Decision-Support for the Selection of Flood Forecasting Models

Background and scope

National Meteorological and Hydrological Services (NMHSs) are tasked to protect human life by issuing timely and accurate flood forecasts. A forecast can be used by civil authorities to evacuate regions at risk from flooding and to take other precautions to protect life. Additionally, a forecast can provide the basis for preparing critical infrastructure for floods in order to minimize damage. Forecasts may also be used to inform operators of reservoirs in an effort to mitigate effects of floods downstream of reservoirs. Flood forecasting is therefore an important service of NMHSs.

The transformation of precipitation into channel flow is a highly complex physical process. A common practice is to use a hydrological model to represent watershed processes. Many different hydrological models have been produced by government agencies, universities, and private companies. They offer a wide range of process simulation options, differing levels of complexity and data requirements, and various degrees of technical support and training. Their application also depends on the forecasting objective, geographical and environmental factors, as well as institutional capabilities. Therefore, the selection of a “best choice” flood forecasting model needs to be based on a systematic approach.

WMO has initiated various programmes and projects with the aim of supporting NHMSs in their efforts to improve forecasting and forecasting based services. The overarching programmatic framework in this regard is the WMO Flood Forecasting Initiative. A key reference for the understanding of flood forecasting and derived services is the “Manual on Flood Forecasting and Warning” which was published in 2011. This Manual provides a comprehensive documentation of the main aspects of flood forecasting. It addresses monitoring networks, data management, and hydrological simulation models. Applications, training needs, and implications of flood forecasting are related to the provision of reliable services.

In response to a recommendation made during a workshop on the Strategy and Action Plan of the WMO Flood Forecasting Initiative, held in Geneva in December 2009, activities were undertaken to organize a workshop on the inter comparison of flood forecasting models with the aim to provide decision support for selecting adequate flood forecasting models in hydrological services. As a result**,** from September 14 to 16, 2011, 29 international experts from operational services gathered at the Federal Institute of Hydrology in Koblenz, Germany. 18 operational flood forecasting systems and models were presented. The aim of the workshop was to discuss operational models and related issues and to initiate a process for providing support in the process of selecting appropriate methods, models, and settings for specific flood forecasting purposes.

During the workshop, a task team, consisting of 12 experts was formed. This team was mandated to further develop a “Decision-Support Tool for the Selection of Flood Forecasting Models” aiming to support hydrological services in the selection of appropriate flood forecasting models under a range of different conditions for their applications.

The guidance materials presented here are the result of the work of the task team that has met from July 8 to 10, 2013 in Koblenz, Germany. The material is targeted for professionals who are tasked to select a flood forecasting model that is best suited under a range of hydrometerological, data and institutional conditions.

The target group for this guide are professionals who may not be specialists in flood forecasting but have a basic understanding of hydrology.

Application purposes for model systems

Hydrological flood forecasting models are used in many types of watersheds. All watersheds share some characteristics. Some examples of shared characteristics include: watershed boundaries, surface runoff and river channels. However, other characteristics may require special consideration when a model system is selected.

Characteristics that differentiate river systems are:

- Short rivers with flashy runoff response (usually in high relief terrain)
- Large rivers with braided main channel
- Downstream of medium-size and large rivers (large lateral inflow at a point)
- River systems influenced by the operation of dams and reservoirs
- River systems with significant storage in lakes
- Braided river system in flood plains
- Seasonal river system (as a result of seasonal climatic conditions or pronounced water use (reservoirs, groundwater pumping, water abstractions) semi-arid and arid area, groundwater pumping area)

The purpose of flood forecasting should guide the selection of models or a model system in those cases where the forecast is required for more than one forecasting location. This is the case in river basins with multiple forecasting locations in different tributaries or sections of the main stem of a river and in basins with large differences in the catchment characteristics. A model system designed to support a specific purpose may include specialized sub-models.

Purposes of flood forecasting include:

- Protection of lives and properties
- Flood risk management
- Optimisation of flood preparedness and flood response measures
- Optimisation of the operation of water infrastructure such as reservoirs, diversions etc.

Forecasting situations which are not covered by the guidance material

The forecasting situations listed below require the use of highly specialized models that cannot be easily classified and described. Mostly, feasible solutions for such problems are individual and cannot be evaluated with the methodology presented in this material.

Excluded forecasting situations:

- Flash floods
- Urban floods
- Coastal and tidal floods
- Coastal inundations, e.g. caused by storm surges

- Outburst floods from glacier lakes, dammed lakes or as a result of dyke failures

Uncertainties:

Measurement uncertainty, the natural variability of hydrological as well as meteorological inputs to water resources systems, and a lack of perfect knowledge of all the physical processes occurring in catchments are causes of uncertainty in hydrological forecasts. For further details please refer to the WMO STATEMENT ON THE SCIENTIFIC BASIS FOR, AND LIMITATIONS OF, RIVER DISCHARGE AND STAGE FORECASTING. (http://www.wmo.int/pages/prog/hwrp/publications/statements/stmnt_limitations08042010.pdf)

One possibility to reduce the forecast uncertainty is to include an appropriate updating procedure in flood forecasting models

Updating procedures are designed to minimise the error of the simulated flood hydrograph by feeding back the river flow up to the time origin of the forecast. If these flow values are available in real time then it is widely accepted that updating procedures should be based upon a real time forecast model to improve its accuracy and lead time. There are many ways in which recently observed river flows can be used to update a forecast, and various updating procedures are available (see WMO Manual on Flood Forecasting and Warning sections 3.2.6 and 3.2.3.2).

