

Sava Flood Forecasting and Warning System (Sava FFWS)

With the demise of Yugoslavia, the hydrometeorological services (HMSs) of the six new independent states have taken over the responsibility for execution of most activities of the former Yugoslav Federal Hydrometeorological Institute. However, some important tasks – such as exchange of hydrological and meteorological real-time and non-real-time data and related information, and coordination of hydrological forecasting activities in the new international river basins remained uncovered. This became in particular apparent in the Sava River basin (SRB), which became the international river shared by five independent states – Bosnia and Herzegovina, Croatia, Montenegro, Serbia and Slovenia. The gap was in part offset by the establishment of the International Sava River Basin Commission (ISRBC) in 2005. Yet, the weaknesses persisted in the real-time data exchange and operational flood forecasting domain and inspired a number of initiatives, led by the ISRBC and the national HMSs, to address and resolve the nagging issue.

Disastrous floods that had hit hard Serbia in May 2014 led eventually to the initiation of the World Bank-funded regional project, with the main objective to develop and establish an integrated real-time flood forecasting and warning system for the entire Sava River Basin (the Sava FFWS). The project was awarded to the international consortium led by the Deltares (along with the Royal HaskoningDHV, Eptisa, the Hydro-Engineering Institute of Sarajevo and Mihailo Andjelic), while its implementation started in mid-2016 and was completed by the end of October 2018. In fact, the developed Sava FFWS has just become fully operational in the 5 countries of the region and the ISRBC.

Main features of the Sava FFWS. The Sava FFWS is based on the Delft-FEWS operational forecasting open data and model platform [23]. The platform (Figure 19) is essentially a sophisticated collection of software modules designed for building a hydrological forecasting system that can easily be customised to suit the specific users' requirements.

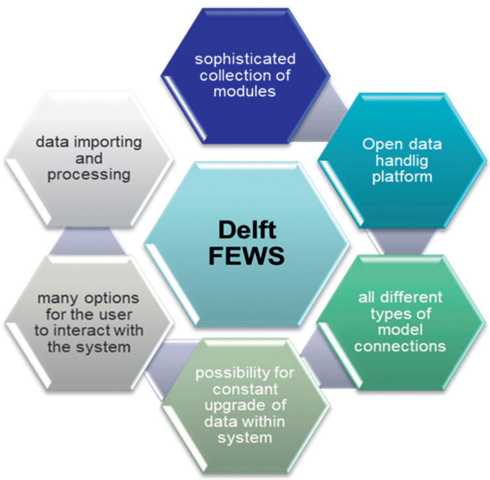


Figure 19. Characteristics of the Delft FEWS open data and model platform [23]

It is a freely available expert software that handles efficiently large amounts of data, integrates various hydrological and/or hydraulic models with real-time observations and the most recent meteorological forecasts, and enables consistent data quality control, standardised work processes, visualisation and reporting. In addition, the Delft-FEWS can orchestrate massive computations – on dedicated hardware and/or in cloud – and allows for remote collaboration between multiple experts and parties working and interacting with the same data. This means that the countries can use independently the models in operational mode, forced with the different meteorological input used by the riparian countries.

In developing the Sava FFWS [12] [21] [10], the Delft-FEWS is used as the backbone for integration of available telemetry data from the network of hydrological and meteorological stations in the region, radar and satellite data, meteorological NWP products, the hydrological and hydraulic models and user interface (Figure 20).

