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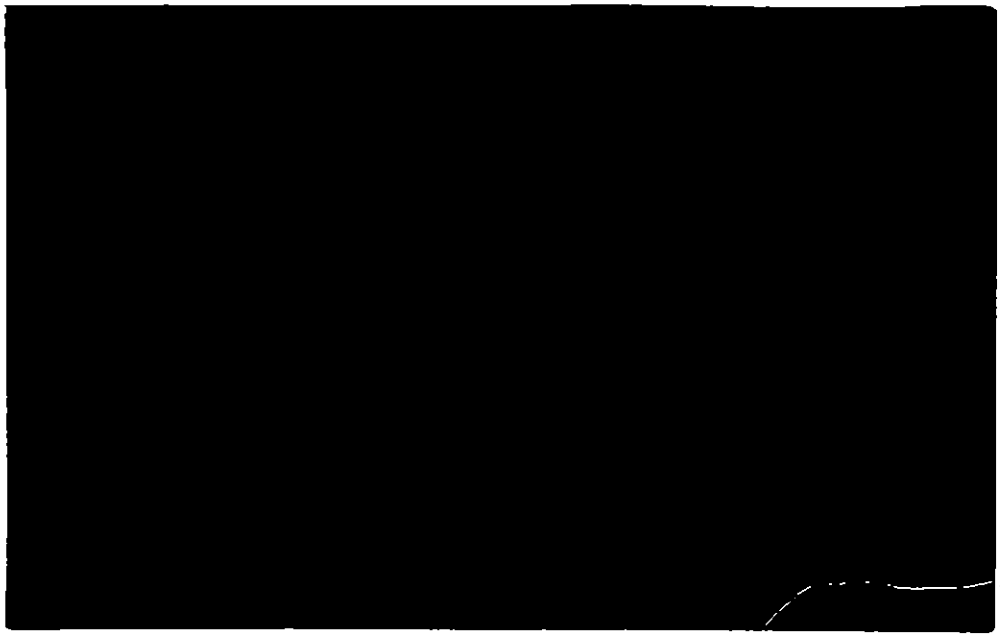

1991

WORKING PAPER NO. 9
REAL-TIME FLOOD FORECASTING FOR THE INDUS BASIN

AUGUST 1991

TERRITORIAL LAND DRAINAGE AND FLOOD CONTROL

STRATEGY STUDY - PHASE II

(TELADFLOCOSS 2)

WORKING PAPER NO. 9

REAL-TIME FLOOD FORECASTING FOR THE INDUS BASIN

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SUMMARY

This Working Paper on real-time flood forecasting (RTFF) replaces the Interim Working Paper submitted in July 1991 and gives our recommendations for the pilot RTFF scheme for the Indus Basin. The intention is that this final Working Paper should be read on its own and there should be only a limited requirement for most readers to refer back to the earlier Interim Working Paper.

The objectives of this Stage I study were to report on the technical viability and cost-effectiveness of RTFF on the Indus Basin.

The development of an operational RTFF scheme as a pilot study on the Indus Basin is considered to be technically feasible. There are two main problems in implementing a suitable system, the current lack of real-time hydro-meteorological data for that part of the Shenzhen Basin draining from the PRC, and the problem of forecasting sea levels in Deep Bay, which will form the lower boundary condition for the model. Solutions to both of these problems are proposed in this working paper, although that of storm surge forecasting in Deep Bay is probably easier to resolve. However, the lack of data from the PRC could be resolved through discussions between the appropriate authorities on each side of the border leading to a freer exchange of such data. There would be considerable benefits to both countries in such an arrangement.

The proposed pilot RTFF scheme would have to be supported by an appropriate flood warning dissemination system, and it is suggested that a series of procedures developed specifically for the Indus Basin are required. It should be possible to give most of the current flooded areas a warning time of at least one hour, and much of the lower catchment would receive a longer period of warning.

The cost of proposed pilot RTFF scheme is $2,843,220. The annual running costs for the scheme are estimated to be $142,000, of which the greatest part is for payment of flood wardens. This figure may be over-generous, particularly if existing Government staff could be identified for such a task.

The average annual flood losses in the Indus Basin are estimated to be $10.4 million. The average annual benefit to be accrued from RTFF is estimated to be $520,000, or $378,000 if the annual running costs of the RTFF are subtracted (all prices quoted are 1992 prices). It is calculated that the investment in the pilot scheme would be recouped in about 10 years through savings in flood damage costs. However, if the potential savings in intangible flood damage costs (loss of life, health risks, anxiety and distress), which are difficult to quantify, were to be taken into account, it is calculated that the investment could be recouped in about half this time.

The proposed pilot RTFF scheme will provide valuable information to Government in real-time during any major flood and will enable modern techniques for data collection and modelling to be tested under Hong Kong conditions. The scheme proposed can readily be extended to other basins such as the Kam Tin, and it is believed that as improved data become available from the PRC and as the staff of DSD and the RO gain experience in operating the system, the benefits to Hong Kong will increase.

1. INTRODUCTION

Indus Basin

1.1 The River Indus located in the North East New Territories drains a predominantly rural catchment (70 sq.km) although there are significant areas of population in numerous villages and the New Town Developments of Fanling and Sheung Shui. Topographically the catchment consists of a steep upland region and a flat valley floor. The highest point (639 mPD) is at Wong Leng in the eastern part of the basin.

1.2 The River Indus is a tributary of the Shenzhen River, the confluence of the two rivers being at Lo Wu. The Shenzhen Basin encompasses most of the North New Territories and the largely urbanized district of the Shenzhen Special Economic Zone in the Peoples' Republic of China (PRC). It drains into Deep Bay in the North West New Territories near Mai Po. The total area of the Shenzhen Basin is 312 sq.km of which 187.5 sq.km drains from the PRC.

1.3 Flows in the River Indus are influenced by the backwater effect from the Shenzhen River. Unfortunately, there is very little hydro-meteorological data available, in Hong Kong, for the PRC and there is no gauging on the Shenzhen River itself. Of particular concern is the fact that the operational rules governing releases from the Shenzhen reservoirs, situated in the PRC on tributaries of the Shenzhen River, are unknown. Releases from the main reservoir enter the Shenzhen River just a few kilometres upstream of the confluence with the River Indus at Lo Wu.

1.4 Water levels along the Shenzhen River from its mouth at Deep Bay to Lo Wu, and consequently, the water levels in the Indus, are dependent on tidal levels in Deep Bay. In the past storm surges have contributed to significant flooding in the Indus. At present no quantified forecasts are made of storm surges because of the difficulty of producing accurate results under the complex conditions experienced in Hong Kong waters.

History of Flooding

1.5 Historically, flooding has occurred regularly on the low-lying land adjacent to the River Indus and its tributaries. However, in recent years the consequence of floods has been made greater by increased population density and the encroachment of fish ponds and other land use changes on the floodplains.

1.6 Historical records of flooding are limited, but in the last decade major floods that occurred in 1982, 1988 after typhoon Warren and 1989 after typhoon Brenda have been relatively well documented. Although there was no loss of life, in all cases large numbers of people were affected, many had to be evacuated from their homes and household property was damaged. Significant areas of agricultural land were inundated and much livestock (pigs and poultry) and fish lost. Additionally there was some disruption to traffic.

1.7 During the 1982 flood, throughout the New Territories, agricultural losses alone were $23 million. Following the 1988 and 1989 flooding, losses in the Indus Basin were estimated at $9.0 million and $8.2 million, respectively. It was estimated in the Phase I study that average annual losses in the Indus Basin are $10.4 million (1992 prices) (Reference 11).

Available Data

1.8 An important data requirement for the proposed pilot Real-Time Flood Forecasting (RTFF) scheme is reliable and representative rainfall obtained automatically in real time. The Royal Observatory (RO) and Geotechnical Control Office (GCO) operate an extensive network of raingauges throughout Hong Kong, many of which are telemetered. Using a system of dedicated telephone lines, "reporting raingauges" are polled at 5 minute intervals. However, within the Indus Basin there is presently, only one reporting raingauge. This gauge (N05) is located in Fanling on the Cheung Wah Estate (Figure 2).

1.9 Rainfall throughout the Indus Basin is very often highly localized, both in space and time and appears to be elevation dependent. Consequently, a single gauge at low elevation is not representative of the whole 70 sq.km catchment and in particular it often fails to represent rainfall on the steeper, runoff producing, parts of the catchment. The Phase II study has recommended that a further seven reporting gauges are located within the Indus Basin. These will be distributed throughout the catchment at locations designed to give a good areal spread and monitor over the range of elevations. Details are given in Working Paper No. 5. The gauges will be used for general data acquisition and as part of the flood monitoring programme of Phase II, and only two of the gauges will be installed solely as a requirement of RTFF. Details are given in Chapter 2.

1.10 As an aid to model calibration and for updating throughout a storm, it is also essential to have gauged flow in real time at various locations within the catchment. At present there are two river flow gauging stations within the Indus Basin, Hok Tau and Shek Pi Tau, neither of which is monitored in real time. The Kam Tin water level station, which is located just to the west of the Indus Basin, is telemetered at 5 minute intervals by the RO and we have used these data in some of the preliminary RTFF analyses to date. It is proposed that this gauge continues to be used when operating RTFF as it will act as a surrogate catchment, mimicking to some extent what is occurring in the western areas of the Indus Basin.

1.11 If the pilot RTFF scheme is to go ahead it is imperative to have some telemetry in the Indus Basin itself. It is particularly necessary that this is introduced at Hok Tau, since this station will act as an indicator of what is occurring generally in the high elevation upper reaches of the Basin. Unfortunately, the Shek Pi Tau station is extremely unreliable during periods of high flow both because of significant bypassing of the station and because the rating equation is suspect. Consequently, it is not felt to be worthwhile telemetering this station. As part of the data acquisition system for the study, it has been proposed in Working Paper No. 5 that four additional water level gauging stations are installed in the catchment. All of these stations will provide useful data for the pilot RTFF scheme. Details are given in Chapter 2.

1.12 Since the lower reaches of the Indus are dependent on tide levels, RTFF must be able to take this into account. Presently sea water levels are monitored at the tide gauge at Tsim Bei Tsui and telemetered in real time to the RO. In the past this gauge has been seriously affected by siltation and periods of historic data are missing. The gauge is presently being moved to a better location.

Proposed Pilot RTFF Scheme

1.13 The proposed pilot RTFF scheme will provide flood warnings for regions of the Indus Basin over which flooding occurs. Following previous floods, reports from villagers have indicated that floodwaters have risen very quickly without warning and they have had no time to move livestock or property to regions of safety (Reference 6).

1.14 RTFF will predict flows and consequently stages exceeding predetermined critical levels at key locations within the Indus Basin. These stages will be used to give an indication of the severity of flooding along reaches serviced by the key locations. The BMP studies will identify areas that will be flooded for various levels of risk, and the RTFF studies will link into this database in order to determine flood extent rapidly in real-time from forecast levels at the key cross sections. With time, as more data become available from the flood reporting aspect of Phase II, estimates of flood depths at different locations will be refined.

1.15 It is proposed that at the core of the pilot RTFF scheme will be a general conceptual rainfall-runoff model, the Probability Distributed Model (PDM) (Reference 7). This model is specifically tailored for real-time application and will be used to transform 5 minute telemetered rainfall data into flow at various "strategic" locations throughout the catchment. The model is designed in such a way that model forecasts can be corrected in real time. Estimated flows from the portion of the Shenzhen Basin draining from the PRC will also be produced by the model. Both models and real time "updating" facilities are described in more detail in Chapter 3.

1.16 The hydrological output from the PDM and water levels predicted by the storm surge/astronomical tide model will be incorporated into a hydrodynamic model which will be used to convert flows to water levels across the floodplain. On the basis of model results and "what-if" scenarios, considering the possible impact of forecast rainfalls, storm surges and future structure (e.g. reservoir) operation, a decision can be made as to whether or not to issue flood warnings. Sea water levels will be based on predicted astronomical tides, but a statistical model of extended ARMA form will be incorporated to forecast storm surges.

1.17 All RTFF modelling will be done on a SUNSPARC II workstation that will be situated at DSD after we have handed the system over to them. Telemetered data will be transferred in real time from the RO computer to the SUNSPARC using a dedicated line, with possibly a duplicate line as a backup as this link is one of the most vital components in the data transfer process. Model runs will be performed automatically every 5 minutes. This will achieve two objectives. Firstly, it will allow model "states" that is the water contents of the conceptual stores within the model to be updated. Secondly, on the basis of results from model runs, alarms will be triggered if certain preset thresholds are exceeded. It will then be up to the system operator to review the situation, instigate "what-if" forecast runs and, if necessary, to issue flood warnings.

1.18 For the Indus Basin, where catchment lag is very short, it is preferable that some sort of rainfall forecasting is incorporated into the system in order to increase forecast lead times. Simple forecasts will take the form of "what-if" scenarios based on typical rainfall profiles. Such profiles could be seasonally adjustable and categorized into light, moderate and heavy with the option of invoking a selection at run time. In future more comprehensive forecasts might be possible using the radar data blended with raingauge data. However, this will not be possible when the system is first operational in 1993. It is important to note that on small catchments with steep headwaters, as in the Indus Basin, peak flow often results from peak rainfall intensity and consequently flood waters will not necessarily rise just because it is still raining. Incorporation of rainfall forecasts will take this into account.

1.19 Since river levels at the lower end of the catchment are sea level dependent it is necessary to incorporate this information in the model and make predictions of future sea levels. The basis of such predictions will be the astronomical tidal predictions published by the RO. These would be stored as 15 minute values. Storm surges such as occur during tropical cyclones will be modelled using an extended form of Auto Regressive Moving Average (ARMA) model to complement the astronomical predictions when necessary. Similarly the model will be very dependent upon inflows from that part of the Shenzhen River draining from the PRC, which is largely ungauged. Further details of this technique are given in Chapter 3.

Effectiveness of the Proposed Solution

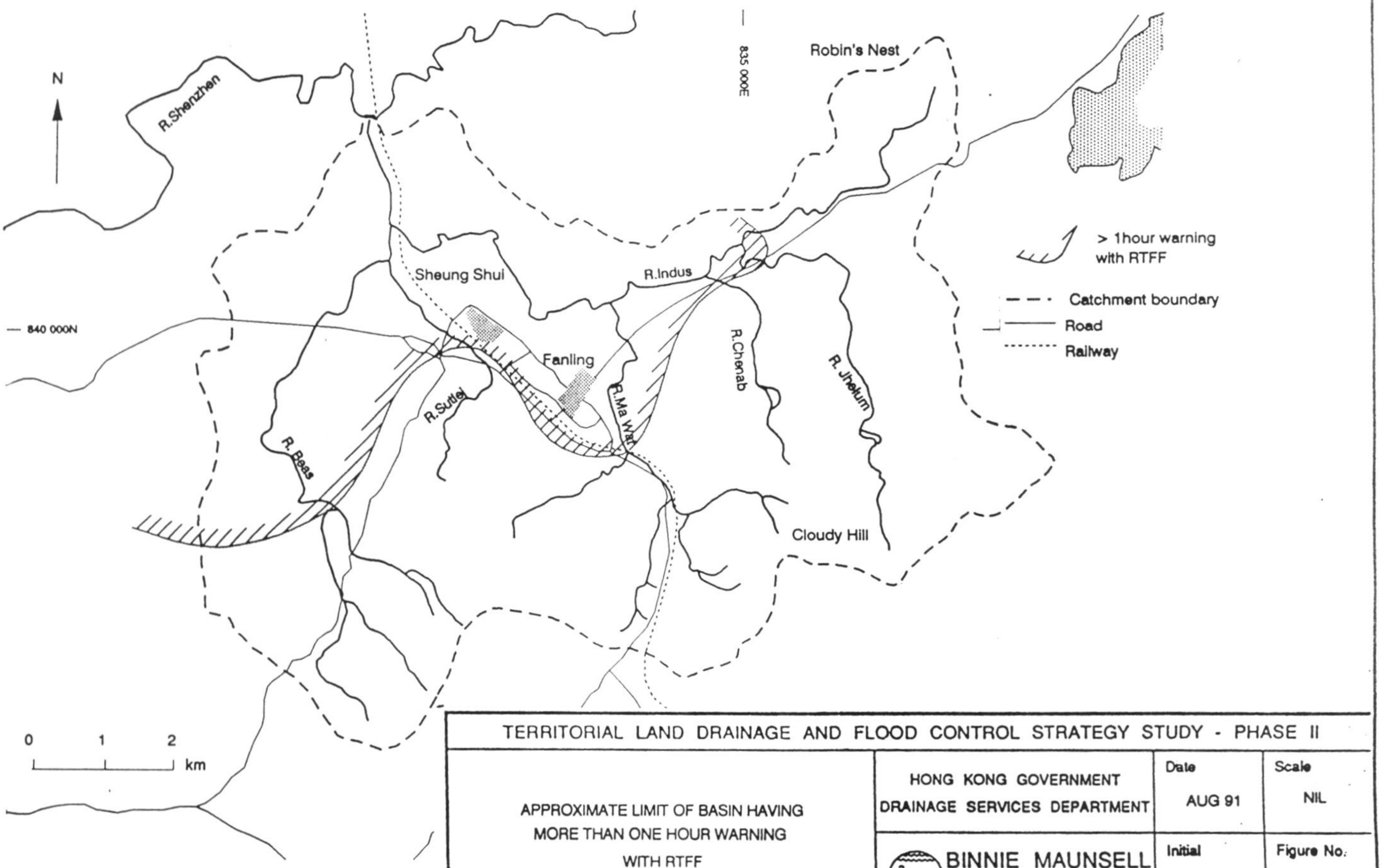
1.20 Research in the UK, Australia and the USA (References 12 and 14) has indicated that with flood warnings of less than one hour people do not respond well and there is little reduction in the amount of flood damage caused. However, the same research has shown that with greater than one hour of warning, significant savings can be made if household contents, cars and livestock are moved to areas of safety. Figure 1 indicates the points downstream of which we believe the proposed RTFF scheme would be able to give a greater than one hour flood warning based directly on the catchment response time. For much of the lower Indus flood warnings of two or more hours should be possible, however.

1.21 The effectiveness of flood warnings are dependent on a number of factors, not least of which is the dissemination of the warning to the public. If warning dissemination is poor this will have a detrimental affect on the overall warning efficiency. Methods of dissemination are discussed in Chapter 4. Other factors that influence effectiveness are:

- time of day; people are generally less efficient at night;
- the preparedness of the population; this should not be too much of a problem in the Indus Basin where floods occur frequently and there is consequently a high awareness of the risks; and
- the number of previous false warnings, which considerably reduces the motivation to act upon warnings.

It is not possible to quantify precisely how reliably floods may be forecast for the basin as a whole as different parts of the basin will have different lead-times. As discussed above however, much of the flood-prone area of the basin can be given a warning time of one hour or more. Experience elsewhere in the world has shown that this is sufficient time to enable the public to respond positively and to permit significant savings in flood damage costs.

1.22 With regard to the last point, one of the primary aims of RTFF must be reliability and it is proposed that the RTFF scheme should initially be implemented for a trial period without issuing warnings to the public. This will ensure that it is operating correctly before any warnings are issued.



TERRITORIAL LAND DRAINAGE AND FLOOD CONTROL STRATEGY STUDY - PHASE II

APPROXIMATE LIMIT OF BASIN HAVING
MORE THAN ONE HOUR WARNING
WITH RTFF

HONG KONG GOVERNMENT
DRAINAGE SERVICES DEPARTMENT

BINNIE MAUNSELL
CONSULTANTS

Date
AUG 91

Scale
NIL

Initial
FAKF

Figure No.
1

1.23 It is felt that flood forecasts and their associated warnings should be judged proficient primarily on the basis of whether or not a threshold exceedance (or non-exceedance) was correctly forecast as the warning system will operate on the basis of a series of thresholds. The probability of correctly forecasting exceedence or non-exceedence of these is covered in Chapter 4. Any further "accuracy" in terms of the level of peak between thresholds should be considered a bonus, not necessarily a target. As more experience is gained with the system, improved rainfall forecasts become available and more detailed information on hydro-meteorlogical conditions in the PRC side of Shenzhen Basin become available it would be possible to forecast the peak levels with more confidence.

Cost Effectiveness of the Proposed Solution

1.24 The cost effectiveness of the pilot RTFF scheme is determined by comparison of the benefits that would accrue from the installation of what we believe to be a soundly designed flood forecasting system, offset by the cost of the proposed scheme. Financial savings arise from the actions taken in the lengthened warning time that results from the operation of the system.

1.25 An estimate of the reduction of tangible damage, that is damage to which a monetary value can be attached, first requires an estimate of pre-warning damage. The socio-economic data required to evaluate flood damage in detail is not available in Hong Kong and the estimated losses quoted in this report are necessarily crude. However, an attempt has been made to derive the annual benefit arising from RTFF in the Indus Basin. Further details of RTFF costs and benefits are given in Chapter 5.

2. ADDITIONAL TELEMETRY NEEDED FOR RTFF

2.1 The proposed additional telemetry that will be used by the pilot RTFF scheme if it is implemented can be summarized as:

- seven new reporting raingauges, six located in the Indus Basin and one in the Kam Tin Basin;
- four new water level gauging stations in the Indus Basin, one each located on the River Ma Wat and the River Beas and two on the River Indus;
- one new water level gauging station, located at Lok Ma Chau, on the Shenzhen River (Basin 10); and
- new telemetry at the existing Hok Tau flow gauging station.

2.2 The types and locations of existing gauges are shown on Figure 2. Table 1 lists the proposed stations and locations are shown on Figure 3.

TABLE 1

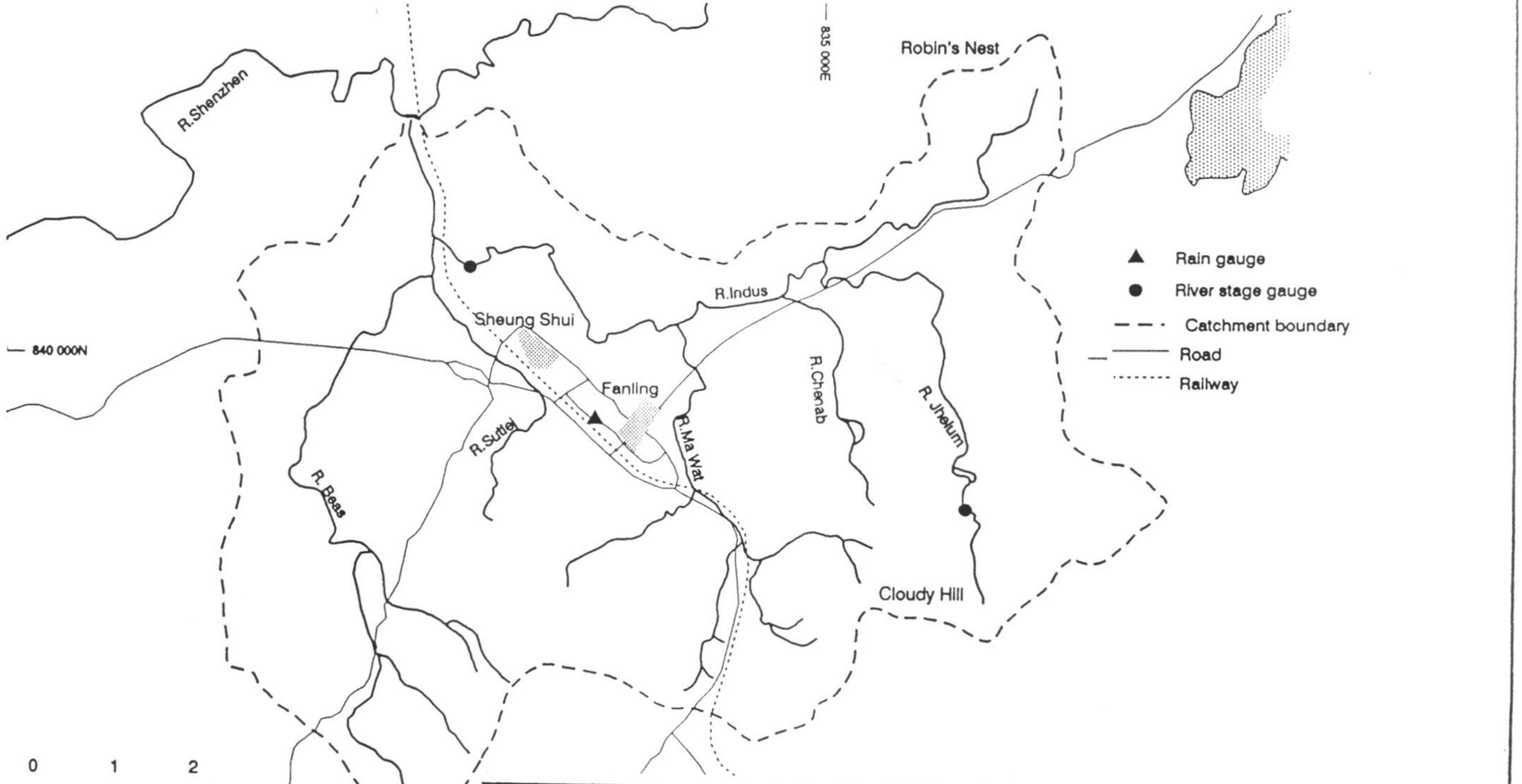
SUMMARY OF NEW STATIONS USED BY PROPOSED RTFF SCHEME

Site Name	Station No.	Type	Location	Comment
River Beas (Haung Tai Po)	PSA1	A	River Beas at NTCR Service Road	Only reasonable location on the Beas River
Gallipoli Lines	PSA2	A*	River Indus at Gallipoli Lines	Best possible location on lower reaches of the Indus River
Lo Wu	PSA3	A	River Indus at Lo Wu	Good location adjacent to confluence of River Indus and Shenzhen River
River Ma Wat (Luen Wo Bui)	PSB1	B	River Ma Wat in Fanling	Best location on the lower reaches of Ma Wat River
Lo Ma Chau	PSB5	B	River Shenzhen at Lok Ma Chau	Good location on the tidal reach of the Shenzhen River Although the site is in Basin 10 it will be a useful indicator of intermediate conditions between Deep Bay and Lo Wu
Robins Nest	PSC1	C	Part-way up Hung Fa Leung (Robins Nest)	Best location would be on top of Hung Fa Leng but cost of telemetry would be prohibitive Selected site is highest point with telephone lines nearby
Cloudy Hill	PSC2	C	Top of Kau Lung Hang Shan (Cloudy Hill)	Excellent location with power and telephone lines nearby
Pak Tai To Yan (FSD Training Depot)	PSC3	C	Fire Services Department training depot at Pak Tai To Yau on Fan Kam Road	Preferred site would be on high ground to east or west but the cost of telemetry would be prohibitive Selected site is just within Basin 9, but is the best of the sites available at reasonable cost Although the site is just within Basin 9 the data is considered suitable for use in the Indus Basin
Hok Tau	PSC4	C*	Hok Tau Reservoir	Appropriate site for monitoring rainfall in the Hok Tau sub-catchment and assessing catchment response by calibrating with discharge record at Station PSD3
Hok Tau	PSD4	D+	Hok Tau Reservoir	Telemetry added to existing WSD river water level gauge

