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Hydrology and Earth System Sciences

HESS Opinions "Classification of hydrological models for flood management"

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Abstract. Hydrological models for flood management are components of flood risk management, which is the set of actions to be taken to prevent flood disasters. It is a cyclical process: initiated by occurrence of an extreme flood it leads through the reconstruction and rehabilitation phase to risk assessment and project planning and implementation, and finally to operation and preparedness for a next extreme flood when the cycle starts again. We subdivide the tasks of flood management into two consecutive parts: planning and operation, which basically require different kinds of hydrological models. For planning, real time runoff is not needed, one works with design scenarios. For this task models should be used appropriate to the tasks at hand, which reflect characteristics of landscape as well as of hydrological scale. For operation, hydrological forecast models are needed which have to meet a different set of conditions. In this paper, requirements for hydrological models as functions of application, geology and topography, and of area size are surveyed and classified, as a first approach for guiding users to the correct type of model to be used in a given location. It is suggested that one always should start flood modeling with an analysis of local conditions and select or develop task and locality specific models.

1 Hydrological tasks for flood risk management

Recent large floods in many regions of the world have created new awareness for the need of systematic approaches to flood disaster prevention. In response to this need flood risk management has developed as a method, which systematically covers all actions for obtaining and managing feasible and financially affordable protection measures against floods. It includes not only measures for protection of people and goods at risk, but also for conservation of environment and riparian ecology. Modern design principles include the requirement that non-technical measures, including measures of temporary protection should be used wherever possible. This approach has been promoted world wide by the International Decade of Natural Disaster Reduction of the United Nations (UN/ISDR, 2004).

Hydrological tools for these actions are flood forecast models and models to determine design floods for flood protection measures. Prerequisite for many temporary flood protection measures is a good forecast of expected flood levels, whereas design for permanent measures requires flood levels for different exceedance probabilities. A survey of requirements for models for flood risk management is given in this paper, which is intended as a first approach towards a systematic determination of the kind of model to be used for a specific flood problem in a specific location, and not as a survey of existing models, for which excellent recent summaries are available (see for example Singh and Woolhiser, 2000).

1.1 Flood protection and risk management

Risk management must be seen as a cycle, as shown in Fig. 1. This figure reflects the fact that there are two parts to risk management, as has been described in detail by Plate (2000). The lower half cycle covers the planning phase and includes planning, design and project implementation. The upper half reflects the operational phase, including maintenance, preparedness, and response and recovery after an extreme event. Although planning and operation are conducted by different actors, it is necessary that they are considered together as part of comprehensive flood risk management for each flood prone location. This is implemented in new German regulations and codes, such as the Directive for the determination of the design flood of the German state of Baden-Württemberg (LFU, 2005). Assume the risk management cycle to start

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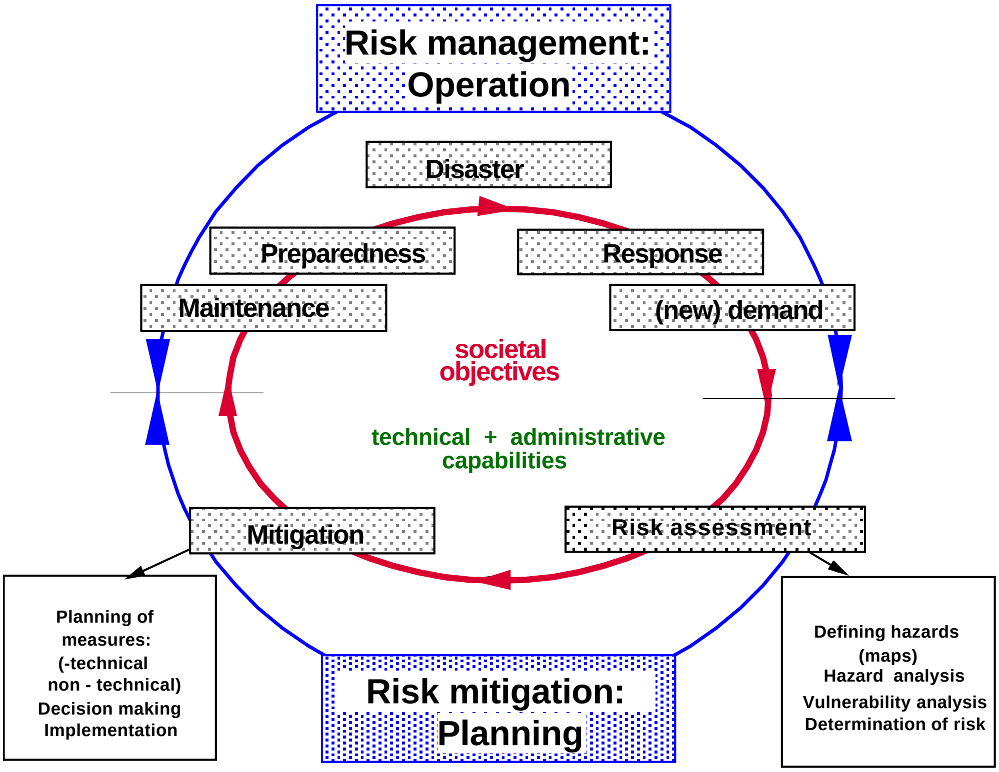

Fig. 1. The cycle of risk management.

with a destructive flood event in the region under study or nearby. After a phase of relief and reconstruction as immediate response to a flood disaster, the flooding situation is reassessed and frequently leads to demands for an improved protection system. A planning phase is initiated, in which options for meeting these demands are identified and their effects evaluated. In particular, for areas that experience floods only infrequently, it is necessary to also develop potential damage scenarios for floods larger than design floods, or for situations of breaking of dikes or dams. Damage assessment methods for dam breaks such as developed by Beltamio de Almeida et al. (2000) should also be used for dikes, although consequences of dike breaks usually are less severe than those from breaking dams that impound large reservoirs.

For each option risks must be determined through the process of risk assessment, which combines hazards – i.e. magnitude of flood levels and their probability of being exceeded – with vulnerabilities, i.e. potential damages for each object at risk – buildings, highways, dikes etc. Hazards are determined and expressed in hazard maps, which show areas of inundation as functions of flood levels of given exceedance probability. Then the risk as expected value of damages in the flooded areas is calculated, just as is done for individual buildings by the insurance industry. This approach has recently been formalized within the European Community through the European Union Flood Directive (EU-FD, EU, 2007) which requires that in accordance with principles laid down in the Water Framework Directive (EU-WFD, EU (2000) which requires basin wide planning) risk maps are to be prepared within a specified time frame.