Updating procedures are easily applied to rainfall runoff models of any type and to simple mass balance type routing models. Applying them to complex hydrodynamic routing models on river sections where river level data is available is a specialist activity and expert help should be sought.

Fundamental requirements for the application of flood forecasting models

The implementation of a flood forecasting system requires both human and computing resources. Sufficient resources must be in place to support not only the development of the system but to operate it and maintain it through time. If resources are not available to a particular organisation they can be sourced in full or in part from external providers. Thus, flood forecasting is constrained by the institutional capability and the availability and types of data and their representativeness and quality.

Table 1 describes some of the most important requirements (column 1). A brief description of each requirement is given (column 2) and an indication of whether the requirement is mandatory or desirable (column 3). An initial suggestion on how the requirement could be met is also provided (column 4). More detail on the general requirements for implementing and operating a flood forecasting system and service are described in Section 2.3 of the Manual of Flood Forecasting and Warning.

Table 1 Organisational, computational and data resources required to support a flood forecasting service

Description	Mandatory / Desirable	How to meet the requirement
Organisational capability		
Ability to configure and calibrate a model		
Hydrologist(s) who understand flood processes Staff who have experience working with numerical software	Mandatory	Recruit suitable staff or train existing staff, can also seek external support
Ability to run a flood model and use the results		
Staff that can be trained to: - review the observations and forecasts that are input to the forecast model - run the models - interpret the output in the context of known flood effects - prepare outlooks or warning products that link with risk maps and information required by civil protection authorities (responsible for protective actions)	Mandatory	Recruit or train staff
Computer resources		
Computer to store data, run models and view output		
Computer hardware is required that can host the software that the flood models run on. The hardware available may range from a stand-alone PC to a network	Mandatory	Simple flood forecasting systems can run on a stand- alone computer. This is a minimum requirement.
Network connections		
Access to data feeds required as input to Flood Forecasting Model Ability to communicate forecasts	Desirable	If access to an internet is not available, data collection and forecast Pcommunication relys on telephones.
Support for computer and networks		
IT staff that can install software and support hardware Staff that can fix these when they stop working	-	-
Data availability	*General notes: Stream level and flow information is a fundamental requirement for flood models. Rainfall data measured on the ground is highly desirable, rainfall estimates and forecasts can be sourced from various meteorological products (e.g. National Weather Service, Global Numerical Weather Forecast)*	
Data management system		
A pre-requisite of a flood forecasting system is a functional data management system. Typically this will be a database able to store time series information and the required descriptive information (e.g. station information).	Mandatory	-
Manual observations of streamflow and rainfall		
Stream level information can be manually observed at locations where gauge boards are installed. Rainfall depth can be observed using a manually read rain gauge. Manual observations require a communication method (e.g. telephone) and a method of entering the data into the flood modelling system (e.g. spreadsheet file)	Mandatory *(either manual or automated or a combination of both)*	-
Automated data collection network		
Automated data collection is desirable and are the backbone of most flood forecasting systems. Compared to human observers, instruments tend to be more reliable (less subject to human error or observer availability) and can provide more frequent, accurate and timely data. Automated instruments, loggers and communication links (telemetry) are more expensive to install and maintain.	Mandatory *(either manual or automated or a combination of both)*	Observation data is often sourced from other organisations, commonly agencies responsible for water resource management. Rainfall estimates and forecasts can be sourced from the National Meteorological Office and from globally available Numerical Weather Forecast (NWP) products.

Costs of flood forecast service

The investment in a flood forecasting system includes the initial cost of setting up the system but by far the largest cost is the ongoing maintenance. This includes the staff wages, data provision, investment in the model including updates, adaptation of hardware.

Minimum communication requirements

To ensure the effectiveness of flood forecasting services, it is necessary to communicate the following basic information for the area of interest based on the output of the forecasting model:

- Quantitative gauge heights in relation to warning and alert levels (that need to be previously established),
- flow volumes (based on rating curves).
- Travel time of flood wave and magnitude (see above),
- shape of the flood wave (peak or extended,
- duration of flood situation,
- recurrence period,
- uncertainty (value to describe probability of occurrence…)

Current Status of Flood Forecasting Models

Introduction

Comparing Hydrological Flood Forecasting Models (HFFMs) is not a new idea. A traditional approach is to select a gallery of models for comparison, and a watershed where models can be run. A common data set is assembled including meteorological data, observations of flow and stage, soil characteristics, and all other data that might be used to parameterize the models. Each model is configured for the watershed using the assembled data. Performance metrics are defined, and calculated for each model in the inter-comparison. The models are then ranked based on the performance metrics. This process may be repeated for a variety of different watersheds in various climates or regions of the world representing different hydro-meteorological conditions. The general idea is to select a single, most appropriate model for a particular set of hydro-meteorological and institutional conditions.

Here, an approch is proposed to support efficient model selection, recognizing that more than one HFFM may perform sufficiently to achieve the goals of a NMHS. Therefore, the principal goal of this guidance-material is to ease the selection of a most suitable HFFM type.