*	*Raingauge required for RTFF only*
+	*Telemetry of river water level gauging station required for RTFF only*

Station types:

A	-	*combined river stage and raingauge*
B	-	*river stage only*
C	-	*raingauge only*
D	-	*existing river stage gauge to be telemetered to the RO's central computer*



TERRITORIAL LAND DRAINAGE AND FLOOD CONTROL STRATEGY STUDY - PHASE II

LOCATION AND TYPES OF EXISTING GAUGES

HONG KONG GOVERNMENT
DRAINAGE SERVICES DEPARTMENT

BINNIE MAUNSELL
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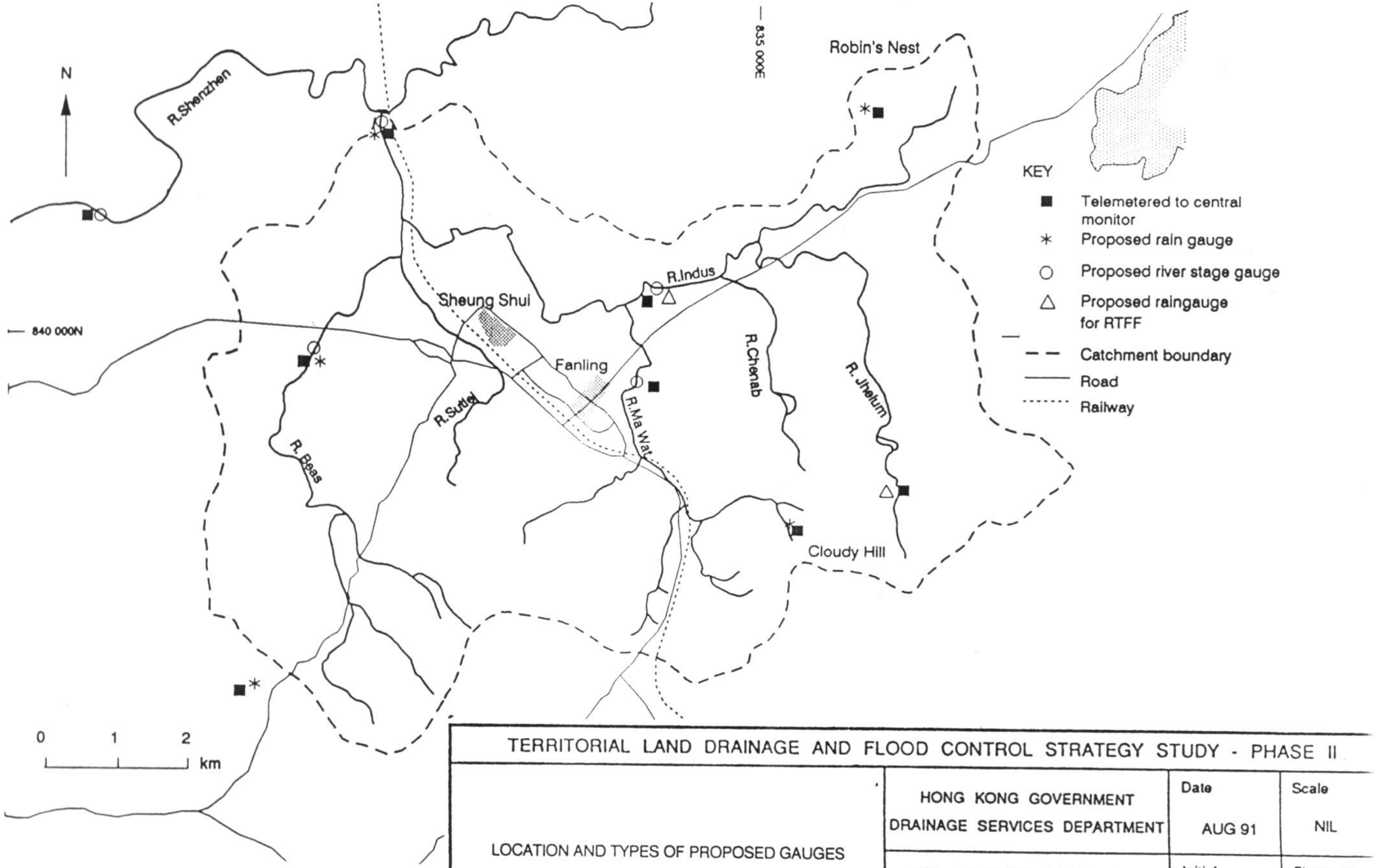


TERRITORIAL LAND DRAINAGE AND FLOOD CONTROL STRATEGY STUDY - PHASE II

LOCATION AND TYPES OF PROPOSED GAUGES

HONG KONG GOVERNMENT
DRAINAGE SERVICES DEPARTMENT

BINNIE MAUNSELL
CONSULTANTS

Date AUG 91

Scale NIL

Initial FAKF

Figure No. 3

2.3 Most of the telemetry listed will be installed for the proposed data acquisition system and flood reporting programme for the Phase II study, whether or not the pilot RTFF scheme is implemented. The additions that are required just for RTFF are:

- one raingauge to be sited at the same location as the proposed water level gauging station at Gallipoli Lines; and
- full telemetry of rainfall and water level gauges at the existing Hok Tau flow gauging station.

The cost of these additions, including the installation of a long telephone cable and power line to the remote Hok Tau site are discussed in Chapter 5.

2.4 It was originally hoped that raingauges could be located on more of the hilltops, notably Hung Fa Leung (Robins Nest) and Wo Hop Shek. However, due to the high cost of installing telephone lines to these remote sites these gauges have had to be omitted. It is therefore imperative that the highest raingauge situated at the top of Kau Lung Hang Shan (Cloudy Hill) be installed.

2.5 Seven raingauges are the minimum required to provide an adequate spread over the catchment. In order to calculate areal catchment rainfall at any given time the isopercentile method will be employed. For each time interval the rainfall at each raingauge as a percentage of its long-term average annual fall is computed. This average annual rainfall will be assessed from the RO maps for the catchment. These gauge percentages are averaged, possibly using weights reflecting the representativeness of each gauge for each sub-catchment of interest. The average percentile in each time interval is then multiplied by the average annual rainfall for the sub-catchments of interest to obtain the areal rainfall input for the time interval. Weighting of gauges could be related to orographic features such as gauge elevation and aspect and would be determined during model calibration. Since the basis of RTFF is rainfall-runoff modelling (there is no time for routing observed flows downstream on such a small catchment) good rainfall estimation is imperative. With the seven raingauges proposed, if one or two are lost during the course of an event there will be enough remaining to continue RTFF operation.

2.6 It is essential for the pilot RTFF scheme that telemetry is installed at the Hok Tau flow gauge, since it is ideally situated to be a real time indicator of what is occurring throughout the upland runoff producing regions of the catchment. It is well located in a deeply incised channel with no chance of bypassing and there is a reliable flow rating curve. The actual contribution of flow to the River Indus via this location is itself usually negligible, because the Hok Tau Reservoir located downstream of the gauge dramatically attenuates its impact. Furthermore, some water is diverted by pipeline from the Lau Shui Heung Reservoir to the Hok Tau Reservoir and then to Plover Cove Reservoir. The runoff contributed to the River Indus through spill from these reservoirs will take account of the attenuation and draw-off.

2.7 The other water level stations will allow water levels to be monitored at key locations throughout the catchment. The station suggested at Lok Ma Chau is located in Basin 10 (San Tin). It will provide a useful intermediate level on the Shenzhen River, between Deep Bay and Lo Wu. It is recommended that in time rating equations should be established for all these stations in order that flows as well as levels can be determined. As the gauges at Lok Ma Chau and Lo Wu are on tidal sections of the river development of a rating equation will not be possible.

2.8 Further details of the proposed additions to the existing telemetry network are given in the Phase II Study Working Paper No. 5 - Hydrological Data Acquisition.

3. RTFF MODELLING AND PROPOSED SOFTWARE

Choice of Model

3.1 In the Interim Working Paper it was suggested that a combination of the PDM rainfall-runoff model developed by IH and the hydrodynamic channel routing component of MIKE 11 would be used as the basis of the RTFF software. The reasons for suggesting this combined approach was to utilize the most appropriate and up-to-date rainfall-runoff modelling techniques with the hydraulics of MIKE 11 which would have been fitted to the Indus Basin as part of the BMP studies. However, there are two inherent problems in this suggested approach, firstly that of how the PDM and MIKE 11 models would be efficiently linked and secondly how this combined software would be supported.

3.2 Because there are obvious practical problems with this software solution, two alternative methods of meeting the main software requirements of the proposed pilot RTFF scheme for the Indus Basin have been investigated. The first of these would be to adhere wholly to the MIKE 11 system adopted for the BMP studies by using the real-time forecasting version, MIKE 11 FF. The second would be to use the equivalent IH software package developed in recent years called RFFS (River Flow Forecasting System).

3.3 MIKE 11 FF is a relatively well tried-and-tested software package for real-time flood forecasting which was developed on PC computers to run under DOS. It has recently been converted to run under UNIX, but has only been applied in this mode very recently. At present the model has been applied only to large catchments and has not been tested in earnest on any catchment as small as the Indus. The normal modelling time step is from one hour to one day, but the model formulation is not ideally suited to real-time application on small catchments. The model may be linked to a real-time data collection system but the user would have to write appropriate software to input data to the database files within MIKE 11 FF as no standard interface software exists. The real-time data are stored within an internal database system developed by DHI. Commercial relational database software can be used for this task, but it can be computationally more efficient to use purpose-written routines to store the data.

3.4 The approximate cost of the MIKE 11 FF software was given by DHI as $196,300 (DKK 165,000), and annual support $30,000 (DKK 25,000). DHI also quoted for installation, training, technical assistance and linking to the RO database for a cost $545,000 (DKK 458,000). Some of this work would be covered by the existing Stage II RTFF lump sum consultancy fees. The likely additional cost of DHI inputs therefore are estimated to be some $200,000. Thus the total cost of DHI software is estimated to be $395,000 with $30,000 required annually for software support.

3.5 The best alternative to the MIKE 11 FF software is the River Flow Forecasting System, or RFFS, developed by IH, that incorporates the PDM rainfall-runoff model. The RFFS software has been utilized in the UK on a wide range of catchment sizes and types and forms the basis of a major real-time flow forecasting system for the whole of the 13,500 sq.km Yorkshire region of the UK National Rivers Authority. Although RFFS was developed for a large basin, the Yorkshire NRA system is currently configured to produce forecast flows and water levels at over 100 points throughout the region, and some of the small headwater catchments modelled are even smaller than the Indus. The software is very flexible and may readily be configured to any river and sub-catchment network. Parts of the software have also been used for a real-time flood forecasting system to protect the city of Lincoln for the Anglian region of the NRA. Three main catchments were modelled in this case having areas of 128, 140 and 300 sq.km, although the model was also applied to sub-catchments of less than 10 sq.km. As for the Yorkshire study, 15 minute telemetry data were used. A summary of the RFFS system as applied in Yorkshire is given in a recent paper, reproduced here as Appendix A (Reference 10).

3.6 The RFFS software developed by IH is proposed in preference to the real-time version of MIKE 11 for a variety of reasons. These include its flexible, reconfigurable structure, making extension to other basins in Hong Kong particularly easy, its resilience to missing data and its use of models tailored to operate in a real time environment. We also believe that the rainfall-runoff model, NAM, used within MIKE 11 is not well formulated for use on such a small, responsive, catchment as the Indus. It is also not well suited to state correction in real time. The IH model uses a continuous formulation through differential equations and is suitable for use at a range of time intervals. NAM is a good model for larger basins, but is not ideally suited to the small, responsive catchments found in Hong Kong.

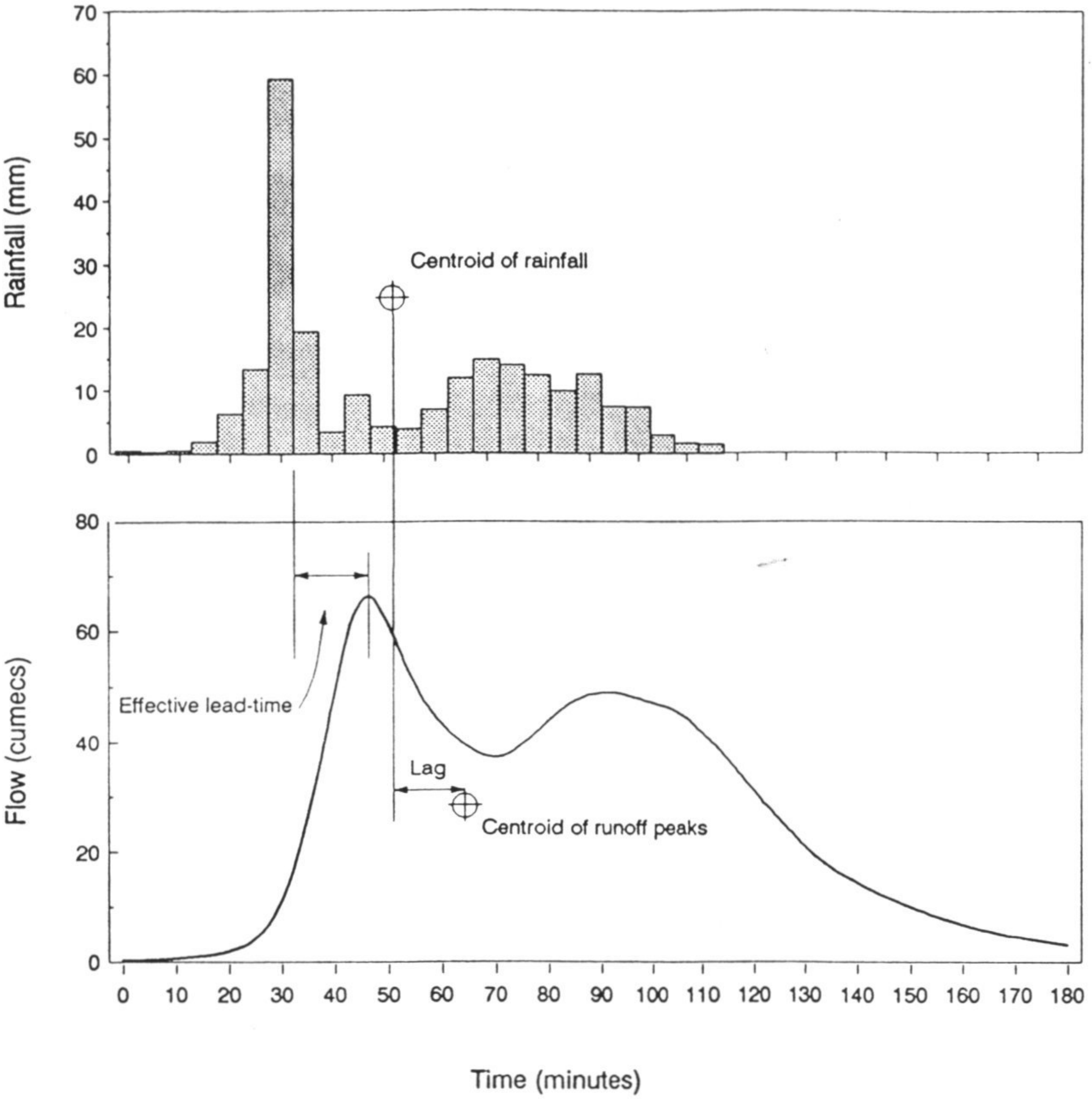
3.7 We believe that the proposed RFFS software is not only technically superior to many aspects of MIKE 11 FF, but will be less expensive to purchase and maintain. Whilst in our Interim Working Paper we suggested that the best option could be to use the PDM rainfall-runoff model developed by IH combined with the hydrodynamic routing model of MIKE 11, we now feel that such an approach will be difficult and expensive to achieve and to support. Consequently, we now recommend that the software for the pilot RTFF scheme on the Indus should be the IH RFFS software.

3.8 The cost of the RFFS software is $168,750 (£12,500); training would be provided at no extra cost as part of the Phase II RTFF consultancy fees. Whilst the PDM component of the RFFS software was allowed for in the Stage II RTFF consultancy fees, the hydrodynamic routing was not. The licence fee for this software would be the $168,750 quoted above. Annual support would cost $27,000 (£2,000). As with MIKE 11 FF, some extra software would have to be written to link RFFS to the RO telemetry database, but this is included in the Stage II fees. Thus the overall cost of using the RFFS software system for the pilot RTFF system for the Indus basin would be $168,750 with $27,000 annual support fee, significantly less than the comparable cost of MIKE 11 FF.

3.9 The RFFS software uses a flexible rainfall-runoff model called PDM (Probability Distributed Model (References 7 and 8), which is a general conceptual model developed specifically for real-time forecasting and which may be readily updated during a flood event using observed telemetered flows. Further details are given in Appendix B of this Working Paper. Copies of a number of more detailed papers from the scientific press are available for interested readers.

3.10 One of the commentators on the Interim Working Paper asked whether the DISPRIN model might be a suitable alternative to either NAM or PDM. The DISPRIN model was developed for use as a real-time rainfall-runoff model on the River Dee in north Wales, but the input-storage-outflow, or ISO function model developed by Lambert (Reference 5) was finally adopted for operational use. The DISPRIN model is a fairly complex semi-distributed conceptual model which had between 11 and 23 parameters, depending upon the complexity of the catchment model selected. This number of parameters is excessive for the current data-poor Indus Basin, and although the model is conceptually sound, it is difficult to establish parameter values for ungauged catchments. The model is also demanding in computer time and memory. The preferred PDM model has only 11 parameters, one of which is always fixed and three others of which have equivalent physical meanings and can therefore be set externally, leaving just 7 parameters to be fitted by objective means. The DISPRIN model is not readily initialized in real-time and has no in-built state correction facility for real time application.

3.11 The use of catchment lag as an indicator of forecast lead-time was discussed in our Interim Working Paper and commented on subsequently by WSD. For responsive catchments such as the Indus, peak runoff will often result from a brief period of high intensity rainfall within the body of the storm, and catchment lag is a poor indicator of lead-time in such cases. This point is illustrated on Figure 4.



TERRITORIAL LAND DRAINAGE AND FLOOD CONTROL STRATEGY STUDY - PHASE II

ILLUSTRATION OF THE EFFECT OF RAINFALL INTENSITY
ON HYDROGRAPH RESPONSE AND THE LIMITATION
OF LAG TIME AS A LEAD-TIME INDICATOR

HONG KONG GOVERNMENT
DRAINAGE SERVICES DEPARTMENT

BINNIE MAUNSELL
CONSULTANTS

Date AUG 91	Scale NIL
Initial FAKF	Figure No. 4

3.12 The hydrographs of forecast flow produced by the PDM model from the various upstream sub-catchments will be routed down those reaches of the upper channel network where flow is predominantly within bank using the kinematic wave model (References 4 and 9). However, for much of the central and lower Indus Basin, flood flows go overbank for even modest floods and a hydrodynamic routing model employing a full-solution of the Saint-Venant equations is required. The RFFS software uses an adaptation of the well known United States National Weather Service's DWOPER/NETWORK hydrodynamic model described by Fread (Reference 1).

3.13 The RFFS software is written in standard FORTRAN 77 and at present runs either on a PC under DOS or on a MicroVAX under VMS. Only minor modifications are required so that the software would run under UNIX on a SUNSPARC II workstation. These will be carried out at the outset of the pilot scheme. The software will be accessed via a user-friendly graphical user interface, using either the Panel-Plus system currently used by IH for their Lincoln model, or more probably using the X-Windows system available on the SUNSPARC.

3.14 A number of technical problems were discussed briefly in the Interim Working Paper, particularly the influence of sea levels in Deep Bay, and the complexities of modelling the Indus as part of the largely ungauged Shenzhen Basin. Further discussion on these topics is given below.

Storm Surge Forecasting

3.15 One of the comments on the Interim Working Paper was that we had not covered the question of the influence of sea levels on the RTFF models adequately. The influence of sea levels on flows and levels on the lower Indus, and our proposals for dealing with the problem, were discussed at some length in Appendix A of that paper (paragraph A.40 to A.46), although only brief coverage was given in the body of the text.

3.16 For an operational RTFF scheme on the Indus Basin, a real-time forecasting model of tidal residuals (the difference between predicted astronomical tide and observed tide) would be required. Values for the predicted astronomical tide at Tsim Bei Tsui would have to be obtained from the RO, probably on an annual basis. These data, which are available as 15 minutes values, would have to be stored on the SUNSPARC computer as the basis for the downstream boundary conditions. However, for some flood events, heavy rainfall may be associated with strong winds and a resultant storm tide surge which would have to be taken into account.

3.17 Ideally storm surge forecasts should be derived from a physically-based numerical model. Such a model is not yet available for Hong Kong waters because of the complexity of the combination of currents, seabed topography and pressure systems affecting the area. The RO have stated that although they have a tidal model which can be used to estimate storm surges, they do not believe that it could be used as part of the proposed pilot RTFF scheme. Because reliable quantitative forecasts of such surges are unavailable at present, the RTFF model will have to make its own short-term forecasts of surge residuals for up to four or six hours ahead.

3.18 In the absence of a suitable numerical model of storm surges, a statistically-based forecasting model will be employed to derive short-term forecasts of sufficient accuracy. Historical storm surge residuals for a number of events would be derived by comparing the observed telemetered tide level at Tsim Bei Tsui with the stored astronomical prediction and computing the tidal residual every 15 minutes. As the RO provide the astronomical data at 15 minute values and as both tide level and storm residuals change only slowly, 15 minute values will be adequate for use within the RTFF model. From our analysis of a number of such events, it is apparent that time series plots of the residuals show considerable persistence which can be used as the basis of a forecasting model. By analyzing data from historical events having a significant storm surge, an auto regressive moving average, or ARMA, model would be developed. Such a model, possibly incorporating explanatory variables such as wind and pressure (a so-called ARMAX model) would provide adequate short-term forecasts for effective RTFF modelling.

3.19 Not all significant flood events are associated with storm surges, and even where heavy rainfall does occur at the same time as a major tide surge, about half the flood peaks on average will occur during the low-tide window. The accuracy of the suggested ARMAX model is difficult to estimate at this early stage, but we would estimate that it would be within approximately 25 per cent of the true value. Thus given that the maximum likely surge in Deep Bay is 2 metres, the surge forecast would be accurate to better than 0.5 metres, and probably would be accurate to about 0.3 metres at Tsim Bei Tsui. This would imply a potential error in forecast levels on the Lower Indus of between 0.1 and 0.25 metres during those events where storm surges coincide with flood producing rainfall. For many flood events, astronomical tide level alone provides an adequate downstream condition for the model. The suggested short-term forecasting model for the downstream tidal boundary condition of the RTFF model will be sufficiently accurate for the proposed pilot scheme. Experience with the model will show whether additional refinement is required, but the model outlined above should suffice for the vast majority of flood events. It is not possible to quantify how successful or accurate the proposed storm surge forecasting mode will be. However, because of the RTFF model's ability to update its forecast using telemetered levels at Lo Wu and Lok Ma Chau in particular, any deficiency in the model will be corrected for in real-time during any flood event.

The Estimation of Flows on the Shenzhen River

3.20 As noted earlier, the Indus Basin is a tributary of the Shenzhen River, which it enters at Lo Wu. The Indus Basin drains some 22 per cent of the total Shenzhen Basin, much of which drains from the PRC and we understand that river gauging data is not presently available to DSD. Whilst rainfall data for the raingauge at Bai On in the PRC is available to the RO, at present on a daily basis, although in the future it will be available every six hours, this does not provide sufficient information to permit estimation of flows from the Shenzhen Basin in real-time. However, the real-time data that will be available from the new Lok Ma Chau gauge will greatly help in keeping model predictions on track during an event.

3.21 We recommend that DSD and the RO pursue their objective of a freer exchange of hydro-meteorological data between Hong Kong and the PRC. These data should include details of discharges from the Shenzhen reservoirs. For the pilot RTFF scheme, however, flows in the Shenzhen River, which forms a boundary condition to the RTFF model at Lo Wu, will have to be estimated. Without measured rainfall data over that portion of the Shenzhen Basin draining the PRC, the simplest method of estimating flows would be to assume that the rainfall was the same as that measured on the Hong Kong part of the catchment. This would provide a reasonable estimate for many storms, but could be very markedly in error in other cases. The variability of daily rainfall over Hong Kong and between Hong Kong and Shenzhen are available from various reports. Further data will be available later in the Phase II study for comparison of short term rainfall in the study area with that at the RO. These data will be reviewed during Stage II of RTFF to determine the most appropriate assumptions for estimating rainfall in the PRC.

