Wallingford Storm Sewer Package

Version for Jeddah, Saudi Arabia

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Summary

A new version of the Wallingford Storm Sewer Package has been developed for Jeddah, Saudi Arabia. In particular new models are incorporated in the Package to simulate rainfall-runoff, including models for percentage runoff, initial abstraction (depression storage) and time dependent runoff.

WALLINGFORD STORM SEWER PACKAGE

Version for Jeddah, Saudi Arabia

1. Background

1.1 In August 1982 the Hydraulics Research Station was commissioned by Sir Alexander Gibb and Partners to assist them in designing storm drainage services for a 45 km^2 area immediately south of the centre of Jeddah, Saudi Arabia. HRS, in co-operation with the Institute of Hydrology, undertook:

(a) to develop a version of the Wallingford Storm Sewer Package for the design and analysis of urban storm drainage which appears appropriate to the runoff conditions in Jeddah;

(b) to make a one-week visit to the site to assess drainage characteristics, to advise on data collection and to assess any rainfall-runoff records;

(c) to review the results of site data collection and advise on its suitability for modelling purposes and the changes required (if any);

(d) to generate a rainfall-runoff model based on the data collected;

(e) to make the model available for design and analysis runs;

(f) to provide support in using the model; and

(g) to contribute to the final report.

1.2 This report describes:

(i) the one-week visit made by Dr Price (HRS) and Mr Packman (IH) to Jeddah and the results of that visit;

(ii) the new rainfall-runoff model for Jeddah;

(iii) the amendments to the Program User's Guide, Volume 2 of Design and Analysis of Urban Storm Drainage: the Wallingford Procedure.

1.3 The first version of the software, including WASSP-CHK, -RAT, -HYD and -SIM, was installed on the Prime computer at Sir Alexander Gibb and Partners' office in Reading on 14 September 1982. The versions of WASSP-CHK and -CST were supplied on 5 November 1982, together with the versions of the other programs.

2. Visit to Jeddah by Dr Price and Mr Packman

The visit to Jeddah was made between 17-24 August during which time Dr Price and Mr Packman, together with Mr F Norman and Mr D Whipple of Sir Alexander Gibb and Partners visited a number of government offices in Jeddah collecting data and other information and spent time viewing the catchment under study.

2.2 Dr Price and Mr Packman's itinerary was as follows:

Wednesday, 18 August:

Visited: (a) the client: Mr Annas Moussa at the Municipality of Jeddah;

(b) Mr Ahmad A Siraj, technical advisor at the Meteorological and Environmental Protection Agency (MEPA);

(c) surface water pumping station;

(d) site.

Thursday, 19 August:

Visited: (a) Mr Michael Wuebbens, Project Manager, Huta Hegerfeld (Civil Engineering Contractors);

(b) Biokat (Civil Engineering Contractors);

(c) MEPA;

(d) site.

Friday, 20 August:

Trip to Taif, 120 miles inland from Jeddah.

Saturday, 21 August:

Visited: (a) MEPA;

(b) Mr Abdulla A Al-Amondi, Ministry of Agriculture and Water Research;

(c) Dr Kamel, Department of Meteorology and Water Resources, King Abdul-Aziz University;

(d) site.

Sunday, 22 August:

Visited: (a) Ministry of Agriculture and Water Resources;

(b) Mr J R Joslin and Mr N Munro, Watson-Saudi Arabia;

(c) University

Monday, 23 August:

Visited: (a) Huta-Hegerfeld (German Civil Engineering Contractors);

(b) Mr Fouad Abdul Baki, Deputy Marketing Manager, Amiantit (Pipe manufacturers).