With risk as important decision criterion the process of decision making is initiated. The EU-FD requires that plans are drawn up for improving protection where needed, for this task also setting a time frame, i.e. the degree of demanded protection is established, plans to meet these demands by technical or non-technical means are prepared by experts, discussed by affected people and administrative bodies, and finally decided on by the owner – in case of a private project – or by responsible political decision makers – in case of a project in the public domain. Then the existing system is improved, or a new system developed. For the operational phase, finished systems are turned over to the system manager's staff, who not only have to maintain the system, but who also have to adequately respond to forewarnings: they have to produce and interpret forecasts from a flood forecast system (if it exists) and warn people at risk immediately before the next extreme event. Then the management cycle starts again.

Listed in the centre of the risk management cycle are societal conditions under which flood risk management has to be performed. They reflect the value system of the society at risk, but also available technology, and scientific understanding of the flood environment – conditions which change with time – due to changes in climate, but mostly due to changes in land use and habitation (a recent study by Schumann et al., 2001 shows that today in Germany there are no observable changes in flood runoff, which can be attributed unequivocally to climate change). Because of these changes, flood risk management is a task to be reconsidered by every generation. Today's objective of flood protection is to provide, with due consideration to environmental requirements and ecological and legal constraints, a safety against the T-year flood, where T is the recurrence interval, and to be prepared for floods that exceed this level.

Decisions based on recurrence intervals reflect an intuitive assessment of the impact of protection system failure. On large rivers in Germany – i.e. on Rhine, Weser and Elbe – T=200 is selected, whereas protection against storm surges in low lying countries, as in the Netherlands, may be as high as T=10 000 or more. Furthermore, flood risk management must include plans for handling residual risks, i.e. risks for the case of protection system failure, caused either by floods larger than the design flood, or by failures due to technical defects or human error. The residual risk usually is defined vaguely as the risk that exists even though protective measures are in place.

An important problem in modern flood risk management is to put the decision process for flood safety on a more objective base, by using a quantitative determination of residual risk as expected damage of failure of the protection system. This aspect is not covered widely in flood management practice. To a first approximation, residual risks may be calculated based on the assumption that every flood exceeding the design flood will cause the same damage, so that risk is product of exceedance probability P_E and damage K, where K is usually quantified in terms of monetary units, i.e. US $. More detailed analyses also consider dependency of damage on design flood level (Merz and Gocht, 2003), in which case risk is the expected value of damage. Residual risks are used as components of cost – benefit analyses, where avoided damage due to a protection system is one of the benefits, whereas monetary risks and construction costs, properly discounted (Loucks and Van Beek, 2005) are parts of the costs. Ideally, the solution that minimizes the cost benefit ratio should be selected, but in practice, monetary risk is not the only type of risk to be considered in flood protection planning.

Ecological damages, as well as social consequences are also important, although there are neither tested indicators for quantifying these risks, nor weights which express relative importance of these indicators in comparison to monetary risks. Indicators and weights are expressions of the social value system of a society, which ultimately translates into political actions. For setting priorities for such actions indices could be useful, which should be functions of weighted indicators. Assignment of weights to indicators is a political task, whereas derivation of indices is a scientific challenge (Birkmann, 2006). As is evident from this discussion, flood risk management is a process, which requires numerous actions at different levels and by many different persons. It is not really a scientific process, because the role of science is to identify causes and consequences and develop tools, not make decisions on values. Among the tools which science can contribute are hydrologic and hydraulic models, which shall be considered in the remainder of this paper.

1.2 Models for operation vs. models for planning

Models for flood protection should be application oriented. For the planning phase one needs models for developing flood inundation and flood risk maps, or models for calculating water levels or discharges for the design of flood protection measures. Furthermore, in preparation for the operational phase, models are needed to determine operation rules, for example for operation of reservoirs. Most reservoir operation rules are based on scenario calculations with historical floods. However, today system operators want dynamic operational models that can be used in real time for deciding releases in anticipation of future floods, or for controlling series of barrages for effective dynamic storage of flood waters, as needed for example on the upper Rhine, in order to meet the protection target of the "Integrated Rhine Program". Flood forecasting models have to be developed, tested on historical events, and put into service in the planning and implementation phase. Such models are also needed for decisions on setting up temporary protection walls, or for evacuating endangered population groups. Development of all plans necessary for response to cases of extreme floods, which exceed the capacity of the protection system, are part of the planning and implementation phase of flood risk management.

Flood forecasting occurs in both phases of the flood risk management cycle: during planning, the forecast model is designed and calibrated, and during operation its successful operation is prerequisite for any effective early warnings. Because an effective flood forecast and early warning system is generally less expensive than technical measures, it often is the most cost effective type of flood protection system, in some cases the only one, in particular for many developing countries. This is the case for some of the large rivers of Asia or Africa, where floods are frequent and lead to large losses of lives – such as in 1998 on the Limpopo in Mozambique, or in 2000 on the Mekong, where more than 3000 people drowned. Flood forecasting is the chosen method for preventing, or at least reducing, such losses of lives in the future.

It follows from these descriptions that there are two important categories of models to be used in flood risk management: forecast models and planning models. These two types of models shall be discussed in the following sections.

1.3 Forecast and prediction

The difference of planning vs. forecast models is illustrated in Fig. 2 (from Plate, 2007). Objective is to forecast water levels $h_a(t_0+T_F)$ at time T_F later than the present time t_0, where T_F is the forecasting time and $h_a(t)$ is the actual value of the water level at time t. A forecast model is used to forecast a value $h_F(t_0+T_F)$. The forecast model must be a function of the initial value $h_a(t_0)$ at time t_0, at which the forecast is made. Regardless of the forecast model used any forecast is only an estimate, and for every forecast an error band exists, which can be expressed by means of a pdf (probability density function) $f_{h0}(t_0+T_F)$, which depends both on $h_0(t_0)$ and on T_F. The larger T_F, the broader the error band becomes, up to a limit when forecast times exceed a certain maximum value T_P, when the initial conditions become irrelevant, and forecasts degenerate into predictions (in the hydrological sense), i.e. $h_F(t_0+T_F)$ is a random variable with $f(h)$ independent of time and initial value.

