A Review of the Optimum Accuracy of Flow and Rainfall Forecasting

WS Atkins Water

R&D Note 433

NRA
National Rivers Authority

A Review of the Optimum Accuracy of Flow and Rainfall Forecasting

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This R&D Note contains a detailed review of the factors affecting the accuracy and timeliness of flow and rainfall forecasts. The result of this review is a set of conclusions and recommendations concerning best practice and R&D activities.

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EXECUTIVE SUMMARY

Flood forecasting problems are classified in terms of the time scale of the catchment response and spatial scale of the flood producing storms. This provides a rational framework for assessing current practice, the scope for increasing effectiveness as well as for performing cost benefit analyses. These two criteria provide the most useful and fundamental classification of flood forecasting problems. An alternative classification according to catchment type, size, land use etc., would lead to numerous categories that in the end would need to be related to the above two fundamental criteria.

A detailed review of the factors affecting the accuracy and timeliness of flow and rainfall forecasts is presented. Where possible these uncertainties have been quantified based on published studies.

The result of this review is a set of conclusions and recommendations concerning best practice and R&D activities. The most important of these are summarised below.

(a) The adoption of a systematic and uniform practice for forecast evaluation in all regions. The advantages of this type of forecasting post-audit are; 1.) objective evaluation of the worth and accuracy, 2.) identification of the effectiveness of flow forecasting according to storm and catchment type., 3.) identification of modelling inconsistencies and weaknesses and 4.) identification of the need for changes in rainfall and streamflow networks. Guidelines as to how this might be carried out are given in the report.

This recommendation recognises that it is not possible to quantify exactly the accuracy of forecasting problems, a priori, as this depends on numerous, widely varying parameters and conditions. It is nevertheless possible to subdivide these forecasting problems into broad categories where an optimal forecasting procedure can be identified.

(b) Identifying the optimal flood forecasting strategy is based on the classification of the flood forecasting problems according to response time of the catchment at the forecast point and the spatial scale of the flood producing storms compared to the catchment area. The optimal strategy recognises that generally flood routing is more accurate than rainfall-runoff modelling which in turn is more accurate than rainfall forecasting and that the most accurate of these should be applied where appropriate. These strategies are summarised in the tables below. The numbers shown should be treated as guidelines only.

Table 1 Classification of catchment type and corresponding flood forecasting approach

Category	Response time scale (hours)	Forecasting approach
I	$T_p < 3$	Rainfall/runoff modelling plus quantitative precipitation forecasts
II	$3 < T_p < 9$	Rainfall/runoff modelling plus flood routing
III	$T_p > 9$	Flood routing

Table 2 Classification of storm type and corresponding rainfall-runoff approach.

Category	Spatial scale of flood producing storms	Flow forecasting approach
(i)	$Lm/Lc << 1$	Semi-distributed rainfall-runoff modelling
(ii)	$Lm/Lc \approx 1$	Lumped rainfall-runoff modelling

(c) The identification of the optimal flood forecasting strategy for a specific site and an evaluation of forecast performance for that site, could then provide the basis for assessing the scope for increasing the accuracy and timeliness of an existing forecasting system. General measures for increasing the timeliness and accuracy of forecasting are given below.

Detailed guidelines for improving an existing forecast system would require a site-specific assessment of the particular measurement network and forecasting approach. The merits of more detailed assessments could be evaluated on a pilot basis for selected forecast sites.

(d) An assessment of the scope for increasing the effectiveness of a flow and rainfall forecasting system should consider not only the accuracy and timeliness of the flood forecast but also how this forecast is converted into a warning for the area likely to be affected and also how well this warning is communicated and interpreted.

(e) The worth of any changes can be assessed by cost benefit analyses which are the subject of a complementary R&D Note.

(f) In the absence of detailed accuracy-benefit relations it may be useful to identify the lead time for each type of forecast point which produces the maximum benefit and use this as a goal for revising forecasting procedures.

(g) There appears to be considerable scope for the introduction of both routing models and rainfall runoff models to increase the lead time and accuracy of forecasts. Indeed, in some cases there seems to be a considerable technological gap between the flood forecasting tools available and routine practice.

(h) The results of several studies show that significant improvements in accuracy are obtained using updating. Updating should be used in all cases, for both river routing and rainfall-runoff modelling. As upstream water levels are used as the basis of forecasts in many regions this can be readily implemented.

(i) Provision of an ensemble of forecasts is recommended where this is possible. This ensemble can be based on radar only, raingauges only, combined radar and rain-gauges or alternatively with rain forecasts, together with no further rain and the present rainfall rate continues. This will provide the forecaster with a feel for the robustness of the forecast.

(j) Semi-distributed models represent the state-of-the-art for operational forecasting in large catchments. Further research and development work is required to establish the worth and operationality of distributed models that incorporate the spatial variability of storm rainfall.

(k) Developments in numerical weather modelling at hydrological scales should be monitored carefully as there has been considerable progress in this area in the last decade and these methods have the potential to improve the accuracy of quantitative precipitation forecasts.

Keywords: floods, forecasting, monitoring, warning, accuracy, reliability, timeliness, radar.

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1. INTRODUCTION

The impact of flooding ranges from the tragic loss of lives, through loss of land, loss of agricultural production, to property damage and disruption of transport and services. To minimise the effect of flooding two complementary approaches exist: flood prevention works and flood warning. Flood prevention works include the design and construction of river banks, structures such as dams and weirs as well as flood storage areas, to protect flood-prone areas. The benefits of flood warning can accrue in three main ways (Reed 1984):

(a) evacuation of
- people and livestock,
- crops (by premature harvesting),
- sensitive and/or easily moved items (for example cars, electrical equipment and furnishing);

(b) amelioration through
- temporary flood proofing (for example sand bags and blankets),
- opportune maintenance (clearing instructions, culverts, etc.),
- early alerting of emergency services,
- orderly disruption of communications (read diversions),

(c) control by
- adjusting reservoir discharges to permit flood attenuation,
- emptying storm tanks and balancing ponds prior to the arrival of floods.

Since the value of flood warning depends on action taken as a result of flood warning, the effectiveness of a flood warning system will depend on the accuracy of the flood forecast itself, the conversion of this forecast into a warning for the area likely to be affected, how well this warning is communicated to those affected and ability of those affected to usefully interpret the warning.

1.1 Objectives

The overall objectives of this R&D project are to provide information, based on existing studies, that will help optimise the <u>accuracy</u>, <u>reliability</u> and <u>timeliness</u> of flow forecasting with special reference to radar rainfall data.

Accuracy implies maximising the probability that flooded areas that receive appropriate flood warnings.

Reliability relates to

i) reliability of instrument (e.g. radar maintenance and down time)

ii) reliability of telemetry system

iii) warning procedures

iv) robustness of the forecasting model to missing or uncertain data

Timeliness refers to the balance between timely but less accurate forecasts and precise forecasts with insufficient lead time to provide significant benefits.

The specific project objectives related to this R&D note are

1. To assess the scope for increasing the effectiveness of flow and rainfall forecasting due to optimised data and model accuracy.

2. To provide background information on the optimum accuracy of flow and rainfall forecasting, needed for a cost benefit analysis

3. To identify and prioritise Research and Development needs for flow and rainfall forecasting in terms of achieving best current practice.

Therefore, this report will be concerned primarily with the accuracy and timeliness of forecasts and only the reliability of the forecasting models (item (iv)) will be considered here. Nevertheless it must be recognised that the reliability of the equipment and the reliability and speed with which warnings are issued are important considerations in an effective flood warning system.

1.2 General Approach

To address the above objectives, the following approach is adopted in this report. Methods suitable for assessing the accuracy of existing flood forecasting and flood warning systems are reviewed and the relation between lead-time and accuracy is illustrated from specific studies in Chapter 2. This leads to a classification of flood forecasting and flood warning problems in terms of 1) the time scale of the catchment response and 2) the spatial scale of flood producing-rainfall.

This classification provides a rational framework for assessing the scope for increasing the effectiveness of flow and rainfall forecasting as well as for performing cost benefit analyses. In particular, the time scale of the catchment response determines how accurately forecasts can be made. For instance, while forecasting by flood routing is the most accurate, this cannot be applied in rapidly responding catchments. An alternative approach would be to divide forecast sites into categories of catchment type, size land use, prevalent storm type, etc. This would lead to numerous categories of forecast site. However for assessing the scope for increasing the effectiveness of forecasting and cost-benefit analyses these would each be related to the fundamental criteria 1. and 2. Furthermore, exceptions to the catchment categories can almost always be found. Thus one small rural catchment with significant groundwater contribution may react slowly while another may respond rapidly depending on slope, aquifer permeability etc. It is the time scale of the response which provides a more practical characterisation of the forecast site.

Chapter 3 reviews the factors affecting the accuracy of rainfall and flow forecasting in detail. In each case these factors are related back to the above classification. Where data are available, quantification of uncertainties based on published studies are provided. Chapter 4 lists recommendations for best current practice for each classification and recommendations for R&D activities.

2. QUANTIFYING FLOW FORECASTING AND WARNING ACCURACY

Flood forecasting is concerned with the prediction of extreme, and therefore often seldom, flood events. Recognising that significant uncertainties may exist in the observations on which these forecast are based and that hydrological modelling provides only approximate representations of the real world, then it is not possible to issue a perfect forecast.

Accuracy is best assessed by a retrospective comparison of forecast predictions and observed flows or water levels. This type of post-audit is useful for identifying weaknesses in the flood forecasting system such as insufficient data or poor model calibration. Similarly, rationalisation of the observation network can be carried out based on historical data.

For the design of a new or improved flow forecasting system, it is necessary to evaluate the impact of these uncertainties. In broad terms, the accuracy of rainfall and flow forecasts depends on the accuracy and representativeness of the observations used to prepare the forecast and the ability of flow forecasting models to accurately represent the precipitation-runoff process at the catchment scale and flood wave propagation in the river network. Major complicating factors are the inherent spatial and temporal variability of both the rainfall and the catchment properties governing rainfall response. These issues are discussed in detail in Chapter 3.

It is important to distinguish between **flood forecasting**; the technical calculation of high river flows and **flood warning**; the dissemination of a flood risk estimate to those areas and people likely to be affected. Methods for assessing existing flood forecasting and flood warning systems are reviewed below.

2.1 Flood Forecasting

The accuracy of forecasts can be evaluated by simple graphical comparison of the observed and forecasted quantities (see e.g. WMO 1992). If this is done, then the measurement accuracy should also be included in the comparison. This is particularly relevant for discharge, which is often derived from water levels using a rating curve. Nevertheless it is often most useful to provide an objective measure of accuracy. A summary of many such measures, commonly applied to forecasting, is given in Table 2.1.

It is recommended that whenever flood forecasting is carried out that such measures be used to provide an objective measure of forecast accuracy. For example, in the flood forecasting system currently in operation in Bangladesh (Refsgaard et al. 1988). 24 and 48 hour forecasts are issued daily for numerous sites along the main rivers. Following each flood season detailed performance statistics are produced for each site for 24, 48 and 72 hour forecasts.

The bias B and the relative bias RB quantify any systematic error. The variance reflects the random errors. A perfect forecast exists only if the bias and the variance are zero. MSE or RMSE is preferred to MAE as they reflect the largest deviations, which are more critical in the case of high flow forecasting. R^2 is the square of the correlation coefficient between the observed and forecasted values. Although R^2 is widely used, care must be taken if appreciable bias is present, since R^2 evaluates the accuracy with respect to random error. For flood forecasting, these statistics should be prepared for significant flood events rather than for continuous long-term records.

2.2 Flood Warning

The accuracy of flood warning can be assessed using simple warning/forecasting statistics such as those summarised in Table 2.2. The accuracy of the flood warning will depend to a large extent on the accuracy of the flood forecast but also on how well these forecasts can be converted into estimates of the inundated area. Essentially, this requires a relation between river levels and the area outside the river affected by flooding. This may be provided by an assessment of historical floods or by using topographical data. Accurate predictions of the inundated area may be difficult for extreme events where historical data are not available or where breaching of the confining channel occurs in an unpredictable manner.

The current flood warning system in England consists of severe weather or flood warnings that emanate from the Meteorological Office through the National River Authorities. The basis for issuing of warnings varies from region to region (Marshall 1991, 1992). Three levels of warning are issued to the public by the NRA; yellow phase - flood is possible, amber phase - flooding is likely and red phase - serious flooding is likely. This system has several advantages. Firstly understandable levels of risk are presented in an easily recognisable form. Phased warnings allow the public to be alerted to the possibility of flooding. This minimises the dilemma often faced by forecasters: whether to issue many, highly uncertain, forecasts well in advance of the flood or fewer, more accurate forecasts where only a limited period is available to prepare for flooding. Too many inaccurate warnings may lead to reduced public alertness. A large number of yellow phase alerts may be acceptable, however, while inaccurate amber and red phase alerts will not. Therefore efforts to improve the accuracy of forecasts and to quantify their accuracy should be concentrated on amber and red phase flood situations.

Flood monitoring

For localised storms in fast responding catchments then general warnings based on radar images followed by flood monitoring may be useful in providing accurate local warnings. Monitoring tends to give many false warnings (Reed, 1984) especially if warning levels set conservatively. In such instances, NRA staff can be used firstly to perform this monitoring after suitable warning and secondly to ensure rapid local dissemination of more severe warnings. Automated alarms activated by water level gauges or remotely from the forecasting centre may also be considered.

Table 2.1 Measures of forecast accuracy.