2.3 Jeddah is one of the fastest growing cities in the world. With only 300,000 people five years ago, it now has a population of approximately 1,200,000. The land area covered by the city has expanded from about 20 km^2 of the old city to approximately 104 km^2 today. Considerable care has been taken over planning this expansion with a fine system of roads forming the basic infrastructure. The whole area gives the impression of being one vast construction site. The new international airport is now nearing completion 20 km north of the old city of Jeddah and is in regular use. A very impressive new Haj complex at the airport is also part completed. Between the city centre and the airport there are some fine individual houses occupying compounds typically of 1ha. The housing density increases towards the city centre with a few multi-storey blocks. The centre of Jeddah contains a mixture of old and new buildings. Attempts are being made to preserve some of the better old buildings, many of which have some excellent examples of wood trellis work around the windows. The construction of these houses is of mud, wood and stone and many are crumbling. South of the city is an area with the very high density housing of variable quality. The Islamic Port is also just to the south of the city, together with Petromin, the local oil refinery. A naval base is further south as is most of the industrial area for the city.

2.4 The new city of Jeddah occupies a coastal strip up to 5km wide, Fig. 2.1; inland there is a range of low hills intersected by wadis (ephemeral streams). To avoid building in the hilly area, the city authorities have reclaimed some of the marsh land adjacent to the sea. This area to the north of the city is largely being used for recreation and has an attractive road lay-out, picnic areas, lagoons, etc. To the west and south of the old city is the Islamic Port which boasts a deep water anchorage. Generally, therefore, the city is below the 30m contour with considerable areas below the 5m contour. Consequently, the water table is high relative to the ground surface, as evidenced by large areas of sandy open ground which appear damp. Open pools of water exist in the study area to the south of the city.

2.5 The drainage of Jeddah posed the city authorities with a dilemma. Annual rainfall is very small typically between 50mm and 100mm but most of the rain occurs during one event consisting of one or more thunderstorms. Flooding is usually generated by this event though the severity of the flooding is variable, both spatially and from event to event. Besides flooding generated by local rainfall, a complicating factor has been rapid runoff from the wadis which discharge their water through Jeddah to the sea. In 1968 Watson - Saudi Arabia recommended a system of storm water channels on the perimeter of the city to intercept flood water from the wadis. These channels, one going north and the other south and both discharging to the sea, have since been constructed and reportedly performed well during a severe event in 1979. Given this protection it remains to drain the area within that bounded by the channels. The dilemma for the city authorities is that although rain-fall is infrequent, increasing pressure is being brought by the inhabitants to preserve the roads from flooding, even though the duration of such flooding may be less than one day/year. Consequently, considerable sums of money are to be spent in providing storm drainage which, for various reasons, will have uncertain and infrequent performance.

2.6 Storm drainage already exists within the area bounded by the north and south channels. The areas currently served are parts of the city centre and to the north. The area south of the city has a trunk sewer through it, but with few connections at present. Watson - Saudi Arabia, who were commissioned to design the existing storm drainage as well as the master plan for the city(7), conceived a drainage strategy in which a network of a main trunk sewers (greater than 1,000mm) would have a few laterals draining identifiable depressions. Generally the trunk sewers follow the more important roads and consequently drain these also. This strategy is probably adequate for low density development, but Jeddah has expanded more rapidly than the planners originally anticipated and it is evident that the density of development is also going to be higher in some areas. Consequently, a revised strategy includes more laterals and hence a greater density of the drainage network. A complicating feature of storm drainage system in the city is the possible need for pumping to drain the low lying areas. This imposes a considerable overhead on the operation of the system and in the need for regular (annual) maintenance. Indeed maintenance of the whole network is an important consideration in design because of the infrequent use of the system. The Municipality has contracted Huta-Hegerfeld (a German civil engineering construction firm) to clean out and repair the existing storm drainage system. Their contract is currently for one year, though it would appear that similar contracts will have to be let on an annual basis.

2.7 As stated above, Watson - Saudi Arabia were responsible for the master planning of the storm drainage for Jeddah. They also have done the detailed design for the existing network including the only surface water pumping station serving part of the centre of the city. This pumping station was completed in 1980 and has not yet been tested in a significant storm event. Kattan-Gibb have now been commissioned to design storm drainage for the southern area of the city bounded by Maccah Road, King Khalid Street and the southern drainage channel but excluding the Petromin complex, the Islamic Port and the Naval Base, Fig 2.2.

