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On the Classification of Hydrological Models for Flood Risk Management

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***Abstract*— The hydrological models are components of a flood risk management, which is the set of actions to be taken to prevent flood disasters. It is a cyclic 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. In the present work the tasks of flood management are subdivided into two consecutive parts: planning and operation, which basically require different kinds of hydrological models. These models should be used appropriate to the tasks, which reflect characteristics of landscape as well as of hydrological scale. This work synthesizes various modelling methodologies available to aid planning and operational decision-making, with emphasis on methodologies applicable in data-scarce regions, such as developing countries. Topics covered include: physical processes that transform rainfall into runoff, flood routing, assessment of likely changes in flood frequencies and magnitudes under climate change scenarios, and use of remote sensing, Geo information systems (GIS) and digital elevation models (DEM) technologies are used in modelling of floods to aid decision-making.**

Keywords — flood disasters, hydrologycal models

I. INTRODUCTION

Adequate scientific evidence exists now to show that the global climate is changing. The three prominent signals of climate change, namely, increase in global average temperature, rise in sea levels, and change in precipitation patterns, convert into signals of regional-scale hydrologic change in terms of modifications in extremes of floods and droughts, water availability, water demand, water quality, salinity intrusion in coastal aquifers, groundwater recharge, and other related phenomena. The increase in the atmospheric temperature, for example, is likely to have a direct impact on the river runoff in snow-fed rivers and on the evaporative demands of crops and vegetation, apart from its indirect impacts on all other processes of interest in the hydrology.

Similarly, a change in the regional precipitation pattern may have a direct impact on magnitude and frequency of floods and droughts and water availability. Changes in precipitation patterns and frequencies of extreme precipitation events, along with changes in soil moisture and evapotranspiration, will affect runoff and river discharges at various time scales from sub-daily peak flows to annual variations. At sub-daily and daily time scales, flooding events are likely to cause enormous socio-economic and environmental damage, which necessitates the use of robust and accurate techniques for prediction of flood frequencies and magnitudes under climate change, and development of flood protection measures to adapt to the likely changes. The knowledge about hydrologic modelling and the use of global climate models (GCMs) is critical in planning and operation for flood management under the climate change. The main objective of this article is to provide a basic background on the hydrologic modelling, the impact assessment methods and the uncertainties in impacts the hydrologic models are concerned with simulating natural processes related to movement of water, such as the flow of water in a stream, evaporation and evapotranspiration, groundwater recharge, soil moisture, sediment transport, chemical transport, growth of microorganisms in water, etc. The hydrologic processes that occur in the nature are distributed, in the sense that the time and space derivatives of the processes are both important. The hydrologic models are classified as distributed models or lumped models depending on whether the models consider the space derivatives (distributed) or not (lumped). The semi-distributed models account for spatial variations in some processes while ignoring them in others. On any time scale, the models may be discrete or continuous in time. Flood management requires models for two consecutive phases: planning and operation, which demand different kinds of models. In [15] is provided a classification of the hydrologic models specifically for a flood management.

The different levels of hydrologic models considered in [15] are:

- the data level, consisting of the GIS and data banks at different time scales, such as seasonal and event scales;
- the model level, consisting of (a) a basic hydrologic model incorporating the topography, digital terrain models, channel networks, sub-catchments, and long-term water and material balance and (b) a transport model operating at seasonal and event scales;
- the output level, which provides outputs in terms of maps and tables for use in decision-making;
- the decision level, which uses information provided by the output level, for arriving at management decisions.

The hydrologic models for floods function on the basis of partitioning the rainfall into various components.

II. Assesment of Climate Change Impacts

It is important to distinguish between climate change and climate variability. *Climate change* refers to a change in the state of the climate that persists for an extended period, typically decades or longer, as distinct from *climate variability*, which refers to variations in the mean state and other climate statistics, on all space and time scales. From year to year, variations in the rainfall at a location, for example, indicate climate variability, whereas a change in the long-term mean rainfall over a few decades is a signal of climate change. This paper concerns the assessment of climate change impact on hydrological processes.

The climate change is generally expected to increase the intensity (flood discharges) and the duration of floods. However, there will be a large variation in how the hydrology of different regions responds to signals of the climate change. Therefore, the regional assessment of the impacts of climate change is important. A commonly adopted methodology for assessing the regional hydrologic impacts of climate change is to use the climate predictions provided by the GCMs for specified emissions scenarios in a conjunction with the process-based hydrologic models to generate the corresponding hydrologic projections. The scaling problem arising because of the large spatial scales at which the GCMs operate compared to those required in most distributed hydrologic models is commonly addressed by downscaling the GCM simulations to hydrologic scales. This commonly used procedure of impact assessment is burdened with a large amount of uncertainty due to the choice of GCMs and emissions scenarios, small samples of historical data against which the models are calibrated, downscaling methods used, and several other sources. The development of procedures and methodologies to address such uncertainties is a current area of research. Vulnerability assessment, adaptation to climate change, and policy responses all depend on the projected impacts, with quantification of the associated uncertainty. General circulation models, also commonly known as global climate models, are the most credible tools available today for predicting the future climate.

The GCMs operate on a global scale. They are used for weather forecasting, understanding climate, and projecting climate change. They use quantitative methods to simulate the interactions of the atmosphere, oceans, land surface, and ice. The most frequently used models in the study of climate change are the ones relating air temperature and carbon dioxide emissions. These models predict an upward trend in the surface temperature, on a global scale. A GCM uses a large number of mathematical equations to describe physical, chemical, and biological processes such as wind, vapour movement, atmospheric circulation, ocean currents, and plant growth. A GCM relates the interactions among the various processes. For example, it relates how the wind patterns affect the transport of atmospheric moisture from one region to another, how ocean currents affect the amount of heat in the atmosphere, and how plant growth affects the amount of carbon dioxide in the atmosphere and so on. The models help in providing an understanding of how the climate works and how the climate is changing. A typical climate model projection used in the impact studies is that of global temperatures over the next century. Such projections of temperature and other climate variables provided by GCMs are used to obtain projections of other variables of interest (but which are not well simulated by GCMs), such as precipitation and evapotranspiration, in the impact studies. GCMs are more skilful in simulating the free troposphere climate than the surface climate. Variables such as wind, temperature, and air pressure can be predicted quite well, whereas precipitation and cloudiness are less well predicted. Some other variables of key importance in the hydrologic cycle, such as runoff, soil moisture, and evapotranspiration are not well simulated by the GCMs too. Runoff predictions in GCMs are over-simplified and there is no lateral transfer of water within the land phase between grid cells. The GCM simulation of rainfall has been found to be especially poor. The ability of GCMs to predict spatial and temporal distributions of climatic variables declines from global to regional to local catchment scales, and from annual to monthly to daily amounts. This limitation becomes particularly pronounced in assessing likely impacts of climate change on flood frequencies and magnitudes of flood peak flows. Flood peak flows in a catchment are generated by high-intensity storms of durations typically ranging from a few hours to a few days. At these time scales the simulations provided by GCMs are almost of no direct consequence. Stochastic disaggregation techniques have been used to disaggregate the longer time simulations provided by the GCMs to the shorter time events necessary in flood hydrology studies. The spatial scale mismatch between the scales of GCM simulations (with grid size of the order of tens of thousands of square kilometres) and those typically required for hydrologic modelling (with spatial scales of the order of a few hundred square kilometres and less) is classically addressed by spatial downscaling.