Definitions	**Symbol**	**Defining Equation**
Forecasted Streamflow	$Q_f(i)$	
Observed Streamflow	$Q_0(i)$	
Number of observations	n	
	M_f	$M_f = \frac{1}{n}\sum_{i=1}^{n} Q_f(i)$
	M_0	$M_0 = \frac{1}{n}\sum_{i=1}^{n} Q_0(i)$

Measures	**Symbol**	**Defining Equation**
Bias	B	$M_f - M_0$
Mean Squared Error	MSE	$\frac{1}{n}\sum_{i=1}^{n}[Q_f(i) - Q_0(i)]^2$
Root Mean Square Error	RMSE	$(MSE)^{0.5}$
Variance	V	$MSE - B^2$
Relative Bias	RB	$\frac{B}{M_0}$
Mean Absolute Error	MAE	$\frac{1}{n}\sum_{i=1}^{n}\lvert Q_f(i) - Q_0(i)\rvert$
Relative Mean Absolute Error	RMAE	$\frac{MAE}{M_0}$
Forecast Efficiency	E	$1 - \frac{MSE}{V}$
R Squared	R^2	$\left[\frac{\frac{1}{n}\sum_{i=1}^{n} Q_0(i)\,Q_f(i) - M_0 M_f}{\left(\frac{1}{n}\sum_{i=1}^{n} Q_0^2 - M_0^2\right)\left(\frac{1}{n}\sum_{i=1}^{n} Q_f^2 - M_f^2\right)}\right]^2$

Table 2.2 *Measures of forecast warning accuracy.*

	Flood Warning	No Flood Warning
Flooding Observed	A	B
No Flooding	C	D

Measure	Symbol	Defining Equation
Critical Success Index (Threat Score)	CSI	A/A+B+C
Probability of Detection	POD	A/A+B
False Alarm Rate	FAR	C/A+C

The simple advection or feature tracking methods for radar-based forecasts are known to be inadequate in representing the growth and decay, characteristic of convective storms. One alternative is to use numerical weather prediction models as the basis of precipitation forecasts. To improve the short-term accuracy of these forecasts, radar and other meteorological data can be assimilated into the predictions. This is entirely equivalent to updating procedures used in hydrological flow modelling. Typical meso-scale models such as the UK Met. Office Mesoscale models represent the storm process on a 16 km grid which is, in general, too coarse for hydrological purposes.

Significant developments in using limited area atmospheric models for weather forecasting have occurred during the past decade. This rapid development indicates that quantitative precipitation forecasting from such atmospheric models are likely to become feasible for flood forecasting applications in the foreseeable future. Indeed this area has been identified as a research topic in the EU IV Framework Programme for the Environment and Climate. Developments in this area, produced by research meteorologists, should be monitored closely.

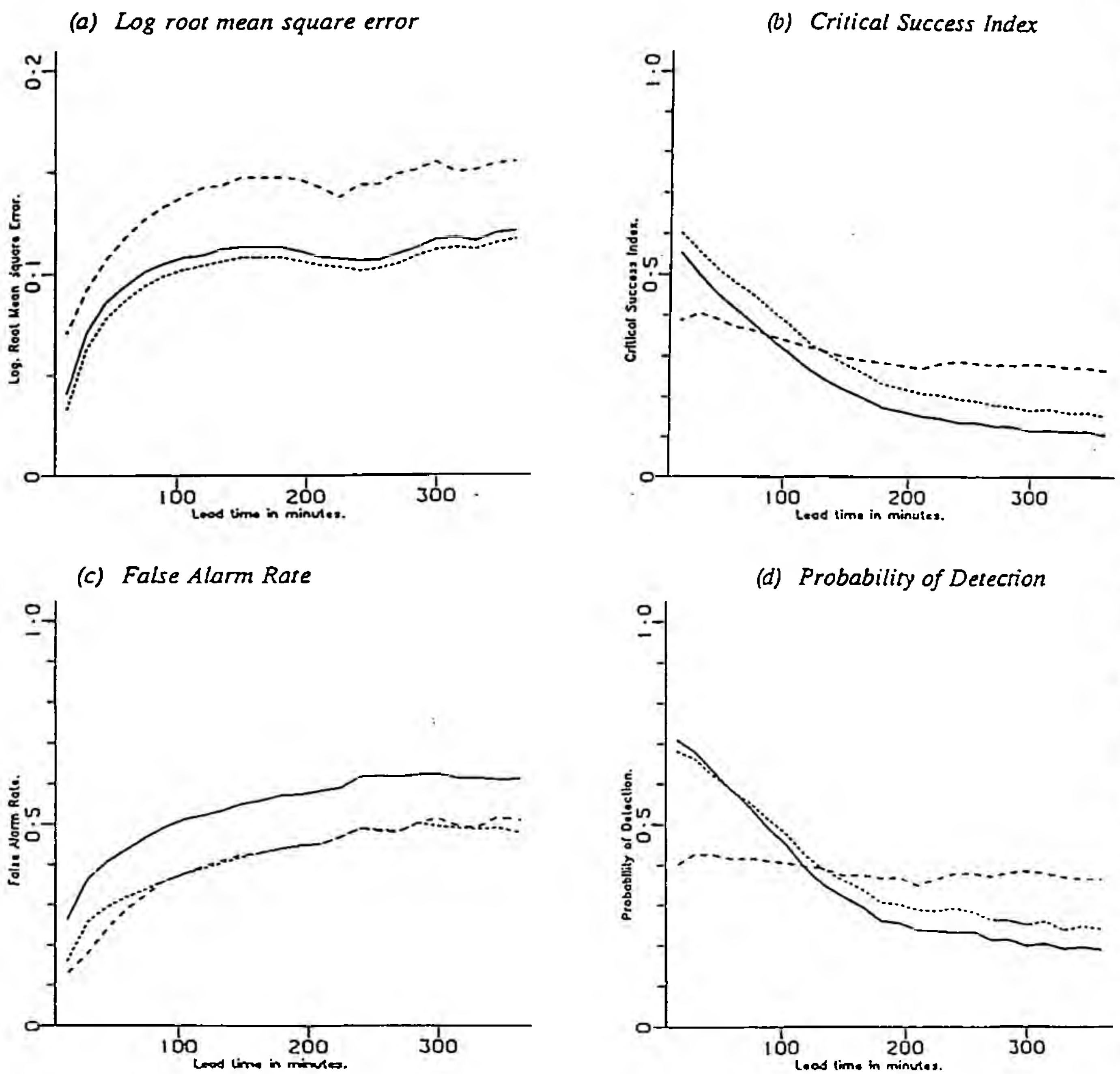
Alternative research developments combine simple cloud models with advection to provide forecast rainfall fields (e.g. Georgakakos and Bras, 1984) and this can also be combined with radar and satellite data (Seo and Smith, 1992; French and Krajewski, 1994). This approach is more suitable for representing meteorological phenomena at hydrological scales. Development and operational implementation of such systems is certainly an area where research work will be of considerable interest to hydrologists.

The value of these forecasts will depend on how quickly the forecasts can be generated, an important issue when human intervention and interpretation are to be incorporated into the forecast.

Rainfall forecasts can be used as a basis for an initial alert of possible flooding or as input to flow forecasting models.

In terms of practical application, radar-based forecasts can be produced operationally, for example, in Thames catchment, to support flood warning.

To summarise, approaches to quantitative precipitation forecasting for hydrological application include; simple forecasting based on radar data advection; full high resolution atmospheric models and simple hybrid atmospheric models. Advection-based schemes represent the operational state-of-the-art whereas the remaining two approaches are the subject of ongoing research. The application of quantitative precipitation forecasts is nevertheless very relevant for small rapidly responding urban catchments where there is a potential for substantial benefit. Whether these benefits can be realised in an operational system has yet to be adequately assessed. The skill scores presented in Figure 3.1 could be used as a preliminary basis for calculating the benefits of rainfall forecasting for the Thames catchments.



Rainfall accumulation forecast error statistics, averaged over 14 storm events, for different lead times: radar data as truth (continuous line: 2 km local forecast; short dashes: 5 km local forecast; long dashes: Frontiers forecast)

Figure 3.1 *Rainfall forecast error statistics as a function of lead time from CEC, 1994.*

3.2 Accuracy and Representativeness of Rainfall Observations

The accuracy of the rainfall observations depends on

1. measurement accuracy of the precipitation by raingauge, radar, etc.

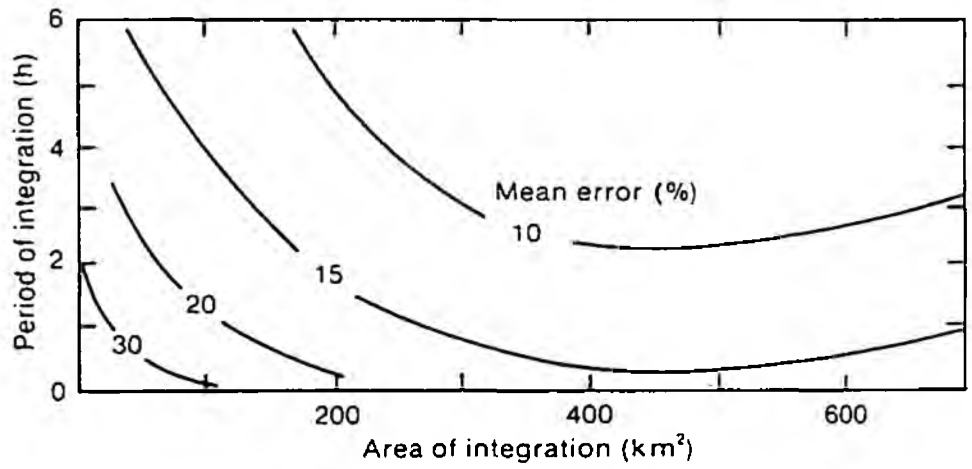
2. representativeness of a raingauge network or radar of the spatial and temporal distribution of rainfall.

The temporal and spatial resolution of flood producing storms is discussed in Sections 3.2.1 and 3.2.2 respectively. Section 3.2.3 considers the measurement accuracy of precipitation measurement from raingauges, radar and combinations of these, including a brief discussion of the various possibilities for ground truth.

3.2.1 Temporal resolution of flood producing storms

The required temporal resolution of rainfall measurements will depend on the response time of the catchment. This will be critical for short term high intensity events (convective or frontal rainfall) in urban catchments where concentration times are very short. In such cases, it is important to provide rainfall measurements at intervals of 15 min or less, with forecasts every at least 1/2 hour to incorporate streamflow measurements in updating. Limiting factors will be the reporting interval and tip size for telemetered raingauges and the reporting time and processing time for radar images. However these probably do not present any real limits in current operations provided data processing is sufficiently automated.

The accuracy of radar estimates of areal rainfall increase as the period over which the intensity is averaged increases. This is illustrated in Figure 3.2 from Collier, (1989), for a radar calibrated using a single raingauge.



Mean error (without regard to sign) in the measurement of areal rainfall using a radar calibrated against a single raingauge, plotted as a function of the area and period of integration. (From Collier 1977.)

Figure 3.2 *Error in areal rainfall as a function of area and period of integration from Collier, 1989.*

3.2.2 Spatial scale of flood producing storms

When the spatial scale (L_m) of the meteorological event is significantly less than the spatial scale (L_c) of the catchment then the accuracy of forecasts assuming uniform rainfall will deteriorate. The catchment response will then depend on the location and path of the flood producing rainfall storms. This will be a problem for large catchments and for smaller catchments during intensive convective storms.

The best forecasting approach in this situation will depend on the catchment response time scale. For larger catchments then the optimal strategy is to partition the basin with discharge stations on the major tributaries and either an extensive network of raingauges or radar/satellite remote sensing. The upstream channel inflows can be forecasted on the basis of observed rainfall. The downstream channel can then be forecasted from these forecasted stream flows or for case III (see Table 2.3), from the observed streamflows. The choice between radar and raingauges will depend on the catchment size, the number of forecasting points and the ability of radar to cover the catchment area. In general, radar will not be used alone but with complementary raingauges for adjustment and backup.

For smaller catchments with a rapid rainfall response, subject to small-scale convective storms and thunderstorms then substantial benefits from forecasts are most likely in population centres. To resolve the high degree of spatial variability in such storms, an optimal raingauge spacing could be estimated from the spatial scale of the storms and their average velocity although both are highly variable. Here it should be pointed out that radar provides two types of information that cannot be obtained from a classical raingauge network, namely a quantitative precipitation forecast and a detailed areal distribution of rainfall. Therefore there are strong arguments for the application of radar in this type of urban forecasting problem.

It is useful therefore to compare the accuracy of radar with that attainable from gauge networks of different densities. (see Figure 3.3). Adjusted radar hourly rainfall totals are compared to number of raingauges in a 1000 km^2 area as part of the Dee Weather Radar Project, (from Collier, 1989). While the radar accuracy are nearly independent of rainfall type, the accuracy of raingauge networks depend critically on rainfall type. Such curves can be used to carry out cost benefit analyses comparing calibrated radar and raingauge networks. Such results should be applied with caution to other areas where such factors as the prevalence of storm types, the size of catchment, the quality of radar image will change the relative accuracies. Furthermore, if the raingauge network is too sparse, then it may not be sufficiently representative to provide accurate adjustment. This is illustrated in Figure 3.2 where the mean error of mean areal rainfall from a radar calibrated with a single gauge is plotted as a function of area and averaging period. Accuracy decreases when the adjustment gauge is no longer representative of the larger area. This type of figure can be used to determine the optimum density of calibrating raingauges.

Bras and Rodriguez-Iturbe (1985) formulate a method for the design of precipitation networks that includes the multidimensional correlation structure of the rainfall process. The spatial correlation is used as a measure of the spatial scale of the flood producing storm. Correlation structures for storms are taken from published studies, however, these vary considerably with the type and intensity of storm.

Application of this type of approach presumes detailed knowledge of the magnitude, type and spatial characteristics of the storm. If this cannot be obtained from existing networks or data from similar climate regions, then a raingauge network must be installed. Indeed in their analysis of convective storms, Bras and Rodriguez conclude that accuracy estimates vary significantly with correlation structure and storm areal rainfall estimates are much more sensitive than long-term mean areal rainfall estimates to gauge density. Therefore a network designed for storm rainfall will be more dense than one designed for mean areal rainfall.

A more operational approach is to install a dense network of rain gauges, after which those that do not significantly alter storm rainfall depths or streamflow forecast results are removed. This is shown for a flood forecasting problem in India in Figure 3.4 (DHI/CWC, 1983). Here, the effect of the network density on flood discharges rather than rainfall totals is examined. Where possible, this approach is preferable because the catchment and model characteristics are included in the evaluation. The optimal accuracy is dependent on whether the peak volume or peak discharge is of interest. Since peak discharge is usually of most interest in flood forecasting a significantly larger raingauge density is required. This confirms the observation above that more dense raingauge networks are required in flood forecasting applications.

Figure 3.5 shows the measured accuracy obtained in a recent analysis of storm rainfall (CEC, 1994). Here an optimal raingauge density can be readily identified for a raingauge network alone and combined raingauge and radar data. Since the results are given for a 60 km^2 area, the horizontal axis can be related to gauge density. Figure 3.3 also compares radar and raingauge network accuracy differentiating according to storm type.