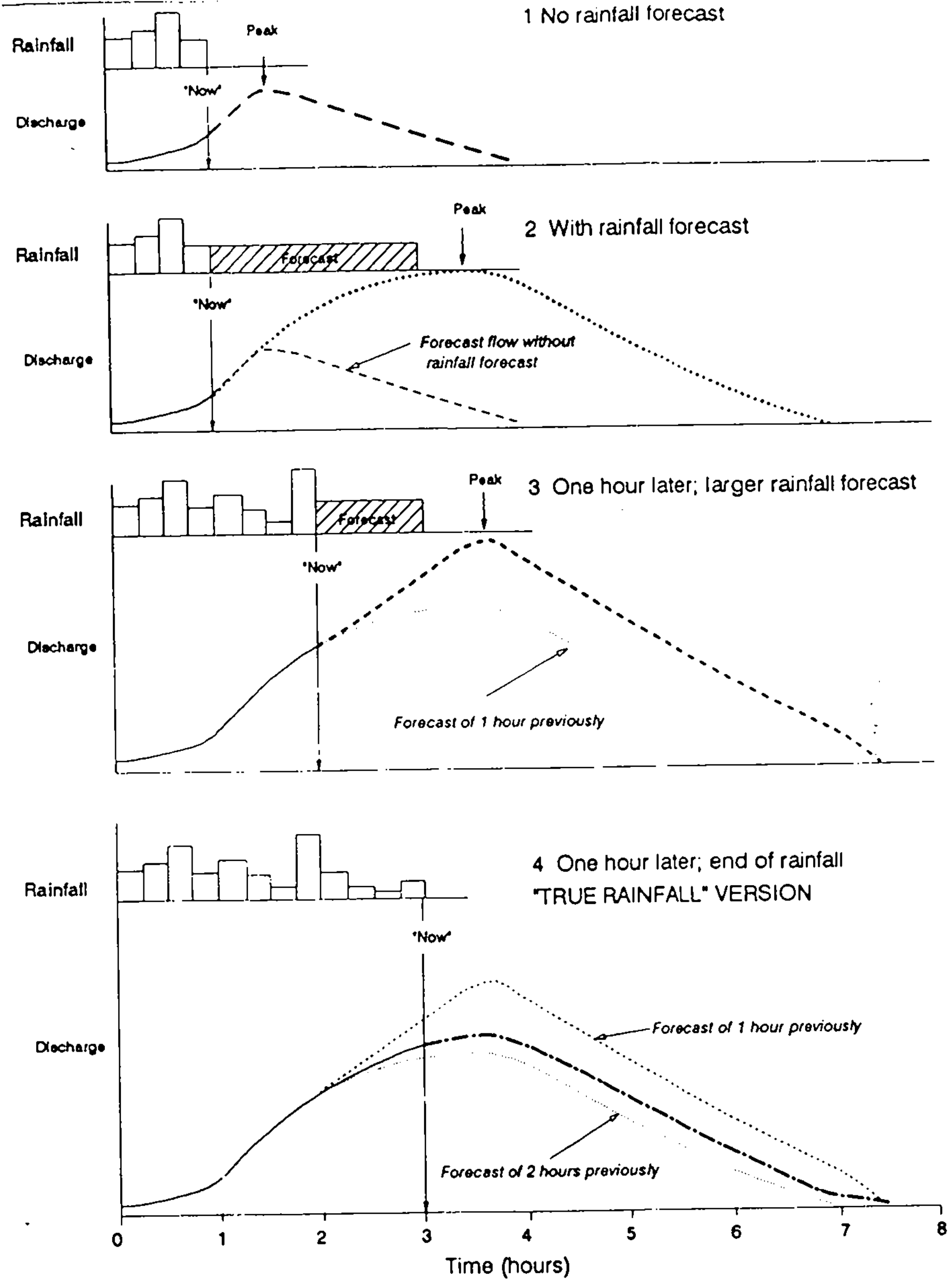
3.22 The best means of estimating areal rainfall over the Shenzhen Basin would be through the weather radar data available in real time at the RO. At present such data are not fully calibrated to provide quantitative spatial data, but this is understood to be a long-term objective of the RO. The calibration of radar data would greatly enhance the performance of a RTFF scheme. It is technically achievable, and IH have implemented operational systems in the UK. If the pilot scheme is successful, DSD and the RO should maintain calibration of radar data as an important objective. Until such a study could be carried out, it will be necessary to assume that the rainfall over the PRC is similar to that over Hong Kong and to update this assumption in real-time using telemetry data on the Shenzhen at Lok Ma Chau.

Updating in Real Time

3.23 Updating in the PDM rainfall-runoff model uses empirical state correction to adjust the water content of the conceptual storages to gain closer agreement between observed and modelled flows. In contrast, error predictor schemes are used for the hydrological channel flow routing model and for the hydrodynamic tidal river model. The former involves using the discrepancy between modelled and observed flows to predict future errors, relying on the persistence of past errors to predict future errors which are added to the model predictions to form the updated forecast.

3.24 A similar scheme is used in the hydrodynamic tidal river model, but in this case the error predictor operates in terms of levels and is used to update predictions of levels from the model. In both cases the error predictor operates externally to the production of the model forecasts and does not need to be built into the model code itself, as is the case for state correction of the PDM rainfall-runoff model. Because the tidal river model operates as a single entity and produces a set of level forecasts for a number of cross-sections for which level measurements are made, the implementation of the error predictor involves the use of a multivariate form of ARMA predictor.

3.25 The model must have some facility for the user to enter a range of "what-if" scenarios for both short-term future rainfall, for storm surges and for releases from the Shenzhen reservoirs in the PRC. These will be built into the software as a series of options which will enable users to select likely scenarios from a short list through a menu system. These "what-if" rainfall scenarios should probably be based on simple storm rainfall profiles typical of some particular part of the year. Thus a conditional probabilistic approach could be adopted based on an assessment of what the remainder of the storm is likely to look like from examination of the storm duration and accumulation up to "time-now". A series of seasonal dimensionless storm profiles might be incorporated within the model and the user might simply select from a series of likely storm continuation patterns based on current telemetered data. The value of simple rainfall forecasts is shown in Figure 5. Further work on development of short-term quantitative rainfall forecasts is desirable either by the RO alone or possibly with the assistance of experienced external consultants. Until such work can be carried out, the proposed range of probabilistic rainfall profiles is believed to offer the best option for "what-if" rainfall forecasting within the proposed pilot RTFF scheme.



TERRITORIAL LAND DRAINAGE AND FLOOD CONTROL STRATEGY STUDY - PHASE II			
SCHEMATIC DIAGRAM OF FLOOD EVENT DEVELOPED DURING A REAL TIME FLOOD	HONG KONG GOVERNMENT DRAINAGE SERVICES DEPARTMENT	Date AUG 91	Scale NIL
	BINNIE MAUNSELL CONSULTANTS	Initial FAKF	Figure No. 5

3.26 The downstream tidal limit scenarios are likely to offer the user less options, partly because it is anticipated that the time series storm surge model to be built into the model should produce better estimates of storm surges in real-time than the equivalent potential rainfall forecast scenarios. Storm surges have a natural persistence which may be detected and modelled, whereas there is no equivalent underlying pattern to rainfall. Thus the rainfall forecasting problem is intrinsically more difficult and must therefore be simplified for ease of use by the system operators during an event.

3.27 The probable release scenarios from the Shenzhen reservoirs could be produced only once information on how the reservoirs were operated under normal flood conditions could be established. We suggest DSD hold discussions with the appropriate authorities in the PRC during the pilot study phase of the RTFF implementation.

4. DISSEMINATION OF FLOOD WARNINGS

4.1 A Territory-wide network of information dissemination already exists for the heavy rainfall/flood warnings currently issued by the RO, but this network is believed to be too complex and unwieldy for use on the Indus Basin alone. In order to avoid confusion, a new, purpose-designed, flood warning dissemination system should be developed specifically for the Indus Basin as part of the pilot RTFF scheme.

4.2 We suggest that it would be best for the pilot RTFF scheme to be operated as a separate entity by DSD. The resultant flood forecasts specific to the Indus Basin should however be issued to the public and Government agencies by the RO, who already have the responsibility for issuing heavy rainfall warnings. It is important throughout the process of warning dissemination that the role of all organizations is clearly defined. In line with overseas experience, we have assumed that some 65 to 75% of households within identified flood-prone areas will receive warnings in any flood event. This figure is based upon post-event analysis of floods in the UK, USA and Australia. However, because of the high population density and good infrastructure of roads and telephones in the northern New Territories, warning dissemination in Hong Kong should be as good as, or better, than that achieved elsewhere in the world given sufficient public-education and training of Government staff.

4.3 The required flood warning dissemination system may require the involvement of the Government Secretariat Emergency Coordination Centre and the Information Services Department so that one or more circulars may be produced and circulated to the public living in the Indus Basin, or likely to pass through it regularly by road or train. The public have been educated as to the meaning of the numerical strong wind and typhoon warning system through a series of such circulars, and it would be sensible to adopt such an approach with the Indus Basin flood warning scheme.

4.4 However, rather than using a numerical system of flood warnings, which might be confused with the strong wind warnings, a system of colour coded warnings and alerts is proposed. A suggested cascade of alerts and warnings is set out below and would be initiated by a series of thresholds determined in Stage II of the RTFF:

Standby - DSD are alerted by the RO that significant rainfall is anticipated and that a flood situation may be developing. DSD will be responsible for assessing the hydrological implications of such anticipated rainfall. DSD should then notify other Government staff that they should be prepared for a call out. 24-hour manning of the DSD flood control room is initiated. No alert or warnings would be issued to the public at this stage however.

The possibility of the standby alert not being initiated will be very small as the RO is manned 24 hours per day. In ~~the~~ many cases it will not be necessary to proceed to the next level of alert.

Yellow Alert - There is a risk that flooding may occur within the Indus Basin. The public should be made aware of this alert (note that at this stage they are just alerted to the possibility of flooding; no warning would be issued at this stage). Staff of Government agencies would be placed on the next level of preparedness.

For the Yellow Alert to be effective it should be initiated about two hours in advance of the predicted time for issuing a Red Warning. We estimate that the probability of correctly initiating a Yellow Alert will be about 60% as both rainfall and sea level forecasts and "what if" scenarios will be involved in the predictions. Of the remaining 40%, some will not progress to a Red Warning and the remainder will be late initiation of the Yellow Alert.

Red Warning - The public are now warned that some flooding is expected to occur and that the Indus is expected to overtop in some reaches. The public are issued with regular information on when and where flooding may be expected. Staff of all Government agencies put on a high state of readiness to respond as far as possible to the event by perhaps sending out maintenance teams to keep bridges and culverts clear, sandbagging key areas to minimize flood damage, by diverting traffic and by assisting with damage prevention as far as possible.

The probability of correctly forecasting with one hours lead time, the time at which threshold(s) will be reached requiring a Red Warning to be issued is estimated to be 90%. The same level of confidence can be attached to forecasts of longer lead times for areas downstream of the one hour lead time boundary shown on Figure 1. The probability is high because it will be based on measured rainfalls, river levels and sea levels; no forecasts of rainfall or sea levels will be necessary. Of the remaining 10%, some cases will be flooding being predicted but not occurring (i.e. false warnings) and in the others, to the warning being issued late which would still however give valuable warning to the lower basin.

Stand-Down - This is an important final link in the cascade of alerts and warnings and must be issued to both the public and Government agencies to indicate that for the time being, no further flooding is anticipated. This would be issued after the alert/warning level had decreased back below the yellow alert level.

4.5 We are aware that the proposed colour coded warning system is similar to the existing countryside fire hazard warning scheme, but feel that this may be beneficial. The public are already aware of the general meaning of these colour-coded warnings and there should be no confusion in also using them for floods as there is no risk a flood alert being issued at the same time as fire hazard warnings.

4.6 Throughout a flood event, the accuracy of the forecast will increase and the level of alert and warning issued would be expected to change, as more data are collected. The public education leaflets will have to explain not only the cascade system of flood warnings, but will also have to explain that during many events, the alert/warning level would be expected to change over time. It is important to ensure that during an event the state of alert or warning does not oscillate up and down as this could confuse the public and would lead to loss of confidence in the forecasts. Experience in the UK shows that with training and experience, flood duty officers are able to ensure that this does not happen, and that the public receive updates to the alert/warning state only when the data clearly indicate that some significant change in catchment state has taken place. There will have to be a very careful programme of public education to ensure that they understand how the system is designed to work. There may also be occasions where different zones of the Indus Basin have different levels of alert/warning due to spatial rainfall variability. For example, flooding may be indicated on the Beas but not on the Indus. Whether the DSD choose to issue different warnings to sub-areas of the basin will have to be resolved during the pilot study stage.

4.7 Whenever an alert or warning is issued, it must be labelled with a very clear timing and it must also be made clear that it supersedes all previous warnings. Thus the warnings may have the form:

"Red flood warning issued for the entire Indus basin by the RO on Thursday 10th August at 13:15 hours. This warning supersedes the earlier yellow alert issued at 12:35 hours. The RO anticipate some flooding along the lower Indus and Beas rivers commencing at approximately 14:45 hours and lasting for some 2 hours. Areas likely to be affected are ... Further bulletins will be issued as more data become available."

4.8 We initially proposed that the radio and television might be used to broadcast warnings of imminent flooding within the Indus Basin. However, it was pointed out that as such broadcasts would be made to the whole Territory, they might cause anxiety in areas not at risk of flooding, and confusion in areas where flooding was possible, but for which the localized flood warning system for the Indus Basin did not apply. It is therefore necessary to develop a more localized and area-specific means of issuing flood warnings to the population within the Indus Basin alone.

4.9 In the UK this can be achieved through local radio stations and regional television networks, but such an option is not available in Hong Kong. Another commonly used method of broadcasting flood warnings and other messages of local interest is through loudspeaker vans touring local areas. This may offer one means of targeting flood warnings to the population of key local areas. The method will possibly only be useful for small, localized areas, because of the time involved in mobilizing vehicles, drivers and assistants who will read out a pre-determined message over the loudspeaker, and in driving to the areas at risk. Through the use of the standby alert system planned for the pilot RTFF scheme, much of this potential delay may be eliminated by mobilizing the staff early in a potential event and having them stationed within the key flood prone areas at an early stage. This system may well provide the most reliable and cost-effective way of issuing warnings to the population of small, localized flood-risk areas.

4.10 Nevertheless, with the short warning times that are going to be achieved over much of the Indus Basin, some other, general dissemination method is obviously also required. Two methods seem to offer the best solution for use within the Indus Basin, a system of local flood wardens, and a telephone warning system which members of the public may telephone to receive up-to-date information about the local flood situation.

4.11 The proposed flood warden system might be set up in one of two ways. The first would use staff of the various local Government agencies, such as DO and DLO (N and TP Districts) plus DSD staff to act as a first point of contact for dissemination of warnings to local communities. The alternative would be to appoint local residents in key flood-prone areas as flood wardens, presumably by paying them a small annual fee. In both cases, the role of the flood warden would be to pass on the details of the flood warning issued by DSD to the local population. This could probably best be achieved through a network of telephone calls where the flood warden telephones three other people with details of the warning, they each telephone three others and so on. For properties not on the telephone, the flood warden and other key members of the warning network should contact these residents personally after passing on the warning through the telephone network. As an aid to warning dissemination in sparsely populated and poorly serviced areas, flood sirens might be triggered by the flood wardens as discussed in paragraph 4.14. The flood warden could also pass details of blocked bridges and culverts together with local flood level data back to the DSD control room by telephone, thus helping to update the forecasts in real-time and assisting maintenance staff.

4.12 A further method of disseminating flood warnings and information on the status of flooding in general would be through use of a telephone "help-line". Throughout a flood event, staff at the DSD control room could produce a series of specific, detailed flood warnings on a relatively simple recording device linked to a telephone. The public could then telephone this number (or numbers perhaps) and listen to up-to-date information on flood status throughout the Indus Basin. The technology for such a system should not be difficult to achieve in Hong Kong as the HKTC is technically capable of supplying and supporting such technology.

4.13 The flood warning dissemination system proposed in our Interim Working Paper was too closely linked to the Territory-wide system of heavy rainfall and flood warning dissemination networks to be wholly effective for the Indus Basin. The revised warning dissemination system now proposed is believed to be more appropriate to the local situation that will result within the Indus Basin from operation of the pilot RTFF scheme. What is required is a series of paths of information which minimize as far as possible the inter-agency communication links which are prone to failure during emergencies, partly because of technology failures of telephone lines, but largely because of human error and institutional failings exacerbated by stress during the emergency. The system should be designed to operate with staff from the minimum number of Government agencies possible and should aim to communicate warnings to the public as rapidly as possible to permit them to react. Should the public choose not to react to a warning, there can be no blame attached to Government, whereas if a warning is not issued because of institutional failings, the public have a right to be concerned.

4.14 The pilot flood siren scheme currently being implemented as a task of the Phase II study will also provide a means of disseminating flood warnings generated by the pilot RTFF scheme. It is suggested that the sirens be triggered manually in response to warnings issued by the DSD duty staff in the RTFF flood control room. Whilst automatic triggering would be possible, as adopted for the pilot flood sirens, it is not recommended to be the sole method of operation for RTFF.

4.15 The proposal to have flood wardens as one primary means of communication combined with the telephone "help-line" should provide two alternative information paths to the public and at the same time permits feed-back from the public to DSD through the flood wardens. Experience in other parts of the world has shown that this two-way transfer of information is vitally important in ensuring that RTFF systems are an effective means of reducing flood damage.

4.16 The system described above should suffice for the common floods of low return period, but would not be fully adequate for rarer events. During the development of what appears to be a major flood, it may be necessary for the DSD duty officer to notify other Government departments such as the DECC, CAS, RHKPF, RHKAAF, FSD and so on. Details of this additional dissemination network have not yet been finalized, and indeed cannot be organized without detailed discussion with the various appropriate organizations. This task is best left until the decision to proceed with the pilot RTFF scheme has been taken in order to avoid confusion.

4.17 Ideally a third line of communication should be sought, preferably one less reliant on the public telephone system. The best possibility here might be to use radio communication links operated by either the RHKPF or the ACC, but again no discussions have been held with such bodies until the decision to proceed with the pilot RTFF scheme has been taken.

5. COST EFFECTIVENESS OF PROPOSED RTFF

Costs

5.1 The costs of the recommended RTFF system are broken down below:

Installation of additional telemetry		: $ 774,470
RTFF development fee		: $1,850,000
RFFS software		: $ 168,750
Production of educational pamphlets		: $ 50,000
TOTAL CAPITAL EXPENDITURE		: $2,843,220
Running cost of additional telemetry	(per year)	: $ 15,000
Software support	(per year)	: $ 27,000
Flood Wardens Duty Allowance	(per year)	: $ 100,000
TOTAL ANNUAL EXPENDITURE		: $ 142,000

5.2 As outlined in Section 3 additional telemetry includes the installation of a raingauge at Gallipoli Lines, and the installation of telemetry and a raingauge at the site of the Hok Tau water level gauging station. Based on the Hong Kong Telephone Company's estimates for line installation and estimates of equipment purchase these costs will be $766,470 for the Hok Tau site and $8,000 for the Gallipoli Lines site. The total ($774,470) is approximately a 50% increase on the cost of telemetry that will be installed throughout the northern New Territories for the purpose of flood reporting and data acquisition; the total cost of which is estimated at $1,382,840.

5.3 It will not be necessary to employ additional Government staff beyond those already identified as necessary for maintaining the telemetry and the stations that will be installed for data collection and flood reporting. The duties of running the RTFF system will presumably fall upon the staff within the Flood Control Unit. As this will be only an intermittent commitment, no additional resources are considered necessary and the marginal cost is zero.

Benefits Analysis

5.4 To determine the average annual benefit to be gained from the pilot RTFF scheme it is necessary to consider the benefits that will arise from flood warnings for floods of different recurrence interval, taking into account the probability of flood occurrence. An estimate of the benefits that will arise from an RTFF scheme requires first an estimate of the costs of flood damage.

5.5 Flood damage is usually categorized as tangible or intangible based on whether or not monetary values can be placed on the consequences of flooding. The tangible costs of flooding can be divided into direct and indirect damages. Direct damages arise from the physical contact of water with property or produce and comprise building fabric and contents damage and agricultural losses. Indirect losses are more difficult to quantify, but are those costs arising from the disruption caused by flooding. This includes traffic disruption, emergency service costs, industrial production losses and retail losses. Intangible losses include loss of life, personal stress and anxiety and ill-health. Intangible factors are influenced by both flood event and social characteristics.

5.6 The pilot RTFF scheme will produce some intangible benefits, which are not readily expressed in financial terms, the greatest of which is obviously the potential saving of lives. Although in recent years loss of life has been avoided the flooding following recent events (typhoons Warren and Brenda) has "emphasised how close some people came to serious injury or death as flood waters rose very quickly and flooded village areas, farm houses, and temporary structures without warning" (Reference 6). There will also be some reduction in anxiety and stress of people living in flood risk areas. Following typhoons Warren and Brenda there were some indications of public misgivings about the lack of flood protection within the Basin and the fact that no warnings were given. It is generally agreed that public expectations regarding levels of service are increasing. These could at least in part be met if reliable warnings were given.

5.7 In the past, assessment of flood damage in the Indus Basin has concentrated on agricultural losses which are reasonably easily assessed and can be determined, at least in part, from claims to the Emergency Relief Fund (ERF). Losses in other categories are much more difficult to quantify, since the detailed socio-economic data required is for the most part unavailable in Hong Kong. However, the Phase I study report (Reference 11) included estimates of flood losses arising from flooding caused by typhoons Warren and Brenda relating to property damage, agricultural losses and traffic disruption. Neither event was particularly severe and Table 2 lists the losses incurred. The estimates were based on standard UK practice, as outlined in Penning-Rowsell & Chatterton (Reference 12) and in the absence of an extensive Hong Kong socio-economic database numerous assumptions were made about social differences between Hong Kong and the UK.

TABLE 2

SUMMARY OF FLOOD LOSSES FOR TYPHOONS WARREN AND BRENDA

	Typhoon Warren ($ million)	Typhoon Brenda ($ million)
Property	3.2	0.5
Traffic	0.7	-
Agriculture	5.1	7.7
TOTAL	9.0	8.2

5.8 The damage estimates determined during the Phase I study for typhoon Brenda were those used in this study as the basis for determining the damage and hence benefits for floods with different return periods. Typhoon Brenda was chosen as the profile storm because it is the most recent event for which data is available and no flood alleviation schemes have been completed since it occurred. The flood mitigation scheme at Sheung Shui was substantially completed between 1988 and 1989 and consequently far fewer properties were affected in typhoon Brenda than in typhoon Warren.

5.9 Typhoon Brenda caused flooding over an area of some 270 ha in the Indus Basin. Flood extents were determined for floods with return periods of 2, 10 and 50 years from the flood extent maps published in the River Indus Study (Reference 6).

Property Damage

5.10 Flood warnings will not significantly affect losses arising from damage to building fabric but will enable some reduction in household contents damage. The damage reducing effects of flood warnings are generally greater for high rather than low flood stages. For example, research conducted in Australia (Reference 2) indicates that with a one hour warning reduction of potential damage to household property can be as high has 29% for a flood of frequency 1:25, 38% for a flood of frequency 1:50 and 43% for a flood of frequency 1:100. Even for floods with shorter return periods it is clear that with some warning simple damage prevention carried out by people does result in considerable damage reduction. It should be noted that the figures given above are presently the best information available, but relate to Australia where the situation is somewhat different to Hong Kong. However, as a starting point they are the best that can be obtained.

5.11 In most events householders will take some damage reducing action, such as moving smaller luxury items and valuable personal affects whether flood warnings are given or not. If it is estimated that in all cases even with no warning there would be a 5% reduction in household contents damage, then flood warning results in potential savings of 24%, 33% and 38% for each of the stated return periods respectively.

5.12 The above figures assume total population response. In reality this is unlikely to occur but communities which are aware of the hazard and have flood experience, usually have a reasonably high degree of preparedness and effective response. It is assumed that the regular flooding in the Indus Basin means local communities are generally well prepared and will implement standard procedures on receipt of a flood warning. In this study, savings of the order of 20%, 29% and 34% have been assumed for floods of return period 25, 50 and 100 years respectively. Estimated savings of 15%, 16% and 18% were assumed for floods of 2, 5 and 10 year return periods.

5.13 It is likely that over time and with practice flood warning dissemination and the operation of the responsible authorities will improve leading to increased efficiency and hopefully greater damage prevention. It is recommended that the preparedness of the authorities responsible for flood warning dissemination is maintained with regular liaison and review meetings and after-event debriefings.

5.14 Flooding in the Indus also causes damage to agricultural buildings and their contents. That is damage to machinery, feedstuffs, seeds, fertilizers and stored crops. Flood warnings would enable some reduction in contents damage through moving machinery to levels of safety (for example lifting equipment off the floor) and temporary flood proofing of buildings, for instance by sandbagging.

5.15 The number of buildings within the area of flood extent was determined for events with return periods of 2, 10 and 50 years, by transposing the flood extents published in the River Indus Study (Reference 6) onto 1:2,000 scale maps. The number of buildings included only those which would have a warning time exceeding one hour (refer to Figure 1). Buildings were divided into permanent and temporary structures. The vast majority of permanent structures are houses and for the purposes of this study it was assumed that all permanent structures were residential properties. Temporary structures are both low quality residential properties (shacks and squatter housing) and farm buildings.

5.16 Field surveys during the Phase I study showed that in areas affected by flooding some buildings are constructed on raised foundations. Consequently, for all floods no matter what the return period some buildings lying in the area of flood extent will have ground floors above the high water mark. In order to take this into account the number of structures not affected by flooding was assumed to be 50% of the total number located in the region of flood extent for the 1 in 2 year event and to be 20% of the total number located in the region of flood extent for the more extreme events. The difference in the reduction reflects the fact that more people will be aware of the risk from the more common 1 in 2 year event than are aware of the risk from the rarer events. Consequently, a greater proportion of the total number of structures will have been built to avoid the more common event than have been built to avoid the rarer events. The reductions were made for both permanent and temporary structures.

5.17 Field surveys during the Phase I study also showed that typically 20% of the older village houses are unoccupied. This reduction was therefore also made to the number of buildings, permanent and temporary, for all flood events.

5.18 Table 3 lists the flood extent and the number of permanent and temporary structures affected by flooding for the events of different recurrence intervals. No flood extent map exists for the 1 in 5 year event and consequently the area flooded and the number of structures inundated was determined by linear interpolation between the 2 and 10 year events.

5.19 It should be noted that although the extent of flooding resulting from typhoon Brenda is close to that of the 1 in 2 year event (273 ha and 330 ha respectively) several villages, notably Tsung Pak Long, Tai Tau Long and San Uk Tsuen are flooded during the 1 in 2 year event but were not flooded during typhoon Brenda. The total number of houses in these villages exceeds 400 and consequently the total number of structures we estimate to be affected by the 1 in 2 year event (510) is far greater than the 260 affected during typhoon Brenda.

TABLE 3

FLOOD EXTENT AND THE NUMBER OF STRUCTURES AFFECTED FOR EVENTS WITH DIFFERENT RETURN PERIODS

Flood Return Period (yrs)	Flood Extent (ha)	No. Permanent Structures Affected	No. Temporary Structures Affected
2	330	240	200
5	465	500	600
10	690	700	1050
50	940	1000	1400

5.20 The average losses incurred on residential properties as a consequence of flooding during typhoon Brenda was determined from the Phase I report. During typhoon Brenda 73 residential properties were flooded to varying depths and damage to individual properties was in the range $15,912 to $546. The mean value is $6,850. Research in the UK has shown that building fabric damage is usually in the range 20-50% of total household damage and in the Phase I study report it is assumed to be 25% of the total. Making the same assumption in this study the average household contents damage was taken to be $5,138 for flood events of all return periods.