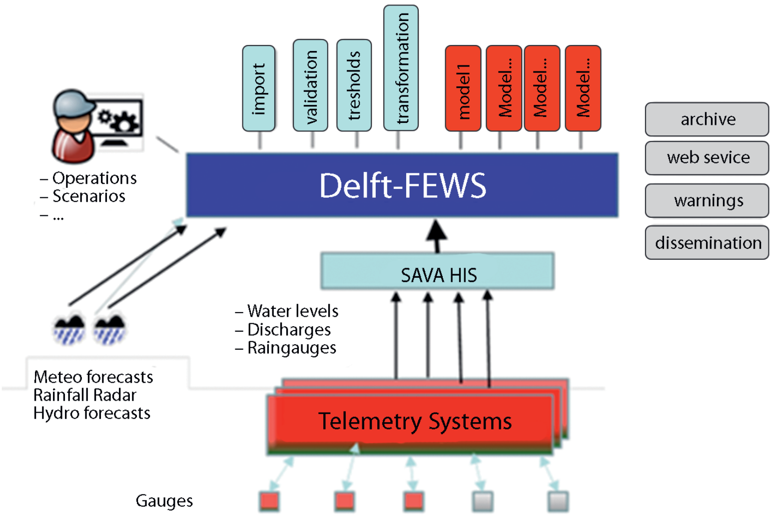


Figure 20. Use of the Delft-FEWS as the backbone for integration of data, models and user interface of the Sava FFWS [12]

The target users of the Sava FFWS are the hydrometeorological and/or water resources management institutions of the riparian states responsible for flood forecasting in their respective parts of the Sava river basin, and they jointly operate and maintain the Sava FFWS.

Real-time data and numerical weather predictions. The Sava FFWS connects to the real-time telemetry data, which are automatically collected in the already existing Sava HIS application hosted by the ISRBC and provides a web service based on the WaterML2 protocol. The telemetry data consist of water levels and discharges at 345 fluvial gauges as well as precipitation, air temperature and snow depths at 257 meteorological gauges in the basin. Automatic validations on doubtful or unreliable measurements are executed, based on set criteria (e.g. exceeding of validation limits, same readings or too high rates of changes). Thresholds based on operational warning levels have been implemented to visualise warnings. Meteorological forecast input is derived from various Numerical Weather Prediction (NWP) models that provide up to 5-day and 10-day forecasts of precipitation, temperatures, snow information, soil moisture, etc. The NWPs include Aladin, NMMB, WRF and ECMWF deterministic models, next to the ECMWF ensemble forecasts for the whole basin. The NWP products used in the Sava FFWS and their characteristics are listed in Table 2. The relevant meteorological information is transformed to catchment average data that is used as input to the hydrological models. Various aggregations have been realised to assist the duty forecasters in interpreting the current and the expected weather situation. To this effect, precipitation radar and satellite images have been implemented, but due to lack of radar and satellite images in the whole Sava basin, they are not currently used as model input, and can readily be included once they become available.

Table 2. NWP products used in the Sava FFWS [12]

Model/source	Spatial resolution (km)	Temporal resolution (h)	Forecasting period (days)	Updated every… (h)
ECMWF	8–10	1	10	12
ECMWF EPS	16–20	1	10	12
Aladin	4.5	1	3	6
Aladin HR	4	1	3	6
NMMB	3–4	3	3	12
WRF SRB	4–6	3	3	12
WRF BiH	2.5	1	4	24
WRF MNE	1	1	5	12
WRF MNE	3	3	5	24

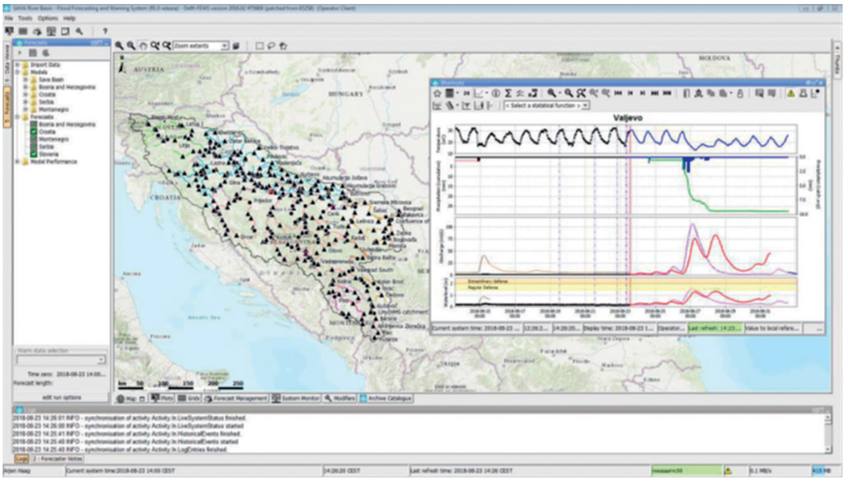


Figure 21. Illustration of the Sava FFWS user friendly interface – given for the hydrological profile Valjevo as an example [10],[12],[21]. It presents GIS map of the Sava River basin, detailed hydrographs, precipitation, temperatures as well as observed and forecasted discharges, water levels and warning status for each forecasting location