The impacts of climate change on floods are essentially assessed in the planning context by addressing the likely changes in the frequencies of given magnitudes of flood discharges. Flood frequencies are believed to be increasing due to climate change.

High-resolution regional climate projections are necessary for assessing, with reasonable confidence, such impacts on flood frequencies.

To overcome the limitations due to the coarse resolution of most existing GCMs, approaches such as stochastic weather generators and delta change methods are employed to examine the likely change in flood frequency due to climate change. Quantification of uncertainties in the projected impacts is particularly critical in the context of flood management, due to the huge economic implications of the adaptation measures.

A. *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.

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.

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.

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.

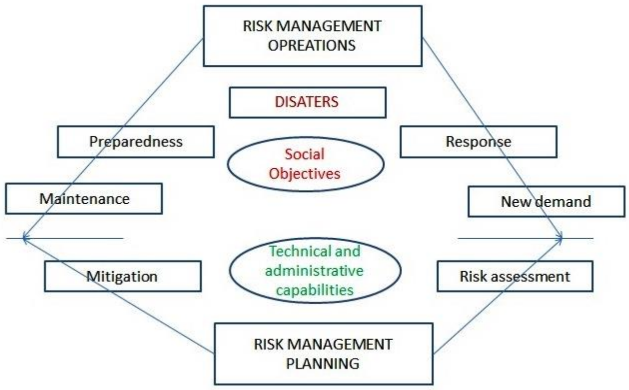

Fig. 1 *Cycle of risk management*

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. It is assumed (that) the risk management cycle starts 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 also to 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 should also be used for dikes, although the consequences of dike breaks usually are less severe than those from breaking dams that impound large reservoirs.

For each option the 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. The hazards are determined and expressed in hazard maps, which show the 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.

The process of decision making is initiated with the risk as an important decision criterion. 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, the plans to meet these demands by technical or non-technical means are prepared by experts, discussed by the 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, the finished systems are turned over to the system manager's staff, who does not only have to maintain the system, but also has 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 center 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. Because of climate changes, the flood risk management is a task to be reconsidered by every generation.

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.

The 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. The indicators and the 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. The assignment of weights to the indicators is a political task, whereas derivation of indices is a scientific challenge. As is evident from this discussion, the 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 are discussed here.

B. Hydrologic modelling for floods

The objective of this section is to provide the necessary background on hydrologic models for use in planning and operations related to floods. Hydrologic and kinematic flood routing, empirical models of artificial neural networks, and fuzzy inference systems for forecasting river discharges and flood routing are discussed. A focus of this is on the modelling approach to be adopted in data-scarce regions, especially in countries where many river basins are poorly gauged, and data on river discharges, soil types, land use patterns, and catchment characteristics are not readily available. The information on global data sets that may be useful in such situations is provided. A review of commonly used hydrologic models in decision-making for flood modelling is given in [1], [6], [15].

The 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. 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. A development of all plans is necessary for response to cases of extreme floods, which exceed the capacity of the protection system, is part of the planning and implementation phase of the flood risk management.

The 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. The flood forecasting is the chosen method for preventing, or at least reducing of losses, for example lives losses 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.

Forecast and prediction

The difference of planning vs. forecast models is illustrated in Fig. 2. The objective is to forecast the water levels $h_a\left(t_0+T_F\right)$ 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 for

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$h_F(t_0+T_F)$. 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.

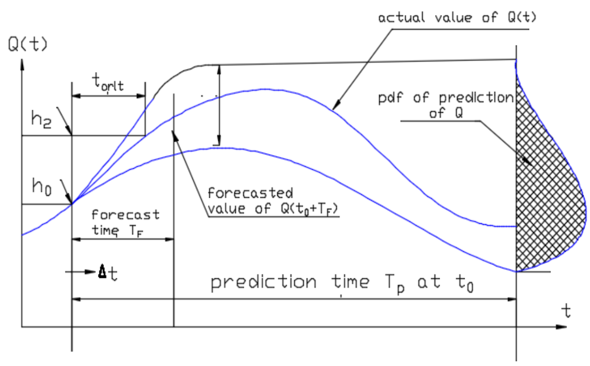

Fig. 2 *Scheme of forecasting and predictions*

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.

The 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.

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. The hydrologists are challenged to provide these models.

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. The 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.

The different sets of parameters may yield the same variance. Therefore, 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 is 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, it is necessary a validation 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.

The hydrological RR-models have three levels, each associated with three different time scales as indicated in Fig. 3. 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.

The 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. The 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.

The hydrologist 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 the different processes. Seasonal processes such as interactions of groundwater and surface water may well be described by models using larger time steps than runoff.

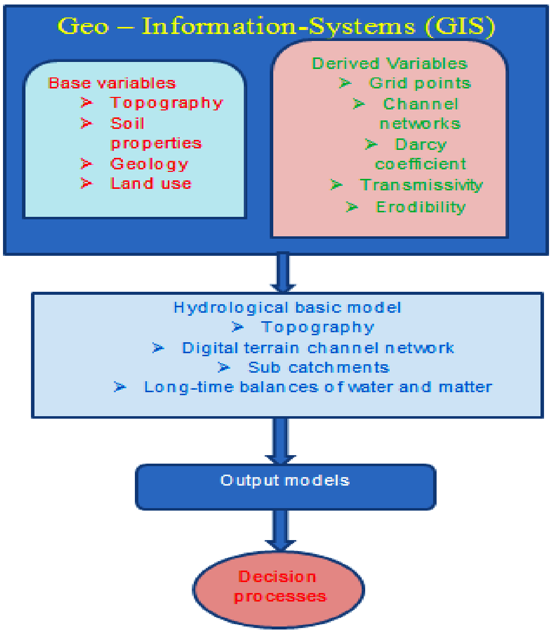

Fig. 3 Levels of hydrological models

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. The 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. 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 the hydraulic models, which range from stationary 1-D models to in stationary 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 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 evapotranspiration. 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. The 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. 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 will be discussed below. Simple models operate by using only translation, assuming a constant velocity of runoff from the element. More complex models are based on linear systems, applied to each element.