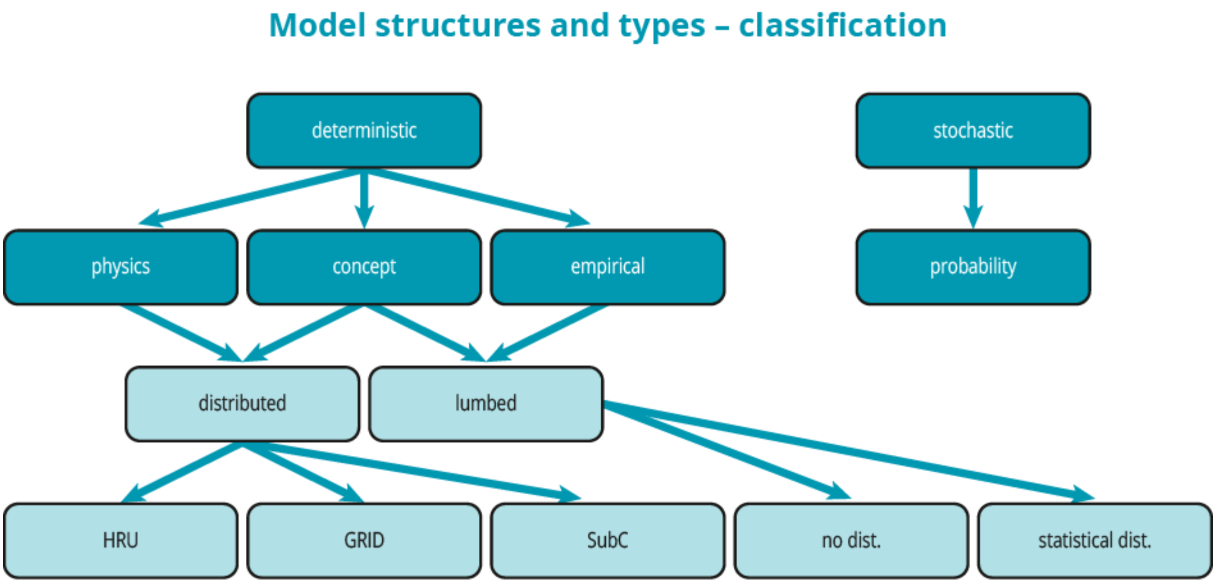
The document contains a short and concise description of the most commonly used HFFMs including a summary, from the model developer’s perspective, of the characteristics of watersheds (hydro-meteorological conditions) where each HFFM is likely to perform well. (See Annex 1)

On this basis, a multiple-criteria based selection tool is presented. The descriptions in the selection tool aim to assist hydrological services in making the appropriate selection for specific applications under a range of controlling factors such as data requirements, the level of professional expertise in a specific service and other factors as described above (see Table 1).

Flood Forecasting Models

Hydrological model type

The diagram below provides an overview of model structures and types of predictive models. In principle all these model types are applicable for flood forecasting.


Model structures and types – classification

Model resolution

The spatial and temporal resolution models depend on a wide range of factors. The temporal resolution depends on the frequency of input data and data assimilation as well as the forecast purpose. The spatial resolution depends on the density of the observing network, interpolation possibilities, variability of the flow conditions and the spatial characteristics of the area for which the forecast is issued.

Examples of operationally used flood forecasting models

Complete information on each of the flood forecasting models is included in the appendix. A brief summary of the information is included in the following table. The summary information describes each flood forecasting model from a scientific and engineering perspective, and also the conditions of application.

Country	Name	Model(s)	Main model type (1, 2, 3, 4, 5)	Data requirements (1, 2, 3, 4, 5)	River routing (0, 1, 2)	Probabilistic forecasting (0, 1, 2)	Rainfall forecast (0, 1, 2)	Institutional + operational effort (1, 2, 3, 4, 5)	Climatic situation (1, 2, 3, 4, 5)
Philippines	Roy Badilia	HBV+MikeFlood/11, HEC-HMS+HEC-RAS, ANUGA	2	3	2	0	0	3	1
UK	Tim Harrison	FEWS+PDM, KW, ISIS, G2G & own developments	4	5	2	1	2	5	4
RSA	Brink	Own routing model (based on Mukingum)	5	1	1	0	0	2	2
Mexico	Faustino de Luna Cruz	SAMO	2	3	-	0	1	3	1
France	Caroline Witwer	Own developments	4	5	2	0	2	5	2, 3, 4
China	Zhou Li	XinAnJiang	1	2	1	0	1	3	2, 4
USA	William Schaffenberg	HEC-HMS	3	4	1	0	1	5	1, 2, 3, 4
Pakistan	Muhammad Shad	FEWS, SAMO, SOBEK	2	1	2	0	2	4	1
general	Mike Butts	DHI Products	4	4	2	-	2	4	-
Italy	Ezio Todini	TOPKAPI	3	3	2	2	2	4	4
Netherlands	Eric Sprookereef	FEWS River Rhine (HBV + SOBEK)	2	4	1	2	1	5	4
Italy	Jutta Thielen	LISFLOOD	3	4	-	2	1	3	2, 3, 4
Finnland	Bertel Vehviläinen	HBV-like	2	5	2	2	2	5	4
Bavaria	Alfons Vodelbacher	LARSIM + WAVOS + FLUX/FLORIS	2	5	2	2	2	5	3, 4
Austria	Hans Wiesenegger	FEWS, COSERO, LARSIM, DHI MIKE, HBV, HOPI, AspS	4	5	2	2	2	5	3, 4
Netherlands	Paolo Reggiani	REW	2	5	2	0	1	4	1
Germany	Dennis Meißner	WAVOS	2	4	2	2	1	4	4

Legend

Main model type
- **1** lumped
- **2** semi-distributed
- **3** distributed
- **4** combined
- **5** HD routing only

Data requirements
- **1** rainfall/upper river flow
- **2** plus rainfall + some data
- **3** plus rainfall hourly, meteo data monthly, DEM, land use
- **4** plus rainfall hourly, meteo date hourly, DEM, land use, snow data
- **5** plus rainfall hourly, meteo data hourly, DEM, land use + e. g. advanced snow-climatic data

River routing
- **0** no routing
- **1** hydrologic routing
- **2** hydraulic routing (S-V-Eqs., K-W-Eqs.)