For flood forecasting it is of major importance that the forecast value is accurate. In many cases an erroneous forecast is worse than no forecast at all. People who had trusted a forecast that went wrong – for example, that forced them to evacuate an area – will not likely trust a future forecast. Consequently, development of dynamic models for real time forecasting with as narrow an error band as possible is a major challenge for hydrological research. At this time, the output of most models is deterministic. An assessment of the error for such models is usually done (if at all) through sensitivity analyses or scenario development, in which the range of possible values of the parameters of a model or of the model inputs are estimated and the results analyzed. Traditional is the assessment of upper and lower bounds, but a modern trend is to determine ensembles from many combinations of probabilistically distributed parameters to obtain estimates in terms of probability distributions of outputs of the model, which then can be further analyzed to yield the ensemble average and error bounds expressed in terms of standard deviations of the ensemble, i.e. Krzysztofowicz (2001). Ensemble weather forecasts have a long tradition in meteorology, however, the accuracy of meteorological forecasts of rainfall is still the weakest link in improving flood forecast models (Todini, 2004).

For designing technical flood protection systems only good predictions of possible future extreme water levels for given exceedance probabilities are needed, and time of occurrence is irrelevant. The classical approach is to use statistical extreme value analysis of data obtained at river gages. For basin wide measures this is not sufficient. Rainfall-runoff models (RR-models) must supplement traditional extreme value models for flood risk management. Hydrologists are challenged to provide these models.

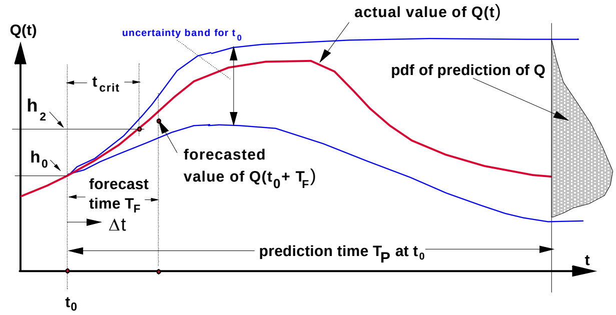

Fig. 2. Defining forecasts and predictions.

2 Rainfall-runoff models for flood management

Two types of RR-models for determination of floods of given frequencies can be distinguished. One type uses rainfall runoff modeling of the continuum of runoff in a river. Historical time series of rainfall (suitably area averaged) are used and the resulting calculated runoff time series is compared with the observed runoff time series. Differences between values from observed time series and from RR-model can be interpreted as realizations of a random process. Their mean value is a measure of model bias – to be corrected by parameter adjustment – and their variance is a measure of uncertainty. Because different sets of parameters may yield the same variance, (a property called "equifinality" by Beven and Freer, 2001), this method may yield good results on the average for the observed time series, but it may fail when extrapolated, as is observed when the probability distribution of extreme values of the observed time series of runoff at some gage is compared with a distribution of extreme values of the calculated series.

The second type of RR-model is event based. It is not intended to be used for the whole time series. Its exclusive purpose is to predict extreme values of runoff – i.e. peaks, volumes, and shapes of flood waves. When used for planning purposes in flood risk management these models use hypothetical rainfall fields. These are T-year area averaged rainfall fields that are more or less uniformly distributed over the basin, under the assumption that the T-year area-averaged rainfall will also cause the T-year flood. For practical applications of this method, the writer (see Plate et al., 1988) has always insisted on validating such models at available gauging stations against extreme value distributions of local runoff.

All RR-models have in common that they have to describe the physical transformation of rainfall into runoff. This requires a common structure for all RR-models. This common model structure will be discussed in the next section.

2.1 Components of RR-models

Hydrological RR-models have three levels, each associated with three different time scales as indicated in Fig. 3 (adapted from Plate and Zehe, 2006). The data level consists of permanent, seasonal, and event based data. Permanent are geometric and geological properties of the basin: basin area, topography and geology, river network and soil composition, as well as properties that change only gradually, such as land use: i.e. forest cover, road networks, urban developments, or large scale climate. Parameters describing agricultural activities and seasonal climate are associated with seasonal time scales and determine seasonal variability of runoff coefficients. And finally, there are data for the event time scale. These depend on the model purpose. Planning requires historical data, whereas forecasting requires short term and real time event data, with time increments ranging from minutes to hours, depending on the size of the basin area.

The second level in Fig. 3 is the level of model formulation and development. The process of model building should start with a thorough assessment of the basin under investigation, orienting the model building process on available hydro-meteorological data, but also on characteristics of the basin, as well as on the basic requirements for decision making as is expressed through the 4-th level of Fig. 3. The decision level determines the information needed, and level 3 is thus determined by level 4.

Hydrologists charged with developing a flood planning or forecast model for a basin should explore and describe its geological characteristics, trace its river networks, identify surface and groundwater interactions. Important flow paths of surface and subsurface flows need to be identified from the beginning, and appropriately reproduced in the model. No universal model exists that fits everywhere. For each situation and each catchment models should be built or adapted appropriate to location and application. They should reflect local conditions and incorporate all important human activities which may modify the rainfall runoff process. Due consideration should also be given to different time scales of different processes. Seasonal processes such as interactions of groundwater and surface water may well be described by models using larger time steps than runoff.

2.2 Types of rainfall-runoff models for flood calculations

In view of what has been said in Sect. 2.1 the choice of a RR-model is determined by intended application, basin scale, and available data, which set conditions for development of a new or adaptation of an existing model. The plethora of available RR-models can be divided into three types: models based on rectangular grids, models based on sub-catchments, and models based on response units. Topography and geometry of grid based models are derived from available large scale digital terrain models (DTMs). From the elevation of the four corners of a grid cell the slope of the cell is determined, and the channel network is derived from these slopes by means of special algorithms (Garbrecht and Martz, 1997; or Crowley and He, 2005). Climate and land use variables are combined with grid models through geographic information systems (GIS). Catchment based models (CBMs), on the other hand are vector oriented. They require subdividing the basin into sub-catchments, whose sizes and topographic characteristics have to be derived from DTMs. This is a lengthy preparatory process, which has the advantage that transfer of landscape features from topographic maps is easier facilitated, and river networks, geology, and land use can be naturally associated with basin features. The third type, models based on response units (REM) divide catchments into units of equal runoff formation. Both CBMs and REMs require that subunits are connected by means of networks of channels, and all models require that due consideration be given to the hydraulics of the channels. Usually, not the discharge is needed for flood studies, but the water level, which only for special conditions can be inferred from stage discharge curves. In most cases, it is necessary to convert discharges into stages by means of hydraulic models, which range from stationary 1-D models to instationary 2-D models, incorporating flood development over flood plains.