For CBMs the RR process for each sub-catchment is described by area models, which not only reflect the soil moisture balance 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, for example 1000 km^2 does not need the same resolution as an area of a few hectares.

RR-modeling in different landscapes

The different characteristics of landscapes require different types of models. For example, floods in mountain valleys have very different characteristics from floods on flood plains of large rivers. Theoretical the 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. It is distinguished four different types of landscapes 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. The 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, the 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 mainly on highways which for technical reasons had been built along the rivers. The 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.

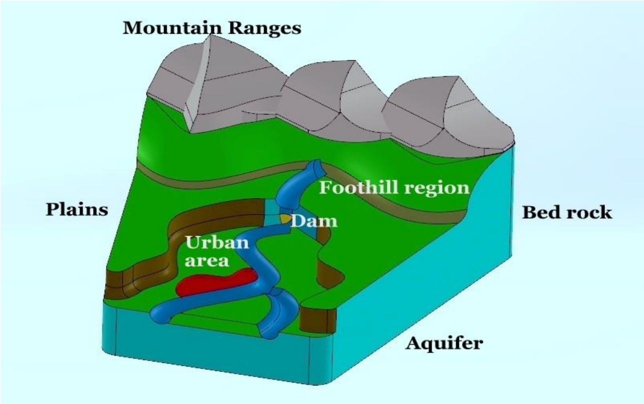

Fig. 4 *Scheme of four different types of landscapes*

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. Extreme floods, often combined with debris and trash plugging, cause such pipes to overflow and produce heavy local flooding.

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.

Partitioning of rainfall

The hydrologic models for floods function on the basis of partitioning the rainfall into various components. Several hydrologic models are available to estimate the flood hydrograph at specified locations in a catchment and for flood routing. The models differ essentially with respect to the methods used for estimating the various hydrologic components and assumptions made, and with respect to how they account for the distributed processes in spatial scales. In the context of floods, estimating the flood runoff volume and hydrograph resulting from a given storm is a critical exercise, and therefore generation of flood runoff from a storm is first discussed. Fig. 5 shows the various processes that take place once the precipitation occurs. As the precipitation falls, part of it is *intercepted* by vegetation and other surfaces and this part will not be available for runoff immediately during a storm. Once the precipitation reaches the land surface, part of it may *infiltrate* into the soil. Part of the rainfall is also trapped by surface depressions including lakes, swamps, and smaller depressions down to the size of small grain size cavities. A small amount is also lost as *evaporation* from bare surfaces and, from vegetation, as *evapotranspiration*.

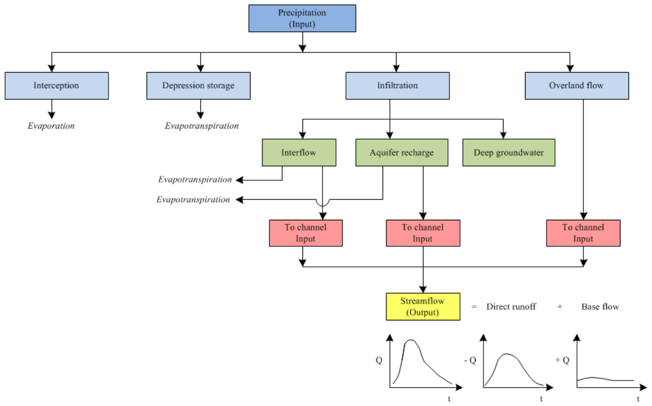

Fig. 5 *Partitioning of precipitation*

The infiltrated water may join the stream (channel) as interflow or may add to the aquifer recharge and deep groundwater storage. The direct runoff, or rainfall excess, is that part ofthe rainfall from which all losses have been removed and which eventually becomes flood runoff. As seen from Fig.1, the direct runoff hydrograph consists of contributions from the channel input to the streamflow through various routes of overland flow, interflow (through flow), and groundwater flow.

Overland flow

As the rainfall intensity increases, and exceeds the infiltration capacity of the soil, water starts running off in the form of a thin sheet on the land. This type of flow is called Hortonian overland flow. The runoff rate in a Hortonian overland flow may be simply estimated by (I–f), where I is the rainfall intensity in cm/hr and f is the infiltration capacity of the soil, also in cm/hr. When the rainfall intensity is less than the infiltration capacity of the soil, all of the rainfall is absorbed by the soil as infiltration. Hortonian overland flow is the most commonly occurring overland flow. The sheet of overland flow is quite thin before it joins a channel, to become channel flow. The *detention storage* – the storage that is held by the sheet flow corresponding to the depth of overland flow – contributes continuously to the channel flow, whereas part of the *retention storage*, held by surface depressions, is released slowly to the streams in the form of subsurface flow or is lost as evaporation. Other parts of the retention storage may add to the infiltration and subsequently recharge the groundwater. Hortonian overland flow occurs when the soil is saturated from above by precipitation. Saturated overland flow, on the other hand, occurs when the soil is saturated from below – most commonly because of subsurface flow. Saturation overland flow occurs commonly at valleys and near river banks. *Throughflow* occurs through macropores in the soil such as cracks, animal holes, and roots. Throughflow reaches the stream channel relatively quickly.

All three types of overland flows – Hortonian overland flow, saturated overland flow, and throughflow – may occur simultaneously during a storm. It is also possible that only a part of a drainage basin – and not the entire basin – may be contributing to the flood runoff at a location. This part of the drainage area, called the *source area*, may be different for different storms in the drainage basin and may also change within the same storm as the storm evolves.

Excess rainfall and direct runoff

Excess rainfall is that part of the rainfall that directly contributes to the runoff – it is neither retained in storage nor is lost as infiltration, interception, and evapotranspiration. Direct runoff is caused by excess rainfall after it travels over the surface as Hortonian overland flow. In flood studies, obtaining the direct runoff hydrograph (DRH) from an observed total runoff hydrograph is an important step.

Two procedures – the SCS curve number method and the rational formula – for estimation of flood runoff are discussed in this article. These methods may be used for estimating flood runoff and flood peaks for hydrologic designs, even with limited data. Many commonly used hydrologic models employ these methods for flood runoff estimation.

III. ESTIMATION OF FLOOD PEAK DISCHARGE

Soil Conservation Service curve number method

Estimating flood runoff from a given storm involves estimating losses from the rainfall. The Soil Conservation Service (SCS) –now called the Natural Resources Conservation Service (NRCS) – curve number method is the most commonly used and simple method for practical applications. It is based on accounting for infiltration losses from rainfall depending on the antecedent moisture content (AMC) and the soil type. The rainfall is assumed to occur uniformly over the entire watershed, during the storm. The fundamental basis for the SCS curve number method is that the runoff starts after initial losses due to abstractions, *Ia*, are accounted for. These losses consist of interceptions due to vegetation and built area that prevent the rainfall from reaching the ground immediately after it occurs, surface storage consisting of water bodies such as lakes, ponds, and depressions, and infiltration. An assumption in developing the curve numbers is that the ratio of actual retention of rainfall in the watershed to potential retention, S, in the watershed is equal to the ratio of direct runoff to rainfall minus the initial abstractions, *Ia* (before commencement of the runoff).