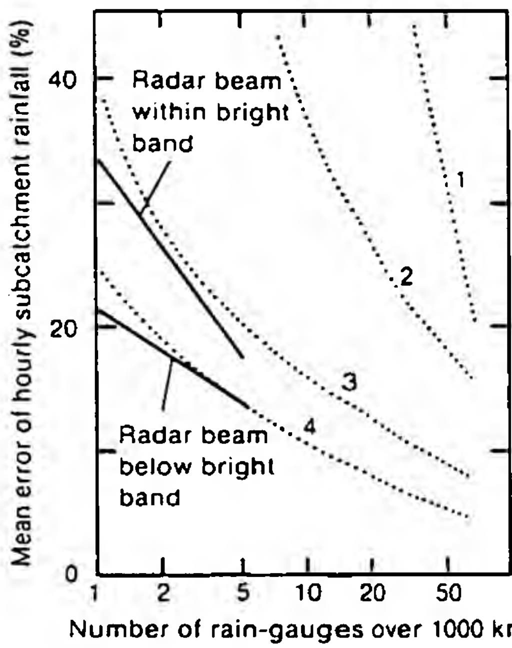
These data can be used to support a cost-benefit analysis comparing raingauge networks and radar-raingauge networks. These figures should be used with caution as such effects as bright band and band infill may reduce radar accuracy for individual events and the role of complementary raingauges becomes more important.

Such studies provide estimates of optimal accuracies for particular forecasting problems but do not address the problem of defining an acceptable accuracy. This will depend on the catchment area and type. The acceptable accuracy for larger slowly responding catchments may be quite low compared to small flashy catchments. In general, it is not possible to specify an acceptable accuracy, quantitatively, for a given network and flow forecasting system.

In the absence of other information, design curves such as that shown in Figure 3.6 can be used to design a forecast network or as a guideline for improving the network. Where rainfall data exist, the spatial characteristics of the storm rainfall can be evaluated using subnetworks to determine whether the network should be reduced or increased and how sensitive the storm rainfall is to gauge density. Where flood warning is based directly on measured rainfall then installation of a dense network and subsequent rationalisation is required. This rationalisation may include finding the minimum number of complementary raingauges for use with radar images.

From an operational standpoint, it appears that quite comprehensive raingauge and radar networks exist. Three of ten regions at that time (Marshall 1991 and 1994), however, base their warnings directly on rainfall, in which case a review of the accuracy and representativeness of the network would certainly improve the effectiveness. Similarly, a comparison of radar results with the reporting raingauges could be used to rationalise the network.

In terms of cost-benefit, it is relatively straightforward to determine the costs of either radar or raingauge coverage. As pointed out earlier, radar will seldom be used without complementary raingauges, and this should be included in a cost-benefit study. However, as discussed above, determining quantitatively whether the resulting accuracy is satisfactory is less straightforward. Instead, the studies above can be used to determine cost-benefits for a fixed accuracy. This comparison will be most critical for urban catchments which rapidly respond to localised intense rainfall where the spatial resolution of a raingauge network will be limiting.



Mean error of the hourly rainfall totals in river subcatchments of average area 60 km^2 as determined from radar measurements in various kinds of rainfall conditions, plotted as a function of the number density of adjusting raingauge sites (———). Also shown for comparison is the mean error of the hourly subcatchment totals as determined from a network of raingauges in the absence of radar, again plotted as a function of the number density of raingauge sites (·········). The set of four dotted curves represents the measurement errors for the raingauge network in the presence of extremely isolated showers (curve 1), typical showers (curve 2), typical widespread rain (curve 3) and extremely uniform rain (curve 4). For all curves the mean error is defined as the mean value of the difference between the estimated rainfall and the 'optimum estimate' without regard to sign. (After Collier 1977; from 'Browning 1978.)

Figure 3.3 *Accuracy of radar and raingauge networks for different storm types from Collier, 1989.*

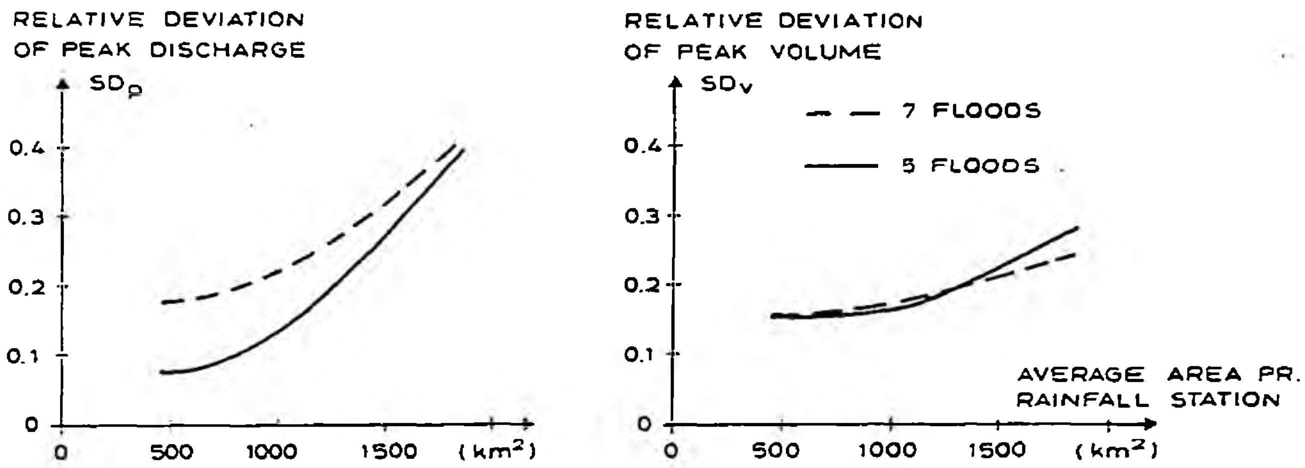
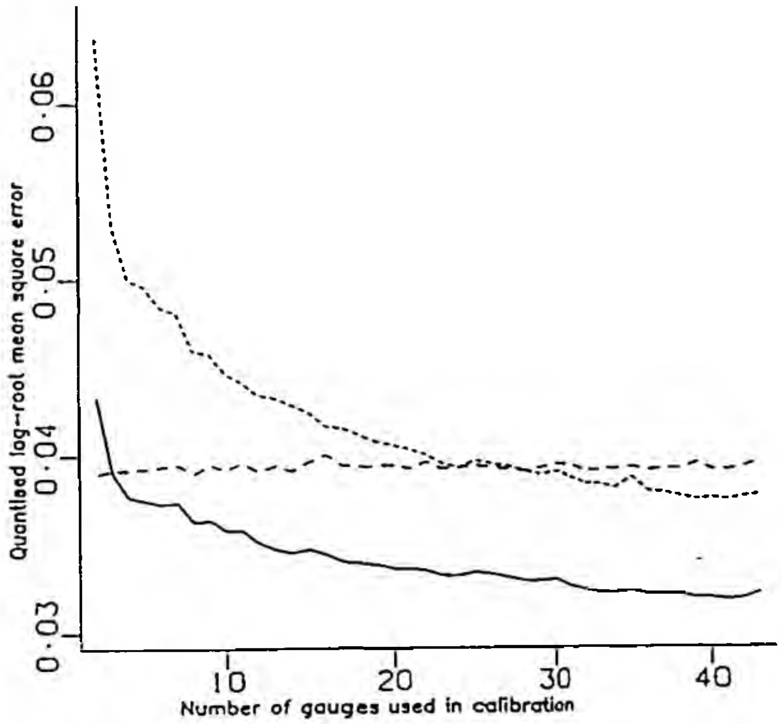
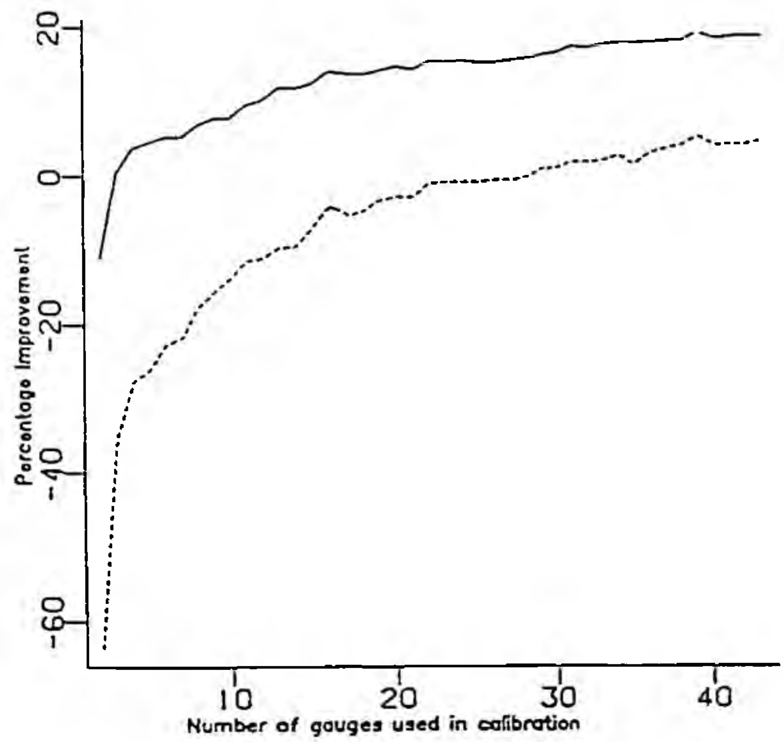


Figure 3.4 *Discharge forecast accuracy as a function of raingauge network density, from DHI/CWC, 1983.*



The effect of number of gauges on rainfall estimation accuracy. Results averaged over 13 events. Continuous line: calibrated radar; short dashes: raingauge-only; long dashes: uncalibrated radar.



Percentage improvement in performance of raingauge-only (dashed line) and calibrated radar (continuous line) estimates of rainfall, relative to uncalibrated radar, as a function of number of raingauges in network. Results averaged over 13 events.

Figure 3.5 *Accuracy of radar and raingauge networks for a 60 km2 area in the Thames region, from CEC, 1994.*

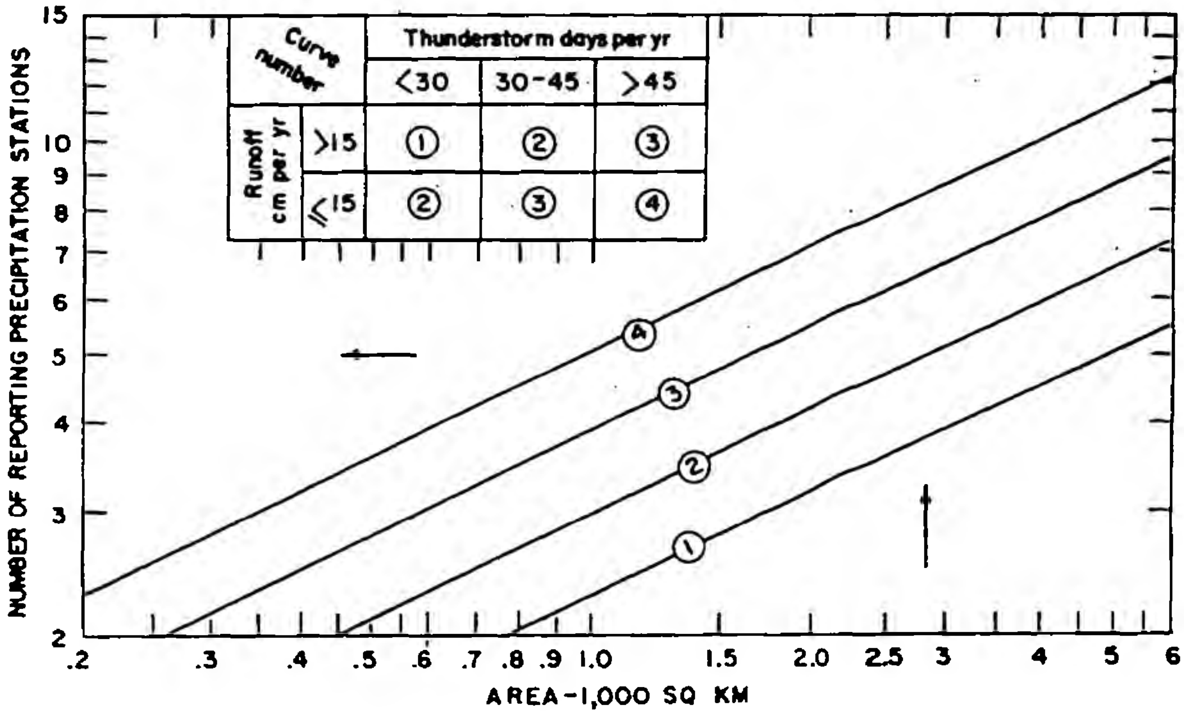


Figure 3.6 *Raingauge network design curves for forecasting applications, from Nemec, 1986.*

3.2.3 Rainfall measurement precision

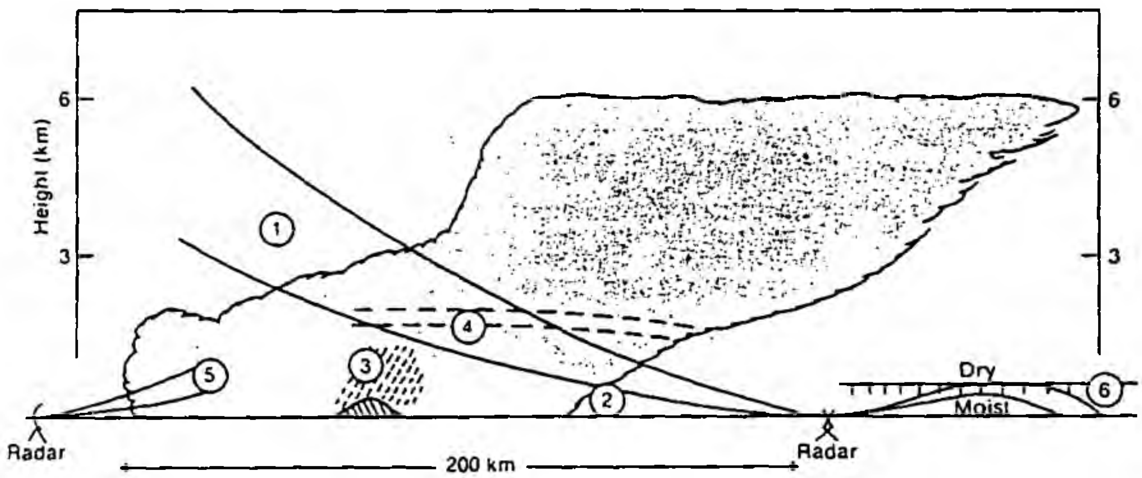
There is, of course, in hydrological forecasting a critical need for accurate measurements of precipitation. The choice of site, the form and exposure of the measuring gauge, prevention of evaporation losses and effects of wind and splashing. For details of the practical aspects of obtaining the optimum conditions for operating rainfall gauges, the reader is referred to WMO,1994.