Hydrological and hydraulic simulation models. A large number of hydrological, hydraulic models have been implemented within the Sava FFWS. Most of them are based upon the existing models available in the beneficiary countries. Where applicable, these have been adapted and made compatible with the Delft-FEWS operational forecasting system. The detailed hydraulic models are coupled with the most suitable hydrological model, and the results of both are stored within the system. Within the Sava FFWS, distinction can be made between default runs, which are scheduled to run automatically at certain predefined time intervals, and the manual user runs, which can only be run manually.

Apart from the models given in Table 3, a framework of the distributed grid-based Wflow hydrological model has been implemented for the beneficiaries in Bosnia and Herzegovina, Serbia and Montenegro, and a separate Wflow model has been setup for Montenegro.

Table 3. Hydrological and hydraulic models in the Sava FFWS and the forecast workflows with NWP [12]

	NWP			Default Run				Manual User Run		
Models	**Hydrological**	**Hydraulic**	**Aladin SI+ ECMWF**	**Aladin HR +ECMWF**	**ECMWF EPS**	**NMMB**	**WRF BiH**	**WRF MNE 1km**	**WRF MNE 3km**	**WRF SRB**
Basin BA/RS/ME	HEC-HMS Sava	HEC-RAS Sava	X		X	X			X	X
	WFlow (BA/RS/ MNE)		X		X	X			X	X
Local	Mike-NAM (HR)	Mike 11 Croatia		X						
	Mike-NAM Una (BA)	Mike 11 Una		X						
	HBV-light Bosna (BA)		X		X	X	X		X	X
	HEC-HMS Sava	HEC-RAS Bosna (ISRBC)	X		X	X			X	X
	HEC-HMS Sava	HEC-RAS (BA) (9)	X		X	X			X	X
	Mike-NAM Vrbas	Mike 11 Vrbas	X		X	X	X		X	X
	WflowMNE		X		X	X		X	X	X
	HEC-HMS Kolubara (SRB)	HEC-RAS Kolubara (SRB) [17]	X		X	X			X	X
	"HBV (SRB) (5) Jadar, Kolubara, Tamnava,Ub, Ljig"		X		X	X			X	X

Data assimilation and predictive uncertainty. Within the Sava FFWS, the Asynchronous Ensemble Kalman Filter (AEnKF) algorithm is used to update the initial conditions for the WFlow hydrologic model to fit the observed discharges over the last couple of days thus improving the forecasts. For the HEC-HMS Sava model with the ECMWF Ensemble forecasts, a statistical post-processing approach [22] is used to arrive at a confidence band around the ARMA corrected streamflow ensemble traces.

Performance indicators. Sava FFWS calculates daily the performance of the NWP and hydraulic and hydrological models for preconfigured lead times by comparing stored forecasts with later obtained observed data. Performance is expressed with two indicators; the absolute bias and the root-mean-squared-error (RMSE). The RMSE gives a good indication of overall performance, while the bias also shows whether the error is a result of over- or underestimation. For each lead time, the performance is assessed over all forecasts available for a configured period of time. The results of the performance assessment can be used in a later stage to decide on the operational use and further improvement of the existing NWP, hydrological and hydraulic models.

Further details about the Sava FFWS interested readers can find at the ISRBC and national forecasting organisations of the 5 Sava riparian states.

Hungarian Hydrological Forecasting Service (HHFS)[16]

The Hungarian Hydrological Forecasting Service was founded on 1 March 1892. Starting from 1929, it operated within the Institute of Hydrology. In 1952 the Research Institute for Water Resources Development (VITUKI) was established, and the HHFS operated within this research institute until it was closed in 2012. From the 1st of August 2012, the HHFS operates in the General Directorate of Water Management (OVF). The main activities of the HHFS are:

- collection and delivery of observed hydrological data
- hydrological forecasting
- collection, processing and delivery of information on the shallow river sections (due to low water levels) of importance for navigation
- collection, processing and delivery of meteorological observations and forecasts
- collection, processing and delivery of data on snow depth and ice phenomena on rivers

Hydrological Forecasting System. Currently, the HHFS is using operationally a system known as OLSER (the Hydrological Simulation and Forecasting Model System) illustrated in Figure 22. Its development (under different names) started as far back as the beginning of the 1980s. As a result, a coupled, deterministic-stochastic model started its operative life at the HHFS in 1983 [17] and continued to be further improved and expanded in the subsequent years and decades (e.g. [9]).