2.8 The study area is approximately $45km^2$ and is currently drained by sewers 91, 92, 93 and 94 designed by Watson - Saudi Arabia; see Fig 2.2. The primary sewer is number 91 which is 8.5km long and runs along Mahjar Street, discharging to the sea through a gravity outfall. This implies that the sewer is surcharged for the last few kilometres. Under design storm conditions the surcharging may extend as far up as the Quarantine Hospital. Because the sewer is surcharged the area served is primarily above the 5m contour. The area below the 5m contour currently drains naturally to the sea. The alleviation of flooding in this area may have to be done by pumping. Other main drains will also be required to drain the higher ground not currently served by sewer 91. There exists the possibility that the southern storm water channel could be used to evacuate flood water from within the study area though this depends on the capacity of the channel and the design flow it intercepts from outside the area.

2.9 Data for the study are few. Although there are several rain gauges in the area most are read manually and read a maximum of 80mm without being emptied. (80mm seems to be a typical large storm). The best that one can hope for from these gauges is an indication of the hourly rainfall. Some recording rain gauges do exist and these give access to better resolution of the rainfall and the possibility of defining a depth-duration-frequency relationship and design rainfall profiles for the Jeddah area. This was not previously considered by Watson - Saudi Arabia who designed on a "maximum storm" concept.

2.10 There are no data on storm runoff other than visual observations and estimates. Watson - Saudi Arabia estimated a maximum flow in the south channel of 120 cumecs during the 1979 event. Eventually records from the surface water pumping station during a storm event coupled with simulation of the contributing network should throw some light on actual percentage runoff and times of flow over the ground surface.

2.11 Provisional estimates of percentage runoff from the study area following a site visit were in the range 40-70%. This may be significantly higher than adopted by Watson - Saudi Arabia in their design in sewer 91 which will reduce the effective area served by the sewer. The sewer, however, is probably over designed so there remains some uncertainty about the actual area served.

2.12 In conclusion:

(a) there are sufficient rainfall data to estimate depth-duration-frequency relationships for the Jeddah area;

(b) there are no data on rainfall-runoff so percentage runoff depression storage and other surface runoff modelling parameters have to be estimated;

(c) the existing surface water pumping station offers the future possibility that rainfall-runoff characteristics in Jeddah may be considered more objectively.

3. Rainfall-runoff Model for Jeddah

3.1 There are six aspects of the existing U.K. version of the Wallingford Storm Sewer Package, WASSP, which require careful assessment and revision before the package may be used overseas:

(a) design rainfall
(b) percentage runoff
(c) depression storage
(d) surface runoff
(e) sewered sub-area model
(f) rainfall-runoff frequency relationship.

These are now considered in turn.

4. Design Rainfall

4.1 The U.K. version of WASSP includes in-built data which enables the engineer to make use of design rainfall statistics for any location in the U.K. with the minimum of effort. This in-built data should not be used outside the U.K. Consequently alternative design data need to be derived for the overseas area considered. It is recommended that the engineer produces his own rainfall depth-duration-frequency curves and profiles and feeds these directly into the programs as data using the formats defined in the Program Users Guide for WASSP.

4.2 The rainfall regime of Jeddah and the Red Sea coast of Saudi Arabia is of a desert climate with a winter "wet" season and a strong topographic effect as the coastal plane gives way to foothills stretching up to an 1800m escarpment. Rainfall is sporadic and gauges sparsely distributed. In Jeddah itself there are two daily gauges, one installed at the original Jeddah airport in 1961, and one installed at the Jeddah Office of the Ministry of Agriculture and Water in 1970. Rain gauges are installed at most airports in Saudi Arabia, and maintained by the Ministry of Defence/Ministry of Environment General Directorate of Meteorology. In addition, the Ministry of Agriculture and Water (MAW) maintain a national network of storage, daily and recording rain gauges, several of which lie within a few hundred kilometres of Jeddah. Much of this data has been computerised, but no storm analysis has been attempted. More particularly, no depth-duration-frequency curves were available for Jeddah.