5.21 In this study damage to temporary structure contents, whether agricultural or residential was estimated to be $35/m^2 and typical building size is assumed to be 25 m^2. This is the formula used in the Phase I report to determine average agricultural building contents damage. Thus average contents damage of the temporary structures is estimated to be $875. It is felt to be justifiable to apply the same average damage loss to both the agricultural and residential temporary structures because many of the people living in these houses have relatively low incomes and few expensive possessions.

5.22 It is recognized that during flood events most people will concentrate on saving personal property rather than agricultural building contents and consequently it was assumed that only 5% of losses would be saved as a result of RTFF. The same percentage saving was assumed for the temporary residential properties since many of these are single storey dwellings and the householders will have very little opportunity to save their possessions. Thus savings resulting from RTFF was assumed to be $44 for all temporary structures.

5.23 It should be noted that the total number of temporary structures estimated in this study is probably an under estimate since large structures shown on the maps probably comprise many buildings.

Agricultural Losses

5.24 Agricultural losses arise primarily from damage to and drowning of crops and loss of livestock (pigs and poultry) and fish. With the limited amount of flood warning that is achievable in the Indus Basin it will not be possible to either harvest or protect crops and so there will be no mitigation of these losses. Primarily, savings will therefore be made by moving or protecting livestock and fish.

5.25 The flooding caused by typhoon Brenda resulted in total agricultural losses, excluding agricultural building damage, of some $7.5 million of which $6.2 million was crops and $1.3 million was livestock and fish.

5.26 In this study it is assumed that either by moving livestock or by netting off fishponds, just 5% of livestock and fish losses can be saved given at least a one hour flood warning. Using this figure the effective saving that would have been achieved during typhoon Brenda is $65,000. Since the total area inundated during the typhoon was 273 ha the per hectare saving in the Indus basin is $238. This saving per hectare was assumed to be constant in order to determine the saving for the floods of different recurrence interval.

Traffic Disruption

5.27 Costs of road traffic disruption caused by flooding can be substantial. These costs arise in two ways; through additional marginal transport costs and through lost opportunity costs caused by delay. Additional marginal transport costs comprise additional fuel, oil and depreciation costs incurred in travelling further or at less efficient speed.

5.28 Flood warning will only serve to mitigate these losses in instances where people forewarned postpone a journey or find an alternative route such that the consequent economic loss is less than that which would have been incurred had no warning been received.

5.29 The approach to determining traffic disruption costs is outlined in the Phase I study report and is summarized as follows:

- determine alternative travel routes
- determine marginal cost of normal traffic flow on the normal route
- determine marginal cost of traffic flow on the diversion route, taking into account reduced speed and additional distance etc.
- calculate the difference in marginal costs
- calculate additional journey times and evaluate the cost of loss opportunity through delay.

5.30 During typhoon Brenda traffic losses throughout the northern New Territories were estimated to have cost $4.6 million. No breakdown of this figure is given, but the Phase I study report states that the pattern of road flooding was similar to that of typhoon Warren.

5.31 During typhoon Warren flooding affected several arterial routes in the Indus Basin but according to the Police this only resulted in delays on the Man Kam To Road, for which there was no appropriate diversion. The total cost of this disruption is estimated to have been $128,000. As a consequence of flooding, the power supply to the computer at the Lo Wu immigration post was interrupted and passport processing had to be carried out manually. This caused delays to passengers on the KCR over a 5 hour period. The cost of this disruption is estimated to have been $556,000. Total traffic disruption is therefore estimated to have cost approximately $700,000.

5.32 The rail disturbance that occurred during typhoon Warren is not common and could be avoided at minimal cost by floodproofing the Immigration Department power room. The flood extent caused by typhoons Warren and Brenda (283 and 273 ha respectively) are not much different to the flood extent of the 1 in 2 year flood (330 ha). Consequently losses arising from traffic disruption is estimated to be $128,000 for the 1 in 2 year event. For events of greater severity an arbitrary 1% increase was assumed for each year increase in return period.

5.33 For the most part the short warnings available in the Indus Basin will only allow savings to be made in a relatively small fraction of the journeys made. In many instances the losses incurred by people postponing journeys before they depart as a consequence of the warning will be nearly as great as they would have been had the journey been undertaken. It is therefore estimated that savings will probably be of the order of 10% of the total.

Summary and Benefit Analysis

5.34 Table 4 lists a breakdown of the benefits to be gained from RTFF for floods with different return periods.

TABLE 4

BREAKDOWN OF BENEFITS FOR A WARNING OF AT LEAST ONE HOUR IN THE INDUS BASIN

Flood Return Period (yrs)	Benefit Relating to Permanent Structures ($)	Benefit Relating to Temporary Structures ($)	Benefit to Agriculture	Benefit to Traffic Disruption ($)	Total ($)
2	185,040	8,800	78,540	12,800	285,180
5	411,000	26,400	110,670	13,814	561,254
10	647,500	46,200	164,220	13,824	871,744
50	1,490,000	61,600	223,720	18,944	1,794,264

5.35 In order to determine the average annual benefit to be obtained

5.35 In order to determine the average annual benefit to be obtained from RTFF it is necessary to take into account the probability of the events occurring in any given year. In effect it is necessary to determine the integral of the curve of benefits against probability. A simplified integration can be determined using the following equation:

$$E(B) = \sum_{i=1}^{n} p_i \, B_i$$

where : p_i is the probability of a flood within the increment i and i-1

B_i is the average benefit to be gained from RTFF in the interval i to i-1

E(B) is the expected annual benefit

n is the flood return period

5.25 Table 5 lists the annual average benefits of floods with different return periods and the cumulative total:

TABLE 5

THE AVERAGE ANNUAL BENEFIT FOR THE RTFF SCHEME

Item	Flood Frequency Return Period (yrs)	Exceedance Probability	Area Flooded (ha)	Benefit ($ million)	Interval Benefit $p_i B_i$ ($ million)	Cumulative Benefit ($ million)
					0.08	
1	2	0.5	330	0.3		0.08
					0.13	
2	5	0.2	465	0.55		0.21
					0.07	
3	10	0.1	690	0.9		0.28
					0.11	
4	50	0.02	940	1.8		0.39

The cumulative total gross benefit is calculated as : $390,000. This is the benefit based on 1989 prices. Assuming an inflation rate of 10% this is equivalent to $520,000 at 1992 prices. Thus the net annual benefit at 1992 prices, allowing for the annual costs of the pilot RTFF scheme ($142,000), is $378,000.

5.36 Although it is very difficult to quantify the intangible benefits that will occur as a consequence of a flood warning system it should be remembered that at present there is a general rise in the affluence of the population in rural areas of Hong Kong and this means that people are increasingly at risk in a flooding situation. Many people now face considerable financial setbacks as a consequence of flooding. The ERF scheme only provides assistance to restart, rather than compensation for loss and does not cover farmers costs. There is no agricultural insurance system in Hong Kong. Furthermore improvements in education and the spread of the media, mean that people are also more aware of their living environment and more likely to be critical of its management. It is therefore not surprising that the people in the villages of the Indus Basin expect something to be done with regard to the flooding problem in their area, especially when they witness the large investments in their vicinity, in the form of new towns. It is apparent that since people do want something to be done they will be ready and willing to act on flood warnings.

5.37 Techniques for appraisal of intangible flood losses are under development in the UK. Research to date indicates that people rate the intangible benefits of a flood warning at least as highly as the tangible benefits. Thus if a monetary value could be placed on the intangible benefits to be gained in the Indus Basin as a consequence of RTFF it would have to be of the same order as that associated with the tangible benefits, that is $520,000 (1992 prices).

5.38 If only the tangible of RTFF are considered and assuming a discount rate of 5%, then the estimated payback period of the proposed pilot RTFF scheme is about 10 years. This compares well with the Phase I (Reference 11) estimate of 7 years. If it is assumed that the intangible benefits are as great as the tangible benefits, the effective payback period is 4 years.

5.39 We feel that throughout this RTFF cost evaluation, the estimate of benefits to be gained from RTFF are fairly conservative. For instance the estimated reduction in household property damage is based on the assumption that people will get just one hours flood warning. While this simplifies the subsequent calculations it should be remembered that most of the properties further downstream of the line indicated on Figure 1 will get more than one hours warning and some may get two to three hours warning.

5.40 It should be noted that the design of the pilot RTFF scheme proposed is such that if the pilot scheme proves successful it would be fairly easy to transfer it to other catchments in Hong Kong for relatively little cost. All that would be required would be reconfiguration of the model network and installation of some additional telemetry. For instance it could be used on the Kam Tin basin, a catchment in which the financial losses arising from flooding are even greater than in the Indus basin. During typhoon Brenda property damage in Kam Tin is estimated to have been $2.8 million and agricultural losses were $6.2 million (Reference 11). Since the major savings arising from RTFF relate to building contents damage the potential savings in the Kam Tin Basin are obviously very great, and could be realized with a very small additional investment.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 The objectives of this stage I RTFF study were to report on the technical viability and cost-effectiveness of implementing an operational pilot RTFF scheme on the Indus Basin.

6.2 The technical viability of the proposed pilot RTFF scheme implementation is affected by a number of separate factors which may be grouped under the headings of:

- data collection,
- modelling, and
- dissemination of flood warnings.

6.3 The data collection topic includes telemetry, infilling missing data and data archiving. As has been explained, much of the data required for the pilot RTFF scheme for the Indus Basin is already telemetered, or will shortly be telemetered as part of the data acquisition task of the Phase II study. The only significant new telemetry input required just for RTFF is the suggested telemetry link to the Hok Tau gauge. The cost of this is some $750,000, and whilst the pilot RTFF scheme could operate without this input, it would be less effective than would be the case if Hok Tau were to be telemetered.

6.4 There will be sufficient rainfall inputs over the Indus basin itself to permit the pilot RTFF scheme to operate with many of the gauges inoperative through the use of the isopercentile method of estimating areal rainfall proposed. In an extreme case, the system could operate with only one raingauge, but the confidence of the resultant forecasts could be low. Similarly, the system will operate very satisfactorily with none of the river level or flow telemetry inputs operating provided that some occasional manual staff gauge readings were input to verify and update the model forecasts. Even with the absence of data from that part of the Shenzhen Basin draining the PRC, the proposed pilot RTFF scheme will provide a valuable insight into the flood situation throughout the Indus Basin during a flood.

6.5 Given that the SUNSPARC II workstation upon which the RTFF software will run is linked over a local area network to other SUNSPARC workstations, computer integrity could be provided by keeping a backup copy of the software on a second machine and by copying the hydro-meteorological database from the dedicated RTFF computer to the backup machine automatically every half to one hour. The weak link in the proposed pilot RTFF scheme is the mini-computer at the RO and the dedicated line between this and the SUNSPARC used for the RTFF system. Consideration might be given to provision of a duplicate line between the RO and the DSD SUNSPARC, however, it is difficult to provide absolute security for the RO mini-computer. Perhaps one option to be discussed with the RO during the implementation phase, would be that of copying incoming telemetry data to the RTFF SUNSPARC before it is written to the RO mini-computer. Because the telemetry comes from three separate networks operated by the RO, GCO and the new DSD system, it is possible that in real-time at least one of these would continue to operate.

6.6 It is suggested that there will be sufficient data to operate an operational RTFF system and that with the exception of the RO mini-computer, effective safeguards could be built into the system to avoid failure during a flood event. However, even given complete failure of the RO mini-computer, data read in the field by staff of DSD and other agencies could be input manually to the model to provide some backup forecasting capability.

6.7 It is suggested that the RFFS computer software recommended as the basis of the RTFF modelling is sufficiently well-proven in the UK to justify its use on the Indus Basin. It has already been applied to a range of operational RTFF systems. A version configured to meet the particular requirements of the Indus Basin could provide forecasts of level throughout the lower basin. There are a number of significant problems in adequately modelling the Indus Basin, particularly the absence of data from the PRC, the difficulty of forecasting storm surges, and the need to use simple probabilistic rainfall forecasts. These rainfall scenarios could in time be supplemented by weather radar data. However, the models proposed will enable the developing flood throughout the Indus Basin to be monitored and forecast in real time, thus enabling reduction in flood damage costs due to the timely issuing of flood warnings.

6.8 The pilot RTFF scheme proposed for the Indus Basin will only produce savings in flood damage costs if an effective flood warning dissemination programme is developed. Because the pilot RTFF scheme will provide information in real time during a flood which has not previously been available in Hong Kong, no such dissemination procedures yet exist. It will be necessary to develop a set of procedures specifically for the Indus Basin, with DSD providing the forecasts through the RTFF models proposed, but with warnings being issued to the public and various Government agencies through the RO, who have long had such a role of issuing similar strong wind and heavy rainfall warnings.

6.9 Further discussions between DSD, the RO, other Government departments and ourselves will be required during the pilot study, but it is suggested that the methods proposed in Chapter 4 could provide the basis of an effective dissemination system. A major programme of public education would be required, not just for those people who live and work within the Indus Basin, but to a lesser extent to those that travel through the basin. Disruption of road and rail communications is one of the inevitable consequences of flooding and can contribute significantly to the damage costs. Therefore the travelling public must be made aware of the colour-graded system of flood alerts and warnings planned such that they may avoid potentially wasted journeys through traffic disruption during periods of high flood risk.

6.10 It is suggested that although there are a number of recognized problems in implementing an operational pilot RTFF scheme for the Indus Basin, none of these problems is insurmountable and that the overall scheme is technically feasible. The proposed pilot RTFF scheme for the Indus could also easily be extended to other basins throughout the New Territories.

6.11 The cost of implementing the pilot RTFF scheme for the Indus is $2,843,220. The potential average annual savings in flood damage from having an effective RTFF scheme are estimated to be $378,000. Thus the estimated potential pay-back period for the investment is estimated to be about 10 years, for tangible benefits alone.

6.12 These cost-benefit calculations have not been able to take account of the savings that might accrue from the reduction in intangible costs, such as loss of life, risks to health, anxiety and distress, even though it has been suggested by some authors that these damage costs may be as high as those tangible costs such as damage to buildings and property. If one accepts that there must be some potential saving in these unquantified, but significant damage costs through the introduction of flood warnings resulting from RTFF, the cost-effectiveness of the proposed scheme must be better than presented.

6.13 The proposed pilot RTFF scheme will be very flexible and could easily be extended to cover other basins in the New Territories for modest additional costs on installation of hydro-meteorological stations and telemetry. Thus once the initial pilot study for the Indus has been completed, extension to the Kam Tin for example, where potential flood damage costs are even greater than on the Indus, would be relatively simple and inexpensive. Again, it is difficult to quantify accurately the savings from such an extension of RTFF, but it is clear that the potential damage reduction would be significant.

6.14 It is suggested that the proposed pilot RTFF scheme for the Indus Basin is cost-effective in its own right. If the additional potential savings due to reduced intangible flood damage cost savings are considered, the scheme becomes even more attractive. The system could also readily be extended to the Kam Tin basin, further enhancing the cost-effectiveness of the pilot study investment.

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APPENDIX A

THE RFFS SYSTEM

Engineers 1991, 8-10 July 1991, Loughborough University

A RIVER FLOW FORECASTING SYSTEM FOR REGION-WIDE APPLICATION

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INTRODUCTION

Since 1988 the Institute of Hydrology, under subcontract to Logica, has been engaged in the design and development of a River Flow Forecasting System (RFFS) for use by the Yorkshire Region of the National Rivers Authority. Whilst currently configured to make forecasts at over 100 sites in the Yorkshire Region the design of the system allows reconfiguration to any river network or set of networks without recoding. In addition, a modular and generic design allows use of a wide choice of hydrological and hydraulic forecasting models and river control algorithms. It is the purpose of this paper to review the general functionality of the hydrological kernel of the RFFS and to describe the models and associated algorithms incorporated in the Yorkshire implementation. Further information on the scope of the Yorkshire RFFS is contained in a companion paper for this conference by Cottingham and Bird. Also Moore et al (1990a) provide additional details of the design philosophy underpinning the System.

THE INFORMATION CONTROL ALGORITHM

At the heart of the RFFS is an algorithm which controls the flow of data required to make forecasts and which selects the model algorithms to be used in their construction. This is the Information Control Algorithm or ICA. A particular configuration of forecast points within a river system is described within the ICA by a set of description files. These files take two main forms:

(i) a Model Component file which defines the form of model structure and data inputs to be used to make forecasts for a particular location or set of locations; and

(ii) a Forecast Requirement file which defines for each forecast point the Model Component to be used to construct the forecast for that point, the type of forecast (eg. river level, flow, snowmelt) and the connectivity with other model components.

A Model Component is typically made up of a number of Model Algorithms, for example for snowmelt modelling, rainfall-runoff modelling and real-time updating. The model algorithms to be used are defined within the Model Component file description. Figure 1 illustrates a typical model component and its associated model algorithms and Figure 2 illustrates the connectivity between model components. This connectivity allows the ICA to represent river systems with complex dendritic structures including bifurcations.

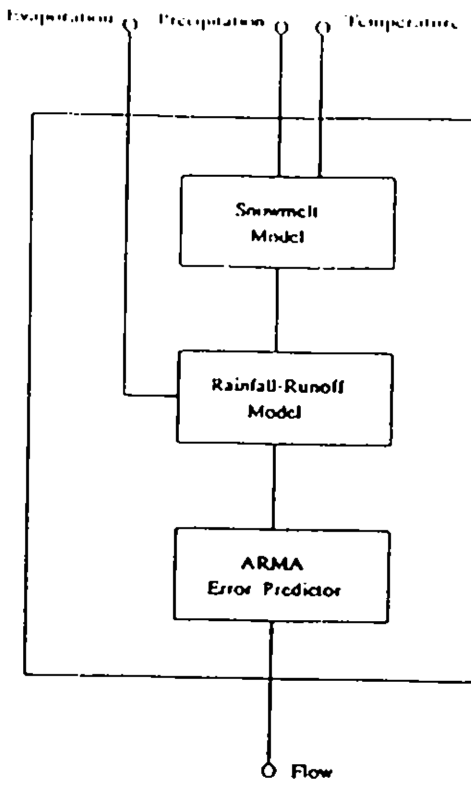

Figure 1 A model component and its associated model algorithms

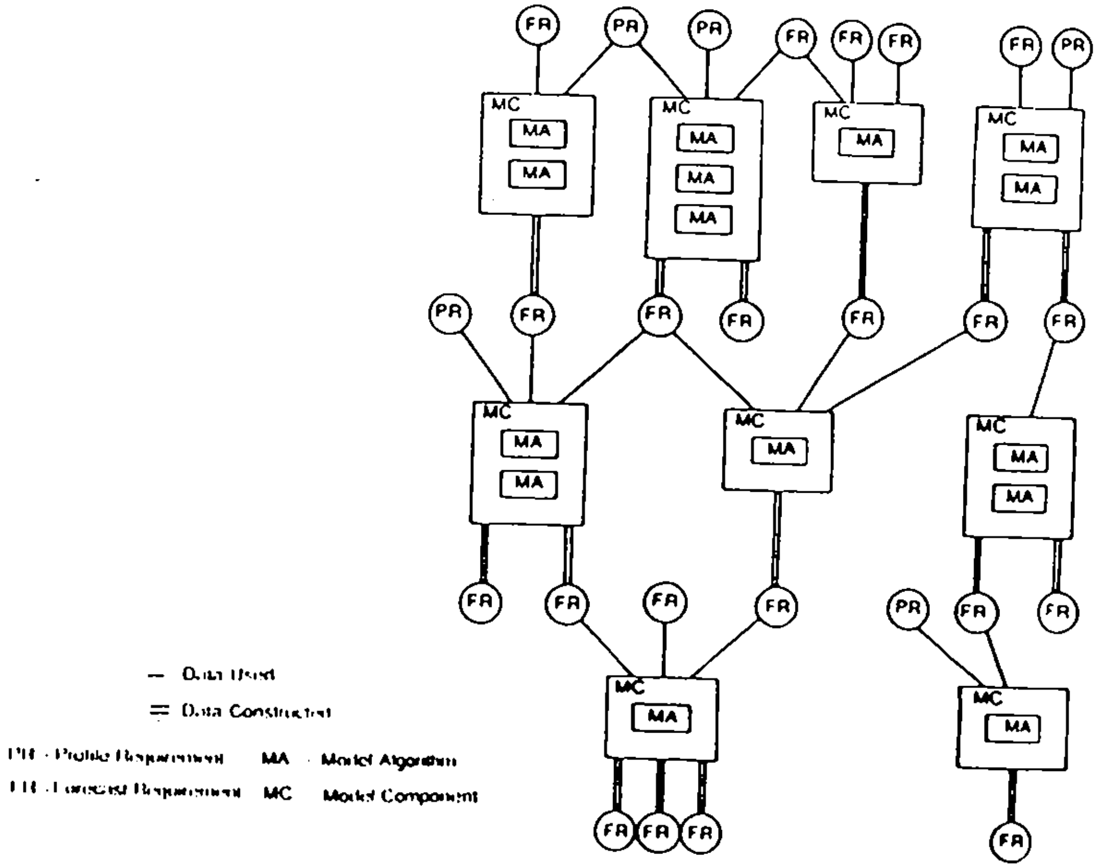

Figure 2 Connectivity between model components

The Model Algorithms are formulated within a generic subroutine structure which allows new algorithms to be coded and accessed by the ICA without recoding of the ICA itself. The generic structure is sufficiently general to allow algorithms of varying complexity to be coded. For example, algorithms can be as simple as calculating catchment average rainfall as a weighted average of raingauge data or may be as complex as ones which incorporate control rules for river gate settings as part of a hydraulic model of a tidal river.

Having constructed a set of Model Component and Forecast Requirement description files to define a structure for the particular forecasting problem, the ICA initially employs these to construct a file used to order the sequence of model component executions. This "order-of-execution" list need only be constructed once for a given forecast network configuration. Operational running of the ICA deploys this list to get the data it requires to make the forecast run and then to execute each model component. The ICA works down the tree network of the river system, in the order dictated by the list, so that forecasts of flow or level are used as input to the next model component downstream. At run time the lead time of the forecasts can be changed as well as various settings controlling the input used by the model components.

The ICA allows the user to dynamically define "subnetworks" within the overall model network configuration. These can be defined, for example, to only execute the non-tidal part of the model, or to execute a selected set of rapidly-responding catchments requiring a flash-flood warning, updated at frequent intervals. On completion of a forecast run the "states" of the models required to initialise a subsequent run are stored; the time selected for storing the states is usually 30 minutes before the present time to allow for delays in receiving telemetry data. The states will be typically the water contents of conceptual stores within snowmelt and rainfall-runoff models or the river levels and flows of channel flow routing models. A subsequent run at a later forecast time origin will start forecasting forwards from the time of storing the states from a previous run.

Operationally in non-flood conditions the system is run automatically once a day at about 7 am following routine data gathering by the Regional Telemetry System. This means that the model states are available to provide good initial conditions from which to run the model for a flood event occurring later the same day, thus avoiding the need for a long "warm-up" period for model initialisation. During flood events the system is run frequently under the control of the RFFS operator.

RFFS MODEL ALGORITHMS

Introduction

The model algorithms used within the ICA fulfil a range of functions. They can serve as simple utilities to set flows to a constant value, for example to represent a fixed compensation release from a reservoir, or to merge data from different sources according to a priority hirearchy to ensure that a data series required for forecasting is complete. The more conventional form of model algorithm performs some specific hydrological function such as rainfall-runoff modelling, channel flow routing, snowmelt modelling or hydraulic modelling of the tidal river. The particular forms of hydrological modelling algorithms implemented as part of the Yorkshire RFFS will be briefly reviewed in what follows.

The PDM: a rainfall-runoff model for real-time use

The Probability Distributed Model or PDM is a fairly general conceptual rainfall-runoff model which transforms rainfall and evaporation data to flow at the catchment outlet. Figure 3 illustrates the general form of the model. Runoff production at a point in the catchment is controlled by the absorption capacity of the soil to take up water: this can be conceptualised as a simple store with a given storage capacity. By considering that different points in a catchment have differing storage capacities and that the spatial variation of capacity can be described by a probability distribution, it is possible to formulate a simple runoff production model which integrates the point runoffs to yield the catchment runoff.

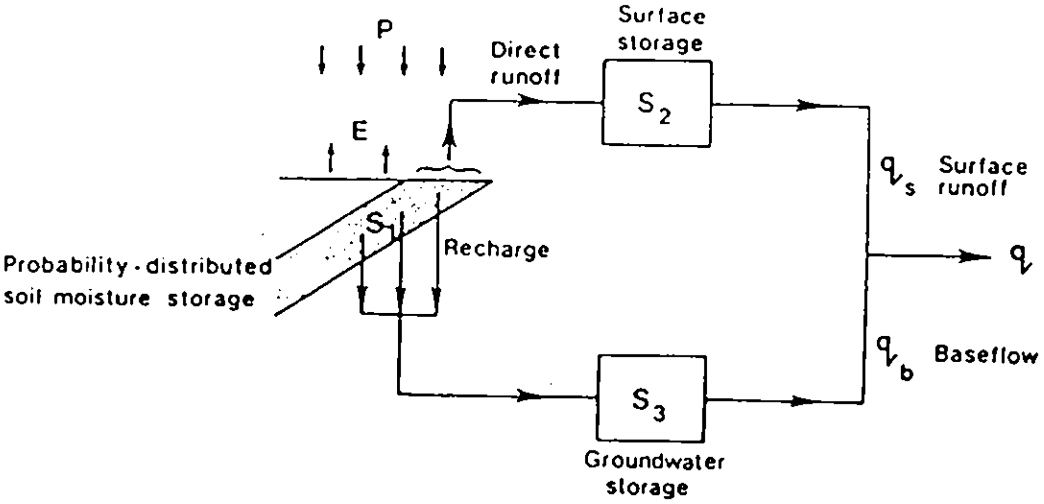

Figure 3 The PDM rainfall-runoff model

The probability-distributed store model is used to partition rainfall into direct runoff, groundwater recharge and soil moisture storage. Direct runoff is routed through a "fast response system", representing channel and other fast translation flow paths. Groundwater recharge from soil water drainage is routed through a "slow response system" representing groundwater and other slow flow paths. Both routing systems can be defined by a variety of nonlinear storage reservoirs or by a cascade of two linear reservoirs (expressed as an equivalent second order transfer function model constrained to preserve continuity). A variety of spatial distributions of store depth are available to define the probability-distributed store model. Alternatively the store model can be replaced by a simple proportional splitting rule for partitioning rainfall to follow surface and subsurface translation paths. A constant background flow can be included to represent compensation releases from reservoirs, or constant abstractions if negative.

The model is specifically tailored for real-time application. Facilities exist to correct the model forecasts in real-time, either by modifying the water contents of the conceptual stores or by augmenting the forecasts with an error predictor: these techniques are discussed later. Further details of the model structure deployed are contained in Moore (1985, 1986, 1988).