A thorough description of radar-based precipitation measurement is given in Collier, 1989. A thorough review and assessment of radar precipitation measurement will be provided in a forthcoming complementary R&D note. The purpose of this section is to briefly summarise the type and magnitude of uncertainties that arise in radar and raingauge precipitation measurements. The main sources of error in radar measurements are summarised in Figure 3.7 taken from Collier, 1989. Perhaps the most serious of these, under UK conditions are **bright band**; the presence of a phase change between ice and water in the vertical and **low-level precipitation growth** or evaporation over hills exposed to moist maritime air found typically in the western parts of the UK. Collier (1989) suggest that bright band leads to overestimation of precipitation by 500-600%. Experience indicates that the bright band can be reliably identified but that corrections to the precipitation rate are less reliable.

Raingauge data are often used to adjust radar measurements, recognising that the spatial and temporal distribution of raindrop size is so great and the vertical profile of reflectivity is not known in real time. The accuracy of radar areal estimates of rainfall adjusted by raingauges for a number of studies are summarised in Figure 3.8. However, as pointed out in the previous section, the presence of highly localised rainfall not adequately captured by the adjustment raingauge network may lead to incorrect adjustments.

In general, because of the above-mentioned limitations in radar accuracy, it is unlikely that radar will be used without complementary raingauges either for adjustment or backup should radar data not be available. The best combination of these data will depend to a large degree on the spatial scale of the flood producing storms, (see Figure 3.5).

Alternative sources of ground truth for radar adjustment include distrometers or vertical pointing radar. Such approaches are very much the subject of current research. Research involving a preliminary evaluation of the application of distrometers is reported in CEC, 1994. The development and application of vertical pointing radar for correcting for bright band is currently being pursued at the University of Salford. These issues will be addressed in detail in a forthcoming R&D note.



Schematic representation of the problem areas associated with the meaurement of precipitation by radar: 1, radar beam overshooting the shallow precipitation at long ranges; 2, low-level evaporation beneath the radar beam; 3, orographic enhancement above hills which goes undetected beneath; 4, the bright band; 5, underestimation of the intensity of drizzle because of the absence of large droplets; 6, radar beam bent in the presence of a strong hydrolapse, causing it to intercept land or sea. (From Browning 1978.)

Figure 3.7 *Main sources of error in radar-based precipitation measurement from Collier, 1989.*

Figure 3.8 *Table containing uncertainties in raingauge adjusted radar estimates compared to raingauge networks reproduced from Collier, 1989.*

Radar areal estimates of rainfall utilizing raingauges for adjustment (mostly after Wilson and Brandes 1979)

Reference	Location	Rain type	Radar λ (cm)	Radar θ (deg)	Relation between Z and R	No. of cases	Observation frequency (min)	Radar range (km)	Area size (km^2)	Duration (h)	Adjustment Type[a]	Adjustment Gauge density (km^2 gauge^{-1})	Error Before adjustment (%)	Error After adjustment (%)	Error using calibration gauges only (%)
Wilson (1970)	Oklahoma, USA	Thundershowers	10	2	$KR^{1.6}$[b]	23	5–10	35–100	3500	Storm	A	3500	51	35	60
											A	1200		30	31
											V	1200		27	31
Brandes (1975)	Oklahoma, USA	Thundershowers	10	2	$200R^{1.6}$	9	5	45–100	3000	Storm	V	900	52	13	21
											V	1600		14	24
											A	900		18	21
Woodley *et al.* (1975)	Florida, USA	Showers, thundershowers	10	2	$300R^{1.4}$	39	5	85–115	570	24	A	1600[c]	43	30	—
Harrold *et al.* (1974)	England, UK	Showers, stratiform	10	2	$200R^{1.6}$	27	1	12–48	50–100	1	A	500	—	19	48[d]
Wilson (1975)	New York, USA	Showers, thundershowers, stratiform	5	1.7	$300R^{1.6}$[c]	41	10	95–112	170	24	V	275	49	22	22
Collier *et al.* (1975)	England, UK	Showers, stratiform	10	1	$200R^{1.6}$	13	1	12–48	700	3	V	233	—	7	—
Jatila and Puhakka (1973a,b)	Finland	Showers, thundershowers	3	1.8	$200R^{1.6}$	6	5	18–28	180	Storm	A	180	43	23[f,g]	—
Huff and Towery (1978)	Illinois, USA	Showers, thundershowers	10	1	$300R^{1.35}$	67[h]	3	20–100	5300	0.5	V	150	55	27	32
Collier (1986a)	England, UK	All types	5	1	$200R^{1.6}$	All data for a year	5	5–75	16	1	V	1300	60	45[i]	—
													100	75[j]	—

[a] A, average adjustment; V, variable spatial adjustment.
[b] Radar estimates adjusted to remove average bias for the total experiment.
[c] Density of raingauge cluster is approximately eight gauges per cluster. Clusters outside area of measurement.
[d] Adjustment gauge not within area of measurement but is 10–20 km distant.
[e] Additional multiplicative factor of 1.7 applied to radar estimates.
[f] Varied coefficient in relationship between R and Z to match point rainfall at central gauge.
[g] Error when observed drop size distribution used is 98%.
[h] Number of 30 min periods in four storms.
[i] No bright-band effects.
[j] With bright-band effects.

3.3 Accuracy and Representativeness of Flow Forecasting Models

Four sources of uncertainty occur in deterministic flow modelling.

(1) Random or systematic errors in the model inputs or boundary condition data, e.g. precipitation or upstream discharge.

(2) Random or systematic errors in the recorded output data.

(3) Errors due to suboptimal parameter values, i.e. inadequate model calibration.

(4) Errors due to incomplete or biased model structure, i.e. the model does not adequately represent the physical system.

The uncertainties in the input and output data are discussed in Sections 3.2 and 3.4 of this chapter. A related issue is, how these uncertainties in the input propagate through the flood forecasting system and how large are these uncertainties compared to the errors in the forecast model due to poor calibration or inadequate model structure. This is addressed in Section 3.3.3

The accuracy and representativeness of the flow forecasting models are examined below.

3.3.1 Forecasts based on channel routing

In many of the longer rivers in Great Britain, satisfactory warnings can be based on a suitable upstream gauging station (Reed,1984). This is reflected in the results of the reviews of forecasting approaches applied in the NRA regions (Marshall, 1991 & 1992), which show that the vast majority of regions apply correlation methods for flow forecasting. For this approach to be successful, the travel time from the upstream gauging site to the forecast site should be sufficient to give accurate warning, 4-6 hours according to Reed, 1984.

The accuracy of the flow forecast will depend on the accuracy of the upstream discharge or water level measurements, the representativeness of the upstream site and the type of flood routing. The accuracy and representativeness of the upstream measurements are discussed in Section 3.4.

The lead time of the forecast can be increased considerably by combining flood routing with suitable rainfall-runoff approaches. The upstream station can then be used as an updating point which should significantly improve the accuracy of the forecast.

Two broad classes of river routing can be defined; hydraulic models and hydrological models.

Hydraulic routing models

The routing of water down a river channel is described by one-dimensional hydrodynamic equations of unsteady flow, known as the St. Venant equations (Chow et al., 1988). Solutions of the full St. Venant equations are referred to as dynamic wave models. Approximations to these equations known as the kinematic and diffusion wave equations are also used. These equations are generally solved numerically.

Dynamic wave models are most applicable for the following cases;

1. Upstream movement of waves such as tidal action or storm surges.

2. Backwater effects caused by downstream reservoirs and tributary flows.

3. Rivers with extremely flat bottom slopes e.g. $S << 0.005$.

4. Abrupt waves caused by rapid reservoir releases or dam failures or abrupt changes in velocity caused by river regulatory works.

The models have the advantage of being generally applicable and can also be used for flood protection design and similar river works. Calibration methods for dynamic wave models are given for example in Cunge et al, 1980.

The main disadvantage of such models is the data requirements in terms of topographical data for channel and flood plain geometry and historical or survey data for specifying roughness coefficients.

The diffusive wave equations are obtained by neglecting inertial terms in the St. Venant equations (Chow et al, 1988) so that backwater but not tidal effects can be treated. Further simplification (Chow et al, 1988) leads to the kinematic wave formulation, applicable to rivers without significant backwater effects and slopes greater than about 0.001.

In all but the simplest river systems, tributary and lateral inflows must be accounted for. This presents problems only when these are not gauged. If rainfall data is available then these can be determined from a rainfall/runoff model. Model parameters can be estimated from similar catchments. Alternatively, a proportion of the flow from a neighbouring gauged catchment may be applied. Such approaches should be adequate provided these tributaries or inflows represent only a small portion of the flood hydrograph.

Hydrological routing models

A wide range of methods fall under this category; impulse response function (Goring, 1984) and related transfer function models (see e.g. Cluckie, undated), Muskingum (Dooge, 1973) and Muskingum-Cunge (Reed, 1984), linear reservoirs, cascade of linear reservoirs, lag and route methods. While correlation methods fall under this general category these are treated as a third, separate category in this report. Reed (1984) provides a useful review of both the correlation and Muskingum approaches used in the UK.

It is beyond the scope of this report to review in detail these various approaches. Instead, it is useful to compare the disadvantages of the simplified hydrological routing models with the hydraulic routing approach. Reed, (1984) provides a useful summary reproduced in Table 3.1 that is still generally valid today.

The following recommendations for best practice can be made for forecasts based on river routing.

- Flood routing is the preferred method of forecasting where this is practical. While the simple correlation methods may be useful, more accurate forecasts will be obtained from the shape and timing of the flood hydrograph resulting from a flood routing model.

- Correlations and in many cases manual correlations are still in widespread use, (Marshall, 1991 & 1992). Flood routing is preferred and should replace correlation approaches.

- Full solutions of the St. Venant equations will be useful under UK conditions where flood hydrographs are affected by; upstream movement of waves such as tidal action or storm surges; backwater effects; and for abrupt changes in velocity caused by river regulatory works.

- The relative merits of the various hydrological routing models are not discussed in detail. The main argument in favour of these approaches is that a particular application does not require the accuracy provided by the complete models. A judgement as to whether these simplified models are appropriate depends on a thorough knowledge of the behaviour of the river reach.

- Reed (1984) suggests that if the accuracy of the inflow data is the limiting factor rather than the adequacy of the routing model, such approaches may be appropriate. In this case, then, the most useful improvement would be to improve the flow measurement accuracy.

- A state-of-the-art review of river flood forecasting for the NRA, Marshall (1991 & 1992) shows that forecast levels were based on upstream levels in six out of the ten NRA regions that existed at that time. Five regions use correlation methods (often manually), and three use routing calculations. Two of these last three, in fact, use both routing and correlations. There is, therefore, considerable scope for the introduction of both hydrological and hydraulic routing models to make optimum use of the measured upstream water levels.

Table 3.1 *Merits and limitations of simplified routing models*

Advantages

1. In many applications of gradually-varied unsteady flow modelling, the acceleration terms in the momentum equation are negligible in comparison with other terms.

2. In most simplified methods, channel geometry does not need to be defined in detail. There is no requirement to assess roughness coefficients throughout the reach.

3. Simplified models may provide answers in much less time than solution procedures based on the complete equations. This is not so relevant given the speed of modem computers. Programming for computer solution is simple; some storage routing methods are simple enough for hand or graphical computation.

4. A given organization may have accumulated considerable expertise with a particular simplified method, whereas use of a complete model may be unfamiliar and difficult to assimilate.

5. The application often does not require the accuracy provided by the complete model. The accuracy of inflow data may be the limiting factor, rather than the adequacy of the routing model itself.

Disadvantages

1. Velocity changes must be small along the channel, since most simplified models exclude acceleration terms. Generally, simplified models cannot allow for backwater or draw-down effects produced by tributary or tidal interactions.

2. A large amount of measured inflow and outflow data is required to calibrate the parameters of simplified models. Any situation different from those found in the calibration data may not be accurately represented.

3. Simplified methods generally do not have the accuracy of a solution procedure based on the complete equations. There is sometimes doubt about how accurate the results are for any application. Simplified methods are generally only able to produce results for known points (eg. gauging stations) whereas complex models can produce levels at intermediate points.

4. The results from simplified models can be particularly sensitive to the time and distance increments adopted.

5. Generally, storage in a reach is not a unique function of known inflows and outflows.

6. Simplified methods may lack the desired generality.

3.3.2 Rainfall-runoff models

There is a vast range of forecasting models for river discharge based on rainfall inputs. One approach to classifying these approaches is presented in Figure 3.9. These categories are by no means mutually exclusive and a particular model system may cover several categories. During the last decade, there has been an increasing interplay between the stochastic and deterministic methods and a joint stochastic-deterministic provides a useful framework for addressing fundamental issues such as spatial variability (scale problems) and assessing modelling uncertainties.

Deterministic models can be classified according to whether the model gives a **lumped** or **distributed** description of the considered area and whether the description of the hydrological processes is **empirical**, **conceptual** or more **physically-based**.

Empirical models can be further divided into the following subcategories.

Empirically hydrological methods. The best known of these is the unit hydrograph model and models applying similar principles (Nash 1955, Sherman 1932). Also included in this group are the non-linear storage models such as the ISO models (Lambert 1972) and IEM models (NERC, 1975)

Statistically based methods. Examples of such models include ARIMA (Autoregressive Integrated Moving Average) models (Box and Jenkins, 1970), CLS models (Todini and Wallis, 1977) and API (Antecedent Precipation Index) model (e.g. WMO, 1994).

Transfer function models. These are based on a general statistical framework developed in linear systems analysis and are fundamentally related to the unit hydrograph approach (Chow et al, 1988). More recently, a newer group emerging from the field of hydroinformatics are techniques based on neural networks and evolutionary algorithms. As yet the practical application of such methods has been limited.