4.3 For earlier stages in the design of the Jeddah storm sewer system, Watson - Saudia Arabia had analysed the Jeddah airport record(7). They distributed daily depths to somewhat arbitrarily defined durations, and compiled a graph of mean intensity against duration. By incorporating further data from four MAW stations in the region of Jeddah (but at attitudes of 570 to 1940m when Jeddah is at 11m!) and including some typical U.K. data, they defined two separate design storms; one for the outskirts of Jeddah, and a similar but more intense storm for the central area. No attempt was made to define the frequency of these storms. Whereas their analysis was the best that might have been expected at that time, a more rigorous analysis can now be attempted. In particular, some idea of frequency of rainfall should be sought and any bias due to Watson's use of U.K. data trends when analysing additional MAW stations(7) should be removed.

4.4 The Jeddah airport gauge is the obvious source of data. Copies of annual summaries of daily rainfall were obtained from the General Directorate of Meteorology for the years 1961 and 1979. Also monthly recording sheets for the years 1970 to 1982 were examined, and observers' comments on storm durations noted. Unfortunately, monthly sheets for earlier years were unavailable being in transit from Dharan following computer processing. In addition, a copy of a paper by El-Sayed and Enani(2) was obtained. Using the airport record, El-Sayed and Enani examined the general climatic features of Jeddah rainfall. They deduced that the average number of rain days a year in Jeddah is 11, with only three days yielding more than 6mm. The corresponding average annual rainfall 61mm, with 85% falling in November, December and January, and 14% falling in a secondary wet season in April and May. They also compiled a list of total depth and duration for the 14 storms on record of greater than 25mm. However, without more information on rainfall bursts, a depth-duration-frequency analysis was impossible. El-Sayed and Enani call for an improvement in observer training, a co-ordination of data collection between the various authorities, and an upgrading of stations, providing back-up intensity gauges - a list of improvements regrettably not yet fully implemented. This list of storms has been expanded by including some burst information gleaned from observers comments, and is included as Appendix 1 of this report.

4.5 Besides the airport gauge, data were requested for several MAW stations in the region. For daily stations, the selection criteria were for coastal stations below 100m and within about 350km of Jeddah. For recording gauges the criteria were relaxed to include more stations. A list of the stations involved is given in Table 4.1 including station type (R-recording, D-daily), altitude, approximate distance from Jeddah, years of record, and approximate annual rainfall (mm).

Table 4.1 MAW stations for which data was requested

STATION NAME	MAW NO.	STATION TYPE	ALTITUDE (m)	DISTANCE (km)	YEARS OF RECORD	APPROX AN RAINFALL (mm)
Lith	J108	D	6	300	1967 →	99
Mastura	J111	D	55	350	1966 →	56
Sadiya	J115	D	60	150	1968-77	53
Showaq	J120	D	46	350	1966 →	98
Mojermah	J122	D	6	150	1966 →	61
Hammamah	J123	D	100	150	1968-72	70
Jeddah	J134	D	11	0	1970 →	48
Rabigh	J140	D	8	300	1969 →	22
Salah	J208	R	570	150	1966 →	160
Khulays	J211	R	60	120	1967 →	66
Mecca	J218	R	280	100	1969-80	73
Aziziyah	J219	R	125	130	1971 →	60
Midah	J220	R	470	175	1970 →	87
Usfan	J221	R	90	70	1971 →	56

4.6 Unfortunately, only monthly totals were received for the daily stations. For the recording stations 10 20, 30 minute; 1, 2, 3, 6, 12 hour; and 1 day falls were received for each notable storm. For the Salah, Mecca and Midah records, however, intensities were obviously less than at the lower altitude stations.

Frequency Analyses

4.7 The original intention had been to combine all the daily stations together, using the "station-year" approach, and thus define a regional 1-day frequency curve. A similar analysis of the recording gauges would yield proportions of 1-day rainfall expected in shorter durations. These proportions could then be applied to the regional 1-day frequency curve.

Any observers' comments on storm durations at the daily stations might give helpful support to the derived depth-duration-frequency curves.

4.8 In the "station-year" approach, short records from several stations are placed end-to-end to give a single, but longer record from which more stable frequencies may be derived. The method requires that stations are close enough to be representative of the same rainfall regime, but separate enough that their records are independent. Put simply, two stations are independent if the same basic storm yields depths at each station which do not rank of similar severity in each individual record. (Note that it is quite possible for two stations to be dependant at long durations, but independent at shorter durations).