The KW model: a channel flow routing model for real-time use

The KW model is a generalised form of kinematic wave model which makes allowance for wave speeds to vary with discharge magnitude. In addition, storage functions are provided to represent flow into washlands to complement the modelling of in-bank flows. The basic form of the model is presented in Moore and Jones (1986) and Jones and Moore (1987). Water movement down a river channel is approximated by the kinematic wave equation with lateral inflow

$$\frac{\partial Q}{\partial t} + c\,\frac{\partial Q}{\partial x} = c\,q$$

where Q is channel flow, q is the lateral inflow per unit length of the reach and c is the wave speed. This is expressed in finite difference form as

$$Q_t^k = (1-c)\,Q_{t-1}^k + c\left[Q_{t-1}^{k-1} + q_{t-1}^k\right]$$

where Q_t^k is the flow at the k th node at time t and q_t^k is the lateral inflow into the k th section at time t-1. Node k is the downstream node of section k. The wave speed, c, is actually time varying, changing as a function of the observed flow at a particular node K. A choice of functions are available including a piecewise linear function over 3 or 4 segments as well as cubic and exponential parametric functions. An auxiliary threshold storage function can be applied, either at selected model nodes to represent overflow into washlands, or to observed lateral inflows to compensate for errors in the rating relationship, especially for out-of-bank flows. A number of forms of parameterised threshold functions are available.

The use of a variety of parametric functions to define the model form is particularly useful for real-time application to large, complex river basins where the use of survey data would be expensive in time or survey data may not be available. However, a tabular form of wave speed-discharge relationship can be used if survey data are available to infer the relation from hydraulic principles (Institute of Hydrology, 1990) and if this method is preferred. Calibration of the parametric model functions is accomplished using the RFFS Model Calibration Facilities discussed later.

PACK: the Pragmatic Snowmelt Model

This model was originally formulated under contract to the Severn Trent Water Authority (now the NRA Severn Trent Region) with additional support from the Ministry of Agriculture Fisheries and Food (Harding and Moore,1988). The snowmelt process is represented in simplified terms using a snow store and a melt store to represent the snow pack storage. Melting of the snow store is controlled by a simple temperature index equation; this could be readily extended to incorporate turbulent heat exchange through the addition of a wind velocity term if required. The resulting melt enters the melt store where it is released slowly from its base. A second higher orifice allows release of water from the pack (snow and melt water) at a higher rate. The height of the orifice varies with the total water equivalent of the pack. This serves to represent the rapid break-up of the pack as a critical liquid water content is reached. A schematic of the structure of the PACK model is shown in Figure 4. An additional component is included to allow for incomplete spatial coverage of snow over a catchment for shallower, older packs. This employs an areal depletion curve to calculate the proportion of the catchment covered by snow, allowing some rain to fall on snow-free ground and effectively enter the rainfall-runoff model directly.

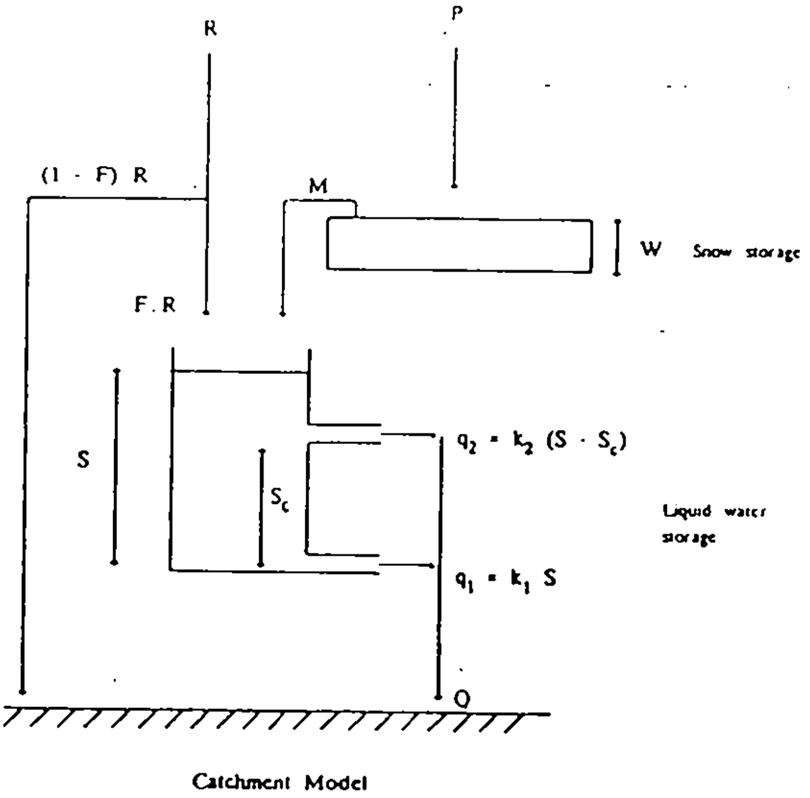

Figure 4 The pragmatic snowmelt model

Two forms of the snowmelt algorithm exist within the ICA. The first is used in "point form" at snow survey sites and excludes the areal depletion curve. This is used to obtain errors between the model snowpack water equivalent and the surveyed amount. These errors are transferred to the the "catchment form" of the model to adjust catchment snowpack water equivalents.

The Hydraulic Model used for tidal river modelling

The hydraulic model incorporated in the ICA is based on the United States National Weather Service's DWOPER/NETWORK program (Fread, 1985) which employs a four-point implicit scheme to solve the Saint Venant equations. However, the code has undergone substantial modification to conform with the generic structure required of an ICA model algorithm, to operate in a real-time environment and to extend its functionality. These extensions include modelling of "static washlands", coping with general multi-branched channel trees and not just a simply-branched single main channel, allowing a "network" or braided channel to form a branch of a tree rather than treating the whole channel structure as a single network (this simplifies the setting up of data structures and can save execution time), more flexible specification of data required for a modelling problem, improved extraction of channel geometry data, and computational refinements to achieve faster execution. The option to model pipes and sewers has been removed. The Hydraulic Model algorithm has also been extended in the Yorkshire RFFS implementation to incorporate a predefined rule for gate operation of Barmby Barrage which serves to inhibit incursion of salt and sediment laden water of the tidal Ouse up the River Derwent.

The ARMA Error Predictor Algorithms

Two forms of updating of model forecasts to incorporate information from the most recently telemetered values of river level and flow are available within the RFFS. The first is state correction which has been briefly discussed in the context of the PDM rainfall-runoff model; at present this form of updating is only available for this model. Both the KW channel flow routing model and the Hydraulic Model employ an ARMA (AutoRegressive Moving Average) model as the basis of updating. This technique exploits the dependence seen in model errors, with runs of overprediction and underprediction being common. The ARMA model structure characterises this dependence through a weighted combination of past model simulation errors and one-step ahead updated forecast errors. The result is a prediction of the future errors which are added to the model simulation forecasts to form updated forecasts for different lead-times. Extensions to the normal form of ARMA error predictor incorporated in the RFFS are a logarithmic form, in which proportional errors are treated rather than the normal additive ones, and a multiple time series form. The latter is applied as a single model algorithm to the error series from the Hydraulic Model for multiple level recording sites along the tidal River Ouse.

MODEL CALIBRATION FACILITIES

A comprehensive range of facilities are provided within the RFFS to calibrate the above models using observed data. Calibration facilities for the PDM rainfall-runoff model, the KW channel flow routing model and the PACK snowmelt model share a common Calibration Shell Program. This shell essentially provides a framework within which any time series model may be optimised (ie. parameters of the model are estimated to minimise a prescribed objective function which makes the modelled time series approximate the observed) and model performance assessed. The shell can also be used to incorporate new models to allow model development to proceed in an efficient manner. A modified form of the Nelder and Mead simplex, or polytope, method is used for optimisation (Nelder and Mead, 1965; Gill, Murray and Wright, 1981). The program may be used in the normal optimisation mode, or to generate plots and statistics to assess the performance of a given model or to generate a response surface plot showing how a pair of parameters affects the value of the objective function. The latter is used to reveal any interdependence between model parameters which may degrade the search for an optimal parameter set. An example of a plot used for performance assessment is shown in Figure 5.

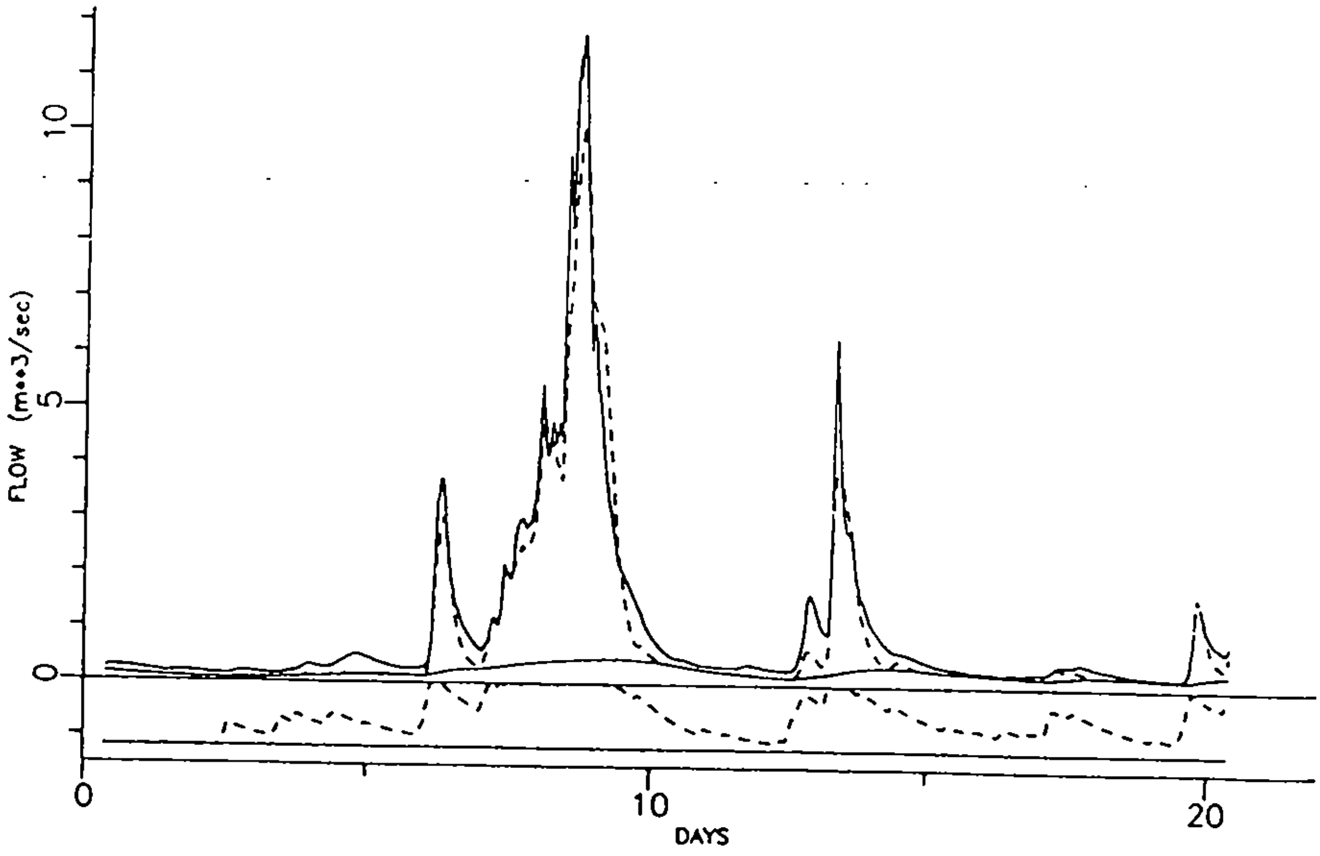

Figure 5 Calibration result for the PDM rainfall-runoff model applied Snaizeholme Beck at Low Houses (Upper dashed line: total forecast flow; Lower continuous line : baseflow forecast; Lower dashed line: soil moisture deficit)

A separate Transfer Function Noise (TFN) Modelling System is provided to support general exploratory data analysis prior to formal modelling. It is also used to identify the "pure time delay" between rainfall and the first significant response at a flow gauging station needed as a parameter within the PDM rainfall-runoff model. The TFN Modelling System incorporates modules for correlation function analysis and fitting of transfer function and ARMA models (Box and Jenkins, 1970). The latter are used to construct error predictors for the KW channel flow routing model forecasts to achieve improved performance in real-time, through the incorporation of the most recently telemetered values of flow.

Whilst the Hydraulic Model has no automatic optimisation facility a mode of running is provided for use in model calibration. Performance statistics, including pooled statistics over a set of sections where river level measurements are observed, are complemented by graphical displays of observed and model simulated levels.

SYSTEM RESILIENCE, MERGING ALGORITHMS AND PROFILE DATA

A requirement of the RFFS Specification was that the flow forecasting system be resilient to data loss. This is accomplished for a point "internal" to the network by ensuring that the model component which constructs forecasts for the point will also infill missing values in the past data. For "external" points, typically rainfall and other forms of climate data, model algorithms are used to merge data time series from a variety of sources. In the event of no data being available provision is made to supply a backup pofile. A hirearchy of priority of data source can be imposed in the case of data being available for a given time from more than one source. For example, in the case of rainfall the priority for a given catchment rainfall might be radar data from Hameldon (the North West radar), radar data from Ingham (the Lincoln radar), raingauge data from n raingauges and then any combination of less than n (allowing for raingauge system malfunction), and a backup rainfall profile. For future times when no observation data are available the priority might be a Local Radar Rainfall Forecast (not currently available but see Moore et al, 1989, 1990b), FRONTIERS forecasts and synoptic forecasts (provided in the Yorkshire RFFS automatically to the modelling computer by a computer/telex facility from Leeds Weather Centre) and finally the backup rainfall profile. The rainfall profiles in the Yorkshire RFFS are seasonally dependent and categorised into light, moderate and heavy with the option of invoking a selection at run time. They are also subdivided into seven synoptic regions over Yorkshire: these correspond with the regions adopted for the synoptic forecasts provided by Leeds Weather Centre.

Another important use for profiles within the RFFS is to provide boundary conditions for the tidal hydraulic model. Astronomical tidal predictions supplied by the Proudman Laboratory are stored as 15 minute values in profile form. These are augmented by tide residual forecasts supplied by the Storm Tide Warning Service by Fax and entered manually into the RFFS. Other uses for profiles are for potential evaporation and temperature to support rainfall-runoff and snowmelt modelling.

THE OPERATIONAL SYSTEM FOR THE YORKSHIRE REGION

The Yorkshire RFFS has been configured to make forecasts at 115 forecast points on the Ouse river network and other river networks within the 13,500 km^2 of the NRA Yorkshire Region. This has required the specification of 208 Forecast Requirement and 89 Model Component files. A total of 16 model algorithms are used and there is a requirement for 49 profiles. There are 1578 state variables of which 488 relate directly to the Hydraulic Model of the tidal Ouse. The configured Yorkshire RFFS awaits completion of the Regional Telemetry System but it is expected to become operational on a trial basis in the Autumn of 1991. Figure 6 shows a forecast produced by the system operated in a mode which accurately mirrors how the system will be operated in real-time: the lower forecast is based on observed data only up to the forecast time-origin and backup profile data beyond this, whereas the upper forecast assumes perfect knowledge of future rainfall. This points to the importance of rainfall forecasts for headwater catchment rainfall-runoff modelling for extended lead-time forecasts; however, this importance diminishes further down the river network when the natural lag time in the river system, observations of river level and the relatively good accuracy of channel flow routing models make forecasts more accurate and resilient.

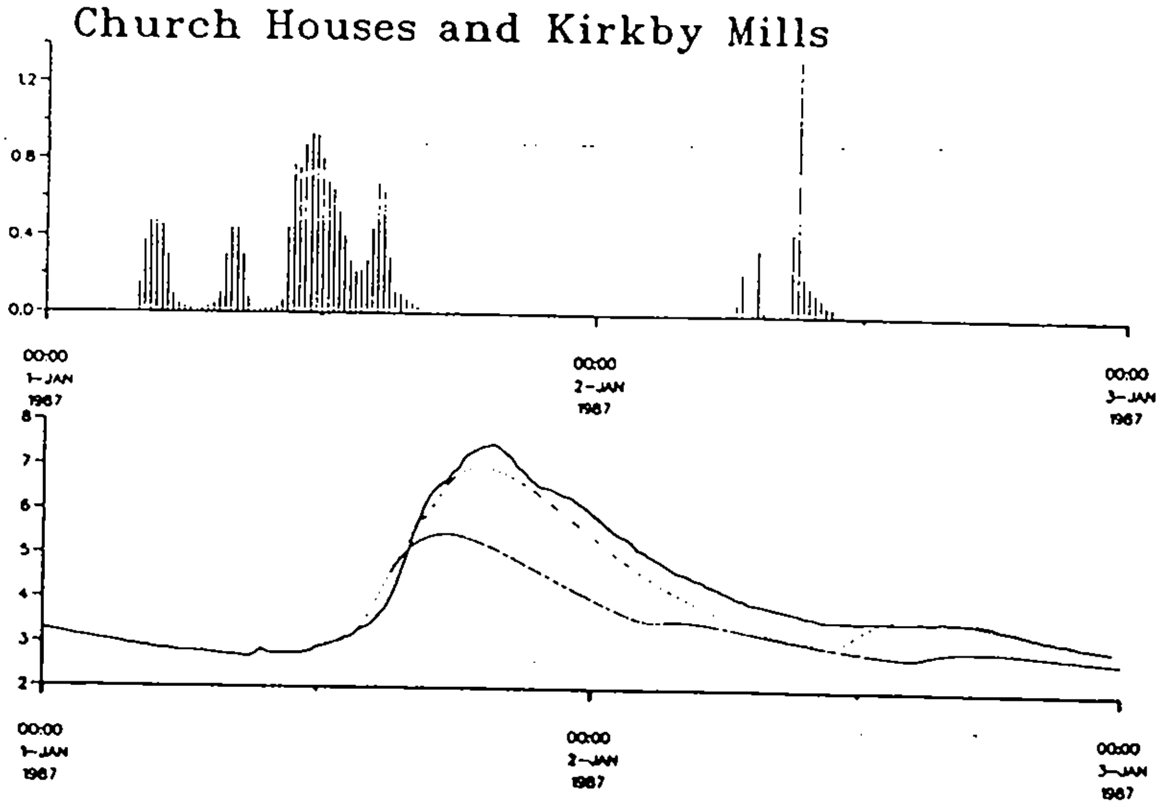

Figure 6 Flow forecast for the River Dove at Kirkby Mills using Church Houses rainfall: the upper forecast assumes perfect foreknowledge of rainfall whereas the lower forecast is based only on observed rainfall up to 12:00 1 January 1987 and a backup rainfall profile after this.

CONCLUSION

The flexible system design of the RFFS, realised through its Information Control Algorithm, makes it ideally suited for application elsewhere within the National Rivers Authority, to other areas of the UK and overseas. Reconfiguration to another river network is achieved externally to the program code through a set of system description files. The generality of the models provided with the System should prove to be applicable elsewhere but if this is not the case, or other models are preferred, then the generic model algorithm structure will readily accomodate new models or control algorithms. This vision of adaptability in the design of the System is expected to prolong the life of the RFFS well beyond the year 2000.

ACKNOWLEDGEMENTS

Funding received from the Flood Protection Commission of the Ministry of Agriculture, Fisheries and Food in support of the Institute of Hydrology's long term research programme on Real-Time Flood Forecasting is acknowledged as playing a major role in underpinning the RFFS model development at IH. Thanks are due for the financial support of the NRA Yorkshire Region and to the staff of the Region and of Logica who have been engaged in the Yorkshire RFFS project.

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APPENDIX B

THE PDM MODEL

Hydrological Sciences - Journal - des Sciences Hydrologiques, 30, 2, 6/1985

The probability-distributed principle and runoff production at point and basin scales*

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ABSTRACT The probability-distributed principle in basin-scale hydrology considers the frequency of occurrence of hydrological variables (model inputs, parameters or elements) of certain magnitudes over the basin without regard to the location of a particular occurrence within the basin. The random assemblage of different parts is considered more important than the relation of the parts, one to another. Rainfall-runoff models based on probability-distributed infiltration capacity and storage capacity concepts, and which generate runoff according to Hortonian and saturation overland flow mechanisms respectively, are distinguished. Two types of probability-distributed storage capacity model are identified, one based on an assumption that storage elements at points in the basin respond independently of their neighbours, and the other where storage elements interact so as to equalize the depth of stored water over the basin. Allowing redistribution of water leads to simplification of the model equations. The probability-distributed principle is also used to represent the process of water translation through the basin. Interpretation of the instantaneous unit hydrograph as a probability density function of translation time is demonstrated and the inverse Gaussian density proposed as a suitable functional form on physical grounds.

Le principe de la distribution des probabilités et la production d'écoulement en un point et à l'échelle d'un bassin

RESUME Le principe de la distribution des probabilités dans l'hydrologie à l'échelle d'un bassin considère la fréquence de l'occurrence des variables hydrologiques (telles que les entrées dans un modèle, les paramètres ou éléments) de grandeurs données sur toute l'étendue du bassin sans regarder l'endroit où a pu être observée une occurrence particulière à l'intérieur des limites du bassin. L'assemblage au hasard des différentes parties est considéré comme plus important que le rapport de chaque partie, l'une avec l'autre. On souligne

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Paper presented at the Anglo-Polish Workshop held at Jablonna, Poland, September 1984. (See report in Hydrological Sciences Journal vol. 30, no. 1, p. 165.)

l'importance des modèles précipitation-débit basée sur les capacités de l'infiltration distribuées suivant une loi de probabilité donnée et les concepts de capacité d'emmagasinement, et qui produisent l'écoulement conformément aux mécanismes de ruissellement décrits par Horton et de ruissellement de surface lors de la saturation. On identifie deux types de modèle de la capacité d'emmagasinement distribuée suivant une probabilité donnée: un modèle est basé sur l'hypothèse que les éléments de mise en réserve aux divers points du bassin donnent une réponse indépendamment de leurs voisins, et l'autre modèle présente des éléments d'emmagasinement qui réagissent l'un sur l'autre afin d'équilibrer la hauteur de l'eau emmagasinée sur toute l'étendue du bassin. Grâce à la redistribution de l'eau on arrive à une simplification des équations de modèle. On utilise aussi le principe de distribution des probabilités pour représenter le processus de transfert de l'eau à travers le bassin. On montre une interprétation de l'hydrogramme unitaire instantané comme fonction de la densité de probabilité du temps de transfert et on propose la densité inverse gaussienne comme forme fonctionnelle bien adaptée pour des raisons physiques.

INTRODUCTION

The conventional approach adopted for modelling hydrological processes is either one based, where possible, on physical laws, or one which invokes a simplified conceptualization of river basin dynamics. The first approach is usually termed physically-based distributed modelling, and the second conceptual modelling; in contrast to the distributed nature of the former, the latter provides a lumped description of river basin behaviour. Physically-based distributed models are rarely entertained for operational applications, such as real-time flood forecasting, on account of their inherent complexity. Shortcomings of the simplified lumped conceptual approach suggest, however, that models of intermediate complexity should be sought which take some account of the spatial variations of hydrological quantities over the basin. One such approach is based on the probability-distributed principle.

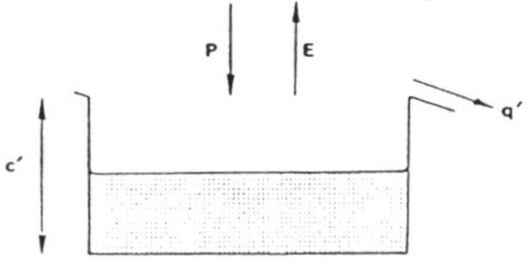
Whereas physically-based models attempt to take account of the actual spatial configuration of hydrological variables over a basin, those based on the probability-distributed principle consider only the frequency of occurrence of hydrological variables of certain magnitudes over the basin without regard to the location of a particular occurrence within the basin. By first characterizing the runoff production process at a point within the basin, probability distributions describing the spatial variation of process parameters over the basin are used to derive algebraic expressions for the integrated flow response from the basin. To make the probability-distributed approach analytically tractable, it is necessary to employ simple representations of the runoff production process operating at a point and of the nature of the interactions between neighbouring points. Two forms of point-runoff production will be considered, one based on the storage capacity concept and the other on the concept of infiltration capacity. In the case of probability-distributed models developed according to the storage capacity concept, distinctions are drawn according to the nature of the interaction between storage elements. Finally, application of the probability-distributed principle to translation of water to the basin outlet leads to a probabilistic interpretation of the instantaneous unit hydrograph and discussion of an appropriate functional form.

PROBABILITY-DISTRIBUTED MODELS OF STORAGE CAPACITY

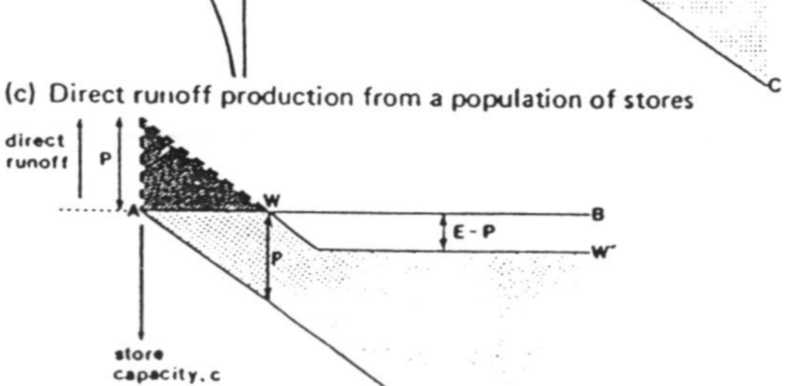
Theory of non-interacting storage elements

Consider that the process of moisture storage (possibly both interception and soil moisture storage) at any point in a river basin may be represented by a simple store or reservoir, characterized by its depth or capacity, c' (Fig.1(a)). The depth

(a) Point representation of runoff production by a simple store



(b) Basin representation by storage elements of different depth and their associated probability density function



(c) Direct runoff production from a population of stores

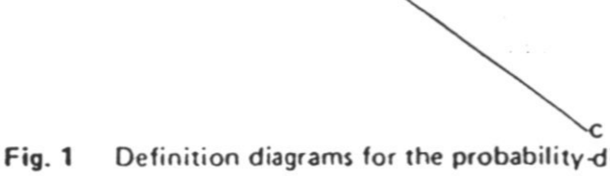


Fig. 1 Definition diagrams for the probability-distributed non-interacting storage capacity model.

of water in storage is increased by rainfall, P, is depleted by potential evaporation, E, and when rainfall exceeds the storage capacity, c', generation of direct runoff, q', occurs. A river basin may be considered to be made up of many such storage elements, each one characterized by its store depth, c, and acting independently of neighbouring storage elements so that no water is transferred between elements (the importance of this independence assumption will be discussed later when the effect of allowing water to redistribute across storage elements is considered). As a consequence, the store depth, c, may be viewed as a random variate with probability density function, f(c), so that the proportion of stores in the basin with depths in the range (c, c + dc) will be f(c)dc.