The parameter *S* depends on the catchment characteristics of soil, vegetation, and land constituting the soil–vegetation–land (SVL) complex and the AMC. With a parameter, CN, to represent the relative measure of water retention on the watershed by a given SVL complex, the potential retention in a watershed with a given SVL complex is calculated as

$$S = \frac{25400}{CN} - 254mm \qquad (1)$$

The parameter CN is called the curve number; it takes values between 0 and 100. The value of CN depends on the soil type and the AMC in the watershed. CN has no physical meaning. The equation for runoff (rainfall excess) is given as

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (2)$$

The following points must be kept in mind while using the SCS curve number method:

1. CN is a parameter that ranges from 0 to 100. A value of 100 indicates that all of the rainfall is converted into runoff and that there are no losses. Completely impervious and water surfaces are examples of this. For normal watersheds, CN < 100. A value of CN close to 0 indicates that almost all of the rainfall is accounted for losses, indicating highly dry conditions and therefore negligible runoff results.

2. CN has no physical meaning. Since it is the only parameter used to compute the runoff from rainfall, it accounts for the combined effects of soil type, AMCs, and vegetation type o the runoff.

3. The soil group is assumed to be uniform throughout the watershed. The rainfall is assumed to be uniformly distributed over the watershed.

4. When a watershed consists of different soil types, AMCs and vegetation types, a composite CN may be determined for the watershed, as an area-weighted CN.

5. The SCS method, when used to estimate runoff from rainfall that has actually occurred, may produce poor results and is rather heavily dependent on the AMCs assumed for the watershed. It is more useful for estimating design flood runoff resulting from a design storm.

6. The SCS method may over-predict the volume of runoff in a watershed.

7. The method is generally used for non-urban catchments. The soils are classified into four groups, A, B, C, and D, based on their runoff potential. The soil from group A comprising soils having the lowest runoff potential. The soil group D having the highest runoff potential. The AMC accounts for the moisture content in the soil preceding the storm for which the runoff is to be computed. The AMC of the watershed is classified into three groups, I, II, and III, based on the rainfall in the previous 5 days and based on whether it is a growing season or a dormant season.

Flood hydrograph from the SCS method

For most hydrologic designs for floods, the peak flood discharge rather than the total flood runoff is of interest. The following procedure may be adopted for constructing the design flood hydrograph, once the flood runoff has been estimated.

The time to peak, T_p, is estimated by:

$$T_p = 0.5D + 0.6t_c \qquad (3)$$

where, T_p is the time to peak (in hours), D is duration of the rainfall excess in hours, and t_c is the time of concentration in hours. The time of concentration is the time it takes from the beginning of the storm for the entire watershed to contribute to the runoff, and is given by the time it takes for the rain to reach the mouth of the watershed from the remotest part of the watershed.

The equation for estimate t_c given below:

$$t_c = 0.0024L^{0.77}S^{-0.385} \qquad (4)$$

Where L = length of channel/ditch from head water to outlet, m *S* = average watershed slope, m/m

Equating the total runoff volume, *VQ*, computed from the SCS method to the area of the triangular direct runoff hydrograph shown in Fig. 6, the peak discharge, q_p, can be expressed as:

$$q_p = \frac{0,208AV_Q}{0.5D + 0.6t_c} \qquad (5)$$

Where *A* is the watershed area in km^2, V_Q is runoff in mm, D and t_c are in hours. In Fig. 2, L_a is the basin lag, which is the time from the centroid of the excess rainfall hyetograph to the centroid of the hydrograph, which in the figure also coincides with the time to peak.

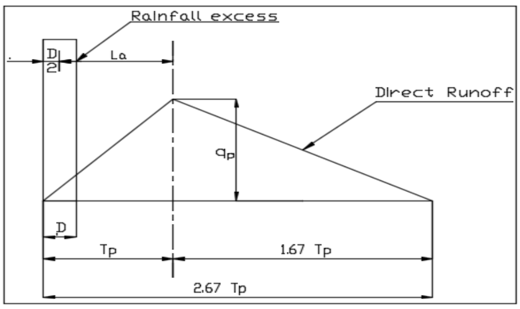

Fig. 6 *SCS triangular hydrograph*

Rational method

The rational method is most commonly used in urban flood designs but is also sometimes used for non-urban catchments. The rational formula is

$$Q_p = 0,278CIA \qquad (6)$$

where Q_p is the peak discharge, m^3/s I is the rainfall intensity, mm/h A is the area of the watershed, m^2 and C is a dimensionless runoff coefficient.

The rational method is most commonly used for hydrologic designs, rather than for estimating peak flows from actual rainfall. The intensity of the rainfall for design purposes is obtained from the intensity–duration–frequency (IDF) relationship for the watershed. The frequency used to determine the intensity is the same as that required for the design flood. That is, the average recurrence interval (ARI) or the return period chosen for the hydrologic designs is used as the frequency in the IDF relationship. Duration of the design rainfall is generally taken as the time of concentration, t_c, for design purposes.

The coefficient of runoff, C, for a given watershed is a major source of uncertainty in the rational method. The coefficient, as seen from the rational formula, (6), aggregates the effect of soil type, AMC, vegetation, land use, degree of soil compaction, depression storage, catchment slope, rainfall intensity, proximity to water table, and other factors that determine the peak runoff for a given storm in a catchment.

The following points must be noted with respect to the rational formula:

1. It is assumed in the rational formula that the frequency of the peak discharge is the same as the frequency of the rainfall.

2. The runoff coefficient *C* is the same for storms of different frequencies.

3. All losses are constant during a storm – the value of *C* does not change with hydrologic conditions (such as the AMC).

4. As the intensity of the rainfall is assumed to be constant over the duration considered, the rational method is valid for relatively small catchments. Some investigators believe that the maximum area should be about 100 acres (about 40 ha).

5. The rational method is generally used for urban storm-water drainage designs. It is also used for small non-urban catchments to estimate peak flows. Where the catchment size is large, it is divided into sub-catchments to obtain the peak flows from each sub-catchment and then the resulting hydrographs are routed using flood routing procedures to obtain the peak flow at the outlet.

6. To account for a non-linear response of the catchment to increasing intensities of rainfall, the value of *C* is sometimes assumed to increase as ARI increases.

7. A probabilistic rational method may be used to obtain the runoff coefficient as a function of the ARI.

Intensity–duration–frequency relationship

Hydrologic designs for floods require the peak flows expected to be experienced. The designs are normally developed for a given return period of a flood event. For example, an embankment along a river may be designed to protect against a flood of return period of 100 years, whereas the urban drainage systems may be typically designed for storms of return periods 2 to 5 years. The return period of an event indicates the ARI of the event.