The stations listed in Table 4.1 (with the exception of Salah, Mecca and Midah) were selected with the criteria of the station year approach in mind.

4.9 As a preliminary analysis, in the absence of daily data, frequency curves of monthly data were derived for each station (excepting Salah, Mecca and Midah). The aim was to examine consistency and independence between the stations, and though the results are discussed here they are not presented in full. In passing it may be noted that an error was found in the MAW record for Jeddah, where the November 1972 depth is entered at 15mm, while a well documented 83mm was observed at Jeddah airport on 3 November. In this and all subsequent analysis, to avoid splitting a single "wet season" into two separate years a July to June year period was adopted.

4.10 The analysis showed a considerable variation between the stations, larger than was expected. Some variability with monthly data might be expected, more than with daily data since climatic controls such as the number of rain days are of greater significance. Not surprisingly, those gauges furthest from Jeddah showed the most deviation from the norm, particularly Rabigh, Lith and Showaq. Accepting variation between stations in the mean of each station's data but not in variation about that mean, the analysis was repeated using standardised data, that is, each station data divided by the station mean. This time the scatter about the norm was less, but still considerable, with closest agreement between the very low altitude stations - Jeddah, Lith, Mojermah and interestingly Rabigh. With hindsight this would support the concept of mean rainfall varying with location along the coastal plane, and "growth factors" for variation about that mean varying with altitude. Equally however the whole scatter might be explained by statistical randomness.

4.11 Turning however to shorter period rainfall, the only suitable data obtained were for the daily gauge at Jeddah airport, and the three recording gauges at Khulays, Aziziyah and Usfan. A similar analysis to that described for monthly rainfall was applied to 1, 2, 3 hourly and 1-day data from the recording gauges. Several gaps in the Khulays record (albeit filled by correlation with nearby stations - usually Aziziyah) meant that the years 1973 to 1977 had to be discarded. For the same reason 2 years were discarded from the Usfan record. This time the analysis showed the three stations were consistent but that Khulays and Aziziyah were quite strongly dependent. For this reason the Aziziyah record was discarded, except for filling in some of the missing years for Khulays 1973 to 1977. The remaining records were combined end-to-end in the station-year manner (10 years of data from Khulays, 2 from Aziziyah, and 8 from Usfan) making a single 20 year record in all. The 20 largest rainfalls in durations of 10, 20, 30 minutes; 1, 2, 4, 6, 12 hours; 1 day and 1 month were abstracted and ranked in the conventional way. The resulting data sequences are given in Appendix 2.

4.12 As usual, each data point was ascribed a frequency depending on its rank position in the data sequence. Thus the highest value has a frequency of about once in 20 years, the second about once in 10 years, etc. In fact, the unbiased estimates of frequency are somewhat less than 1/20 and 1/10 since these rainfall depths might not have been exceeded if we had had more than 20 years of data. The actual frequencies depend on the underlying frequency distribution. For random rainfall depths occurring at random intervals, the expected distribution is the Poisson distribution, for which the time frequencies are given by:

$$\text{return period} \quad T = \exp \left\{ \sum_{j=I}^{N} \left({}^{1}/I \right) \right\}$$

where N is the total number of years of record
and I is the rank number.

In practice, rainfall values are plotted against $\ell n(T)$, which values are also given in Appendix 2. The resulting frequency curves are shown in Fig 4.1. Also shown in Appendix 2 and Fig. 4.1 is the 1-day sequence for the Jeddah airport record 1962-1982. (The common record length of 20 years is purely fortuitous and arises from having to discard the year 1962-1963 since the photocopy was illegible.)

4.13 Two things are immediately apparent from Fig. 4.1:

(i) the severe compresion in the combined Khuleys Azizyah Usfan record for durations about 180 minutes; and

(ii) the large discrepancy between the "combined" data and Jeddah data for return periods above 3 years.

The first implies a typical storm duration of about 3 hours. The second is discussed in Sections 4.1-22 below.

4.14 Smoothing the curves of Fig. 4.1, and taking off depths at return periods of 20 years, the values of Table 4.2 below were obtained. Larger return periods were not considered, not wishing to extrapolate beyond the range of the data.