If stores of all possible different depths are arranged in ascending order of depth from left to right and with their open tops positioned at the same horizontal level, then a wedge-shaped diagram results if lines AB and AC are drawn through the store tops and bottoms respectively (Fig.1(b)). Note that this diagram does not represent the statistical population of stores, but stores of different depth; it will be used to establish the water level profile across stores of different depth resulting from a sequence of wet and dry periods. The probability of occurrence of stores of a particular depth is specified through the density, f(c), and is displayed alongside the wedge-shaped diagram in Fig.1(b).

Now consider the basin to be saturated following a prolonged wet period so that all storage elements are full, and evaporation then occurs at a rate E. At the end of a unit time interval the water level profile will be as shown in Fig.1(b). If rainfall, P, occurs in the next unit time interval, then the water level at the end of this interval will be that depicted by the line AWW' in Fig.1(c). The hatched triangular area indicates the volume of direct runoff produced in the interval as a result of store capacities of increasing depth being progressively replenished and starting to spill. The actual volume generated must be obtained by weighting runoff generation from a store of a given size by its probability of occurrence as specified through the density, f(c). This procedure will be developed next.

At the end of the unit interval, all stores of capacity less than P will be contributing direct runoff; the critical capacity below which all stores are full at some time, t, will be denoted by $C^* \equiv C^*(t)$, and in this example $C^*(t) = P$. The proportion of the basin occupied by stores with depths less than or equal to $C^*(t)$ will be:

$$\text{prob}(c \le C^*(t)) = F(C^*(t)) = \int_0^{C^*(t)} f(c)\,dc \qquad (1)$$

in which the function F(.) is the distribution function of store depths, and is related to the density function through the relation $f(c) = dF(c)/dc$. Since $F(C^*(t))$ defines the saturated proportion of the basin, it follows that the contributing area of direct runoff generation from a basin of area A is:

$$A_c(t) = F(C^*(t))\,A \qquad (2)$$

The instantaneous rate of runoff generation per unit area from the entire basin, $q(t)$, is obtained by multiplying the net rainfall rate, denoted by $\pi(t)$, by the proportion of the basin which is saturated, so that:

$$q(t) = \pi(t)\, F(C^*(t)) \tag{3}$$

Considering the i-th wet interval, $(t, t + \Delta t)$, during which time the net rainfall rate is constant and equal to $\pi_i = P_i - E_i$, then the critical capacity will increase according to:

$$C^*(\tau) = C^*(t) + \pi_i(\tau - t), \qquad t \leqq \tau < t + \Delta t \tag{4}$$

and the volume of basin direct runoff per unit area generated in this interval will be:

$$\begin{aligned} V(t + \Delta t) &= \int_t^{t+\Delta t} q(\tau)d\tau = \int_t^{t+\Delta t} \pi_i\, F(C^*(\tau))d\tau \\ &= \pi_i \int_t^{t+\Delta t} \int_o^{C^*(\tau)} f(c)dc\, d\tau \\ &= \int_{C^*(t)}^{C^*(t+\Delta t)} F(c)dc \end{aligned} \tag{5}$$

The evolution of the water profile across stores of different depth as a consequence of a series of net rainfalls, $\pi_i = P_i - E_i$, in successive unit time intervals, $i = 1,2,3,\ldots$, falling on an initially saturated basin, is illustrated in Fig.2. A number of horizontal (or deficit) segments, $D_k \equiv D_k(t)$, and sloping (or

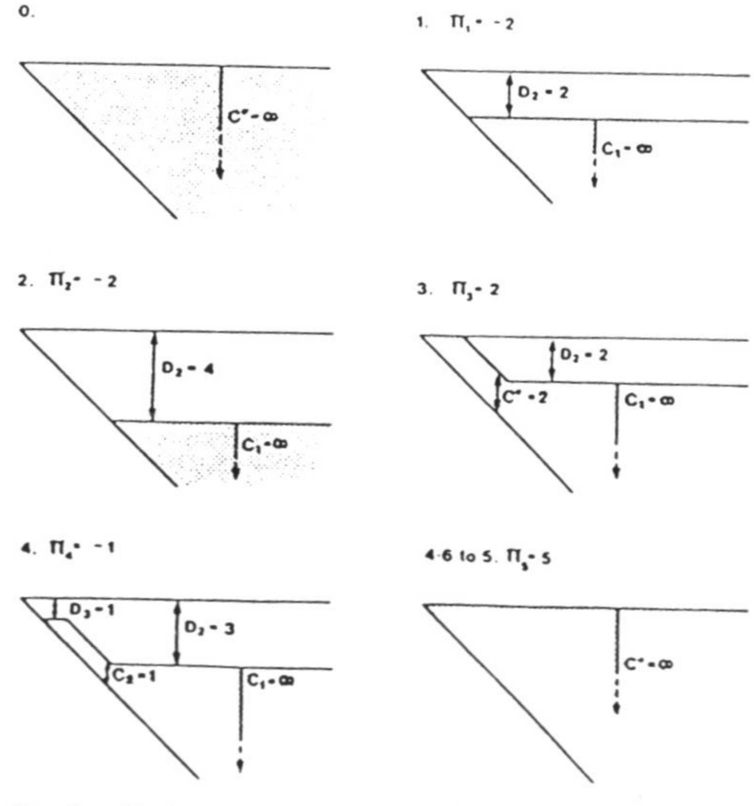


Fig. 2 Evolution of the water profile across non-interacting stores of different depth in response to net rainfalls, $\pi_i = (-2, -2, 2, -1, 5)$, falling in successive unit time intervals on an initially saturated basin.

content) segments, $C_k \equiv C_k(t)$, are formed across the assemblage of stores as a result. Instantaneous direct runoff, $q(t)$, resulting from this series of net rainfalls is controlled solely by the temporal evolution of $C^*(t)$ over this period, and may be calculated using equations (3) and (4) for an appropriate distribution of store depths. The critical capacity, $C^*(t)$, will vary according to (4) during a wet interval. However, whereas the interval, Δt, is usually taken to be the measurement interval of rainfall, it may be less if a deficit segment is replenished during this time. For example, in the interval (4,5) in Fig.2, at time 4.6 the critical capacity $C^*(t)$ jumps abruptly from 3 to ∞ as the deficit segment is fully replenished, so two intervals, (4,4.6) and (4.6,5) must be used. Also, if the density, $f(c)$, is bounded to the right by c_{max}, the maximum store depth (as would be the case for triangular or power distributions), and $C^*(t + \Delta t)$ would exceed c_{max} according to (4), then Δt must be chosen when $C^*(\tau)$ first equals c_{max}, and $C^*(\tau) = c_{max}$ used over the remainder of the rainfall sampling interval. It will be understood that integrals developed later involving an infinite upper limit on c should be replaced by c_{max} in the case of right-bounded density functions.

Expressions describing the volume of distributed soil moisture over the basin as a whole will now be developed. The total storage available in the basin is given by:

$$S_{max} = \int_0^\infty c\, f(c)dc = \int_0^\infty (1 - F(c))dc = \bar{c} \tag{6}$$

which by definition is equal to the mean store depth, $\bar{c}$, over the basin; here, S_{max} is expressed as water depth over the basin. By considering each horizontal deficit segment and sloping content segment in turn across the water level profile, AWW', in Fig.3, a general expression for the actual basin soil moisture deficit at at any instant in time is obtained:

$$SMD(t) = \underbrace{\Sigma_{i=2}^{k} \int_{C_i+D_{i+1}}^{C_i+D_i} (c - C_i) f(c)dc}_{\text{sloping}} + \underbrace{\Sigma_{i=3}^{k} \int_{C_i+D_i}^{C_{i-1}+D_i} D_i f(c)dc}_{\text{horizontal}}$$

$$+ \underbrace{\int_{C_2+D_2}^{\infty} D_2 f(c)dc}_{\text{last horizontal}} \tag{7}$$

Here $D_{k+1} = C_k = 0$. It follows from equations (6) and (7) that the basin soil moisture storage is:

$$S(t) = S_{max} - SMD(t) \tag{8}$$

and continuity gives the actual evaporation over the i-th interval, $(t, t + \Delta t)$, as:

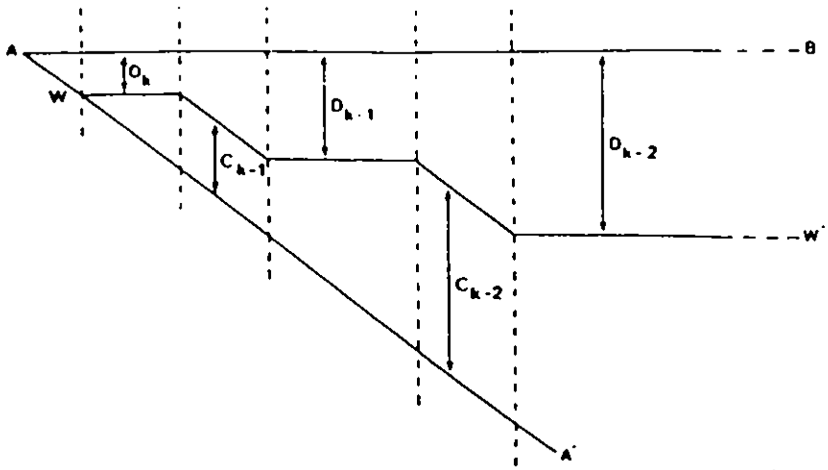


Fig. 3 Definition diagram for deriving expressions for basin soil moisture storage, soil moisture deficit, actual evaporation and drainage for the probability-distributed non-interacting storage capacity model.

$$E'_i = \begin{cases} S(t) - S(t + \Delta t) & P_i = 0 \\ E_i \Delta t & P_i \geq E_i \\ P_i \Delta t + S(t) - S(t + \Delta t) & 0 \leq P \leq E_i \end{cases} \tag{9}$$

Using $D^* \equiv D^*(t)$ to denote the depth of the minimum deficit segment (i.e. $D^* = D_k$), the instantaneous rate of actual evaporation at time t, when $\pi(t) = P_i - E_i$, is:

$$E'(t) = \begin{cases} E_i \int_{D^*(t)}^{\infty} f(c)dc & P_i = 0 \\ E_i & P_i \geq E_i \\ P_i + (E_i - P_i) \int_{D^*(t)}^{\infty} f(c)dc & 0 \leq P_i \leq E_i \end{cases} \tag{10}$$

Figure 4 illustrates the relationship between the ratio of actual to potential evaporation and soil moisture deficit that results from assuming store depths to be distributed according to either exponential or lognormal distributions. The range of relationships provided by these functions appears to be reasonably realistic, bearing in mind other relationships presented in the literature based on experimental data (see, for example, Fig.4 of Moore & Clarke, 1982). Explicit dependence of actual evaporation from an individual storage element on its moisture deficit through a specified functional relation would lead to the horizontal and sloping water level profile in the wedge-shaped diagram becoming curved, and the probability-distributed theory would become analytically intractable. This presents an important shortcoming of the approach. The problem may be circumvented, although at some cost in terms of representing reality, by assuming that actual evaporation varies as a function of basin soil moisture deficit as expressed by equations (8), (7) and (6). This problem will be discussed further when redistribution of water between stores is considered.

An extension of the approach is possible to allow for drainage to baseflow. By considering now that a storage element is open at the bottom allowing drainage to occur at a constant rate, γ, until

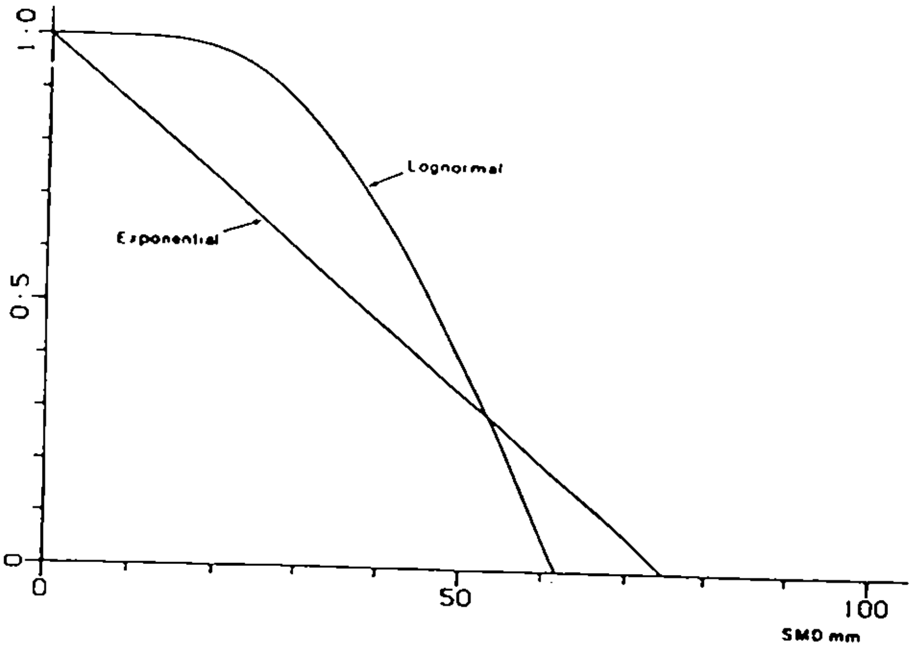


Fig. 4 Relation between the ratio of actual to potential evaporation, E'/E, and soil moisture deficit, SMD.

the store empties, then the instantaneous drainage rate, $b(t)$, from the population of storage elements at time, t, can be calculated as follows. Consider first of all a dry period. At some time t during this dry period let the water level surface across the population of stores be as depicted by the line AWW' in Fig.3. Drainage occurs at the instantaneous rate γ from all stores containing water, that is from all stores of depth greater than $D_k = D^*(t)$. The instantaneous drainage rate from the basin at time t, is therefore:

$$b(t) = \int_{D^*(t)}^{\infty} \gamma f(c)dc = \gamma(1 - F(D^*(t))) \qquad (11)$$

Over a dry interval, $(t, t + \Delta t)$, the critical deficit, $D^*(\tau)$, will vary according to:

$$D^*(\tau) = D^*(t) - (\pi_i - \gamma)(\tau - t) \qquad (12)$$

where the interval, Δt, is usually the sampling interval, but may be a shorter interval if a content segment is fully depleted. Note that the emptying of a content segment will result in an abrupt instantaneous increase in $D^*(\tau)$, in an analagous manner to replenishment of a deficit segment during a wet period causing $C^*(\tau)$ to change its value abruptly.

We may now calculate the volume of water drained in the i-th interval, $(t, t + \Delta t)$, as:

$$B(t + \Delta t) = \int_{t}^{t+\Delta t} b(\tau)d\tau = \gamma\Delta t - \int_{D^*(t)}^{D^*(t+\Delta t)} F(z)dz \qquad (13)$$

Now consider the complications introduced when drainage occurs under raining conditions. Provided that the instantaneous rainfall rate is less than the evaporation rate ($P_i \leq E_i$) then equations (11) and (13) clearly still hold. However, when rainfall exceeds the evaporation rate, then drainage from stores with depths less than $D^*(\tau)$ must also be considered, even though some or all may remain empty due to drainage losses. Two cases must be considered.

Case 1: $\pi_i \geq \gamma$ When the net rainfall exceeds the drainage rate then all stores will drain at the instantaneous rate, γ. Therefore the instantaneous drainage rate from the basin over the wet interval, $(t, t + \Delta t)$, is:

$$b(\tau) = \int_0^\infty \gamma\, f(c)dc = \gamma \tag{14}$$

that is it remains constant and equal to the maximum rate, γ. Also the volume of drainage over the interval $(t, t + \Delta t)$ will be:

$$B(t + \Delta t) = \gamma\Delta t \tag{15}$$

Case 2: $\pi_i \leq \gamma$ When the net rainfall rate is less than the drainage rate then stores with depths less than $D^*(\tau)$ will lose water by drainage at a rate, π_i, whilst stores with depths greater than $D^*(\tau)$ will drain at the maximum instantaneous rate, γ. Consequently the instantaneous basin drainage rate will be given by the sum of two integrals:

$$\begin{aligned} b(\tau) &= \int_{D^*(\tau)}^\infty \gamma\, f(c)dc + \int_0^{D^*(\tau)} \pi_i f(c)dc \\ &= \gamma + (\pi_i - \gamma)\, F(D^*(\tau)) \end{aligned} \tag{16}$$

Integrating $b(\tau)$ over the interval, $(t, t + \Delta t)$, to obtain the volume of basin drainage, $B(t + \Delta t)$, results in the same expression derived for the no-rain case, and given by equation (13). Note that since $\pi_i \leq \gamma$ then the minimum depth of store containing water, $D^*(\tau)$, will decrease over the interval $(t, t + \Delta t)$, and Δt must be chosen such that equation (12) is satisfied; thus the time $t + \Delta t$ may coincide with the time at which a contents segment is fully depleted and not the end of the sampling interval. The above development is exact and replaces the approximation given in Moore & Clarke (1983).

The above completes the development of the probability-distributed theory for non-interacting storage elements, providing expressions for basin direct runoff, drainage, and actual evaporation, both in terms of instantaneous rates and as volumes (expressed as depth over the basin) over any interval of time. Expressions for the basin soil moisture storage and soil moisture deficit at any instant in time have also been derived.

Translation of direct runoff and drainage, generated at points within the basin, to the basin outlet remain to be considered in order to obtain the total basin runoff hydrograph. How the probability-distributed principle may be applied to the translation problem will be dealt with later. The effect of relaxing the assumption that storage elements respond to rainfall inputs independently of each other will be considered next.

Theory of interacting storage elements

If the assumption that storage elements act independently of each other is relaxed, and water is allowed to redistribute itself between stores, then the probability-distributed theory becomes both simpler and more flexible. Two modes of redistribution will be considered initially. The first mode allows water to redistribute in such a way as to cause all storage elements to have an equal depth of water, $C^*(t)$, except those with depths less than $C^*(t)$ which will be full. This will be called "equal storage redistribution". A second possibility is to suppose water redistributes so that a constant deficit, $D^*(t)$, is maintained across the population of stores, except stores with depths less than $D^*(t)$ which will be empty. This will be called "equal deficit redistribution". The effect of allowing redistribution according to these two modes of behaviour is to replace the water level profile of deficit and content segments seen in Fig.3, by either a single content segment or a single deficit segment depending on the mode assumed. A little thought quickly leads to rejection of the equal deficit redistribution mode as a realistic candidate, since immediate redistribution according to this mode will result in an abrupt switch from no contributing area of direct runoff to the total basin contributing as the deficit $D^*(t)$ is completely replenished by rainfall. On the other hand the equal content redistribution mode appears as an attractive candidate, since the temporal evolution of $C^*(t)$ will reflect the overall wetness of the basin, and it is $C^*(t)$ which is used to determine the contributing area of direct runoff generation. The equal storage redistribution mode will be adopted consequently in the development to follow.

Consider that the water level across the assemblage of stores of different depth is as depicted in Fig.5 so that all stores contain water to a depth $C^*(t)$, except those that are smaller than $C^*(t)$ which will be full. The total water in storage over the basin is:

$$S(t) = \int_0^{C^*(t)} c f(c) dc + C^*(t) \int_{C^*(t)}^{\infty} f(c) dc \qquad (17)$$

Making use of the general result:

$$\int_0^{x} c f(c) dc = x F(x) - \int_0^{x} F(c) dc \qquad (18)$$

basin water storage at time t may be re-expressed as:

$$S(t) = \int_0^{C^*(t)} (1 - F(c)) dc \qquad (19)$$

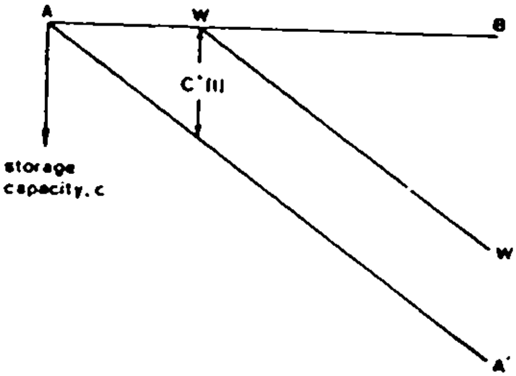


Fig. 5 Water level across stores of different depth according to the equal storage mode of water redistribution.

This equation assumes great importance, since it allows the basin water storage to be calculated for a given critical content, $C^*(t)$, and vice versa. It corresponds to the area above the distribution function of storage depth between zero and $C^*(t)$. Over the wet interval, $(t, t + \Delta t)$, the critical capacity, $C^*(\tau)$, will vary according to equation (4), the instantaneous direct runoff according to equation (3), and the volume of basin runoff generated in the interval will be given by equation (5). If net rainfall $\pi_i \leq 0$ in the interval $(t, t + \Delta t)$, then no direct runoff is generated. The basin storage can be determined by continuity as:

$$S(\tau) = S(t) + \pi_i \, (\tau - t) \qquad (20)$$

and equation (19) solved for $C^*(\tau)$ given $S(\tau)$ when required at the beginning of a subsequent wet interval in order to calculate basin direct runoff.

A weakness in the above development is that the redistribution of water between stores ensures that evaporation occurs at the potential rate throughout the basin until it dries up completely. This defect is readily overcome by allowing the actual evaporation rate to depend on the basin soil moisture deficit, $S_{max} - S(t)$. A number of possible functional relations are reviewed in Moore & Clarke (1982), but the linear relation:

$$\frac{E_i'}{E_i} = 1 - \frac{(S_{max} - S(t))}{S_{max}} = \frac{S(t)}{S_{max}} \qquad (21)$$

will be used for the purposes of illustration; dependence on storage $S(t)$ at the beginning of the i-th interval, $(t, t + \Delta t)$, may be assumed for simplicity, so that actual evaporation, E_i', is also constant over the interval. The continuity equation for basin storage (equation (20)) requires to be modified by substituting π_i with $\pi_i' = P_i - E_i'$, and is now valid for $\pi_i' \leq 0$.

Generalization to accommodate drainage to baseflow, γ_i, is also accomplished by substituting $(P_i - E_i' - \gamma_i)$ for π_i in the continuity equation (20) and in the expressions used to compute direct runoff generation in a wet interval (equations (3), (4) and (5)). To take account of the dependence of drainage on the amount of water in storage, $S(t)$, a simple linear relation:

$$\gamma_i = k_b \, S(t) \qquad (22)$$

may be invoked, where k_b is a groundwater recession constant with units of inverse time. The continuity equation in this general case becomes:

$$S(\tau) = S(t) + (P_i - E_i S(t)/S_{max} - k_b S(t))(\tau - t) \qquad (23)$$

during a period, $(t, t + \Delta t)$, when no runoff generation occurs.

The general development of the probability distributed theory of interacting storage elements is now complete. It should be emphasized that, for interacting storage elements, no redistribution of water is necessary during periods of direct runoff generation since all stores will contain the same depth of water, except of course those of smaller depth which will be full. Redistribution of water to equalize the depth of water in each storage element only occurs during periods when stored water is being depleted. Equalization of storage levels during inter-storm periods does not seem too unreasonable, and the unique relationship between soil moisture storage, $S(t)$, and critical capacity, $C^*(t)$, which results, leads to considerable simplification.

Development of the probability-distributed theory of storage capacity for a particular distribution

Development of the general theory for a particular distribution of storage capacity will serve to clarify the approach outlined above, and in particular demonstrate the importance of equation (19), obtained when redistribution of water between stores of different capacity is allowed. The spatial variation in store capacity over a basin will be assumed to be well represented by the reflected power distribution function:

$$F(c) = 1 - (1 - c/c_{max})^b \qquad 0 \leq c \leq c_{max} \tag{24}$$

The corresponding density function is:

$$f(c) = \frac{dF(c)}{dc} = \frac{b}{c_{max}}\left(1 - \frac{c}{c_{max}}\right)^{b-1} \qquad 0 \leq c \leq c_{max} \tag{25}$$

and both distribution and density functions are plotted for a range of values of b in Fig.6. Parameter c_{max} is the maximum store capacity in the basin, and parameter b controls the degree of spatial variability of store capacity over the basin; as special cases, $b = 0$ implies a constant value of capacity over the basin, and $b = 1$ implies that capacity varies uniformly from 0 to c_{max}

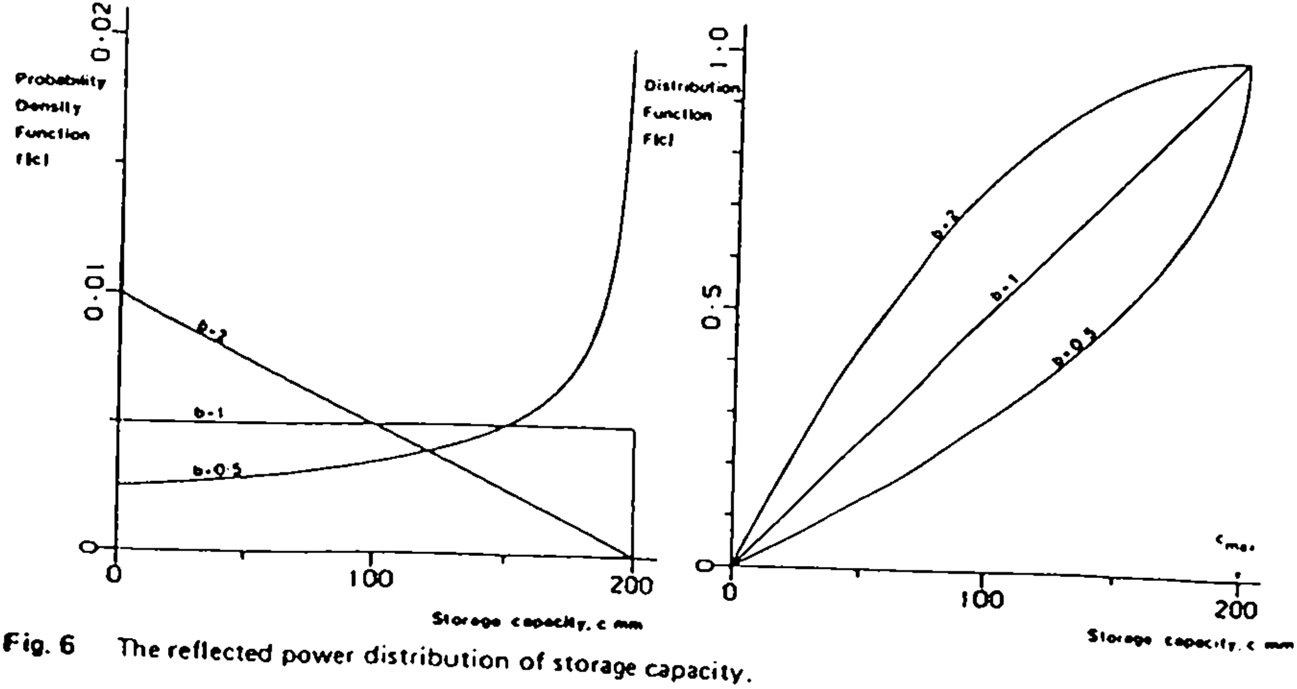

(a) Probability density function
(b) Distribution function

Fig. 6 The reflected power distribution of storage capacity.