Lumped conceptual models such as the Stanford modelling system (Crawford and Linsley, 1966, Hydromp 1975) operate with different but mutually related storages representing physical elements in a catchment. As the parameters and variables represent catchment averages in a lumped description the equations are semi-empirical but physically based.

Distributed Hydrological models. Today several general purpose catchment models based on the governing partial differential flow equations exist; SHE (Abbott et al, 1986), MIKE SHE (Refsgaard and Storm, 1995), IHDM (Beven et al, 1987) and THALES (Grayson et al, 1992). Generally the detailed description of water movement in such models and the treatment of the spatial variability of catchment properties (such as soil heterogeneity), are not called for in flood forecasting applications. However, it may be important to properly treat the spatial distribution of rainfall correctly where $Lm/Lc << 1$. (case i). Here, Lm is defined as the spatial scale of the meteorological event and Lc is the spatial scale of the catchment. This is supported by theoretical studies (such as Davis and Nnaji, 1982; Troutman, 1983) that show significant variations in the flood hydrograph depending on the location of the raingauge and storm in such cases.

To address this issue, several types of semi-distributed models have been developed. One approach applicable to larger catchments is the division of the river system into a series of catchments or subcatchments connected to the river network. Each subcatchment is modelled using some form of rainfall-runoff model that provides lateral inflow or tributary flow that is then routed through the river network. Several of the conceptual models can be structured in this manner, applying simplified routing methods, although such approaches are often difficult to apply to dendritic river networks.

More recent developments have recognised that, with access to weather radar data, a much greater spatial resolution of rainfall events can be obtained. Moore et al (1994) present a distributed model based on digital terrain maps and simplified process equations discretized on the same spatial grid as the incoming radar images. The main advantage is a better representation of the spatial variability of the rainfall. Cluckie (undated) describes two variants of this type of distributed model. The first, based on transfer functions, is a multiple input single output approach. The second is a grid-based approach designed for radar rainfall input based on a combination of ISO rainfall-runoff models and transfer function routing.

It is not the intention of this review to discuss and compare each model in detail but rather to compare the advantages and disadvantages of model types in the main categories.

As a conceptual model attempts to represent the various hydrological processes such as interception baseflow, etc. during a flood event it might be expected to provide more accurate hydrological predictions than time series based approaches. Nevertheless time series models with no physical basis can often produce equally good forecasts. The conceptual model results are only as good as the conceptual representation of the actual catchment processes.

For forecasting applications lumped conceptual models are preferable to most of the empirical models, particularly the empirically hydrological and statistical based methods. This is consistent with DHI experience, (see for example Figure 2.3) which suggests that conceptual models by including a representation of the catchment behaviour provide improved accuracy for longer lead times. For short forecast lead times, these two model types are comparable. Similar conclusions were reached by Kitandis and Bras, (1978).

Operationally, it appears that transfer function and lumped conceptual models are either under development or in use in several regions. There is little to suggest that results from these two model types will be significantly different provided they are adequately calibrated. The advantage of employing rainfall-runoff is the increase in lead time. As pointed out earlier, several regions employ upstream levels for forecast prediction downstream. An increase in lead time can be achieved by introducing rainfall-runoff modelling and using updating on the upstream level to improve the model accuracy.

DHI's general experience with application of lumped versus distributed hydrological models suggest that with traditional, relatively sparse, raingauge networks, that fully distributed models do not significantly outperform lumped, conceptual models. This is supported by the results of a recent model intercomparison study (DHI, 1993) based on six catchments in both Denmark and Zimbabwe ranging in size from 40-1000 km^2 and representing a wide range of climate, hydrology, and catchment characteristics. The modelling performance and predictive capabilities of three models, NAM (a lumped conceptual model), SHE (a fully distributed physically-based model), and WATBAL (a hybrid model using a distributed surface water modelling with a lumped groundwater component) were examined. For the lumped model NAM, catchment average rainfall was used, whereas SHE and WATBAL could use the available spatial distribution of the rainfall. The distributed models do not however significantly outperform the NAM model. For larger catchments a semi-distributed approach is nevertheless recommended. (see Table 3.2).

Table 3.2 Classification of storm type and corresponding rainfall-runoff approach

Category	Spatial scale of flood producing storms	Flow forecasting approach
(i)	$Lm/Lc << 1$	Semi-distributed rainfall-runoff modelling
(ii)	$Lm/Lc \approx 1$	Lumped rainfall-runoff modelling

Recent research, however, on catchments with very high resolution rainfall data indicate that distributed models may, in certain cases, provide improved results compared to lumped models. Michaud and Soorooshian, (1994), compare a complex distributed model (KINEROS), a simple lumped model (SCS) and a simple distributed model based on the lumped model for a semiarid test catchment with a relative dense raingauge network. They conclude that the spatially lumped model performed very poorly compared to the simple distributed model approach. These results were obtained on a flash flood prone catchment with lead times of 30-75 minutes subject to severe thunderstorms where $Lm/Lc << 1$, so the spatial distribution of rainfall becomes important.

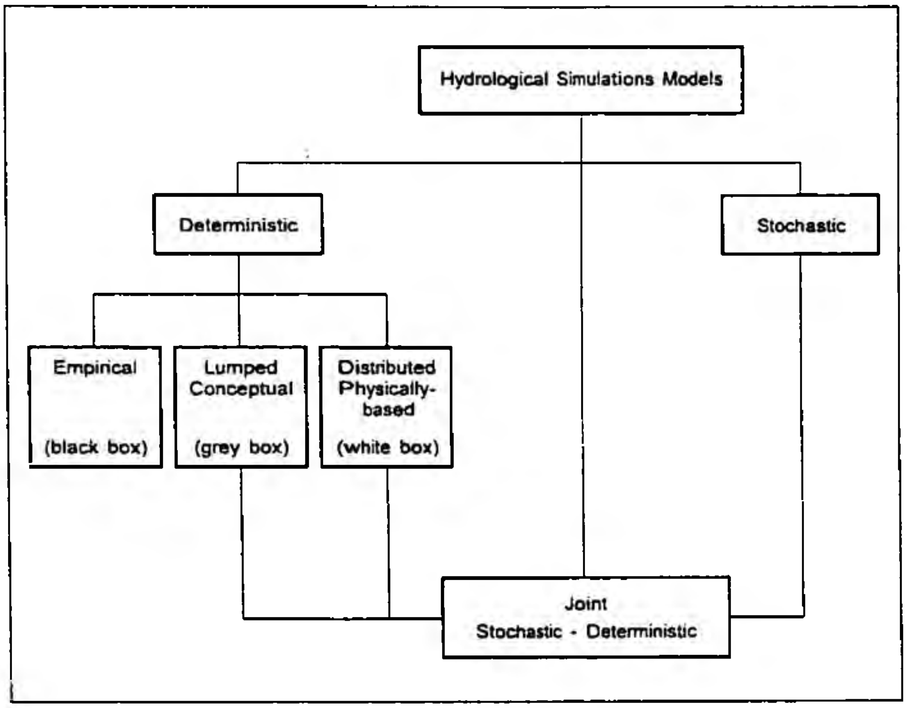


Figure 3.9 *Classification of hydrological models according to process description.*

3.3.3 Hydrological model calibration and reliability

In model calibration, an estimation is made of the parameters which cannot be assessed from field data. This is achieved either by (1) manual trial-and-error, or (2) automatic optimisation procedures, or a combination of these. A thorough discussion of automatic calibration and associated problems is given in Gupta and Sorooshian (1985) and Sorooshian et al (1993). While automatic calibration was used extensively during the 1970's, it is now recognised that there are several disadvantages with these techniques.

1. The criterion to be optimised has to be a single numerical quantity. An appropriate quantity may be difficult to select.

2. Models with many parameters may produce several local optima instead of a global optimum.

3. It is often assumed that the model parameters are mutually independent but this is often not the case.

4. Automatic routines may attempt to compensate for data errors by adjusting model parameters resulting in physically unrealistic values.

Testing of the calibration or validation of a hydrological model is discussed in detail by Klemes (1986). The process of calibration and validation should provide a good indication of how well the model represents the hydrological processes involved. An important point to note is that if the model is to be used for flood forecasting, then calibration and validation should focus on reproducing flood hydrographs particularly the rising stage of hydrograph, where the accuracy of predictions is most critical.

Much information regarding the robustness or sensitivity of a hydrological model is also obtained during the calibration process.

The propagation of uncertainties in hydrological and hydraulic models is the subject of much current research. (Beven and Binley, 1992, Moore, 1995, Melching et al, 1990, Schaarup-Jensen & Hvitved-Jacobsen, 1994). The usual approach is to combine a statistical or stochastic description of the measurement and model uncertainties with a deterministic model of the flow problem.

The most straightforward approach is to use sensitivity analyses such as those carried out by Salomonson et al (1975) and Yeh et al (1978) to determine the effect of parameter uncertainties for the Stanford and Sacramento watershed models respectively.

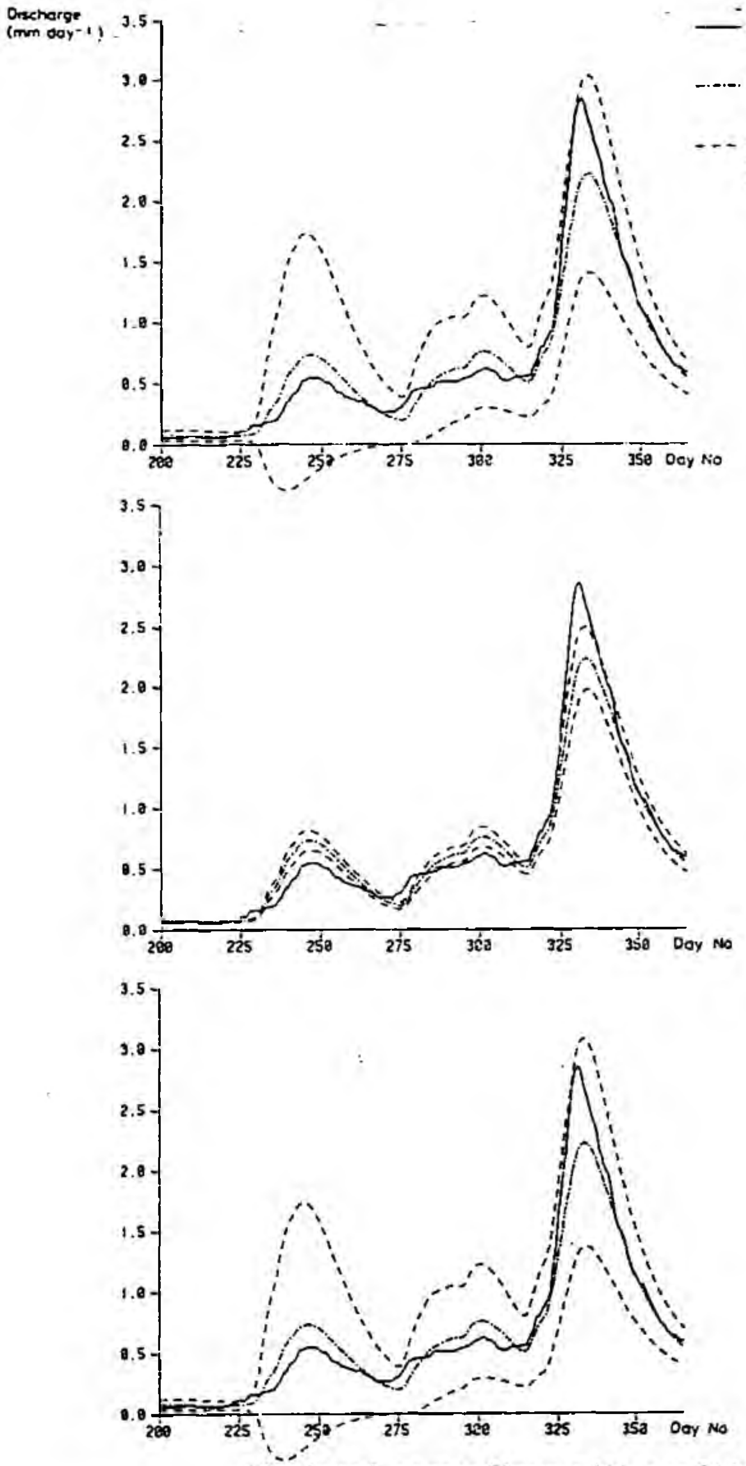
Kalman filtering and state space theory developed within the field of statistical control theory (Gelb, 1974) has been widely applied in hydrology. The key model parameters and input variables are treated as statistical variables described by their mean and variance. Combinations of kalman filtering and lumped conceptual rainfall-runoff models have been applied by (Kitanidis and Bras, 1978, Georgakakos et al, 1988) for the Sacramento model and (Refsgaard et al, 1983, Storm et al, 1988) for the NAM model.

The most general approach to this problem is the Monte-Carlo method, where the statistical distributions of the model parameters and input variables are sampled and used to drive the deterministic model. This process is repeated until stable statistics of the output, such as the mean and variance, can be generated. This approach requires significant computing resources and is therefore impractical in forecast situations.

Mean value first-order second moment analysis (MVFOSM) has been applied to runoff prediction errors by Garen and Burges (1981) and Kuczera (1988). Melching et al (1990) provide a general framework for estimating runoff reliability for such methods as the Monte Carlo and MVFOSM methods and applies this framework to uncertainties in flood forecasting caused by parameter uncertainty in the HEC-1 model.

Another general framework is provided by the GLUE (Generalised Likelihood Uncertainty Estimations) procedure introduced by Beven and Binley, (1992), for model calibration and uncertainty prediction. In this approach, less restrictive assumptions, regarding the form of the error and uncertainties in the model parameters, are made.

While several procedures are available for analysing the reliability and sensitivity of hydrological models, it is difficult to derive general conclusions from the published studies as the results are very dependent on the model type and catchment. It might be expected that for a well-calibrated rainfall-runoff model that adequately represents the important runoff processes in the catchment that the major factor contributing to the error in predicted flows is the error in rainfall. This is, indeed, the conclusion of Refsgaard et al. (1983), using Kalman filtering (see Figure 3.10) to examine error propagation for a particular catchment and is confirmed in DHI's experience in many of practical hydrological modelling studies. Moore, 1987 suggests that a threshold of rainfall-runoff modelling has been reached and the main key to improving model performance is improved estimation of areal rainfall. Nevertheless, this conclusion depends strongly on the catchment size and response time and evidence for this is limited (see Section 3.2.2).



