INSTITUTE OF HYDROLOGY

A REVIEW OF BRITISH FLOOD FORECASTING PRACTICE

by

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SUMMARY

The feasibility and success of a flood warning scheme depend on many factors, of which data acquisition and procedures for disseminating warnings are particularly important. Although the review examines these topics in some detail, the core of the material presented refers to the application of flood routing and rainfall/runoff models to flood forecasting. The continued use is recorded of simple correlation techniques for flood routing. The report describes the Muskingum family of flood routing methods and explains the particular merits of the variable parameter Muskingum-Cunge technique. Rainfall/runoff methods are reviewed under four headings: unit hydrograph techniques, nonlinear storage methods, transfer function methods, and conceptual models. Nonlinear storage models are seen to be well suited for flood forecasting; they are relatively simple in structure, not too difficult to calibrate, and can be readily implemented. The transfer function approach is explained in simple language and its particular attributes for real time forecasting compared to those of the more familiar unit hydrograph approach. The review considers in detail the problem of how best to correct flood forecasts by reference to telemetered flow measurements. Three methods are distinguished: error prediction, state-updating, and parameter-updating. Other topics reviewed include the role of weather radar, the particular obstacles faced in flood warning on rapidly responding catchments, and general guidance in matching a forecasting technique to a particular catchment. The report cites more than 120 references.

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"Time present and time past
Are both perhaps present in time future,
And time future contained in time past"

T S Eliot

1. INTRODUCTION

1.1 A distinction between flood forecasting and flood warning

This report is concerned with both flood forecasting and flood warning. Flood forecasting can be defined as "the prediction of stage, discharge, time of occurrence, and duration of a flood - especially of peak discharge at a specified point on a stream - resulting from precipitation and/or snowmelt". This lengthy definition is taken from an international glossary of hydrology[1]*. The same source defines flood warning as the provision of "advance notice that a flood may occur in the near future at a certain station or in a certain river basin". Although not beyond criticism, these definitions serve to distinguish the specific task of calculating a forecast (flood forecasting) from the broader activities that underlie the provision of a flood warning. Thus, for example, we speak of a flood forecasting model but a flood warning scheme.

1.2 Background to review

Interest in flood forecasting methods has developed apace in the decade since the formation of regional water authorities in England and Wales. The period has seen the widespread introduction of sophisticated data gathering systems - some dedicated to flood warning, others multi-purpose - and an increasing awareness that flood warning and flood alleviation are complementary activities. In the same period, studies of flood forecasting methods have been carried out in universities and research institutes, with the University of Birmingham, the Water Research Centre (WRC), and the Institute of Hydrology (IH) to the fore.

Completion of the Flood Studies Report in 1975 saw a widening of IH applied research activity to examine problems other than design flood estimation, notably low flow estimation and real time flow forecasting. A particular milestone was the Dee Weather Radar and Hydrological Forecasting Project[2], in which the Institute collaborated in the development and calibration of a comprehensive flow forecasting model of the (Welsh) Dee and implemented the overall forecasting method on a real time minicomputer. Research has since been directed at the development of time series methods of flow forecasting[3] (under WRC funding) and at water quality forecasting[4] (with EEC and water authority support). Further IH work on real time flow forecasting is funded by a Ministry of Agriculture, Fisheries and Food (MAFF) research commission and it is under these auspices that a review of British flood forecasting practice has been undertaken.

1.3 Purpose of review

The report has been written for the hydrologist and the engineer who have a strong interest in flood forecasting practice. The review has three main aims:

* to report existing flood forecasting practice in Great Britain
* to identify areas in which greater use could be made of hydrological modelling techniques
* to consider what generalizations can be drawn from the diversity of flood forecasting experience.

The first aim is self-explanatory. The second aim is designed to bridge the gap between research and application. As well as providing advice on the choice of forecasting method to suit a given flood warning problem, it is hoped that the report will increase the awareness of hydrological modellers to the particular

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* Numbers denote references which are listed at the end of the report.

requirements of operational flood warning. The third objective is to find some common threads in the wealth of flood warning system developments of recent years.

1.4 Scope of report

Flood forecasting is a diverse topic, even within British conditions. No two flood warning problems are precisely the same and there are numerous ways in which hydrological models can be used to augment warnings based on "experience".

The feasibility and success of a flood warning scheme depend on many factors, notably data acquisition and operational procedures. The report considers these and other topics in some detail, but the heart of the material presented refers to the application of flood routing and rainfall/runoff models to flood forecasting. Special mention is made of the value of weather radar to flood forecasters, of the ways in which flood forecasts can be corrected by reference to telemetered flow measurements, and of the particular problems of effective flood warning on rapidly responding catchments.

1.5 Previous reviews

The only recent review of British flood forecasting methods appears to be that of Farnsworth[5]. This stemmed from a 2-day symposium of water industry delegates on river flood forecasting and warning, held at the Hydraulics Research Station in March 1978. The report provides a brief summary of flood warning systems in use and developments foreseen. A broadly similar colloquium was held at Medmenham in June 1980 under the auspices of the Water Research Centre and the Institute of Hydrology. The meeting allowed a further useful interchange of experiences and ideas on flood forecasting, and the material presented there has provided one of the many building blocks of this report.

Earlier reviews of flood warning methods include a seminar paper by Hall[6] in 1975 and a UK report to WMO/UNESCO in 1973[7]. Discussions and papers on flood warning have been a feature of successive River Engineers' Conferences held at Cranfield and arranged by MAFF.

The World Meteorological Organization has recently published a summary of flash flood forecasting techniques and warning systems. The report[8] is largely based on practice and research in the USA but an annex classifies general preferences in 45 member countries.

2. FLOOD WARNING SYSTEMS - SOME GENERAL REMARKS

2.1 A permissive power

Under powers consolidated by the 1976 Land Drainage Act, the ten Regional Water Authorities and the Greater London Council are permitted to provide and operate flood warning schemes in England and Wales. This is a permissive power rather than a duty. The manner in which these authorities provide flood warnings is not directly regulated, although MAFF guides such practice in various ways, notably by grant-aiding approved schemes. Different arrangements apply in Scotland and in Northern Ireland but these are again characterized by a permissive power to provide flood warnings.

Following a conference held to discuss flood warning after widespread flooding in 1968[9], MAFF clarified separate roles for the (then) river authorities and the police. Although local circumstances and the evolution of flood warning systems have led to some blurring of the division of responsibility, it is still largely the police who disseminate flood warnings in Britain. Some reference is made in Sections 2.2 and 5.7 to the need for, and format of, agreed action by the police. However, for a comprehensive examination of flood warning dissemination, the reader is referred to recent work by the Flood Hazard Research Centre at Middlesex Polytechnic[10].

2.2 Benefits of flood warning

Cost/benefit analyses of flood warning schemes are likely to be much less precise than those for flood alleviation works[11,12]. The essential difficulty in establishing the value of a flood warning is that the benefit derives only from action taken (or deferred) as a result of the warning. For example, if we consider the flooding of residential property: how many householders will receive the warning in sufficient time to act? What proportion will respond effectively? And what value will their actions have? These factors depend on the overall effectiveness of the flood warning system: on the quality of the flood forecast itself, on how well the warning is communicated, and on the level at which public awareness of flood risk is maintained. Considerations such as these demonstrate that calculating the flood forecast is only part of a flood warning system. (See Chapter 5 for a discussion of procedural aspects of flood warning.)

Flood warning benefits can accrue in three main ways: through the removal of items from the risk area, by lessening the impact of flooding, or by controlling the flood itself. For example:

Evacuation of:

* people and livestock
* crops (by premature harvesting)
* sensitive and/or easily removed items (eg. cars, electrical equipment, furnishings, manufactured goods).

Amelioration through:

* temporary flood-proofing (eg. sandbags, blankets, adhesive tape)
* opportune maintenance (clearing obstructions from screens, culverts, watercourses etc.)
* early alerting of emergency services
* orderly disruption of communications (especially road diversions)
* suspension of sensitive works (eg. sewer repairs).

Control by:

* adjusting reservoir discharges (to permit flood attenuation where possible)
* emptying storm tanks and balancing ponds prior to arrival of the flood.

The above list is by no means complete. The introduction of a new flood warning scheme may reduce the manpower needed to monitor developing floods and/or allow more effective deployment of staff and resources in combatting a flood. Less tangible benefits may also arise: for example, following serious flooding of a particular locality, the provision of a flood warning scheme may be an expedient compromise between taking no action and proceeding with flood alleviation works.

The benefits of flood forecasting have been studied in detail by Chatterton, Pirt and Wood[13] of Severn-Trent WA. Their work draws attention to the close link between warning time and damage reduction. They demonstrate the need to integrate benefits over a range of return periods, from moderate to extreme flooding. In arriving at estimates of the average annual benefit, they assume an imperfect response to warnings but a near perfect flood warning system. To be any more realistic would require a thorough uncertainty analysis, not least of the forecasts themselves.

Potential benefits of a national network of weather radars and improved short-period rainfall forecasts were reported by a joint CWPU/WRC/Met.Office study in 1978. The report[14] includes an attempt to quantify benefits attainable through use in flood warning. A more recent study[15] has confirmed that the major benefit of a national network of radars lies in improved flood warning. The potential value of both weather radar and quantitative precipitation forecasting (QPF) has also been examined in the North West Radar Project[16]. Much will depend on the success of the Met. Office's FRONTIERS project[17] for QPF as it moves from the development stage to operational deployment in the next few years.

Not only are the benefits difficult to assess; it may also be difficult to estimate the costs of developing forecasting methods and of operating and maintaining the overall flood warning system. Only the hardware costs are likely to be known with reasonable certainty. It must indeed be difficult to present a complete cost/benefit analysis for a flood warning scheme.

2.3 Criteria for flood forecasts to be useful

The three watchwords in flood forecasting are accuracy, reliability and timeliness.

Accuracy is clearly important if the forecast is to form the basis of specific flood alerts. If the forecast of peak river level is substantially in error then a false alarm may be raised or, worse, the system may fail to warn. In contrast to flood estimation for engineering design - where a poor answer is better than none - in flood warning it may be preferable not to issue forecasts than to do so using an inaccurate model. In such cases, a suitable compromise may be to monitor the river closely, with alert levels set conservatively low. (See Section 2.4).

Reliability of a flood warning system is primarily concerned with instrumentation, telemetry and procedural matters. But, however well designed these aspects are, it is inevitable that the forecasting model will have to live through periods of outstation malfunction. It is therefore desirable that the forecasting method should reliably cope with imperfect or missing data: by validation checks, appropriate default values, and "slimmed-down" models.

Accuracy and reliability are fairly obvious requirements; accuracy suggests we need a "good" model, reliability hints that simplicity and robustness may be important. But the requirement that gives flood forecasting a flavour (and language!) of its own is timeliness.

If warnings are issued consistently late then the system is likely to be of little value, irrespective of the accuracy of modelling. A balance has to be struck between issuing a timely but potentially inaccurate forecast (based on partial data for the event) and the more cautious approach of compiling a good picture of the event before issuing an accurate but useless forecast (because it leaves insufficient time for dissemination of the warning and effective action by recipients).

In British conditions (ie. relatively short, rapidly responding river systems) the response time of the catchment often imposes an upper limit on the lead time* that can realistically be provided. Anything from 3 to 6 hours is generally useful, with limited benefits accruing from shorter warning times also[13]. There is optimism that, within a few years, weather radar and satellite data will enable the Met. Office to produce reasonably accurate quantitative precipitation forecasts (QPF) up to 6 hours ahead[17]. Such forecasts would greatly extend the scope for rainfall/runoff model based flood forecasts on rapidly responding catchments.

2.4 Flood monitoring

It is, of course, possible to give flood warnings without recourse to a forecasting model. In essence the procedure is to monitor the river system at a reference site and to issue a flood warning when the level reaches a predetermined threshold. By setting the alert level low enough it is possible to provide adequate periods of warning, especially on slowly responding catchments. However, an inherent difficulty with the monitoring approach is the tendency to give a large proportion of false warnings and this in itself may discredit the warning system. The setting of alert levels is discussed further in Section 5.10.

The value of flood monitoring as a means of short-period flood warning should not, however, be underestimated. Coupled with an efficient data gathering and display system, monitoring of river level at, or upstream of, the risk area is an extremely valuable aid to effective flood warning. As resources allow, an element of flood forecasting can be introduced to provide more accurate and/or longer warnings.

2.5 Components of a flood warning system

Flood warning systems can usefully be considered in three parts: information gathering, information appraisal, and action. This report is primarily concerned with the information appraisal component of the system - giving a review of British flood forecasting methods. But it is hoped that sufficient will be said of data acquisition and procedural aspects to ensure that requirements of the overall flood warning scheme are kept in mind when considering refinements in flood forecasting methods.

3. DATA ACQUISITION

3.1 Relevant variables

The variables primarily of interest in flood warning are river level, river flow and rainfall. Tide measurements may be important where tidal influences are marked. Advanced methods of flood forecasting may additionally require climate data, soil moisture measurements, and observations of snowpack characteristics. Many factors influence the range of variables monitored, not least modelling philosophy and outstation costs.

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* "lead time" is one of several terms defined in the glossary at the end of the report.

3.2 Instrumentation

A wide range of instrumentation is available and used in Britain. The biggest single choice is in the measurement of river level, there being many types of float, pressure and dipper sensors. Some use is also made of ultrasonic and electromagnetic methods of flow gauging[18 19].

The type of raingauge most suited to real time use is the tipping bucket, which counts unit depths of rainfall. The most commonly used increment is 0.5 mm but, where more detailed definition of the temporal distribution of rainfall is required, a 0.2 mm or 0.1 mm bucket is employed. If data are logged at half-hourly intervals, a 0.5 mm tipping bucket will define the average rainfall intensity in each interval with an absolute error up to 1 mm/hr. (The dynamic calibration of 0.1 mm tipping bucket gauges is considered by Calder and Kidd[20].) Some use is made of daily raingauges where observers are on hand to relay information; but a daily data interval is generally too coarse for all but the most slowly responding British rivers.

Several types of climate station are available, some of which allow remote interrogation in real time. Put simply, these measure rainfall, temperature, humidity, radiation and wind speed and direction. Air temperature data can be useful for estimating snowmelt rates while wind data can provide a guide to estimating wave surcharging in wide estuaries. However, the principal application of climate station data is to carry out a Penman calculation of potential evaporation and/or some simple budget of soil moisture.

An alternative or supplement to soil moisture calculations based on potential evaporation estimates is to monitor soil moisture directly by neutron probe or tensiometer*. The neutron probe is used by several authorities, notably AWA Lincolnshire River Division, to assess soil moisture periodically; a weekly interval between measurements is typical. Whereas attempts to develop an automatic version of the neutron probe have been generally unsuccessful, automatic pressure transducer tensiometers have potential for real time use[21].

Another instrument development particularly relevant to flood warning systems in Scotland and North East England is an automatic weather station designed for subarctic conditions[22]. Developed through field trials on Cairngorm the station can provide data for snowpack modelling studies. Severn-Trent WA has recently opted to install heaters to ensure that telemetering raingauges always report precipitation. The forecasting of snowmelt is taken particularly seriously by Northumbrian WA who have a network of snow observers equipped to take depth and density measurements[23].

Perhaps the most exciting development in instrumentation is weather radar. Although by no means a new concept[24], experience has only recently progressed to a fully automatic weather radar station[25]. Sited at Hameldon Hill in North West England, this is seen by many as the first of a network of purpose-built weather radars covering most of England and much of Wales[15]. (A second of this new generation of radars is scheduled to become operational in 1984: the London

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* Neutron probes provide a direct measure of soil moisture content over a wide range of conditions. Tensiometers are less effective in very dry conditions and measure only the soil water potential. However, a "bank" of tensiometers (ie. sited at several depths) allows estimation of the vertical profile of soil moisture, from which information on soil behaviour can be gleaned.

weather radar sited on the Chilterns.) Three older radar sets remain in service at Clee Hill, Upavon and Camborne; all four radars provide input to a composite radar "picture" prepared in real time at the Meteorological Office Radar Research Laboratory, Malvern[26].

The effectively instantaneous scanning of precipitation over a large region and the presentation as a gridded picture of rainfall intensity (with colour coded gradation) make radar a most useful aid to the flood forecaster. The most obvious advantage is the spatial coverage provided by radar; no longer is there a fear that a storm is slipping through the raingauge network undetected. A second important benefit is the insight gained into storm movement from a sequence of radar-derived pictures. This opens the door to short-period rainfall forecasting and it is with this principal aim that the Meteorological Office is promoting an integrated network of radars[27 15]. A third asset of radar data is the facility to calculate average rainfall intensity over predesignated areas, the obvious application (in flood forecasting) being to hydrological catchment areas.

Although weather radar has great potential for flood forecasting, there are also some drawbacks. The most obvious is cost, not just of the radar set but also of the technology and equipment necessary to interpret the returned signal and to display and store the rainfall images. Another difficulty is that the conversion of signal intensity to rainfall intensity is neither straightforward nor invariant. The problem is tackled by re-calibration of the rainfall/signal relationship in real time. In the case of the Hameldon Hill radar[16], a network of five telemetering raingauges provides the "ground truth". Fairly complicated algorithms have been developed to accomplish the task and, although there is scope for further refinement, these calibration procedures are now providing improved estimates of rainfall intensity[28]. The role of weather radar is discussed further in Section 6.8.

3.3 Telemetry systems

Telemetry systems are designed to control the transmission of data from an instrument site (or outstation) to a control centre (or basestation). Without a telemetry system, data acquisition has to rely on observers, either stationed at the instrument site or sent on patrol in response to an initial alert.

OUTSTATIONS

Outstations differ in the level at which they communicate data to the basestation. An interrogable outstation acts as a slave to the flood warning system, providing data only on request. In contrast, an alarm outstation is capable of initiating a report to the basestation when an exceptional condition occurs: for example, if a threshold river level is exceeded. Some outstations (eg. Dynamic Logic's Teltel Alarmlog[29]) can fulfil both roles. The essential quality of an alarm outstation is its ability to provide an initial alert. Once this has been raised the flood warning machinery can move up a gear to provide frequent interrogation of a wide network of outstations.

The practice of interrogating only a subset of outstations may be particularly attractive in telemetry schemes based on public telephone lines, the object being to economize on telephone call charges. With ordinary outstations, this practice has the drawback that the data series collected are incomplete, forestalling or complicating the use of particular types of forecasting model. (For example, many rainfall/runoff models need to know the pre-event flow to initialize the simulation of runoff.) This difficulty can be avoided by the use of outstations with interrogable data stores - as, for example, in the minicomputer based system being installed by the Greater London Council. As well as fulfilling its primary role of flood monitoring and forecasting, the system will make daily data collection calls to all outstations for archival purposes. Interrogable data stores are also of some value in radio telemetry based forecasting systems. For example, outstations in the Haddington flood warning scheme[30] maintain a record of the last 48 values, and the facility to retrieve data in retrospect strengthens the system's capability to recover effectively following telemetry failure.

Programmable outstations are also possible. As long ago as 1973, Cumberland River Authority collaborated with Bestel-Dean Ltd in the development of an alarm raingauge based on an analogue catchment model. This "leaky bucket" model linked the raising of alerts to a cumulative index of rainfall akin to a short-term antecedent precipitation index. Indeed, the concept stemmed from the much earlier development of an electro-mechanical API counter[31].

Nowadays, digital methods have generally superseded analogue techniques. A particularly advanced development is the data collection platform (DCP) on trial for Severn-Trent WA at Cefn Brwyn. This second generation DCP eavesdrops on an adjacent automatic weather station, carries out Penman type calculations and transmits potential evaporation estimates daily via a geostationary satellite (METEOSAT II) and telecommunication links from a satellite receiving station to the user. Although much of the thinking behind this development concerns streamlining data collection for archival purposes, Severn-Trent WA is also exploring its real time applications[32].

However, intelligent outstations have not been widely used in British flood warning schemes. Most authorities prefer to keep outstations fairly simple both to ease field maintenance and to avoid duplicating "clever" gadgetry. Another factor cautioning against undue distribution of sophisticated equipment is the harsh operating environment of many outstations, dampness and vandalism being particular evils.

Power consumption is another consideration in outstation design. At key sites, some form of back-up supply is generally warranted. A joint mains/battery supply remains the ideal choice but, with the advent of microelectronic equipment with very low power drain, other supply systems are now practical. The incorporation of crystal clocks in intelligent outstations leads to possible further reductions in power requirements; the clock can be used to activate the outstation prior to a scheduled interrogation by the basestation[30].

BASESTATION

At its simplest, the basestation can consist of a flood warning duty officer equipped with a telephone. Increasingly though, some element of automation is provided to speed up what can be a particularly time-consuming and frustrating task. Some systems merely automate the dialling. Others carry out the entire interrogation process and provide a hardcopy listing of the latest values sensed at outstations. (In the case of raingauge measurements, a cumulative value is usually logged). Other valuable aids are systems which automatically note an alarm condition (raised by an outstation) and transmit the information on to one or more duty officers.

For flood warning schemes with a large data intake - and/or where computer modelling is required - the solution commonly adopted is telemetry scanning controlled by a dedicated real time computer. For example, the Dee and North West WA telemetry systems are controlled by PDP11 minicomputers. One technique is to

separate the telemetry control task from the flood modelling and forecasting task. For example, Severn-Trent WA utilize a dedicated datascanner for telemetry control and link this with a multipurpose IBM minicomputer only periodically or when an explicit need arises[33]. While there are drawbacks in utilizing two computers rather than one - for example, the unproductive time that the computers spend talking to each other - the approach insulates the relatively fixed telemetry control software (suited to a low level programming language) from the more ephemeral modelling software (suited to a high level language). Moreover the division of labour means that the more powerful microcomputer is not tied down to routine monitoring. A number of telemetry schemes - perhaps notably those designed principally to monitor water supply systems - are controlled by computers that are virtually unprogrammable as far as the hydrological modeller is concerned. It seems that the desirability of real time modelling has either not been foreseen or been accorded low priority in the choice of basestation equipment.

The possibility of using low-cost microprocessor technology to provide an automatic flood warning system has been explored in the Haddington flood warning scheme[30]. In this the basestation is a desk-top microcomputer built around a Motorola M6800 microprocessor. This controls data transmissions from four outstations (one sited adjacent to the basestation) and passes flood alerts and instrument malfunction warnings to a remote monitoring device (at a site manned 24 hours per day). In this implementation the telemetry control and display software are written in a low level programming language but the hydrological model is compiled from FORTRAN.

COMMUNICATIONS

In Britain, most flood warning systems use either telephone or radio telemetry for data communication from outstations. Whereas in many overseas countries radio telemetry is generally preferred, the relatively high standard and dense network of British telecommunications deny any clear preference here.

Several classes of telephone line are possible: PSTN (public switched telephone network), exclusive British Telecom (BT) line, or private line. A private line is only to be preferred if cheaper or more secure than a PSTN line; this essentially restricts the option to short distances. Exclusive BT lines are relatively expensive and are more suitable when the level of traffic is consistently high, as for example on a data link between computers. The majority of telephone telemetry in British flood warning is by (ordinary) PSTN line. Some authorities, for example the Greater London Council, make use of "emergency modified" and "emergency" options whereby British Telecom undertake to respond to telephone faults immediately or with high priority.

Various types of radio communication are used: VHF, UHF and microwave. VHF systems are quite numerous but newer systems generally use UHF or microwave. A hierarchical design - whereby a multi-channel microwave system provides the "spine" of communications, UHF scanners are used for links to most outstations, and telephone telemetry handles the more remote outstations - has been adopted in the Thames WA and North West WA regional communications systems[34].

The principal advantage of radio telemetry over PSTN telephone telemetry is that frequent interrogations are possible at negligible marginal cost. Another advantage is that radio communication is generally not disrupted by flooding - a weakness of telephone systems that is sometimes cited by supporters of radio telemetry. The drawbacks of a radio system include the relatively high capital cost, the need for specialized maintenance and repair, and the susceptibility to interference or disablement in freak weather conditions (notably, electrical storms). Another, perhaps less important, drawback is that it is rarely economic to design a radio system to be secure against failure of a particular component - for example, damage to an antenna - whereas there is considerable "design redundancy" in the public telephone network.

A certain amount of bureaucracy attends both types of telemetry. There are restrictions on the connection of equipment directly to PSTN lines and it is usually necessary to communicate through BT approved modems. As regards radio telemetry, it is necessary to seek detailed approval from the Home Office for new schemes; the allocation of a frequency and maximum power stipulations may present difficulties.

Communications technology is, of course, developing rapidly. Commercial radio telephone systems, teletext systems, satellite links, optic fibre signalling, etc. may in due course play important roles in data communication for flood warning. At present though, the choice between telephone telemetry and radio telemetry remains contentious. Finally, it should be noted that many of the cost disadvantages of radio telemetry may not apply if it is possible for a flood warning system to share a multipurpose regional communications scheme.

3.4 Data base management

Perhaps the most marked characteristic of computer controlled telemetry systems is their capacity to generate vast quantities of data. Good management of data storage is essential if the system is to serve for data archiving as well as flood forecasting. However, even in systems where data are retained only for short-term use, much thought is often required in structuring the data base.

Design considerations in data handling are well summarized by Evans[35]. The Dee Real Time Hydrological Forecasting Project provides a very detailed account of the design and implementation of a minicomputer based flow forecasting system.

A particular consideration may be the need to store model forecasts in addition to the data sequences derived from telemetered observations. This is generally required where attempts are made, either automatically or manually, to correct forecasts in the light of recent model performance. (Methods of "real time correction" are discussed in Section 4.4). The data storage requirement can multiply still further if the philosophy followed requires a number of forecast hydrographs to be generated consecutively, each one conditional on a particular assumption about future rainfall or about operational control of a flood retention storage. Evans gives an example of how to estimate data storage requirements[35].

Prior to placing newly telemetered observations in the data base, some form of validation is generally carried out. The most basic technique is simply to check that readings are within a meaningful range (eg. that a 15-minute rainfall accumulation is non-negative and less than 100 mm). A more advanced check is to examine the pattern of recent values of individual variables; for example, the Severn-Trent WA system[33] queries river level changes greater than either 50% or 1.0 metre. Inter-station comparisons provide a third level of sophistication.

Carried out manually, these tasks are relatively straightforward though time-consuming; however, their automation can be tricky. Whereas an experienced eye can spot a rogue value instinctively, a computer has to rely on a checking formula. Validation of raingauge readings is particularly difficult because of the acute variations in rainfall intensity that can occur both in space and time. Practical experience of computerized validation of telemetered data has been gained by several authorities although, as yet, it is a detail of system design which has not been widely publicized. Effective data validation extends the scope

for computer surveillance of instrument failure. Whether the control of data quality is manual or automatic, fault reporting is an important part of flood warning procedures.

4. FLOOD FORECASTING METHODS

4.1 Introduction

4.1.1 Variety of methods

Very many methods of flood forecasting are in operational use in Britain. Whereas flood warning procedures (see Chapter 5) often follow a divisional or regional pattern, there is much greater variety in the methods used to calculate forecasts. A few authorities, notably Severn-Trent WA, are evolving a regional strategy for flood forecasting but, in the main, methods are tailored to local requirements and preferences.

Factors influencing the choice of flood forecasting method may include:

* the frequency and level of threat to life and property
* the availability of historic data
* outstation, telemetry and computer resources
* staff time and abilities, personal preferences
* the fulfilment of a dual purpose (eg. a single forecasting model applicable to both flood and low flows)

But the dominant influence is likely to be the nature of the catchment. To illustrate the diversity of flood forecasting problems that exist in Britain, six examples will now be described briefly. Figure 4.1.1 provides a key to the catchment locations.

FIGURE 4.1.1

Location of example catchments

KEY:

A - Ouse at York
B - Medway at Tonbridge
C - Roding at Redbridge
D - Tyne at Haddington
E - Yeading Brook West Branch
F - Rhondda at Trehafod

4.1.2 Examples of flood forecasting problems

OUSE AT YORK (3315 km^2)

Major flooding of the city of York has been a problem for many centuries. Although a relatively slowly responding catchment, once the response to rainfall commences, river levels at York can rise as rapidly as 2 metres in 6 hours. That weather conditions on the vale of York can be quite different from those in the Pennine headwaters, further emphasizes the need for a structured flood warning system.

The Ouse at York has three main tributaries draining the more or less parallel dales of the Swale, Ure and Nidd - (See Fig. 4.1.2). Each tributary is gauged in its lower reaches and these river levels are the key to flood forecasting for York. Lesser influences are the prevailing weather conditions and the state of controlled flood plain storages. The time of travel of flood water (from the tributary gauging stations to York) offers a reasonable lead time for forecasts of river level at York. However, the dependence on flood flows in three tributaries - which may or may not be synchronous - makes accurate flood forecasting at York that much more difficult than on simpler river systems.

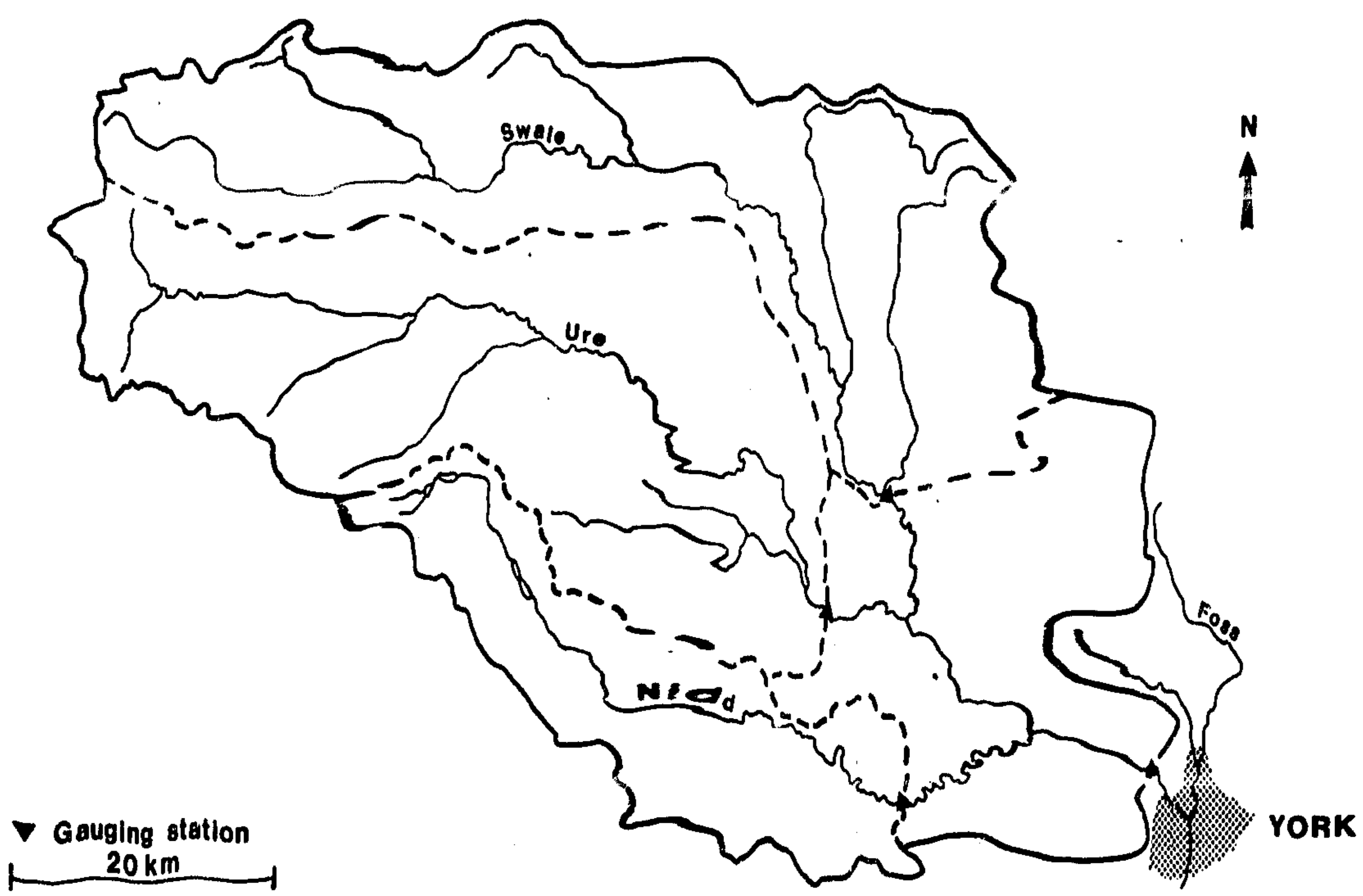


FIGURE 4.1.2 Ouse at York - catchment plan

The major floods experienced in January 1982[36] highlighted some of the forecasting problems that can occur on large river systems. Snowmelt was a significant component, as it was also in the severe floods of March 1947. In addition to progressive inundation direct from the main river, backwater and flood-locking effects on lesser tributaries flooded other parts of the city and presented a particularly difficult flood warning problem. The impact of small rises in water level (in terms of additional flood damage), the opportunities for taking action (to reduce the effects of flooding), and the stress to resources presented by a prolonged flood alert, illustrate the importance of being able to forecast the trend of water level changes at the height of a flood.

MEDWAY AT TONBRIDGE (522 km^2)

Flooding of the middle reaches of the Medway is largely controlled by the major flood retention storage recently constructed west of Tonbridge. (See Fig.4.1.3). The principle of this on-line flood storage is to retain flood flows behind an embankment built across the flood plain, while allowing a continuous controlled discharge through a gated structure throughout the course of a flood event[39]. The effect is therefore to prolong the event and to increase flooding upstream of the embankment while eliminating or substantially reducing flooding downstream, the degree of success being dependent on the severity of the event.

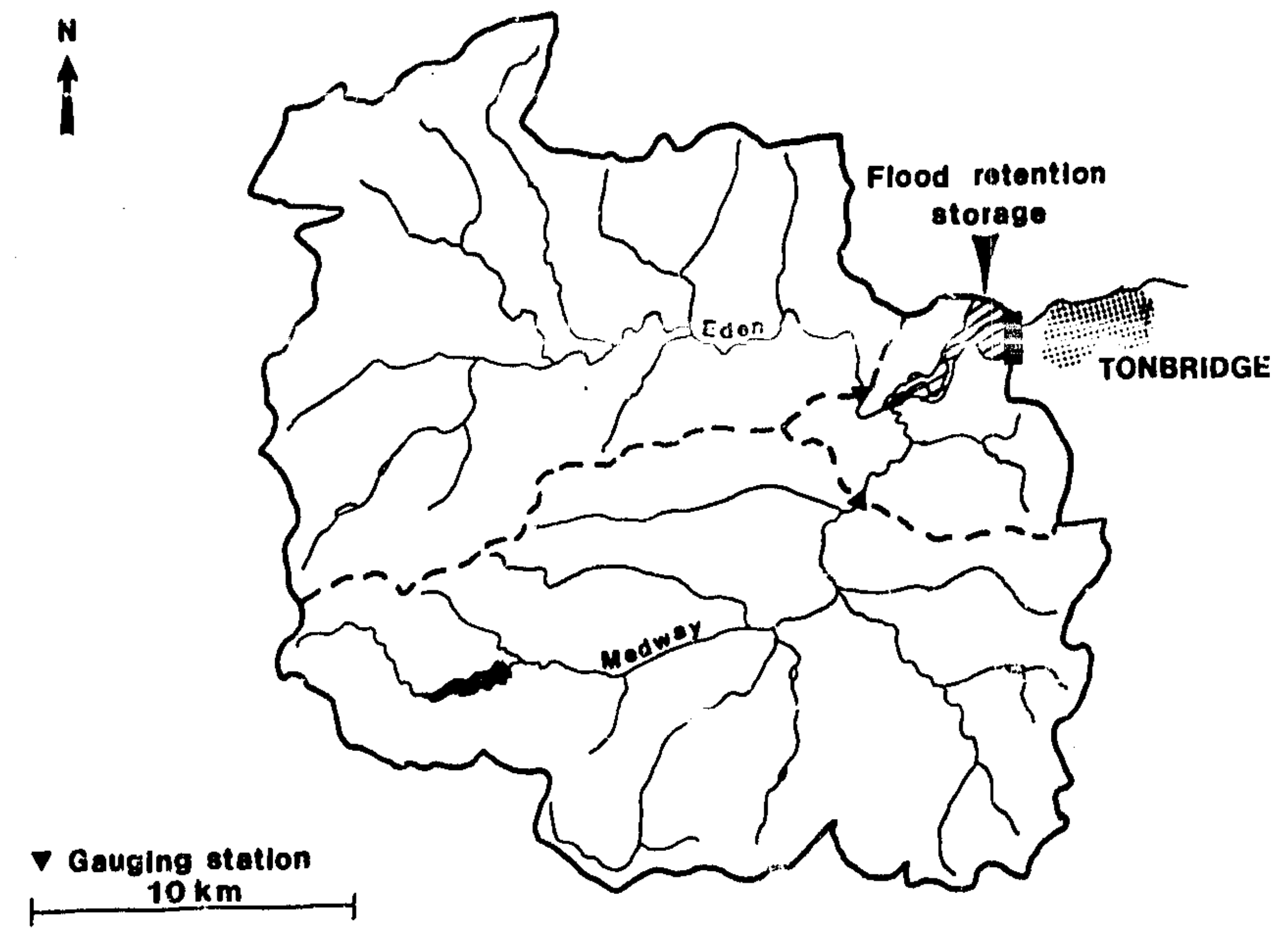


FIGURE 4.1.3 Medway at Tonbridge - catchment plan

Operation of the control structure presents a challenging problem. While in most events the principal objective is to minimize flooding downstream, in a very severe flood it is necessary to increase the controlled discharge to prevent overtopping of the embankment. Operation of the structure is usefully enhanced if inflows to storage can be forecast. In contrast to many flood warning problems, relatively long forecast lead times are of interest; this is because effective operation of the storage is more sensitive to the volume of flood runoff than to exceedance of a particular inflow rate.

Upstream of the flood retention storage the river receives flow from two main branches: the Eden and the upper Medway. Gauging stations on these tributaries provide the basis of short-term forecasts by flow routing, with longer lead time forecasts dependent on rainfall measurement and rainfall/runoff modelling.

RODING AT REDBRIDGE (303 km^2)

The Roding presents a fairly unusual flood forecasting problem. The catchment is long and narrow, draining the west flank of Essex into London. (See Fig.4.1.4). At first sight it appears that forecasts can be based on an upstream gauging station (the Roding at High Ongar, 95 km^2), the shallow gradient providing an adequate period of warning. However, these ideal conditions are perturbed by the fact that the lower part of the Roding is heavily urbanized and generates a significant quick response to rainfall, ahead of the main (rural) catchment response. Additional difficulties include flood gauging problems at High Ongar (essentially arising from the shallow gradient) and the need to interpret the effects of flood alleviation works when forecasting river levels in the lower reaches.

A comprehensive forecasting system for the Roding would probably entail a detailed hydraulic model of the High Ongar/Redbridge reach and a subcatchment rainfall/runoff model to forecast the urban response. However, given the reduction in flood warning benefits brought about by the flood alleviation works, fairly simple judgements based on upstream river levels may provide a more cost-effective solution.