Probalistic Forecasting
- **0** no probalistic forecast
- **1** quantile regression etc.
- **2** ensembles

Rainfall forecast
- **0** no rainfall forecast
- **1** rainfall forecast
- **2** RADAR nowcast

Institutional an operational effort
- **1** low
- **2**
- **3** intermediate
- **4**
- **5** high

Climate situation
- **1** tropical/megathermal climates
- **2** dry (arid and semiarid) climates
- **3** mild temperate/mesothermal climates
- **4** continental/microthermal climate
- **5** polar climates

Forecast lead time and general implications

The forecasting lead-time requirement depends primarily on the lead-time requirement for flood warning, and may extend from as little as 1-2 hours to several days ahead. In the latter case, the shorter lead-time forecasts may be used in issuing the actual operational warning, while forecasts at the longer lead-time are used mainly as guidance in moving to a flood alert status, rather than to guide the issuing of a flood warning. For example, for a large-scale flood event in a UK situation, given a week's lead-time, the sequence of information actions might be (Golding 2009):

- 3-5 days ahead: issue 'advisory' or 'period of heightened risk'; engage in awareness raising activities through the media, mobilize support organisations for the vulnerable; initiate 'participatory' information sharing by local flood response organisations
- 1-2 days ahead: issue 'early warning' or 'watch'; activate mitigation measures for flood minimization and protection of critical infrastructure; provide active support to vulnerable groups; move to a consultative engagement with those in the most vulnerable areas
- Hours ahead: issue 'flood warning'; activate emergency response; evacuate most vulnerable groups if appropriate; provide 'prescriptive' advice to individuals

Although required lead-times differ as a function of the forecast requirement and the considered area, it is convenient to distinguish between two types of forecasting requirement:

- Flood Warnings are typically issued for lead-times at which emergency response actions need to be taken.
- Outlook Statements are used to prepare for mitigating expected flood impacts.

A comparison with the catchment response time indicates whether sufficient lead-time can be obtained using catchment observations (e.g. river flows, raingauges) or rainfall forecasts are required as inputs.

The ratio between lead-time requirements and catchment response time can be formalised by using a simple classification scheme for flood forecasting, originally developed by Lettenmaier and Wood (1993).

Considering first a single forecasting point in a catchment, the adapted classification scheme compares the desired warning time (Twarning) to the total response time (Ttotal) at the location for which the forecast is to be provided. This response time is further subdivided into the hydraulic response time (travel time through main river, Triver) and the hydrological response time (which is less than the response time of the catchment, Tcatchment).
An additional lead-time (Tsurge) is also applicable for coastal forecasting situations (although coastal forecasting is outside the scope of the present study). This division is somewhat arbitrary but generally the river channel is considered to be the main river (system), whilst the hydrological response is the response of sub-catchments before water flows into the main river system.
The situations in Table A.3 are defined, and these general categories are illustrated in Figure A.2, and indicate the types of forcing inputs which may be required at each forecasting point in the catchment. For example, for Type 1 situations, rainfall forecasts are essential and, if conditioning of outputs is used, this would require an archive of forecast values (perhaps

obtained using a hindcasting exercise). For catchments with multiple forecasting points, then each point needs to be considered in turn and the forcing inputs assessed.

Table – Links between lead-time requirements and catchment response (adapted from Lettenmaier and Wood 1993)

Type	Catchment	Criterion	Description and key forcing inputs for flood warnings
1	very fast responding basins	$T_{warning} >> T_{total}$	The desired lead-time is such that the warning or outlook must be issued on the basis of water that has not yet fallen as rain. In this case a rainfall forecast is the only means to provide a timely warning when using a flood forecasting model
2	small to medium basins	$T_{warning} < T_{total}$ and $T_{catchment} >> T_{river}$	The warning or outlook will be issued on the basis of water that is already in the catchment and is mainly determined by the hydrological travel time. This may be the case for point I in Figure A.2
3	medium size basins	$T_{warning} < T_{total}$ and $T_{catchment} \sim T_{river}$	The warning or outlook will be issued on the basis of water that is already in the catchment and river and the response time is determined by the hydrological response time and the hydraulic response time. This may be the case for forecast point IV in Figure A.2.
4	large river basin	$T_{warning} < T_{river}$ or $T_{catchment} << T_{river}$	The warning or outlook will be issued on the basis of water that is already in the main channel; or the hydrological response time is insignificant compared to the hydraulic response time. This may be the case for the forecast point VII in Figure A.2, assuming catchments E and F have only minor contributions.
5	coastal / tidal zone	$T_{warning} >> T_{surge}$	The desired lead-time is such that the warning or outlook may be issued on the basis of wind conditions that have not yet occurred. In this case wind and pressure forecasts are necessary for a timely warning.