TABLE 4.2 Depth-duration-frequency data from combined Khulays - Aziziyah - Usfan record

Return Period (years)	Duration (mins)						
	10	20	30	60	120	180	1 Day
1	8.0	13.0	15.0	16.5	17.3	17.5	18.0
2	11.5	18.5	21.5	27.0	30.5	32.5	38.5
3	13.0	21.5	26.0	34.0	40.5	44.0	50.0
5	15.5	25.5	31.5	40.5	48.5	52.0	57.0
10	18.0	30.0	36.5	47.5	55.5	58.6	63.5
20	21.0	34.5	41.5	53.0	61.5	64.0	67.0

4.15 The values in Table 4.2 are plotted as Fig. 4.2, on which the 1-day value is plotted at 18 hours or 1,080 mins. This is because the 1-day value corresponds to a fixed observation day, and not to "any 24 hour period" possibly crossing a day boundary. Thus 1-day depths could refer to any duration between the 12 hour data on Appendix 1 and a true 24 hour period. They have been plotted at the average value 18 hours. The effect is rather academic since the curves are very flat in this region anyway. (In other parts of the world, standard factors of 1.11 to 1.13 are used to increase the 1-day rainfall to 24 hour rainfall. In this case that would give 24 hour rainfall greater than the observed 1 month rainfall!)

4.16 Also plotted on Fig. 4.2 are the 1-day depths from the Jeddah record, and the storm data from Appendix 1. These serve to reinforce the point that the discrepancies between the combined and the Jeddah data are considerable. On seven occasions over a period of 23 years (about 1 year in 3), storms were observed in Jeddah that from the combined curves would have been expected only one year in 20. Some adjustment of the curves to match the Jeddah data better was obviously needed.

4.17 With so little depth duration data available for Jeddah, any attempt to adjust the results of Table 4.2 must be based largely on intuition. There are a number of ways in which adjustments could be made. Each "row" might be increased by a fixed ratio given by the 1-day values from the two records, or, considering the shorter durations could still apply to Jeddah, a variable ratio might be used, reducing to one at perhaps 1-hour or 10 minutes. Similarly, the frequency curves of Fig. 4.1 might be straightened at higher return periods (where the sampling errors are greatest) yielding a more consistent form of frequency curve across the durations. This last approach would have been adopted implicitly if the Gumbel distribution (for example) had been used in deriving the values of Table 4.2 from Fig. 4.1. However, the curvature of the frequency curves is considerable and appears to follow an increasing trend with duration. Moreover, it is mirrored in the Jeddah data. It sugests an upper limit on rainfall depth, governed by climatic controls, but it could be just a sampling phenomenon; the data sequences are short and derive from very few storms (three a year on average greater than 5mm).

4.18 To try and resolve these problems, the depth-duration-frequency data of Table 4.2 were examined more closely following the recommendations of Bell(1). Using information from several non-arid countries, Bell found that short duration rainfall, expresssed as a ratio of one hour rainfall, could be represented by a single relationship applying equally to each country and each return period. He also proposed a single growth curve relating T year to 2-year or 10-year rainfall depth. He deliberately excluded rain durations greater than 2-hours, but noted in passing some equations relating 1-hour to 1-day amounts. These implied a linear relationship in the Jeddah region, suggesting that the 1-hour: 1-day ratio from the combined record of this report could be applied to Jeddah 1-day values, and thereafter either Bell's ratio for shorter duration rainfall or the ratios derived from the combined record.

4.19 Bell's depth duration ratios have been verified in arid climates too. Table 4.3 gives values derived by Kappus et al(3) for the Persian Gulf; values derived from the Kuwait Ministry of Public Works depth duration curves and values derived by Wan(6) using data for Saudi Arabia itself. Wan used data from 18 stations on the West coast of Saudi Arabia, but mostly from the escarpment area mentioned earlier. He gives two sets of ratios, the first for stations having annual rainfall greater than 140mm, and the second for stations for average annual rainfall of 90-140mm (note that Jeddah has 50-60mm, Khulays, Aziziyah and Usfan 55-65mm). Wan's higher rainfall areas agreed with Bell's ratios, but to the lower rainfall areas where rain storms were shorter but more intense.