Simulated streamflows with confidence limits assuming: (a) only uncertainty on precipitation input (σ_p = 60%, σ_{K1} = 0, σ_{COF} = 0); (b) uncertainty on model parameters (σ_p = 0, σ_{K1} = 15%, σ_{COF} = 5%); (c) uncertainty on both precipitation input and model parameters (σ_p = 60%, σ_{K1} = 15%, σ_{COF} = 5%).

Figure 3.10 *Comparison of magnitude of the effect of errors in model parameters and rainfall from Refsgaard et al, 1983.*

3.3.4 Updating

Updating or conditioning the forecasts on observed streamflow or water levels provides a practical method of reducing the sensitivity of the flow forecasting model to uncertainties in rainfall data as well as taking advantage of the persistence in hydrological flows to reduce prediction errors.

Forecast updating procedures can be grouped according to whether the input variables(such as precipitation, temperature), state variables (such as water content in soil or a linear reservoir storage), model parameters (such as infiltration capacity or routing constants) or output variables (discharge) are modified (WMO, 1992). In fact, operational updating methods may modify more than one of these groups. Reed, (1984), provides a quite detailed discussion of the general principles and advantages of various updating approaches. He considers updating on state variables, parameters and streamflow using error prediction techniques based on experience with various flow forecasting models. In particular, he is concerned with which approach is preferable.

From the above-mentioned work, the WMO intercomparison (WMO, 1992) and DHI's own experience the following general conclusions can be highlighted.

- Since input updating leads to changes in the model state, the effect may be similar to state updating.

- State updating ought to compensate for errors from unrepresentative rainfall data.

- Parameter updating will deal with suboptimal parameter estimates.

- The error prediction approach is useful as it does not presuppose the source of model error.

- Transfer function models and ISO models lend themselves readily to state-updating and therefore to forecast modelling.

- Kalman filtering-based updating allows simultaneous modification of both model states and model variables, based on their uncertainty, however little is known, a priori, about these uncertainties.

- Automatic corrections do not usually distinguish between timing or phase errors, causing a shift in the flood hydrograph and magnitude or amplitude errors, causing a change in the hydrograph peak. It should be noted that Rungø et al,1991 present a simple automatic streamflow updating procedure capable of distinguishing phase and amplitude errors.

- Updating is usually applied to rainfall-runoff models or hydrological routing models. Updating in connection with hydraulic routing models is less frequent and most often the error prediction model is used based on discharge. Experience has shown that in cases where there is uncertainty in the rating curve due to loop or hysteresis effects, etc then updating directly on water level is preferred, (see Section 3.4).

- Subjective updating is time-consuming requiring experienced and proficient staff. Therefore automatic procedures are preferable in real-time forecasting.

- While updating improved accuracy for short lead-times, most participants in the WMO study agreed that a good (representative) model is necessary to achieve consistently good forecasts at longer lead times.

- The introduction of updating provides significant benefits in terms of accuracy and should be included in all flow forecasting systems.

3.3.5 Urban catchments

Urban flooding can be of two distinct types. Firstly urban areas can be inundated from rivers overflowing their banks. Secondly, urban flooding can occur as a special case of flash flooding, case I, see Chapter 2. Such floods arise primarily from inadequate storm drainage facilities and are often aggravated by clogged inlet pipes and channels or outlets of retention basins.

One reason for flow forecasting in urban catchments is to optimise real-time control of storage basins, pumps etc to mitigate flood problems. Because acceptable lead-times may be shorter in such applications it may be better to chose strategic water level (or flow) sites and work with accurate short-term forecasts rather than earlier less accurate rainfall forecasts. This may be particularly useful for high intensity and highly localised convective storms.

Since such flooding often affects sewage system, forecasts of urban runoff can assist in sewerage treatment and in the handling of polluted flood water.

3.4 Accuracy and Representativeness of Flow Measurements

Standard procedures for many aspects of streamflow measurements are summarised by the International Standards Organisation (ISO, 1983). Discharge measurement usually involves obtaining a continuous recording of water level that can be converted into a discharge using a rating curve defined by discharge gaugings. The accuracy of the discharge gauging will depend on the stability and suitability of the site, the type and accuracy of flow measurement, the frequency of gauging, etc. For a discussion of aspects such as site selection, gauging frequency the number of verticals, etc the reader is referred to the ISO standard and such texts as WMO, 1994 and Maidment, 1993. For sites affected by backwater, corrections can be made based on the fall or water surface slope determined using two water level sites (MWEM, 1979). For sites affected by tides WMO recommends using numerical modelling of the flow to obtain a continuous discharge data.

WMO recommend (WMO, 1994) an accuracy of 5% for discharge measurements. This is based on the realisable accuracy of the traditional current meter gauging at 20 % and 80 % of the water depth rather than on any independent accuracy criterion. The number of verticals and the duration of the velocity measurement are the prime sources of uncertainty in velocity-area gaugings. Studies (Herschy, 1978, Carter and Anderson, 1963) suggest uncertainties due to random error in the constituent measurements of width, depth and velocity lead to uncertainties of 3-5 %. Systematic uncertainty or bias results from errors in calibrated tapes, cables and winches for depth and width measurements and incorrect current meter calibration.

Flow measurement using weirs or flumes is suitable for smaller streams. However, errors in flood discharges may occur if the rating curve is extended beyond the calibrated range. In situ calibration may be necessary for larger flows.

Less conventional gauging methods include dilution gauging, moving boat methods, ultrasonic and electromagnetic methods. Dilution gauging is most suitable for steep mountain streams where mixing occur readily while moving boat methods are best suited to large rivers and deep channels. Ultrasonic methods are not suited to wide shallow or weedy rivers or where there are substantial sediment loads. Electromagnetic methods are useful for weedy rivers or rivers with silty or moving beds. The accuracy of these methods are comparable to current meter measurements.

Three important issues related to discharge measurement data for flood forecasting are 1.) the representativeness of the discharge site 2.) extrapolation of the rating curve at high flows and 3.) loop ratings.

Often the gauging sites in operation in a river system are chosen for water resource studies rather than for flood forecasting. This means that the sites are located further downstream in a river reach to ensure adequate measurement of the total catchment runoff, whereas a gauging site for flood forecasting should be sited as far upstream as possible to maximise the lead-time. On the other hand, the gauging site should not be located so far upstream that it is not representative of the downstream flows due to the presence of significant lateral inflows or tributary flows. Furthermore, for flood flows, a significant fraction of the flow may leave the main river channel as overbank flow. This may occur upstream or downstream of the measurement reach so that the recorded discharges are no longer representative of the downstream discharges.

The second issue is the validity of the stage-discharge relation at high flows. For extreme floods, water levels far beyond the range for which discharge measurements have been made may occur and large errors may arise. Several methods exist for extrapolating rating curves. The most reliable approach for a relatively stable reach is to use gauging data from previous years. Another simple method is to extend the stage-area and stage-velocity curves and then take the product. Where there is channel control, extrapolations can be made directly from the Manning equation or the conveyance-slope method in the case of uniform flow.

For some rivers, the stage-discharge relation may exhibit hysteresis or looping with higher discharges for the same stage on the rising limb of the flood hydrograph than for the falling limb. (Henderson, 1966).

Most of the issues discussed above are well-known topics in traditional hydrology. It is unlikely, under UK conditions, that the accuracy of water level measurements and stage-discharge relations (rating curves) can be significantly improved. Rating curves are nevertheless often uncertain due to measurement error and loop effects which introduces noise when used in updating. It is therefore preferable to update directly on water level for hydraulic routing. The improvement in applying direct water level updating is shown for a site in Bangladesh in Figure 3.11

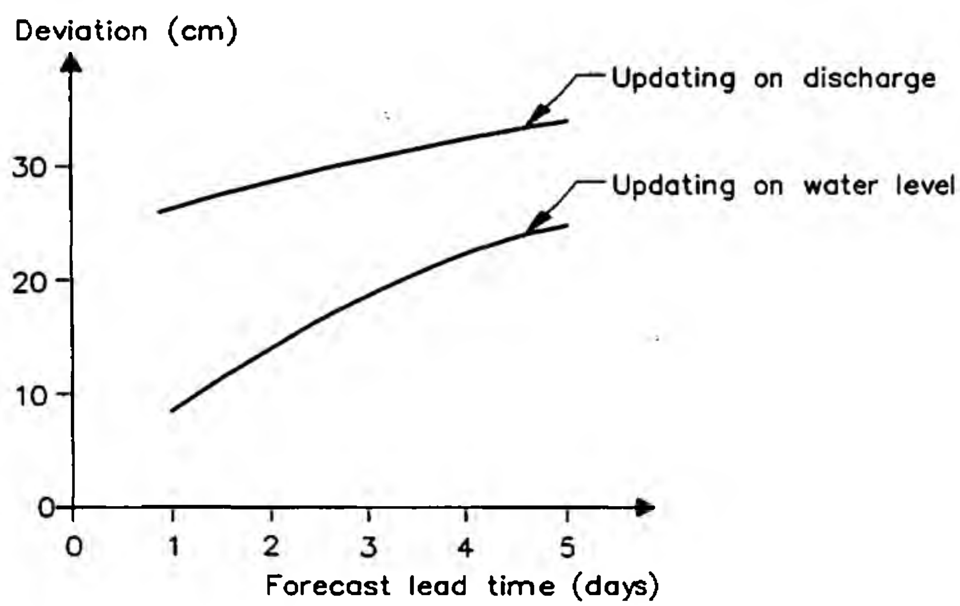


Figure 3.11 *Comparison of forecast accuracy by hydraulic routing using updating on water levels and discharge, from DHI 1994.*

4. CONCLUSIONS ON BEST PRACTICE AND RECOMMENDATIONS

The type of flow forecasting problems that may be encountered can be classified according to the response time of the catchment and the spatial scale of the flood producing storms. This classification provides a rational framework for assessing the scope for increasing the effectiveness of flow and rainfall forecasting as well as for performing cost benefit analyses. These two criteria provide the most useful and fundamental classification of flood forecasting problems. An alternative classification according to catchment type, size, land use etc., would lead to numerous categories that in the end would need to be related to the above two fundamental criteria.

In each case, the best practice is given in Tables 2.3 and 3.2 reproduced below. The boundaries between cases I, II, III may not be as sharply defined as indicated but should be used as guidelines.

Table 2.3 Classification of catchment type and corresponding flood forecasting approach.

Category	**Response time scale (hours)**	**Forecasting approach**
I	$T_p < 3$	Rainfall/runoff modelling plus quantitative precipitation forecasts
II	$3 < T_p < 9$	Rainfall/runoff modelling plus flood routing
III	$T_p > 9$	Flood routing

Table 3.2 Classification of storm type and corresponding rainfall-runoff approach.

Category	**Spatial scale of flood producing storms**	**Flow forecasting approach**
(i)	$Lm/Lc << 1$	Semi-distributed rainfall-runoff modelling
(ii)	$Lm/Lc \approx 1$	Lumped rainfall-runoff modelling

The accuracy of a flood forecasting system is best assessed by a retrospective comparison of forecast predictions or warnings and observed flow or water levels or inundated areas.

The optimum accuracy of a flood forecasting system depends on 1.) the accuracy and 2.) the representativeness of the rainfall forecasts, rainfall observations, flow forecasts and flow observations. Specifying an optimum accuracy, a priori, is an extremely difficult task. A more pragmatic approach adopted here is to obtain an optimum accuracy in general terms by adopting the recommended forecasting approaches presented in Tables 2.3 and 3.2.

To evaluate the scope for improving an existing forecast system it is necessary to evaluate its present performance. A procedure for examining the performance site by site for each region is given below. From an objective evaluation of forecast sites, those sites where forecasts are less accurate can be readily identified. Post-auditing of the flow and rainfall observations will reveal the reasons for these inaccuracies, such as poor model performance, poor rainfall forecasts, etc. These observations will form the basis for identifying improvements.

An assessment of the scope for increasing the accuracy and timeliness of an existing forecast system should be based on identifying the optimal forecasting approach and an evaluation of current performance. General measures for increasing the accuracy and timeliness of forecasting are given below in section 4.2. More specific guidelines for improving an existing forecast system would require a site-specific assessment of the particular measurement network and forecasting approach. The merits of more detailed assessments could be evaluated on a pilot basis for selected sites.

An assessment of the scope for increasing the effectiveness of a flow and rainfall forecasting system should consider not only the accuracy and timeliness of the flood forecast but also how this forecast is converted into a warning for the area likely to be affected and also how well this warning is communicated and interpreted.

An important issue remains; what are the costs of these improvements and how are these related to the financial benefits. This issue is addressed in a complementary R&D note.

4.1 Improved Forecast Evaluations

Information regarding the performance of the flood forecasting and flood warnings are not readily available. It also appears that evaluation of flood forecasting performance is not carried out systematically or uniformly.

The advantages of a post-audit of flood forecast or warning performance are; 1.) objective evaluation of the worth and accuracy, 2.) identification of the effectiveness of flow forecasting according to storm and catchment type, 3.) identification of modelling inconsistencies and weaknesses and 4.) identification of the need for changes in rainfall and streamflow networks.

It is recommended that a uniform practice for flood forecasting evaluation be adopted and implemented over all NRA regions. This evaluation should refer to standards set out in the national Emergency Response Levels of Service (ERLOS).

This should include the following elements:

Distribution and extent of forecasting problems

Classify all forecast points into categories according to T_p

Case I	0-3 hours
Case II	3-9 hours
Case III	> 9 hours

For each forecast point subdivide the catchment into

- urban	(> 50 % urban, for example)
- rural	(> 80 % rural, for example)
- mixed	

This would lead to a table of forecast points for each region

Catchment type/ forecast point	Number	Total Area	Number of Urban	Number of Rural	Number of mixed
Case I					
Case II					
Case III					

For each forecast point, identify which type of storms produce flood warnings and their relative frequency.

The above information will be useful for future cost-benefit analyses as well as identifying the critical forecasting problems type both for each region and overall.

Present success of warning/forecasting

The next step would be to evaluate the present success rate of warnings or accuracy of flow forecasts, again subdividing the forecast points into cases I, II or III. For cost benefit analyses the percentages of

1. warned and flooded
2. not warned and flooded
3. warned not flooded

should be sufficient. For an evaluation of flow model performance, a set of measures such as a subset of those given in Table 2.1, for either water level or discharge or both, could be adopted. Flood warning statistics such as those given in Table 2.2 should be examined.