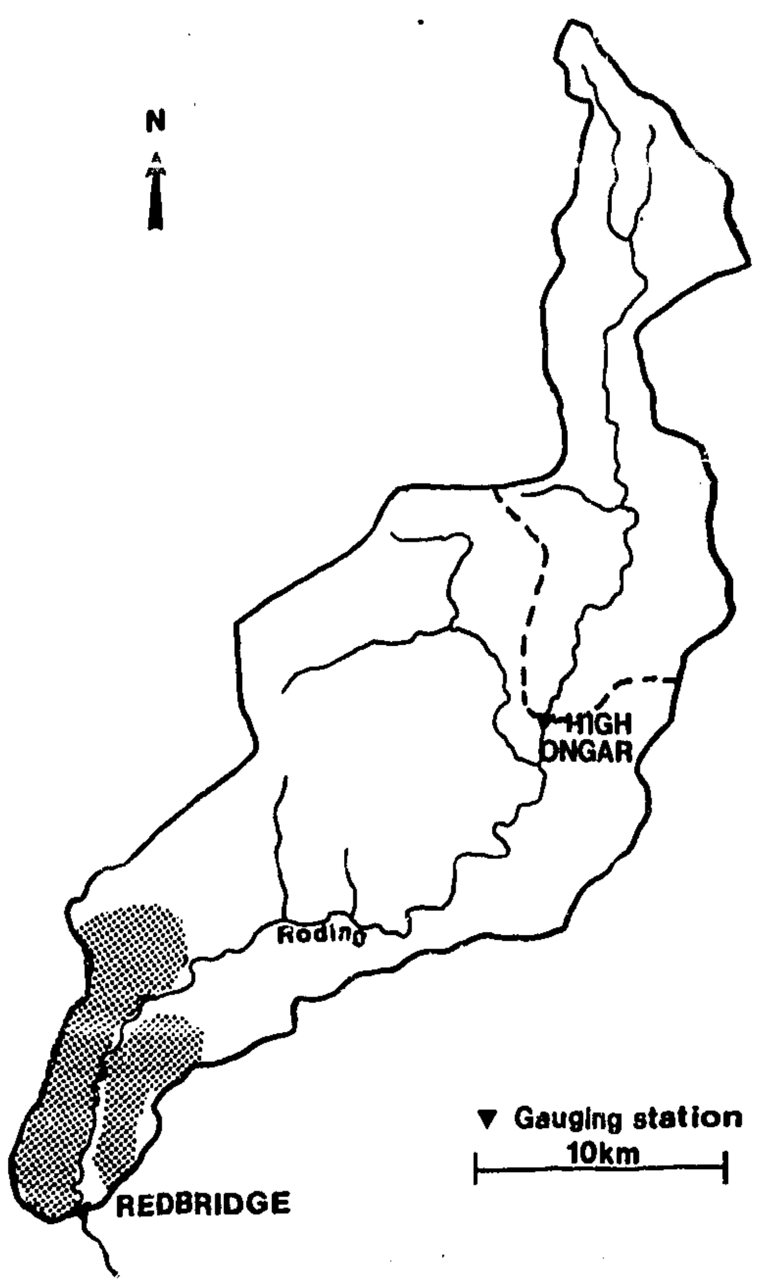


FIGURE 4.1.4

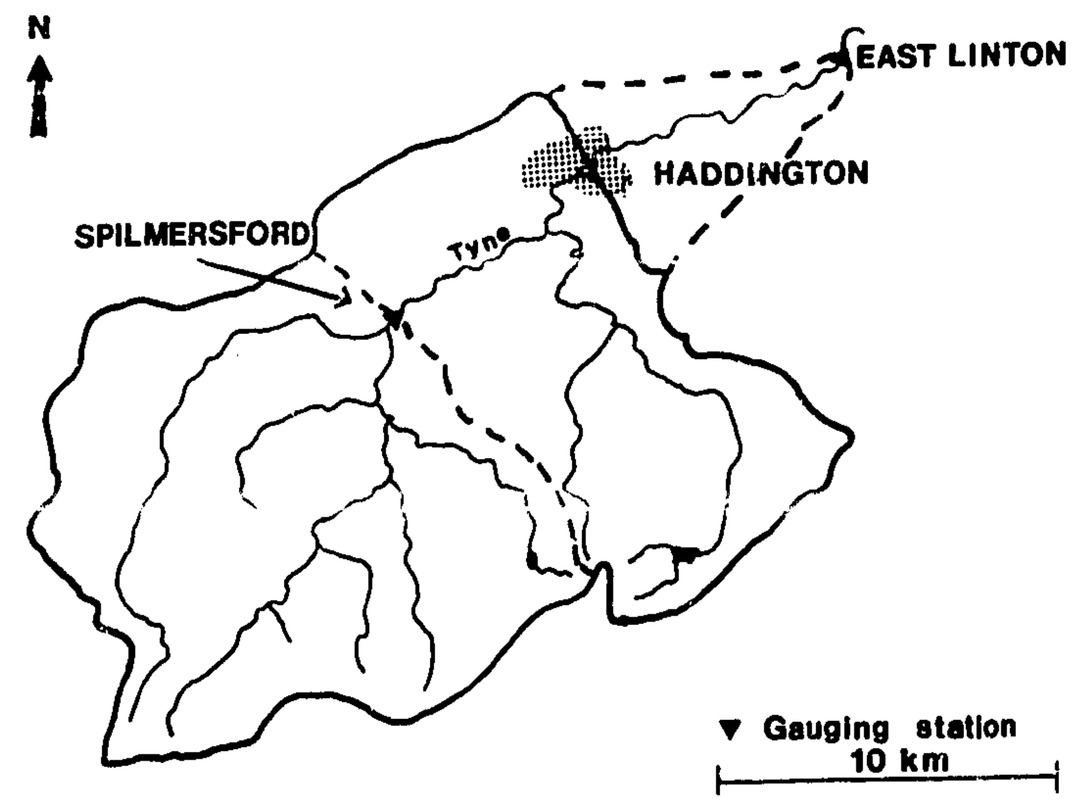
Roding at Redbridge - catchment plan

TYNE AT HADDINGTON (270 km^2)

The Tyne rises on the northern slopes of the Lammermuir Hills of south-east Scotland and flows through the town of Haddington causing periodic inundation[40,30]. (See Fig.4.1.5). The runoff is concentrated by two tributary systems, one of which joins the main branch of the Tyne immediately upstream of the town. This, combined with the steepness and fan-shaped drainage pattern of the tributary systems, presents a flood warning problem which upstream monitoring of river levels cannot entirely meet. Some reliance must therefore be placed on rainfall measurement and rainfall/runoff modelling. A notable feature is that Haddington is particularly susceptible to summer flooding. This makes rainfall/runoff modelling more difficult in some respects since due account has to be taken of the antecedent condition of the catchment which, on occasions, may be very dry. On the other hand, it is reassuring to know that history argues against snowmelt and frozen ground being important on this catchment.

FIGURE 4.1.5

Tyne at Haddington - catchment plan



YEADING BROOK WEST BRANCH AT WESTERN AVENUE (18.4 km^2)

A tributary of the river Crane, the Yeading Brook West Branch drains a largely suburban corner of north-west London. (See Fig.4.1.6). With much of the catchment sewered, the response to rainfall is quite rapid despite only moderate gradients. Some properties within the catchment are subject to periodic inundation and receive warnings from an adjacent water level alarm gauge. This is one of a network of 22 instruments installed by the Greater London Council on brooks and watercourses to provide "dial-out" alarms to local residents (via a flood warden) and borough council emergency officers. This approach offers rapid dissemination of flood alerts but provides no forecast of future conditions. Water level in the Yeading Brook West Branch is also telemetered at Western Avenue.

Flood forecasting on rapidly responding catchments such as the Yeading is a demanding problem, requiring automated rainfall measurement and rainfall/runoff modelling[41]. It is customary to think of intense thunderstorms as the main threat

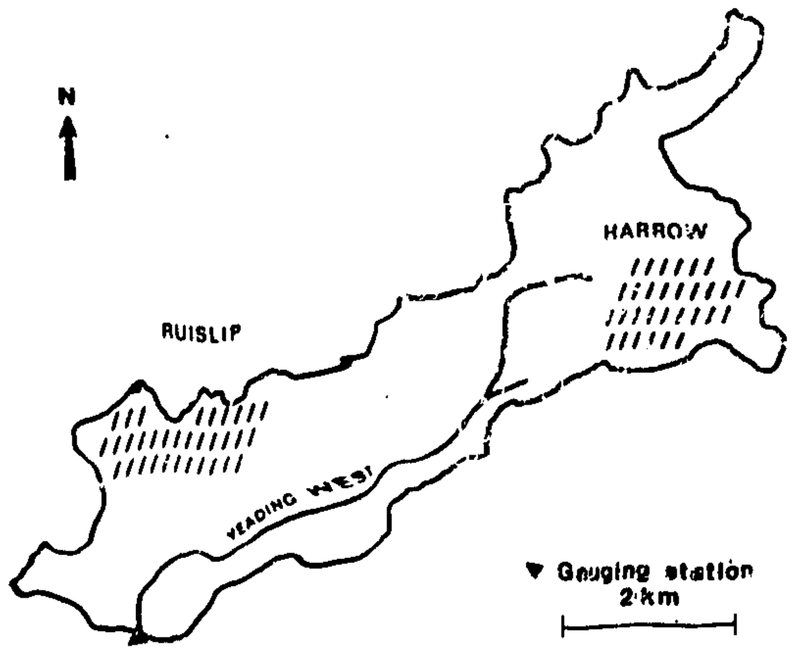


FIGURE 4.1.6

Yeading Brook West Branch - catchment plan

on fairly small, urbanized catchments but more complex storms of longer duration can be equally devastating. Haggett's detailed analysis[42] of the August 1977 London storm provides a salutary example of the limitations of even a dense network of telemetering raingauges in representing cellular rainfall activity. It is not surprising, therefore, that the GLC sees weather radar as a key component in providing model-based flood warnings for catchments such as the Yeading.

Perhaps, in one respect, the requirement for formal warnings on small catchments is reduced because many of those in a position to benefit are likely to be alerted by the severity of rainfall experienced locally.

RHONDDA AT TREHAFOD (100.5 km^2)

The Rhondda, a major tributary of the Taff, rises in two parallel valleys: the Rhondda Fawr and Rhondda Fach. (See Fig. 4.1.7). These are archetypal South Wales valleys - straight and steep-sided, with development strung along the bottom.

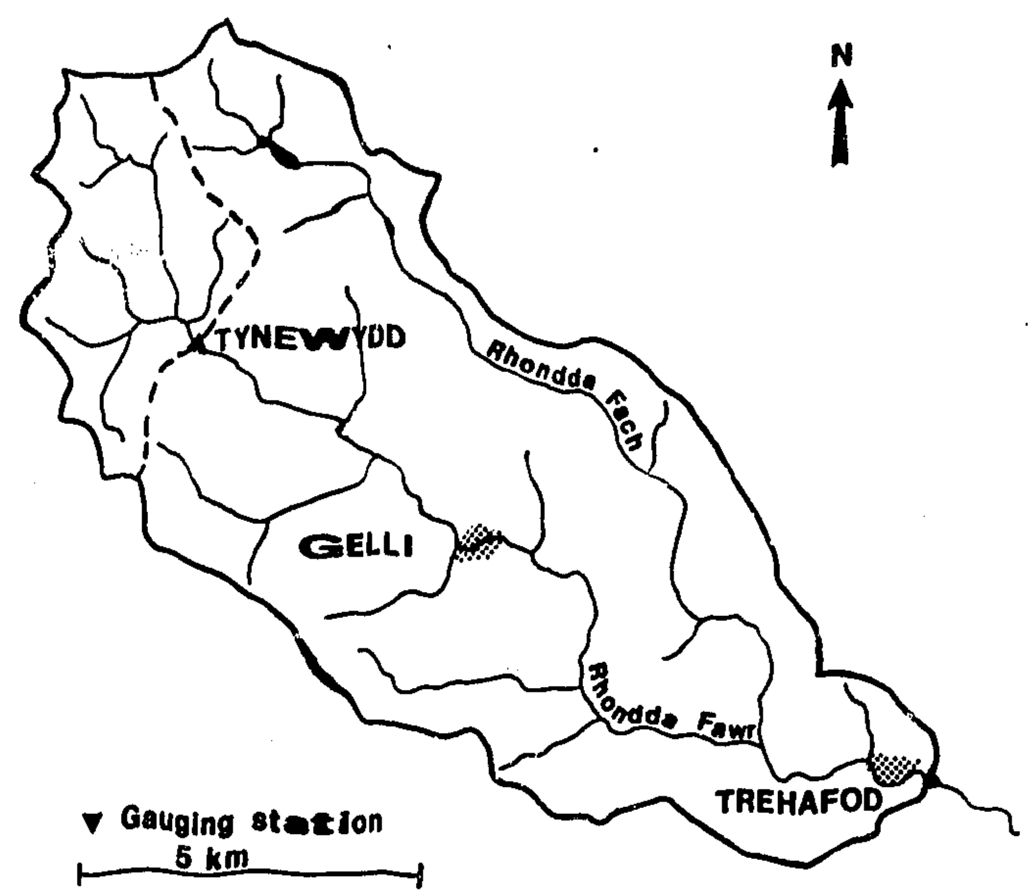


FIGURE 4.1.7

Rhondda at Trehafod - catchment plan

The speed of response to heavy rainfall is startling and the theoretical warning time provided by an upstream gauging station (Tynewydd) is limited to between about ½ and 1½ hours for the middle and lower reaches of the river⁺. Research[43] has confirmed that longer periods of warning could be possible by rainfall/runoff modelling only if quantitative forecasts of rainfall were available. It is perhaps not surprising that, following the severe floods experienced in December 1979, Welsh WA proceeded with major improvements to flood defences at Gelli and Trehafod[44].

4.1.3 Relevance of catchment response time

The above descriptions have hopefully drawn attention to the importance of catchment response time in determining feasible approaches to flood forecasting. Various definitions are possible but it is convenient to follow Flood Studies Report terminology and characterize catchment response time by Tp, the time to peak of the 1 hour unit hydrograph[45].

Given rainfall and runoff data for several flood events, it is possible to derive an average unit hydrograph for a catchment and, in effect, "observe" Tp. Alternatively, an estimate of Tp can be made from readily calculated catchment characteristics using the equation:

$$Tp = 46.6\ MSL^{0.14}\ S1085^{-0.38}\ RSMD^{-0.4}\ (1 + URBAN)^{-1.99}$$

where MSL is main stream length (km), S1085 is channel slope (m/km), RSMD is an index of flood producing rainfall (mm), and URBAN denotes the fraction of the catchment area that is urbanized.

Table 4.1.1 gives estimates of Tp for some catchments relevant to the six flood forecasting problems described in Section 4.1.2. Where available, "observed" values of Tp have been given for comparison.

Table 4.1.1 Some catchment response times

CATCHMENT	Tp VALUES estimated (hr)	Tp VALUES observed (hr)	
Ouse at York	15	-	
Roding at Redbridge	-	30	(rural component of response)
Tyne at East Linton	8	9	
Yeading Brook (W. Br.)	4.5	3	
Rhondda at Trehafod	4.5	2.5	

Taking these catchments to be broadly representative of British flood forecasting problems, an attempt is made in Table 4.1.2 to give guidance on matching the general approach to forecasting to the characteristic response time of the catchment.

Table 4.1.2 Implication of catchment response time for approach to flood forecasting - some approximate guidelines

RANGE OF Tp VALUES (hr)	APPROACH
Tp < 3	Rainfall/runoff modelling plus quantitative rainfall forecasts
3 < Tp < 9	Rainfall/runoff modelling
Tp > 9	Flood routing

⁺In practice, longer periods of warning can be provided by setting alert levels sufficiently low but at the expense of potentially more frequent false warnings.

Such generalizations are, of course, very crude. Before discussing the limitations of Table 4.1.2 we consider briefly the link with Table 4.1.1 and the example flood forecasting problems described earlier.

Rapidly responding catchments such as the Yeading and Rhondda pose a challenging flood forecasting problem. Whereas on the Rhondda, analysis has shown that quantitative rainfall forecasts are required if the existing (short-period) warnings are to be significantly enhanced[43], it is conceivable that progress might be made on the Yeading with a rainfall/runoff model alone[41]. Similarly, whereas the Tyne at Haddington requires a rainfall/runoff approach[30], it is conceivable that flows at East Linton might be forecast by flood routing. (The East Linton gauging station is sited approximately 8 km - and 2 hours travel time - downstream of Haddington). The Ouse at York and the rural component of the Roding at Redbridge are clearly suited to a flood routing approach.

Possibly the most suspect part of the Table 4.1.2 guidelines concerns the applicability of flood routing methods. The success of the routing approach stems primarily from the time advantage gained by basing warnings on river level at an upstream site rather than the risk site itself. This time advantage roughly corresponds to the mean flood wave travel time from the upstream station to the risk site. Since Tp is a measure of the time taken for a 1 hour pulse of rainfall to produce its greatest contribution to the catchment runoff rate, it is not a particularly appropriate index of flood wave travel time. (The difference between Tp values calculated for the upstream and downstream sites would be a better pointer). For example, research on Newborough Fen[46] has indicated that, while many fenland catchments have a fairly slow response to rainfall (ie. high Tp), flood routing methods of forecasting may be ineffective*.

Another situation where flood routing alone may be insufficient is on a generally slowly responding catchment that has one or more quick responding tributaries that are sometimes crucial to short-period flood forecasts. The answer is, of course, to combine flood routing and rainfall/runoff methods (see Section 4.5.1).

4.1.4 Contrast between flood forecasting and design flood estimation applications

The demands put on a rainfall/runoff or flood routing model for flood warning are rather different to those imposed in other applications, for example design flood estimation[45]. In the first instance, the model should be capable of providing a reasonable forecast based on data available at the time of forecast, ie. without recourse to additional information such as daily raingauge readings (or the time of peak flow!) that are available only in retrospect. This very obvious requirement is surprisingly easy to overlook when adapting flood estimation methods to flood forecasting.

In design flood estimation applications, the aim is to provide either a peak flow estimate or a stylized design hydrograph. In flood warning applications there is likely to be more emphasis on timings and the reproduction of distinctive shapes on the rising limb and crest segment of the hydrograph.

*This is because of the tendency for the main drain to behave more like an elongated reservoir than a graded channel, with water levels rising and falling in unison along the length of the drain and being more controlled by downstream conditions at the pumping station than by upstream inflows. Flood warning from upstream gauging stations may be similarly ineffective on largely groundwater-fed streams because of the dominance of storage effects over translation effects.

A further distinction is that flood forecasting on ungauged catchments is rarely considered*. Application of generalized models to ungauged catchments is inherently inaccurate. Whereas for engineering design a relatively uncertain flow estimate may be quite acceptable, for flood warning it may be better not to warn than to do so with great inaccuracy. In flood warning, some form of river level measurement at or near the risk site is highly desirable; otherwise it will be very difficult to interpret model forecasts.

This leads on to consideration of the most fundamental difference between flood forecasting and other applications : the use of downstream flow information available in real time. If, as is usual, the forecasts made refer to flow at a telemetered site, the opportunity exists to compare recent flow observations with the corresponding values simulated by the rainfall/runoff or flood routing model. We shall see in Section 4.4 that there are a number of alternative ways of making a "real time correction" to model forecasts although there is as yet little operational experience of such methods in British flood warning practice.

4.1.5 Ordering of material presented

Detailed consideration of flood forecasting techniques begins with flood routing methods (Section 4.2) and rainfall/runoff modelling methods (Section 4.3). These are very lengthy sections and some relaxation of conventions has been necessary to avoid tiresome subsection numbers and yet retain an overall structure in the report. Section 4.4 takes up the question of how best to correct forecasts by reference to telemetered flow data. Subsequent sections consider large river systems, rainfall forecasting and snowmelt forecasting.

4.2 Flood routing

4.2.1 Introduction

On many of the longer river systems in Great Britain, satisfactory flood warnings can be based on an upstream gauging station. This approach is generally to be preferred where practicable. The alternative of basing forecasts on rainfall measurement and rainfall/runoff modelling is more prone to error. It is, of course, the river that floods and for that reason a measure of river flow is generally a better indicator of flood potential than is rainfall. (By the same argument, flood routing methods can be of some use in floods arising from snowmelt whereas rainfall/runoff methods require special consideration of snow accumulation and melt.)

The upstream gauging station may be part of a general purpose river gauging network or be specifically designed for flood warning. A well-defined flood rating is desirable though not essential. Many of the simpler flood routing methods work in terms of river level rather than flow. It is, of course, river level at the risk site that is the crucial variable in terms of inundation and hence warnings are usually based and issued in terms of river level.

This section mainly discusses "pure" routing methods, ie. methods relying solely on river level and/or flow measurement. For the approach to be successful, the travel time of flood peaks from the upstream gauging station to the risk site needs to be long enough to allow an adequate period of warning to be given. (Say, 4 to 6 hours). But the gauging station must not be so far upstream that it is unrepresentative of flows to be expected at the risk site. The two criteria:

*One exception is in the representation of ungauged tributaries in comprehensive models of major river systems (see Section 4.5.1).

* far enough upstream to give a useful period of warning
* not so far upstream as to be unrepresentative

limit the applicability of pure routing methods to flood warning on fairly long river systems; but, as discussed in Section 4.1.3, it is difficult to generalize a definite rule.

In some cases, particularly on a long narrow catchment with few tributaries (eg. Fig 4.1.4), a gauge catching runoff from as little as 25% of the area may provide a good index of flooding to be expected. In other situations, for example on a fan-shaped catchment with no dominant tributary (eg. Fig.4.1.5), it is obvious that no matter where sited, an upstream gauging station will be insufficiently representative to form the sole basis of accurate flood warnings. Where there are two, or perhaps three, notable tributaries it may be possible to set up flood warning gauging stations on each (eg. Fig.4.1.2). Multiple correlation methods (Section 4.2.4) or flood routing models proper (Section 4.2.5 et seq.) can then be used to combine information from the tributary gauging stations and yield a forecast for the risk site. In such situations, the relative timing of the flood response on the various tributaries can be particularly significant.

The flood routing techniques in common use in Great Britain can be classed under four headings: experience methods, correlation methods, multiple correlation methods, and river routing models proper. The latter category is very wide, but the grouping here serves to illustrate that, proportionately, routing models are not yet widely used.

4.2.2 Experience methods

"Experience methods" are the fall-back technique of most authorities. The flood warning duty officer assesses the flooding to be expected by reference to an upstream gauging station, with personal judgement providing the model. To aid objectivity, the officer may turn to a register of previous floods. From this, a flood is selected that appears most similar to the current event, typically taking time of year and approximate duration of heavy rainfall into account. (This type of "experience" approach can, of course, also be used when there is no upstream gauging station, eg. when forecasting from rainfall information alone.) In essence these methods rely on future floods being formed, and transmitted through the river system, in comparable fashion to historical events. If records are also available for a downstream gauging station, experience methods can be consolidated into correlation techniques

4.2.3 Correlation methods

River level correlations between upstream and downstream gauging stations are probably the most common method of flood warning in Great Britain. In simplest form, the downstream peak river levels are plotted on ordinary graph paper against the upstream peak river levels, and a simple line or curve drawn through (eg. Fig.4.2.1). A formal regression analysis can be carried out in order to determine the best-fitting linear relationship for predicting downstream peak level from upstream peak level. Sometimes the relation is shown without the scatter of points from which it was derived (eg. Fig.4.2.2). This has the advantage of making for objectivity in the method - desirable if inexperienced or functional duty officers are to use it - but the drawback of implying that an absolute relationship holds.

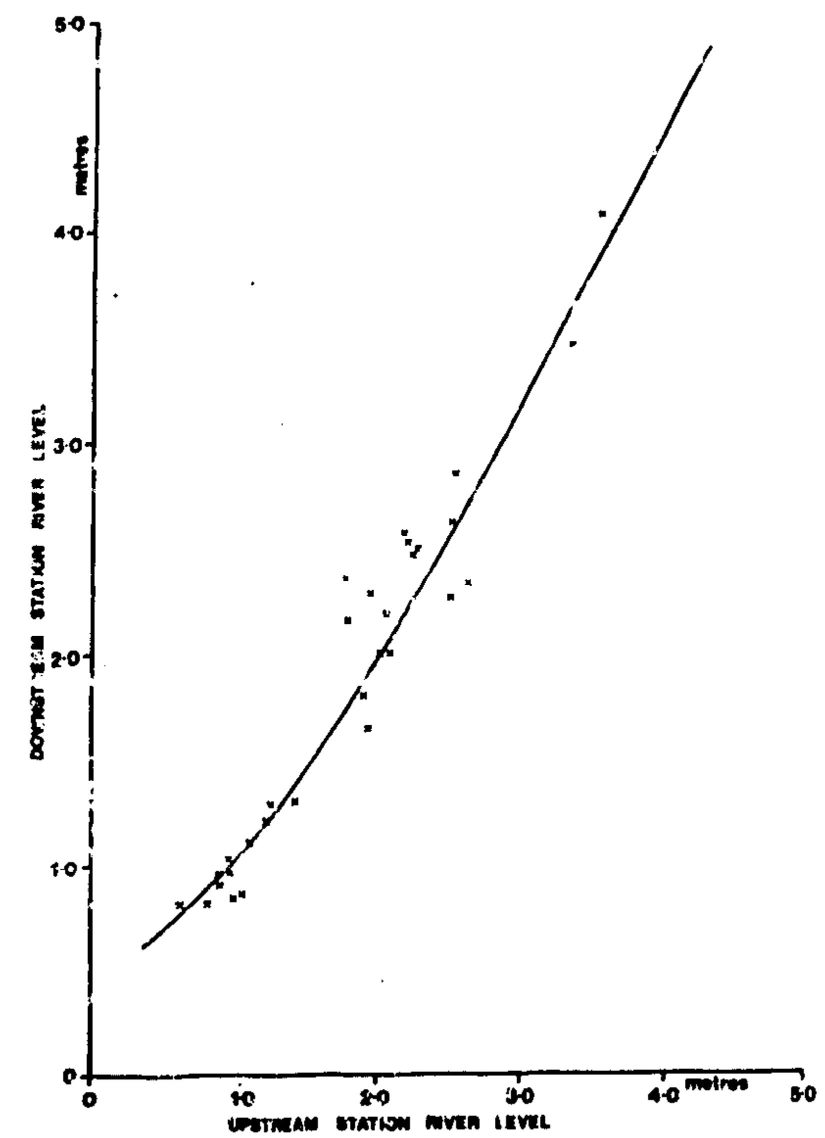


FIGURE 4.2.1

Simple upstream/downstream plot of peak river levels

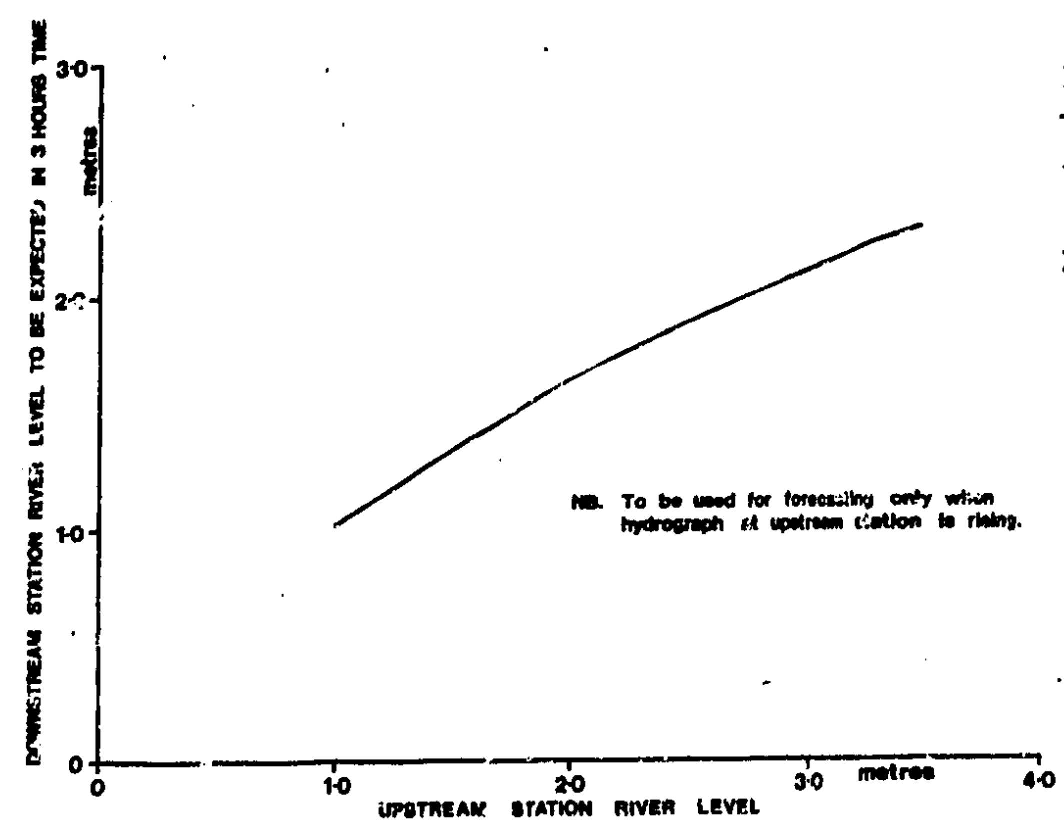


FIGURE 4.2.2

Upstream/downstream relationship between peak river levels

EXPLAINING THE SCATTER

If a long record of past events is available at both stations, an attempt is often made to explain some of the residual variation (or scatter) about the fitted

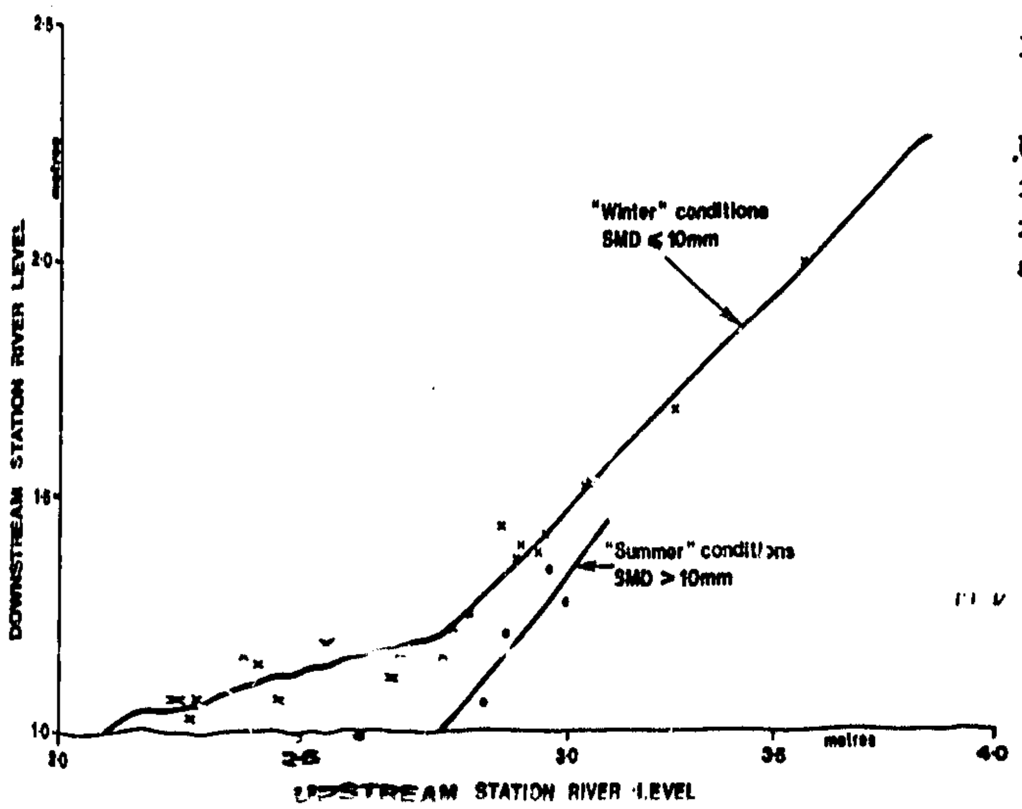


FIGURE 4.2.3

Upstream/downstream relationship between peak river levels for "summer" and "winter" conditions

relationship. For example, Fig 4.2.3 shows an explanation in terms of catchment wetness prior to the event. The inference is made that the intensity of flood runoff is attenuated (between the upstream and downstream gauging stations) more when the catchment is initially dry than otherwise. Note that the sub-relation for "summer" conditions is not extrapolated for use in major events; in an extreme flood, the antecedent catchment condition is less relevant. In Fig 4.2.4, the

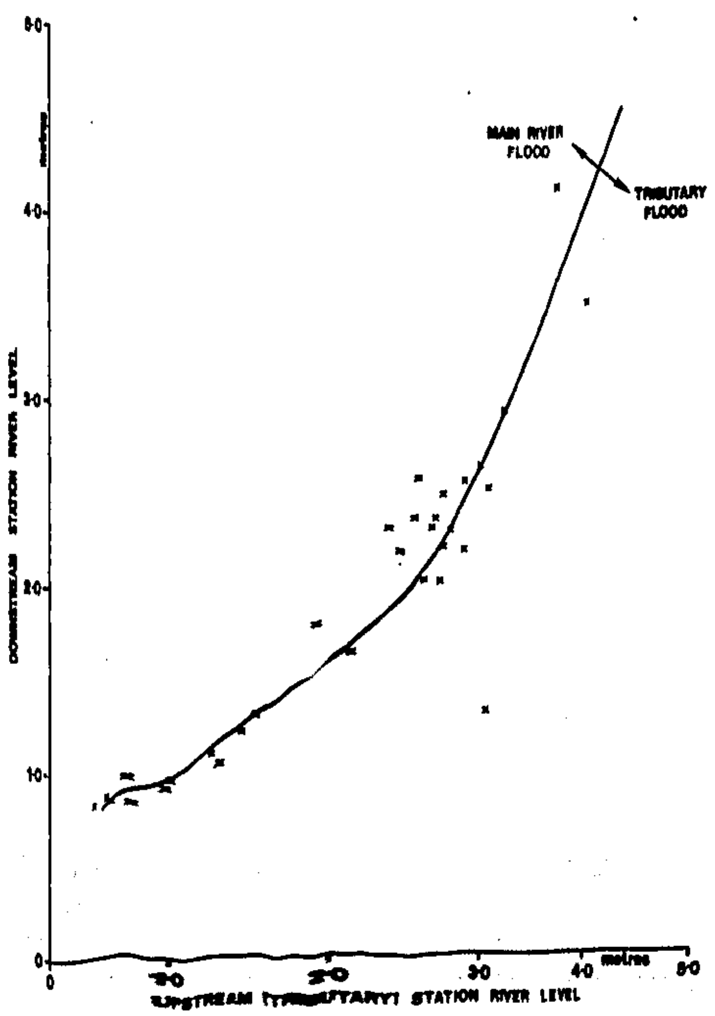


FIGURE 4.2.4

Upstream/downstream relationship between peak river levels indexed by representativeness of upstream station

scatter is attributed to how representative the upstream station is in a particular flood; for the example shown, the upstream gauging station is sited on a tributary rather than the main river.

FLOOD PEAK TRAVEL TIMES

Although not all authorites issue information on timings, an indication of the time at which peak river level (or some critical river level) can be expected is highly desirable and generally given. The simplest technique is to base the estimate on average travel times of previous flood peaks. With this approach the river level correlation gives height to be expected in (say) 3 hours time - as, for example, in Fig 4.2.2. If it is thought desirable for the duty officer to be aware of the uncertainty in the prediction of timings, a histogram of observed flood peak travel times can be inset on the level-to-level graph (eg. Fig. 4.2.5). Where experience has shown that the highest floods invariably propagate down the river system more quickly (not universally true of British rivers because of the attenuating effect of flood plain storage), it may be convenient to express the systematic component of travel time variation by an additional axis on the graph (eg. Fig 4.2.6).

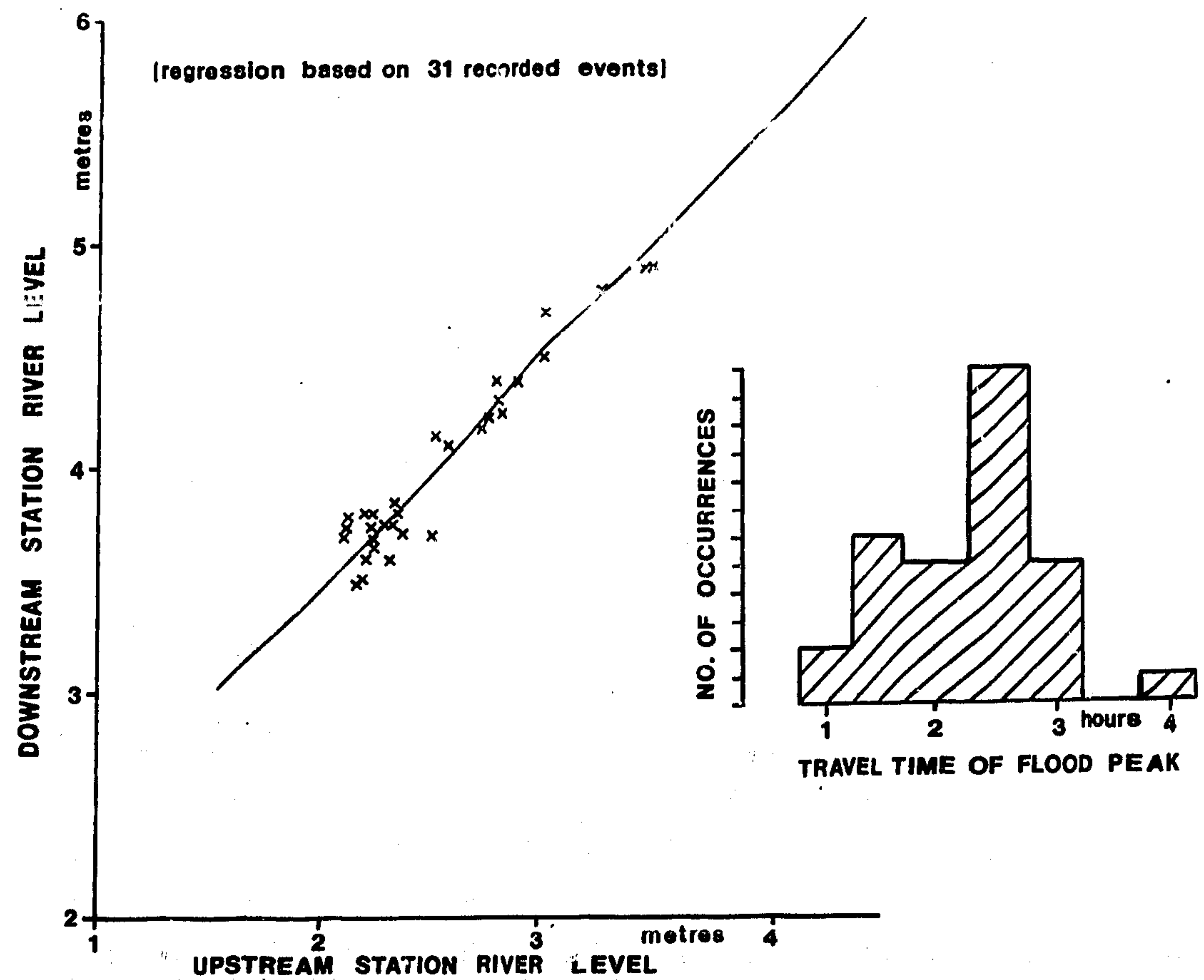


FIGURE 4.2.5 Level-to-level graph with histogram of travel times

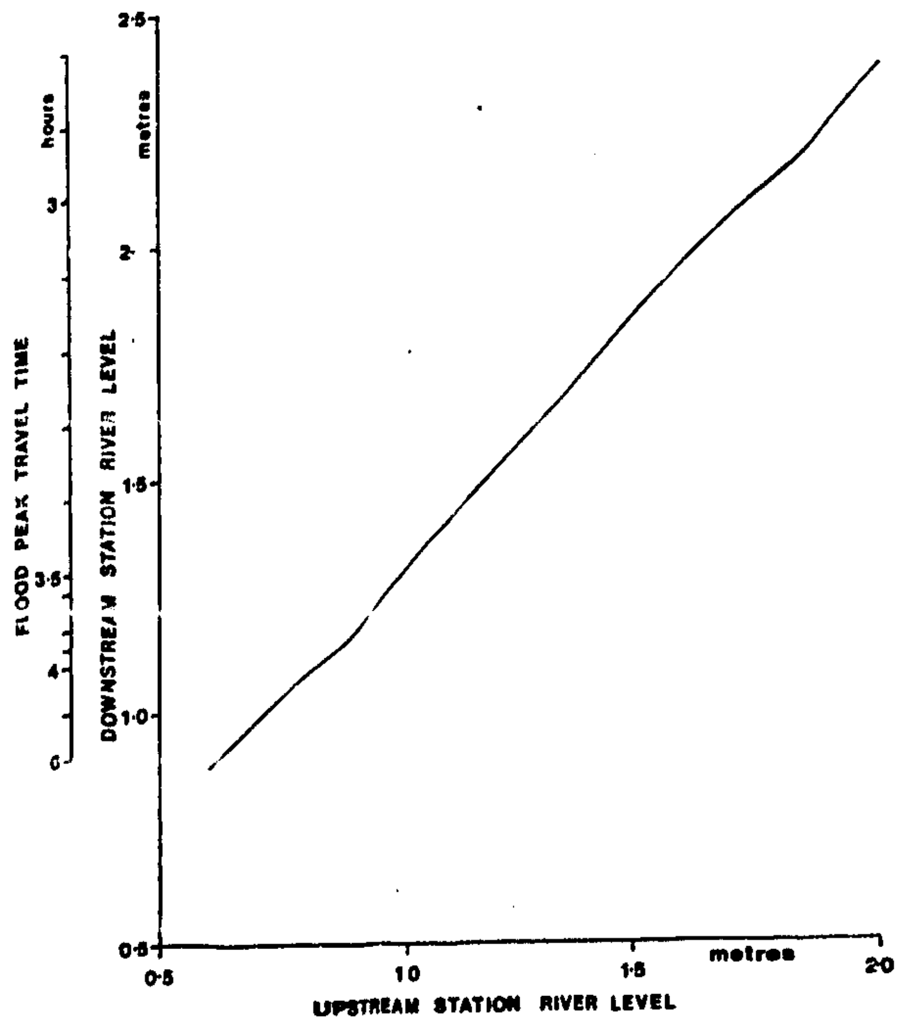


FIGURE 4.2.6

Upstream/downstream relationship - with travel time axis

USE ON RISING LIMB

Although usually derived by an analysis of <u>peak</u> river levels only, these level-to-level relationships are often successfully applied before the upstream hydrograph has peaked. For example, the issue of a new alert is generally linked to the exceedance of the relevant threshold at the upstream gauging station - to wait for the peak may be too late! In real time operation it is not always possible to detect that the upstream level has peaked until a short time later - another reason for using the relationship whenever a new upstream river level is sensed.

LEVEL OR FLOW ?

If rating curves are available for both upstream and downstream gauging stations there is the option of making the correlation in terms of flow rather than level. This would seem in principle to be a good idea. The flow in a river is a relatively conservative variable; it grows logically as each tributary joins but may also decay along a river reach where flood plain storage (or other effects) cause attenuation. In contrast, river <u>level</u> is more directly affected by local characteristics of the channel and may vary greatly (even allowing for datum levels) between the upstream and downstream sites. Working in terms of level is confusing if there have been any significant changes in channel or station structure during the period of record. Seasonal weed growth, or sediment problems, may create further discrepancies that can only be resolved satisfactorily by conversion to flows. Thus, carrying out the correlation in terms of flow would appear preferable - if practicable.

Against this it can be argued that it is ultimately the <u>level</u> at the risk site that is pertinent to flood warning and that derivation of a rating there may

be impractical. But is this relevant? In most cases the downstream gauging station is quite close to the risk site. While inferences of level at the latter may be problematic - perhaps requiring a simple hydraulic model of the intervening reach - this would seem to be quite a separate issue from how best to correlate measures between the two (relatively distanced) gauging stations.

Another criticism sometimes levelled against correlation of flows is that the necessary rating relationships are highly uncertain in extreme events. However, a counter to this argument is that extrapolation of level-to-level relations is <u>too</u> easy. Working in terms of flow makes one more aware of the uncertainties of extrapolation and provides a suitable incentive to refine rating relationships by direct gauging of flood flows.

Having put the case for deriving flow-to-flow correlations quite strongly, it is as well to remark that (once derived) such relations would usually be converted into level-to-level form for ease of application.

4.2.4 <u>Multiple correlation methods</u>

Where a river has two (or three) notable tributaries, eg. Fig 4.1.2, some form of multiple correlation may be successful in forecasting downstream river level from levels recorded at two (or three) upstream gauging stations sited on different tributaries. Such relationships can be derived either subjectively, by extension of the single station case (see Section 4.2.3) or formally, by multiple regression analysis.