Owing to decades of continuous development and upgrading, the Hungarian forecasting system has grown into a mature and complex tool containing snow accumulation and snowmelt, soil frost, effective rainfall, runoff, flood routing and backwater effect modules, extended with statistical error correction modules (Figure 18).

16 For more information see www.hydroinfo.hu/en/

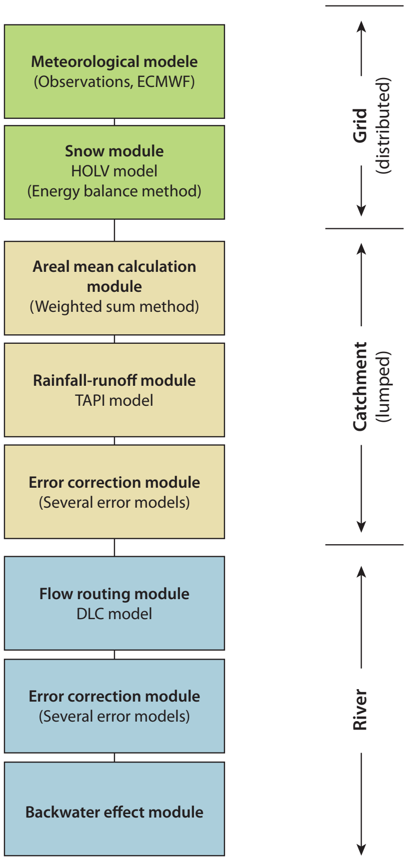


Figure 22. Modules of the OLSER Forecasting System [8]

Key functions of the OLSER modules are as follows:

- the meteorological module takes into account meteorological observations and forecasts on a 0.1 x 0.1 degree resolution grid
- the snow module is based on the HOLV model performing snow package calculations for 33 sub-catchments on a 0.1 x 0.1 degree grid over the entire forecast domain and handles all snow-related processes
- the areal mean calculation module producing spatial averages which serve as meteorological input for all sub-catchments
- the rainfall-runoff module is based on the TAPI rainfall-runoff model using Antecedent Precipitation Index (API) for its calculations
- the flow routing module is using the Discrete Linear Cascade Model (DLCM)
- the error correction and predictive uncertainty module contains special Kalman filter algorithms developed to consider for example the patterns in hydropower plants operation
- the backwater effect module handles the interaction on a tributary flow and the receiving river

The forecasting system is in daily operation and produces every morning 6-day lead time water level forecasts for the Danube, Tisza and Drava rivers, and their tributaries. Normally, it is run daily, but in emergency, i.e. during floods, it is run more frequently. The forecasts are published and provided to the public and all the users concerned with flood risk and water resources management.

Further details on the forecasting system used in Hungary is available from the HHFS website and the cited papers.

FFWS: New trends and possible future developments

Flood forecasting and warning systems have been shown to reduce impacts and save lives, and these systems are becoming an increasingly important tool for flood risk and water managers, and emergency response services.

The distinct advantage the hydrologists have nowadays over their predecessors is the advancement of science and technology. Better scientific understanding of physical phenomena and processes allows us to produce better and more realistic models, improve measurements of hydrological and meteorological variables, and improve prediction of model inputs. Dramatic advancements in affordable technology have made the application of modern hydro and meteo science and hydraulics to flood forecasting possible mainly due to the following three factors: 1. The availability of very fast computers, with significantly more memory and data storage capability than was available even just 10 years ago; 2. Widespread availability of high-resolution GIS-based data sets from remote-sensing sites, which are needed for model parameter estimation and calibration; and 3. Highly reliable telecommunications systems for data transmission from ground-based and satellite data collection platforms (DCPs). In addition, the expansion of the Internet and the proliferation of mobile phones have had a dramatic impact on the distribution of flood warnings.