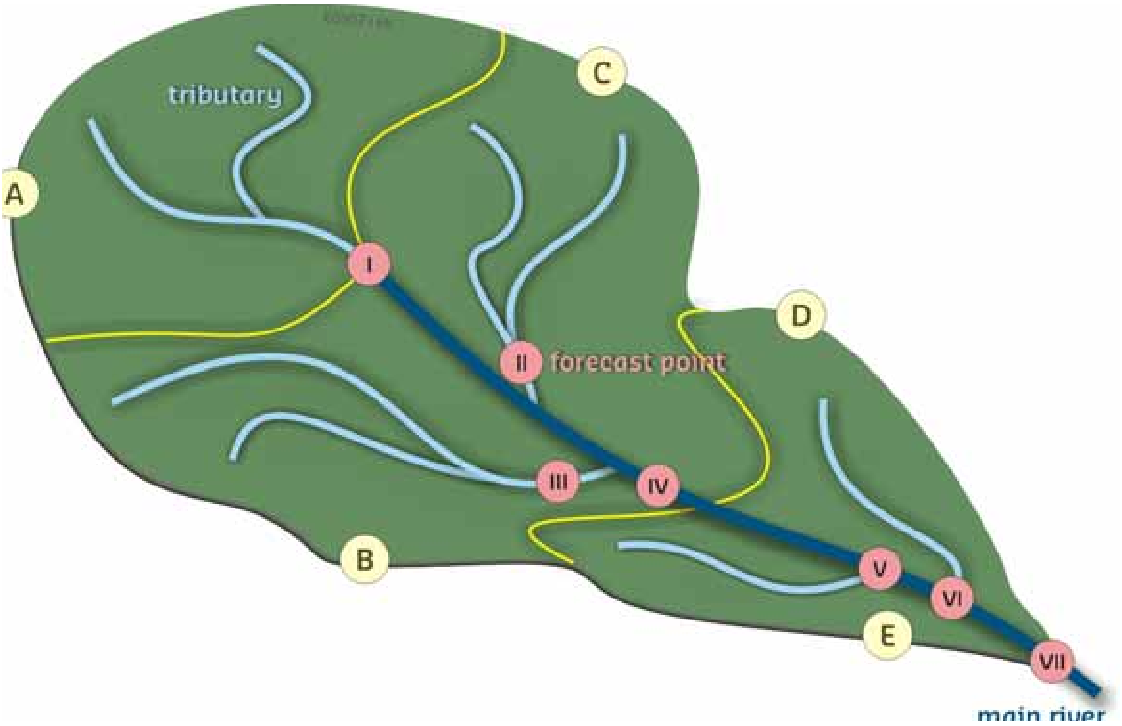


Figure: Schematic layout of a catchment, including the main river, tributaries and catchments (adapted from Lettenmaier and Wood 1993).

In estimating the actual time available, an allowance also needs to be made for the various time delays in the decision-making and warning process, which can include (Environment Agency 2002):

- The time taken for information to be received by telemetry
- The time taken for a routine real-time model run
- The time taken for flood forecasting and warning staff to decide to act upon a forecast of levels exceeding a Flood Warning trigger level (e.g. whilst performing 'what if' runs)
- The time taken for all properties to be warned (e.g. via an automated dialling system).

Guidance for the selection of the Model Type for Flood Forecasting

This section presents two tools for selecting models. First selection criteria are listed, the second part describes the tools in detail.

Model Selection Criteria

- Hydroclimatic condition
    - Tropical/megathermal climates
    - Dry (arid and semiarid) climates
    - Mild Temperate/mesothermal climates
    - Continental/microthermal climate
    - Polar climates

- Catchment characteristics
    - Terrain
    - Size
    - Landuse
    - River network
    - Exposition
    - Water abstractions, reservoirs, lakes etc.

- Forecast purpose
    - Short term/long term
    - Quantitive forecast/ flood outlook
    - Warning/management
    - Stage/volume
    - Depth/duration
    - Gage related/ area related

- Institutional and operational requirements and professional capabilities
    - low
    - low – intermediate
    - intermediate

    - intermediate – high
    - high
        - ▪

- Model type
    - lumped
    - semi-distributed
    - distributed
    - combined
    - routing only
- Routing
    - no routing
    - hydrologic routing
    - hydraulic routing (Saint-Venant’s eqs., kinematic wave eq.)
- Data availability
    - Rainfall type and characteristics
    - Gauge information (stage/discharge)
    - Wetness conditions/soil moisture
    - Topography, landuse, soils

Explanation of the decision matrix and the decision tree

The proposed methodology to select the best suited model consists of a two step approach. It contains a decision aiding matrix and a decision tree.

In the decision matrix, 9 questions related to flood characteristics and processes lead stakeholders to select, in a first step, appropriate general model types for their specific forecasting context. Once a suitable model type is identified, the second step is to use the decision tree which allows for composing tailored forecasting model configurations that best suit the forecasting purpose under prevailing conditions as described above.

Guide to the use of the decision matrix/decision tree

Decision matrix

The “decision matrix” indicates possible choices of models and their configuration/modules. It is not a deterministic approach. Answers to questions might lead to different outcomes. This requires a comprehensive, iterative re-evaluation of boundary conditions and the feasibility of the solutions found. Please also refer to explanatory remarks while working with the matrix.

The Matrix holds nine questions with multiple possible answers. Each answer yields a direct consequence for the selection of a forecasting model.

The first two questions help selecting the basic model type that is appropriate for the given situation and watershed. Three more questions support the choice of model features to take into account key processes. Questions 6 and 7 are targeted to finding the right rainfall input type and resolution. Up to this point the questions provide guidance towards a first-pass model selection based on basin and hydro-meteorological characteristics as well as required lead time.

The final two questions take into account constraints in the development and application of the chosen model. Please note that if questions 8 and 9 impact on your model choice, you should try to improve related data issues and/or service capabilities, and revise model selection.