The formal approach is to determine a predictive relationship by regressing observed peak river levels, h_d, at the downstream gauging station against the corresponding peak river levels, h_1, h_2, ... , at the upstream gauging stations; eg.:

$$h_d = a_o + a_1 h_1 + a_2 h_2 \qquad (4.2.1)$$

where a_o, a_1 and a_2 are parameters determined in the regression analysis. The approach is straightforward in theory but requires caution in practice. A large number of observations are needed to fit a 2-variable regression model such as Equation 4.2.1, if the parameters of the model are to be determined with reasonable accuracy. Having derived a relationship, this is often most effectively used in graphical form. A 2-variable regression model can be translated into a diagram displaying a family of relationships between the downstream station and upstream station no.1, indexed by river level at upstream station no.2 (see Fig 4.2.7). The approach is particularly appropriate where upstream station no.2 is on a less important tributary. This can be seen as a refinement to ad hoc methods of explaining the scatter about a simple upstream/downstream relationship (considered in Section 4.2.3). As before, it may be preferable to correlate flows rather than levels. Linear flow relations generally give nonlinear level relations, hence the curved lines in Fig 4.2.7. Figure 4.2.8 shows a co-axial presentation of three separate 2-variable regression models; this is for a large river system with four gauging stations on the main river and three gauged tributaries that join at discrete intervals.

Three-variable regression models - developed for three-pronged configurations such as the Ouse catchment to York (Fig 4.1.2) - are very demanding in data. Perhaps 40 flood events, recorded at each of the three upstream gauging stations and at the downstream gauging station, would be sufficient to determine the (four) model parameters. But multiple correlation is not always an appropriate technique, even when the necessary data are available. A basic problem is that

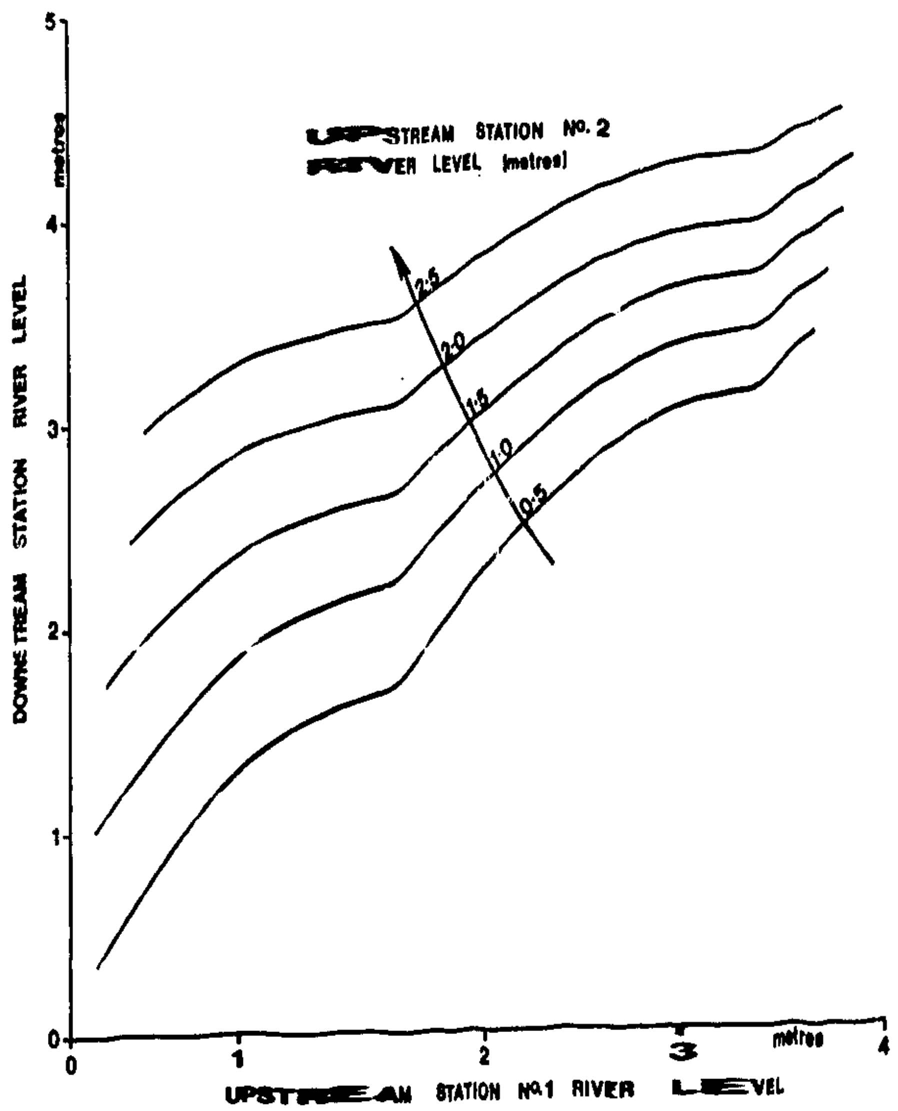


FIGURE 4.2.7

Graphical presentation of a 2-variable regression model for peak river level forecasting

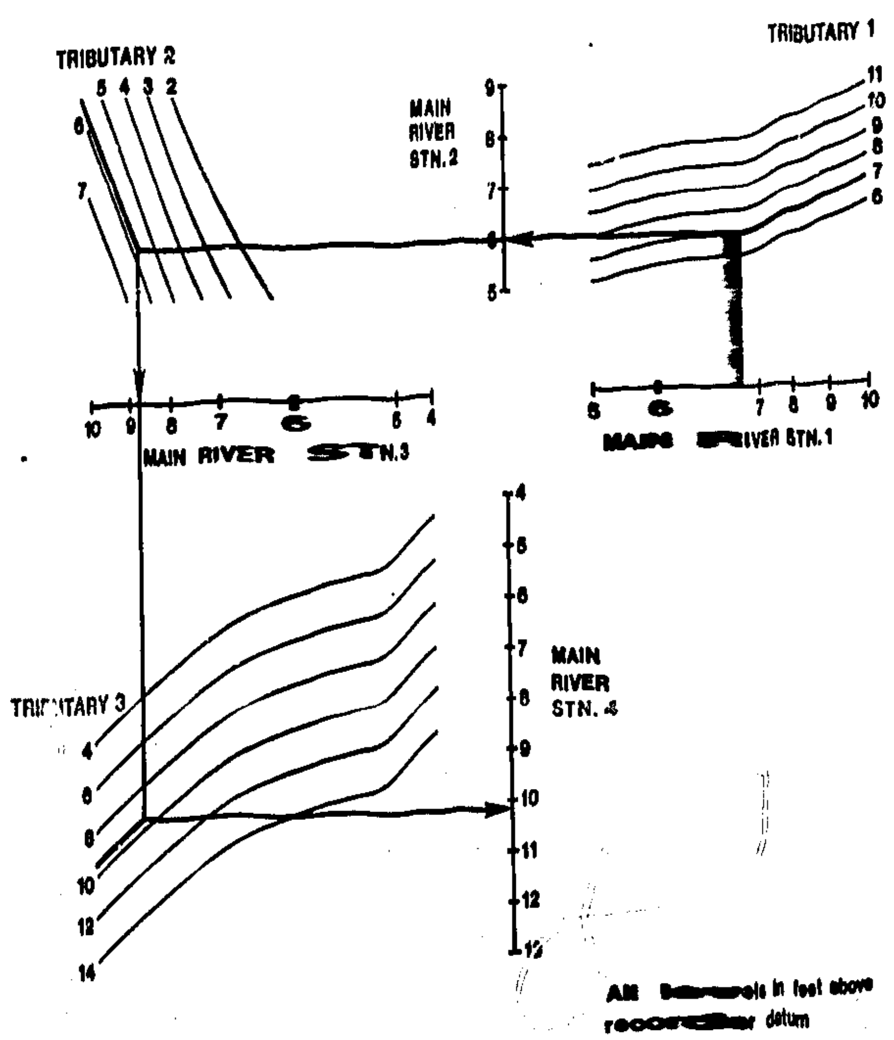


FIGURE 4.2.8

Co-axial diagram for peak river level forecasting along a main river with several discrete tributaries

tributary hydrograph response shape and timings may concur in some events and differ in others. In such circumstances the complete upstream hydrograph, as opposed to just its peak value, is pertinent to forecasts of downstream conditions. If this weakness is found or feared it is probably advisable to move to river routing models proper.

4.2.5 River routing models - suitability for flood warning

It should be noted at the outset that little use has yet been made of river routing models for operational flood warning in Great Britain. However, with real time computing now a reality in a number of water authorities, the scope for applying more sophisticated techniques (than "experience" and correlation methods) is widening. Allied to this is the interest already being shown in using river routing models in the design of river improvement works.

Two broad classes of river routing models can be distinguished: hydraulic and hydrological. The hydraulic methods are generally based on solution of the St. Venant equations for gradually varying flow in open channels, either in full or with simplifying assumptions. The better known simplified hydraulic models are the kinematic wave and linear diffusion equation methods. The hydrological models are most often based on storage routing - as in the Muskingum method. Another hydrological approach, though less common, is to emulate the rainfall/runoff modeller by adopting a simple empirical model - such as the unit hydrograph - to interrelate upstream and downstream flows.

SIMPLE OR COMPLEX MODELS?

A full solution of the St. Venant equations would appear to be the ideal approach; being physically well-founded, the method should be accurate. But the approach has disadvantages, most notably in data requirement. Extensive channel and flood plain surveys are needed, not only topographic but also to determine suitable roughness coefficients. Moreover, intricate programming and a powerful minicomputer are needed to implement the full solution in real time. If the simpler models can do the job almost as well, are the complex methods worth applying? The merits and limitations of simpler models are summarized in Table 4.2.1, with apologies to Miller and Cunge[47], on which the format (and some of the detail) of the table is based.

Information gathered in this review suggests that flood warning authorities in Great Britain view the more complex hydraulic models with suitable suspicion. These are being adopted only in special circumstances: where simpler methods clearly fail or where detailed models are available as a by-product of other studies*. The most obvious example of the former is when, due to tidal influence or tributary interaction, backwater and drawdown effects make for a non-unique relationship between level and flow. Sophisticated hydraulic-based models such as FLUCOMP[48] - developed by the Hydraulics Research Station - then have a role to play, although as yet no operational experience of such methods has been gained by British flood warning authorities. (Severn-Trent WA is currently assessing a variant of FLUCOMP to provide forecasts in tidally affected reaches.)

The remainder of this chapter dwells on the Muskingum family of methods - for the following reasons. Firstly, the Muskingum, Muskingum-Cunge, and variable

*Hydraulic models, either physical or mathematical, are used fairly widely in the design of major river improvement works. Such works often produce a change in the routing effect, thus disturbing flood warning methods based on "experience" or level-to-level correlations.

Table 4.2.1 <u>**Merits and limitations of of simplified routing models**</u>

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. 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. Simplified routing models may be more readily integrated with hydrological models of subcatchments.
6. 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 drawdown 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.

parameter Muskingum-Cunge (VPMC) methods are collectively the most popular river routing models used in Great Britain. Secondly, the interrelationship of the methods - in particular, the analogy with the linear diffusion method - is not always well understood. And thirdly, the methods have much to commend them for real time forecasting applications.

4.2.6 <u>Muskingum method</u>

The Muskingum method is based on simple ideas relating to the storage of flood water in a river reach. Storage, S, is increased by inflow, I, and reduced by discharge, Q, according to the continuity equation:

$$\frac{dS}{dt} = I - Q \qquad (4.2.2)$$

Using the concept of total storage comprising "prism" storage and "wedge" storage (see, for example, Wilson[49]), McCarthy[50] formulated the storage function:

$$S = K[\varepsilon I + (1-\varepsilon)Q] \qquad (4.2.3)$$

where the storage coefficient, K, has the dimension of time and ε is a dimensionless weighting factor. This is generally known as the Muskingum equation.

Writing Equation 4.2.2 in finite difference form we have:

$$\frac{S_2 - S_1}{\Delta t} = \frac{I_1 + I_2}{2} - \frac{Q_1 + Q_2}{2} \qquad (4.2.4)$$

where suffices 1 and 2 denote values at the beginning and end of a routing period of duration Δt. Application of Equation 4.2.3 at both instants yields:

$$S_2 - S_1 = K[\varepsilon(I_2 - I_1) + (1 - \varepsilon)(Q_2 - Q_1)] \qquad (4.2.5)$$

Finally, combining Equations 4.2.4 and 4.2.5, we obtain on rearrangement:

$$Q_2 = C_o I_2 + C_1 I_1 + C_2 Q_1 \qquad (4.2.6)$$

where

$$\begin{aligned} C_o &= -(K\varepsilon - \Delta t/2)\ /(K - K\varepsilon + \Delta t/2) \\ C_1 &= (K\varepsilon + \Delta t/2)\ /(K - K\varepsilon + \Delta t/2) \\ C_2 &= (K - K\varepsilon - \Delta t/2)/(K - K\varepsilon + \Delta t/2) \end{aligned} \qquad (4.2.7)$$

Equation 4.2.6 is the operational form of the Muskingum method; it is used in a step-by-step fashion to determine the outflow (from the reach) from the inflow hydrograph and knowledge of the outflow at some initial time (eg. the beginning of the flood event).

Calibration of the model requires evaluation of the Muskingum parameters K and ε. Various graphical and analytical techniques have been used - particularly in US practice - with an element of trial and error being customary. (See, for example, Linsley et al[51]).

ALLOWANCE FOR TRIBUTARY AND LATERAL INFLOWS

In all river routing models there is the question of allowing for ungauged lateral inflow and/or gauged tributary inflow to the reach. It is convenient to discuss such allowances in the context of the Muskingum method.

Usually the routing reach is defined by upstream and downstream gauging stations. We shall see later that the division of the reach into several subreaches is an important aspect of the Muskingum-Cunge method for rather esoteric reasons. But our interest here is that the subdivision allows gauged tributary flows to be added into the river model part way down the reach, to mimic the actual river system. (See Fig. 4.2.9.) As well as enabling gauged tributary flows to be included at an appropriate point, the procedure can be used to allow for ungauged inflows along the reach. These <u>lateral</u> inflows are usually estimated to be a fixed proportion of a nearby gauged subcatchment flow (quite often, of the upstream gauging station) with a time offset if appropriate; the proportion is generally calculated by area, sometimes factored by averaged annual rainfall. Alternatively, tributary and/or lateral inflows can be based on rainfall measurement and a rainfall/runoff model. (See Section 4.5.3). The lateral inflows (however estimated) are generally apportioned by subreach length and each one treated as an additional inflow to the subreach; the inflow is then said to have been "distributed" along the reach.

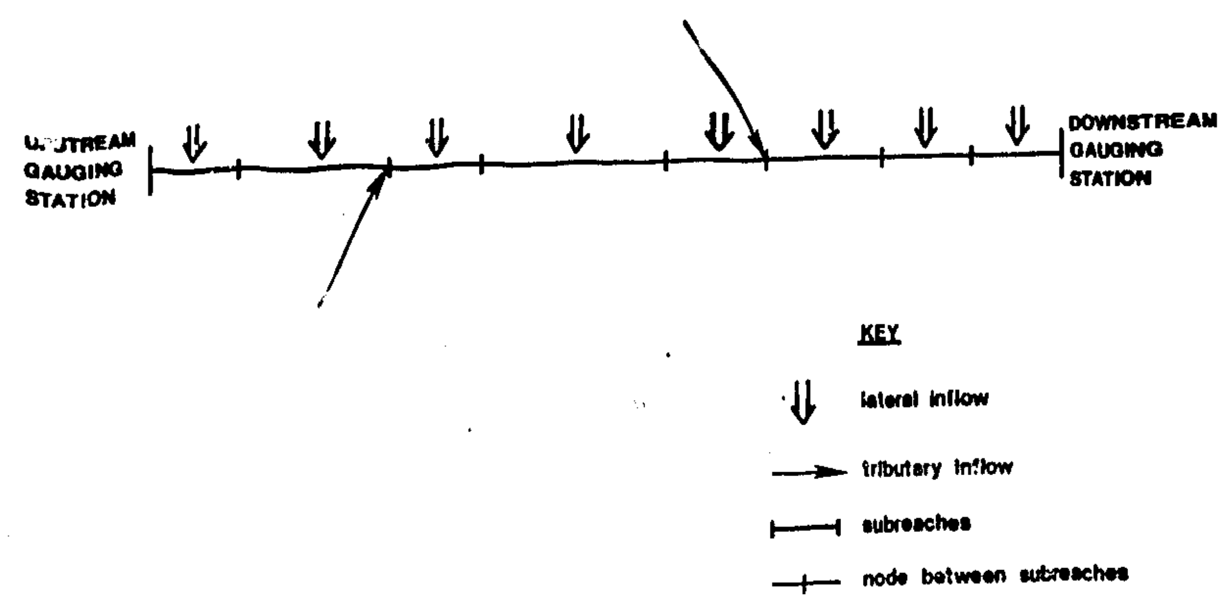


FIGURE 4.2.9. Typical structure of a river routing model representation of a reach

With the division into subreaches, the problem arises in the Muskingum method of how to assign parameter values K and ε to the subreach models. A rough-and-ready technique is to apportion the reach value of K by subreach lengths, and to retain the reach value of ε throughout. But, because the basic Muskingum method is purely empirical, one is left to experiment with fairly arbitrary choices.

From the above analysis there is little to commend the Muskingum method apart from its simplicity of implementation (by Equation 4.2.6), once calibrated. Cunge's recasting of the method[52] as an approximation to the linear diffusion equation solution - completely re-vitalises the technique and puts it in the category of a simplified hydraulic routing model. As we shall see, the essential simplicity of implementation is retained.

4.2.7 <u>Muskingum-Cunge method</u>

The essence of Cunge's refinement[52] is that, with an appropriate choice of space and time steps (ie. subreach length Δx, and routing period, Δt), the Muskingum method can provide a good approximation to solution of the linear convection/diffusion equation:

$$\frac{\partial Q}{\partial t} + \omega\frac{\partial Q}{\partial x} = \mu\frac{\partial^2 Q}{\partial x^2} \qquad (4.2.8)$$

Here Q(x,t) is flow in the river at displacement x and time t, ω the kinematic wavespeed parameter, and μ the diffusion parameter.

The linear diffusion equation arises from a simplification of the St. Venant equations. In most British rivers the primary influence on momentum is that of the friction slope, with a secondary effect due to the water surface slope. Assuming that a unique relationship holds between depth and flow, and making various other assumptions[53], the St. Venant equations simplify to Equation 4.2.8. The least reasonable assumption made is that the wavespeed and diffusion parameter (ω and μ) are constants. This limitation is removed in the variable parameter Muskingum-Cunge (VPMC) method - discussed in Section 4.2.8 - in which ω and μ are permitted to vary with flow, Q.

From Cunge's analysis it can be deduced that:

$$Q_{x+\Delta x,t+\Delta t} = c_0 Q_{x,t+\Delta t} + c_1 Q_{x,t} + c_2 Q_{x+\Delta x,t}$$

or, in Muskingum notation:

$$Q_2 = c_0 I_2 + c_1 I_1 + c_2 Q_1 \qquad (4.2.6)$$

provides an acceptable finite difference representation of the linear diffusion equation (Equation 4.2.8) if:

(i)
$$\begin{aligned} c_0 &= (\omega\Delta x - 2\mu - \omega^2\Delta t)/(\omega\Delta x + 2\mu + \omega^2\Delta t) \\ c_1 &= (\omega\Delta x - 2\mu + \omega^2\Delta t)/(\omega\Delta x + 2\mu + \omega^2\Delta t) \\ c_2 &= (\omega\Delta x + 2\mu - \omega^2\Delta t)/(\omega\Delta x + 2\mu + \omega^2\Delta t) \end{aligned} \qquad (4.2.9)$$

and (ii) the space and time steps are chosen to satisfy:

$$\Delta t > 1.625\ \mu/\omega^2 \quad \text{and} \quad 2.6\ \mu/\omega < \Delta x < 1.6\ \omega\Delta t \qquad (4.2.10)$$

The inequalities are taken from recent work by Jones[54] which corrects flaws in Cunge's original analysis. Jones presents more comprehensive rules for selecting Δx and Δt but, if inequalities 4.2.10 are satisfied, his analysis shows that an accurate approximation to the linear diffusion equation solution is assured. Although it is customary to work in terms of K and ε, where:

$$K = \Delta x/\omega \quad \text{and} \quad \varepsilon = \frac{1}{2} - \frac{\mu}{\omega\Delta x} \qquad (4.2.11)$$

their avoidance is both simpler and theoretically sounder[55].

In choosing the time interval, Δt, it is important to bear in mind also steepness of the flood hydrographs to be routed. If the upstream hydrograph is to be defined adequately, the time interval should be no more than about one fifth of the hydrograph rise time. Thus we have the added condition:

$$\Delta t < 0.2\ T_R \qquad (4.2.12)$$

where T_R is the shortest hydrograph rise time that is likely to be of concern.

Implementation of the Muskingum-Cunge method is very straightforward: all that is required is repeated applicated of Equation 4.2.6 with appropriate allowances for tributary and lateral inflows (see Section 4.2.6). Calibration of the method is, however, quite complicated. Details of how μ and ω can be estimated from channel geometry and observed flood peak travel times are given in Appendix 1.

If the Musk... ...ge method has a critical weakness, it lies in the assumption that ... is independent of flow. Simple hydraulic considerations demonstrate that ... velocities increase with stage while the flow is within bank. Hence the m... is unlikely to give reliable results if applied well below or above its range of calibration. This limitation is avoided in the variable parameter Muskingum-Cunge method.

4.2.8 Variable parameter Muskingum-Cunge method

In the variable parameter Muskingum-Cunge (VPMC) method the wavespeed parameter, ω, and diffusion parameter, μ, are permitted to vary with flow, Q. Calibration of VPMC is based on evaluation of ω and μ for a range of flows, for both within bank and out-of-bank conditions. The calculation formulae for ω(Q) and μ(Q) have the same basis as in the fixed parameter case. (See Appendix 1). A typical pattern of variation of ω is shown in Fig 4.2.10. In practice some adjustment to the wavespeed curve is often made following trial routings with the model.

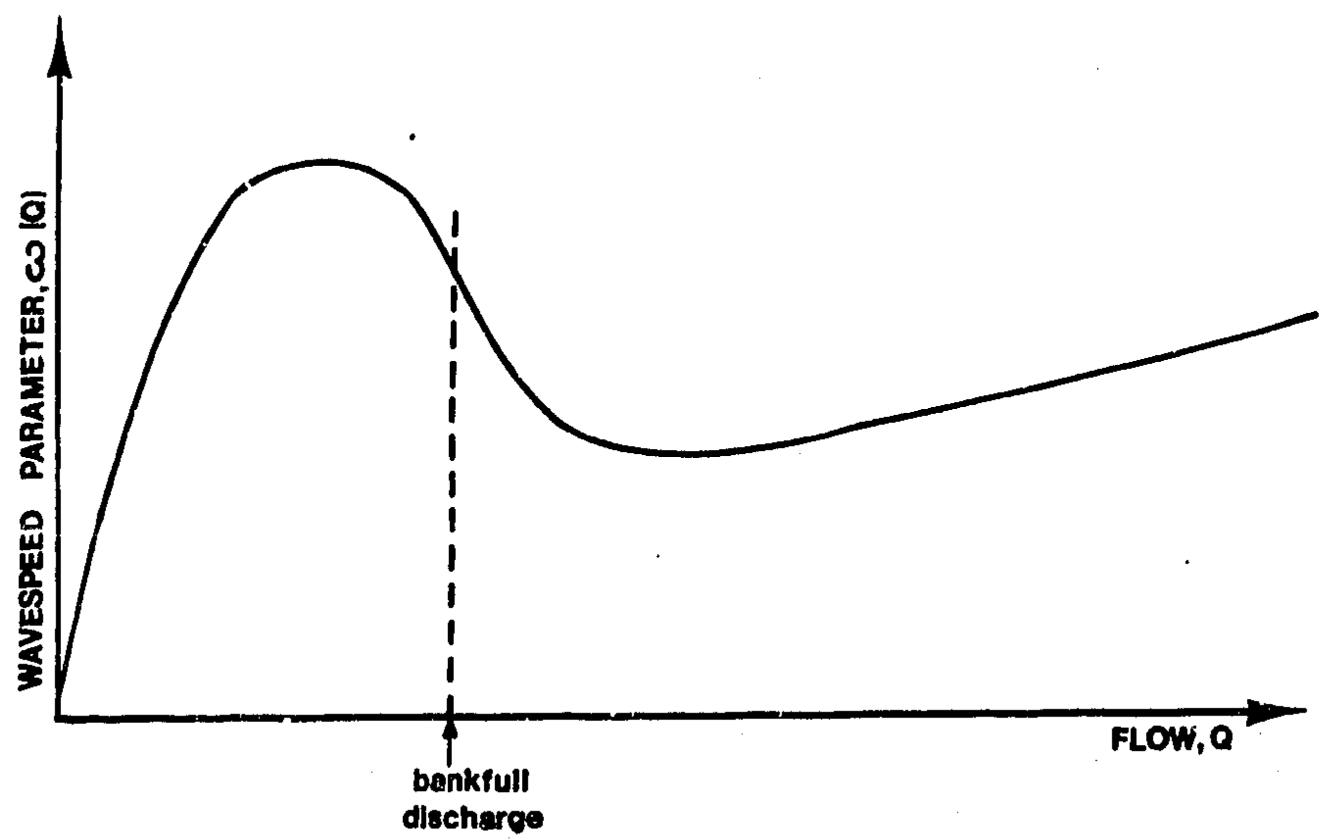


FIGURE 4.2.10 Typical pattern of wavespeed parameter variation with flow

Full details of the VPMC method are given in Price's report "FLOUT - a river catchment flood model"[56]. The FLOUT package comprises VPMC flood routing and (optional) subcatchment rainfall/runoff modelling. Its primary application is in design flood estimation on large river systems, for which it is being increasingly used. The principal merits of VPMC are that it offers a degree of physical realism, and flexibility to use flood peak travel time data, without making undue demands for topographic and roughness data. One drawback of the method - apart, of course, from its inability to deal directly with tidal or backwater influences - is that a large number of observed flood peak travel times may be required to determine the wavespeed parameter curve with confidence.

Development of the VPMC method for flood forecasting has been carried out, or sponsored, by several water authorities[57 58 59], although it is as yet not routinely used. It is interesting to note that a forerunner of the method - the variable parameter diffusion (VPD) method - was developed for real time use as long ago as 1975, and remains an active part of the Dee river hydrological forecasting model[60 2].

4.2.9 Other river routing models

Pending detailed comparisons with VPMC, Severn-Trent WA have implemented a home-grown routing model called DODO. This might be described as a variable lag, two-part storage routing method; its most distinctive feature is the separate treatment of inbank and out-of-bank flows. There is also an allowance for water entering "dead" (ie non-flowing) storage. DODO is calibrated by numerical optimization (see Appendix 2) and has been applied to about 90 reaches in the Severn and Trent basins. Most of the reaches are defined between gauging stations but a few enable routing of subcatchment flows produced by a rainfall/runoff model. The method has the strength of simplicity in implementation but, as yet, a slightly hazy theoretical background. It is, however, gratifying (at least, from an applied research standpoint) to see a river routing model being evaluated operationally on such a large scale.

Although not so legion as rainfall/runoff models, many other river routing models have been formulated, some with potential for real time application. Jones and Moore[61], for example, present a simple channel flow routing model in which travel speed is allowed to vary with discharge. While analogous to VPMC in some respects, this model has the particular merit of being able to make direct use of downstream flow data (sensed in real time) to adjust forecasts. We discuss the general topic of "real time correction" in Section 4.4 although not with specific reference to river routing models.

The estimation of lateral inflows bedevils all river routing models. Section 4.2.6 discussed the problem in the context of the Muskingum method and outlined some of the semi-standard ways of allowing for ungauged inflows. A more radical approach is as follows. First, a preliminary estimate of the routing model parameters is obtained and the upstream hydrograph routed to the downstream site without any allowance for lateral inflows. The simulated hydrograph is then compared to the actual, and the shortfall attributed to ungauged inflows. A further step would be to attempt to relate this "residual" hydrograph to rainfall on the relevant subcatchment areas, thereby calibrating a model for the lateral contribution. Alternatively, inspection of the residual hydrograph may serve to confirm that a particular way of allow... ...teral inflows is reasonable. The procedure has the merit of attempting ... ...l use of the downstream site data. But it should be noted that ... of the downstream hydrograph into routed and locally generated comp... ...only strictly valid if the sub-models are linear, eg fixed paramete... ...um-Cunge routing and a linear rainfall/runoff model.

Returning to simple methods, a longstanding alternative to Muskingum is the "lag and route" approach. The flood routing is accomplished by lagging (ie delaying) the inflow hydrograph by a fixed time and then routing it through a hypothetical storage (often, a "linear" reservoir). Sometimes referred to as Clark's method[62 63], use of the technique persists elsewhere but not, it seems, in Britain. Precisely the same "lag and route" approach can be used as a rainfall/runoff model, and this is considered in detail in the next Section under the heading "nonlinear storage models". Somewhat paradoxically, the latter usage is very much a British speciality.

4.3 Rainfall/runoff modelling

In what follows, rainfall/runoff modelling techniques of flood forecasting are considered under four headings:

M1. UNIT HYDROGRAPH METHODS
M2. NONLINEAR STORAGE MODELS
M3. TRANSFER FUNCTION MODELS
M4. CONCEPTUAL MODELS.

A local numbering convention has been adopted in this Section and the prefix "4.3" dropped. It is hoped that this aids readability while retaining some structure in the report as a whole.

There is, of course, scope to apply "experience" methods when seeking to forecast peak flows from rainfall (cf. flood routing discussion of experience methods, Section 4.2.2). Some authorities - for example, Anglian WA Lincolnshire River Division - maintain a register of historic floods for consultation during a flood event. Such information can be developed by a combination of regression analysis and reasoned conjecture into co-axial correlation methods of flood forecasting, perhaps the best known example of which are the "Linsley curves"[64]. Whereas correlation methods clearly have a useful role in flood routing (see Sections 4.2.3 and 4), the rainfall/ runoff equivalents have generally fallen into disuse. Perhaps an explanation for this lies in the realization that rainfall data have more influence in flood forecasting than can be expressed by depth and duration alone.

M1 UNIT HYDROGRAPH METHODS

M1.1 Introduction

Unit hydrograph techniques have been considered for flood forecasting by many water authorities. Anglian WA Essex River Division have unit hydrograph methods that are used operationally for flood warning[65]. The Lincolnshire River Division have a similar scheme although it is not yet implemented on a dedicated minicomputer. The flood warning scheme operated by Wessex WA Somerset Division[66] is another fully operational, minicomputer-based system but differs in using transfer function models rather than unit hydrograph models. As we shall discuss in Section M3.5, these two classes of rainfall/runoff model have several similarities but also some important differences.

The unit hydrograph approach is unfashionable amongst hydrological researchers. Physical modellers argue that advances in hydrological forecasting will only come through adopting models that take explicit account of the physics of flood formation[67]. Advocates of statistical methods criticize the unit hydrograph approach for being inefficiently parameterized and ill-suited to real time forecasting[3]. However valid these criticisms, scientific endeavour is no substitute for engineering pragmatism; it is clear that the unit hydrograph technique still has something to offer the forecaster who seeks a simple but effective representation of catchment flood response.

M1.2 Structure

The unit hydrograph approach to modelling the link between rainfall and runoff has two striking features. The first point to note is that the transformation is broken down into steps: rainfall is reduced to net rainfall by the abstraction of "losses", then net rainfall is transformed into rapid response runoff by the unit hydrograph itself, and finally an allowance is made for slow response runoff. (See Fig M1.1). The second notable feature is that a linear relationship is assumed between net rainfall and rapid response runoff - the relationship being uniquely defined by the unit hydrograph.

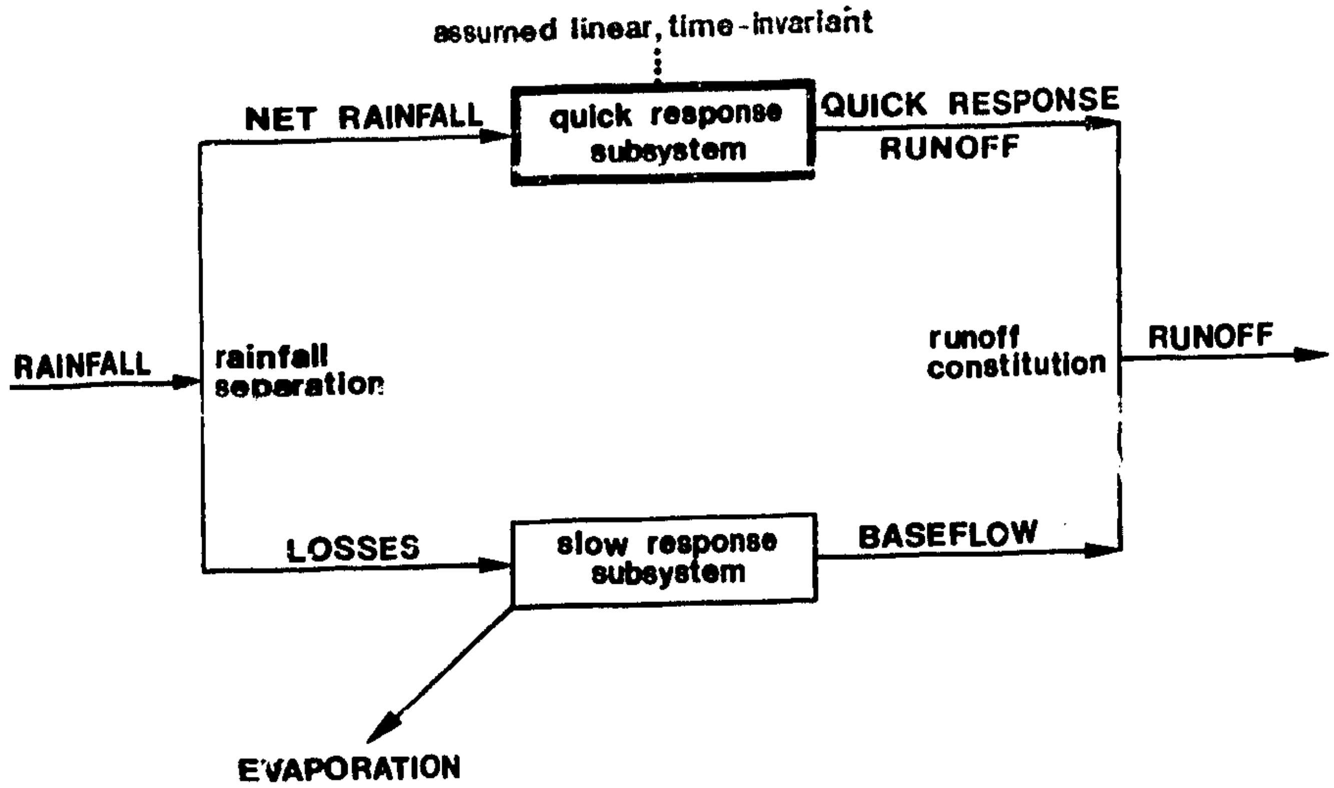


FIGURE M1.1 A system representation of the unit hydrograph approach

This assumption of linearity - which, incidentally, does not mean that the overall model structure is necessarily linear - has the great merit of allowing powerful techniques of linear systems analysis to be used to calibrate the core of the model. Whereas many other rainfall/runoff models have to rely on indirect methods of fitting (ie. "trial and error" or numerical optimization), the unit hydrograph model can be calibrated by a direct analysis of recorded rainfall/runoff events. This is undoubtedly a redeeming quality.

M1.3 Unit hydrograph derivation

There are many methods of unit hydrograph derivation. Some of the differences in formulation are radical enough to make for a distinct end-product.

For example, adoption of a particular functional form (such as Nash's choice of a Gamma distribution for the instantaneous unit hydrograph[68]) will restrict the derived unit hydrograph quite severely. But if a general method of linear systems analysis is used[69 70] the outcome is unlikely to be greatly influenced by the choice of technique.

Many analysis techniques have been proposed for unit hydrograph derivation, of which some are more successful than others in combatting instabilities that can arise in the analysis of individual flood events[45 71 72]. However, if, as is usual, merely an average unit hydrograph is being sought from consideration of a number of events, adoption of some simple standard method of unit hydrograph derivation is generally adequate[73 74]. The most widely used technique in British practice appears to be the least-squares ordinate method (alias "matrix inversion") with or without smoothing[45]. For those seeking to minimize computational effort, the technique of superposing events prior to derivation offers a short-cut to an average unit hydrograph[74].

M1.4 Rainfall separation

More crucial than the method of unit hydrograph derivation is the choice of a rainfall separation technique. Prior to publication of the Flood Studies Report, the most frequently considered techniques were loss rate methods: eg. the fixed loss rate (ϕ-index) method and Horton's method. (See Fig M1.2). The variable loss rate concept is based on the theory of a limited capacity for a given soil type to absorb water by infiltration, the capacity decreasing as the soil moisture content rises. Although such threshold effects are clearly important on small homogeneous areas, the loss rate approach is less relevant at catchment scale. Vegetation, soil inhomogeneity and topographic slope all influence the extent to which rainfall is "lost" as far as the generation of rapid response runoff is concerned. In particular, the loss rate approach makes no allowance for the fact that much of the runoff may be arising from only part of a catchment. This concept of "contributing areas" can be represented in proportional loss methods of rainfall separation. (See Fig M1.3).

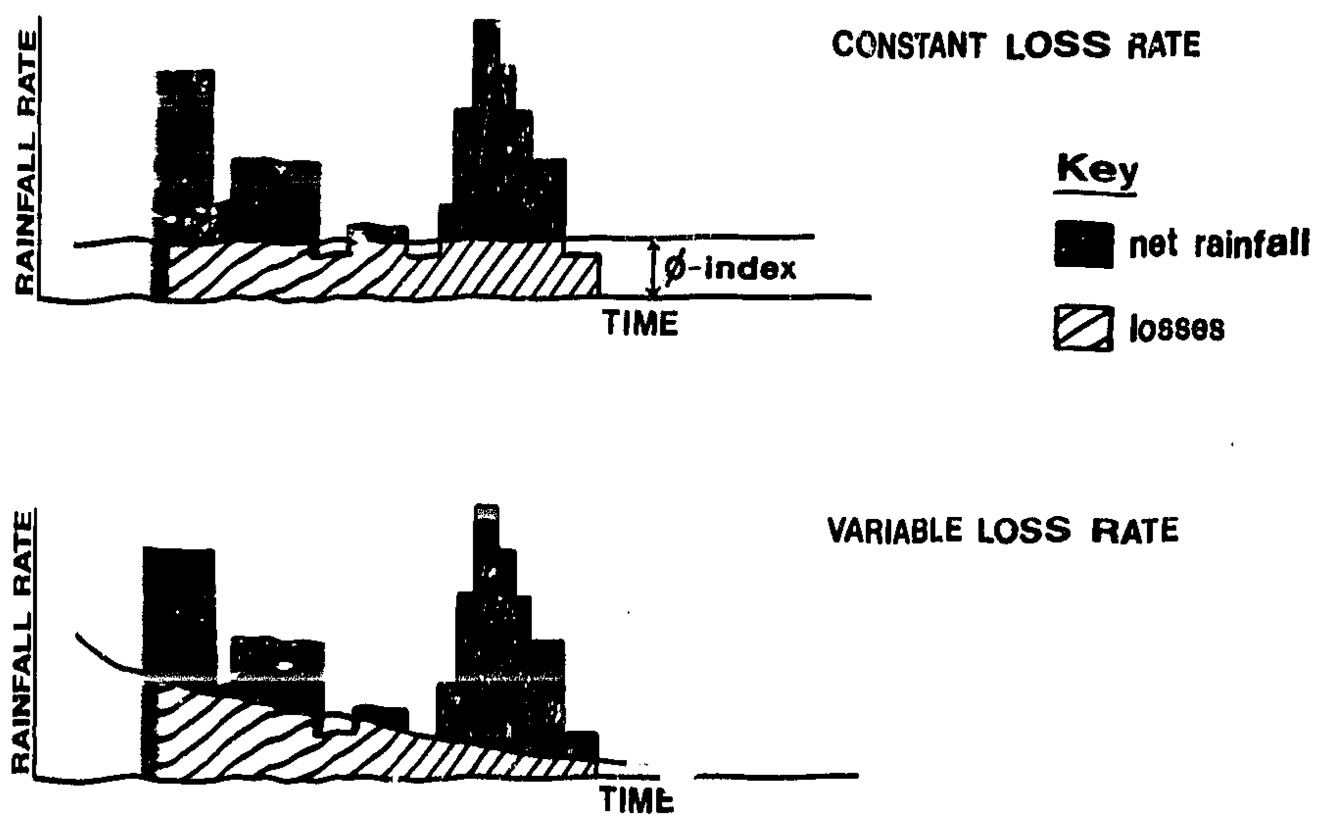


FIGURE M1.2 Rainfall separation - loss rate methods

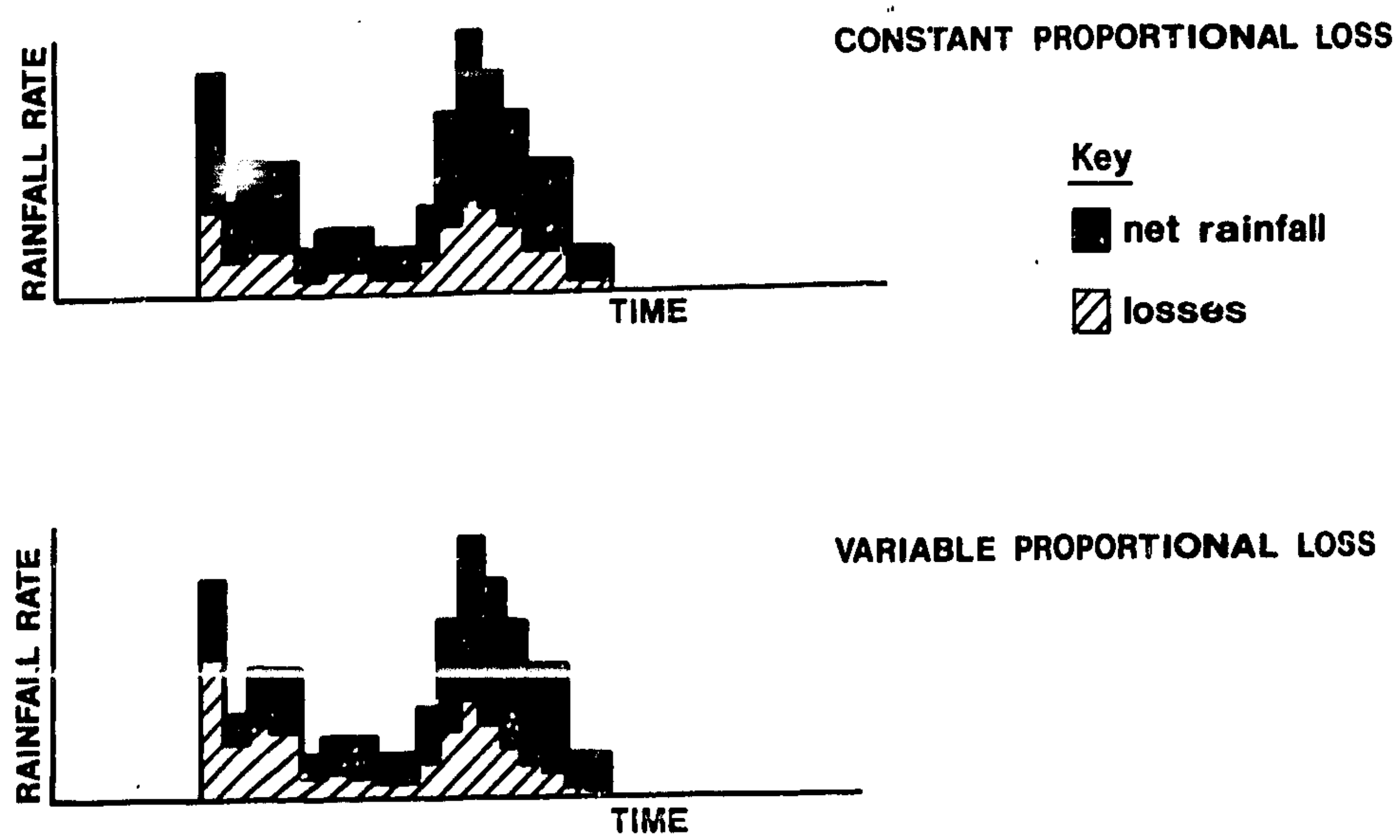


FIGURE M1.3 Rainfall separation - proportional loss methods

The unit hydrograph method of flood estimation developed in the Flood Studies Report (FSR)[45] assumes a fixed proportional loss method of rainfall separation. The percentage runoff (PR) applicable to a storm of depth P, coinciding with an antecedent catchment wetness index of CWI, is given by:

$$PR = SPR + 0.22(CWI-125) + 0.1(P-10) \qquad (M1.1)$$

where SPR is a standard percentage runoff determined by soil type, topographic slope and land use. However, it was suggested in the FSR that application of the unit hydrograph model to flood forecasting should allow a variable proportional loss, the percentage runoff varying from interval to interval according to:

$$PR_t = k.CWI_t \qquad (M1.2)$$

where k is a parameter to be determined.