Grid based models are preferred for large scale continuous models, such as for climate investigations, but they are also applied frequently for flood modeling, both for flood forecasting (i.e. Todini, 1996) and for planning flood protection systems. With their help the continuum of floods is determined from long term rainfall time series of observed and area-averaged rainfall and water balances, including calculations of the time series of evapo-transpiration. Such models are also useful for event based models, for design or for forecast, in order to determine the initial moisture state of the area element.

All area models have in common that they use a vertical component for determination of that part of the storm rainfall which becomes flood runoff, and a horizontal component for the routing of the rainfall excess to the nearest channel of the river network. Models for runoff use runoff coefficients ranging from simple constants which are empirically correlated to soil and groundcover parameters, to sophisticated functions obtained from water balance models, for which the area element is represented by an equivalent vertical soil column consisting of different layers (i.e. Todini, 1996; Refsgaard and Storm, 1995; De Roo et al., 2000). Water balance models separate the rainfall (minus interception) into surface storage, and groundwater replenishment by means of an infiltration – soil water transport model of varying complexity (Liang et al., 1996; Todini, 1996; Crowley and He, 2005).

Runoff is routed from the area elements – cells, subcatchments or REMs – to the point of interest on the channel network. Routing models should reflect the considerations of relative size of area element to channel network to be discussed in Sect. 2.3. Simple models operate by using

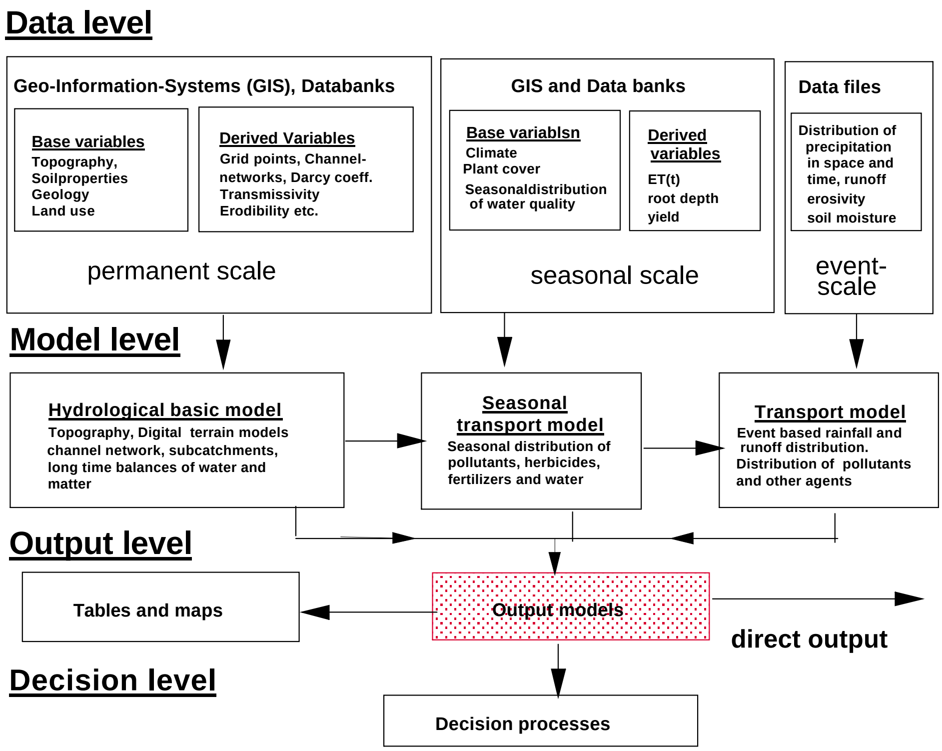

Fig. 3. Levels of hydrological models (adapted from Plate and Zehe, 2006).

only translation, assuming a constant velocity of runoff from the element. More complex models are based on linear systems, applied to each element. For example, Crowley and He (2005) use three parallel linear reservoirs, one for surface runoff, one for interflow, and one for baseflow, or groundwater runoff.

For CBMs the RR process for each sub-catchment is described by area models, which not only reflect the soil moisture balance (i.e. Bronstert, 2005) but also incorporate distinctive catchment features, such as local topography and land use such as urbanization and the network of roads and railways. The connectedness of the sub-catchments follows the channel network, in which runoff from sub-catchments is routed downstream. Such a model can be very detailed, depending on the resolution into sub-catchments, and the submodels selected for hydrological processes. How much detail is to be incorporated will depend on the model purpose, and on the scale of the region. Obviously, a flood model for a basin of, say, 1000 km^2 does not need the same resolution as an area of a few hectares.

2.3 RR-modeling in different landscapes

Different characteristics of landscapes should require different types of models. For example, floods in mountain valleys have very different characteristics from floods on flood plains of large rivers. Theoretical hydrologists tend to use the same type of model for all types of catchment, although it seems obvious that the model should reflect the dominating processes for the type of landscape for which the model is to be applied. We recommend to distinguish four different types of landscapes and to develop models accordingly. These are (a) high mountain ranges, (b) foothill ranges with or without vegetation, (c) large flood plains, and (d) urban areas, as indicated schematically in Fig. 4. A fifth region is the area affected by coastal processes, for example delta regions which are subjected to storm surges. Such a subdivision is important for design of flood protection measures. From a physical point of view, it is useful to further subdivide these area types. Within each of these areas there exist sub-areas with their special hydrological characteristics, for example forested regions, or wet lands etc. – and a subdivision of sub-catchments into such characteristic subareas eventually leads to decomposition of sub-catchments into many different REUs. Mountain areas are mainly threatened by flash floods – intensive and local rainfall events, which lead to rapid increase of water levels and velocities in runoff channels. In general, river courses in these areas are deeply incised, and flooding usually is restricted to a narrow strip along the river, where due to high velocities damages to bank protection works and structures – as in villages where houses have been built too close to the creeks – can be very heavy, aggravated by frequent occurrence of debris jams, in particular on bridges. Frequently extensive damage occurs

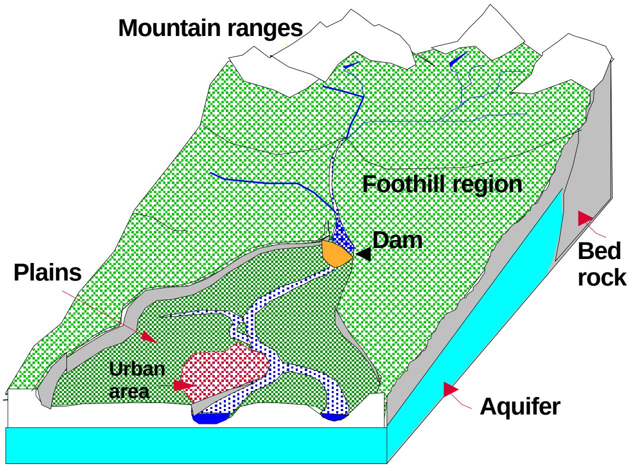

Fig. 4. Types of hydrological areas.

mainly on highways which for technical reasons had been built along the rivers. Flood protection in such areas consists at most of bank protection works, more usual is a flood protection strategy which on each side of the creek leaves a strip of land where no human activity is permitted, or where land use is restricted to agriculture. In such valleys, a detailed analysis of floods is frequently of little use: planning models in such areas usually are hydraulic models for extreme flood scenarios based on historical floods.