MODEL TYPE

Question 1 | Catchment size?

	small(headwater)	medium	large
Catchment model	lumped	semi distributed	distributed
Routing	mostly not needed	hydraulic/hydrologic	hydraulic, hydrologic, gaug to gauge correleation

Question 2 | Catchment relief ?[1, 2, 3]

	flat/plain	moderate/hilly	pronounced/mountaneous
Catchment model	lumped	semi-distributed	distributed

MODEL FEATURES

Question 3 | Does soil wetness affect flood generation?[4]

	no	to some extent	yes
Soil water budegt feature required	not	recommended	needed

Question 4 | Is snowmelt important for flood generation?[5]

	no	to some extent	yes
Snow module	not needed	recommended	needed

Question 5 | is river regulation (reservoirs/lakes/diversions) affecting floods[6]

	no	to some extent	yes
Storage module	not needed	recommended	needed

DATA REQUIRMENTS

Question 6 | What is the predominant flood cousing rainfall?[7]

	seasonal	frontal/advective	convective
Reommeded data resolution	daily	daily/hourly	hourly/sub-hour

Question 7 | What is the required leadtime?[8]

	short	medium	long
Required rainfall data	observed rainfall	rainfall nowcast is recommended (e.g. radar)	rainfall nowcast and/or forecast from NWPs is required

CONSTRAINTS

Question 8 | is distributred/gridded data available?[9]

	no	yes
Catchment model	lumped model is only option	semi-distributed/distributed model is feasible

Question 9 | What is the level of capability of the service?[10]

	low	internediate	high
	only simple tools feasible (correlations etc)	run lumped/black box simple models	all options availble

Legend

1) Only basic data required (mean slope; area....)
2) DEM, soil type, landuse, also required
3) Usually, deatiled data are used and then aggregated
4) Climate data is needed, evapo-transpiration estimates needed, soil water measurements are indicated for calibration
5) Temperature data required, preferably radiation and wind
6) Controlled river regulation requires operation rules
7) Raingauge density is often insufficient for small basins/convective rainfall.
8) Concentration times need to be considered. Indications for lead times: short lead time is in the range of half or less of the concentration time. Medium is in the range of the concentration time. Long is a multiple of the concentration time.
9) disaggregartion of data (especially rainfall) is often a source of error
10) The capability of a service is depending on quality and quantity of available staff and resources (computers etc)

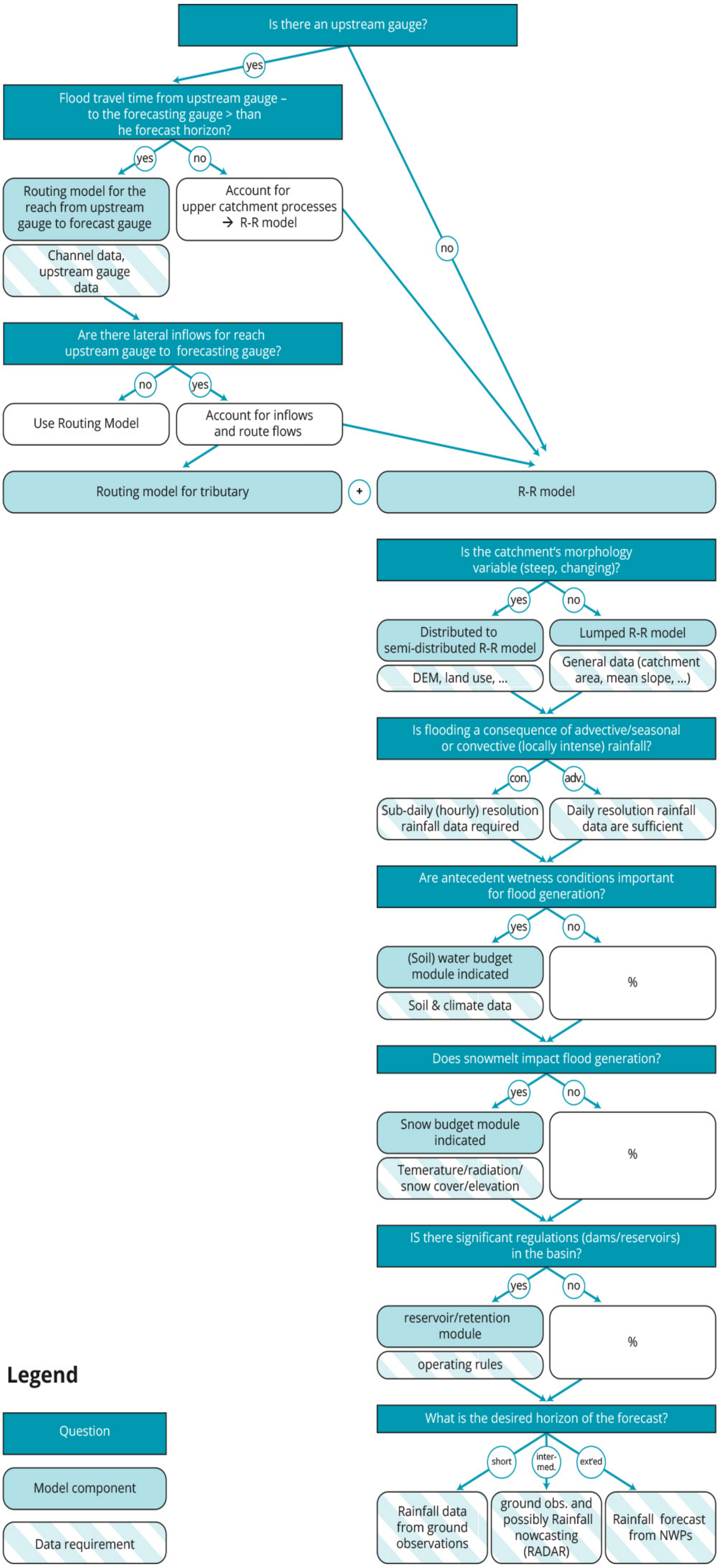
Decision tree

The “decision tree” consists of a number of questions which are sequentially evaluated. Depending on the answer, a certain path emerges and, consequently, specific selections of model components and required data are made.