This method of rainfall separation has been applied by Biggs[66] (Wessex WA, Somerset Division) in the context of a transfer function model (see Section M3). The FSR definition of catchment wetness index:

$$CWI = 125 - SMD + API$$

was followed but with soil moisture deficit (SMD) calculated from a simple budgeting model based on mean daily potential evaporation, and without a 5-day limit on the antecedent precipitation index (API). Biggs calibrated the rainfall separation parameter, k, by trial and error while using a recursive least-squares algorithm to determine the remaining parameters of the rainfall/runoff model (see Section M3).

In research for Severn-Trent WA, Simpson[75] applied Equation M1.2 in a unit hydrograph model. Having determined values of k for a number of individual events, he related the variation in k to the initial CWI for each event: higher values of initial CWI tending to yield higher values of k. The net result was a rather more complicated rainfall separation model (than Equation M1.2) that accentuated the variation of percentage runoff with catchment wetness. The research report prepared by Simpson provides a detailed description of how to apply a unit hydrograph model to real time forecasting, giving a step by step guide to model calibration.

Wide-ranging research by MacGregor included consideration of a "time-variant" proportional loss model. One version represented the distribution of losses through the course of a storm event by an exponentially decaying PR. The research was very ambitious: attempting to resolve methods of rainfall separation, unit hydrograph derivation, real time updating, and application to ungauged catchments. Perhaps not surprisingly, the reports[76 77] were rather inconclusive. South West WA have since opted to implement transfer function methods to meet their operational requirements catchment by catchment.

Other exponents of the unit hydrograph approach to flood forecasting have generally adopted a fixed percentage runoff, with the percentage runoff value being either constant for all events or related to antecedent condition. This type of model can be achieved by simply working out percentage runoff values for past events and studying their variation with any readily available index of catchment wetness. Such an index could be a fairly direct measure (such as soil moisture deficit estimates or neutron probe counts), a less explicit representation of catchment wetness (such as an antecedent precipitation index), or a surrogate variable (such as time of year or antecedent flow). For example, the FSR definition of catchment wetness index:

$$CWI = 125 - SMD + API5 \qquad (M1.3)$$

can be generalized and a percentage runoff relation sought in the form:

$$PR = a.SMD + b.API5 + c \qquad (M1.4)$$

where SMD is the pre-event soil moisture deficit and API5 is the 5-day antecedent precipitation index. This approach, which caters for the possibility that the FSR equations (Equations M1.1 and M1.3) may be inappropriate for a given catchment, has been followed by Cameron (WRC)[78] and Wormleaton[79] (for AWA Essex River Division) with mixed success. The need to determine three parameters (a, b and c in Equation M1.4) is an obvious drawback. For example, both researchers found catchments for which the value of "b" (derived by regression) was negative; intuition suggests, of course, that percentage runoff ought to increase (not decrease) with antecedent rainfall. Bearing in mind that Equation M1.4 does not simulate a varying percentage runoff during an event, the allocation of three parameters to the rainfall separation part of the model seems rather extravagant.

Loss rate methods of rainfall separation are now used only rarely - in the UK at least - with publication of the FSR marking the trend towards proportional loss methods. Reed[43] has shown that a uniform loss rate is workable as a real time method of rainfall separation - although rather clumsy. In a study of the Rhondda catchment he determined a predictive relationship for the ϕ-index value, [illegible]:

$$PHI = 0.687\ AVER^{0.844}\ ROMIN^{-0.225} \qquad (M1.5)$$

where AVER is a measure of average rainfall intensity (evaluated to time "now") and ROMIN is the runoff rate (ie. flow) at the beginning of the event, all variables being taken in mm/hr. Kent River and Water Division of SWA have considered a variable loss rate method of rainfall separation in exploratory flood forecasting studies in connection with real time control of the Medway flood retention storage. (See Section 4.1.2).

On a philosophical note, it is rather worrying that such radically different approaches as loss rate and proportional loss separations can both produce tenable representations of rainfall losses within a rainfall/runoff model. When calibrating the methods, the net rainfall depth is known a priori from the volume of rapid response runoff. Thus, in calibration, the two methods yield the same net rainfall depth but different profiles. But when applied to estimate losses without reference to the volume of rapid response runoff (as, of course, is the case in real time forecasting) the separation rules may give radically different profiles and depths.

As part of continuing research into improved methods of flood estimation, the Institute of Hydrology is examining methods of rainfall separation most appropriate in a unit hydrograph approach to modelling. The latter qualification is important; the three components - rainfall separation, unit hydrograph and baseflow synthesis - must hang together if the most is to be made of the unit hydrograph approach.

M1.5 Baseflow synthesis

The third, and frequently least important, component of a unit hydrograph model is the method of baseflow synthesis. Real time forecasting applications often assume a uniform baseflow contribution, taken equal to the runoff rate at the beginning of the event[66]. Alternatives are to project baseflow by extending the preceding hydrograph recession or to synthesize it as a straight line of predetermined gradient.

Perhaps, one of the golden rules of modelling for forecasting purposes is that the method adopted for real time use should be consistent with that assumed in calibration. If this tenet is accepted, is it sensible to use a complicated method of baseflow separation in analysis and yet adopt a simple representation in application? On a slightly different subject, is it sensible to derive unit hydrographs of widely varying time bases (eg. Fig. M1.4) if only one unit hydrograph is to be embedded in the final model? These apparently unconnected conjectures have a common link when it is realized that the time base of a derived

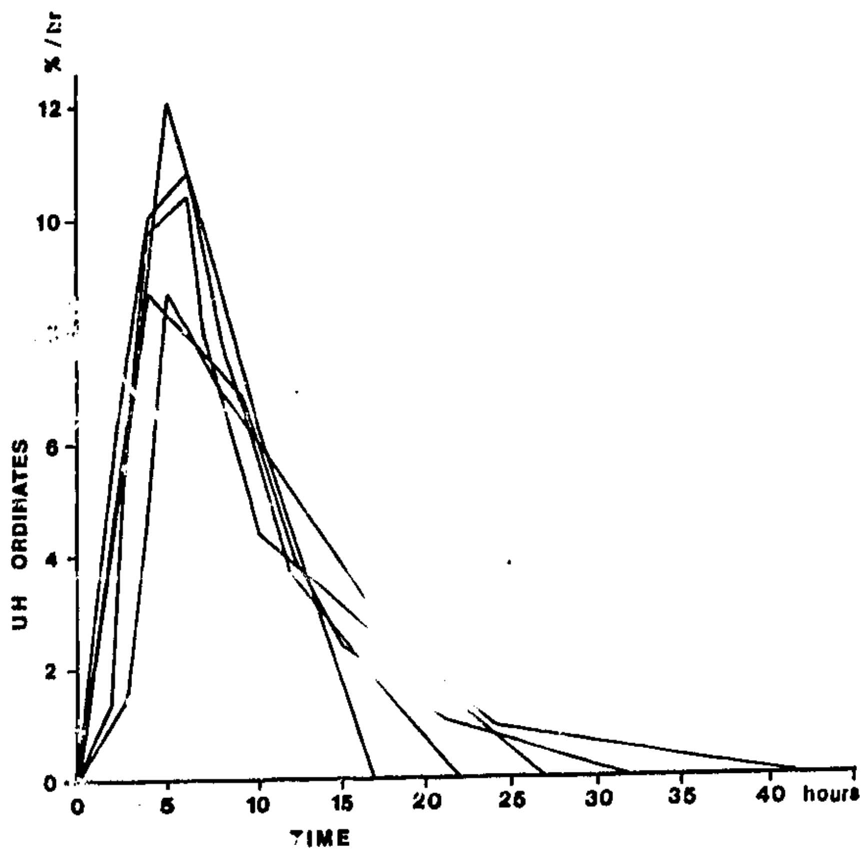


FIGURE M1.4

Unit hydrographs derived by individual analysis of events (restricted least squares method[72,74]) unit hydrograph is largely determined by the method of baseflow separation chosen in analysis. These considerations led Reed[43] to assume a time base for the unit hydrograph *a priori*, and to use this to determine a simple baseflow separation consistent with requirements (see Fig. M1.5).

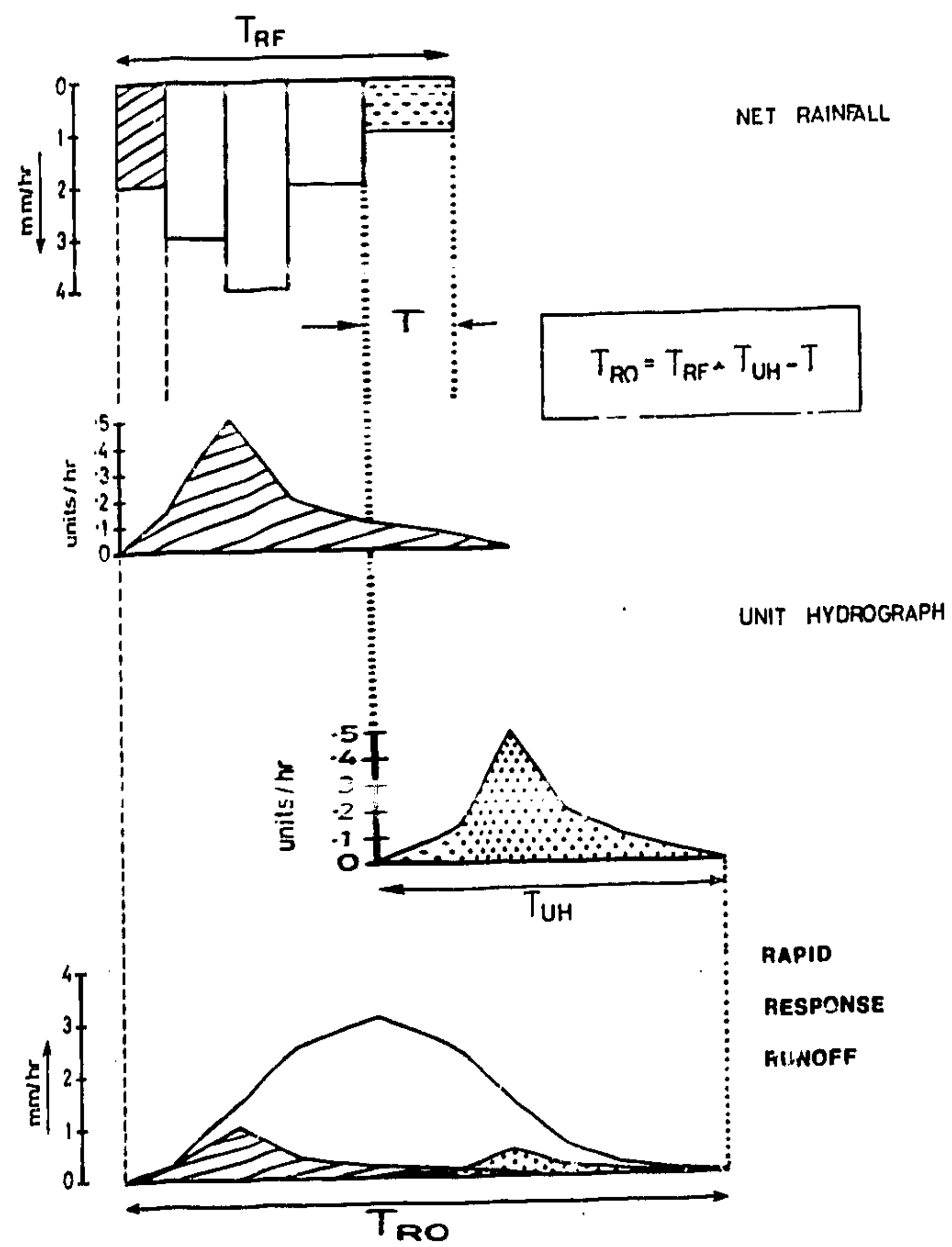


FIGURE M1.5

Illustration of link between time bases of net rainfall and rapid response runoff implied in a unit hydrograph model

M1.6 Application

Anglian WA Essex and Lincolnshire River Divisions make considerable use of unit hydrograph models for flood forecasting. Although differing in detail, these applications are similar in their use of a fixed value of PR for an event, the value being determined by an antecedent catchment wetness index. Both divisions do, however, adjust the PR value in real time if telemetered flow data show the initial estimation to be inappropriate. Options to adjust timing aspects of the model, or of the model output, are also employed. (See Section 4.4 for a discussion of real time correction methods).

One feature of the Essex application[65] is the generalization of the model to ungauged catchments. Wessex WA Somerset Division are currently reorganizing and simplifying their flood forecasting system and have opted to re-introduce unit

hydrograph methods. One factor behind this decision is that consideration is now being given to application on ungauged catchments; the intention is to take advantage of the FSR unit hydrograph/losses model[45] to synthesize flood forecasts. This represents the unit hydrograph by a simple triangle. In the Essex application, a 3-parameter form has been preferred and generalization obtained by regressing model parameters on catchment characteristics. It remains to be seen how well these models perform (how do you assess performance if there is no streamflow gauge?). "A crude model is better than none" is true in most circumstances; but a word of warning is sounded in Section 4.1.4 that flood warning applications may be an exception.

Unit hydrograph modelling carried out by North West WA has made use of two simplifications. Firstly, on some catchments they forwent rainfall separation and linked response runoff to total rainfall. This approach yields "unit hydrographs" that do not have unit volume, since the volume of response runoff is equivalent to perhaps only 40% of the total storm depth. The effect of basing a model on an average of such unit hydrographs is to assume a fixed proportional loss separation, with percentage runoff constant for all events. The approach provides an interesting short-cut but will only be as good as the implied method of rainfall separation.

The second simplification relates to conversion of a calibrated unit hydrograph model to graphical form. This can be done in various ways. A technique used by North West WA[80] is to subject the model to a number of synthetic storms and to construct graphs relating simulated peak flow to rainfall intensity and duration. (See Fig. M1.6). The technique can, of course, be applied with any rainfall/runoff model and is particularly useful in conjunction with rainfall forecasts.

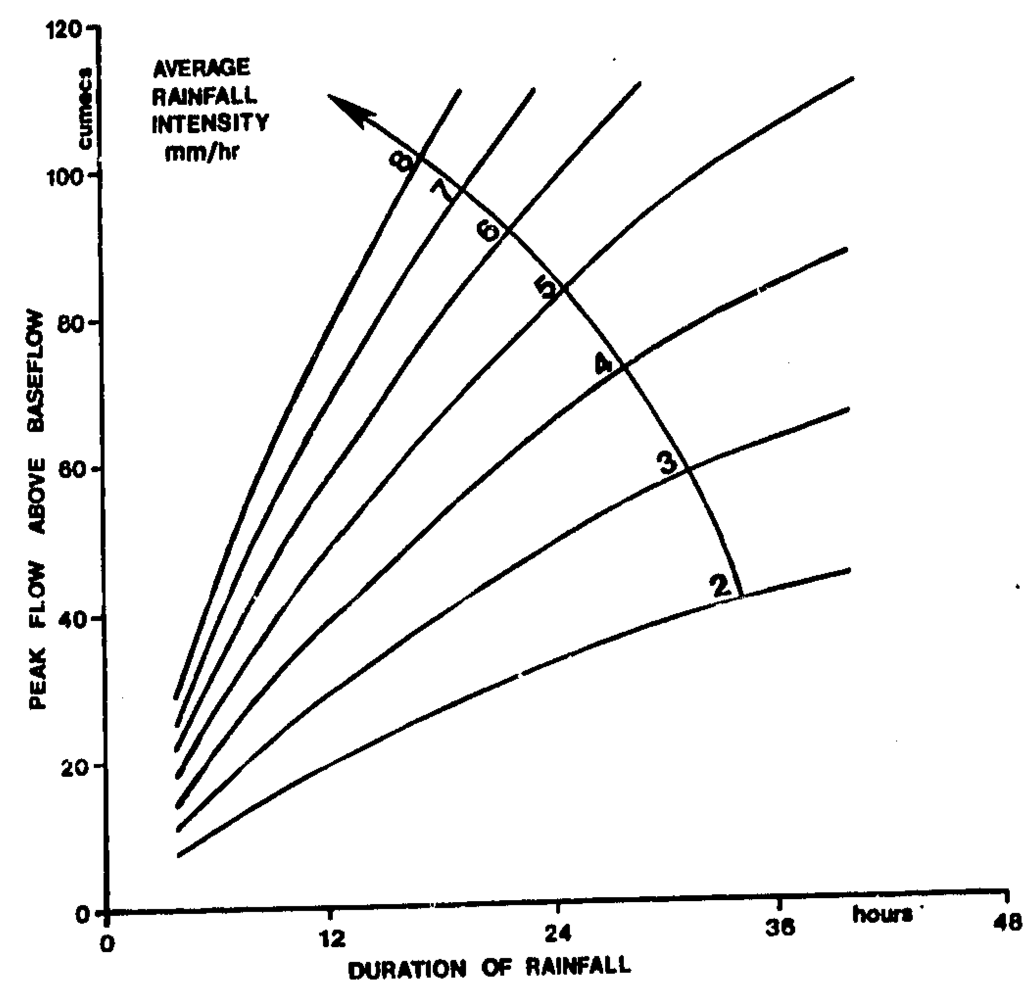


FIGURE M1.6

Graphical presentation of a simplified unit hydrograph model

M1.7 Suitability for real time use

The unit hydrograph approach is not ideally suited to real time application. In particular, baseflow synthesis is inconvenient and often appears an irrelevant detail. Because it is an event model rather than a continuous model (see glossary) there are various initialization problems. It is necessary to be able to determine when an event begins and also when it ends; otherwise, if a second storm occurs soon after the first, the "initial catchment condition" may be ambiguous. Usually it is also necessary to know the pre-event flow.

In contrast to nonlinear storage models (Section M2) and transfer function models (Section M3), a unit hydrograph model is not readily "started up" part way through a flood event. This liking for a complete database is perhaps the most limiting drawback of unit hydrograph methods for real time use.

M2 NONLINEAR STORAGE MODELS

M2.1 Introduction

A number of authorities use, or have investigated, nonlinear storage models. The best known technique is the ISO-function approach developed by Lambert[81 82]; this is a deceptively simple "lag and route" model that has found application in low flow, as well as flood flow, forecasting. Another fairly simple rainfall/runoff model - the Isolated Event Model (IEM) - has been adapted by the Forth River Purification Board[30] to provide flood warnings on the (Scottish) Tyne. Although originally conceived as a general purpose simulation model[83 84], IEM shares several features with the ISO-function approach and it is both convenient and instructive to consider the two together under the general heading of "nonlinear storage models".

M2.2 Structure

ISO-MODELS

The key assumption in the ISO-function approach is that at any time the outflow from the catchment, q, is uniquely related to the quantity of water stored within the catchment, S. This quantity is taken to include all natural forms of storage in the catchment (eg. surface water, soil moisture, and groundwater). Thus:

$$q = q(S) \qquad \text{(M2.1)}$$

The second important concept is that the water balance equation for the catchment is satisfied at all times, ie.:

$$\frac{dS}{dt} = p - q \qquad \text{(M2.2)}$$

where p denotes the inflow to storage, q the outflow, and t is time. Equations M2.1 and 2, coupled together, form an Inflow-Storage-Outflow or ISO-model, the type of model being determined by the functional form chosen for the storage/outflow relation (Equation M2.1).

In flood forecasting applications, p is taken as the average rainfall intensity over the catchment and q as the runoff rate from the catchment; other "outflows" such as evaporation are assumed negligible. The omission of an allowance for rainfall losses is not as damaging as at first appears.

Some indirect compensation is possible during model calibration; and it is usual, in application, to update the modelled runoff by reference to observed flow values. More will be said of this method of "state-updating" both here and in Section 4.4.

On many catchments there is a greater delay between rainfall and subsequent runoff than can reasonably be modelled by storage routing alone. Lambert[81] introduced translation effects by constructing Equation M2.1 to relate outflow "now" to catchment storage L hours previously, where L is a pure time delay or translation lag. Though slightly different, it is simpler to introduce the time delay by lagging the rainfall prior to storage routing. Thus Equation M2.2 is replaced by:

$$\frac{dS}{dt} = p_{t-L} - q_t \qquad \text{(M2.3)}$$

where the suffix t-L denotes that the rainfall has been delayed in the model by L hours. This is the approach now generally taken in application of the ISO-model[2], and it is also normal practice to adopt common units for the inflow and outflow. In what follows, p and q are taken in mm/hr, S in mm, and t in hours.

Before considering particular types of nonlinear storage model it is instructive to expand the differential in Equation M2.3 to make use of the known dependence of q on S (Equation M2.1). Writing:

$$\frac{dS}{dt} = \frac{dS}{dq}\,\frac{dq}{dt}$$

yields $$\frac{dq}{dt} = (p_{t-L} - q_t)\,\frac{dq}{dS} \qquad \text{(M2.4)}$$

This form of the water balance equation shows that it is the differential dq/dS, rather than the function q(S) itself, that determines model behaviour. The general structure of ISO-models is summarized in Fig. M2.1 which illustrates the way in which a telemetered flow value, qNOW, can be used to re-initialize solution of Equation M2.4, thereby updating the forecast hydrograph. Another feature, highlighted in Fig. M2.1, is that flow forecasts up to L hours hence are independent of rainfall beyond time "now".

ISOLATED EVENT MODEL

Turning to the Isolated Event Model (IEM)[83], the most important difference is that rainfall losses are represented explicitly by applying a runoff coefficient to the rainfall, prior to storage routing*. Net rainfall, n, is defined by:

$$n_t = ROP.p_t \qquad \text{(M2.5)}$$

The runoff proportion, ROP, is determined from the initial (ie. pre-event) soil moisture deficit (SMD) according to:

$$ROP = PERC.e^{-PERI.SMD} \qquad \text{(M2.6)}$$

(A non-zero value of SMD leads to a runoff proportion lower than the saturated value, PERC). The PERC and PERI parameters determine the volume of runoff. Two further parameters - AC and DEL - relate to the timing of the response. DEL is a pure time delay and is synonymous with the ISO-model's L; for clarity the

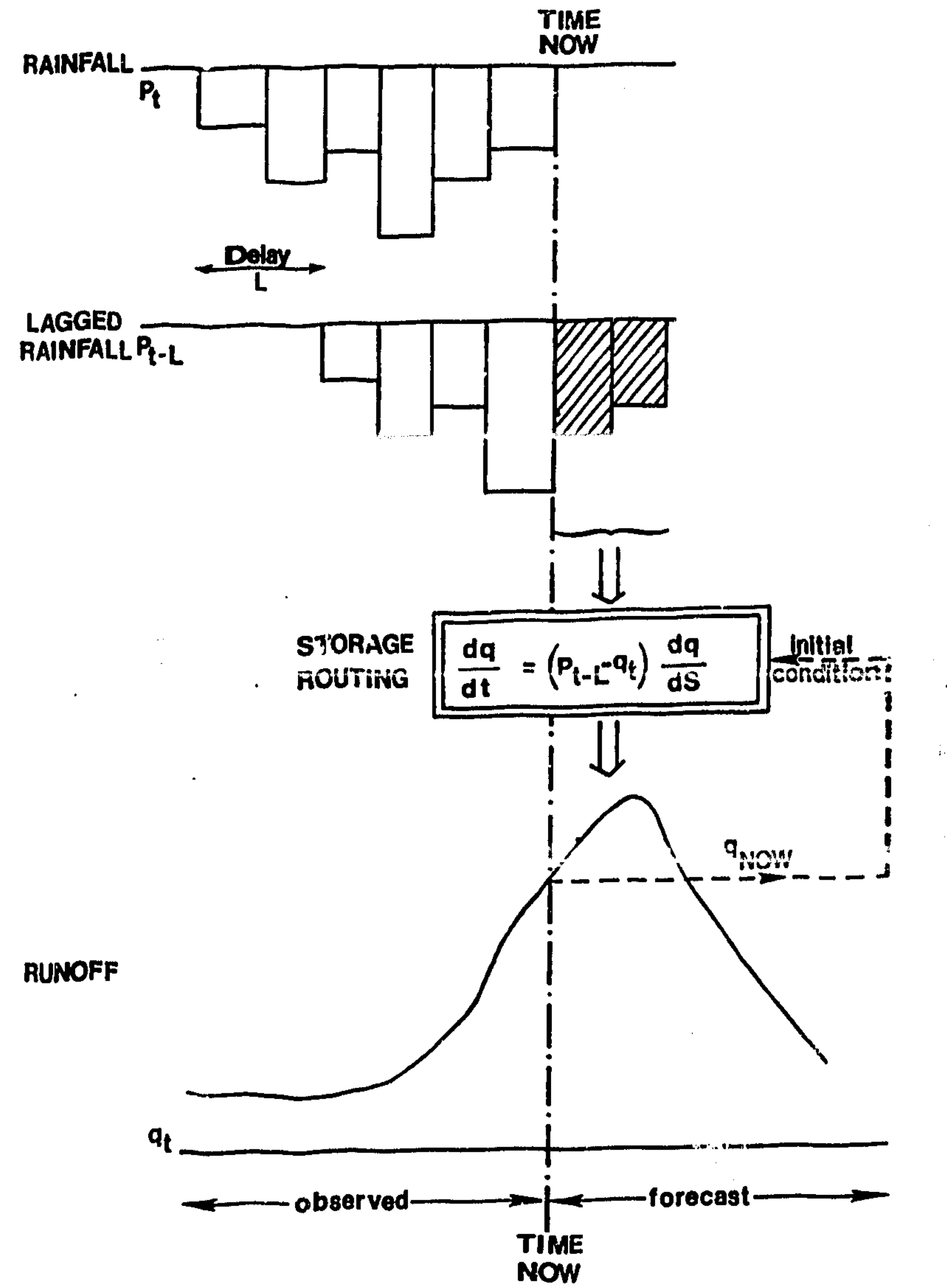


FIGURE M2.1 ISO-model structure and real time use, showing state-updating by reference to telemetered flows

notation L is used here. AC is a routing coefficient defining the storage/outflow relationship:

$$S = AC.\sqrt{q} \qquad (M2.7)$$

*An alternative idea, the augmented hydrograph approach[85], is to apply a loss factor after storage routing.

Combining Equation M2.7 with the continuity equation:

$$\frac{dS}{dt} = \frac{dS}{dq} \cdot \frac{dq}{dt} = n_{t-L} - q_t$$

yields the differential equation:

$$\frac{dq}{dt} = (n_{t-L} - q_t) \cdot \frac{2\sqrt{q}}{AC} \qquad (M2.8)$$

The structure of IEM is summarized in Fig. M2.2.

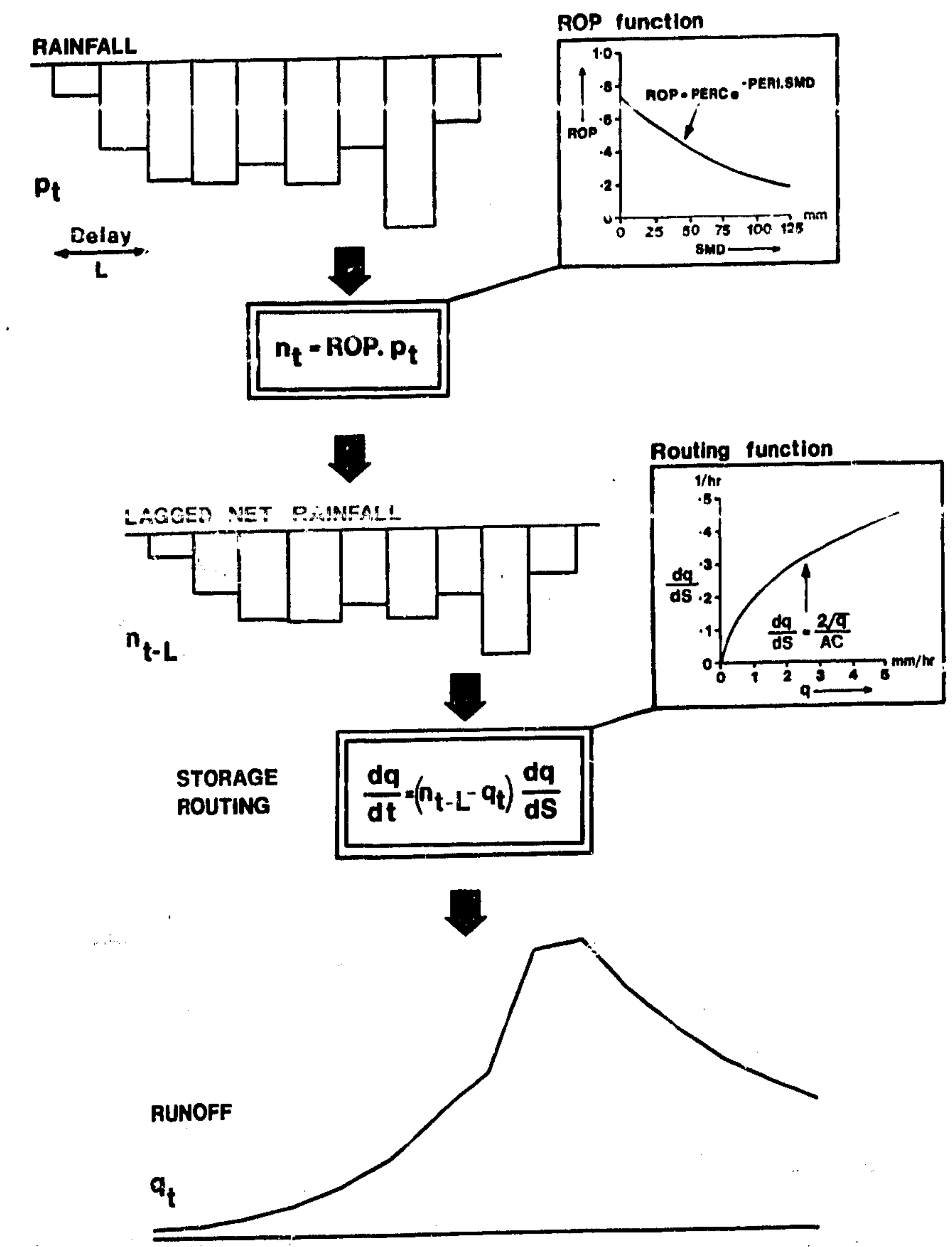


FIGURE M2.2 Nonlinear storage model structure, with (inset) ROP and routing functions corresponding to the Isolated Event Model

GENERALIZED NONLINEAR STORAGE MODEL

Comparing the ISO-model with the Isolated Event Model it is seen that the former offers a more general storage/outflow relationship but no explicit rainfall separation. A more general nonlinear storage model[43], combining features of both methods, is given by the equations:

$$n_t = ROP \cdot p_t$$

$$ROP = ROP(cwi)$$

$$\frac{dq}{dt} = (n_{t-L} - q_t)\frac{dq}{dS} \qquad (M2.9)$$

$$\frac{dq}{dS} = \frac{dq(q)}{dS}$$

where ROP is a function of some antecedent catchment wetness index (cwi) and the routing function, dq/dS, is a function of the outflow (q).

The particular type of nonlinear storage model is determined by the functions chosen for ROP and dq/dS. For example:

type I ISO-function:
$$ROP = 1, \quad \frac{dq}{dS} = \frac{q}{k} \qquad (M2.10)$$

type II ISO-function:
$$ROP = 1, \quad \frac{dq}{dS} = \frac{1}{K} \qquad (M2.11)$$

standard IEM:
$$ROP = PERC.e^{-PERI.SMD}, \quad \frac{dq}{dS} = \frac{2\sqrt{q}}{AC} \qquad (M2.12)$$

The parameters of the model are the coefficients appearing in these functions together with the pure time delay, L.

A modified version of IEM has been developed by the Forth River Purification Board[30 40]. This uses the pre-event runoff rate, q_o, as the index of antecedent catchment wetness and takes the form

modified IEM:
$$ROP = a+b\ell n(q_o), \quad \frac{dq}{dS} = \frac{2\sqrt{q}}{AC} \qquad (M2.13)$$

Although less physically related to rainfall loss mechanisms than SMD, pre-event flow has the advantage that it is readily available in real time. This modified IEM has also compared favourably with the standard IEM in a recent study of the Lincolnshire Lymn catchment[86]. Some other forms of nonlinear storage model are considered in Section M2.5.

SOLUTION METHOD

The first order differential equation representing the storage routing component of the nonlinear storage model (eg. Fig. M2.2) is solved progressively to determine $q_{t+\Delta t}$ from q_t and n_{t-L}. Although analytical solutions are possible for the particular routing functions considered above, a numerical solution is entirely satisfactory and is more generally applicable if other functional forms are chosen for dq/dS[43]. The Newton-Raphson iterative method is then an appropriate way of solving for $q_{t+\Delta t}$.

M2.3 Calibration

In most applications, nonlinear storage models are calibrated by trial and error - often using numerical optimization procedures (see Appendix 2). Lambert[81 82] gives a technique for both choosing and calibrating an appropriate storage/outflow relationship (Equation M2.1). However, because the method is based on recession curve analysis it is more suitable in low flow forecasting than for flood forecasting. McKercher[87] calibrated type I ISO-function models by minimizing the residual sum of squares between observed and simulated flows. Analysing several months of half-hourly data at a time, he derived seasonal values of the parameters k and L. Subsequently, Green[88] indicated that optimization on isolated events is preferable because it gives greater emphasis to good performance on the rising limb of flood hydrographs.

M2.4 Application

Nonlinear storage models are particularly suited to real time forecasting. One feature already alluded to is that flow forecasts up to lead time L can be made without recourse to forecast rainfalls. (See Fig. M2.1). Another characteristic of the formulation is the opportunity to incorporate telemetered flow data directly into the model, as illustrated by the broken line in Fig. M2.1. Solution of the differential equation (Equation M2.4 for ISO-models, Equation M2.8 for IEM) requires an initial condition, ie. knowledge of the outflow, q_o, at some initial time, t_o. In "simulation mode" this is taken as the pre-event flow. However, in "updating mode" the latest telemetered flow is used to re-initialize solution of the differential equation, thus ensuring continuity of observed and modelled flows at time "now". This technique of state-updating a model is discussed further in Section 4.4 where other forms of real time correction are also considered.

Nonlinear storage models have been applied to flood forecasting by Welsh WA, Northumbrian WA, Forth RPB and the Greater London Council; the simplified rainfall/runoff models developed by North West WA[16] for use with radar derived rainfall data are also rather similar in effect. ISO-function models remain an integral part of the (Welsh) Dee flood forecasting system[89] and are implemented in updating mode on a dedicated real time minicomputer[2].

Both Welsh WA Dee and Clwyd Division and Northumbrian WA make limited use of graphical versions of the ISO-model. Fig. M2.3, taken from work carried out at the Institute of Hydrology[43], illustrates how a nonlinear storage model can be recast as a co-axial diagram; flow forecasts are read off from knowledge of the flow at time "now" and an appropriate rainfall forecast. In the particular application for Welsh WA Taff Division a 2-part nonlinear storage model was used (type II at low flows, type I at high flows) together with a runoff proportion (ROP = 0.74) but a zero pure time delay (L=0)*. As Fig. M2.3 demonstrates, even a fairly complicated nonlinear storage model can be condensed to a simple graphical form.

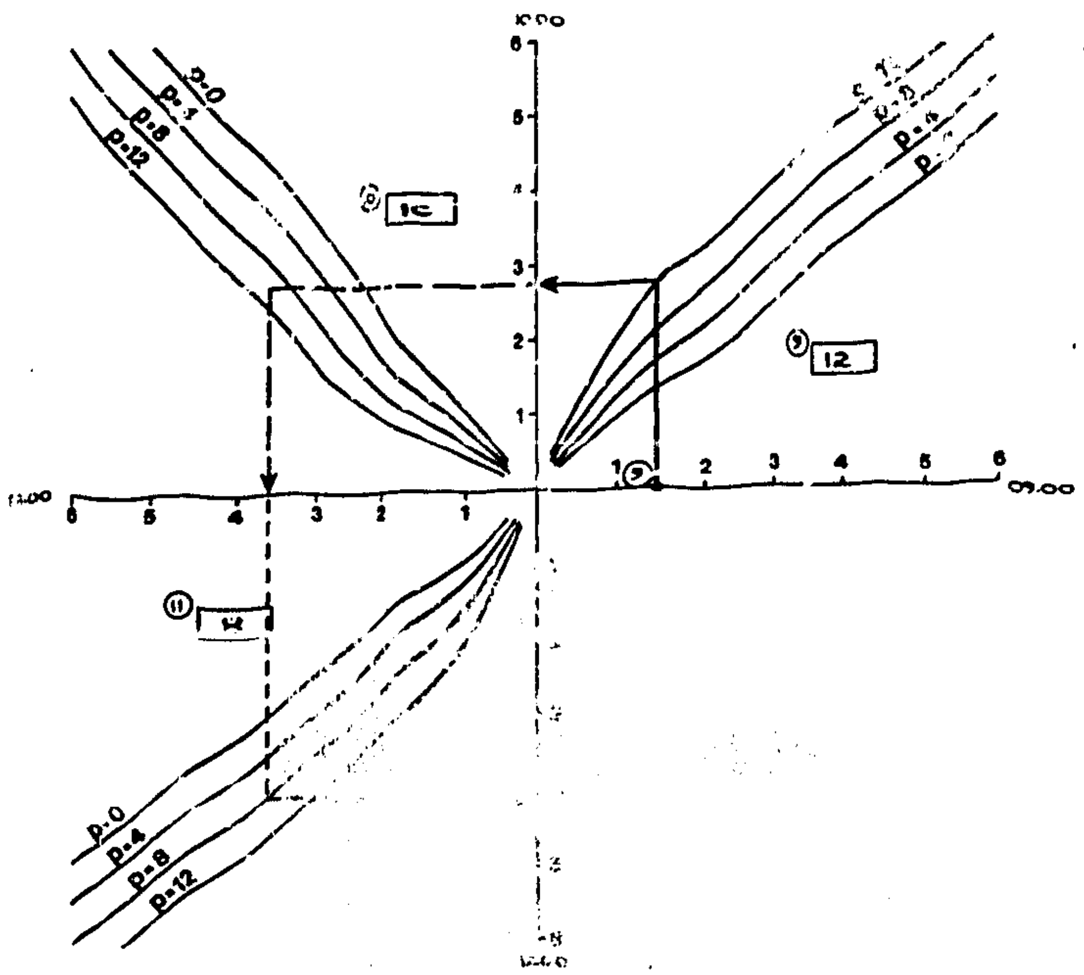


FIGURE M2.3

Graphical application of a nonlinear storage model (see text for details of example shown)

NOTES:

i Circled numbers denote clock hours

ii Flow entered on +ve axis is telemetred flow in mm/hr

iii Rainfall entred [illegible] is forecast depth [illegible] hour commencing a [illegible]

iv Projected line [illegible] and 3 hour ahead fore[illegible] of flow in mm/hr

The nonlinear storage model* applied in the Forth RPB's flood warning system[30] is the modified IEM (Equations M2.13). This uses the observed pre-event flow to determine the runoff proportion applicable to the current event. However, the implementation does not otherwise update forecasts by reference to telemetered flows. The reluctance to incorporate real time correction methods is explained in part by a measure of confidence in the basic "simulation mode" model and in part by the fact that the telemetered flows refer to a site considerably upstream of the risk area - and may therefore not always be representative.