In foothill regions, or in the geologically ancient mountains which are typical for the State of Baden-Wuerttemberg, in Germany, extreme precipitation or snow melt usually lead to more widespread inundations than in mountain valleys, and velocities are not of the same importance. Distinguishing characteristics of floods in such regions is their impact on villages and agricultural lands. Flood protection measures in such areas consist of reduction of peak flows by means of retention basins in the upper parts of the small rivers, and removal of narrow sections in villages, with dikes in particularly sensitive stretches of the rivers or creeks. Flood protection of villages and small cities against the 10 to 30 year flood is secured by these measures; floods of lower probability are reduced, but not avoided. Usually many retention basins are used in a basin, each of which protects a small area up to a level of T=20 to 50, and all of them in combination reduce flood frequencies in the lower parts of the rivers to about T=100 years. Dikes, although standard measures for flood protection for larger rivers, are rarely used on small rivers (with catchments of a few hundred km^2). For planning measures in foothill regions RR-models should be used, whose structure depends on the catchment's size, as will be described in the next chapter.

In the plains of low lands velocities are even less important. Damage is mainly caused by high water levels, and in some situations due to interaction with groundwater – groundwater tables being raised in inundated areas, which in turn flood basements or cause backing up of sewerage channels. The greatest threat to human lives comes from wide spread inundations, in particular when over very wide areas the water level rises only slowly, and escape routes are cut off so that people are trapped on higher grounds, if help does not come soon enough. Dikes are the natural measures for protecting low lands, but dikes may fail, or water levels reach heights above the design height of the dike system. Today one finds that in many parts of the world protective measures include also widening of the river flood plain between dikes, by new dike lines further inland, with a double dike system. In some cases existing dikes are altogether removed, or the formerly inundated flood plains are replaced by flood polders, which are flooded only when the water level in the main river exceeds a certain critical value. Obviously, forecasting future discharges or water levels for such areas is of considerable importance – not only for warning endangered populations, but also for the purpose of operating side polders or retention basins in the catchment of the river.

Urban areas need special hydrological models, to incorporate sewer systems and runoff conditions from streets and houses. Hydraulic RR-models are needed to describe flooding from rainfall, as well as from rivers, on whose banks cities are located. In Germany, smaller natural water courses have been made part of the local sewer system, and many of the small creeks flowing through cities or villages have been confined into pipes. Extreme floods, often combined with debris and trash plugging, cause such pipes to overflow and produce heavy local flooding. Typical flood situations were observed in the city of Dresden during the August flood of 2002, which was caused both by flash floods from small tributaries flowing into the city and bank overflow of river Elbe. A third important cause of damage for Dresden was the raised groundwater table due to inundation of the city. Consequently, it is necessary that urban drainage models for cities are integrated into detailed RR-models of rural areas, not only to evaluate the effect of the basin river network on urban flooding, but also to assess effects of urbanization on runoff from catchments.

2.4 Hydrological scales and their significance in flood calculations

The choice of a RR-model is not only dependent on type of area, as described in the previous section. An additional decision criterion for model selection is the hydrological scale of the area a subject which owes much of its scientific erudition to Dooge (1986), but which will here be discussed from an application oriented perspective. Hydrological scales have become important elements of categorizing basins (Plate, 1992; Blöschl and Sivapalan, 1995). Hydrological scales are defined both by size of the area, and by locally dominant processes and their representation in models. Of special importance is the relative significance of overland flow as compared to runoff in the channel network of the area.

This is illustrated in Fig. 5. In this figure the smallest scale is associated with the area element a (an element roughly of $1\,m^2$). Surface runoff from this area element flows as overland or baseflow to the nearest channel. Runoff from all area elements in sub-area A_j combine into overland flow inputs with characteristic runoff time t_C, the time of concentration from area A_j. The total basin has n sub-areas, i.e. j=1,2,...n. Runoff from each area A_j is routed through the channel network. The process of flow routing in the channel network has a characteristic time t_f, the routing time. The ratio of t_C/t_f is a suitable indicator for selection of a model scale. A measure for t_C is the rise time of the unit hydrograph for an area, for which formulas are available, based on describing unit hydrographs by means of a gamma function (Ihringer, 1996). A measure for t_f is the flow time in the channel network, expressed through length and estimated velocity of the main channel of the network.

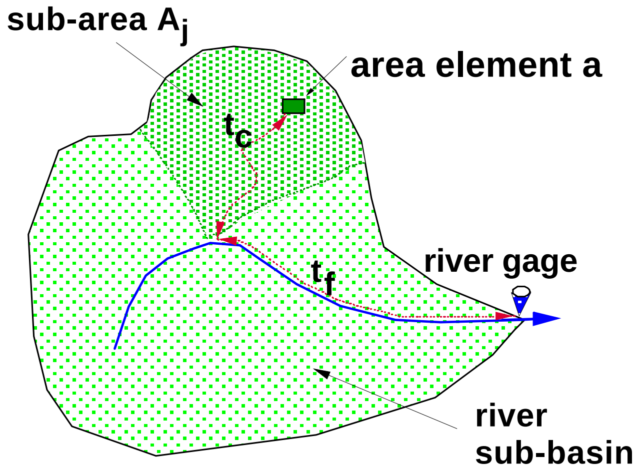

Fig. 5. Defining flow times in hydrological basins.