(i.e. store capacity has a rectangular distribution). The area above the curve, and bounded by the dashed lines in Fig.7, is equal to S_{max} and given by equation (6); specifically for the reflected power distribution:

$$S_{max} = \int_0^{c_{max}} (1 - F(c))dc = c_{max}/(b + 1) \qquad (26)$$

and it follows that the mean store depth is $c_{max}/(b + 1)$.

If at some time, t, the basin moisture storage, S(t), is known, then the corresponding critical capacity $C^*(t)$ can be obtained by solving equation (19) for $C^*(t)$. The unique relationship between storage, S(t), and critical capacity, $C^*(t)$, expressed by equation (19), applies only to interacting storage elements, when the water level across stores of different depth will be of the simple form shown in Fig.5, and not of the complex, segmented form shown in Fig.3. Solution of equation (19) for $C^*(t)$ in the case of the reflected power distribution is obtained as follows:

$$S(t) = \int_0^{C^*(t)} (1 - F(c))dc = \int_0^{C^*(t)} (1 - c/c_{max})^b dc$$
$$= S_{max}\{1 - (1 - C^*(t)/c_{max})^{b+1}\}$$

which yields

$$C^*(t) = c_{max}\{1 - (1 - S(t)/S_{max})^{1/(b+1)}\} \qquad (27)$$

Although the reflected power distribution gives the above straightforward solution of equation (19) for $C^*(t)$, it is worth noting that this attribute is not always shared by other possible candidate distributions of store capacity; for example, a triangular density requires the solution of a cubic equation in $C^*(t)$ over part of its range, and a lognormal density demands an iterative

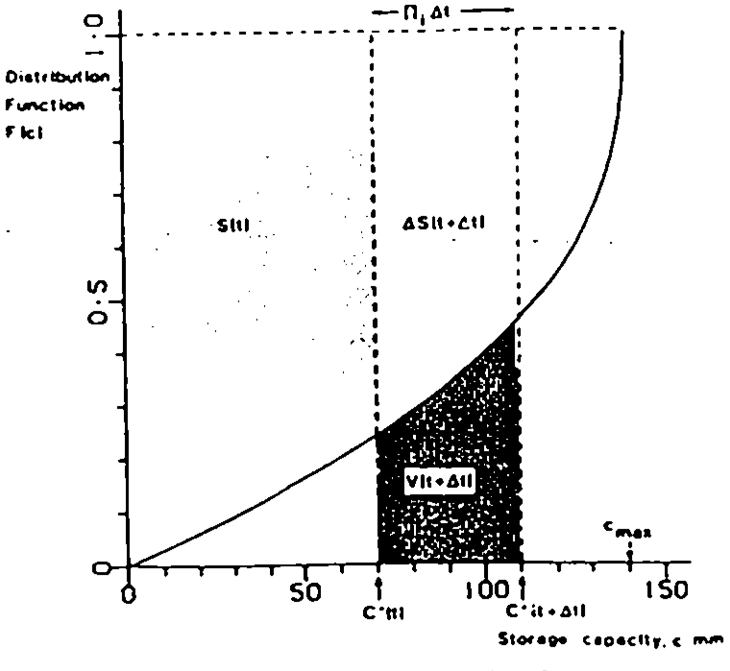


Fig. 7 The storage capacity distribution function used to calculate basin moisture storage, critical capacity, and direct runoff according to the probability-distributed interacting storage capacity model.

solution such as Newton-Raphson.

Reference to Fig.7 indicates the relationship between $C^*(t)$ and $S(t)$, the stippled area representing the basin storage, $S(t)$. Rain falling in the interval $(t, t + \Delta t)$ will generate a volume of direct runoff given by equation (5) so that:

$$
\begin{aligned}
V(t + \Delta t) &= \int_{C^*(t)}^{C^*(t+\Delta t)} F(c)\,dc \\
&= \Pi_i \Delta t - S_{max}\{(1 - C^*(t)/c_{max})^{b+1} \\
&\qquad - (1 - C^*(t + \Delta t)/c_{max})^{b+1}\}
\end{aligned}
\tag{28}
$$

where $\Pi_i = P_i + E_i' - \gamma_i$, and $C^*(t + \Delta t) = C^*(t) + \Pi_i \Delta t$ in the general case of soil storage dependent evaporation, and drainage. The addition to soil moisture storage:

$$
\Delta S(t + \Delta t) = \Pi_i \Delta t - V(t + \Delta t)
\tag{29}
$$

is indicated in Fig.7. If $C^*(t) + \Pi_i \Delta t$ exceeds c_{max} then the above requires modification, as follows. The critical capacity $C^*(t + \Delta t)$ will be equal to c_{max} (the maximum possible) and the volume of direct runoff generated will be:

$$
\begin{aligned}
V(t + \Delta t) &= \Pi_i \Delta t - S_{max}(1 - C^*(t)/c_{max})^{b+1} \\
&= \Pi_i \Delta t - (S_{max} - S(t))
\end{aligned}
\tag{30}
$$

and $S(t + \Delta t) = S_{max}$. Alternatively, the interval Δt may be chosen so that $C^*(\tau)$ first reaches the value c_{max} at the end of this interval and equals c_{max} for the remainder of the rainfall sampling interval; then no modification to equation (28) is required. Equations (28) and (30) may be used together with equation (27) for $C^*(t)$ to construct a family of rainfall-runoff relationships (Fig.8) for given conditions of basin soil moisture, $S(t)$.

The sequence of water balance calculations for successive wet and dry periods is as follows. Drainage to baseflow, γ_i, and actual evaporation, E_i, are obtained from equations (22) and (21) using the current value of soil moisture storage; net rainfall over the interval will be $\Pi_i = P_i + E_i' - \gamma_i$. During periods when no direct runoff is generated, the continuity equation (23) is used to update the soil moisture storage. At the beginning of a storm period, the current value of storage is used in equation (27) to obtain the critical capacity. This allows the volume of runoff generated in the interval to be calculated from either equation (28) or equation (30), which is then used in equation (29) to calculate the addition to storage, and so on.

The above may be compared with the procedure for deriving runoff according to the independent storage element theory. Equation (28) (or equation (30)) remains valid as the solution of equation (5) for a reflected power distribution of stores. However, there is no unique relation between storage and critical capacity, as expressed by equation (27), and evaluation of $C^*(t)$ must be obtained by continuously updating the water profile of content and deficit

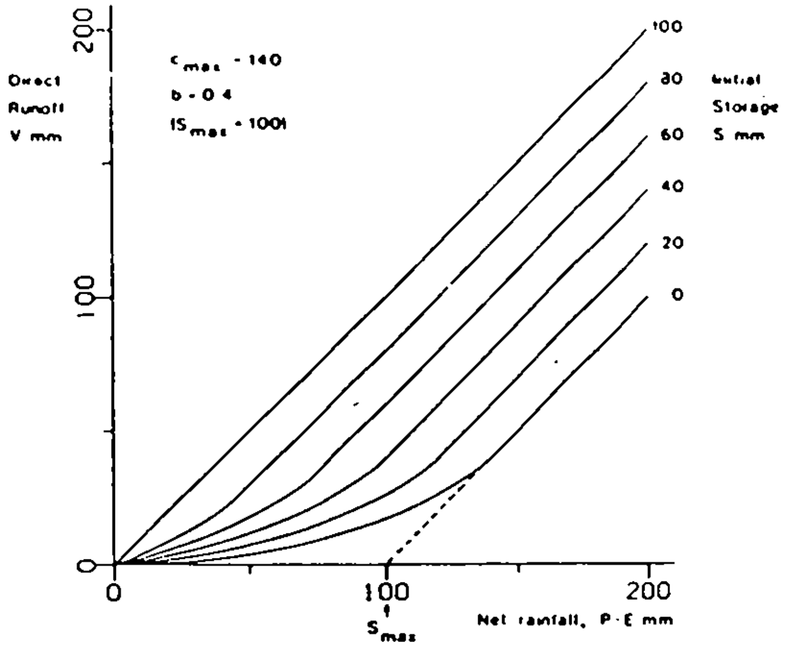


Fig. 8 Rainfall-runoff relationship for the probability-distributed interacting storage capacity model.

segments in the manner illustrated in Fig.2. Details of the steps involved in this calculation can be found in Moore & Clarke (1981, p. 1373). Computation of soil moisture deficit and baseflow must also take account of the particular configuration of content and deficit segments, and demands solution of equations (7), and (11)-(16) respectively.

Historical perspective

The concern so far has been to present a rigorous development of the theory of probability-distributed models of storage capacity; full recognition of the published research which underpins this theory has not always been given. It is now timely to present a brief historical perspective of the theory's development. Use of the probability-distributed principle to account for the effects of areal variability in losses on runoff formation has enjoyed considerable attention over the last three decades. Kharchenko & Roo (1963) review work carried out in the USSR since the 1950s, beginning with the analysis presented by Bagrov (1950) and including Popov's (1956) use of exponential and hyperbolic distributions to represent spatial variation in "absorption losses". Kharchenko & Roo also treat rainfall as a probability-distributed input and show how it influences the basin runoff when used in conjunction with probability-distributed absorption losses over the basin. More accessible accounts of Popov's work, including its application to snowmelt flooding, are to be found in Popov (1962, 1973, 1980).

Research in China may be traced back to the early 1960s, and to studies at the East China College of Hydraulic Engineering (ECCHE), beginning with the work of Zhao & Zhuang (1963). Subsequent developments of the probability-distributed approach are documented in ECCHE (1977) and Zhao *et al*. (1980) where the resulting model is referred to as the Xinanjiang model. The reflected power distribution of storage capacity is adopted in this model because it gave best agreement with observed rainfall and runoff data. It also gives a straightforward solution for the critical capacity, C*(t), (equation 27)). The theory of interacting storage elements presented here derives largely from the above-cited research in China and the USSR, and the illustration using the reflected power distribution is drawn from the work of Zhao and his co-workers. However, the presentation of the theory given here differs from that contained in the above-cited works, and aims to clarify its link with the theory of independent storage elements.

In the German Democratic Republic, Becker (1974) also developed a probability-distributed model based on interacting storage elements. He recognized that interception storage provided by a forest canopy would vary over the basin, ranging from zero at unvegetated sites to some maximum value where the canopy was deepest. The simple storage element was used to represent the interception process at a point, its capacity was viewed as a random variate from a rectangular distribution, and expressions for throughfall (water spills) and canopy water storage derived. These expressions may be obtained as special cases of the equations developed here for direct runoff generation using the reflected power distribution with $b = 1$. Becker explicitly acknowledges that redistribution of water between stores was invoked to arrive at an analytically tractable solution.

The exact analytical theory for independent storage elements was developed a decade later by Moore & Clarke (1981, 1982, 1983) and Moore (1983). The present paper has aimed to establish and clarify the link between the two theories, one based on independent storage elements and the other on interacting storage elements.

PROBABILITY DISTRIBUTED MODELS OF INFILTRATION CAPACITY

Other research on the application of the probability-distributed principle to derive models of direct runoff generation has not been based on the variability of storage depth over the basin but rather on the spatial variation in the rate at which water can enter the soil. These developments of probability-distributed models based on the concept of infiltration capacity will now be considered.

Perhaps the best known development of the probability-distributed principle in hydrology is contained in the Stanford Watershed model developed by Crawford & Linsley (1966). They used a rectangular distribution to describe the spatial variation of infiltration capacity over the basin and allowed the maximum infiltration capacity parameter of this distribution to vary as a function of soil moisture storage.

As a simple illustration of the type of runoff calculation made in the Stanford Watershed model, consider the rectangular distribution function of infiltration capacity, $F(i) = i/i_{max}$, presented in Fig.9. Rain falling at a rate P in a unit interval will generate runoff at all points in the basin with infiltration capacity less than P: the proportion of the basin contributing runoff will therefore be F(P). The total volume of direct runoff generated in the basin in the unit interval, and indicated by the hatched area in Fig.8, will be:

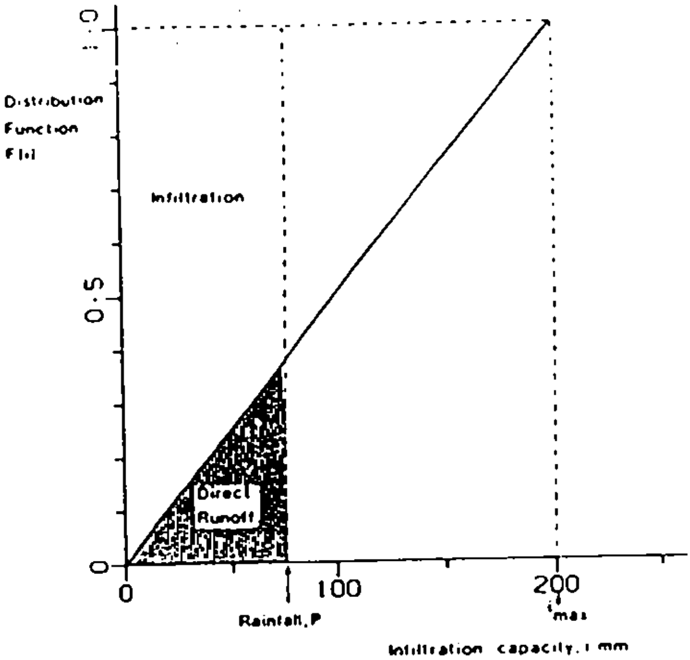


Fig. 9 Basin direct runoff production and infiltration to storage according to the probability-distributed infiltration capacity model.

$$V = \int_0^P F(i)\,di \qquad P \leq i_{max} \qquad (31a)$$

$$V = P - i_{max} + \int_0^{i_{max}} F(i)\,di \qquad P \geq i_{max} \qquad (31b)$$

and the addition to soil moisture storage will be $\Delta S = P - V$ (ignoring evaporation). Dependence of infiltration capacity on soil moisture in the Hydrocomp version of the model (Hydrocomp International, 1969) is represented by allowing the maximum infiltration capacity parameter to vary inversely with soil moisture, S, according to a modified Philip equation (Philip, 1957):

$$i_{max} = 2i_o/(S/S_o)^2 \qquad (32)$$

where i_o is an infiltration parameter, and S_o is a reference level of moisture storage.

The distributed infiltration capacity component of the Stanford Watershed model has been used in modified form in various USGS rainfall-runoff models (Dawdy *et al.*, 1972; Dawdy *et al.*, 1978; Alley *et al.*, 1980). Different distributions of infiltration capacity have been developed by other workers. Pitman (1973, 1976) used a symmetric triangular distribution, Clark (1980) considered a power distribution, and Moore (1983) obtained an exact expression for direct runoff generation according to a lognormal distribution of infiltration capacity. Supporting evidence for the use of a lognormal distribution can be found in a number of empirical and theoretical studies on the spatial variation of infiltration (Nielsen *et al.*, 1973; Warrick *et al.*, 1977; Smith & Hebbert, 1979; Sharma *et al.*, 1980).

The distinction between distributions of infiltration capacity used in the Stanford Watershed model and its derivatives and the probability-distributed models for storage capacity should be made clear. In physical terms, infiltration capacity specifies the maximum rate of entry to soil moisture storage, whereas storage capacity refers to the depth of water storage available. Probability-distributed infiltration capacity models generate direct runoff according to the Hortonian overland flow mechanisms, in contrast to the saturation overland flow mechanism inherent in models based on the storage capacity concept (Dunne, 1982). The observed dependence of infiltration capacity on soil moisture storage demands that probability-distributed infiltration models incorporate such dependence explicitly, through relations such as equation (32) or the Green-Ampt type equation used by the USGS models. In contrast, models based on distributions of storage capacity have soil moisture storages which are determined directly through the distribution function of store depths; for example, the mean storage capacity is equal to the maximum storage available in the basin (see equation (6)).

Probability-distributed models of storage capacity and infiltration capacity discussed up to now have accounted in different ways for the loss-accounting component of runoff generation. Two components of runoff have been generated, one produced at the surface and called direct runoff and the other below ground and termed drainage to baseflow, and expressions have been developed for the integrated response of these components from the entire basin. However, no account has been taken up to now of how translation of direct runoff and drainage through the basin to the basin outlet will shape the resulting hydrograph. Only the volume of basin direct runoff and drainage have been determined and not their distribution over time as observed at the basin outlet. How the probability-distributed principle may be applied to represent the mechanism of water translation through the basin will be dealt with next.

PROBABILITY-DISTRIBUTED MODELS OF TRANSLATION TIME

Translation of direct runoff to the basin outlet

When direct runoff is generated from the spilling of a full storage element, this runoff will be assumed to travel independently of runoff from neighbouring elements, and to be routed to the basin outlet by means of a linear channel with constant delay, t. Each member of the statistical population of stores will be characterized not only by its capacity c, but by its translation time t, and both c and t may be considered to be random variates from some distribution. The density of store depths $f(c)$, may now be replaced by the bivariate density $f(c,t)$, where t is the time taken for direct runoff from stores of depth c to reach the basin outlet. This formulation allows for possible interdependence of the variables c and t; for example, a positive correlation for c and t may be justified on the grounds that in close proximity to the stream channel the water table will be close to the ground surface so that effective store depths and travel times will both be small, whereas further away from the channel, deeper storage elements will be more abundant and be associated with longer times of travel. A contrary argument in favour of a negative correlation between c

and t was presented by Moore & Clarke (1981). Note that to simplify notation, arguments of the function, f(.), are used to denote different probability density functions: f(c), f(t) and f(c,t).

For the general bivariate case the basin runoff rate at time t will be given for probability-distributed models of storage capacity by:

$$Q(t) = \int_0^t \pi(\tau) \int_0^{C*(\tau)} f(c, t - \tau) dc d\tau \tag{33}$$

For the degenerate case when the bivariate density factorizes to the product of two independent densities, $f(c,t) = f(c)f(t)$, equation (33) becomes:

$$Q(t) = \int_0^t \pi(\tau) \int_0^{C*(\tau)} f(c) dc \; f(t - \tau) d\tau \tag{34}$$

Substituting equations (1) and (3) reduces the above to

$$Q(t) = \int_0^t q(\tau) \; f(t - \tau) d\tau \tag{35}$$

which indicates that basin runoff is given simply by the convolution of the basin direct runoff, q(t), with the probability density function of translation time, f(t). Note the equivalence of f(t) to the instantaneous unit hydrograph or kernel function, and the probabilistic interpretation of f(t)dt as the probability of the travel time being in the range (t, t + dt). Equation (35) for basin runoff applies to all mechanisms of direct runoff generation considered here (that is, based on distributed infiltration capacity or storage capacity concepts).

Translation of drainage to the basin outlet

Two possibilities present themselves when considering translation of drainage to the basin outlet. The simpler option is to merely sum the instantaneous direct runoff and drainage rates and to convolve this quantity with the density of travel times so that the basin runoff is given by:

$$Q(t) = \int_0^t (q(\tau) + b(\tau)) \; f(t + \tau) d\tau \tag{36}$$

Conceptually this might be justified by considering direct runoff and drainage to be contributions from hillslope segments to the channel system, and therefore should share the same translation properties from thereon as controlled by the channel network. Thus the characteristics of the density of travel times, f(t), would be dictated by the characteristics of the channel network.

Alternatively, direct runoff and drainage may be considered to take separate paths to the basin outlet, so that basin runoff is given by the sum of a translated direct runoff component and a baseflow component, that is:

$$Q(t) = \int_0^t q(\tau) \; f(t - \tau) d\tau + \int_0^t b(\tau) \; f_b(t - \tau) d\tau \tag{37}$$

Distributions of translation time

The problem of choosing a density function to describe the random nature of the travel time taken for direct runoff generated from a storage element to arrive at the basin outlet will now be examined. A simple exponential density of translation times was adopted for the purposes of illustration by Moore & Clarke (1981), who pointed out that its use was equivalent to regarding the translation process as a single linear reservoir. An important advantage of the exponential density is that a simple recursive solution to the convolution integral of equation (35) can be obtained. However, the simple exponential recession behaviour obtained does not conform to observed recessions, which tend to fall abruptly immediately following the peak, and subsequently at a much slower rate. If the total runoff is considered to be the sum of direct runoff and baseflow components according to equation (37), then an exponential distribution may be appropriate for the baseflow density, $f_b(t)$. Indeed, use of two different exponential densities for direct runoff and baseflow components would allow recessions to fall abruptly when runoff is dominated by direct runoff and later at a slower rate as baseflow assumes dominance. However, a distribution of unimodal, positively skewed form would seem more appropriate for representing the attenuating influence of the hillslope and stream channel on the hydrograph shape at the basin outlet.

An approximately analogous translation problem arises in the theory of Brownian motion where a particle moving with uniform velocity ν undergoes linear Brownian motion so that it takes a variable amount of time, t, to cover a fixed distance, x. Then the translation time, t, is a random variable with probability density function:

$$f(t,x;\ \nu,\ \sigma) = \frac{x}{\sigma\sqrt{2\pi t^3}} \exp\left\{ -\frac{(x - \nu t)^2}{2\sigma^2 t} \right\} \qquad t \geq 0 \qquad \nu \geq 0 \qquad (38)$$

where x/ν is the mean translation time, and σ^2 is a diffusion constant. By invoking this analogy in the present context, direct runoff is assumed to be generated only from those points in the basin at a distance x from the basin outlet, and travels at a constant velocity ν along paths of different length. The time taken to reach the basin outlet will depend on the particular path taken. Eagleson (1970) demonstrates how this density may be obtained as a linearized solution to the Saint Venant equations of open channel flow, and its relation to the convection-diffusion equation.

The density may be expressed in the standard form known as the inverse Gaussian density (Johnston & Kotz, 1970; Folks & Chhikara, 1978):

$$f(t;\ \mu,\lambda) = \left(\frac{\lambda}{2\pi t^3}\right)^{1/2} \exp\left\{ \frac{-\lambda(t - \mu)^2}{2\mu^2 t} \right\} \qquad t \geq 0 \qquad (39)$$

obtained from equation (38) using the reparameterization $\nu = x/\mu$, $\sigma^2 = x^2/\lambda$, where the new parameters μ and λ are positive and of dimension time. A special case is the one parameter distribution:

$$f(t;\ \lambda) = \left(\frac{\lambda}{2\pi t^3}\right)^{1/2} \exp\left(-\frac{\lambda}{2t}\right) \qquad (40)$$

obtained when $\mu \to \infty$, and corresponds to pure diffusion. Venetis (1968) shows how this density may be derived as the impulse response function of one-dimensional flow in a homogeneous isotropic confined aquifer.

The inverse Gaussian density is unimodal and positively skewed and a particular feature is its heavy tail (Fig.10). It would appear to be a suitable choice for the density of translation time f(t), both on account of its shape characteristics, and its physical interpretation through its relation to the Saint Venant equations of open channel flow and the general convection-diffusion equation. Its relation to the equations of groundwater flow also suggest that, in the form of equation (40), it would be a suitable choice for $f_b(t)$, the density of drainage translation time.

Of course there is no necessity to seek a parametric function to represent the density of translation time, f(t). Indeed f(t) may be dealt with as an empirical density function whose form is to be determined from rainfall and runoff data. Then classical methods for identifying the instantaneous unit hydrograph may be used, or those based on constrained programming solutions which aim to ensure that the shape of the empirical density is physically realistic.

DISCUSSION

Simplified representations of direct runoff generation and soil moisture at a point within a river basin have allowed the probability-distributed principle to be applied to obtain analytical expressions for the runoff response from the basin as a whole. If more complex point representations are entertained, possibly incorporating more of our understanding of the physics of runoff generation and soil moisture storage, then this analytical tractability is soon lost. Recourse must then be made to numerical integration procedures in order to derive the basin response. An example is provided by the work of Takagi & Matsubayashi (1980)

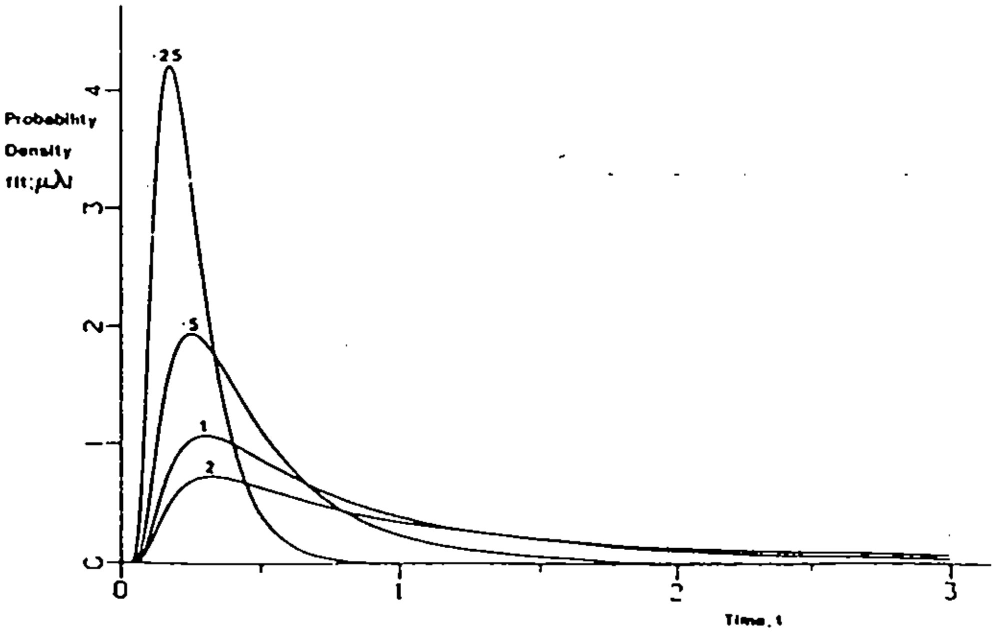


Fig. 10 Inverse Gaussian probability density function of translation time for various values of mean translation time, μ, with $\lambda = 1$.

where a hillslope segment is chosen as a characteristic response element, and a simplified representation of discharge from the base of the hillslope segment, based on Darcy's law, is employed. A statistical distribution of hillslope elements over the basin is envisaged, each member being characterized by a set of parameters whose probability distributions represent their variability over the basin, some being considered uniform and therefore constant. Slope length and inclination are used as morphological parameters, and hydraulic conductivity and effective porosity as soil parameters. Since an analytical expression cannot be obtained for the basin response, responses from many individual elements are derived and weighted according to their probability of occurrence over the basin in order to calculate the total basin response. Thus the integral over space is replaced by a discrete summation of weighted responses from hillslope elements.