The Greater London Council has applied the standard Isolated Event Model (Equations M2.12) to an 18.4 km^2 suburban catchment[41]. (See also Section 4.1.2). Effective use of the model for flood warning on this quick responding catchment awaits commissioning of the London weather radar.

M2.5 More advanced nonlinear storage models

The representation of translation effects by a pure time delay is simplistic and an alternative is to incorporate a time/area diagram. (See, for example, Wilson[49]). Mandeville considered several schemes in his original work on IEM[84]. Green adopted a triangular distribution of travel times and noted the smoothing effect on outflow in development work on the Dee subcatchment ISO model[88].

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*When interpreting nonlinear storage models it is important not to mistake the pure time delay parameter for the catchment lag. For example, a type II ISO-model has a mean lag time of L+K not L.

Although conceptually preferable to a pure time delay, the introduction of a time/area diagram enlarges the parameter set (thus possibly adding to calibration problems) and makes the dependence of flow forecasts on rainfall forecasts less clear-cut.

A time/area diagram is one feature of a semi-distributed catchment model developed by Wessex WA for the Bristol Avon catchment[90]. (Section 4.5 discusses various approaches to comprehensive modelling of river systems). The rainfall/runoff segment of the model incorporates a triangular time/area diagram and subsequent routing of net rainfall through a 2-parameter nonlinear storage. However, studies indicated that the exponent value in the storage/discharge equation was not in itself very important and that a linear reservoir would suffice (ie. a type II routing function).

An extended version of IEM was developed as part of the 1st International Workshop on Real Time Hydrological Forecasting and Control, held at the Institute of Hydrology in 1977[91]. A 2-parameter storage/outflow relationship was assumed together with a fixed runoff proportion, leading (in the notation of Section M2.2) to the formulation:

$$\text{extended IEM:} \quad ROP = c, \qquad \frac{dq}{dt} = a q^{b} \qquad \text{(M2.14)}$$

where a, b and c are model parameters. As an alternative to using a pure time delay, a moving average filter was applied to provide in effect a time/area diagram - in its simplest case adding two parameters to the set, making five in all. Although the model did not perform dramatically better than the 3-parameter ISO-model against which it was assessed, the research demonstrated how a nonlinear deterministic rainfall/runoff model can be recast in stochastic form and calibrated by use of an extended Kalman filter[92]. Such methodology parallels the development of transfer function representations of unit hydrograph models, considered next.

M3 TRANSFER FUNCTION METHODS

M3.1 Introduction

The tranfer function approach recasts unit hydrograph methods in a statistical framework whereby the model is efficiently parameterized and naturally suited to real time use. Following theoretical developments[93] and pilot studies at the Institute of Hydrology, the University of Birmingham and elsewhere, experience is now being gained in the practical application of transfer function models to flood warning problems. The approach has been used by Wessex WA Somerset Division in an extensive computerized flood warning system[66].

Transfer function models are not, as yet, widely understood within flood warning authorities. They are phrased in statistical language that is difficult for the non-specialist to comprehend and, if the most is to be made of the approach, it is necessary to gain a grounding in time series analysis. However, once calibrated the models are particularly simple to implement in real time and offer several advantages over the unit hydrograph approach to flood forecasting.

M3.2 Structure

In its simplest form, a transfer function model assumes a linear relationship between flows, q_t, and rainfalls, p_t, so that the flow one time step ahead can be estimated from an equation such as:

$$\hat{q}_{t+1} = \delta_1 \hat{q}_t + \omega_o p_{t+1} + \omega_1 p_t + \omega_2 p_{t-1} \qquad (M3.1)$$

Here δ_1, ω_0, ω_1 and ω_2 are model parameters and the notation $\hat{q}$ denotes that the flows are as estimated rather than observed. In this example, $\hat{q}_{t+1}$ is calculated from one previous flow value - there being a single autoregressive (AR) parameter δ_1 and three moving (MA) parameters ω_o, ω_1 and ω_2. Equation M3.1 represents a simple transfer function model with a (1,3) ARMA structure. The model structure is illustrated in Figure M3.1 and an example of its application is given in Table M3.1.

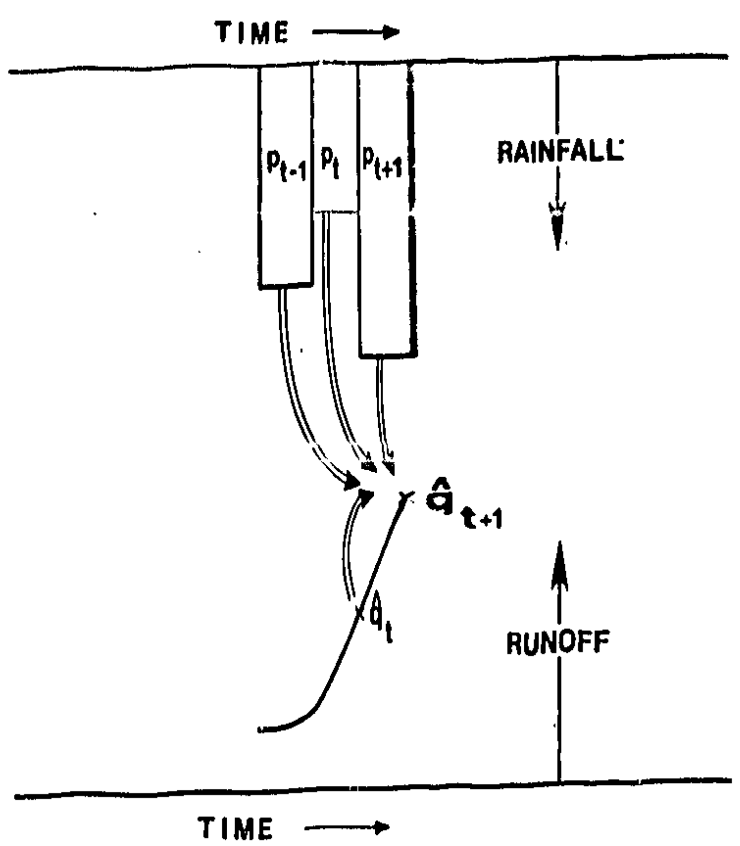


FIGURE M3.1

Illustration of the dependence of $\hat{q}_{t+1}$ on $\hat{q}_t$ and three rainfall values in a transfer function model with (1,3)ARMA structure

Application of a transfer function model to a flood event is generally initialized by knowledge of the pre-event flow, q_o. Equations such as M3.1 can then be applied repeatedly - at successive time steps - to evaluate $\hat{q}_1$, $\hat{q}_2$, $\hat{q}_3$, .. from knowledge of the rainfall inputs, p_t. However, a particular feature of transfer function models is the ability to re-initialize at any time during a flood event. In the case of the model defined by Equation M3.1, all that is required to carry out the re-initialization is the latest telemetered flow value, q_t, and the three rainfall observations: p_{t+1}, p_t and p_{t-1}. This feature means that transfer function methods can recover rapidly following periods of information loss brought about by computer, telemetry or instrument failure. Re-initialization can in fact be carried out at each time step, the effect being to update the model forecast with respect to the latest telemetered flow. This form of real time correction, which we refer to as state-updating, is discussed briefly in Section M3.5 and, more generally, in Section 4.4.

TABLE M3.1

Example application of a transfer function model with (1,3) ARMA structure

NB. All flows and rainfalls in units of mm/hr

TIME	FLOW OBS'D	FLOW EST'D	RAINFALL (three values)			MODELLED RESPONSE (δ_1=0.9, ω_o=0.1, ω_1=0.4, ω_2=0.2)				EST'D FLOW AT NEXT TIME STEP
t	q_t	$\hat{q}_t$	p_{t+1}	p_t	p_{t-1}	$\delta_1\hat{q}_t$	$\omega_o p_{t+1}$	$\omega_1 p_t$	$\omega_2 p_{t-1}$	$\hat{q}_{t+1}$
0	1.00	1.00	-	-	-	0.90	-	-	-	0.90
1		0.90	3	-	-	0.81	0.3	-	-	1.11
2		1.11	2	3	-	1.00	0.2	1.2	-	2.40
3		2.40	4	2	3	2.16	0.4	0.8	0.6	3.96
4		3.96	-	4	2	3.56	-	1.6	0.4	5.56
5		5.56	-	-	-	5.00	-	-	0.8	5.80
6		5.80	-	-	-	5.22	-	-	-	5.22
7		5.22	-	-	-	4.70	-	-	-	4.70
8		4.70	-	-	-	4.23	-	-	-	4.23
9		4.23	-	-	-	3.81	-	-	-	3.81
10		3.81	-	-	-	3.43	-	-	-	3.43
11		3.43	-	-	-	3.09	-	-	-	3.09
12		3.09	-	-	-	2.78	-	-	-	2.78

On many catchments there is a sufficient natural delay before the output (flow) responds to a change in input (rainfall) that a pure time delay can be incorporated in the model structure. This strategy helps to economize on the number of parameters needed in the model, thus easing calibration problems. Moore and O'Connell[3] define a general TF(r, s, ℓ) model by an equation equivalent to:

$$\hat{q}_t = \delta_1 \hat{q}_{t-1} + .. + \delta_r \hat{q}_{t-r} + \omega_o p_{t-\ell} + \omega_1 p_{t-\ell-1} + ... + \omega_{s-1} p_{t-\ell-s+1} \qquad (M3.2)$$

where the transfer function (TF) model has r autoregressive parameters, s moving average parameters, and a pure time delay parameter ℓ measured in time intervals*. Inclusion of a pure time delay means that flow forecasts up to ℓ time steps ahead can be made without recourse to rainfall forecasts. (Contrast with Fig. M3.1 where flow one time step ahead is dependent on rainfall in the interim.)

Although it is possible to develop transfer function models that relate flow to total rainfall, it is usual to follow the philosophy of unit hydrograph methods and distinguish net rainfall. The choice of an appropriate rainfall separation method is again important but, in this respect, the greater sophistication of transfer function methodology can offer no better guidance - just a multitude of possibilities. The Wessex WA Somerset Division implementation uses the variable proportional loss method, the variability being controlled by the catchment wetness index, CWI_t. (See Section M1.4 for a discussion of rainfall separation methods).

Moore[3] discusses in depth several alternatives to conventional methods of rainfall separation. One technique is to monitor catchment wetness and to switch

*In the notation of Section M2, the pure time delay L is ℓΔT where ΔT is the time interval.

from a slow response, low volume TF model to a fast response, high volume one when a predetermined catchment wetness index is exceeded. (See Fig M3.2). Another treatment is to separate rainfall into two components (according to the prevailing catchment wetness), to direct one component to a slow response TF model and the other to a fast response model, before combining the two outputs to estimate the total flow. (See Fig. M3.3). These approaches allow nonlinear effects to be incorporated and circumvent the need for baseflow separation. However, the added sophistication is at the expense of increasing the number of parameters to be estimated in model calibration.

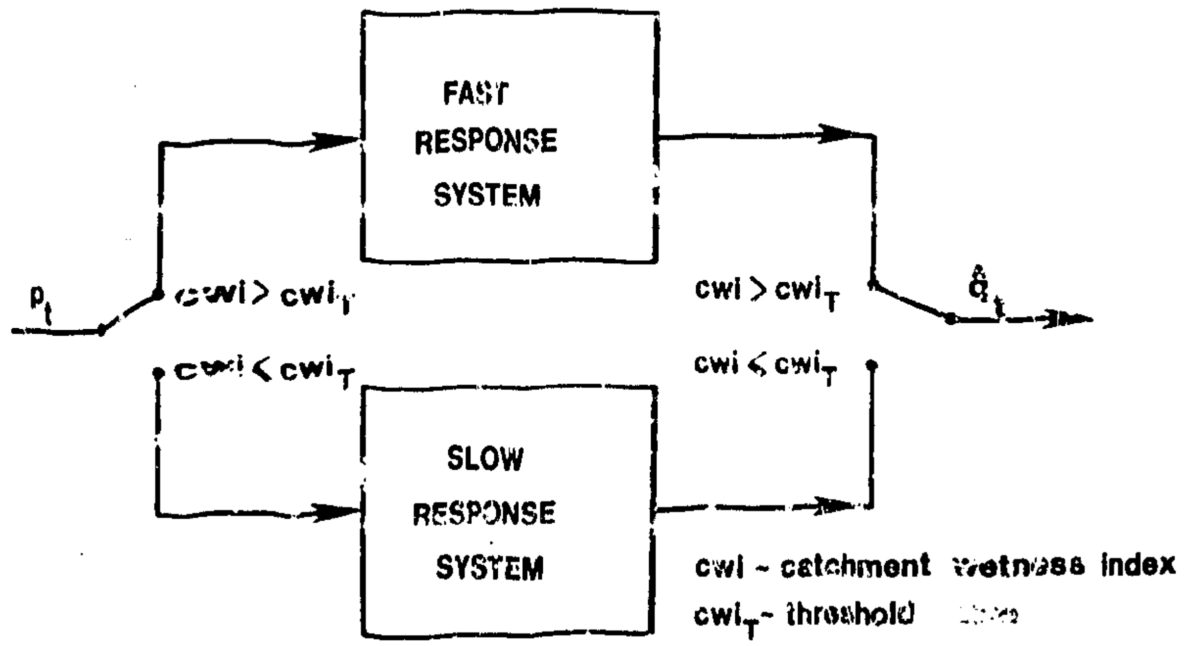


FIGURE M3.2 System representation of a nonlinear TF model with switched components

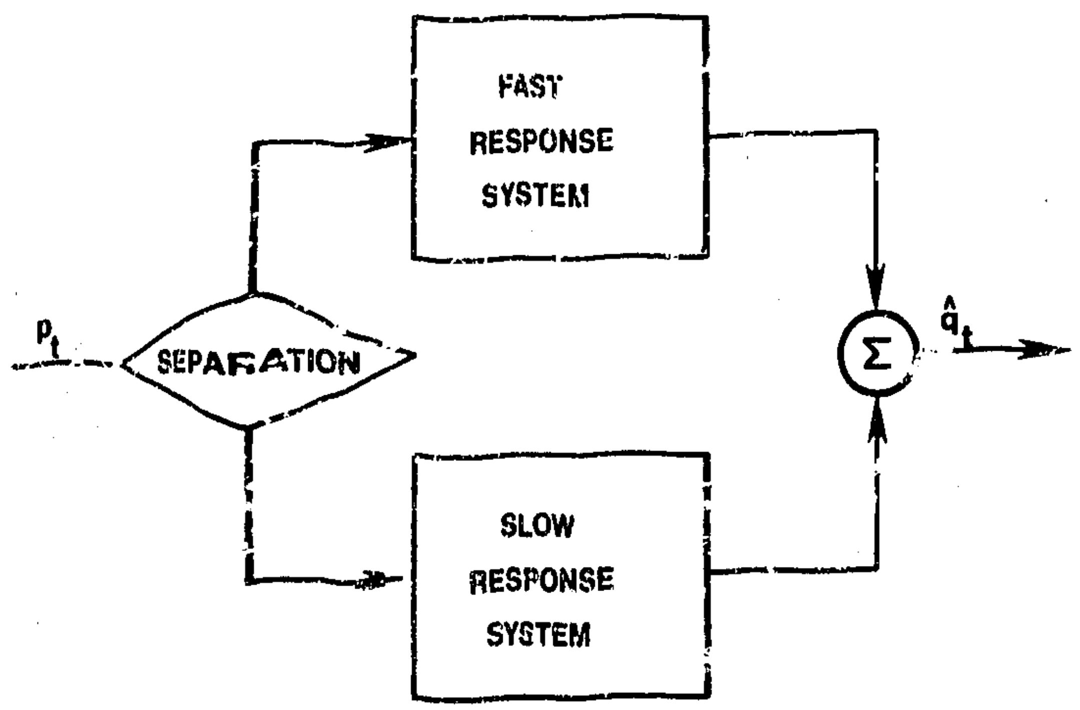


FIGURE M3.3 System representation of a nonlinear TF model with parallel components

M3.3 Calibration

The calibration of transfer function models calls for specialized computer programs and an understanding of time series analysis. The computer package most tailored to hydrological forecasting applications is CAPTAIN - a computer aided procedure for time series analysis and identification of noisy processes[94]. However, some general purpose statistical packages, particularly GENSTAT[95,96], also provide comprehensive facilities for calibrating transfer function models.

The two main stages in calibration are to determine an appropriate model <u>structure</u> and then to estimate the model parameters themselves.

Determining the model structure amounts to deciding suitable values for r, s and ℓ in Equation M3.2, in other words choosing the "order" of the transfer function model. The order of the model may be inferred from the impulse response function of the data, which is usually calculated by first "prewhitening" the input (rainfall) series; this amounts to transforming the series so that it consists of approximately uncorrelated values. Determining the appropriate transform is equivalent to fitting an ARMA model to the input series and can in itself be a complicated procedure[3,94]. Applying the same transform to the output (flow) series, the impulse response function is given by the cross-correlation function of the two transformed series. A degree of judgement is required to infer appropriate values of r, s and ℓ from the impulse response function; at this stage, the graphical and interactive facilities of the CAPTAIN package are particularly helpful.

Various algorithms can be used to estimate the model parameters in stage two of the calibration procedure. The recursive least-squares method is probably the simplest and is sometimes adequate. However, this algorithm is known to give statistically inconsistent estimates if the residual error (or "noise") series is autocorrelated, as is often the case. For this reason alternative techniques such as the Instrumental Variable (IV) algorithm are of interest. This highly sophisticated technique provides consistent parameter estimates but [illegible] with other iterative procedures, poor convergence can sometimes be a prob[illegible]

As the name implies, time series analysis methods a[illegible] study continuous time series of data. In the context of [illegible] generally desirable to calibrate a rainfall/runoff model [illegible] events so that emphasis is given to good performance at th[illegible] technique is therefore needed to concoct a time series out [illegible] events. Moore and O'Connell tackle this important problem [illegible] dummy observations between events that anomalous autoco[illegible] cross-correlations are suppressed in the concatenated se[illegible] and flow observations are given values equal to the mean [illegible]tive series.

CALIBRATION BY NUMERICAL OPTIMIZATION

The above description may be rather frightening to the non-specialist; surely a simpler method of calibrating transfer function models is possible? One alternative is as follows.

A particular model structure (eg. TF(2,2,ℓ)) is assumed <u>a priori</u> and the parameters determined by numerical optimization, ie. trial-and-error adjustment of the model parameters until a best fit to the observed flow data is obtained. Alternative model structures (eg. TF(1,2,ℓ)) can be considered subsequently, again on a trial-and-error basis.

This approach to calibrating transfer function models is anathema to the purist - unnecessary trial and error is, after all, unscientific. However, despite its inherent weaknesses (see Appendix 2), numerical optimization is an accepted means of calibrating many other hydrological models and the extension to transfer function models is not unthinkable.

M3.4 Application

Wessex WA Somerset Division have gained several years experience in the application of transfer function methods to real time flood forecasting. The approach adopted by Biggs[66] is a good illustration of the close relationship between unit hydrograph and transfer function methods. Net rainfall is determined by the variable proportional loss method (see Section M1.4) and a TF model used to forecast quick response flows from net rainfalls and previous quick response flows. Finally, a baseflow allowance - taken equal to the pre-event flow - is added. A recursive least-squares algorithm was used to calibrate the TF model. The flow forecasting model is embedded in a real time computer program that, amongst other features, calculates subcatchment rainfalls from a network of recording raingauges and allows flood forecasts to be extended by the inclusion of forecast rainfalls. The method of real time correction envisaged in the Somerset scheme was to state-update the model by replacing estimated flow values by observed flow values as soon as they become available[65]. However, as reported in Section 4.4.4, the overall scheme has recently been re-appraised.

As referred to in Section M1.4, South West WA are moving towards the use of tranfer function models. To assist routine calibrations for many catchments, they have developed a simplified package of time series analysis programs, called ENSIGN. Like CAPTAIN, the ENSIGN package is user-friendly; but, unlike CAPTAIN, it has relatively few options and makes no use of interactive graphics. Models have been implemented on a trial basis for four sites requiring flood warnings.

Research at the Institute of Hydrology has considered the application of transfer function models - some with an associated "noise" model - to several British catchments[3]. Possibilities of on-line calibration of linear system models have been studied at the University of Birmingham[93]. The "ultimate" in this approach to flood forecasting is the concept of installing a model that develops and refines itself automatically. There is nothing technologically impossible here; rather the doubt is whether such sophistication will produce better models and/or forecasts, given the uncertainty inherent in modelling a catchment system and in estimating inputs to the system by a few point measurements.

M3.5 Contrast with the unit hydrograph approach

Some of the research papers produced on time series methods of flood forecasting begin and end with a condemnation of traditional methods[3]. This is regrettable. While the newer methods have much to offer they are not absolutely good nor are the older methods irrevocably bad. If progress is to be made it is important to distinguish the particular advantages and weaknesses of each approach.

The discussion that follows centres on comparison of the unit hydrograph and transfer function approaches, since this is the area in which the rivalry between deterministic and stochastic methodologies is most apparent. However, the question of whether (and to what extent) to translate other deterministic models into stochastic equivalents reaches beyond the scope of this report.

ADVANTAGES OF THE TRANSFER FUNCTION APPROACH

The transfer function approach provides a more efficient parameterization of a linear system without serious loss of generality. The large number of parameters involved in the derivation of a unit hydrograph by the usual "matrix inversion" or "least squares ordinate" method can lead to problems of instability. It is frequently necessary to employ some form of smoothing in order to arrive at an acceptable unit hydrograph and this smoothing can lead to a loss of objectivity. While derivation of unit hydrographs from individual events invariably poses such problems, research has shown that the derivation of an average unit hydrograph from analysis of a group of events is inherently more stable[74].

Possibly the most important advantage over unit hydrograph methods is that transfer function models are ideally structured for real time use. Once calibrated they are simple to use, either manually, graphically or by computer. As outlined in Section M3.2, they are extremely easy to initialize or re-initialize. In contrast, unit hydrograph methods are often cumbersome to implement in real time and are much less tolerant of data loss. (See Section M1.7).

Another merit of the transfer function approach is that, given the statistical formulation, estimates of forecast uncertainty can be derived fairly readily.

DISADVANTAGES OF THE TRANSFER FUNCTION APPROACH

The one serious drawback of transfer function models is the complexity of calibration. While computer packages, such as CAPTAIN, provide clear, user-friendly access to the necessary time series analysis algorithms, the calibration of transfer function models still requires a good deal of skill. Perhaps the potential danger is that, in grappling with "prewhitening" and "lag-one cross-correlations", the new user may lose sight of other aspects of the flood forecasting problem, for example the importance of rainfall separation.

The neglect of baseflow separation, sometimes advocated in the transfer function approach, is a mixed blessing. While it avoids the very real problems of synthesizing a baseflow component in real time, the concept of relating net rainfall to total flow seems to be a step backwards and is clearly suspect on those catchments - admittedly few - where baseflow can constitute a major component of flood flows.

REAL TIME CORRECTION

A clear difference between the approaches is that transfer function models can be readily state-updated whereas unit hydrograph models cannot. This would appear to weigh heavily in favour of the transfer function approach. However, it is as yet unclear whether state-updating is the most effective means of improving forecasts by reference to telemetered flows. As we shall see in Section 4.4, other methods of real time correction - applicable to both approaches - may well be preferable.

SUMMARY

In summary, while the transfer function approach has certain advantages over the unit hydrograph approach in real time use, it is not clear that the added sophistication is justified in every application. A weakness remaining in both approaches is the difficulty in determining an appropriate rainfall separation method.

M4 CONCEPTUAL MODELS

M4.1 Introduction

What are generally referred to as conceptual models have found scarce application to flood forecasting in Britain. Tucci and Clarke[97] suggest two reasons for this. Firstly, there are the well known problems associated with calibrating many-parametered models. It is usually necessary to resort to optimization methods and these can fail to converge, converge to only a local optimum, or yield optimum parameter values that are outside a meaningful range[98] (see Appendix 2). The second factor highlighted by Tucci and Clarke is that there is rarely an obvious way of using telemetered flow data to improve the short-term forecasts of a conceptual model.

When considering catchment models in broader terms, it is usual to distinguish conceptual and empirical types. One definition of a conceptual model is a model that maintains an explicit soil moisture or "water balance" calculation, hence the alternative terminology "explicit soil moisture accounting" or ESMA model[99]. A detailed review of conceptual catchment models is given by Fleming[100]; a typical model structure is illustrated in Fig. M4.1. While

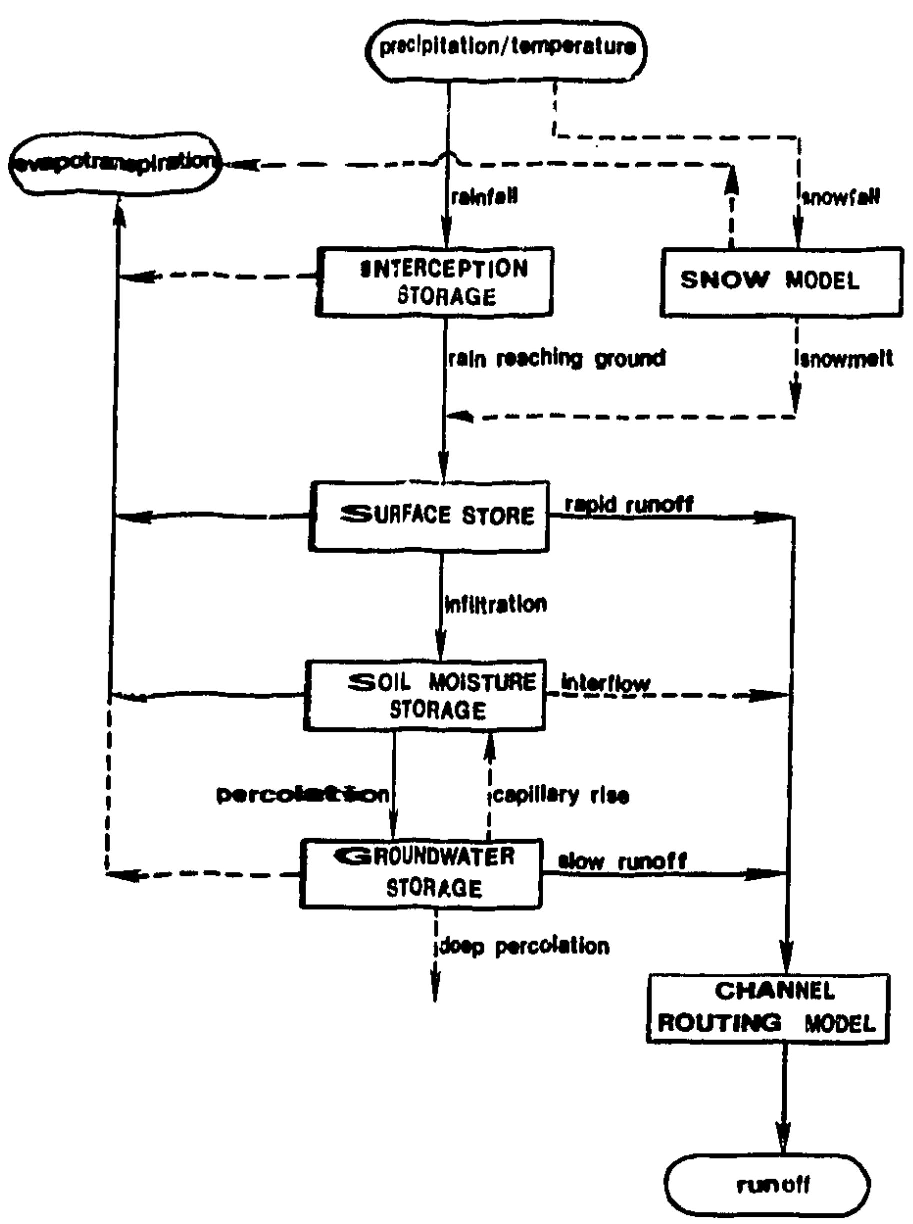


FIGURE M4.1

Typical structure of a conceptual (ESMA) model

explicit accounting is prerequisite to a comprehensive simulation model, it is possible that this property is merely an encumbrance in flood forecasting, particularly if telemetered flow data are available to allow real time correction of forecasts.

Although other authorities - notably, Thames WA Conservancy Division[101] - have developed conceptually based catchment models, only Severn-Trent WA have them in the front line of flood forecasting. Thus the remarks that follow relate largely to the subcatchment model adopted by Severn-Trent, here referred to as the ST model.

M4.2 The ST model

The ST model is described briefly by Bailey and Dobson[37], from which Fig. M4.2 is taken. Although used operationally for flood forecasting for many sites in the Severn and Trent basins, certain aspects of the model remain under development and a detailed description is not yet available.

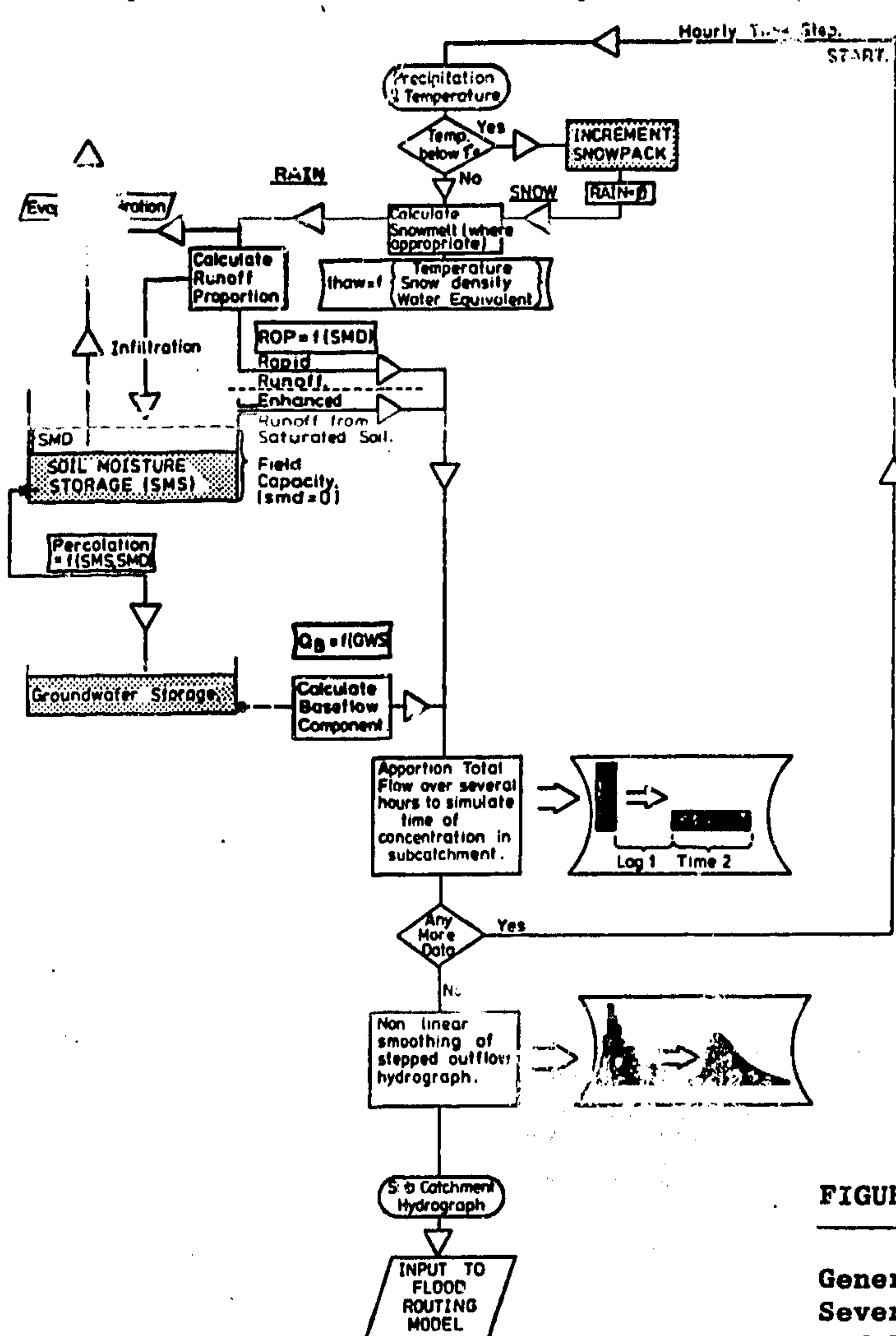


FIGURE M4.2

General structure of the Severn-Trent (ST) subcatchment model (from Bailey & Dobson[37])

As conceptual models go it is of medium complexity. It is rather less detailed than HYSIM - the general purpose catchment simulation model developed by Manley[102] - but a good deal more sophisticated than the Isolated Event Model (see Section M2.2), to which parts of the ST model bear some resemblance.

The ST model comprises a rainfall/runoff model and an optional snowmelt model. The rainfall/runoff part has about a dozen parameters. The likeness to the Isolated Event Model (IEM) is seen in the "lag and routing" applied to the runoff, and in the key role played by an empirical relationship between runoff proportion (ROP) and soil moisture deficit (SMD). The latter differs in several respects. Firstly, the ROP function is rather more complicated than that used in IEM and allows soil moisture excesses (ie. negative SMD's). And secondly, as would be expected of an ESMA model, the ST model maintains an explicit budget of soil moisture, whereas IEM relies on a supplied value for the pre-event SMD.

A feature of the soil moisture submodel is the representation of potential evaporation by long-term mean values for the time of year. This accords with research by Calder et al[103] which has shown that the use of an appropriate soil moisture regulating function is more crucial to obtaining good simulations of soil moisture than is a sophisticated potential evaporation calculation scheme. (It is interesting to note that a similar simplified representation of potential evaporation was used in the calculation of SMD for Wessex WA's Somerset Division flood forecasting scheme[66] - see Section M1.4). This means that there is no reliance on real time climate data. More positively, the research points to the important role that a dense network of telemetering raingauges can play in maintaining a good representation of spatial variations in catchment wetness.

The complexity of formulation of the ST model makes a computer implementation desirable. Severn-Trent WA have twin flood forecasting systems at Malvern and Nottingham. Each has a dedicated telemetry scanner coupled (on demand) to an IBM Series 1 minicomputer on which the flow forecasting models are run[33]. Normally the models are run at least once per day and values of the state variables (eg. the contents of the soil moisture and groundwater stores) retained for initialization of the next run. The principal form of real time correction applied is an error prediction method; this reconciles simulated flows with telemetered flows, to produce a corrected forecast. (See Section 4.4.3).

As indicated in Fig. M4.2, the ST model includes a snowmelt subroutine. This is under development but some brief details are given in Section 4.7.

A conceptual model of this complexity inevitably attracts critics. Those with a feel for conceptual modelling may debate the particular formulation chosen; those of an empirical persuasion will argue that the calibration of a model possessing so many parameters leaves too much to numerical optimization (Appendix 2) or subjective judgements. Against this it must be said that the model has been developed and implemented in a very professional manner and is by no means as hard to use as it is to calibrate.

Before selecting the ST model for flood forecasting, Severn-Trent WA carried out or commissioned studies of several candidate models, including HYSIM, IEM and a unit hydrograph method[75, 104, 105]. The argument given[105] for preferring a conceptual model to an empirical method rests largely on the assertion that an ESMA model is better equipped to simulate flows over a wide range of conditions. This seems a reasonable hypothesis and is particularly relevant where the benefit of flood forecasting accrues only in extreme events, as is the case for many of the sites for which Severn-Trent WA provide flood warnings.

M4.3 More sophisticated catchment models

In recent years, research has been directed at the development of a new breed of catchment model[67, 106]. These differ from traditional conceptual models in two important respects.

Firstly, an attempt is made to derive and solve physical equations for the component processes (eg. snowmelt, subsurface flow). Because these are "true" equations it is possible to determine appropriate parameter values from scientific study (eg. of soil samples) rather than by optimization.

Probably the most troublesome aspect of catchment modelling is that of spatial variability, both of inputs (climate variables) and the system itself (soil [illegible]). The second important feature of physics based models, such as [illegible][67] and [illegible][106], is that they are spatially distributed, representing [illegible] network of subareas or nodes. This feature leads to large and [illegible] formulations requiring sophisticated numerical solutions on powerful [illegible]ters.

[illegible] researchers believe that this type of modelling holds the key to an [illegible]rstanding of runoff formation through experimental application to intensively monitored catchments. But will such models be a practical proposition for operational flood forecasting? A pessimistic view is that any complex hydrological model - no matter how physically realistic - will be dependent on extensive survey work to select appropriate parameter values for the particular soils, land use, stream channels etc, and that in many applications this data requirement will be prohibitively expensive to meet. Perhaps the more likely course is that advances made with the physical approach will filter through into better design of traditional models. As regards the treatment of spatial variability, the "semi-distributed" approach discussed in Section 4.5.1 seems well established in British flood forecasting practice.

4.4 Real time correction

4.4.1 The problem

How best to use telemetered flow data to correct a forecast is a central theme in flood forecasting. Figure 4.4.1 illustrates the basic problem. Our model is yielding a flow forecast that telemetered observations show to be inaccurate. Should we trust the forecast produced by the model or should we somehow try to correct the forecast in the light of recent model performance?

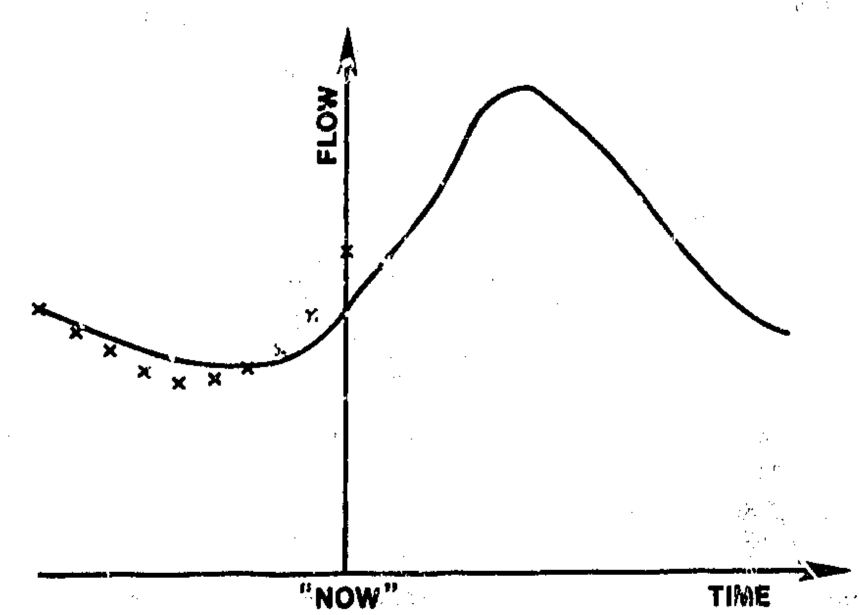


FIGURE 4.4.1

The need for real time correction

KEY

—— model simulation

× telemetered flows

The question can arise in both flood routing and rainfall/runoff modelling methods of flood forecasting. For clarity we consider only the latter and, in the first instance, only one rainfall/runoff model: the Isolated Event Model (IEM).

As described in Section M2.2, IEM is a fairly simple rainfall/runoff model having four parameters. Two of the parameters control the rainfall separation and the other two determine how the net rainfall is distributed in time as runoff. Application of the model to simulate flow from rainfall measurements is illustrated in Fig. M2.2. As in other "event" models, the observed pre-event flow, q_0, is needed to initialize the modelling of runoff. This presents little difficulty in flood forecasting applications because, for reasons discussed in Section 4.1.4, flows at the site for which forecasts are required are usually available in real time.

Figure M2.2 illustrates application of IEM in "simulation mode". No use is made of telemetered flows subsequent to the initialization procedure at the beginning of the event. As illustrated in Fig. 4.4.2, the forecast hydrograph wells up with each new rainfall observation received. Assuming that the telemetered flows differ significantly from the modelled flows, we are left with the classic problem depicted in Fig. 4.4.1. Should we correct the forecast? If so, how?

4.4.2 Approaches

There are at least three distinct ways of correcting a "simulation mode" forecast by reference to telemetered flows: error prediction, state-updating and parameter-updating. (See Table 4.4.1). All three techniques are applicable to our example rainfall/runoff model, IEM.