2.4.1 Point scale

The scale of the area element a, measured in m^2, is called the point scale. At this scale, t_f has no meaning. Processes on this scale are mainly vertical, they are significant for flood modeling only insofar as they determine the separation of runoff into infiltration, surface storage (and eventual evapotranspiration) and overland flow. Processes on this scale are highly non-linear and locally very variable, local soil characteristics and plant cover determine local runoff, which sets in after infitration capacity is exceeded (i.e. Bronstert, 2005). As has been shown (i.e. Zehe et al., 2005) macro-pores induce two types of switching mechanism in the conversion of rainfall into runoff: they are activated when the infiltration capacity of the soil matrix is almost saturated and overland flow sets in, and they lose their effect when macro-pores which are closed at the bottom are filled, so that only matrix infiltration and infiltration into open macro-pores are effective. Other influences on the process of converting rainfall into runoff are local depressions and micro-topography (depression storage), which retain part of the runoff, or frost phenomena influencing or preventing infiltration, or local effects on runoff production during snow melt. Because of the potential variability of point scale processes for different area elements a, processes on the point scale are considered mostly for homogeneous areas, such as agricultural fields or forest areas on homogeneous soils.

2.4.2 Micro-scale

Models on the point scale are building blocks for micro scale models. The idea of subdividing a catchment into contributing areas – i.e. different areas with similar infiltration potential – assumes the existence of homogeneous or almost homogeneous areas, which are aggregations of area elements a with similar infiltration characteristics. For each of these contributing areas, the determination of the beginning of runoff and of an area averaged t_C is important for any sub-area A_j. RR-models for floods must consider these processes in detail if t_f/t_c is small.

More generally, Plate and Zehe (2006) define micro-scales as the scales of models which can be described by means of the fundamental conservation laws of continuum physics, i.e. by means of partial differential equations. Typical models of this kind are hill slope models, which must be used if extreme rainfall effects on surface erosion or pollutant transport have to be considered. Extensive investigations on this scale have been made at Karlsruhe University as summarized in Zehe et al. (2001).

2.4.3 Meso-scale

The meso-scale is defined as that scale in which RR-models are described by conceptual models based on system functions. Basic element is one system function $u_j(t)$ for each of the sub-areas A_j, with t_{cj} = characteristic time of concentration for area A_j. For the low mountain ranges of central Germany this scale is associated with areas ranging from 1 to several km^2. Usually, the sub areas have small creeks, so that t_f/t_c is non-zero, but their effect is included into the concentration time. Typical for this scale are models of the unit hydrograph type. There is no clear limit in area for the use of unit hydrograph models; its application depends on catchment characteristics and available data. Generally, in flat lands unit hydrographs can be used for larger catchments than in mountainous country. However, because of lack of data hydrologists are frequently forced to use unit hydrographs also in other large areas. On the other hand, where data conditions are adequate (and sufficient time and resources are available), modeling on this scale can also be based on micro-scale or grid based models, including full hydraulic models of the channel network.

The importance of meso-scale processes increases with increasing area size. Flow in the river network increasingly dominates the rainfall runoff process. In order to capture spatial differences, it is recommended today to separate larger catchments into sub-catchments, which are connected through the runoff network. Runoff from sub-areas can be calculated by means of unit hydrographs, but other models based on more detailed physical modeling of the rainfall runoff process in small catchments may also be suitable. Models combining sub-catchment runoff with river networks are particularly advantageous for situations in which the geological or topographic properties are very different in different sub-catchments, causing very different runoff forming processes in different parts of the catchment. For example, it becomes possible to model different reaction characteristics of the rainfall runoff, depending on the time development of local infiltration rates. This was well illustrated in the study of Casper et al. (2003) in the Eyach-valley of the Northern Black Forest. He could identify numerous different sub-processes contributing to the time development of the runoff process, with large differences in runoff formation between bogs with limited retention potential on one end of the spectrum, and permeable sandstone on the other end.

For meso-scale processes, the spatial and/or temporal variability of the rainfall field may need to be considered. The scale of the rainfall field is superimposed on the scale of the catchment. Locally, it is well known that extreme rainfalls, which cause only minor floods in a large catchment, may locally lead to very high runoff peaks, or to local flash floods. And for large scale rainfall events, the temporal variability of the rainfall field may completely mask the effect of the catchment. A simple example may serve to illustrate this point. Let the area averaged rainfall field be temporally variable, as expressed through a rainfall intensity function $I(t)$ of duration T_D, where:

$$I(t) = \frac{1}{A_G} \int_A I(t, A) \cdot dt \tag{1}$$

is the rainfall averaged over the catchment area A_G. Let the unit hydrograph for the catchment be given by a function $u(t)$:

$$u(t) = f(t, T_A) \tag{2}$$

with characteristic time T_A (for example, T_A = rise time of the unit hydrograph).

Assuming the runoff coefficient φ to be independent of time the discharge can be determined by means of the convolution integral:

$$Q(t) = Q_B(t) + \varphi \cdot A_G \cdot \int_0^t I(\tau) \cdot u(t-\tau) \cdot d\tau \tag{3}$$

where A_G = size of the catchment, and $Q_B(t)$ is the base flow. If the characteristic time T_D of the rainfall event is short compared to T_A, i.e. $T_A/T_D \Rightarrow \infty$, then $I(t)$ can be approximated by a delta function $I_0 \cdot \delta(t)$, and the solution of Eq. (3) is:

$$Q(t) = Q_B(t) + \varphi \cdot I_0 \cdot A_G \cdot u(t) \tag{4}$$

i.e. only catchment characteristics shape the discharge hydrograph. For the other extreme case, i.e. for $T_A/T_D \Rightarrow 0$, the unit hydrograph degenerates to unity, and:

$$Q(t) = Q_B(t) + \varphi \cdot A_G \cdot I(t) \tag{5}$$

i.e. the dynamics of the runoff process is determined exclusively by the dynamics of the rainfall and by its distribution in space, as expressed by Eq. (1). Equation (1) applies mostly to small catchments, where an area average rainfall as calculated by Eq. (1) is appropriate. For large spatial scales, spatial rainfall distributions as well as time distribution of area averaged rainfall fields need to be considered, which requires that the total area should be subdivided into sub-catchments with local area averaged rainfall inputs. Such an approach is particular important for forecasting flash floods, whereas for design models the actual distribution of the rainfall is of secondary importance.

As a consequence it can be concluded that meso-scale models must be used also for cases where times t_L and t_F are of the same order of magnitude. In such cases runoff formation on sub-catchments is of equal importance as runoff in the channel network. This approach should be used for areas ranging from a few 10 s km^2 to a few 100 s km^2. In the writers experience it is particularly useful to subdivide larger catchment into smaller catchments according to water divides, and to describe runoff from sub areas (of a few km^2 size) by means of unit hydrographs and runoff in channels by means of 1-D calculations with St. Venant equations, or even simpler by means of flood routing models, such as the well known method of Kalinin-Miljukov. Our IHW-Model by Ihringer et al. (1990), Ihringer (1996) and see also Plate et al. (1988) was developed based on this principle and has been applied successfully for flood determinations in central mountain regions of South and Central Germany.