As discussed previously a design rainfall depth or intensity is required for determination of peak flood flows. The design rainfall intensity is obtained from the IDF relationships developed for a given location. The IDF relationships provide the expected rainfall intensity (I) for a given duration (D) of the storm and a specified frequency (F). IDF relationships are provided as plots with duration as abscissa and intensity as ordinate and a series of curves, one for each return period. The intensity of rainfall is the rate of precipitation, i.e., depth of precipitation per unit time. This can be either instantaneous intensity or average intensity over the duration of rainfall.

The average intensity is determined as:

$$i = \frac{P}{t} \tag{7}$$

Where P is the rainfall depth and t is the duration of rainfall.

The frequency is expressed in terms of return period (T), which is the average length of time between the rainfall events that equal or exceed the design magnitude. If local rainfall data are available, IDF curves can be developed using frequency analysis.

A minimum of 20 years of data is desirable for development of the IDF relationship.

The following steps describe the procedure for developing IDF curves:

Step 1: Preparation of annual maximum rainfall data series

From the available rainfall data, rainfall series for different durations (e.g., 1, 2, 6, 12, and 24 hr) are developed. For each duration, the annual maximum rainfall depths are calculated.

Step 2: Fitting a probability distribution

A suitable probability distribution is fitted to each of the selected duration data series. Generally used probability distributions are Gumbel's extreme value distribution, normal distribution, log-normal distribution (two parameter), gamma distribution (two parameter), and the log-Pearson type III distribution. The most commonly used distribution is Gumbel's extreme value distribution. The parameters of the distribution are calculated for the selected distribution. Statistical tests such as the Kolmogorov–Smirnov goodness of fit test may be performed to ensure that the chosen distribution fits the data well.

Step 3: Determining the rainfall depths

The precipitation depth corresponding to a given return period is calculated from the analytical frequency procedures as:

$$x_T = \bar{x} + K_T s \tag{8}$$

where x_T is the precipitation depth corresponding to the return period T, $\overline{x}$ is mean of the annual maximum values obtained in Step 1, s is the standard deviation of the annual maximum values obtained in Step 1, and K_T is the frequency factor, which depends on the distribution used.

For Gumbel's distribution:

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0{,}5772+\ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\} \tag{9}$$

For the normal distribution, K_T is the same as the standard normal deviate z and is given by:

$$K_T = z = w - \frac{2{,}515517+0{,}802853w+0{,}010328w^2}{1+1{,}43788w+0{,}189269w^2+0{,}001038w^3} \tag{10}$$

Where:

$$w = \left[\ln\left(\frac{1}{p^2}\right)\right]^{1/2}, 0 \le p \le 0{,}5 \tag{11}$$

In (11), p is the exceedance probability P ($X \geq x_T$), where X denotes the random variable, rainfall, and x_T is the magnitude of the rainfall corresponding to the return period T. It may be noted that p = 1/T. When p > 0.5, (*1−p*) is substituted in place of p in (11), and the resulting K_T value is used with a negative sign in (8).

For the log-Pearson type III distribution, the frequency factor depends on the return period and coefficient of skewness, Cs. When Cs = 0, K_T is equal to the standard normal deviate (10). When $C_s \neq 0$:

$$K_T = z+(z^2-1)k+\frac{1}{3}(z^3-6z)k^3-(z^2-1)k^3+zk^4+\frac{1}{3}k^5 \tag{12}$$

Where

$$k = \frac{C_s}{6} \tag{13}$$

and z is given by (10).

The precipitation depth thus calculated from the frequency relationship (8) can be adjusted to match the depths derived from annual maximum series by multiplying the depths by 0,88 for the 2-year return period values, 0,96 for the 5-year return period values, and 0.99 for the 10-year return period values. No adjustment of the estimates is required for longer return periods (>10-year return period). The corresponding intensities are obtained simply by dividing the depth by the duration.

Flood routing

In the text above, construction of (design) flood hydrographs was discussed, by estimating the design storm intensity for a given return period from the IDF relationship corresponding to the design duration, the time of concentration, t_c, and the peak flood runoff, q_p. The traverse of a flood in a river stretch is discussed in this section, and methodologies to estimate the hydrographs at various locations in the river stretch are given. A flood travels along a river reach as a wave, with velocity and depth continuously changing with time and distance. While it is difficult to forecast with accuracy the time of occurrence and magnitude of floods, it is possible to estimate fairly accurately the movement of the flood wave along a river, once it is known that a flood wave is generated at some upstream location in the river. Such estimation is of immense practical utility, as it can be used in flood early warning systems. In this section, the specific problem of how a flood wave propagates along a channel – a stream, a river, or any open channel – is discussed along with the theoretical framework available for forecasting the propagation of the flood wave. Imagine a flood wave travelling along a straight reach of a stream, which initially has uniform flow conditions. As the flood wave crosses a section, the velocity (or discharge) and the depth of flow at that section change. Determining the track of these changes in depth and discharge, with time and along the length of the river, is called flood routing.

A flood wave is, therefore, represented by a hydrograph, as shown in Fig. 7. In practical applications, the general interest would be in estimating the discharge and depth of flow at a given location along the stream at a specified time, given the flood hydrograph at an upstream section. The hydraulic method of flood routing uses the Saint-Venant equations discussed in the next section, whereas the hydrologic method of flood routing uses a simple hydrologic continuity in terms of relating the change in storage in the channel length to the difference between inflow and outflow. In this section, only the channel routing methods are covered. The reservoir routing method, which is used in routing the floods through a reservoir, is not discussed here.

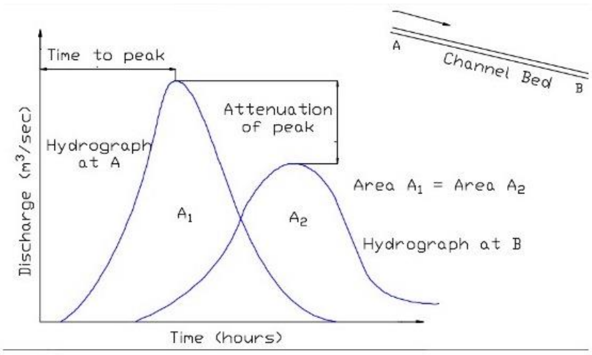

Fig. 7 *Flood hydrographs*

Hydraulic routing: the Saint-Venant equations

The flood flow is unsteady – because the flow properties (depth and velocity) change with time – and is gradually varied, because such change with time is gradual. To derive the governing equations for such a wave movement, we use the principles of continuity (conservation of mass) and momentum (essentially, Newton's second law of motion) for the one-dimensional unsteady open channel flow.