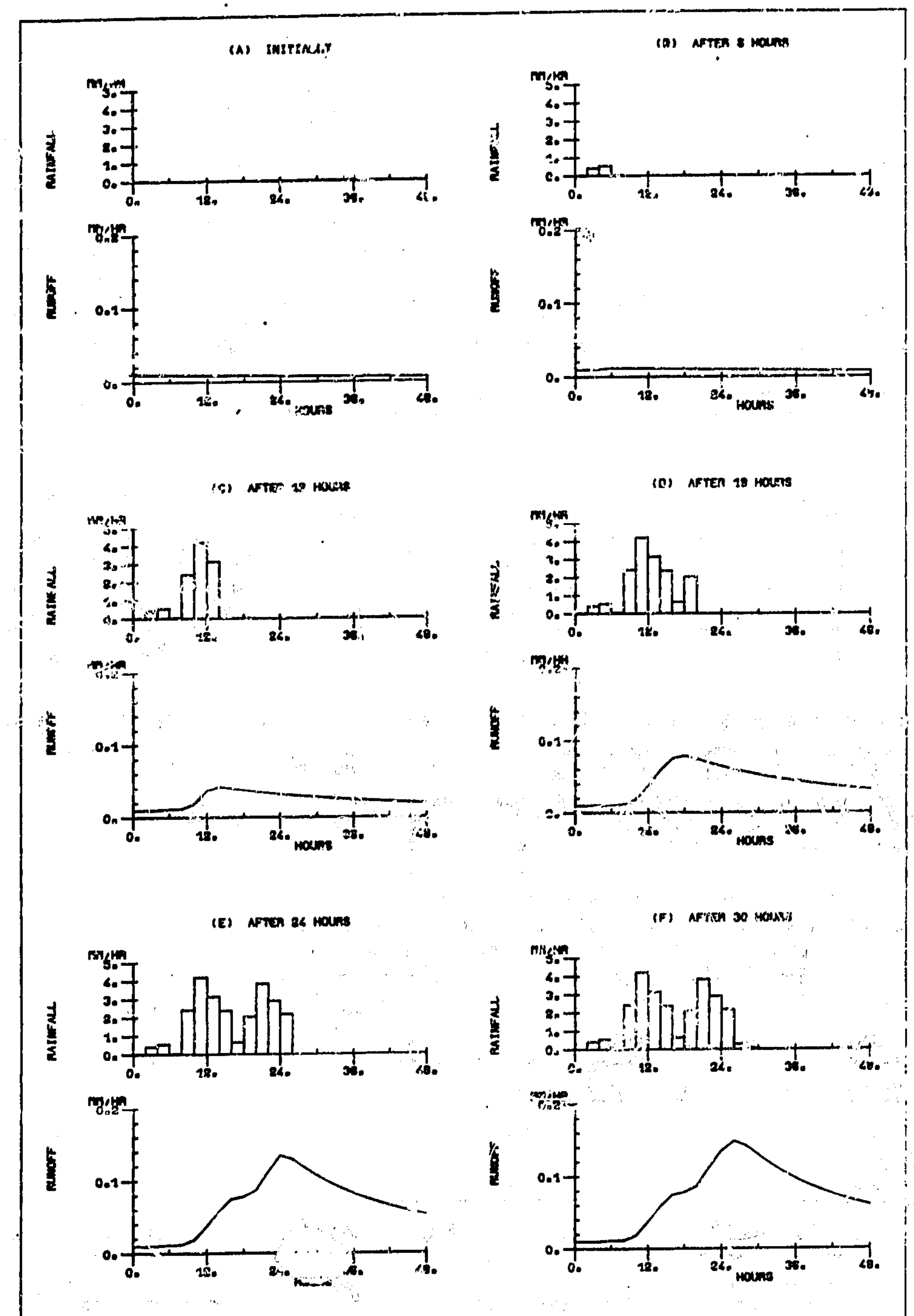
Table 4.4.1 Methods of real time correction

ERROR PREDICTION	-	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.
STATE-UPDATING	-	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.
PARAMETER-UPDATING	-	in which one or more of the model parameters are adapted in the light of recent model performance.

ERROR PREDICTION

The most obvious approach to the problem posed by Fig. 4.4.1 is to accept that a discrepancy exists between the model forecasts and the flow observations and to try to anticipate how this is likely to develop in the near future (ie. within the forecast lead time). The aim of the approach is to reconcile what the model is telling us will happen with what the telemetered flow observations say is

FIGURE 4.4.2 Snapshots of the simulation provided by IEM for an event on the Lymn at Partney Mill (Lincs.)



happening. The reconc[illegible] st easily done graphically, as Fig. 4.4.3 illustrates. Flood f[illegible] the USA[107] refer to this technique as "blending", ie. blendi[illegible] eces of information together. A less elegant but more precise term [illegible] ediction"[108], since the essence of the technique is to predict the model err[illegible] ture time steps from the model error noted in the recent past. (This is, [illegible] urse, error forecasting but use of the word prediction helps to avoid ph[illegible] ses like "model forecast error forecasting model"!). We shall see in Section 4.4.3 that a natural way to formalise error prediction is found in time series analysis.

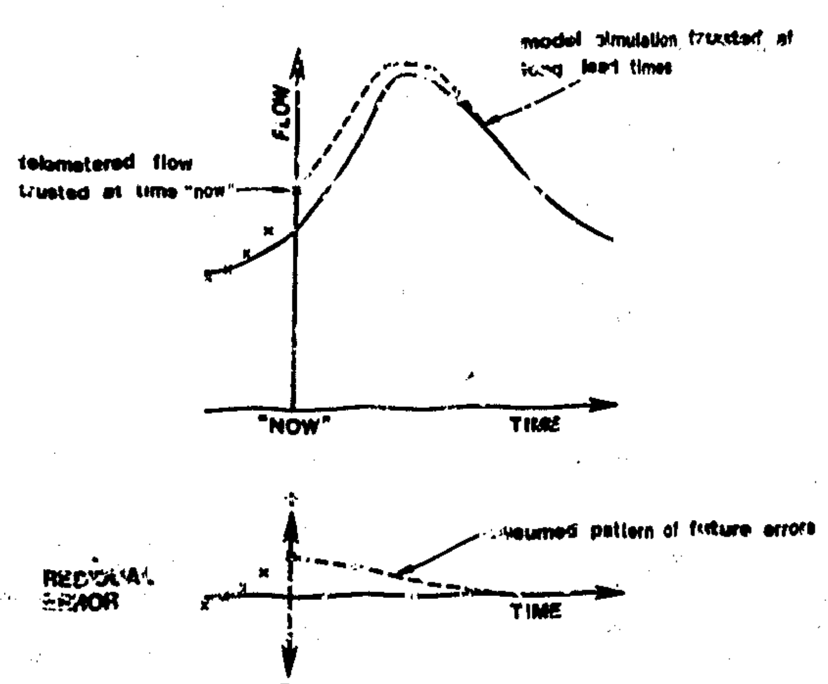


FIGURE 4.4.3

Reconciliation of model forecasts and telemetered flows by simple blending

STATE-UPDATING

A quite different approach to real time correction of IEM – at least in principle – is to use the latest telemetered flow to update the "state" (ie. content) of the model's nonlinear reservoir. Because of the unique relationship assumed between the reservoir content, S, and outflow, q:

$$S = AC.\sqrt{q} \qquad (M2.7)$$

updating the state of the reservoir corresponds to updating the modelled outflow. Thus the effect is to re-initialize or re-centre the model forecast so that it tallies with the observed flow at time "now". (See Fig. 4.4.4).

To demonstrate the wider concept of "state-updating" it is helpful to consider a second example, for which the ST model (Sectio[illegible] M4.2) [illegible] convenient choice. The ST model has three distinct storages: a soil moisture store, a groundwater store, and (when applicable) a snowpack store. (See Fig. M4.2). Normal use of the model to simulat[illegible] flow requires that these stores are initialized, in some way, prior [illegible] the event. Once initialized, the model is "driven" by the relevant input variables (primarily, rainfall observations). The stores are augmented or deplet[illegible] ording to the "rules" of the model (in which the model parameters play th[illegible]) and the flow thereby simulated. The contents of the various sto[illegible] e "state" of the model which in turn represents the state of the [illegible]. If at any time it is possible to gain an independent estimate of one [illegible] state variables – for example, if soil moisture can be deduced from neutron p[illegible] easurements at a representative site – then the content of the relevant store can be di[illegible] updated. Possibly it is easiest to [illegible] re-initialization of the model.

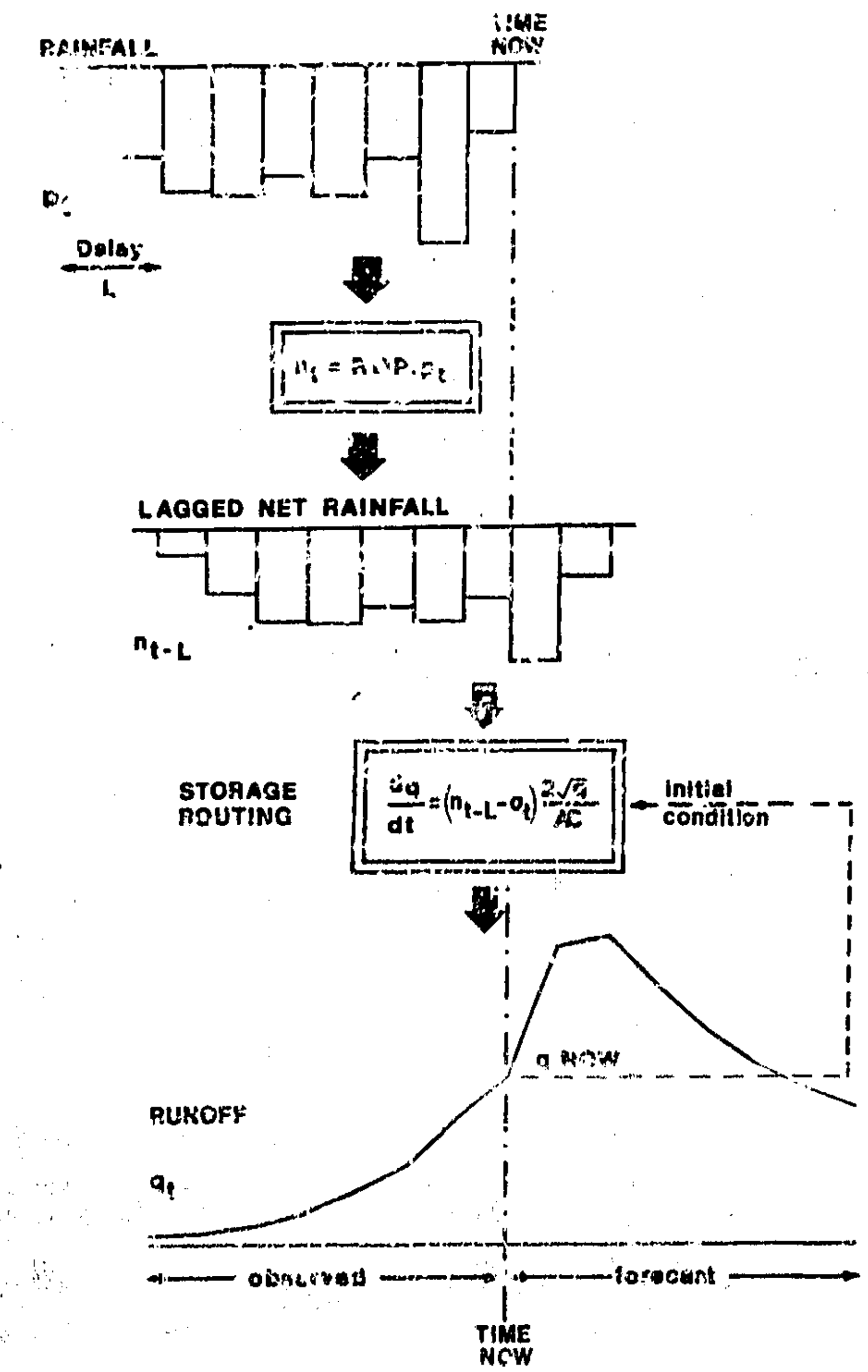


FIGURE 4.4.4

Structure of IEM for real time forecasting, illustrating re-initialisation (state-updating) by reference to telemetered flow

As we shall see in Section 4.4.4, in real time flood forecasting applications we are primarily concerned with model structures that can be state-updated by reference to telemetered flows. The broad philosophy behind the state-updating approach is that the model can be trusted for short-term flow forecasting provided that it is always starting from the right place. This is achieved by frequent or perpetual re-initialization.

PARAMETER-UPDATING

The third approach [illegible] real time correction is more drastic. One or more of the model parameters are adjusted in some systematic (usually progressive) manner until model performance is more in keeping with recent flow observations. This is the parameter-updating approach, sometimes referred to as parameter adaptation or, simply, adaptive forecasting[97]; however, the latter term is rather vague. When choosing the parameter-updating approach to real time correction it is necessary to ask several questions. Which parameters should be modified? And by what criteria? The possibilities are, of course, legion. Usually no more than two parameters are adjusted, perhaps a "volume" parameter (eg. the IEM parameter "PERC") and a "timing" parameter (eg. the IEM parameter "DEL"). Often the adjustment is made to minimize some sort of least-squares criterion between recent model forecasts and telemetered flows. This raises further questions. Should the criterion be weighted to give more emphasis to very recent flow discrepancies? How frequently should parameter-updating be attempted?

WHICH APPROACH?

When it comes to using one of the above approaches to correct a model forecast for a particular event, the effect of the various corrections may well be rather similar. For example, for the situation illustrated in Fig. 4.4.1, it is likely that all methods will ensure that the forecast is raised somewhat. The distinctions made here between error prediction, state-updating and parameter-updating methods are narrow ones; other writers would no doubt use different terminology and, perhaps, different classifications. In striving to gain insight into which methods are most appropriate for what model, it is perhaps pertinent to reflect on the nature of the error to be corrected.

If the simulation mode forecast and the flow observation differ randomly, there's little that can be done - the lack of precision in forecasting has to be accepted. If, as is more often the case, there is a marked tendency for the model forecasts to be low or high (or early or late) in successive time periods then various causes can be postulated, eg.:

(i) the rainfall data are unrepresentative
(ii) the model is poorly initialized for the current event.
(iii) the parameter values of the model are inappropriate.
or (iv) the overall model structure is flawed.

In looking at these four sources of error - and there are, no doubt, others - it is seen that the parameter-updating approach is the right one to deal with (iii) and that the state-updating approach ought to help with (ii) and possibly (i). But given that we can only guess the source of error in modelling the current event, perhaps there is much to be said for the error prediction approach, since this use does not presuppose a particular cause.

Before making recommendations on the crucial question: "which approach?", we consider methods of real time correction in further detail and with reference to experience gained in UK application.

4.4.3 Error prediction

Most real time correction undertaken in British flood forecasting practice is of the error prediction type. Graphical methods are the most common, with the forecaster deducing a suitable compromise forecast when presented with model forecasts and telemetered flows that disagree. (See Fig. 4.4.3). It is, of course, all down to common sense. Often, the latest telemetered value and the trend of the model forecast are all that are needed to deduce a good short-term corrected forecast[1]. However, automating what the forecaster's eye can judge instinctively is not particularly easy. The main difficulty is the distinction of "timing" and "value" errors, a subject we return to in Section 4.4.6. Anglian WA Essex River Division apply a "shift and scale" correction to model forecasts produced by a unit hydrograph model[65]. The forecaster determines an appropriate proportional adjustment to the forecast hydrograph and/or an appropriate timing

correction and gets the computer to re-calculate and display the forecast. Of course corrections deduced visually can be rather subjective.

A way of formalizing error prediction is to fit a time series model to the sequence of errors. The observed flow series, q_t, is taken to consist of a deterministic component, $\hat{q}_t$, and a stochastic 'noise' term, η_t:

$$q_t = \hat{q}_t + \eta_t$$

The deterministic component is simply the output from our basic model, sometimes referred to as the process model. The object of the approach is to fit a time series model to the noise component which can then be used for error prediction.

The usual practice[109, 3] is to seek an ARMA model which, when fed with a purely random input series a_t, reproduces the observed error series, η_t. If the process model is a transfer function model (see Section MC), the overall model assumes the structure of a transfer function noise model" as illustrated in Fig. 4.4.5. While it is thematic to fit a stochastic noise model when using a process model phrased in statistical terms, the technique is quite general and can be applied to study the error sequence of any model. Once calibrated, the noise model is used to estimate likely errors at future time steps and the error forecast added to the deterministic model forecast. (See pp. 43-44 of Moore[3]).

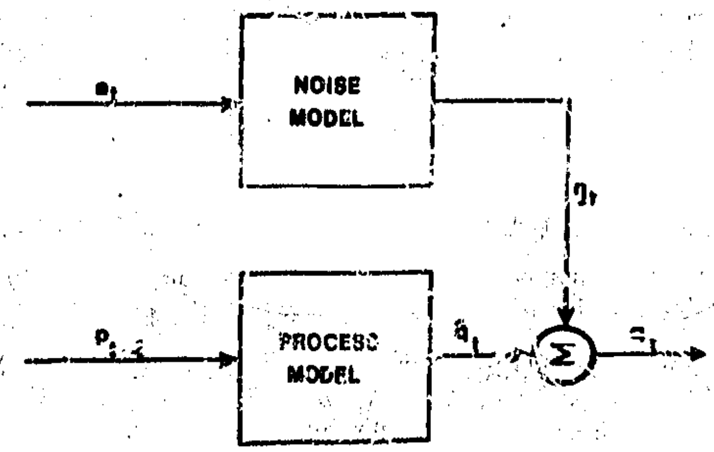


FIGURE 4.4.5

System representation of a transfer function noise model (after Moore & O'Connell[3])

The calibration of noise models can be rather specialized. The task is aided by the availability of standard time series analysis packages[94, 95, 96], although a certain confidence and statistical insight is undoubtedly required. Sometimes a relatively simple autoregressive (AR) model will suffice and this can be fitted by multiple linear regression. Replicas of the error series, η_t, are lagged by one, two, ... data intervals and a regression sought between η_t and η_{t-1}, η_{t-2}, ... The regression equation then constitutes the noise model.

Once calibrated, time series noise models are extremely simple to apply. The approach provides a logical route to automating visual methods of error prediction and is to be generally recommended. However, a note of caution is sounded in Section 4.4.6 concerning the susceptibility of automatic correction methods to be led astray by timing errors.

Several real time correction methods - primarily of the error prediction type - have been considered by Bramley[110]. The conclusions reached included preferences for:

(i) error prediction rather than parameter-updating
(ii) use of an autoregressive model to forecast model errors up to a fixed lead time

(iii) use of a simple exponential decay to blend the corrected forecast back to the simulation forecast beyond this lead time
(iv) estimation of the error prediction model by a recursive least-squares algorithm, with exponential weighting to give emphasis to recent model errors.

This research was carried out on error series produced by various forerunners of the ST model (Section M4.2). Pending final resolution of the subcatchment and flood routing models, Severn-Trent WA have implemented a variable blending technique for real time correction. This follows the scheme of Fig. 4.4.3 with the subtle refinement that the period over which the blending takes place is reduced if recent errors have been variable, but extended if they have been steady.

4.4.4 State-updating

The state-updating technique is used by a number of flood warning authorities, primarily in connection with the ISO model (Section M2). Unlike most other rainfall/runoff models, the ISO-function method was devised specifically with flow forecasting in mind[82]. It is readily state-updated in the manner illustrated in Fig. M2.1 and described (for IEM) in Section 4.4.2. ISO-models are used by Welsh WA in a variety of forms and by Northumbrian WA in a convenient graphical version. Where telemetered flow data are available, these are generally used to state-update the ISO model forecasts. The simplified rainfall/runoff model developed by North West WA has strong similarities and is likewise designed with state-updating in mind[16]. Viewed as a "simulation mode" model, ie without state-updating, the ISO model is very crude - since no explicit account is taken of rainfall losses. Thus state-updating the ISO model can be considered more an essential than a refinement. This raises the interesting question of whether a second layer of real time correction is appropriate!

The formulation of transfer function models (Section M3) makes them very easy to apply in state-updating form. Telemetered flows are inserted in place of previously forecast values as soon as they become available. This is the approach employed in Wessex WA Somerset Division's computerized flood warning scheme[66]. Their experience has revealed no major weakness but they have recently opted to use much simpler unit hydrograph methods in a replacement scheme*. Research by Moore[3] indicates that a noise model (see Section 4.4.3) is in general a more reliable way to correct a transfer function model forecast.

Subsequent to inter-model comparisons by Simpson[75], Severn-Trent WA examined further possibilities including an updating version of Manley's HYSIM model[105]. This is a sophisticated general purpose catchment model of conceptual type. (See Section M4). The method of real time correction tried with HYSIM was to scale the rainfall input to the model in such a way as to make modelled and telemetered flows agree at time "now". This can be viewed as a version of state-updating since the adjustment of the input alters the contents of the various stores in HYSIM but does not alter the model parameters. Manley et al[105] express reservation about this form of updating, quoting a crucial example where it downgraded a generally good "simulation mode" forecast to a poor "corrected" forecast. This fear of inadvertently making matters worse is to be faced in all methods of real time correction but state-updating techniques are, perhaps, particularly prone to producing poor corrections from time to time.

* The switch to unit hydrograph methods is being undertaken as part of a general overhaul and simplification of Somerset Division's flood forecasting system. The strategy includes the synthesis of unit hydrograph models for ungauged catchments.

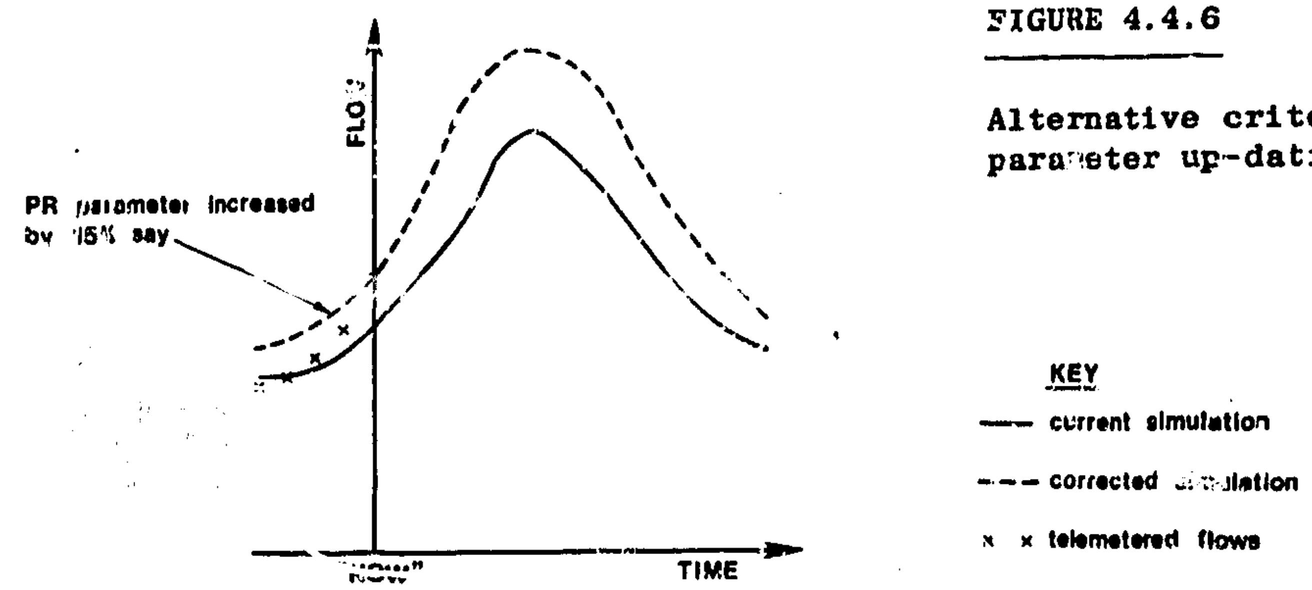
4.4.5 Parameter-updating

Parameter-updating methods of real time flow forecasting are, in Britain, as yet largely confined to research use. However, the potential of a simple parameter-updating method for operational use has been partially investigated by Severn-Trent WA.

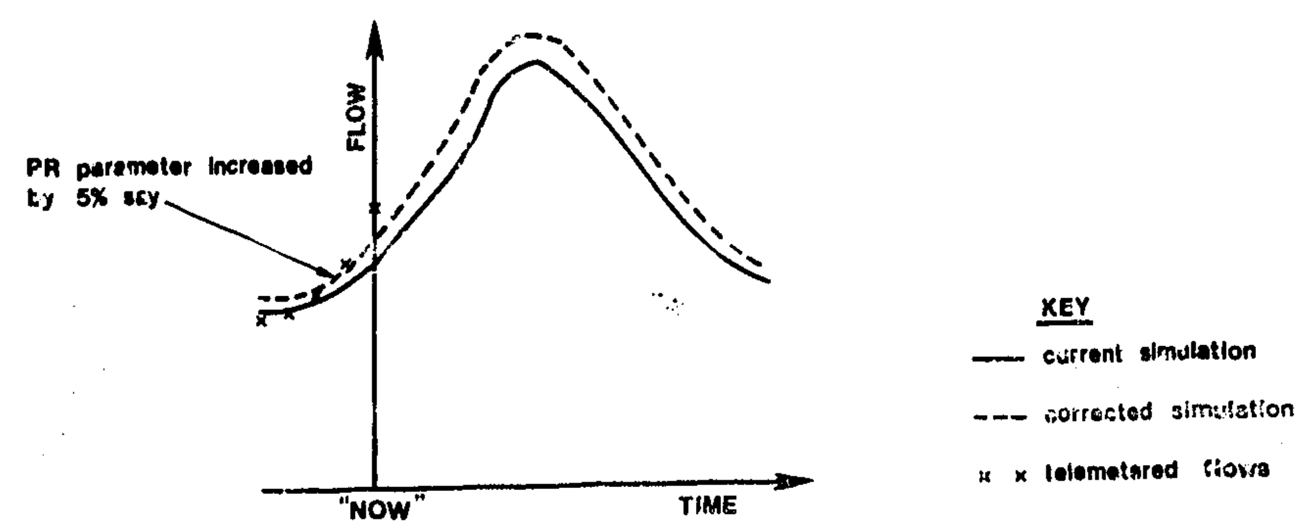
Simpson[75], in a research study for Severn-Trent WA, considered updating the percentage runoff (PR) parameter of a unit hydrograph model. (See Section M1.4). The method used was as follows. First, an initial estimate of the PR value applicable to the current event is made from the antecedent catchment wetness. Thereafter PR is adjusted automatically as each newly telemetered flow becomes available. The basis of the adjustment is to match the observed and modelled volumes of runoff over a short period prior to time "now". Simpson et al[104] note that this criterion is rather more stable than merely adjusting PR to match the latest telemetered flow value. (See Fig. 4.4.6). Simpson expressed confidence in this development but subsequently another rainfall/runoff model has been favoured for operational use in Severn Trent WA[37]. (See Section M4.2). However, Anglian WA Essex River Division have gained operational experience of adjusting PR in real time in a broadly equivalent manner (see Section 4.4.3).

FIGURE 4.4.6

Alternative criteria for parameter up-dating



(a) Matching latest telemetered flow



(b) Matching volume represented by recent telemetered flows

There are, of course, many ways in which a rainfall/runoff model might be parameter-updated for real time use. Some very sophisticated techniques - such as Kalman filtering[91] - allow the simultaneous updating of both model states and model parameters, according to the certainty with which each are known. However, it seems that the information required to quantify model and measurement errors *a priori* makes such methods of little practical value in everyday hydrological forecasting. Possibly the greatest stumbling block is that in catchment modelling applications we have a very uncertain estimate of the true input to the system. The potential for sophisticated updating methods is thus perhaps rather greater in flood routing applications[111], where the input is sometimes relatively well defined.

4.4.6 Timing errors

A possible difficulty in moving from human (subjective) to automatic (objective) correction concerns the distinction of "timing" and "value" errors. Interpreted visually, an assessment can be made of whether a model error can be substantially explained by a simple timing adjustment. However, if the error sequence is defined solely in terms of flow discrepancies as set time intervals - as is currently the general practice - an automatic method of correction will be oblivious to the special nature of a timing error.

It is sometimes said that timing errors are unlikely to be a serious problem in real time forecasting[35, 104]. The implication would appear to be that such errors arise only from faultily timed data. If, as is intended here, a timing error refers to any consistent timing discrepancy between forecast and telemetered flows, it would seem presumptive to say that such errors could not arise in other ways. One alternative cause might be if point rainfall data for the current event were atypical (in terms of timing) of rainfall over the catchment as a whole. Another possibility might be that a timing error arises simply through model imperfection.

Whatever their cause, it is desirable that timing errors should not confound the method of real time correction adopted. Further development appears warranted if automatic systems are to replace or augment visual reconciliation of model forecasts and telemetered flows.

4.4.7 Recommendations

There is insufficient operational experience of real time correction methods to make definitive recommendations for British flood forecasting practice. However, the following observations are given for guidance.

1. If time and facilities permit the flood duty officer to intervene, visual comparison of model forecasts and telemetered flows is the simplest and probably most reliable means of real time correction.

2. Automatic methods of correcting forecasts - whether they be of the state-updating, parameter-updating or error prediction type - may confuse a duty officer. Unless he can understand the way in which the model forecast is changing, he may be left with only two options: to reject the forecast or to rely on it [illegible]. Too much reliance on automatic methods may engender a false sense of [illegible]ity. In most cases it is therefore desirable that the uncorrected (ie. simulation mode) forecast should be available for comparison.

3. If there is insufficient time or facilities for the duty officer to intervene (eg. in flood warning systems of the "burglar alarm" type), an automatic method of real time correction may be required.

4. In choosing an appropriate method of real time correction, it may help to consider the likely cause of errors in the model forecast. If a particular part of the model is known to be important but error-prone, then a parameter-updating technique may be appropriate. In contrast, a state-updating technique may be indicated if the input data or the initialization of the model is considered suspect. If little is known of the particular weakness of the forecasting model, an error prediction method is probably the safest choice.

5. Error prediction methods based on time series analysis can be used to model the residual error of any model forecast; they provide a natural way to formalize visual correction methods.

6. A potential weakness of automatic methods is that the correction may be led astray by a timing discrepancy between forecast and telemetered flows. Further research is warranted into error criteria that take account of possible timing anomalies.

7. The ISO-model is peculiar in that state-updating is virtually essential to its use. Should the ISO-model be found unsatisfactory for a particular application it is probably advisable to consider a more general nonlinear storage model than to apply an additional "layer" of real time correction.

8. If good quality telemetered flows are available from a site near to the risk area, then "simple model plus sophisticated correction" would seem preferable to "sophisticated model plus simple correction".

9. If few historical data are available to calibrate a model, then parameter-updated models, that can learn as they go along, may be an attractive possibility for automatic flood warning systems. However, the necessary methodology is rather specialized and the value of such models has yet to be proved in British flood warning practice.

4.5 Modelling of large river systems

4.5.1 The semi-distributed approach

Some of the larger river systems in Britain merit a fairly comprehensive approach to flood forecasting. A well documented example is the (Welsh) Dee[2]. This 1815 km^2 river basin is represented in the Dee flow forecasting system[89] by a combination of subcatchment rainfall/runoff models and main river flood routing. (See Fig. 4.5.1). This semi-distributed approach to catchment modelling has several advantages: it allows flow forecasts to be generated for several sites, extends the lead time attainable by flood routing alone, and permits direct account to be taken of spatial variations in rainfall. The approach is generally recommended[112] for flood estimation on catchments greater than 500 km^2 and has been followed - most notably by Severn-Trent WA[37] - in the development of flow forecasting models for large river systems. Figure 4.5.2 provides a further example of the semi-distributed approach to model building; the case illustrated is but a small subset of the overall flood forecasting model for the Severn basin.

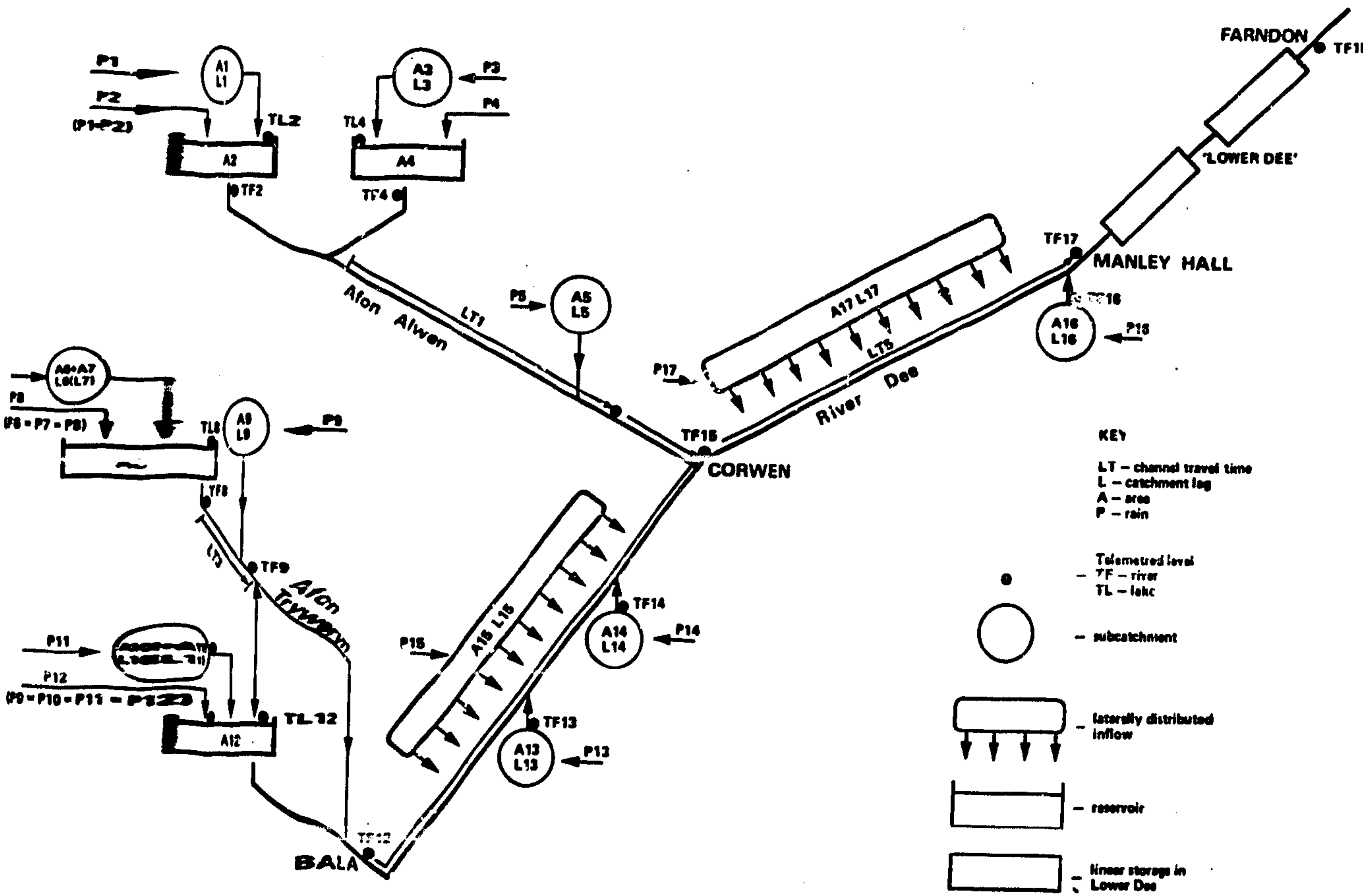
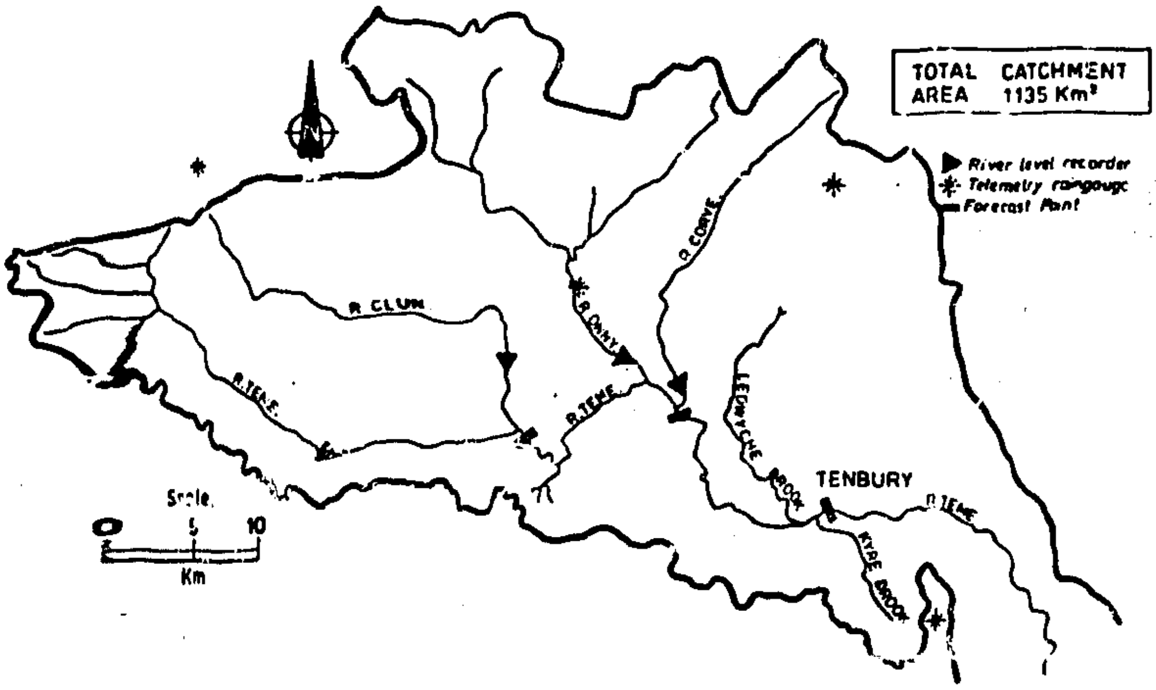


FIGURE 4.5.1 Schematic of river Dee model[2].



(a) Catchment plan

(b) Schematic of routing model showing inflows from subcatchment rainfall/runoff models

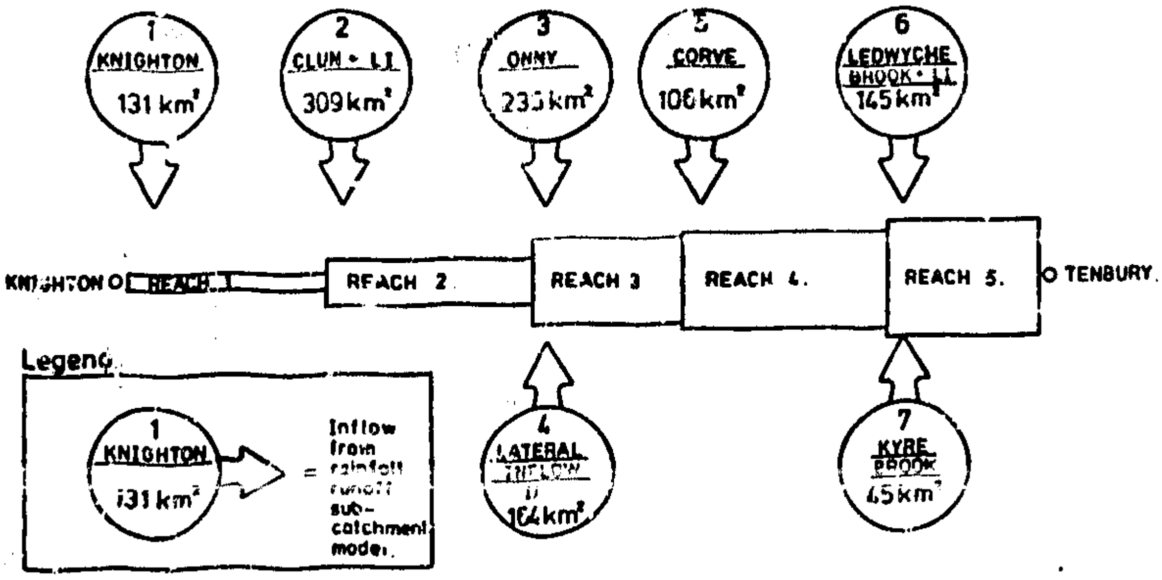


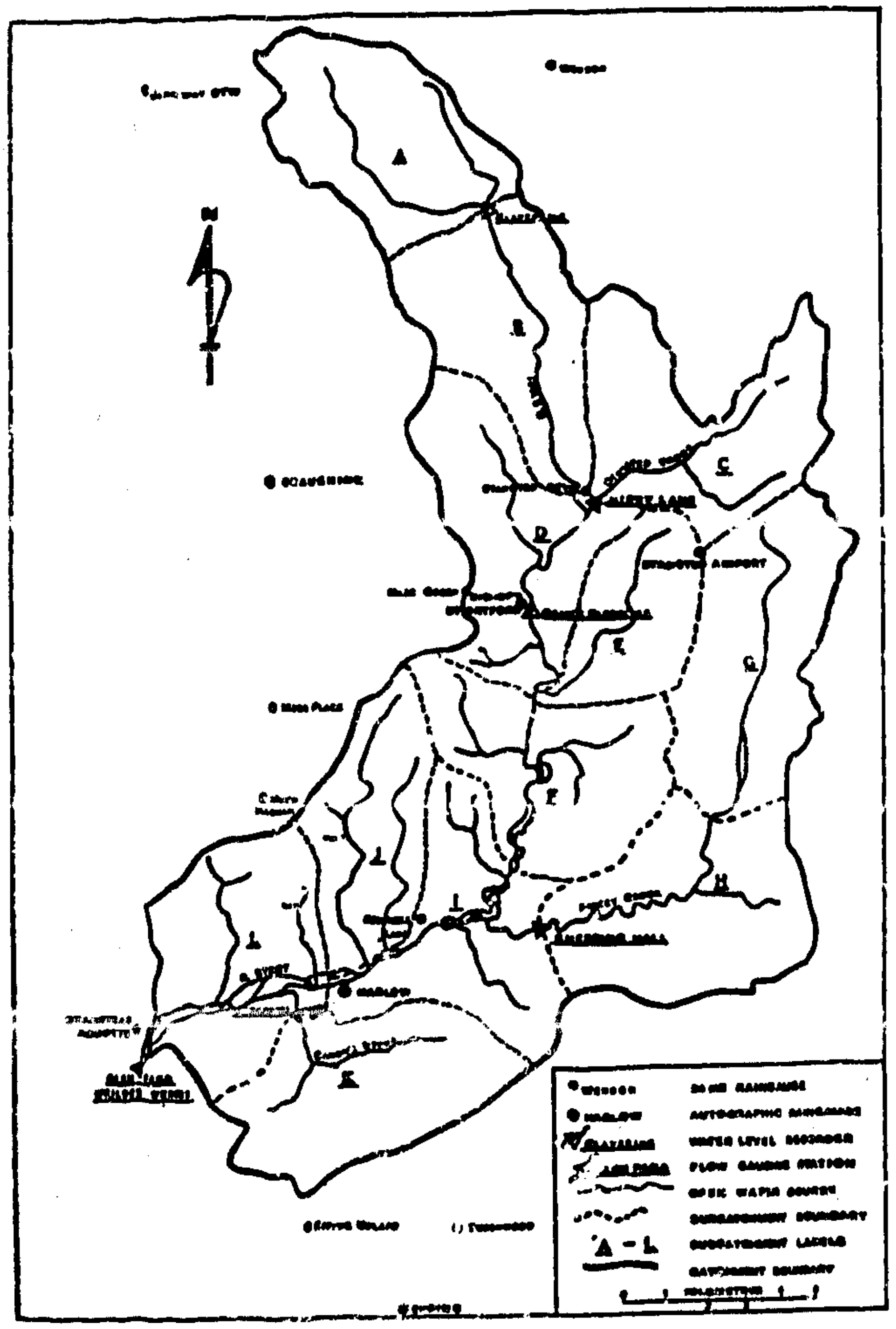
FIGURE 4.5.2 Semi-distributed approach applied to the river Teme (after Bailey & Dobson[37])

4.5.2 Distributed models

A more radical approach is to adopt a fully distributed catchment model; this is a model that has a large number of discrete elements interconnected to mimic the spatially distributed nature of a river system. It is arguable whether the new breed of physics based catchment models (see Section M4.3) will find direct application to flood warning in Britain. As noted at several points in this report, model sophistication may be subordinate to "update-ability" when considering real time forecasting applications. But, with high-quality spatial definition of rainfall fields possible by radar (see Section 6.8), it is inevitable that attention will turn to some kind of distributed model structure that can take advantage of spatially variable data.