2.4.4 Macro-scale

The scale of the IHW model is the scale in which runoff generating processes associated with characteristic times t_c are of equal importance as channel flows with characteristic time t_F. With further increase of catchment size, ratio t_C/t_F decreases asymptotically to 0, when dynamics of the runoff process is fully dominated by channel flow. This is the case of macro-scale modeling, and refers to catchment sizes ranging from about 1000 to several 10 000 s km^2. On this scale, there is no need to model surface runoff in detail. Naturally, runoff coefficients φ have to be determined for all sub-areas, but retention and runoff characteristics of sub-areas can be represented by simplified functions, such as exponential (linear reservoir) functions, or by local runoff coefficients φ_A

that are constant for each sub area A. However, for macro scale models the importance of the hydraulic component increases, which is required for converting the large discharges of this scale into flood levels, in particular when technical flood protection measures are planned. Such models are subject of classical hydraulics (i.e. Henderson, 1966) and not discussed in this paper.

2.4.5 Scale transitions and uncertainties

It may seem that the best flood model would be built up by combining point scale models into models for ever increasing scales. Apart from the fact that this approach cannot work for larger areas because of the sheer number of elementary area elements to be considered, the discussion of Sect. 2.4 has made clear that this approach is not necessary because with increase in size of the area the collective effect of the different processes changes. For example, whereas on the point scale local distribution of macropores may be important (Zehe et al., 2001), they become insignificant when averaged over large areas the law of averages stating that with increase in the number of elements of a homogeneous ensemble the variance of the average decreases in proportion. In the same way, large scale features of hill slopes, such as local topography, may become insignificant when going to a macro scale. As a consequence, it is an interesting problem to find the limit conditions from when on one can use models of a larger scale – i.e. to use macroscale models with lumped parameters instead of hill slope models. In most cases this question cannot be answered, because for larger areas the use of a model is data driven: the availability of data dictates what type of models can be used. Nevertheless, it is necessary that for each location a close survey is or should be conducted, in order to identify hydrologically significant features of every area. For example, it should be evident that an infiltration model (which determines groundwater recharge as well as runoff coefficient) for sandy soils cannot be the same as an infiltration model for karstic surfaces. The availability of information for soil and land cover has much improved over the years through the availability of space or remote sensing data and GIS technology, but the routinely transformation of space information into hydrological parameters has yet to be developed. At this time, the translation of satellite information into soil parameters etc. depends on ground truth observations. This adds to the uncertainty of models, and is part of the epistemic uncertainty with which the modeler has to live.

3 Comparison of flood models for planning and forecasting

3.1 Advantages and disadvantages of flood models for planning

The principal statistical tool for planning flood protection works is extreme value analysis. Extremes of runoff are determined by two independent methods (which ideally are complementing one another). The first and more traditional method uses directly extreme values of time series for discharges (or water levels) for determination of design floods – typical is a flood with a recurrence interval of once every 100 years – i.e. the 100 year flood. There are a number of disadvantages to this approach. It relies on measured time series of water discharges (or water levels) at a point, i.e. it obviously requires presence of a gage on the river near the spot for which one wants to determine the design flood. For statistical reasons it needs observations of long time series for a reasonable fit to a – generally unknown – probability distribution of extremes. The most important advantage of this method is that it avoids uncertainties of the generating process of the extremes. There exists a vast literature on extreme value analysis, which shall not be discussed here.

The second method uses RR-models. They also depend on statistical inputs, this time of rainfall fields. Uncertainty of runoff prediction from RR-models primarily stems from prediction of the extreme rainfall event for the catchment, i.e. the inherent uncertainties of extents and intensities of rainfall fields. Additional uncertainties are caused by the time variability of soil moisture and other dynamic catchment parameters needed to convert rainfall into runoff. Advantages of RR-models are obvious. Rainfall inputs are less dependent on local conditions, and thus rainfall statistics can be generalized for large areas. Furthermore well calibrated RR-models can be used for flood prediction – not only peak values – at every point in a catchment.

Because different extreme value distributions applied to the same data set may yield very different extreme flood peak values, it is actually not sufficient if only the recurrence interval is specified. For completeness of specifications, also the method of determination of the extreme values should be given, as for example in the recommendations of the US Interagency Advisory Committee on Water Data (IACWD, 1982). However, the actual recurrence interval for design floods is never accurately known because of numerous potential errors due to model complexity (model error), incomplete information on parameters (parameter error) or insufficient or inaccurate data (data and sampling errors). The true recurrence interval of an observed flood peak can never really be ascertained. An error range of ±15%=30% is not uncommon, and this may mean – for example when determining the 100 year flood – to design not for the 100 year flood, but for floods of recurrence interval of 150 or 50 year. Already small changes in the flood level may cause large changes in calculated probability. This is illustrated in Fig. 6 where ratios x_{100}/x_{20} (i.e. of the 100-year to the 20 year flood), and ratios x_{1000}/x_{100} (i.e. of the 1000 year flood to the 100 year flood) are shown as function of coefficient of variation CV_x for the two parameter gamma distribution. (This distribution has been found give best fits to long data series of larger basins in South Germany, LfU, 1999). For two parameter distributions, such a presentation is unique, for three parameter distributions one obtains a family of curves with skew coefficient CS_x as third parameter.

For two parameter gamma distributions CS_x and CV_x are related as CS_x=2CV_x, where the magnitude of CS_x is restricted by the fact that already for CS_x=2 gamma distributions reduce to the exponential. Thus, if one assumes an average skew factor of 1, corresponding a CV_x=0.5, one finds both curves to show differences of 30% between the 1000 and 100 year flood, or between the 20 year flood and the 100 year flood, respectively, corresponding to a tenfold resp. fivefold range of return periods. This uncertainty has epistemic and natural causes. Epistemic uncertainty includes both data and model uncertainty, whereas natural variability is due to the complexity of the natural processes and catchment characteristics leading to runoff variability. These uncertainties add up to a wide range of potential exceedance probabilities, as was well illustrated in a number of examples in a recent paper by Merz and Thieken (2005).