It seems unlikely that such probability-distributed models based on complex physically-based point representations of runoff production have a major role to play in operational water resource applications. However, they do appear to provide an avenue whereby the effect of basin scale on hydrograph response may be usefully investigated. Models based on simplified point representations of runoff production and used within a probability-distributed spatial framework to obtain analytical expressions for basin runoff do seem to provide a valuable bridge between lumped conceptual models and physically-based models of runoff production at the basin scale. They essentially encompass the conventional conceptual approach to rainfall-runoff modelling as a special case and provide a means of accounting for spatial variability in runoff production in a simple way.

CONCLUSION

This paper has aimed to highlight the role of the probability-distributed approach as a formulating principle in many rainfall-runoff models in use today. The principle's widespread application serves as a testimony of its value in rainfall-runoff model formulation. Two types of probability-distributed model have been identified, one based on infiltration capacity, which controls entry of water into the soil, and the other based on storage capacity, which controls subsurface saturation. Early models based on the storage capacity concept, and developed in the USSR, China and the GDR, have been shown to invoke the assumption of redistribution of water on entry to storage, which leads to an analytically tractable and flexible model formulation. More recent research by the author has demonstrated that an exact analytical model formulation can be obtained without requiring that water is redistributed below ground. Further generalization of this approach to account for bounded probability distributions and to include a groundwater component has been developed here.

Probability-distributed infiltration capacity models are structured to generate runoff according to the Hortonian overland flow mechanism, in contrast to the subsurface saturation excess mechanism inherent in models based on the storage capacity concept.

Which mode of runoff production will be dominant will depend on climate, soil, vegetation and topography, but in general models based on infiltration capacity are likely to be appropriate for more arid regions. Dependence of infiltration capacity on soil moisture storage must be incorporated explicitly through an infiltration equation in models based on the infiltration capacity concept; however, soil moisture storage is determined directly by the distribution function of storage capacity in storage-based models.

Finally, it has been shown that translation of runoff generated at points in the basin outlet can be regarded as a problem of defining a probability distribution of translation time. The inverse Gaussian density is presented as a suitable translation time distribution.

ACKNOWLEDGEMENTS This research was funded by the Ministry of Agriculture, Fisheries and Food under their Flood Protection Commission programme, and by Thames Water under their Real Time Forecasting and Control programme.

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APPENDIX C

COMMENTS AND RESPONSE FOR INTERIM WORKING PAPER ON RTFF

TERRITORIAL LAND DRAINAGE AND FLOOD CONTROL STRATEGY STUDY - PHASE II INTERIM WORKING PAPER ON REAL-TIME FLOOD FORECASTING FOR THE INDUS BASIN

RESPONSES TO COMMENTS

The Interim Working Paper on RTFF for the Phase II Study was submitted to DSD and circulated to various Government departments for their comments via Binnie-Maunsell Consultants' letter reference NRT/0617/0/930 dated 1st July 1991. Comments on the report were received from the following Government departments:

A. Drainage Services Department, Sewage Treatment Division

B. Civil Engineering Services Department, Civil Engineering Office

C. Water Supplies Department, Planning Division

D. Drainage Services Department, Electrical and Mechanical Projects

E. Civil Engineering Services Department, Geotechnical Control Office

F. Drainage Services Department, Mainland North Division

G. Drainage Services Department, Design Division

H. The Royal Observatory, Hong Kong

A. Drainage Services Department, Sewage Treatment Division

Comments from Chief Engineer/Sewage Treatment, Drainage Services Department in letter reference DSD/ST/G08/01 dated 8th July 1991

Comments	Responses
A1 I refer to your letter dated 1st July 1991 on the captioned subject. Please be advised that I have no comments on your Interim Working Paper on RTFF.	-

B. Civil Engineering Services Department, Civil Engineering Office

Comments from Chief Engineer, Port Works, Civil Engineering Office, Civil Engineering Services Department in letter reference (21) in PWO 6/1905/88 VI dated 11th July 1991

Comments	Responses
B1 Referring to the Interim Working Paper on "Real-Time Flood Forecasting for the Indus Basin" which accompanied your letter dated 1st July 1991, please be advised that this Division has no comment on this Paper.	-

C. Water Supplies Department, Planning Division

Comments from Chief Engineer/Planning, Water Supplies Department in letter reference (23) in WWO 4/137/1382/88 III dated 16th July 1991

Comments	Responses
C1 I have the following comments on the captioned working paper:	
C1.1 <u>Sections 2.6 - 2.8</u> Use of catchment lag as an indicator of forecast lead time for small or upland catchments is generally impracticable. Perhaps, it may be applicable to large or lowland catchments particularly for short duration storm rainfalls.	We would agree that catchment lag alone is a poor indicator of possible forecast lead times and have tried to make this point clear in our Interim Working Paper. The point is discussed in more detail in para 3.11 of the final Working Paper.
C1.2 <u>Section 3.7</u> Is PMD also a parametric model (i.e. a set of parameters) such as DISPRIN model? The latter was used in River Dee regulation employing IUH for convolution operation, cascade of equal and unequal linear reservoirs for flow routing and non-linear process for moisture accounting, and has been proved quite good for application in Hong Kong. It seems that unlike DISPRIN, PMD has omitted the quick return flow from subsurface storage.	The PDM model is a parametric model like the DISPRIN model. PDM has been developed in recent years specifically for real time flood forecasting applications and is we believe the most suitable model for the small mixed land-use catchments found in Hong Kong. Mr Moore of IH is fully familiar with DISPRIN having worked on it with its originator whilst both were at the Water Research Centre, and having applied this model to early phases of the River Dee RTFF system in Wales.

Comments	Responses
C1.2 <u>Section 3.7</u> (cont'd)	DISPRIN is a complex model with from 11 to 23 parameters depending upon how it is configured to any particular basin. Parameters must be fitted subjectively, which is not a good practice, and the model requires good quality data from a well gauged catchment, a situation that unfortunately does not exist on the Indus basin. PDM is a simpler model whose parameters may be fitted by objective means and is better suited to data scarce situations such as the Shenzhen basin. We have expanded upon our reasons for preferring the PDM in para 3.10 of our final Working Paper.
C1.3 <u>Section 7.9</u> The error term in real-time flood forecasting has two sources, one being the discrepancy attributable to the forecasting model in converting rainfall to runoff, the other being attributable to the uncertainty of future rainfall. Little is known about the errors introduced by inadequate knowledge of future rainfall amounts. In view of the above, it would be practicable for some cases to use real-time rainfall data for flood forecasting. Its advantage is to give a nearly-actual forecast flood peak at the time when most intense rainfall has fallen. If forecast rainfall is considered necessary and practicable, depth and duration of rainstorm and its profile would be important. I would suggest the following criteria be considered:	We agree with the sentiments expressed here and hoped that the explanation of the value of rainfall forecasts given in Sections 7.9 to 7.12 and illustrated in Figure 8 would be helpful to readers. The commenter is right in saying that the use of "real-time (i.e. measured) rainfall ... will give a nearly-actual forecast flood peak at the time when most intense rainfall has fallen". As shown in para 3.11 of the Final Working Paper, the flood peak will result from a brief period of high-intensity rainfall within the body of the storm, and the flood peak may occur before the end of the rainfall.
i) If a long duration storm is expected, forecast rainfall may be used for flood forecasting. A storm pattern (say at 5 min. intervals) for forecast rainfall is desirable and hence a real-time rainfall forecast model may be contemplated.	However, during the early stages of a storm, one cannot use only measured rainfall or the forecast peak may be underestimated. If rain continues to fall, and if the RO and DSD expect the rain to continue, it is unwise to base flood forecasts on telemetered rain up to "time-now" alone; some sort of future rainfall scenario or forecast is required. Whilst the problems of deriving such rainfall forecasts are recognized, it has always been important with operational RTFF systems to give users the opportunity to consider "what-if" scenarios associated with various rainfall forecasts. Further discussion is given in para 3.25 of the Final Working Paper.

Comments	Responses
ii) If the storm duration is relatively short and the forecast lead time is large enough to give flood forecasting and warning, then real-time rainfall data could be used for flood peak prediction.	Generally firm warnings to the public of imminent flooding would not be issued on the basis of such rainfall forecasts; warnings would only be needed at a later stage of the event once the main high intensity rainfall had occurred as the commenter rightly states. However, the rainfall forecast can significantly increase the lead time of potential flooding which would be used to place the various Government and private agencies on standby. It is not intended that the public should be issued with flood warnings based upon inherently imprecise rainfall forecasts, but such early indications of a developing potential flood should be of considerable value in initiating the process of setting up the official response mechanisms for the various agencies to be involved in flood warning dissemination and damage mitigation. Given the very short firm lead times possible for much of the Indus basin, it is vital to begin the mobilization of the various agencies as early as possible and this is where the value of rainfall forecasts will be felt. It is suggested that whilst there will inevitably be some false alarms from such a procedure, provided only the staff of Government and private agencies are put on standby "unnecssarily", there is no danger of the public loosing confidence in the process of RTFF.

D. Drainage Services Department, Electrical and Mechanical Projects

Comments from Chief Engineer/Electrical and Mechanical Projects, Drainage Services Department in letter reference (36) in DSD/EM/P129 dated 15th July 1991

Comments	Responses
D1 I refer to your letter dated 1st July 1991 on the captioned subject. Please be informed that I have no comments on the Working Paper.	-

E. Civil Engineering Services Department, Geotechnical Control Office

Comments from Principal Government Geotechnical Engineer, Geotechnical Control Office, Civil Engineering Services Department in letter reference (10) in GCP 1/10/434 VIII dated 19th July 1991

	Comments	Responses
E1	Thank you for circulating this interim working paper, which allows us to follow your thoughts on this subject, prior to the formal submission of the completed working paper. I have only minor comments on this report:	
	a) In paragraph 6.1, the second "PDM" should read "BMP".	Text amended.
	b) Paragraphs 6.3 and 6.4 refer to problems which may arise from placing the lower boundary of the catchment at Lo Wu. I consider that this is more promising than is indicated in the report, provided that reasonably accurate boundary conditions can be established from semi-empirical relationships, taking into account all relevant inputs in the area, as well as tide gauge readings from Tsim Bei Tsui. I look forward to seeing the results of the pilot study in which these problems will be more fully addressed.	Noted. This topic is to be covered in Sections 3.15 to 3.19 of the final working paper.
	As a general comment on the accuracy of terrain data used in the real time flood forecasting, a careful balance needs to be applied between the high levels of accuracy required to model flows across floodplains which contain many almost flat areas separated by small steep slopes, and the increased processing time required for more complex terrain models. I would like to see the terrain models once digitized, to see the complexity which has been achieved during data capture, and to see how this affects the speed of computation of the real time flood model.	Noted. MIKE 11 is primarily a one-dimensional hydraulic model. Psuedo 2-d flow is simulated across floodplains. The accuracy of the mathematical model is compatible with the terrain data. The terrian models will be available for demonstration once digitized. Further comments on this point are presented in Section 1.14 of the Final Working Paper.

F. Drainage Services Department, Mainland North Division

Comments from Chief Engineer/Mainland North, Drainage Services Department in letter reference MN 5/21/1 dated 26th July 1991

Comments	Responses
F1 <u>GENERAL COMMENTS</u>	
We wish to pay our compliment to the Institute of Hydrology for producing this concise and yet easily comprehensible working paper on a relatively innovative subject, RTFF. Having said that, it may be appropriate at the outset for us to give a few general comments on matters, we feel, should be given more emphasis in the final version of the Working Paper. The Brief calls for a report on the technical viability and cost-effectiveness of RTFF in the Indus Basin before Government makes the decision on whether to go ahead with pilot testing on this non-structural measure. So it is natural to divide our general comments into the same two headings.	Comment appreciated.
F1.1 1. <u>Technical Viability</u>	
a) The Interim Working Paper is rather "low-key" in treating the <u>sea level influence</u> on the RTFF. (This subject is only mentioned briefly at Para 6.4 and at some lengths at Appendix A - Para A.40 - A.46). Inevitably, hydrologists are unlikely to be as familiar with storm surge forecasts as they are with forecasting fluvial processes (WMO No. 704*). The lower Indus is tidal even under ordinary astronomical tides, and the tidal wave influence may extend further upstream should a storm surge happen in Deep Bay during the passage of a tropical cyclone, which unhappily may also produce fluvial (heavy rainfall-induced) floods. Historically, it seems that in Hong Kong sea flooding is more catastrophic than fluvial flooding (for instance, in 1937, 11,000 people were killed when some lowlying villages along the coast of Tolo Harbour were inundated by a storm surge caused by a typhoon).	This point has been expanded upon in Sections 3.15 to 3.19 of the Final Working Paper. We do not wholly agree that hydrologists cannot provide storm surge forecasts. As such quantitative forecasts are not currently available from other sources, it seems necessary for the consultants to address this problem as they have done in the UK.

		Comments	Responses
F1.2	b)	The Interim Working Paper also seems to have underestimated the hydrological complexities of the Indus Basin. Firstly, at the head of the Indus Basin there are a number of Water Supply/Irrigation Reservoirs and other structures, whose operations can have significant effects on flows in the Lower Indus Basin. Secondly, the behaviour of the Lower Indus Basin depends on the hydrological conditions of the Shenzhen River with 60% of its catchment lying on the PRC side. For instance, a spillage from the Shenzhen Reservoir may have an effect on flooding scenarios in the Lower Indus. In this case, we feel that a river gauge along Shenzhen River at Muk Wu is probably required to monitor flood waves arising from such spillage. On the otherhand, rainfall falling on the PRC side of the Shenzhen Basin would have to be somehow generated from measured rainfalls at the Hong Kong raingauges using a suitable extrapolation function and daily exchanged data from the Bai On Weather Station. Also, the hydrological characteristics of the PRC side of the Shenzhen Basin need to be studied with reference to Maps and LANSAT Imageries (e.g. from the French SPOT or the U.S. EOSAT). We have provided you with a list of contacts in this regard at the fee negotiation stage.	We agree that the Interim Working Paper may have over simplified the hydrological complexities of the Shenzhen Basin, but do not believe that the Indus Basin itself poses any major insurmountable problems. Para 3.20 to 3.22 of the Final Working Paper have addressed this problem in more detail. The effects of the upstream reservoirs on flows in the lower Indus can be accommodated without major problems as can the effects of other minor structures. The large proportion of the Shenzhen Basin which has no gauged rainfall or flow data is of course a major problem. However, we would even expect to be able to estimate rainfall inputs over this catchment using a combination of weather radar and data from the Bai On weather station. Such estimates may well be of low reliability as will estimates of runoff from the PRC part of the basin. However, this does not seem to preclude the attempts being made to develop an operational RTFF system for the Indus Basin. We believe that one of the main benefits of the pilot studies will be to investigate the effects of these and other problems on forecast flows on the lower Indus. There seems to be a real need for DSD to have the technical means of estimating flood levels in real time from the extensive network of existing and proposed telemetering rainfall and river level sites. Major investment has been made in data acquisition and it would be a pity not to take advantage of this valuable real-time database.
F1.3	2.	Cost-Effectiveness No particular mention has been made of costs of the RTFF, nor its benefits. We appreciate that cost-benefit analysis for any project is not easy and the subject is by no means an exact science. Moreover, the costs and benefits of a flood warning scheme is particularly difficult to evaluate. Nevertheless, some attempt must be made if the expenditure on the RTFF is to be justified. For the benefits, please also mention the intangible ones. Moreover, we are wondering if the scheme needs to be extended to other Hong Kong Sub-Basins of the Shenzhen River so as to enhance the cost-effectiveness of the Scheme. Also a mention of the up-dated costs of pilot testing would be very appropriate.	We have addressed the cost-effectiveness of the pilot study RTFF scheme in Chapter 5 of our Final Working Paper.
F2	SPECIFIC COMMENTS		
F2.1	Summary, Para S.1		
		Insert 'cost-' before 'effectiveness' at the last sentence.	Agreed.

Comments	Responses
F2.2 Summary, Para S.7, line 11 "what if?" scenario testing is also required for sea level predictions, and hydraulic structure operation modes.	Agreed. See paras 3.25 and 3.26 of the Final Working Paper.
F2.3 Para 1.8 Attention should be given to automatic generation of missing data (possibly from previous data and real time data from neighbouring gauges). More drastically, should the RTFF system fail during an event, some standby nomographs should be available to the forecaster so that he can still make use of available data to give some service, though curtailed.	The system will have facilities to cope with missing data. The most likely form of system failure will be that of the data link to the RO computer, or the RO computer itself. If there is no in-coming telemetry, it will be difficult to produce sensible forecasts through nomographs or any other method. As the SPARC workstations will be linked by the local area network, failure of the machine dedicated to RTFF can be covered by having a backup system on one of the other SPARCs. Thus provided at least some of the telemetry data is working, a reasonable degree of safety against failure can be built into the proposed system.
F2.4 Para 2.6 Please explain the last sentence in greater details.	Catchment lag is essentially a post event measure; it is the time delay between centroid of rainfall and flood peak. During an event one does not know when the centroid of rainfall has been attained.
F2.5 Para 2.8 Same comments as Para S.7 in Summary.	See response to Para S.7.
F2.6 Para 3.4 This states that NAM is a daily model and only works in discrete time steps. We doubt whether this is true. In WP No. 40, NWNT Base Strategy Studies, Appendix 7 gives a detailed description of the Hydrologic Model in S11 (a former main frame version of NAM), the soil moisture accounting processes were given as continuous functions or differential equations. Discrete time-steps are only used as a numerical solution technique. Also according to August 1986 issue of "World Water" the NAM/S11 have worked in Real-Time Flood Forecasting in India with time steps of 1 hour or less.	We have commented in para 3.3 of the Final Working Paper.
F2.7 Para 3.7 - 3.9 These together with Figure A-2 are a little too brief. Please let us have more details about the Probability-distributed Model (PDM) for the rainfall-runoff process in RTFF.	Full details of the PDM are given in Moore 198~~[illegible]~~, a copy of which will be provided.5
F2.8 Para 3.11 Please check the evaporation data availability with RO/WSD.	We have already spoken to RO about the availability of evaporation data, both historically for model calibration, and in real time through telemetry of RO automatic weather stations.

Comments	Responses
F2.9 Para 4.3 Please clarify whether the real-time correction (in terms of amplitude and phase corrections) applies to forecast water levels as well as to forecast flows. If this is so, the correction algorithm has also to be built into the hydraulic routing model MIKE 11-HD.	We have replied in paras 3.23 and 3.24 of the Final Working Paper.
F2.10 Para 5.1 If we are going for a hybrid model such as PDM/MIKE 11-HD for RTFF, close co-ordination between the two specialist organizations (IH/DHI) is a pre-requisite for the success of such a model, irrespective of which option (A or B) is going to be adopted. Do you have any preliminary discussion with DHI about such co-ordination? We are also concerned about the future support of such a hybrid model.	The original intention was to link the PDM rainfall-runoff model with the hydrodynamic routing modelling component of MIKE 11. This is the approach adopted for our flood forecasting system for the City of Lincoln, where we have linked PDM to the LORIS hydrodynamic model of Hydraulics Research Limited. The Information Control Algorithm (ICA) contained with our RFFS software permits any suitable hydrodynamic model to be configured as part of the overall model. For the Yorkshire NRA system, an adapted US National Weather Service routing model has been utilized in the same way. However, as discussed in the Final Working Paper, we now believe that a RTFF model containing a mixture of IH and DHI software may not be an optimal solution, and we propoe that the entire RTFF software system be provided by IH based on their RFFS software.
F2.11 Para 5.3 We are interested in the case history of previous linking of the PDM with a hydrodynamics model similar to MIKE 11. Please give more details.	See response to Para 5.1.
F2.12 Para 6.1 In line 10, should 'PDM' be replaced by 'BMP'?	Agreed.
F2.13 Para 6.5 We have made a visit to the Hok Tau Stream Gauge and found that it is too remote to be telemetered. Further, this gauge upstream of Hok Tau Reservoir may not be representative of the flows in downstream Tan Shan Ho (River Jhelum) because of the inflows/outflows at Hok Tau Reservoir.	The reason for telemetering this station is that it would act as an analogue of all small upland catchments within the Indus. Because it is upstream of the reservoir, little flood flow is likely to be generated which would contribute to the Lower Indus. This gauge provides the only possible flow gauging point within the Indus without constructing a new gauging station. The cost of telemetry may be high, but without an upland gauge somewhere within the basin RTFF will be difficult.
F2.14 Para 7.4 Same comments as Para S.7 in Summary.	Agreed.

Comments	Responses
F2.15 Chapter 8 Your paper is strong on ideas as to how to gather enough information to determine a flood warning should be issued. However in Chapter 8 there are less strong ideas on dissemination. Reliance on UK, USA, or Australian systems may not be acceptable to NT villagers who are already less than enthusiastic on Flood Sirens. We need to gauge how NT villagers would react to receiving flood warnings otherwise the technically sound forecasting system may be doomed to failure. We need to know this before we embark on pilot testing. Perhaps DO/N can assist in gauging local reactions, and opinions.	We will be adding to flood dissemination proposals in Chapter 4 in our Final Working Paper. We would be delighted if DO/N could provide some assistanace on the acceptability of flood warnings to the public.
F2.16 Para 9.3 A flood warning based on RTFF disseminated independently with the heavy rain oriented flood warning may cause confusion to the public.	Provided a clear warning dissemination procedure can be established by the Consultants in collaboration with DSD and RO, there need be no confusion. What is required is a local flood warning dissemination system specifically for the Indus basin. We agree that the public must be clear of what they are being warned and to what area and period of time such warnings related. The dissemination system will have to involve a major programme of public education.
F2.17 Reference A copy of Reed (1984) for our information would be appreciated.	A copy of this report together with other key papers can be obtained from BMC.
F3 APPENDIX A	
F3.1 Para A.38 A full title of Moore et al (1990) does not appear in the list of references.	A copy of the paper referenced is available from BMC.
F3.2 Para A.43, Sentence 2 Can we see these time series so as to share this suggestion with you?	We will forward the time series data through BMC as requested.
F3.3 Para A.43, Last Sentence The explanatory variables should also include wind direction, atmospheric pressure at sea level.	Noted. See paras 3.18 and 3.19 of the Final Working Paper.

Comments	Responses
F3.4 Other Comments Ideally, according to WMO-No. 704, to forecast the marine and freshwater influences deterministically in tidal rivers, the interactive coupling of an open sea hydrodynamic surge model, a bay/estuary model, a hydrodynamic river model and a hydrologic model is required. You are now concentrating on the last two types of models. We are aware that RO has a nested storm surge model comprising an open coastal model whose outputs will be fed into a single layer vertically integrated bay model. You may like to consider using this deterministic model to generate sea levels at Tsim Bei Tsui.	We believe that the WMO comments relate primarily to the design flood case, not that of RTFF. Because of the short lead times involved on the Indus Basin, there is a need to forecast storm surges during some flood events only for some 4 to 6 hours ahead. It is neither necessary nor feasible to use a full deterministic model for this purpose in the case of an RTFF system. An ARMAX time series model provides suitable accurate surge forecasts for short lead times and we believe this option should be adopted for the pilot study RTFF system. RO have emphasised to us the problem of modelling storm surges deterministically, hence the suggestion that we use an ARMAX model.

G. Drainage Services Department, Design Division

Comments from Chief Engineer/Design, Drainage Services Department in letter reference (15) in SP 1/4/151 dated 22nd July 1991

Comments	Responses
G1 With reference to your letter reference NRT/0617/0/930 dated 1st July 1991, I have the following comments on your "Interim Working Paper on Real-Time Flood Forecasting for the Indus Basin":	
G1.1 Para 6.1 - Proposed Model Configuration In the 10th line, "The design models proposed for the PDM" should read as "The design models proposed for the BMP".	Corrected.
G1.2 Para 7.3 - The User Interface The users will most likely be in trouble if they have to operate the system for the first time without a comprehensive manual. Therefore the recommendation of a fairly brief user manual is not supported.	An adequate manual and training would be provided.

H. The Royal Observatory, Hong Kong

Comments from Director of the Royal Observatory, The Royal Observatory in letter reference ROG 7/89 dated 5th August 1991

Comments		Responses
H1	I refer to your letter dated 1st July 1991. A number of points are offered for your consideration. Because they have been discussed at the meeting held at DSD on 2nd August 1991, this brief list serves more as an aide memoirs than as a detailed exposition.	
H1.1	Input to RTFF Model	
2.	The failure of individual rain-gauges or river stage gauges should be allowed for.	Agreed and taken into account. See para 2.5 of the Final Working Paper.
3.	Simple schemes to generate "forecast" rainfall might be offered as a default before RO forecasts become available (para 7.4 and 7.7 relevant).	Noted and taken into account. See paras 3.25 and 3.26 of the Final Working Paper.
4.	The need to obtain rainfall data north of Shenzhen River for RTFF deserves further examination.	Agreed and will be highlighted.
	Operational Consideration	
5.	Para 7.9 - 7.11 and Figure 8 illustrate very well the hour-to-hour changes in the situation very commonly found in the operation of warnings. Procedures will have to be developed to avoid confusing the public by flip-flops in warning information.	Noted and taken into account. See Chapter 4 of the Final Working Paper.
6.	On the dissemination of warning, a target audience will have to be clearly identified and a matching dissemination network, probably hierarchical in structure like those already in place for typhoon warnings, etc, set up.	Noted and taken into account. See Chapter 4 of the Final Working Paper.
7.	Thoughts should be given to the issue of whether the Government Secretariat Emergency Coordination Centre should be involved.	Noted and would be addressed at pilot testing stage.
8.	In the interest of public safety, the Royal Observatory will give support to RTFF to the extent its resources allow. We have an open mind about the mode of operation of the warning service. This is a subject which DSD, RO and yourself could explore further.	Noted and would be addressed at pilot testing stage.

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