A simple empirical distributed model - the runoff routing model[113 114] is widely used for design flood estimation in Australia and has been considered for flood forecasting by Thames WA Lea Division[115]. The model represents the catchment by a tree-like structure of nonlinear storages (see Fig. 4.5.3.). Although fairly cumbersome to apply, the runoff routing model is efficiently

(a) Catchment plan



(b) Model structure

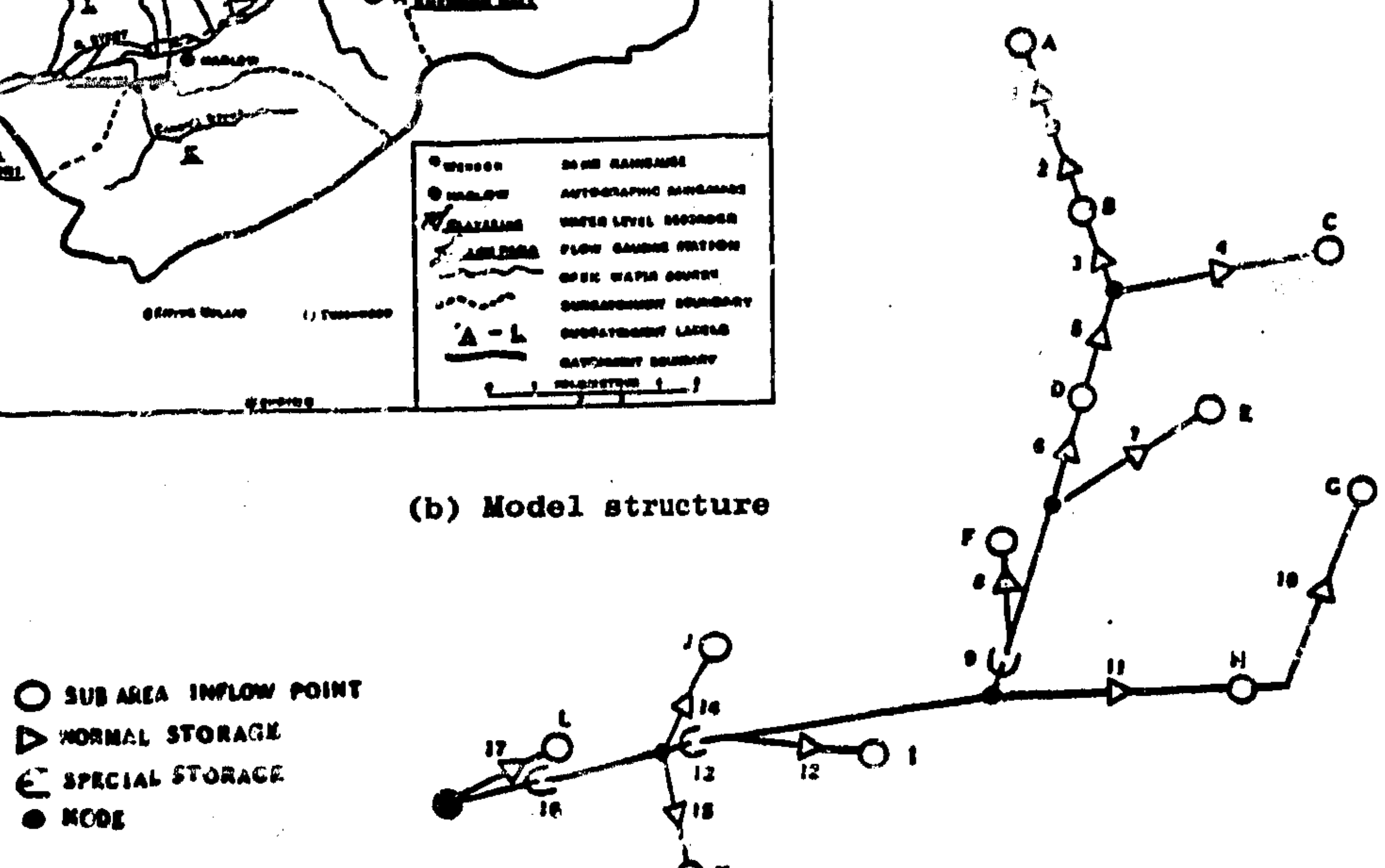


FIGURE 4.5.3 Runoff routing model representation of the Stort (from Edmeades[115])

parameterized; basic versions have three to five parameters. As in the semi-distributed approach, spatial variation in rainfall can be taken into account and flow forecasts produced for several sites. Perhaps the principal weakness of using the runoff routing model for flood forecasting is the lack of an obvious way of incorporating telemetered flow data from tributary gauging stations to improve model forecasts.

4.5.3 Simple combinations of rainfall/runoff and flood routing methods

If a flood routing method is found to provide inadequate warnings, the general approach to extending forecast lead times is by the addition of a rainfall/runoff model. We consider two ways in which a simple (ie. 2-station) flood routing method can be enhanced.

In the first example (Fig. 4.5.4a) the obvious approach is to fit a rainfall/runoff model to the upper subcatchment. The model can be used to forecast flows at the upstream gauging station from telemetered rainfalls; these flows are then routed to provide an extended forecast lead time for the downstream site.

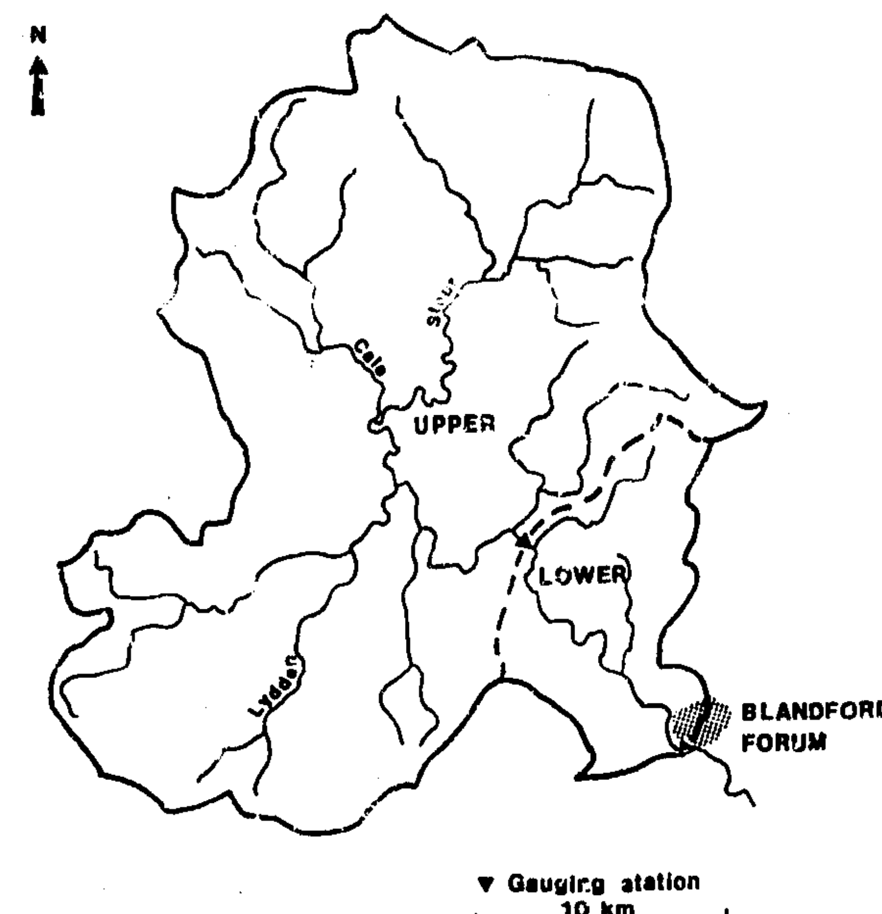


FIGURE 4.5.4

Simple combination of rainfall/runoff and flood routing methods

(a) An example were a rainfall/runoff model of the upper subcatchment may be appropriate

A slightly different approach may be appropriate in cases like Fig. 4.5.4b, where any inadequacy in the flood routing method is likely to stem from the upstream gauging station being insufficiently representative of flows to be expected at the downstream site. Here, a rainfall/runoff model can be fitted to the lower subcatchment with the aim of improving the estimation of lateral inflow between the two gauging stations (see Section 4.2.9). Although the calibration of such a subcatchment model is rather complicated (since the contribution from the lower catchment has to be inferred from the upstream and downstream hydrographs) the approach would seem to meet a fairly common requirement.

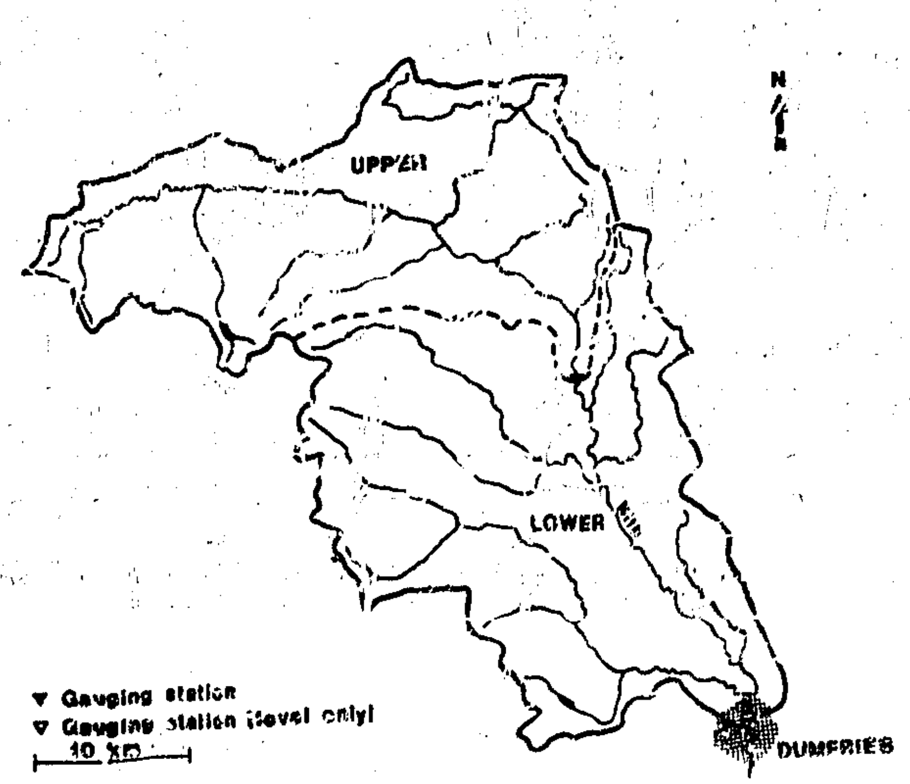


FIGURE 4.5.4

Simple combination of rainfall/runoff and flood routing methods

(b) An example where a rainfall/runoff model of the lower subcatchment may be appropriate

Comparison of Figures 4.5.4a and b highlights the importance of matching the model to the instrument network or, where practical, the instrument network to the modelling strategy. Clearly the approach of Fig.4.5.4b would have little to commend it if the only telemetering raingauge was sited in the upper subcatchment.

4.6 Rainfall forecasting

4.6.1 The role of rainfall forecasts

Rainfall forecasts are useful in several aspects of flood warning. The most prevalent application is as an initial alert to the flood warning duty officer. Many authorities make use of the "heavy rainfall warning" service available from the Met. Office (see Section 5.10). This role for rainfall forecasts is widely accepted but, as yet, issuing flood warnings on the strength of forecast rainfall is not.

In the past, the general policy of flood warning authorities appears to have been only to issue warnings supported by fact, usually an observed or telemetered river level. There remains a reluctance in many authorities to issue warnings on the basis of telemetered rainfall. This reluctance stems partly from a healthy distrust of rainfall/runoff methods and partly because "rogue" raingauge readings are very much harder to detect than their river level counterparts. However, with the greater investment in weather radars (see Sections 3.2 and 6.8), and in the development of quantitative precipitation forecasts (QPF), it seems likely that greater attention will be focussed on the use of rainfall/runoff models for flood warning. In particular, the combination of rainfall/runoff modelling and QPF offers the possibility of effective flood warning on rapidly responding catchments.

At present, rainfall forecasts generally available to flood warning authorities are qualitative or semi-quantitative. Having been alerted by a heavy rainfall warning, the flood warning duty officer may keep in touch with the local

Met. Office forecast centre and, perhaps, extract a "best guess" or pessimistic forecast of how the event might continue. The information is then used in a fairly subjective manner; the duty officer might calculate a flood forecast conditional on a particular continuation of rainfall and bear this in mind when determining whether to issue a flood warning.

Some authorities have more specific arrangements with the Met. Office. For example, Severn-Trent WA receive semi-quantitative rainfall forecasts daily at 16.00 hrs, as part of their routine monitoring procedures. The forecasts are qualified by a confidence index on a 3-point scale. Arrangements also allow for a routine review of the rainfall forecast at 22.00 hrs and 06.00 hrs (any increases being notified to the flood warning duty officer) and a special review in the event of a major change at any time.

There is, perhaps, a basic dilemma in using rainfall forecasts for flood warning. The forecasts are likely to be of greatest value on rapidly responding catchments. Such applications demand near instantaneous preparation of flood forecasts - something that is unlikely to be realised by manually produced, verbally transmitted rainfall forecasts. Part of the problem is the trickiness of rainfall forecasting but part undoubtedly stems from the division of duties between two organizations. In contrast, the US National Weather Service has both rainfall and flood forecasting responsibilities, as does the Australian Bureau of Meteorology.

4.6.2 The FRONTIERS system

Meteorological Office weather forecasters have access to increasingly sophisticated real time monitoring facilities, of which weather radar and satellite-derived cloud imagery are most obviously helpful for short-period rainfall forecasting. The Met. Office's "total system" approach to producing quantitative precipitation forecasts (QPF) is described by Browning and Collier[116], from which Fig. 4.6.1 is taken.

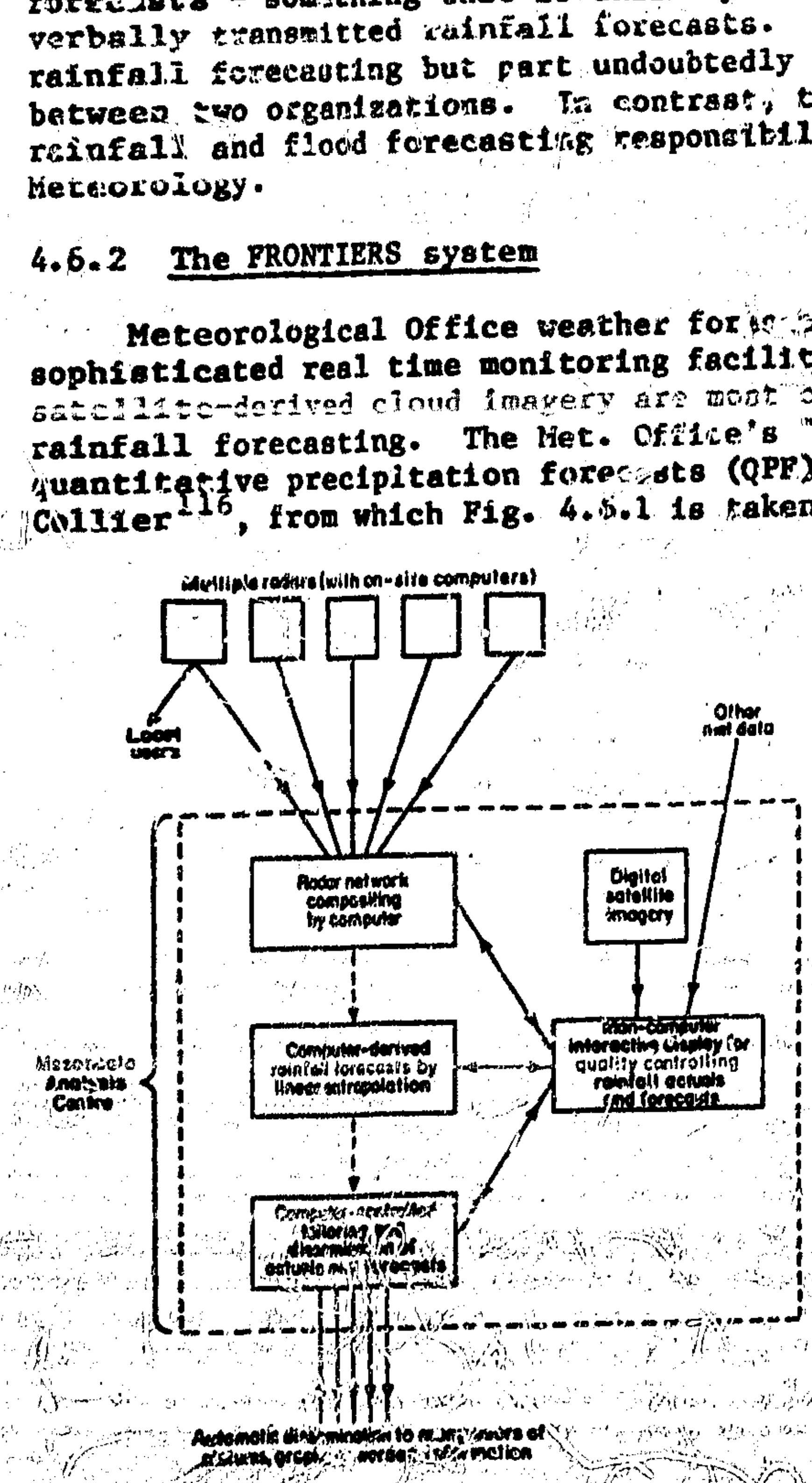


FIGURE 4.6.1

The Met. Office's "total system" approach to quantitative precipitation forecasting (from Browning & Collier[116])

Referring to the components shown in the figure, considerable operational experience has already been gained of weather radars[2, 18] (and their associated data processing and display tasks) and of the integration in real time of data received from several radar sites[26]. There is much current activity in developing the FRONTIERS system[17, 26] by which the meteorological forecaster can interact effectively with the computerized components of the total system. A particular asset will be the improved quality control of real time radar data. As regards rainfall forecasting, several flood warning authorities — notably North West WA, Thames WA and the Greater London Council - plan to be able to receive QPF by inter-computer transfers.

In those parts of Britain well served by weather radar, this would seem to be the ideal approach to integrating rainfall forecasts into flood forecasting. However, given that parts of England and Wales and much of Scotland are unlikely to receive quantitative coverage in the near future[15], and that not all flood warning problems will justify the overheads of such integration, ad hoc methods of rainfall forecasting are also of interest.

4.6.3 Simple algorithms

Given a few telemetering raingauges it is unlikely that attempts to forecast spatial trends in rainfall will be particularly successful. Many rainfall/runoff models are, however, content with point values of rainfall and the basic requirement is therefore a projection of values to be expected at individual raingauge sites.

The natural persistence of meteorological phenomenona suggests that the assumption of zero rainfall beyond time "now" is in general a poor forecast if the last few rainfall observations indicate continuing rainfall. In interactive flood forecasting systems, the problem is overcome by the duty officer's judgement - perhaps backed up by the local Met. Office forecaster. But in automatic flood warning systems a better short-term forecast (than zero rainfall) is clearly appropriate.

Time series models provide a natural medium for short-term rainfall forecasting. For example, Reed[63] found a simple autoregressive model useful in extending the warning time provided by rainfall/runoff methods on the rapidly responding Rhondda catchment (see Section 4.1.2). The model adopted to forecast rainfall was:

$$RF_{NEXT} = 0.8\,RF_{LATEST} - 0.2\,RF_{PREVIOUS} \qquad (4.6.1)$$

where RF denotes point rainfall and the meaning of the suffices is obvious. Equation 4.6.1 was applied recursively to forecast rainfall up to 3 hours ahead, with the one constraint that any negative values be set to zero. This crude rainfall forecasting algorithm partially corrected the tendency of the rainfall/runoff models tested to produce short-term flow forecasts that consistently "lagged behind reality". (See Fig. 4.6.2).

4.6.4 A probabilistic approach

A somewhat different approach to short-term rainfall forecasting has attracted research in the USA[117]. Past storms in the region are analysed and a probabilistic model constructed in terms of the depth, duration and profile of individual rainfall bursts, and the inter-arrival time of distinct bursts. Then, given knowledge of the temporal characteristics of the storm up to time "now", Bayesian techniques are used to sample the range of possible continuations of the

event. Depending on the resources available, flood forecasts are developed for some or all of the scenarios. Although rather sophisticated and demanding, the approach offers perhaps the ultimate type of output - a statement of the likelihood, given present conditions, that a critical flow or level will be exceeded. A much simpler version of the probabilistic approach has been considered in West Germany[18].

4.6.5 Possible interaction with rainfall/runoff model calibration

This subsection considers the possible pitfalls of an approach that is as yet largely restricted to research use. The material presented is rather tentative and is perhaps a little beyond the legitimate scope of a review of British flood forecasting practice. It is included to stimulate thought about what may be an important area in future: the overlap between rainfall forecasting and rainfall/runoff modelling.

An increasingly common approach - at least amongst researchers - is to calibrate a rainfall/runoff model with a specific lead time in mind. For example, Moore derives n-step ahead "predictors" based on a transfer function model[3] and Green improved the quality of practical flood forecasts by a 1-step ahead optimization of ISO model parameters[88].

Both the method and effect of the approach can be rather difficult to decipher. In what follows it is suggested that the question of optimizing model forecasts at a specific lead time is intrinsically linked to rainfall forecasting. The connection is obscured by real time correction (Section 4.4) and in rainfall/runoff models that include a pure time delay parameter. It is therefore convenient to illustrate the link by reference to a model structure - such as the unit hydrograph - that simulates an immediate response to net rainfall.

Figure 4.6.2 shows 2 hour ahead forecasts produced by a unit hydrograph model under various assumptions about future rainfall. In the absence of a rainfall forecast, the forecast flows on the rising limb of the hydrograph are consistently late when compared to the flows subsequently observed. This arises in part from the failure to anticipate continuing rainfall in the 2 hour forecast period. Some form of rainfall forecast is required and, as we have seen in Section 4.6.3, a simple forecasting algorithm corrects part of the discrepancy. (In this example, perfect foreknowledge of rainfall further improves the 2 hour ahead flow forecasts but cannot, of course, correct deficiencies in the basic rainfall/runoff model.)

Instead of invoking rainfall forecasts, the tendency for 2 hour ahead flow forecasts to lag behind reality might be cured by re-calibrating the unit hydrograph model at a 2 hour lead time. This might be done in various ways but the effect would probably be to "sharpen up" the unit hydrograph (to give a slightly faster and more intense response) and/or increase the percentage runoff parameter slightly. Provided that the objective function used to re-calibrate the model was the minimization of 2 hour ahead forecast errors, it is likely that the end-product would be a model that - in the absence of a rainfall forecast - performed rather better than that shown in Fig. 4.6.2.

In the example considered above it is manifest that the "calibration at a specific lead time" approach is filling in for a short-term rainfall forecast. The question arises as to whether matters are any different when considering rainfall/runoff models that have a pure time delay parameter, L. A feature of such models (Sections M2 and M3) is that flow forecasts up to L hours ahead are independent of future rainfall and can therefore be made without recourse to

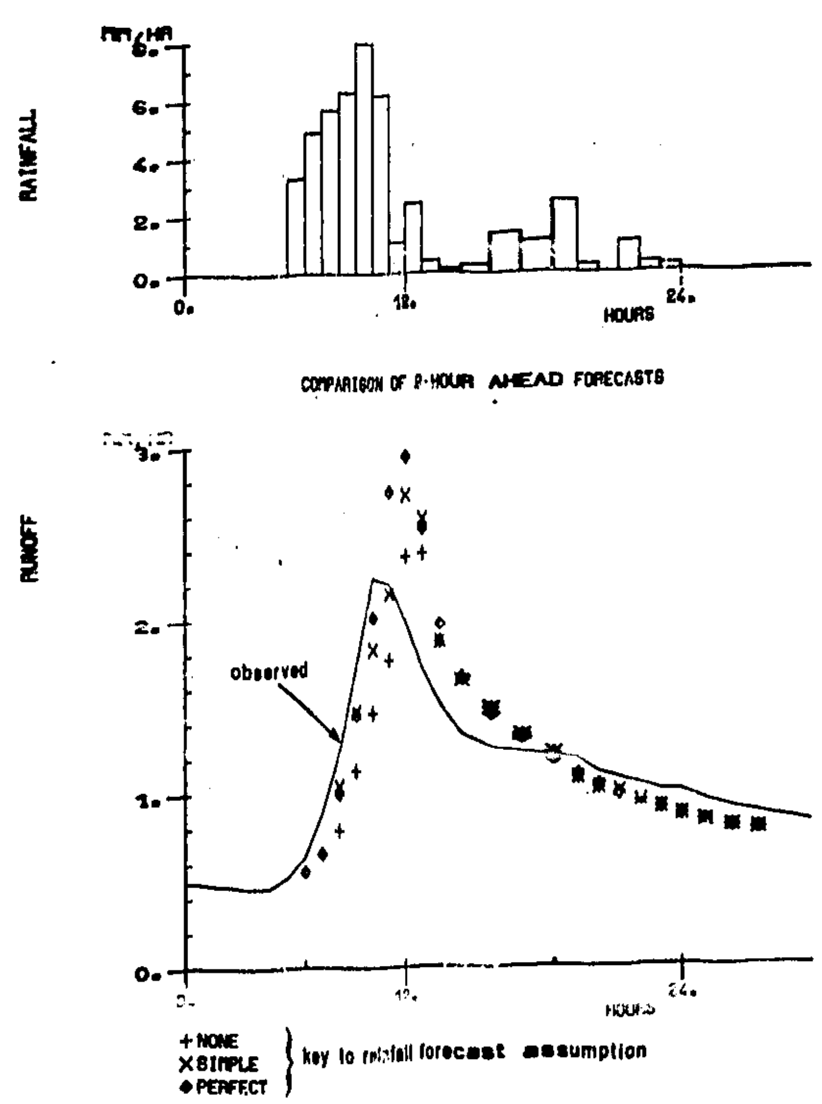


FIGURE 4.6.2

Two-hour ahead flow forecasts on a rapidly responding catchment (the Rhondda at Trehafod) - the significance of short-term rainfall forecasting

rainfall forecasting. The answer probably lies in whether the pure time delay represents a physical property of the catchment or is merely a modelling convenience. Should the latter be the case then even a standard approach to model calibration (ie. at zero lead time) may infer some short-term rainfall forecast.

The "calibration at a specific lead time" approach is undoubtedly a convenient way of improving short-term flood forecasts - because it circumvents the need to consider rainfall forecasting - but the price to be paid is that the resultant rainfall/runoff model may not be quite what it appears to be.

A potential danger is that a model with a built-in rainfall forecast might subsequently be used with explicit rainfall forecasts. The rainfall/runoff model favoured by North West WA has a pure time delay parameter and this ranges from zero on some catchments to 5 hours on others[16]. The model is currently used to good effect with telemetered river levels and radar derived rainfall values. But, once QPF becomes available under the FRONTIERS system (see Section 4.6.2) the temptation to combine explicit rainfall forecasts with the existing rainfall/runoff models is obvious. The effect of such usage might be a "double accounting" for forecast rainfall, if the existing models already make some allowance for continuing rainfall.

Perhaps the general point to be made from the above discussion is that rainfall forecasting is an intrinsic part of flood forecasting if a rainfall/runoff model is being used. Although it is convenient to assign the rainfall forecasting to the meteorologist, and the rainfall/runoff modelling to the hydrologist, the flood forecasting problem may not always respect the demarcation!

4.7 Snowmelt forecasting

Measuring and modelling snowpack behaviour presents a difficult problem for flood forecasters in Britain. Snowmelt forecasting is relatively well met in subarctic conditions by empirical methods such as the "degree-day" method (eg. Gray[63]). But in much of Britain, significant snow accumulations are relatively infrequent, may be spatially quite varied and short-lived, and may (or may not) be accompanied by a frozen subsoil. These factors conspire to make snowmelt forecasting a difficult problem.

Not surprisingly, most flood warning authorities rely on subjective or "experience" methods of forecasting snowmelt runoff. Floods arising predominantly from snowmelt are rather more frequent in Scotland and North East England than elsewhere in Britain. But, as Table 7.4 of the Flood Studies Report[119] indicates, a significant proportion of the worst floods on record throughout Britain have a snowmelt contribution - catchment size being more influential than region.

Several authorities take snowmelt forecasting fairly seriously. Archer has carried out research into snowmelt rates at catchment scale[23 120]; and both Northumbrian WA and Severn-Trent WA have networks of snow observers equipped to take depth and density measurements. (In British conditions, knowing the extent and characteristics of the snowpack is as much of a problem as the snowmelt modelling itself). Air temperature information is obtained from the local Met. Office forecaster although Severn-Trent WA make some use of a small network of interrogable climate stations.

As indicated in Section M4.2 (Fig. M4.2), the subcatchment model adopted by Severn-Trent WA includes a snow component. This is based on the simplified method of snowmelt estimation referred to by Jackson[121]. The potential melt rate, M (mm/day), is given by an empirical equation such as:

$$M = (1.32 + 0.305\,V)T - 0.236V\Delta \qquad (4.7.1)$$

where T is air temperature (°C), Δ is the dewpoint depression (°C), and V is a mean windspeed (knots). Equation 4.7.1 can be viewed as a refinement of the degree-day method. The dependence on V recognizes the importance of the turbulent energy exchange between the air and the snow surface. The term "- 0.236VΔ" accounts for the reduced potential for melt when the air is unsaturated; snowmelt and evaporation are then competing to use the available energy.

Whether complicated physics based models of snowpack behaviour[122] offer significant benefits to the flood forecaster over empirical methods is as yet unclear. In snowmelt forecasting, the opportunity undoubtedly exists to exploit sophisticated scientific techniques - such as remote sensing and physics based models - to help resolve an acknowledged problem. Perhaps the real question to be answered is whether the likely benefits justify the resources needed to implement the science.

Because snowmelt is primarily a large catchment problem - at least as regards flood forecasting, some of the sting can be taken out by the use of flood routing methods (see Section 4.2). Correct modelling of snowmelt contributions may then be more a refinement than an essential, since short-term flood forecasts can be based largely on upstream river level information.

4.8 A note on model intercomparisons

It might be thought that this review should compare modelling techniques numerically and, perhaps, reach definite conclusions about preferred methods. In fact, this is not very practical.

Comprehensive intercomparisons of hydrological models are likely to be very lengthy and may lead to only vague conclusions. The "Intercomparison of conceptual models used in operational hydrological forecasting", initiated by the World Meteorological Organization in 1968 and completed in 1974, is an excellent example of a thoughtfully planned comparison study failing to produce explicit recommendations on the choice of method[99]. Despite its title, the WMO Project considered the performance of models in "simulation mode" only, arguing that updating would not appreciably affect the accuracy of models <u>relative</u> to each other[123]. This conclusion seems very doubtful.

A thorough assessment of rainfall/runoff methods of flood forecasting might need to consider:

(a) at least four distinct approaches (unit hydrograph, nonlinear storage, transfer function and conceptual models).
(b) perhaps four different model structures in each approach (eg. several methods of rainfall separation in the unit hydrograph approach).
(c) several methods of real time correction (eg. error prediction, state-updating or parameter-updating for a transfer function model)
(d) perhaps several alternative types of rainfall forecast (eg. none, qualitative, quantitative, perfect)
(e) various objective functions both for model calibration and performance assessment
(f) application to a range of flood forecasting problems (perhaps six catchments?)

It is readily seen that a comprehensive comparison of flood forecasting methods would be long-winded and costly.

As an alternative to the above, the author believes that there is much to be gained by detailed case studies of particular models applied to particular catchments, each study seeking to make progress in only one or two aspects at a time. This is, in fact, the approach generally being followed in research in British flood forecasting methods[43 75 93].

It is perhaps worth remarking that standardization of methods is not as great a virtue in flood forecasting as it is in design flood estimation. For one thing, there is much less emphasis on application to ungauged catchments. Whereas it is very difficult to verify that a synthesized design flood really <u>does</u> represent a 50-year event (say), in flood forecasting it is possible to assess model performance after each event for which it serves operationally.

5. FLOOD WARNING PROCEDURES

5.1 Introduction

Many authorities take particular pride in tight flood warning procedures and good public relations. It should be said at the outset that, whereas flood forecasting is a desirable component of many flood warning systems, effective operational procedures are absolutely essential; the benefits of flood warning arise from the actions taken as a result of the warning (Section 2.2) rather than simply from a forecast proving to be correct.

Warning procedures differ from authority to authority and, sometimes from river to river. Although other practices are discussed, several references are made in Sections 5.2 to 4 - by way of an example - to Welsh WA's flood warning procedures for the river Dee[124].

5.2 Meaning of flood warnings

Many authorities attach fairly precise meanings to various levels of flood warnings or flood alerts. Conventions differ widely; the interpretation of river Dee alerts is as follows:

1st alert - flooding of agricultural land is possible

2nd alert - further flooding of agricultural land is possible, which may affect property and persons.

3rd alert - very serious flooding outside normal experience is possible.

A feature to note is the cautious wordings "is possible" and "may affect". These recognize the impracticality of being specific within the framework of a general flood warning, and the desirability of erring on the safe side. (Given the latter it is perhaps surprising that, in theoretical studies, so much emphasis is given to deriving statistically "best" flood forecasts rather than conditional ones, say of the form outlined in Section 4.6.4). Several authorities prefer colour-coded to numbered alerts, presumably for the greater impact that a "red warning" message carries.

The types of warning issued by Northumbrian WA broadly resemble the classifications used in storm tide warnings[125]:

preliminary warning - generally qualitative warning of possible flooding problems.

flooding imminent - flooding highly probable; identifies specific areas at risk; gives time that maximum inundation is expected.

danger confirmed - inundation to a significant level will occur; gives expected peak level and time.

flood cancelled - danger over

A still different approach is the risk level system used by AWA Essex River Division[126]. Up to as many as seven risk levels are distinguished, each corresponding approximately to a particular return period event. Risk level 1 corresponds to a flood that can be expected relatively frequently with higher risk levels denoting increasingly rare events.

5.3 Designating areas at risk

Given that a river can pose different threats in different reaches it is common practice to distinguish subareas to which a flood alert applies. There are perhaps two distinct considerations.

First, there is the possibility that the flood is concentrated in only part of the river system; this may be due to the nature of the storm event or merely because flooding of lower reaches of the river commences much later than upstream - making separate warnings appropriate. In the case of the river Dee, the strategy is to distinguish two main areas: the upper Dee and the lower Dee.

A second concern is: given a particular forecast flow, which areas are likely to be inundated? This question is sometimes answered by reference to flood zone maps maintained by the authority. If these maps are copied to the police (and other relevant organizations), flood warnings can be issued for specific river zones - as, for example, in the flood warning systems operated by North West WA[16] and Anglian WA, Essex River Division[126]. Perhaps the one disadvantage of the approach is the possible confusion created by a plethora of warning messages indicating different levels of alert in various parts of a single river system.

An alternative is for flood maps issued to the police to be contoured only in terms of general alert levels for the river (i.e. without detailed zoning). Appropriate discrimination, of which individuals or zones need warning first etc., can instead be embodied in standing orders agreed with the police. (See Section 5.7).

5.4 Criteria for alerts

Most authorities set precise criteria for the issue of flood warnings; these are designed to minimize possible subjectivity introduced by individual duty officers. Most often the criteria relate to exceedance - or forecast exceedance - of a specific flow or river level at the gauging station most relevant to the risk area. More than one criterion may be specified; for example, 2nd alerts on the lower Dee are triggered by river level at Corwen or flow (or forecast flow) at Manley Hall, whichever condition is exceeded first. Where there may be a need to move livestock from riparian areas, the criteria may also reflect the desirability that this be done in daylight.

5.5 Format of warnings

Warnings are generally communicated to the police by telephone or telex. Most procedures require that warnings should conform to a strict content and wording, and be formally logged.

Although many authorities include forecast peak river levels and times in warning messages, others do not. One argument against their inclusion is that the numbers can lead to subjective judgements being made by the police and others via whom the warning is passed. For example, if standing orders agreed with the police indicate some drastic action is to be instigated if the river level exceeds 3.5 metres then, if the forecast level is only slightly higher, one officer might decide to defer action. Whereas, on another occasion, a colleague might precipitate action on receipt of, say, a forecast level of 3.4 metres. Such subjective interventions are more readily condoned if the police officer is privy to the fact that flood forecasts are sometimes inaccurate.

An argument in favour of including river level and timing information in warning messages is that it encourages feedback during the flood event. A further reason may be that the flood warning authority does not, of course, wish to be accused of withholding more detailed information that could conceivably be of value. Where peak levels of inundation are forecast, it is fairly common to transmit these in relative terms - eg. the level is expected to rise a further 0.25 metres in the next 3 hours; absolute timings are then inferred from the clock

time attached to the issue of the warning. However, other authorities insist that all warnings be given in absolute terms.

In prolonged major floods it is inevitable that the broadcasting authorities will be drawn into the dissemination of flood warnings. Local radio and regional television services provide a powerful means of mass communication but are unselective. This means that particular attention has to be paid to the wording of statements to avoid unnecessary public alarm. Because of the lack of control on the timing and emphasis given to warning messages by the broadcasting authority, "live" interviews may be preferable in some instances.

5.6 Staffing arrangements

Staffing practices differ widely according to the scale of the flood warning system and to authority preferences. The early stages of a possible flood event are handled by a flood warning duty officer, often from home. Preliminary warnings or first alerts are sometimes raised by the duty officer where the speed of response to rainfall precludes a more formal procedure. As conditions worsen, additional staff are alerted and a control room opened. Responsibility for flood warnings then passes to a flood controller or co-ordinator, usually a fairly senior operations officer or rivers engineer. The duty officer usually continues the task of flood monitoring and forecasting, aided by technical assistants as appropriate. Another separate role - often filled by an administrator - is that of communications officer, logging messages in and out of the control room and, perhaps, dealing with public relations matters. It is general policy to avoid excess manning in the early stages of a flood and to arrange shift working. Obviously there can be conflicts if, for example, hydrometric staff called out to take flood gaugings deplete the pool of technical assistants available to man the control room.

In a major event, additional staff may be pressed into service to fulfil many detailed roles: for example, to liaise with particular outside bodies or to organize equipment and labour for remedial action. Where necessary the flood controller may consult authority senior management before issuing high level alerts or when faced with circumstances beyond the scope of existing procedures.

5.7 Agreed action

General practice in Britain is for flood warnings to be issued principally to the police. This accords with the duties and responsibilities of the police, of which perhaps the most relevant are to protect life and property and to co-ordinate functions of the emergency services.

The wide-ranging nature of police work is such that it is unlikely that the police officer receiving a flood warning will have intimate knowledge of its implications. It is therefore common practice for the flood warning authority to draw up and agree formal procedures for the police to follow. These are formatted as simply and logically as possible and every attempt made to remove ambiguity and subjectivity. Some of the more obvious actions taken by the police are patrolling areas of risk, closing flooded roads, providing communications links and otherwise co-ordinating the action taken by emergency services. However, in many cases, the police also undertake the alerting of residents, companies, landowners etc. known to be at risk. These specific actions are usually guided by flood zone maps and/or lists of people, property, streets, etc. at risk, the material generally being prepared by the flood warning authority. The police may also warn local councils and public utilities but more often the flood warning authority notifies those kindred bodies directly, perhaps providing more detailed information of likely flooding.

Rather different circumstances prevail in London. (See Fig. 5.1). For a number of reasons - of which, local authority structure and the difficult nature of flood warning on small, highly urbanized catchments, are two - the Greater London Council directs flood warnings principally at borough councils. The GLC has in recent years made use of a radio-paging system whereby appropriate borough council emergency officers are "bleeped" and receive the flood warning message by telephoning an answering service agency. This frees the flood warning duty officer from issuing duplicate messages while ensuring as far as possible that the relevant borough councils are properly alerted.