In differential form, the governing equations are written as:

Continuity:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}-q=0 \qquad (15)$$

Momentum:

$$\left(\frac{1}{A}\right)\frac{\partial Q}{\partial t}+\left(\frac{1}{A}\right)\frac{\partial\left(Q^2/A\right)}{\partial x}+g\frac{\partial y}{\partial x}-g\left(S_0-S_f\right)=0 \qquad (16)$$

In these equations:

$\left(\frac{1}{A}\right)\frac{\partial Q}{\partial t}$ - Local acceleration term,

$\left(\frac{1}{A}\right)\frac{\partial\left(Q^2/A\right)}{\partial x}$ - Convective acceleration term,

$g\frac{\partial y}{\partial x}$ - Pressure force term,

$g\left(S_0-S_f\right)$ -gravity force term.

Where Q is the discharge (m^3/s), A is the area, m^2, q is the lateral flow per unit length of the channel (m^3/s per m), x is the distance along the channel, y is the depth of flow, g is the acceleration due to gravity, S_0 is the bed slope of the channel, and S_f is the friction slope. Equations (14) and (15) are together called the Saint-Venant equations. In the momentum equation, the *local acceleration* term describes the change in momentum due to change in velocity over time, the *convective acceleration* term describes the change in momentum due to change in velocity along the channel, the *pressure force* term denotes a force proportional to the change in water depth along the channel, the *gravity force* term denotes a force proportional to the bed slope, and the *friction force* term denotes a force proportional to the friction slope.

It is not possible to solve (14) and (15) together analytically, except in some very simplified cases. Numerical solutions are possible, and are used in most practical applications. Depending on the accuracy desired, alternative flood routing equations are generated by using the continuity equation (except the lateral flow term, in some cases) while eliminating some terms of the momentum equation. Based on the terms retained in the momentum equation, the flood wave is called the *kinematic* wave, the *diffusion* wave, and the *dynamic wave*, as shown:

|—— Kinematic wave

|————— Diffusion wave

|—————————————Dynamic wave

The kinematic wave is thus represented by $g(S_0-S_f) = 0$, or $S_0=S_f$, the diffusion wave by $g\frac{\partial y}{\partial x}-g\left(S_0-S_f\right)=0$, $g\partial y/\partial x-g(S_0-S_f)=0$, resulting in $\partial y/\partial x=(S_0-S_f)$, and the dynamic wave by the complete momentum equation (15).

In most practical applications, the wave resulting either from the simplest form of the momentum equation, i.e., the kinematic wave, or from the complete momentum equation, i.e., the dynamic wave, is used. For the kinematic wave, the acceleration and pressure terms in the momentum equation are neglected, hence the name *kinematic*, referring to the study of motion exclusive of the influence of mass and force. The remaining terms in the momentum equation represent the steady uniform flow. In other words, the flow is considered to be steady for momentum conservation and the effects of unsteadiness are taken into consideration through the continuity equation. Analytical solution is possible for the simple case of the kinematic wave, where the lateral flow is neglected and the wave celerity is constant. However, the *backwater effects* (propagation upstream of the effects of change in depth or flow rate at a point) are not reproduced through a kinematic wave. Such backwater effects are accounted for in flood routing only through the local acceleration, convective acceleration, and the pressure terms, all of which are neglected in the kinematic wave. For more accurate flood routing, numerical solutions of the complete dynamic equation are used.

Numerical solutions

With the availability of high-speed computers, it is presently possible to solve the dynamic wave equations through numerical methods (such as the finite difference method). The numerical methods start with *initial* and *boundary* conditions. At time t=0, the uniform steady flow conditions are specified at all locations. These constitute the initial conditions. At distance x=0, the flood hydrograph is known. This, together with other flow conditions (such as free over-fall at a location, flows from other sources joining the channel, submergence at a junction, etc.) along the length of the channel define the boundary conditions. The solution of the Saint-Venant equations gives the variation of discharge (and depth) with time along the length of the water body (river, stream, or channel), which may be used for real-time flood forecasting.

A finite difference scheme is presented here to solve the Saint-Venant equations numerically.

Continuity:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q \qquad (15)$$

Momentum:

$$S_0=S_f \qquad (16)$$

The momentum equation can be, in general, expressed in the form:

$$A=\alpha Q^{\beta} \qquad (17)$$

The advantage of expressing the momentum equation in this form is that the variable A can be eliminated in the continuity equation, by differentiating (17) with respect to t:

$$\frac{\partial A}{\partial t} = \alpha\beta Q^{\beta-1}\left(\frac{\partial Q}{\partial t}\right) \quad (18)$$

Substituting for $\partial A/\partial t$ in (15) to give:

$$\frac{\partial Q}{\partial x} + \alpha\beta Q^{\beta-1}\left(\frac{\partial Q}{\partial t}\right) = q \quad (19)$$

The kinematic wave celerity, c_k, may be expressed as:

$$c_k = \frac{dQ}{dA} = \frac{dx}{dt} \quad (20a)$$

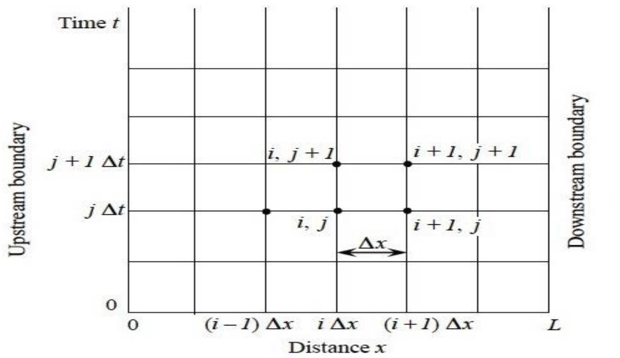

Fig. 8 *Grid on the x–t plane used for numerical solution of the Saint-Venant equations*

with dA = Bdy,

$$c_k = \frac{1}{B}\frac{dQ}{dy} \quad 20b)$$

B is the top width of flow.

Fig. 8 shows a general x–t plane of a finite difference scheme. In the explicit method of solution the initial conditions at x=0 and t=0 are both known. This procedure defines an explicit scheme of solution.