It is very difficult to overcome these uncertainties. Some improvement is found by regionalization based on many different runoff gages in a region. Regionalization was also used by Ihringer (LfU, 2005) who developed a regionalization model, which permits to estimate the 100 year flood peaks for every point in the German State of Baden-Württemberg. But it must be realized that in the end the decision for flood protection measures is a political decision, which leads to a politically acceptable recurrence interval, typically based on large historical floods. For example, the design flood for the Upper Rhine (Rhine between Basel in Switzerland and Mannheim at the confluence of Rhine and Neckar) has approximately a T=200 years, but it is based on the extreme value observed in 1882, (shifted in time to account for Rhine corrections made after 1882, so that peaks of Neckar and Rhine floods coincide), plus freeboard. This approach may appear rather simple in terms of modern hydrology, but it had the advantage of being plausible and politically acceptable.

3.2 Advantages and disadvantages of forecast models

The major difference between forecasting and planning models is accuracy. Flood forecast models require higher accuracy than planning models. Flood forecast models require that an exact peak value is forecast, in contrast to results from planning models, as has been discussed in 3.1. It will never be possible to accurately identify the recurrence interval of an extreme event that has actually happened. It could have been

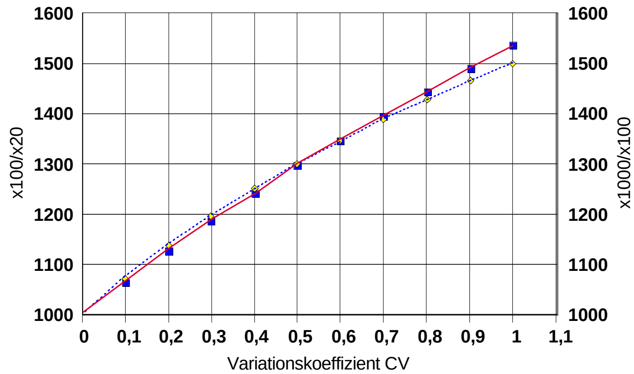

Fig. 6. Ratios Q_{1000}/Q_{100} and Q_{100}/Q_{20} (multiplied by factor 1000) as function of coefficient of variability CV_x of the two-parameter gamma-distribution.

a more frequent, or a less frequent event. The case of flood forecasting is different, after a flood one knows for certain that the forecast has been accurate, or accurate enough. On the other hand, a forecast model does not have to correctly model the physical basis of the rainfall-runoff process, so that any method which is reasonable and yields acceptable results may be used, for example those from regression analysis, or from artificial neural networks which have been trained on past records. The overriding concern is to include the error band in the discussion of the results, i.e. to use the probability distribution of potential outcomes as basis for a purpose oriented forecast, for example take the ensemble average as best estimate, and give error bands based on exceedance probabilities.

What is meant by a good forecast has to be specified not only intuitively (by how the warned PAR (= people at risk) feel about the forecast) but objectively, by means of an objective criterion, which is derived from past events of varying magnitude.of varying magnitude. Many different statistical quantities have been suggested and used, (for some recent uses see Bravo et al., 2009, or Wu et al., 2005) which do not really meet this requirement. Obviously, a criterion based on the average performance of a flood hydrograph, such as the criterion by Nash and Sutcliffe (1970) is not sufficient. The criterion must be geared to weigh the course of the hydrograph of the future, as observed from a known point of the hydrograph of the past. A possible criterion could be based on the following considerations.

It is evident that for short times (short in relation to a critical time, which depends on the size of the catchment or basin) the requirements for complexity of forecast models are not very high – because the discharge cannot have discontinuities, for physical reasons. If there is no other information available, the best forecast for the near future is to forecast the value at time t_0+T_F as being equal to the value at t_0. The performance of a forecast, expressed through a forecasted value $h_f(t+T_F)$ after time T_F should be judged relative to this value. This implies that the deviation of the forecasted value $h_f(t+T_F)-h_0(t)$ from the present value should be large relative to the deviation of the actual value $h_a(t+T_F)$ from the forecasted value $h_f(t+T_F)$, i.e. from $h_a(t+T_F)-h_f(t+T_F)$. In terms of quadratic deviations (to eliminate the need for sign corrections) this condition is expressed by an index (Kitanides and Bras, 1980)[1]:

$$I_F(T_F) = 1 - \frac{\sum_n \left[h_f(t+T_F) - h_a(t+T_F)\right]^2}{\sum_n \left[h_f(t+T_F) - h_0(t)\right]^2} \qquad (6)$$

for which during calibration the sums have to be taken at each time $t=i\cdot\Delta t$, $i=1, 2, ...n$ over the whole forecast interval $T_F=n\cdot\Delta t$ of the event, where Δt is the time increment. A positive value close to 1 of $I_F(T_F)$ indicates good, a small or even negative value poor performance, i.e. if $I_F(T_F)$ is close to 0 or even negative, the performance of the forecast is not better than taking the value of today (at time t) as forecast for the value at time $t+T_F$. It is concluded that forecast models are even more dependent on a good data base than planning models. Only many comparisons of actual with forecasted data can establish confidence in a forecast model.

4 Conclusions

This paper makes a case for considering models for flood forecasting and models for planning of flood protection structures as important but quite different tools for managing flood risks. Flood risk management is seen as a comprehensive approach for handling the consequences of extreme flood events so that they do not lead to flood disasters. The objective of development or adaptation of models is their intended application. This requires that we distinguish models by scale and by topographic context: models for large basins in topographically flat country require different approaches than, for example, models for flash floods in mountain areas. As prerequisite of model choice a thorough understanding of local topography and climate processes is essential. But models should not only reflect local scales and local terrain features and geology, but they also should be determined by the intended application. By pointing out the different conditions and requirements for the use of flood management models, this paper is an attempt to give guidance to persons involved in flood management.

Differences in the types of models for planning versus models for flood forecasting are stressed, although the paper is descriptive in nature. Analytical concepts for model structures and calculations cannot be covered, and for details references are given which reflect mostly the experience of the author and his team at the University of Karlsruhe. Hydrologists today must be aware that their work can serve two very different purposes: one is to better understand nature, and the other is to provide analytical tools for helping water managers and design engineers to better handle their design and management problems. A better understanding of nature is obtained by observing, measuring, and modeling of hydrological processes at the smallest scales and by extending the resulting models to larger ones by integration over more and more small scale area elements. Engineers, on the other hand, need models which reproduce only those model components which are relevant to quantify the runoff process with sufficient accuracy for their purposes. In looking at planning models and forecast models for floods, the two different aspects of modeling become particularly evident.

[1]Note that this is similar to the criterion of Nash and Sutcliffe (1970), except that height h replaces discharge Q, and the initial value $h_0(t)$ at time t replaces the average value of the complete hydrograph.

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