Forecast methodology

For each forecast point, the basis on which forecasts or warnings are made will be either;

1. heavy rainfall warnings only
2. raingauge only
3. radar + raingauge
4. rainfall-runoff model
5. routing

For each region this would result in a table of the form

Catchment type/ forecast point	Heavy rainfall	Raingauge only	Raingauge + radar	Rainfall runoff	Routing
Case I	%	%	%	%	%
Case II	%	%	%	%	%
Case III	%	%	%	%	%

The above compilations can then be used to readily identify where improvements can be made in accuracy and methodology and where these will have the largest effect. In particular, implementation of the best practice given in Tables 2.3 and 3.1 should be given first priority. Recommended measures to increase the effectiveness of existing forecasting approaches are outlined below.

4.2 Flow Forecasting Models

In addition to the best practice summarised in Tables 2.3 and 3.2 above, the following recommendations are made for increasing the effectiveness of existing flood forecasting systems.

- Updating of forecasts models, both for rainfall-runoff and river routing models, should always be used. Since many regions use upstream water levels as the basis for forecasts, this can be readily implemented.

- Rainfall forecasting is the least accurate, rainfall-runoff modelling in between and river routing the most accurate flow forecasting approach. Since river routing is generally the most accurate forecasting approach, this should be introduced wherever the lead time is large enough to be beneficial. Routing is preferred to correlation methods.

- Correlation and often manual correlations are routinely used. There appears, therefore, to be a considerable technological gap between the range of modelling approaches currently available and those routinely applied to flow forecasting in the UK. Hydraulic routing should be used where tidal effects, backwater effects, rapid reservoir releases or abrupt velocity changes occur and affect flood levels.

- For sites where a larger lead-time can be beneficial, then the use of water level stations even further upstream combined with routing should be examined or rainfall-runoff models to be introduced. In either case, updating is to be used to improve the accuracy.

- An ensemble of forecasts based on radar only, raingauges only, combined radar and raingauges or assuming no further rain or alternatively that the present rainfall rate continues is recommended where this is possible. This will provide the forecaster with a feel for the sensitivity or robustness of the forecasting model and catchment.

- Semi-distributed models represent the state-of-the-art as far as operational forecasting of large catchments is concerned. There are only a few indications that distributed models perform better when distributed rainfall is available. Further R&D in this area is required.

- To improve the lead-time for flood warning, routine forecasting procedures, such as data collection and processing as well as quality assurance should be automated. Procedures for automatic quality assurance, i.e. error checking and correction, for example by rapid visual assessment of streamflow and rainfall data, will be very important both for forecasting using updating procedures and also for forecasting used for real-time control.

5. R&D RECOMMENDATIONS

There are several outstanding problems in connection with radar-based precipitation measurement; such as correction for bright band, orographic enhancement, improved calibration for localised storm rainfall, etc. These issues will be addressed in more detail in a related R&D note.

For short lead-time forecasting, there is a need for further research related to numerical weather modelling at hydrological scales, to obtain quantitative precipitation forecasts.

Sufficiently general and practical methods to determine the impact of uncertainties on forecast accuracies in real-time are required. Perhaps the simplest and most readily interpreted approach is the automatic production of an ensemble of forecasts.

There are some indications that the improvements in rainfall-runoff model accuracy can be achieved using a distributed rather than lumped approach. Further work should be carried out to determine the applicability of such models and their performance in comparison with spatially lumped models.

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7. GLOSSARY

Calibration	The process by which a model is fitted to observed data.
Continous model	A rainfall/runoff model capable of operating continuously in time (as apposed to an event model).
Error prediction	A method of real-time correction in which recent discrepancies between simulated and telemetered flows are studied and a corrected forecast constructed by adding error predictions to the simulation mode forecast.
Event model	A rainfall/runoff model intended for use during (and immediately following) periods of significant rainfall.
Flood (river or channel routing	A formulation that provides a means of estimating flows, principally from measurements of flow at upstream sites.
Flood warning	The communication of flood risk, which may include flood water levels and their timing to those likely to be affected.
Forecasting	Employment of a model to predict future conditions, thereby gaining a time advantage (see "lead time").
Lead time	The time by which the forecast of an incident precedes its occurrence (or non-occurrence).
Monitoring	Regular scanning of hydrometric data (especially river levels) with a view to intensifying such activity, initiating forecasting, or issuing warnings if pre-set levels exceeded.
Objective function	A criterion or set of criteria by which model parameters are determined (during calibration). Sometimes the same criterion is used to assess the model (during verification).
Post-audit	Review of flood forecast or flood warning performance following a flood event or flood season to quantify the performance of the forecast and warning system.
Rainfall/runoff model	A formulation that provides a means of estimating flows, principally from measurements of rainfall.
Response or lag time	A characteristic time by which the response to rainfall is deferred (Precise definitions vary).

State-updating	A method of real-time correction in which the catchment outflow (or some other observable quantity) acts as a state variable so that a telemetered observation can be used to update the state of the model (and hence its forecasts) directly.
Updating	A procedure for real-time correction of a rain or flow forecasting model using the current model performance (ie comparison of model prediction and real-time measurements of discharge or water level). This approach takes advantage of the latest available data to provide a forecast and to correct inaccuracies in the forecasting model.

2.3 Discussion of Lead-time Versus Accuracy

Intuitively, the expected accuracy of a forecast will decrease (forecast error increase) with increasing lead-time because the forecasted streamflow in the immediate future is not expected to deviate significantly from the current situation. This arises from the persistence of river discharges. How the uncertainty increases with lead-time will depend on the speed of response of the catchment as well as the accuracy of the forecasting approach.

Where these forecasts are based on rainfall measurement then flow forecasts beyond the time of concentration of a particular catchment will have little value and this presents an upper limit for forecasting lead time.

For rainfall forecasts there is also likely to be an upper limit to the lead time over which weather systems can be predicted deterministically because of the turbulent and chaotic nature of meteorological flows, (Lorenz, 1993).

For flow forecasting systems the accuracy of short-term forecasts can be considerably improved by including observations about the state of the catchment or river flow in the forecast model. This provides the optimum start point for forecasts. This process is referred to as updating and is discussed in more detail in Chapter 3. Nevertheless it should be emphasised here that updating provides an effective means of increasing the accuracy of the flow forecast particularly when the uncertainties in rainfall measurements are large.

These general observations are summarised in the results of the WMO Real-time Intercomparison of Hydrological Models shown in Figure 2.1. A more detailed description of this study can be found in WMO, 1992. Results are shown for two catchments; Bird Creek (2344 km^2) in USA and Orgeval (104 km^2) in France.

Figure 2.1 shows the root mean square error as a function of forecast lead-time for 11 rainfall-runoff models. The Orgeval events have the general form shown in Figure 2.2. The time of concentration for this catchment is approximately 10-12 hours. The plateau reached by most models corresponds to the overall model accuracy. As several of the models are very similar in structure, the differences at large lead times represent the accuracy of model calibration as well as differences in modelling approaches. For shorter lead times, the variations represent the efficiency of the updating routines. In some cases updating produces poorer accuracy for intermediate lead-times, (Figure 2.2). A similar but more variable pattern is shown for the larger Bird Creek catchment. The accuracy of rainfall forecasting as a function of lead-time shows similar general behaviour, although the persistence of rainfall is generally shorter than for runoff (see section 3.1).

The value of updating using a number of different modelling approaches is highlighted in Figure 2.3 from Refsgaard and Havnø, 1981. The results are based on a 200 km^2 test catchment with a time of concentration of around 4 days. Without updating the models would run predictively and the mean square error would be essentially constant (Figures 2.2 and 2.3) at all lead times, reflecting the quality of the model calibration and the ability of the model to represent the catchment hydrology. With updating the forecasts at short lead times are considerably improved by taking advantage of the persistence in streamflow. It is interesting to note that the lumped conceptual model NAM outperforms the ARIMA (black box) model at larger lead times.

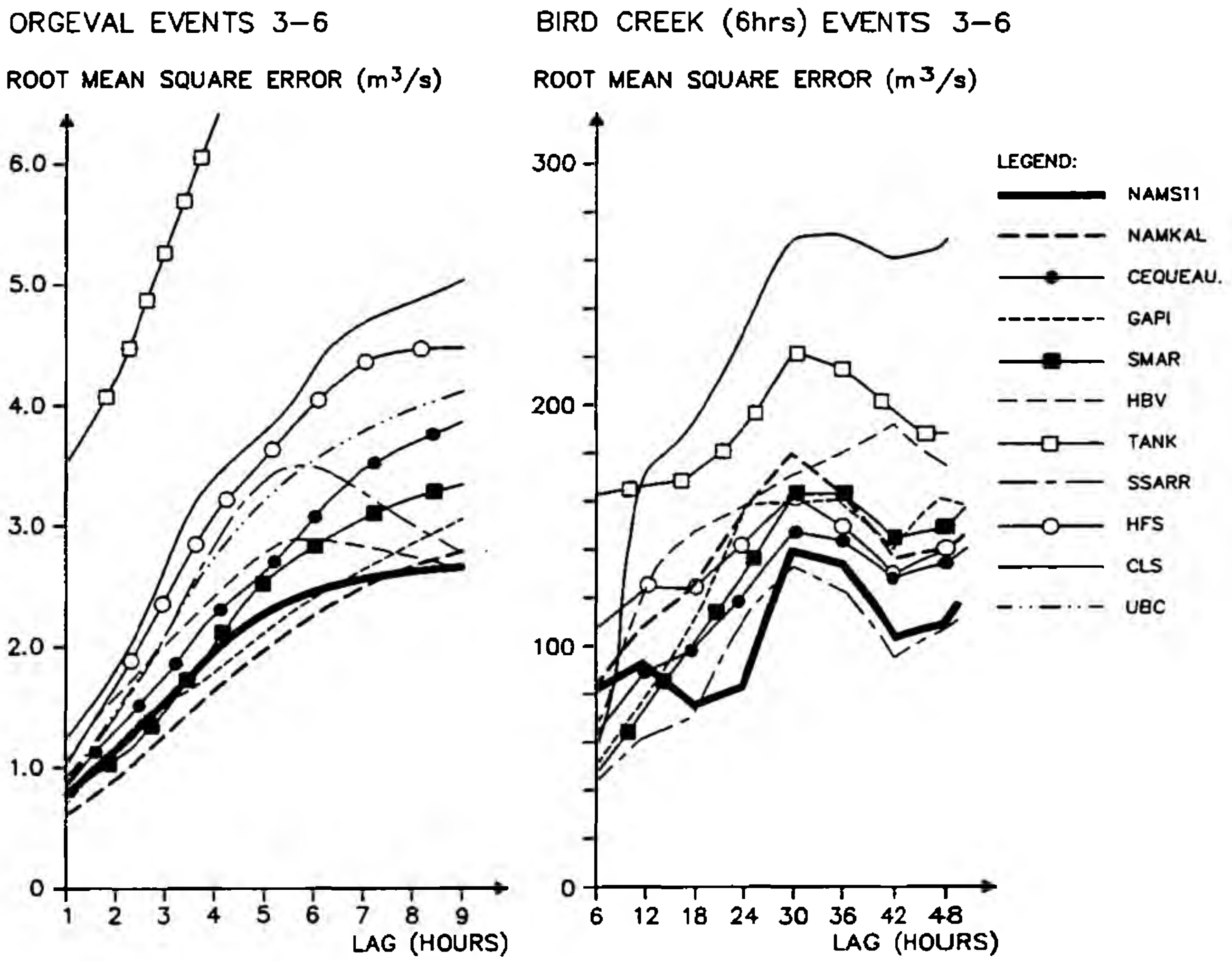
How flow forecasting accuracy varies as a function of lead time, for a particular catchment, then, is strongly dependent on the use of updating and a function of time scale of hydrological response for the catchment. The level of accuracy depends on the forecasting model accuracy and the accuracy of the hydrological observations.

It is not possible, however, to quantitatively determine, a priori, how accuracy will increase with lead time for a given flood forecasting approach in a particular catchment. This can only be achieved by an assessment of the existing forecasting system. The above studies demonstrate clearly the value of using updating in flood forecasting and it is therefore recommended to use updating in all cases. Nor is it possible to quantify, a priori, how a change in forecasting accuracy will lead to a change in warning accuracy. For cost-benefit analysis on the catchment scale it may be useful to establish the lead times or range of lead times that provide the maximum benefit and use this as a goal for revising forecast procedures to achieve maximum accuracy for this lead time.

The approach adopted in this report is to subdivide these forecast problems into broad categories where an optimal forecasting procedure can be identified. For effective flood forecasting this best approach should be adopted and the accuracy optimised.