A finite difference form of the derivative of Q_{i+1}^{j+1} may be obtained as follows:

$$\frac{\partial Q}{\partial x} \approx \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} \quad (21)$$

$$\frac{\partial Q}{\partial t} \approx \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta t} \quad (22)$$

$$Q \approx \frac{Q_{i+1}^{j} + Q_i^{j+1}}{2} \quad (23)$$

$$\frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} + \alpha\beta\left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\beta-1}\left(\frac{Q_{i+1}^{j+1} - Q_{i+1}^{J}}{\Delta t}\right) = \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2} \quad (24)$$

$$Q_{i+1}^{j+1} = \frac{\left[\dfrac{\Delta t}{\Delta x}Q_i^{j+1} + \alpha\beta Q_{i+1}^{j}\left(\dfrac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\beta-1} + \Delta t\left(\dfrac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}\right)\right]}{\left[\dfrac{\Delta t}{\Delta x} + \alpha\beta\left(\dfrac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\beta-1}\right]} \quad (25)$$

It can be shown that, by choosing Q as the dependent variable rather than A, the relative errors resulting from the numerical computations may be reduced. The coefficients α and β are determined by writing the momentum equation in the form A=αQβ.

The following steps summarize the solution procedure:

1. Initial values of Q are set at x=0 (for all t) and at t=0 (for all *x*). These may be specified from the known base flow conditions.

2. The time and space steps, Δt and Δx, are chosen to satisfy the courant condition, $\Delta t \le \Delta x / c_k$, for numerical stability. For a given Δx, the smallest time step, Δt, that satisfies the courant condition is chosen.

3. Advancing from the time step *j* (corresponding to *t* = 0) to the next time step, *j* + 1, (25) is applied from i = 1 to i = i_{max}, one step at a time, to obtain the values of Q at all space steps at the time step j+1, where i_{max} corresponds to last time step at the downstream boundary. This is repeated until the last time step is reached.

Hydrologic routing of floods: Muskingum method

The Muskingum method of flood routing is a hydrologic routing method. The basis for the equation of continuity in hydrologic routing is that the difference between the inflow and outflow rates is equal to the rate of change of storage is given by the equation:

$$I - Q = \frac{dS}{dt} \quad (26)$$

Where I - inflow rate, Q - outflow rate, and *S* - storage. Considering a small time interval Δt, the difference between the total inflow volume and total outflow volume may be written as:

$$\bar{I}\Delta t - \bar{Q}\Delta t = \Delta S \quad (27)$$

Where $\bar{I}$ - average inflow in time Δt, $\bar{Q}$ - average outflow in time Δt, and ΔS - change in storage. With $\bar{I} = (I_1 + I_2)/2$, $\bar{Q} = (Q_1 + Q_2)/2$ and $\Delta S = S_2 - S_1$, where subscripts 1 and 2 denote the variables at the beginning and end of the time interval,

$$\left(\frac{I_1 + I_2}{2}\right)\Delta t - \left(\frac{Q_1 + Q_2}{2}\right)\Delta t = S_2 - S_1 \quad (28)$$

The time interval Δt should be sufficiently small that the inflow and outflow hydrographs may be assumed to be straight lines in that time interval.

The Muskingum equation is written as:

$$S = K\left[xI + (1-x)Q\right] \tag{29}$$

In this equation, the parameter x is known as the *weighting factor* and takes a value between 0 and 0,5. A value of x = 0 indicates that the storage is a function of discharge only, in which case,

$$S = KQ \tag{30}$$

Such storage is known as *linear storage* or *linear reservoir*. When *x*=0,5 both the inflow and outflow contribute equally in determining the storage. The coefficient K, which has the dimensions of time, is called the *storage-time constant*. It is approximately equal to the time of travel of a flood wave through the channel reach.

When a set of in flow and out flow hydrograph values is available for a given reach, values of S at various time intervals can be determined. By choosing a value of *x*, values of *S* at any time *t* are plotted against the corresponding $\left[xI + (1-x)Q\right]$ values. If the value of x is chosen correctly, a straight-line relationship as in (29) will result. If the chosen value is incorrect, the points will yield a looping curve. A trial and error procedure is used to obtain the correct value of x so that the points yield nearly a straight line. The value of K is given by the inverse slope of this straight line. The value of *x* lies between 0 and 0.3, for natural channels. Within a given reach, the values of x and K are assumed to be constant, in routing. The flow rate Q_2 at the downstream point 2 will be:

$$Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_1 \tag{31}$$

Where

$$C_0 = \frac{-K_x + 0{,}5\Delta t}{K - K_x + 0{,}5\Delta t}, C_1 = \frac{K_x}{K - K_x + 0{,}5\Delta t} \tag{32}$$

And

$$C_2 = \frac{K - K_x - 0{,}5\Delta t}{K - K_x + 0{,}5\Delta t}$$

And

$$C_0 + C_1 + C_2 = 1 \tag{33}$$

IV. BRIEF REVIEW OF COMMONLY USED HYDROLOGIC MODELS

A large number of hydrologic models exist today with varying degrees of data requirements that may be used for purposes such as estimation of flood runoff, routing of flood hydrographs, and assessment of flood inundation, which may be done with a GIS interface. The hydrologic processes that occur in nature are *distributed* in the sense that the time and space derivatives of the processes are both important. The models can be classified as distributed and lumped depending on whether the models consider the space derivatives (distributed) or not (lumped). The semi-distributed models account for spatial variations in some processes while ignoring them in others. On the time scale, the models may be discrete or continuous time models. Table 1 represent the list of hydrological models which are used in the practice.

TABLE 1 COMMONLY USED HYDROLOGIC MODELS

Model name/acronym	**Remarks**
Agricultural Non-Point Source Model (AGNPS)	Distributed parameter, event-based, water quantity and quality simulation model
Agricultural Runoff Model (ARM)	Process-oriented, lumped runoff simulation model
Agricultural Transport Model (ACTMO)	Lumped, conceptual, event-based runoff and water quality simulation model
Antecedent Precipitation Index (API) Model	Lumped, river flow forecast model
Areal Non-point Source Watershed Environment Response Simulation (ANSWERS)	Event-based or continuous, lumped parameter runoff and sediment yield simulation model
ARNO (Arno River) Model	Semidistributed, continuous rainfall–runoff simulation model
Catchment Model (CM)	Lumped, event-based runoff model
Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS)	Process-oriented, lumped parameter, agricultural runoff and water quality model
Constrained Linear Simulation (CLS)	Lumped parameter, event-based or continuous runoff simulation model
Cascade Two-dimensional Model (CASC2D)	Physically based, distributed, event-based runoff simulation model
Daily Conceptual Rainfall–Runoff Model (HYDROLOG)-Monash Model	Lumped, conceptual rainfall–runoff model
Distributed Hydrological Model (HYDROTEL)	Physically based, distributed, continuous hydrologic simulation model
Distributed Hydrology Soil Vegetation Model (DHSVM)	Distributed, physically based, continuous hydrologic simulation model
Dynamic Watershed Simulation Model (DWSM)	Process-oriented, event-based, runoff and water quality simulation model
Erosion Productivity Impact Calculator (EPIC) Model	Process-oriented, lumped parameter, continuous water quantity and quality simulation model
Geomorphology-Based Hydrology Simulation Model	Physically based, distributed, continuous