Basically, the different elements of the decision tree are “question”, “model component”, and “data requirement”. To keep things simple and straightforward, only a few (two or three) answers are possible.

The approach neglects the *existing* data situation of a potential forecaster but helps to identify which data and modelling components are required on the basis of the governing flood-causing *processes*. Therefore, at the conclusion of the decision tree, it may be found that additional data collection is necessary before a model may be implemented. If this is not feasible, another model type has to be chosen according to the data situation and forecast objective.

The answers to the series of questions lead to an array of modelling components, each associated with certain data requirements. The first three questions of the decision tree determine whether a rainfall runoff model is needed or a simple, flood routing based approach is suitable for the specific forecast situation. The six questions related to the rainfall runoff model do help selecting appropriate modules which take into consideration the dominant hydrological processes in the considered catchment. They also guide the user with regard to the data requirements for the modules.



The conditions that imply an approach exclusively based on hydrodynamic models represent a particular case. A combined use of both methodologies is suggested in complex river systems.

Example use of the decision matrix

The four examples given below illustrate how the decision matrix can be used to guide the selection of an appropriate HFFM. Keep in mind that the decision matrix helps in identifying the necessary characteristics of the HFFM, and more than one model configuration may meet the identified requirements.

Example 1

The watershed is located in Central Asia and has a drainage area of 47,000 km^2. The terrain is mountainous with steep slopes, extensive bare rock with some shallow soils, and sparse vegetation. The elevation ranges from 1000 m up to 4000 m. The main river draining the watershed is approximately 500 km long. Half of the runoff in the watershed is due to snow that accumulates in the winter and melts in the spring. Multiple villages are located along the river and would benefit from reliable flood forecasts.

I The watershed is classified as "large" which points to a distributed modelling approach in order to represent variation in precipitation and temperature. A number of river reaches will be necessary to route the flood wave down the main river between the multiple villages.

II The watershed is classified as "pronounced" and further points to a distributed modelling approach are required. This will be especially important for representing the strong temperature gradients that exist in mountainous terrain and are a strong influence in snow melt.

III The shallow soils will have very little moisture storage capacity. Any storage capacity will be quickly saturated when the long spring melt season begins. There is likely to be little dependence on antecedent soil moisture conditions. Therefore, a detailed continuous soil moisture model is probably not necessary.

IV The climate includes both snow and rain and therefore snow modelling will be a central focus.

V There are no major reservoirs or water abstractions. Therefore no storage module is needed.

VI The advective rainfall is the primary cause of flood events. However, due to the fact that the catchment may react fast, also as a consequence of intensive snowmelt, it is recommended to set up the flood forecasting model on an hourly time step.

VII The required lead time for the forecast purpose is medium. That is why it is recommended to use rainfall nowcast based on radar technology. If such technology is not available, it may be sufficient to use real time information from precipitation gauges. In the later case it is necessary to carefully check whether such information allows for producing y forecast with the lead time required.

VIII Gridded data is available. Therefore, and based on the fact that the catchment has a pronounced relief and drainage system, it is highly recommended to use a distributed model.

IX The capacity of the service is considered high, that implies well trained staff and sufficient resources. As a consequence, it seems promising to use a distributed complex model with real time data.

Example 2

The watershed is located on a small island in the tropics and has a drainage area of 10 km^2 with an elevation range from 5 m up to 20 m. The watershed is mostly jungle but some small plots have been cleared for agriculture. Runoff is mostly caused by thunder storms that may occur daily, but at other times there may be several weeks between storms. Large cyclone storms also pass over the island. There is a village at the outlet of the watershed that would benefit from reliable flood forecasts.

I The watershed is classified as "small" which means that a lumped hydrological model is likely to be sufficient. River routing may not be necessary.

II The watershed is classified as "flat" which further points to the possibility that a lumped approach may provide good results.

III The watershed is subject to storms that may arrive irregularly. Evapo-transpiration will be strong between storms and dry the soil. There is likely to be a strong dependence on antecedent soil moisture, indicating a need for a continuous soil moisture model.

IV Snowfall never occurs; a snow model is not needed.

V River regulation does not affect flood generation; a reservoir module is not required.

VI The island often receives precipitation from intense thunder storms which are short in duration but often produce high rainfall rates, which points to a short time interval. Additionally, the small watershed size further points to a short time interval. Hourly precipitation will be a minimum requirement and sub-hourly precipitation may be necessary.

VI The watershed is small with a quick response time. This points to a "short" forecasting horizon. A good rain gauge network may be sufficient.

VII The watershed is small with a quick response time. This points to a "short" forecasting horizon. A good rain gauge network may be sufficient.

VIII Neither gridded nor detailed data is available. A lumped model is the only viable option.

IX The service can not rely on staff that is experienced in the used of complex and demanding computer models. The solution for this case seems to be a simple lumped model or an empirical approach.