WMO Intercomparison 1987

of Models for Real–Time Forecasting



NAMS11 is the predecessor of MIKE 11

Figure 2.1 *Forecast error as a function of lead time from "WMO Real-time Intercomparison of Hydrological Models", 1992.*

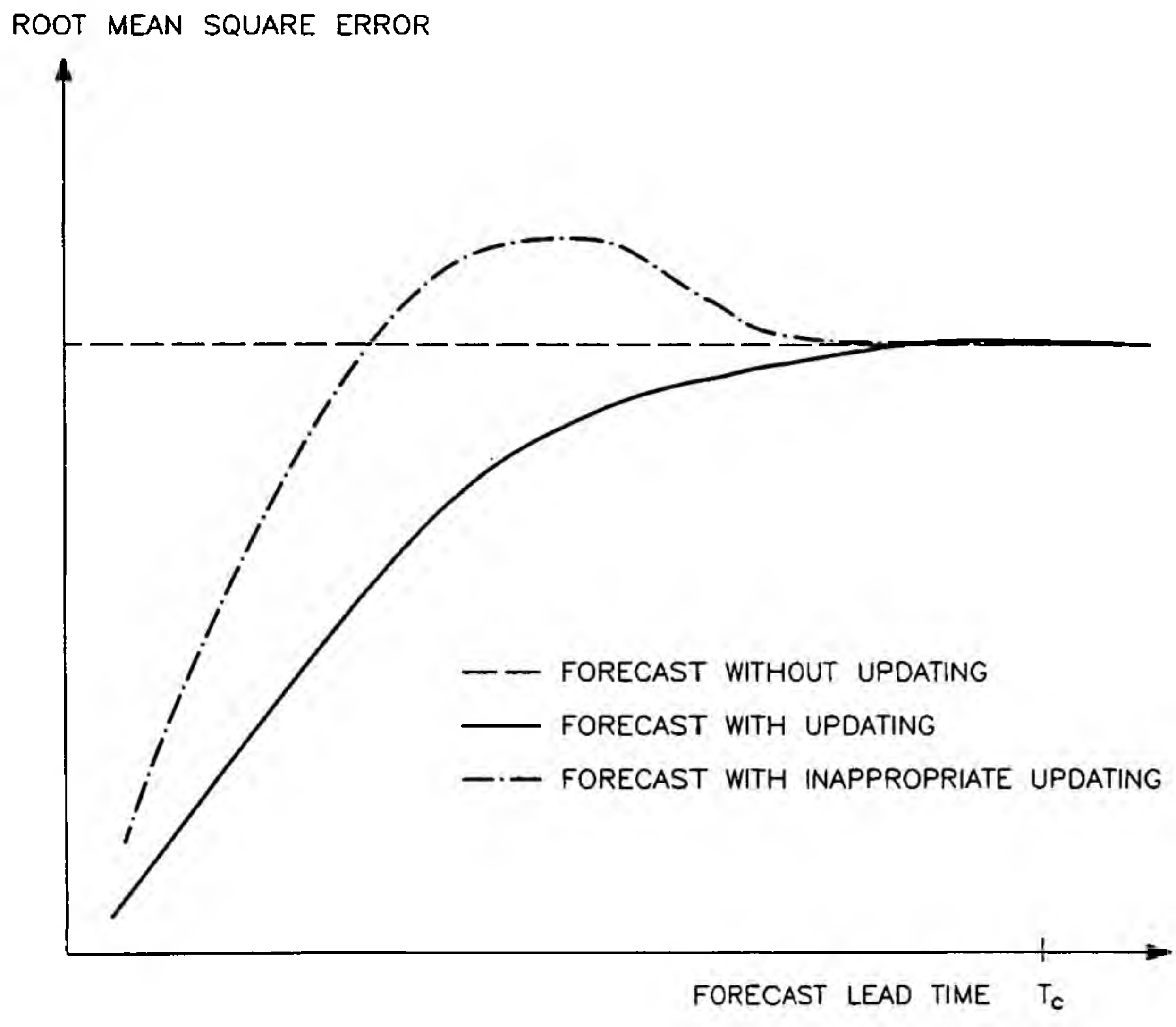


Figure 2.2 *General behaviour of forecasting error as a function of lead time.*

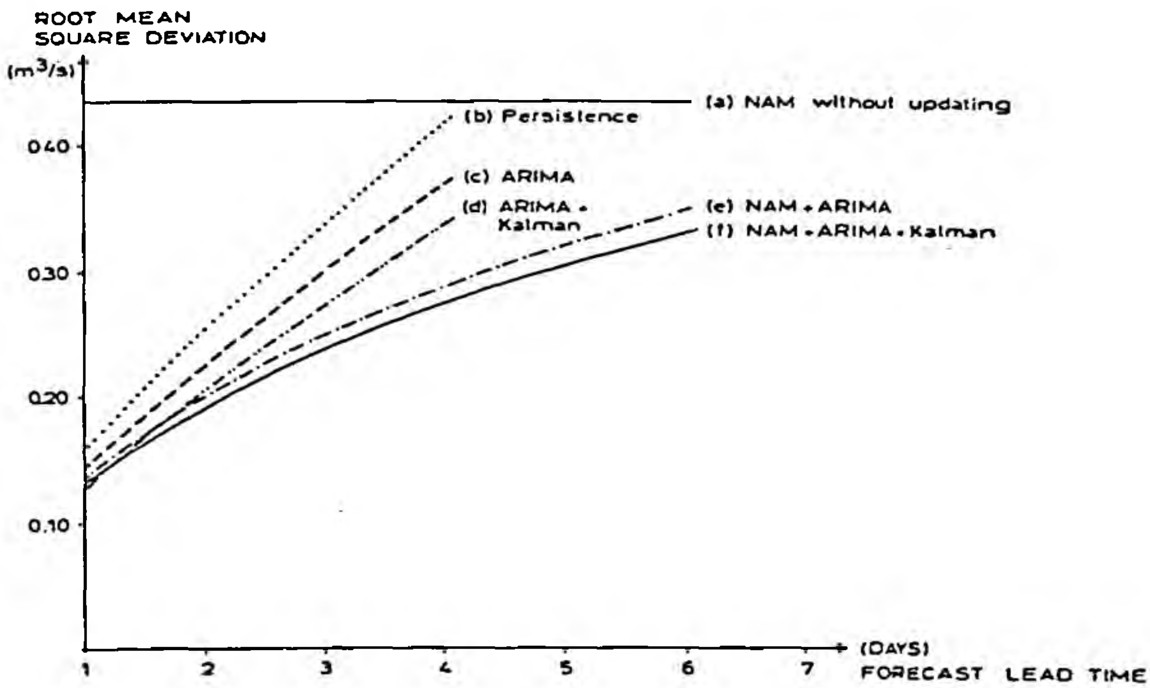


Figure 2.3 *Forecasting error as a function of lead time from Refsgaard and Havnø, 1981.*

2.4 Classifying Forecasting Problems

Criterion 1: Time scale of catchment response

The nature of the hydrological forecasting problem can be specified by relating the forecast lead time (T_f) to the time to peak flow of the catchment at the forecast point T_p. The time to peak flow of the catchment at the forecast point can be measured by time of concentration i.e. the time of travel from the farthest point in the catchment to the forecast point. For large natural basins with complex drainage networks the time of concentration will be greater than the time to peak flow. The time to peak flow consists of the two components; the hydrological response time of the catchment or the time between precipitation falling on the catchment and a corresponding peak in the river flow (T_c) and the travel time through the river or channel system (T_r). This leads to the following three cases.

Case A. $T_f > T_c + T_r$

The required lead time is larger than the time of concentration at the forecast point, in which case meteorological forecasting is required. Both precipitation forecasting and flow forecasting using precipitation-runoff modelling may be necessary.

Case B. $T_f < T_c + T_r$, $T_c << T_r$

The response time scale of the catchment/channel network is dominated by the routing time of the flood wave through the channel system. This is typical for large river systems. This permits streamflow forecasts from observed flows (or water levels) upstream of the forecast point. In such cases it may be possible to base flow forecasts on channel routing models alone.

Case C. $T_f < T_c + T_r$, $T_c >> T_r$

The time of concentration is dominated by the hydrological response time of the catchment but the forecast lead time is shorter than the time of concentration. Stream flow forecasts should be based on observed rainfall (from either telemetered raingauges or radar) and incorporate rainfall-runoff modelling.

Application of this classification system requires that the forecast lead time and the catchment response time scales be specified. The forecast lead time may vary with the type of warning procedures used, as well as the speed of the telemetry or radar system, data processing and forecasting procedures, the speed of communication of the forecast/warning to the affected area and the speed and willingness of those affected to react to a warning. Various measures to reduce the necessary lead time using automated warning systems, direct contact between the forecast centre and flood wardens, etc could be contemplated. Such considerations are beyond the scope of this report but are important components of any flood warning system.

The routing time for a river system is not a constant but depends on the size of the flood event. As the water levels approach bankfull discharge the flood wave velocity increases with increasing discharge. However above bankfull discharge, the velocity of the flood wave (celerity) decreases and attenuation of the flood wave increases as water is lost out-of-bank and flow resistance increases. The flood hydrograph will also be attenuated where off-stream storages can contain part of the flood volume.

The hydrological response time of a specific catchment will depend on a number of factors, such as catchment size, catchment slope, land use, soil type , etc. In addition to these fixed parameters, the response time will also depend on dynamic variables such as the catchment wetness, groundwater levels the distribution of rainfall including storm type and direction, particularly in larger catchments and the operation of controlled storages. The availability of significant groundwater storage in a catchment will, in general, lead to a larger time of concentration and significant persistence in the streamflow. Nevertheless, the speed of response of catchments dominated by groundwater contributions to river flow will depend on catchment slope, aquifer permeabilities and groundwater levels during flood-producing rainfall.

In summary, the appropriate time scales are, in reality, variable quantities so the boundaries between the three categories are not sharply defined. For the purpose of this report the following classification system and recommended forecasting approach based on Reed (1984) will be used. This catchment classification is presented in Table 2.3

Table 2.3 Classification of catchment type and corresponding flood forecasting approach. (Reed, 1984)

Category	**Response time scale (hours)**	**Forecasting approach**
I	$T_p < 3$	Rainfall/runoff modelling plus quantitative precipitation forecasts
II	$3 < T_p < 9$	Rainfall/runoff modelling plus flood routing
III	$T_p > 9$	Flood routing

Criterion 2: Spatial scale of flood producing storms

When the spatial scale (L_m) of the meteorological event is significantly less than the spatial scale (L_c) of the catchment then the accuracy of forecasts assuming uniform rainfall will deteriorate. Lettenmair and Wood, 1993 suggest this occurs when the ratio $L_m/L_c < 0.7$. This will be a problem for large catchments and for smaller catchments during intensive convective storms. The best forecasting approach in this situation will depend on the catchment response time scale. These issues are discussed in more detail in Chapter 3. For the purposes of this report we will distinguish between flood producing storms where $Lm/Lc << 1$, (case i) or otherwise (case ii).

3. ASSESSING THE ACCURACY OF FLOW FORECASTING SYSTEMS

The accuracy of flow forecasting systems will depend on the accuracy and representativeness of

1. rainfall forecasts
2. rainfall observations
3. flow forecasting model
4. flow observations

Each of these categories will be addressed in the following sections.

A major issue in a discussion of accuracy assessment is how to define quantitatively an acceptable accuracy. There are no simple guidelines for specifying an acceptable accuracy and this will depend on for what purpose the forecasts are issued. In reality this needs to be specified by those issuing or using the forecasts. Such questions as, how many false alarms or unwarned floods are acceptable to those affected?, are not readily answered.

The approach adopted here is to specify the optimum strategy for flood forecasting according to the type of catchment and storm-producing rainfall.

A quantitative assessment of the accuracy of a flow forecasting system, a priori, is a difficult task and even when hydrological modelling has been performed, quantification of the accuracy or reliability of the modelling system is the subject of much recent research (Moore 1995a, Melching et al., 1990, Beven and Binley, 1992). Nevertheless it is possible to specify guidelines as to the best possible strategy for forecasting or the changes most likely to achieve significant improvements in accuracy given some knowledge of the catchment and rainfall types. In fact, this optimal strategy or best practice according to catchment type is contained to a large extent in Table 2.3

It is important to note that, in general, flood routing is more accurate than rainfall-runoff modelling which is, in turn, more accurate than rainfall forecasting. Therefore, where appropriate, flood routing should be implemented as the first priority, rainfall-runoff modelling as the second priority and rainfall forecasting as the last priority. Table 2.3 shows the most accurate forecasting approach that is appropriate.

For case I, the optimal forecasting strategy, in terms of accuracy, is to obtain the most accurate rainfall forecast. The expected accuracy of such rainfall forecasts is discussed in Section 3.1. Whether such forecasting will lead to realisable benefits will be addressed in the forthcoming cost benefit analysis.

Similarly for case III, the optimal strategy is to obtain the most accurate flow routing. The accuracy and applicability of flow routing models are discussed in Section 3.3.

For case II, there exists the possibility of a trade-off between issuing a late warning based on more accurate flow routing or issuing earlier but less accurate warnings based on rainfall-runoff models. Some authors (Walsh, 1992, Davis and Nnaji, 1982) suggest early but less accurate warnings are more useful. This is a generalisation which should be examined in each case and can only be determined from a site-specific cost benefit analysis. Nevertheless, as the most widespread routine forecasting approach appears to be station to station correlation (Marshall, 1991,1992), there is considerable scope for increasing lead-time by the application of rainfall-runoff modelling. A discussion of rainfall-runoff modelling is given in Section 3.3. If the introduction of a rainfall-runoff model is combined with an updating procedure based on the existing upstream discharge/water level observations then both forecast accuracy and lead-time can be significantly improved. Where appropriate, such updating should be transparent, i.e. the forecast with and without updating should be available at the time of forecast and post-auditing used to confirm the utility of updating.

This leads to the idea of scenario forecasts or an ensemble of forecasts. Essentially the forecaster is not provided with a single forecast but instead a range of forecasts for different scenarios. For example, the forecast could be presented based on radar precipitation only, or telemetered raingauge data, or combined radar and raingauge data, or assuming no further rain, or alternatively the present rainfall intensity will continue. This will provide the forecaster with a feel for the sensitivity or robustness of the forecasting model and catchment.

3.1 Rainfall Forecasts

As pointed out in Chapter 1, these forecasts are most relevant for rapidly responding catchments, typically small urban catchments prone to flash flooding. For larger catchments, persistence in the flow hydrographs increases the value of model updating using flow observations. The purpose of this section is to determine the expected accuracy and reliability that can be obtained from quantitative precipitation forecasts at the present time, rather than a detailed evaluation of rainfall forecasting methods.

Reviews of radar-based short-term precipitation forecasting methods are given in Browning and Collier (1989) and Collier (1989). Testing of various radar-based rainfall forecasting approaches on urban catchments in the Thames region has been reported by Moore,(1995b) and Moore et al, (1993). As pointed out in Moore (1995b) there is only limited data available with which to assess rainfall forecasting in the application of flood forecasting. For all radar-based forecasting, any errors or uncertainties in the precipitation measurements will propagate in the forecasts. The magnitude and effect of these uncertainties are discussed in Section 3.2.

Combining information from satellite and radar images and conventional meteorological data is used in the FRONTIERS forecasting system (e.g. Collier, 1989). Recent evaluations of quantitative precipitation forecasts using FRONTIERS and various other radar-based forecasting methods (Moore, 1995b, CEC 1994) indicate that, for short lead times, the radar-based approaches are more accurate, while for larger lead times (1.5-3 hours) that the FRONTIERS forecast is superior. This suggests that the choice between these will depend on the optimal lead time for a given catchment. The accuracy of the rainfall forecasts as a function of lead-time from the CEC study in the Thames region are shown in Figure 3.1. This figure shows the log root mean square error as well as the skill scores, critical success index, false alarm rate and probability of detection, as a function of lead time. The skill scores are defined in Table 2.2 in the context flood warning. For rainfall forecasts, the same definitions apply, where the rows and columns given by flood warning, no flood warning, flooding observed, no flooding are replaced by rain forecasted, no rain forecasted, rain observed, no rain observed, respectively.