(GBHM)	hydrologic simulation model
Generalized River Modelling Package–Systeme Hydrologique Europeen (MIKE-SHE)	Physically based, distributed, continuous hydrologic and hydraulic simulation model
Global Hydrology Model (GHM)	Process-oriented, semidistributed, large-scale hydrologic simulation model
Great Lakes Environmental Research Laboratory (GLERL) Model	Physically based, semidistributed, continuous simulation model
Groundwater Loading Effects of Agricultural Management Systems (GLEAMS)	Process-oriented, lumped parameter, event-based water quantity and quality simulation model
Hydrologic Engineering Center–Hydrologic Modelling System (HEC-HMS)	Physically based, semidistributed, event-based, runoff model
Hydrologic Model System (HMS)	Physically based, distributed-parameter, continuous hydrologic simulation system
Hydrological (CEQUEAU) Model	Distributed, process-oriented, continuous runoff simulation model
Hydrological Modelling System (ARC/EGMO)	Process-oriented, distributed, continuous simulation system
Hydrological Simulation (HBV) Model	Process-oriented, lumped, continuous streamflow simulation model
Institute of Hydrology Distributed Model (IHDM)	Physically based, distributed, continuous rainfall–runoff modelling system
Integrated Hydrometeorological Forecasting System (IHFS)	Process-oriented, distributed, rainfall and flow forecasting system
Kinematic Runoff and Erosion Model (KINEROS)	Physically based, semidistributed, event-based, runoff and water quality simulation model
Large Scale Catchment Model (LASCAM)	Conceptual, semidistributed, large-scale, continuous, runoff and water quality simulation model
Macroscale Hydrolgical Model–Land Surface Scheme (MODCOU-ISBA)	Macroscale, physically based, distributed, continuous simulation model
Mathematical Model of Rainfall–Runoff Transformation System (WISTOO)	Process-oriented, semidistributed, event-based or continuous simulation model
Modular Kinematic Model for Runoff Simulation (Modular System)	Physically based, lumped parameter, event-based runoff simulation model
National Hydrology Research Institute (NHRI) Model	Physically based, lumped parameter, continuous hydrologic simulation model
National Weather Service River Forecast System (NWS-RFS)	Lumped, continuous river forecast system
Pennsylvania State University–Urban Runoff Model (PSU-URM)	Lumped, event-based urban runoff model
Physically Based Runoff Production Model (TOPMODEL)	Physically based, distributed, continuous hydrologic simulation model
Predicting Arable Resource Capture in Hostile Environments – The Harvesting of Incident Rainfall in Semi-arid Tropics (PARCHED-THIRST)	Process-oriented, lumped parameter, event-based agro-hydrologic model
Purdue Model	Process-oriented, physically based, event runoff model
Rainfall–Runoff (R–R) Model	Semidistributed, process-oriented, continuous streamflow simulation model
Regional-Scale Hydroclimatic Model (RSHM)	Process-oriented, regional scale, continuous hydrologic simulation model
Runoff Routing Model (RORB)	Lumped, event-based runoff simulation model
Simple Lumped Reservoir Parametric (SLURP) Model	Process-oriented, distributed, continuous simulation model
Simplified Hydrology Model (SIMHYD)	Conceptual, daily, lumped parameter rainfall–runoff model
Simulation of Production and Utilization of Rangelands (SPUR)	Physically based, lumped parameter, ecosystem simulation model
Simulator for Water Resources in Rural Basins (SWRRB)	Process-oriented, semidistributed, runoff and sediment yield simulation model
Snowmelt Runoff Model (SRM)	Lumped, continuous snowmelt–runoff simulation model
Soil–Vegetation–Atmosphere Transfer (SVAT) Model	Macroscale, lumped parameter, streamflow simulation system
Soil Water Assessment Tool (SWAT)	Distributed, conceptual, continuous simulation model
Stanford Watershed Model (SWM)/Hydrologic Simulation Package–Fortran	Continuous, dynamic event or steady-state simulator of hydrologic

IV (HSPF)	and hydraulic and water quality processes
Stochastic Event Flood Model (SEFM)	Process-oriented, physically based event-based, flood simulation model
Storm Water Management Model (SWMM)	Process-oriented, semidistributed, continuous stormflow model
Streamflow Synthesis and Reservoir regulation (SSARR) Model	Lumped, continuous streamflow simulation model
Surface Runoff, Infiltration, River Discharge and Groundwater Flow (SIRG)	Physically based, lumped parameter, event-based streamflow simulation model
Systeme Hydrologique Europeen/Systeme Hydrologique Europeen Sediment (SHE/SHESED)	Physically based, distributed, continuous streamflow and sediment simulation
Systeme Hydrologique Europeen Transport (SHETRAN)	Physically based, distributed, water quantity and quality simulation model
Tank Model	Process-oriented, semidistributed, or lumped continuous simulation model
Technical Report-20 (TR-20) Model	Lumped parameter, event based, runoff simulation model
Tennessee Valley Authority (TVA) Model	Lumped, event-based runoff model
THALES	Process-oriented, distributed-parameter, terrain analysis-based, event-based runoff simulation model
Topographic Kinematic Approximation and Integration (TOPIKAPI) Model	Distributed, physically based, continuous rainfall–runoff simulation model
Two Parameter Monthly Water Balance Model (TPMWBM)	Process-oriented, lumped parameter, monthly runoff simulation model
US Department of Agriculture Hydrograph Laboratory (USDAHL) Model	Event-based, process-oriented, lumped hydrograph model
US Geological Survey (USGS) Model	Process-oriented, continuous/event-based runoff model
University of British Columbia (UBC) Model	Process-oriented, lumped parameter, continuous simulation model
Utah State University (USU) Model	Process-oriented, event/continuous streamflow model
Water and Snow Balance Modelling System (WASMOD)	Conceptual, lumped, continuous hydrologic model
Waterloo Flood System (WATFLOOD)	Process-oriented, semidistributed, continuous flow simulation model
Watershed Bounded Network Model (WBNM)	Geomorphology-based, lumped parameter, event-based flood simulation model
Xinanjiang Model	Process-oriented, lumped, continuous simulation model

In the current work is given 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 models must be distinguished 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 mountainous areas. As prerequisite of model choice a thorough understanding of local topography and climate processes is essential. The models should not only reflect local scales and local terrain features and geology, but they also should be determined by the intended application. This paper is an attempt to give guidance to persons involved in flood management by pointing out the different conditions and requirements for the use of flood management models.

V. Conclusion

In the current work is given 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 models must be distinguished 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 mountainous areas. As prerequisite of model choice a thorough understanding of local topography and climate processes is essential. The models should not only reflect local scales and local terrain features and geology, but they also should be determined by the intended application. This paper is an attempt to give guidance to persons involved in flood management by pointing out the different conditions and requirements for the use of flood management models.

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