Example 3

The watershed is in the middle latitudes and has a drainage area of 2,000 km^2. The terrain is composed of low hills with deep soils that support productive agriculture. Elevation ranges from 25 m up to 200 m and snow is rare. The climate is generally a Mediterranean-type with a dry season approximately half of the year followed by a wet season when large-scale storms may arrive on an interval of 3 to 10 days apart. There are three small cities along the river that would benefit from reliable flood forecasts.

I The watershed is classified as "intermediate" which points to using a number of catchments and some river reaches in order to route the flood wave.

II The watershed is classified as "moderate" which further points to using a semi-distributed approach. This could be achieved with many small catchments or with a grid-based technique.

III The watershed experiences long, dry summers with no precipitation and when no floods occur. The winter season includes periods when storms occur in rapid succession and the soil may remain near saturation for several weeks. However, there are also periods of days or weeks between storms when the soil would dry. Therefore it may be necessary to select a continuous soil moisture model, though it may not be absolutely necessary.

IV   The watershed rarely receives snow and therefore a snow modelling component is probably not necessary.

V   The watershed is equipped with artificial water storage. A storage module is necessary in order to model the flood attenuation in the storages as well as to define adequate flood mitigation options for the operation of the reservoirs.

VI The watershed is primarily affected by advective storms, and this may permit a daily time interval. However, it may still be appropriate to pursue an hourly time interval to provide improved resolution of the flood wave routing.

VII The watershed has an intermediate response time and is classified as an "intermediate" forecasting horizon. A good rain gage network is required with Quantitative Precipitation Forecast (QPF). Alternatively, RADAR rainfall may be used with a RADAR-based nowcast for the future precipitation estimate.

VIII Gridded data is partially available. It is therefore recommended to use a distributed model.

IX The capacity of the service is generally high, therefore the model should be as complex as necessary.

Example 4: Applying the decision matrix for the Kuban river basin

The watershed of the Kuban River is located on the northern slope of the Caucasian range and has a drainage area of 58,000 km^2. Around 50% of the basin area has mountain relief with harsh terrain and high altitudes reaching 4000 m. Length of the main river is 870 km. The river runoff has mixed origin; the major components are snowmelt waters (35%) and rain waters (45%). Snow pack duration varies from 70 days in plain part to 200 days a year in mountains. Summer rainfalls of convective origin induces rain floods. Icecaps total area in the basin is 204 km^2 (1,5% of the basin area). The Kuban river basin is densely populated has developed economical facilities. There are rather highly developed water usage facilities (reservoirs, canals), that influence the runoff regime of the river.

I The watershed area is large. This means that runoff formation processes are variable along the basin area. Such variety should be described using distributed model. Also large watershed points to necessity to use routing model to represent flood wave movement along the river reach.

II The basin's relief is mountainous. Mountains cover around half of the basin. The river runoff generation area is located in mountains. Altitudinal zonation effect makes runoff conditions much more variable along the watershed and thus demands for more detailed description of spatial runoff formation processes variability with using distributed model.

III Antecedent wetness conditions affect flood generation. Water processes in aeration zone effects water regime of the river significantly. Thus soil submodel is needed.

IV Snow melt is important. Snowpack formation is significant on the watersheds. Melt waters give around 35% to the total river runoff. Thus incorporating snow submodel is essential.

V There is water infrastructure in the basin. A number of reservoirs on the main river and its tributaries impact on runoff propagation. It is necessary to take into account such water activities by using reservoir submodel.

VI The flood-causing rainfall pattern is mainly convective. The convective rainfall characteristic means that there is a need in hourly or sub hourly resolution precipitation data. The present rain gauge network in the river basin is quite rare in mountain areas and provides precipitation measurements twice daily. Only daily (or 12 hour) precipitation resolution is available.

VII Long range forecast is required. To run the hydrologic model in operational mode with several days lead time, meteorological forecast lead time of up to several days is required. The forcing for such forecast is provided by NWP models. Two mesoscale models (COSMO, WRF) are running in the Hydrometcentre of Russia and forcings from two centers (NCEP, UKMO) are received twice daily.

VIII Gridded data is available. A fully distributed model is possible.

IX The service capability is high as staff is highly qualified. The forecasting centre that will operate the model has scientific employee and software engineers, experienced in distributed modeling. The forecast center is equipped with personal computers as long as main computer of high computational capacity. It is used for various recourses demanding purposes like data assimilation, running mesoscale meteorological models and etc.

According to decision matrix questions 1-5 answers the model of choice is distributed with soil, snow and reservoir submodel. It is the most appropriate hydrologic model, capable of simulation and forecasting river flow for the river. Staff and computational demands formulated in questions 8-9 are met in the forecast centre. Situation with precipitation data (questions 6-7) is bothering the model of choice. NWP models forcings are available, but the observed rainfall data is insufficient for running distributed model (question 6). There is no possibility to use model of choice from decision matrix (distributed model) and thus there are two main outcomes from the decision matrix analysis:

1. Modernization of the observational network is needed for the basin in order to meet appropriate hydrological model demands. Now a vast project of Roshydromet network modernization is being done on the Kuban river basin – majority of stations are automated, a number of Doppler radars are installed.
2. Until network modernization project is complete less data demanding but less effective hydrologic model is chosen for operational forecasting in the basin - semi-distributed model operating on daily time step is used. As soon as data availability is increased the distributed model (model of choice from decision matrix) should be developed and implemented in operational use.

Reference

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