Looking into the future, there is no doubt that further advancements in affordable technology would provide ample opportunities for improvement and expansion of the existing flood forecasting and warning systems in the world as well as in the Danube basin.

What is more, there is the fast-growing development of global and continental-scale flood monitoring, modelling and prediction systems. Such is, for example, the European Flood Awareness System (EFAS) shortly reviewed above. EFAS represents an operational continental-scale flood forecasting system, which became operational in 2012 with several European organisations having responsibility for producing and providing the flood information to EU and other European countries. EFAS was developed as a complementary system to the existing national and regional flood forecasting systems in European countries, and proved to be of great benefit to the national agencies and hydrological forecasting services.

Similarly, the Global Flood Awareness System (GloFAS),[17] which was developed jointly by the European Commission and the European Centre for Medium-Range Weather Forecasts (ECMWF), provides countries with information on upstream river conditions as well as continental and global overviews. GloFAS couples output from NWP model ensembles from the ECMWF Ensemble Prediction System with a hydrological model covering continental domains. In the meantime, the Global Flood Awareness System has been upgraded to version 2.0. It consists of a number of improvements to the hydrological forecasting chain. Version 2.0 follows the migration of the GloFAS prototype to the ECMWF operational environment as a 24/7 service, and includes the following major features:

- version numbering system for the GloFAS cycles
- calibrated LISFLOOD routing component
- updated reference discharge climatology
- improved initialisation of the real-time forecasts
- available GloFAS datasets

Capitalising on ever-increasing scientific understanding of physical phenomena and processes coupled with new advances in technology, it is not difficult to foresee that the global hydrological models will further be expanded and refined in the future, in parallel with development and improvement of the local, national and regional flood forecasting and warning systems.

A bright future of the FFWSs is more than welcome as counterweight to a rather gloomy picture of the world succumbing to numerous negative impacts of climate change, including the increase in intensity and frequency of disastrous floods.

Concluding notes

In the hope that these notes may prove beneficial to the prospective students, it is very important to recognise that a flood forecasting and warning system is a complex, live structure operating in real-time. As such, it is only as good as its weakest component, i.e., each component of the system is crucial for the system to fulfil its mission.

As an illustration, consider the real place of model development in building up an effective operational forecasting system. Model development and usage represent just a small fraction of the costs of establishing and running an operational hydrological forecasting system. Yet, the system is worthless without models; they play the same role as the heart in the human body. Small, no doubt, but one cannot exist without it.

At the very end, let us recall a few proverbial Murphy-inspired Laws of Hydrological Forecasting:

The flood always hits on Sunday at 2 a.m. when there is nobody in the forecasting centre.

17 For more information see www.globalfloods.eu/

If the above Law does not apply, then the flood comes when the staff is windsurfing on the nearby lake.

If one is lucky, one meets only once in a lifetime the flood that is greater than the design flood.

If one is unlucky this happens regularly.

The 100-year-flood returns every ten years minimum twice.

When the Big Flood comes the online data collection system fails within minutes.

When the Big Flood comes all our precious hardware breaks down in maximum T hours, where T is one fifth of the concentration time of the catchment.

The probability of the joint occurrence of unfixable computer bugs in the code of our forecasting model and the Big Flood is equal to one.

A decent forecast of a flood peak specifies either the flood peak value or the time of occurrence, never both!

List of acronyms used

EUSDR: European Union Strategy for the Danube Region
EUSDR PA 5: European Union Strategy for the Danube River – Priority Area 5
DR: Danube Region
DFRMP: Danube Flood Risk Management Plan
DSPF: Danube Strategic Project Fund
FFWS: Flood Forecasting and Warning System
NWP: Numerical Weather Prediction
ECMWF: European Centre for Medium-Range Weather Forecast
QPF: Quantitative Precipitation Forecast
Sava FFWS: Sava Flood Forecasting and Warning System
ISRBC: International Sava River Basin Commission (ISRBC)
SRB: Sava River Basin
HMS: Hydrometeorological Service
DCP: Data Collection Platform

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