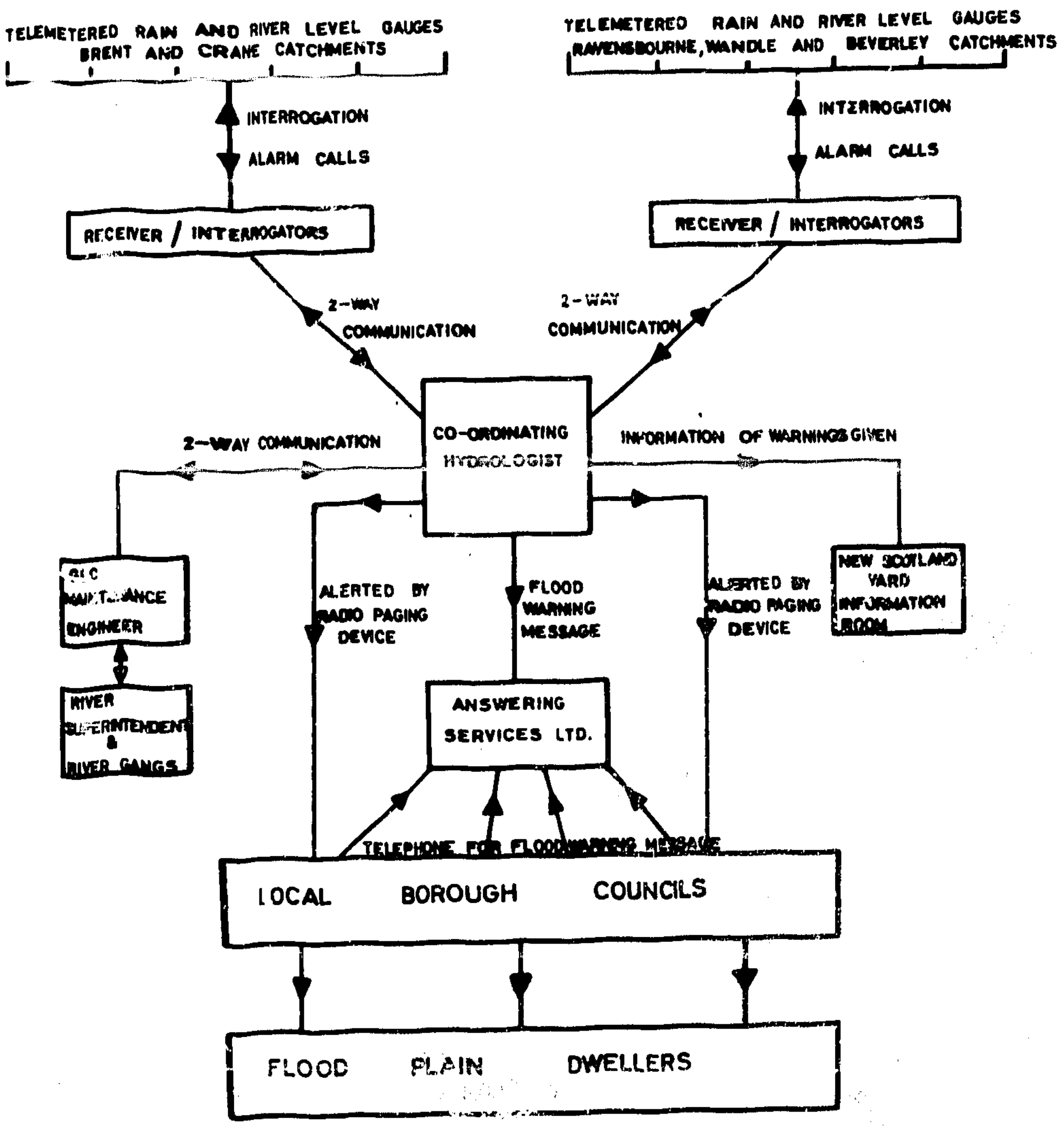


FIGURE 5.1 Flow chart of Greater London Council non-tidal flood warning arrangements

Many authorities take great care to ensure that procedures agreed are not allowed to wane. Some hold annual meetings at which procedures are reviewed and renewed with the police and other recipients of flood warnings. Some authorities go further and stage occasional major incidents to test out part or all of the flood warning chain. It is perhaps worth noting that most authorities have to deal with several police forces, in the case of North West WA no fewer than seven.

The dissemination of flood warnings has been considered as a subject in its own right in a recent study by the Middlesex Polytechnic flood hazard research centre[10].

5.8 Interpretation of forecasts

A convenient dividing line between flood forecasting (the province of the hydrologist?) and flood warning (that of the operations manager or rivers engineer) is the conversion of forecast flows to levels.

In the absence of a detailed hydraulic model, the interpretation of forecast levels at a reference site, in terms of risk of inundation elsewhere, requires intimate knowledge of the river gained from past experience of flooding*. Northumbrian WA have a compact method of recording (and looking up) the implications of particular flood flows. At each gauging station for which flow forecasts are calculated, a stage-discharge graph is annotated to indicate the area and extent of flooding problems experienced at various flows. (See Fig. 5.2). The presentation in graphical form conveniently encapsulates any uncertainty in the rating curve extrapolation used to convert forecast flows to levels. Such a figure can also be used to register that there may not be a one-to-one relationship between exceedance of a given level at the gauging station and a particular inundation effect downstream. A feature of the approach is that the diagram can be amended easily as further experience of flood behaviour is gained. An alternative way of achieving a broadly similar effect is the two stage method of linking forecast flows to a sliding scale of risk levels, which are then interpreted in terms of flood effect with the aid of flood zone maps. This approach fits in well where warnings issued to the police are highly systematized, as for example in AWA Essex River Division's flood warning procedures[126].

It is perhaps worth repeating that most flood forecasting models are calibrated to yield a "best" estimate of flow at a specific lead time (possibly assuming something about rainfall in the intervening period - see Section 4.6). Little attention appears to have been paid to structuring forecasting models to provide an estimate of the likelihood of a particular flow being exceeded given present conditions. This probability, if known, would go a long way to helping the interpretation of forecasts in terms of risk of inundation and, hence, to rationalizing the criteria by which flood warnings are issued.

A rather subjective factor that can enter into the interpretation of forecast flows is the public judgement of forecasting errors. For example, if the system has been criticized for a recent failure to warn, interpretations of forecasts may err on the cautious side, ie. deciding to issue a warning when inundation seems possible rather than probable. Even such a pragmatic application as this would benefit from a more scientific approach to risk assessment.

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*One senior manager made the incisive remark that greater sophistication in catchment monitoring and modelling was needed to compensate for the relatively short apprenticeships that modern flood warning duty officers serve.

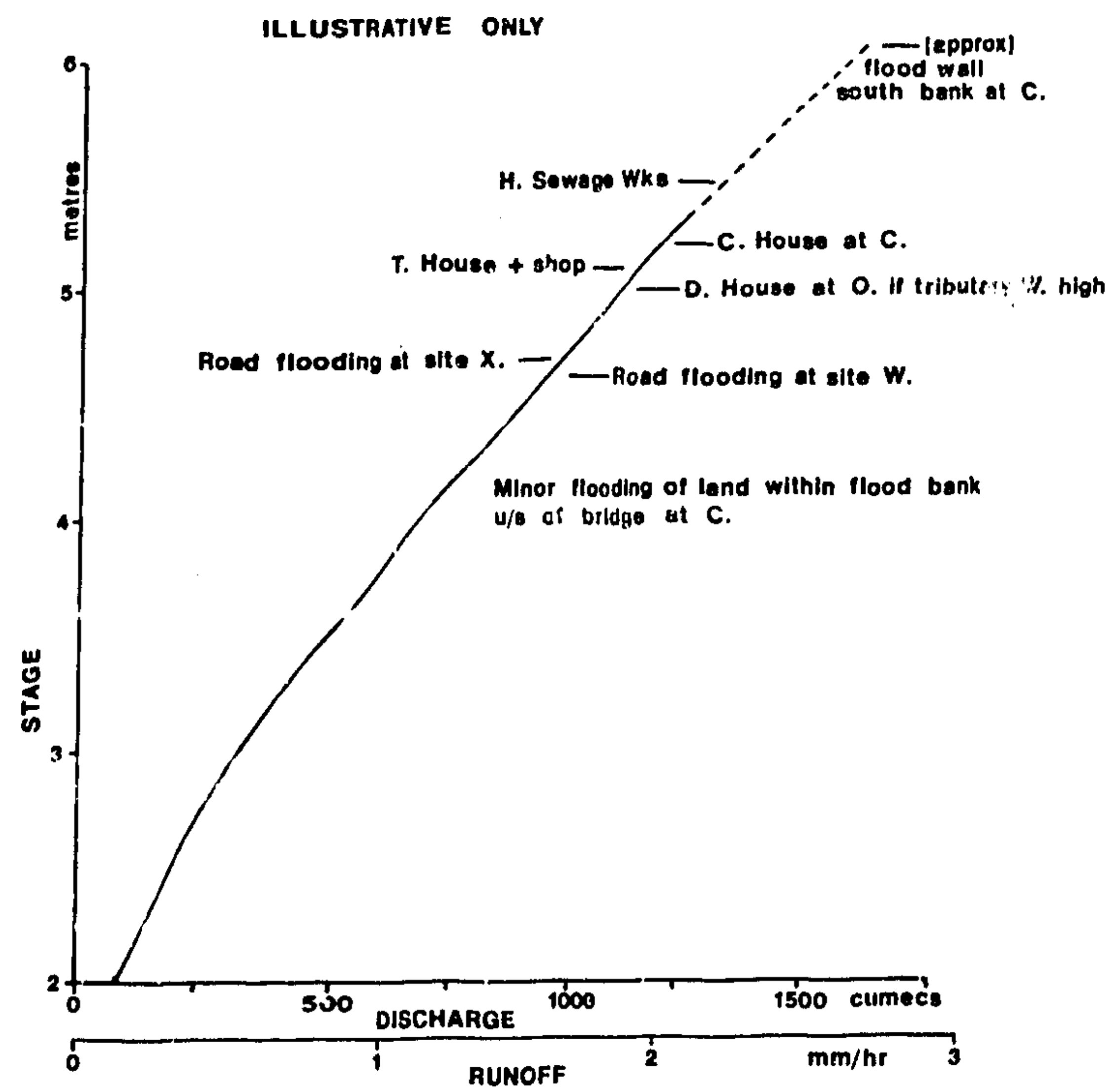

FIGURE 5.2

Aid to the interpretation of flow forecasts: an annotated stage/discharge graph

5.9 Routine monitoring

Most flood warning procedures incorporate rules for routine monitoring. For example, it may be the practice on a change of roster for the incoming duty officer to take formal note of river levels, catchment wetness conditions, the prevailing synoptic situation etc.. The procedures may also specify that steps be taken to verify that relevant equipment - especially communication links - are in normal order. Other factors to be checked may include reservoir states, the setting of flood gates and pumping stations, and tide tables.

Some authorities, notably those in the drier east and south of Britain, update indices of catchment wetness at regular intervals. Typically this involves noting recent daily rainfall totals (to update an antecedent precipitation index) and acquiring or calculating a new estimate of soil moisture deficit (for example, using the Met. Office's MORECS service).

5.10 Initial alerts and intensification

The setting up of equipment and procedures to alert duty officers to a new threat of flooding is a particularly important aspect of flood warning. Unlike warnings that are to be issued externally, a considerable measure of overcautiousness is acceptable in initial alerts. The emphasis is to ensure that the flood warning duty officer is always alerted early enough to appraise the situation before the need to issue formal warnings arises, even if this policy means a very high ratio of initial alerts to actual flood warnings.

The two forms of initial alert most used are Met. Office heavy rainfall warnings (HRW's) and outstation alarms. HRW's are highly valued by many authorities. Typically the local Met. Office is contracted to supply verbal warnings - to a 24 hour manned authority control centre - if more than 25 mm of rainfall is expected; sometimes two thresholds are set: eg. a high intensity warning if more than 15 mm is expected within 6 hours and a low intensity warning if more than 25 mm is expected with 24 hours. These HRW's are warnings rather than forecasts and, in line with the initial alert role that they play, a high ratio of false warnings (compared to failures to warn) is both expected and accepted. Different arrangements apply in some authorities; for example, Severn-Trent WA receive regular rainfall forecasts as a matter of routine (see Section 4.6.1).

The simplest type of outstation alarm is that based on exceedance of a pre-set river level. There is, however, the classic dilemma of setting the alarm level sufficiently low (to provide adequate warnings in the event of a major flood) but sufficiently high (to avoid ludicrously frequent alarms). Some refinement would appear to be possible by linking the alarm to both river level itself and the rate of river level rise. Although this might call for a fairly intelligent outstation, the technical requirement is really not very different from that of a raingauge alarm based on exceedance of a pre-set depth/duration (eg. 15 mm in 6 hours). The latter type of alarm is well established in many authorities; perhaps surprisingly, the former is not.

Increasingly, alarms are being provided by telemetry control and flood forecasting computers which monitor river levels, rainfall accumulations, etc. on a near continuous basis; in a few instances, alarms are also raised on the basis of model forecasts. In the North West WA system, the control computer raises an alarm should any appropriate variable exceed a pre-set threshold; typically, this corresponds to a 5 times/year occurrence[16]. Radar derived rainfall data provide another means of triggering initial alerts. Section 6.8 discusses the application of weather radar to flood forecasting in some detail.

Perhaps one of the most prominent benefits of computer controlled telemetry and modelling systems is the opportunity to increase initial alert thresholds safe in the knowledge that the situation can be assessed rapidly when an alarm occurs. Although possibly an unheralded aim, higher initial alert levels reduce staff call-out costs; moreover the concomitant reduction in false alerts helps to galvanize duty officer response when a new alert is raised.

Procedures for the intensification of monitoring and forecasting activities, as a flood situation builds up, vary fairly widely. A particularly flexible approach is possible in computerized systems which allow the "menu" of stations being interrogated to be varied according to need in a particular event.

5.11 Summary

There are many facets of operational flood warning that lie well beyond the scope of this report. Authorities are generally reluctant to publish details of their flood warning procedures or to discuss failings openly. This is quite understandable, not least because the flood forecasting element of flood warning is intrinsically so uncertain. However, there are undoubtedly lessons to be learned from the performance of flood warning systems in major events: lessons for the flood warning authority, lessons for others with similar problems or systems, and perhaps lessons for applied hydrological research. It is hoped that penetrating investigations - such as that carried out by MAFF into flood warning arrangements prevailing in NW London in 1977[127] - are given sufficient circulation to fulfil this wider aim.

6. DISCUSSION

6.1 The role of flood warning

Flood warning can sometimes be viewed as an alternative to flood alleviation as a means of reducing risk to life and property, albeit a less effective one. Even if the flood forecast is correct, the dissemination of the warning swift and thorough, and the public response prompt and effective, there remains the fact that the warning does not eliminate flooding but merely allows some reduction in damage. In practice there are large uncertainties attached to each component, making the assessment of achievable flood warning benefits highly problematic.

Flood alleviation works, on the other hand, reduce flood damage in a fairly definable way by making inundation less frequent. Benefits can usually be estimated by integrating an appropriate section of the pre-works damage/frequency relationship. However, if construction of embankments, or retention storage, frees previously flood-prone land for development there is the possible consequence that damages incurred in an extreme flood could be much increased. Thus the need for a flood warning scheme may persist post-works with the emphasis shifting to warning against an extreme event. Indeed, it can be argued that the very act of carrying out flood alleviation works increases the onus on an authority to provide some sort of flood warning scheme, because of the denaturalization of the river regime and the false sense of security that works may engender.

Although flood warning is a permissive power rather than a duty, most authorities seem to take the view that the public expect to receive reasonable warnings of inundation of property. The impracticality of guaranteeing this makes authorities understandably cautious in publicizing flood warning provisions.

6.2 Incentives to flood warning

Shortcomings exposed in a recent flood incident provide an obvious incentive to improved flood warning. It is generally possible to instigate new warning procedures fairly quickly, perhaps as an interim measure until river improvement works are carried out or while improved flood forecasting methods are developed.

Another strong influence is the enhanced scope for flood warning presented by technological developments. A particularly striking example is weather radar. Such developments raise expectations and ipso facto create pressure for improved flood warning.

6.3 Real time computers

Increasingly, computers are being used to control real time data acquisition and, in some cases, to carry out flow forecasting calculations. Ideally, the computer, database software, telemetry system, etc. should be tailored to the flood warning problem and the method of forecasting adopted. In practice, though, it is likely that the choice of computer system will be influenced by wider factors : for example, a need to fulfil monitoring and perhaps control functions of water supply installations, or to gather data for routine archive as opposed to real time use. It is inevitable that compromises have to be made; one danger is that because flood warning is seen to be an ephemeral concern it may be accorded low priority in the specification of real time computer systems.

Most authorities favour divisional or regional telemetry schemes where practical. Attention is generally focussed on the recording and display of data - and on the reliability of data acquisition - with the implementation of flood forecasting programs following as circumstances allow. An alternative approach is to concentrate resources on a particular flood warning problem. Although rare as yet, this approach is likely to gain ground in the general trend towards more personalized, distributed and dedicated computers. Direct connection of sensors and telemetry to microcomputers with high level programming capability may make de-centralization a more fashionable approach to flood forecasting.

There are of course arguments for and against small-scale forecasting systems. Perhaps paradoxically, an advantage may be the greater opportunity for standardization - with only model parameters differing between one system and another. It appears that the real time monitoring and modelling systems installed in the past have been too "one-off" to allow much sharing of development costs. With the balance of hardware and software costs shifting, it is likely that greater attention will be focussed on curtailing development costs, by avoiding unnecessary duplication of software - especially that concerned in the interrogation, storage and display of data.

6.4 Flood warning by monitoring

With an efficient data collection and display system it may be sufficient to base flood warnings on present conditions rather than adopt forecasting techniques. This may be attractive where river level is monitored some distance upstream of the risk site. Of course the success of such an approach relies on a relationship existing between river conditions at the two sites but, by setting alarm levels from experience, it is possible to use the relationship without actually formulating a model of it.*

Good presentation of rainfall and flow data can similarly allow reasoned flood warnings to be issued without recourse to formal methods of flood forecasting. In essence, the duty officer supplies the model by visually relating cause (heavy rainfall) to effect (rising river levels). Scope for successful application of subjective methods has been greatly enhanced by computer graphics developments. Whereas formerly, deductions had to be made from simplified information, or time lost in drawing up graphs, it is now feasible in computerized systems to display updated hydrographs and hyetographs only moments after interrogation.

6.5 Flood routing

Routing methods of flood forecasting are generally to be preferred where practical. Fairly simple graphical methods based on correlation of upstream and downstream flows or river levels continue to be found useful. However, if hydrograph shape and timings are important, or tributaries confound the problem, a flood routing model proper is called for.

Flood routing models range from the simple to the highly complex; most require computer implementation. The variable parameter Muskingum-Cunge (VPMC) method seems to offer an appropriate compromise between simpler but less realistic

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*One extension of the approach is for farmers to have access to an interrogable river level gauge and for them to set "action levels" according to personal circumstances.

methods and more complicated hydraulic methods with large data and computing requirements. Some further development of VPMC for real time use would be valuable. Fuller solutions of the St. Venant equations are appropriate for reaches subject to tidal or backwater influence.

6.6 Rainfall/runoff modelling

A wide range of rainfall/runoff models can be considered for flood forecasting in British conditions. Unit hydrograph methods have a structure and familiarity that appeal to many engineering hydrologists. The approach is, however, less suited to real time forecasting than it is to design flood estimation.

Transfer function models are broadly equivalent to unit hydrograph methods but intrinsically better suited to real time use. They are simple to implement and easily re-initialized but their calibration calls for not inconsiderable statistical expertise. A common weakness of transfer function and unit hydrograph methods is the lack of convincing guidance on rainfall separation techniques.

Nonlinear storage models are well suited to real time use. The approach requires some conviction in the particular model structure chosen for calibration; a proportional loss method of rainfall separation is generally adopted, linked to an index of catchment wetness. ISO models form a special class of nonlinear storage model in that they make no explicit allowance for rainfall losses; their successful application generally relies on real time correction using telemetered flows.

Conceptual models are generally rather cumbersome for real time use. An appropriate choice of model structure calls for a relatively deep insight into those factors most relevant to runoff generation. Conceptual models are usually calibrated by numerical optimization of continuous sequences of flow and climate data. Proponents argue that it is necessary to have a physically sound model if the model is to perform reliably in extreme events. Sceptics reply that parameter values derived by "blind" optimization may be spurious and those fixed a priori may be subjective. The compromise between physical realism and parametric efficiency was well put by Nash and Sutcliffe[128] in 1970, when discussing principles of river flood forecasting, but appears to have gone largely unheeded. There can be little doubt that spatially distributed, physics based models offer the only long-term prospect of significant improvement in rainfall/runoff modelling; in the meantime, the choice between empirical and conceptual methods remains contentious.

6.7 Real time correction

Real time correction of forecasts using telemetered flow data is a dominant theme and sets flood forecasting applications apart from more traditional uses of hydrological models - for example, design flood estimation and studies of land use change. There is insufficient operational experience of real time correction methods to make definitive recommendations for British practice. However, a number of detailed observations are given for guidance in Section 4.4.7. Perhaps a useful rider is provided by Simpson et al[104]:

> "In considering the development of systems for real time forecasting of high flows it may be important to use a model which is not so complex as to exclude the forecaster from any interactive role".

6.8 Weather radar

The role of weather radar in British flood forecasting practice is a particularly stimulating area for discussion. There have been many reports and papers[129 130 131] published over the last decade extolling the virtues of radar for flood forecasting. However, in general these appear to have made light of the rainfall/runoff modelling and procedural aspects of flood warning.

RADAR DERIVED RAINFALL PICTURES

Experience gained by North West WA and others - since commissioning of the first fully operational unmanned weather radar at Hameldon Hill in North West England - has removed any lingering doubts about the value of radar derived rainfall pictures. Such pictures provide a quality of spatial coverage and dynamic tracking of storm systems that is impossible from a network of telemetering raingauges alone. Qualitative use of weather radar pictures is now firmly established in a majority of flood warning authorities in England. The spread of radar pictures to other authorities is inhibited only by cost.

The "JASMIN" units used to store pictures have a capacity of only nine images; thus many users have ready access only to pictures of rainfall variation over the last two hours. Prototypes of a second version of the JASMIN unit are currently under construction and these are expected to provide greater flexibility for short-term storage (and replay) of pictures.

FLAGGING EXTREME RAINFALLS ACCORDING TO RIVER CATCHMENTS

Computer evaluation and analysis of radar derived rainfall data is a powerful extension to visual display. Of particular interest in flood forecasting is the ability to focus attention on individual river catchments. While this might be achieved using more sophisticated display systems than currently available - for example, by overlaying catchment boundaries, river systems and flood risk sites on selected parts of a weather radar picture - the present approach is for subcatchment rainfall information to be supplied in digital form.

In the North West WA implementation[16], the Hameldon Hill radar computer calculates average rainfall values for 94 discrete areas and passes these values to the authority's multipurpose control computer at 15-minute intervals. One use of these data would be to "flag" extreme rainfalls on individual subcatchments according to pre-set depth/duration criteria.

Bussell[132] discusses the potential of weather radar for providing short-period warnings of extreme flash floods such as the June 1979 event at Skipton. He concludes that if this potential is to be fulfilled:

> "there is an increasing need for ever closer co-operation between the meteorologist, the hydrologist and the emergency services on a real time basis."

While it is possible to envisage the development of flood warning procedures for a number of recognized flood risk zones, it is difficult to see how contingency plans can be made sufficiently general to cater for sites where little or no flood risk is perceived.

QUANTITATIVE USE OF RADAR DERIVED RAINFALL DATA

A third level of sophistication is the use of radar derived rainfall data to produce flood forecasts by rainfall/runoff modelling and this is the approach being taken by North West WA. Subcatchment rainfall data are fed into formulae representing simple rainfall/runoff models of the areas, and appropriate alarms raised on the basis of forecast flows. In the initial development, such "radar-driven" models have been installed for about 20 subcatchments.

Whereas visual display and the flagging of extreme conditions can proceed with semi-quantitative rainfall estimates, it is perhaps necessary to demand relatively accurate rainfall estimates where hydrological models are to be used to generate explicit forecasts of flow. Is weather radar sufficiently accurate? The much quoted 75 km radius within which radar derived rainfall information is "quantitative" (rather than "qualitative") is, of course, only a broad guide. Factors such as hill-screening and ground clutter degrade information in particular quadrants and zones. Experience gained in the North West Radar Project[16] has confirmed that it is essential to calibrate the rainfall/radar-reflectivity relationship in real time, by reference to telemetering raingauges. The calibration techniques now available appear to be moderately successful. Research has shown that, for most of the North West WA region, the calibrated radar data provide a more accurate representation of hourly rainfall than can be obtained from a slightly denser network of telemetering raingauges alone (not such a surprising conclusion!). However, with calibration factors ranging from x 0.1 to x 5.0 - the variation being ascribed primarily to rainfall type and the presence/absence of "bright band" effects[28] - there is reason to question the ability of current weather radar systems to deliver rainfall estimates that are sufficiently accurate for hydrological forecasting. A pessimistic view is that rainfall/runoff modelling has enough pitfalls in itself without having to contend with potentially inaccurate rainfall data. An optimistic view is that the effect on flood forecasts of a moderate under- or over-estimate of areal rainfall can be corrected by reference to telemetered flows. Perhaps the onus is on the hydrological modeller to specify a required accuracy of areal estimation of rainfall.

A concise summary of the British experience is provided by Bailey[133]:

> "weather radar ..... has been found to give accurate information on the timing and location of rainfall but not always on amounts or rates of fall".

Certainly, any further improvement in calibration techniques (whether by telemetering raingauges, combination of information from "overlapping" radars, etc.) would be welcome and should significantly extend the scope of flood forecasts based on rainfall/runoff models.

QUANTITATIVE PRECIPITATION FORECASTS

Reference is made in Section 4.6.2 to Met. Office plans to provide quantitative precipitation forecasts (QPF) through the FRONTIERS system. Whereas most flood warning authorities recognize the usefulness of qualitative radar pictures, and many believe that rainfall measurement by radar can be sufficiently accurate to meet the demands of rainfall/runoff model based methods of flood forecasting, there is some scepticism concerning QPF. Will the forecasts be moderately accurate? Will they be prepared and distributed quickly enough? When will QPF's begin to be supplied on an operational basis?

A national network of weather radars would undoubtedly enhance the Met. Office's weather forecasting capability and provide flood forecasting authorities with additional valuable information. If such a network is to be sought, it is right that the development should be steered to meet both Met. Office and water industry requirements[15]. Such a partnership calls for different but equally

significant commitments : that of the water industry to new funding and that of the Met. Office to ensuring that the investment matures. Given that the benefits in terms of improved flood warning are difficult to quantify, and that much hinges on the degree to which the FRONTIERS system succeeds in producing quantitative precipitation forecasts, the partnership must inevitably proceed on trust.

7. RECOMMENDATIONS

How to read this report!

The review has been written for the hydrologist and the engineer who have a strong interest in flood forecasting practice. The report has an enormous centre (Chapter 4) which the non-specialist may find hard to digest; however, read without Chapter 4, the material may inevitably appear superficial. Chapter 6 provides something of a summary which the busy manager might resort to. But the serious student or forecasting aficionado is directed to the detailed "contents" list at the beginning of the report; this should serve as a guide both to the structure of the review and in the selection of particular items of interest.

Specific recommendations

The review has sought more to communicate than to judge; there are few general answers to be found to flood forecasting problems. However, a number of specific points which have emerged from the review are listed below.

7.1 Flood warning problems differ widely in character and there may be good reason to design telemetry systems and flood forecasting methods on a "one-off" basis. However, given the breadth of experience currently being gained, there may soon be scope for a greater interchange of methodologies. The sharing of computer software may be particularly appropriate if a trend towards localized microcomputer based systems materializes.

7.2 It is desirable that the choice of computer for telemetry control should recognize the needs of flood forecasting modellers, either by the support of a high level programming language or through compatibility with a further computer on which modelling can be carried out.

7.3 There is need of publication of operational experience gained in the use of automatic data validation and "in-filling" techniques.

7.4 Flood warnings based on monitoring river levels should not be undervalued. There is scope to refine monitoring methods by linking the issue of an alarm to both river level and rate of river level rise.

7.5 Simple flood routing methods based on regression continue to be found useful in some flood warning schemes. It is recommended that, where practicable, correlations are sought between flows rather than levels.

7.6 The variable parameter Muskingum-Cunge method of flow routing has much to commend it. There is, however, need of clearer guidance as to how the method is best implemented in real time.

7.7 There is need of a greater awareness of the special character of real time forecasting applications of hydrological models. Models designed to simulate past events may require substantial modification for real time use. It is recommended that, where practicable, models are calibrated in the real time structure in which they are destined for use.

7.8 Basic attributes sought in a flood forecasting model are accuracy, reliability and timeliness. It is especially desirable that, where possible, model forecasts are interpreted or corrected by reference to telemetered flow data.

7.9 Although other forms of real time correction may be appropriate with particular models, the "error prediction" method is to be generally recommended.

7.10 One goal of further research should be the development of an objective function that is capable of balancing "value" errors and "timing" errors.

7.11 The transfer function method is intrinsically suited to real time forecasting. However, its proponents could do much to make the approach more comprehensible by offering simple unidirectional guidance in the choice and calibration of transfer function models.

7.12 Scope exists to make greater use of physics based models and remote sensing techniques in snowmelt forecasting.

7.13 It is suggested that the application of generalized rainfall/runoff models to forecast flows on ungauged rivers is unlikely to yield forecasts that are sufficiently good to be the sole basis of flood warnings. An exception to this may be the application of simple rainfall/runoff models (based on catchment characteristics) and radar derived rainfall data to "flag" extreme conditions in localities for which no regular flood warning scheme is justified.

7.14 Weather radar has qualities that make it exceptionally useful in flood forecasting. However, techniques using quantitative rainfall data in models are still being developed and much work remains to be done on the calibration and quality control of radar rainfall data. Perhaps a theoretical study, of the tolerance of flood forecasting models to errors in rainfall estimation, would complement operational assessments.

7.15 Calibration of rainfall/runoff models to yield optimum forecasts at a specific lead time may make an implicit allowance for continuing rainfall. This may create difficulties if the model is subsequently used with explicit forecasts of rainfall.

7.16 Effective flood warning on rapidly responding catchments may be heavily dependent on rainfall forecasts. This calls for close co-ordination of meteorological and hydrological services. In certain cases there may be a role for simple algorithmic methods of rainfall forecasting.

7.17 Consideration should be given to carrying out research into methods whereby the issue of a flood warning is linked to the probability of a specified flow being exceeded given present conditions and probabilistic scenarios of future rainfall.

ACKNOWLEDGEMENTS

The review was carried out as part of a research project funded by the Flood Protection Commission of the Ministry of Agriculture, Fisheries and Food. The co-operation of flood warning authorities in making material available is gratefully acknowledged; the author also wishes to thank the many individuals who found time to discuss flood forecasting methods and developments, particularly those who commented on the report in draft. Finally, I thank Margaret Clayton, Jackie Peckham, Joy Patching and Margaret Hebbert for their patience in preparing the manuscript.

While every effort has been made to check the material presented, it should not be assumed that references to specific flood warning authorities necessarily reflect that organization's policy or current practice.

APPENDIX 1 Calibration of Muskingum-Cunge and VPMC river routing models.

Muskingum-Cunge method

The diffusion parameter, μ, is calculated in terms of an attenuation parameter, α, from:

$$\mu = \alpha \bar{Q}_p / L \qquad \text{(A1.1)}$$

Here L is reach length and $\bar{Q}_p$ a reference peak discharge. $\bar{Q}_p$ is sensibly chosen as the average peak discharge of flood events against which the model is being calibrated.

The attenuation parameter is calculated from channel and flood plain geometry by:

$$\alpha = \frac{1}{2} \left\{ \frac{1}{L} \sum_{i=1}^{M} \frac{P_i}{S_i^{1/3}} \right\}^{-3} \sum_{i=1}^{M} \frac{P_i^2}{L_i S_i^2} \qquad \text{(A1.2)}$$

where P_i is the plan area (at the reference discharge), L_i the length, and S_i the bottom slope of the ith subreach. (A number of subreaches are chosen - not necessarily of equal length - in order to ensure that the adopted value of α adequately reflects variations in channel geometry along the reach). For an inbank flood the simpler formula:

$$\alpha = \frac{1}{2\bar{B}} \left\{ \frac{1}{L} \sum_{i=1}^{M} \frac{L_i}{S_i^{1/3}} \right\}^{-3} \sum_{i=1}^{M} \frac{L_i}{S_i^2} \qquad \text{(A1.3)}$$

can be used, where $\bar{B}$ is the average channel breadth at the reference peak discharge.

The wavespeed parameter, ω, can be estimated crudely from the observed travel time, T_p, of flood peaks along the reach, ie:

$$\omega = \frac{L}{T_p} \qquad \text{(A1.4)}$$

However, it is preferable to correct this estimate for the attenuation effect by using instead:

$$\omega = \frac{L}{T_p} - \frac{2\alpha}{L^2} \cdot Q^* \qquad \text{(A1.5)}$$

where Q^* is the observed attenuation of flood peaks, ie.:

$$Q^* = Q_p^{upstream} - Q_p^{downstream}$$

In practice, a number of flood events are studied and an average value of ω derived. The estimate can be refined on the basis of trial routings should any systematic mistimings be noted.

VPMC method

In the variable parameter case, values of α are generally calculated for an inbank flood and for an extreme flood. The latter calculation is best made using both flood surveys and topographic surveys to arrive at estimates of the inundated areas, P_i. Given these two points of reference, an attenuation parameter curve is constructed along the lines of Fig A1.1. In the variable parameter case Equation A1.1 is replaced by:

$$\mu = \alpha Q / L \qquad \text{(A1.6)}$$

to calculate the diffusion parameter, $\mu(Q)$.

Instead of deriving an average value of ω, values calculated for individual events are plotted against peak discharge and a curve constructed with the broad properties of Fig 4.2.10 in mind. This wavespeed parameter curve can be adjusted subsequently as a result of trial routings with the model.

If channel geometry varies drastically along the reach it may be advisable to estimate subreach values of ω. Price[56] presents a formula for this, together with many more details of how to get the most out of the VPMC method.

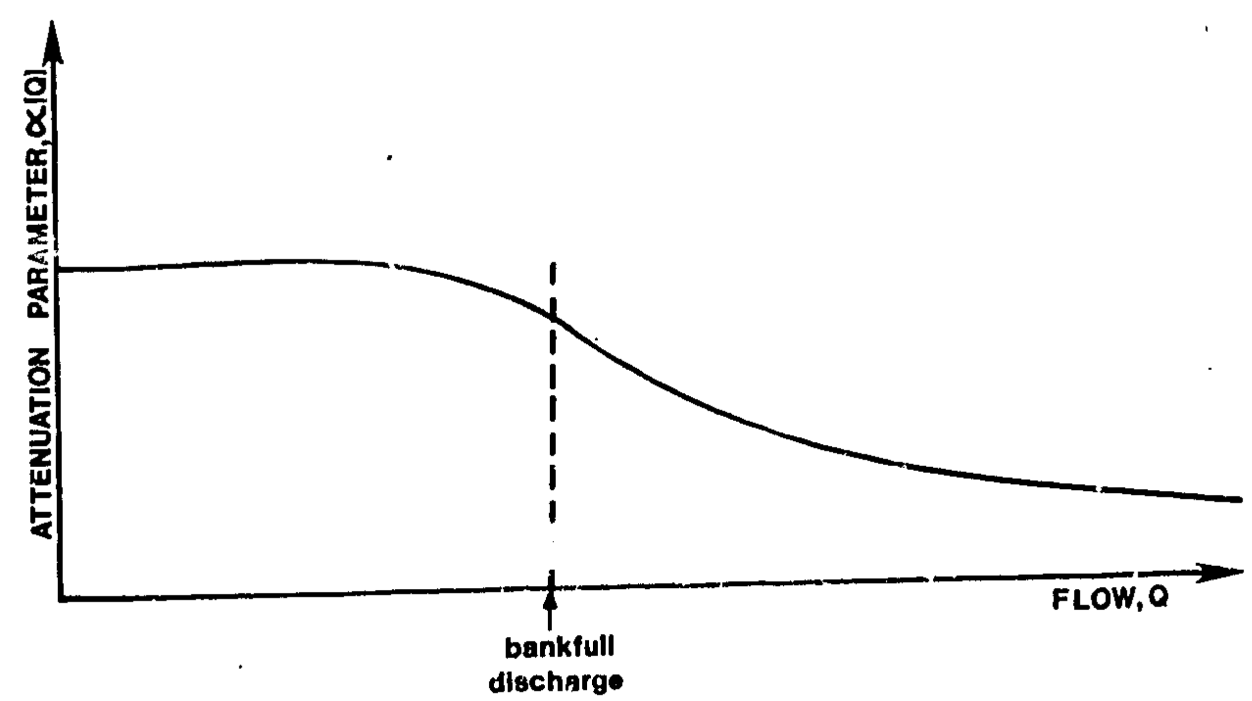

FIGURE A1.1 Typical pattern of attenuation parameter variation with flow

APPENDIX 2 Model calibration by numerical optimization

Numerical optimization is an accepted means of calibrating many hydrological models. The technique amounts to trial-and-error adjustment of model parameters until a best fit is obtained between modelled and observed flows; but the trials are arranged systematically so that progress to an optimum set of parameters is hopefully rapid. Although the basic principle is very simple, when it comes to fitting many-parametered models (ie models which have many parameters), numerical optimization is a curious mixture of art, science and computational power - and a subject in its own right.

The two key decisions are: what criterion of fit and which optimum-seeking numerical method?

Choice of objective function

It is usual to arrange the optimization as the minimization of an objective function. The most commonly used criterion is least-squares, ie minimization of the sum of the squares of the differences between observed and modelled flows. These flows are generally taken at equal time interval and may refer to a single flood event, a much longer period of record including a wide range of flows, or several flood events treated collectively. In the latter case, the optimization might seek to minimize the overall "error sum of squares" or, perhaps, an objective function that is explicitly weighted towards good simulation of peak flows. The choice of objective function ought to reflect the particular aspect of performance sought. Thus, for example, it is not clear that a least-squares criterion is necessarily appropriate in flood forecasting applications, where good representation of the rising limb of hydrographs may be at a premium.

Choice of optimization method

If the calibration problem posed is reasonably simple then any of a range of optimization methods should suffice. Some methods will be computationally more efficient than others but, with computer power becoming ever cheaper than brain power, mathematical nicety may not be too important.

Direct search methods were among the first computerized optimization techniques to be exploited by hydrologists, and they continue to be found useful. Clarke[134] gives a detailed account of Rosenbrock's method[135] and the simplex method of Nelder and Mead[136]. However, a wide range of optimization methods is now available in computer subroutine libraries such as NAG[137]. In some applications it is possible to use "gradient methods", which exploit information about the rate at which the objective function changes with respect to changes in the model parameters.

If the calibration problem posed is complex then optimization methods may run into difficulties, some methods more readily than others. (Acton[138] provides an eminently readable account of the dos and don'ts of function minimization.) Many-parametered models inevitably cause difficulty if their calibration is left entirely to an objective function and an optimum-seeking routine. The optimization may fail to converge, converge only to a local optimum, or yield parameter values that are outside a meaningful range[98]. The underlying difficulty is parameter intersensitivity, two or more parameters competing to explain a single observed feature of catchment response. It is difficult to specify guidelines as to what constitutes an achievable optimization task; for example, a 6-parameter model may "optimize" on one data set without difficulty whereas a 4-parameter model may struggle to "optimize" on another. However, in general, the

greater the number of parameters, the less likely that numerical optimization will provide a satisfactory calibration unaided.

Some optimization procedures allow constraints to be put on parameter values. This facility is attractive for some applications: for example, when a parameter of a conceptual model is known (by physical reasoning or separate studies) to fall within a given range. However, constrained optimization is not a remedy for ill-defined calibration problems. In such cases the optimization may "bump up against" one of the constraints and "run along it". The constraint is then said to be "binding" on the solution. Rather than tolerating one or more of the parameters being optimized to an extreme value (ie equal to the lower or upper limit specified in the constraint), it seems preferable to fix the offending parameter at an average value or, better still, to simplify that part of the model structure.

Because of the problems caused by parameter intersensitivity, it is fairly common practice to use a <u>staged</u> approach: optimizing only a subset of parameters in any given "run", the remaining parameters being held constant. Some practitioners favour the use of a second method of optimization to help confirm that a truly optimal parameter set has been reached[98]. (As with any model fitting exercise, the ultimate test is how the calibrated model performs on an independent set of data.)

Used by someone with a "feel" for the particular model, and an awareness of the pitfalls of placing too much reliance on the trial-and-error aspect of the technique, numerical optimization can be a very effective means of calibration.

Application to flood forecasting models

The rainfall/runoff and flood routing models used by Severn-Trent WA are calibrated by the Rosenbrock method and a least-squares criterion of fit. Typically, the optimization is carried out collectively for about ten flood events. Although the ST subcatchment model (Section M4.2) has very many parameters in its most general version, parts of the model are determined by separate analyses and a staged optimization approach used to calibrate the six or seven remaining parameters. This is nevertheless an ambitious application and its successful resolution rests on a judicious combination of conceptual insight and numerical optimization.

Nonlinear storage models (Section M2) are usually calibrated by numerical optimization. A detailed description of how to calibrate the Isolated Event Model is given in the Flood Studies Report[83] and this has been followed, with minor variations, in the GLC's calibration of IEM for flood forecasting[41]. Other applications[40 90] have relied on intelligent trial-and-error rather than formal numerical optimization.

GLOSSARY

Calibration	The process by which a model is fitted to observed data.
Continuous model	A rainfall/runoff model capable of operating continuously in time (as opposed 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.
Forecasting	Employment of a model to predict future conditions, thereby gaining a time advantage (see "lead time").
Lag time	A characteristic time by which the response to rainfall is deferred. (Precise definitions vary).
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).
Parameter-updating	A method of real time correction in which one or more of the model parameters are adapted in the light of recent model performance.
Rainfall/runoff model	A formulation that provides a means of estimating flows, principally from measurements of rainfall.
Real time	A qualifier implying that the calculation or operation referred to is carried out within the life-span of the event being analysed (with the aim of controlling or forecasting its outcome).
Real time correction	The process by which flow data available in real time are used to adjust model forecasts either directly or indirectly.
River routing model	A formulation that provides a means of estimating flows, principally from measurements of flow at upstream sites.
Simulation mode	The normal mode in which a rainfall/runoff model is used to estimate flow (ie. without reference to concurrent flow data).

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.

Time "now" — The time of forecast. (Usually this is taken to be the time of the last observation used).

Verification — The process by which a calibrated model is tested by reference to additional data (ie. additional to those used in calibration).

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