4.20 In this study, depth-duration values derived from Appendix 2 show quite marked variation with return period. Three sets of ratios have been included in Table 4.3, averages (a) over all the data, (b) over the top half of the data (i.e. return periods greater than 2 years) and (c) over the bottom half of the data. Differences between columns (b) and (c) were statistically significant. Comparing the ratios two points emerge. Firstly, the 1-day and even the 120 minute values of each set (a), (b) and (c) are much lower than the others, reflecting the generally shorter and more isolated storms. Secondly, while the overall ratios (column a) are in fair agreement with Bell's, more frequent occurrences tend towards Wan's ratios (dominated by short duration amounts) and rarer occurrences the opposite (a more even distribution). The different ratios for rare and frequent occurrences suggest different storm mechanism might apply.

Table 4.3 Depth-Duration ratios from various sources

Duration mins	Bell (1969)	Kappus et al (1978)	Kuwait MPW	Wan (1976) (a)	(ii)	Combined Record (a)	(b)	(c)
5	.29	.31	.30	.29	.37	–	–	–
10	.45	(.47)	.45	(.45)	(.55)	.43	.38	.49
15	.57	.57	.55	.56	.65	(.57)	(.52)	(.63)
20	.65	(.67)	.63	(.64)	(.73)	.68	.62	.74
30	.79	.81	.75	.78	.85	.81	.77	.87
60	1	1	1	1	1	1	1	1
120	1.25	1.34	1.28	1.20	1.20	1.13	1.14	1.12
1 Day		2.4		2.1	1.7	1.3	1.4	1.3

Figures in brackets were found by graphical interpolation between quoted values.

4.21 Turning to frequency analysis, Table 4.4 shows that support for Bell's single set of frequency factors is less consistent. For the combined data set, as already discussed, the shape of the frequency curve depends on the duration considered, with a distinct flattening at high return periods and long durations. Three sets of values are included in Table 4.4 - for durations of 10 minutes, 1 hour and 1 day.

Table 4.4 Depth-Frequency ratios from various sources

Return Period (yrs.)	Bell (1969)	Kappus et al (1978)	Kuwait MPW	Wan (1976) (a)	(ii)	Combined Record 10 min	1 hr	1 day	Jeddah 1 day
1	.83	-	.75	-	-	.70	.61	.47	.36
2	1	1	1	1	1	1	1	1	1
5	1.33	1.62	1.31	1.37	1.52	1.35	1.50	1.48	2.01
10	1.56	2.09	1.60	1.61	1.85	1.57	1.76	1.65	2.28
25	1.84	2.71	1.94	1.92	2.28	1.96	2.04	1.74	2.44

Generally, the curves for arid areas are steeper than Bell's; the one-day curves (Kappus, combined and Jeddah) are steeper than the others, until in the Jeddah area curves the "upper limit" mentioned earlier becomes significant. Overall it is difficult to conclude why Bell's findings of a constant depth-duration and a constant depth-frequency relationship should not be present in the combined data set. It may be due to the short records available, or due to fundamental differences in very dry climates. Without closer agreement transposition of Table 4.2 to Jeddah conditions remains a matter of some conjecture. It underlines the need for more good quality, short duration data.

4.22 Having considered these methods of adjusting the combined record, the approach finally adopted has been to accept the combined record, with all its idiosyncrasies, and to adjust separately for mean and frequency curve based on the relationships observed at 1-day and 1-month durations. The mean rather than the two year value has been used here because it is distribution free and considered more stable. In practice the difference is probably negligible. Firstly, the 1-day and 1-month means for Jeddah were found, from Appendix 2, to exceed the combined record values for factors of 1.14 and 1.07 respectively. Considering these as separate estimates of an underlying factor of 1.10, the depths in Table 4.2 could be increased accordingly. That is, the same factor as observed for daily and monthly data has been applied to hourly and 10-minute data (broadly what Bell would recommend). Secondly, dividing the 1-day and 1-month sequences of appendix 2 by their respective means, and plotting against log (T), it was possible to derive, for each record, a single growth curve applicable to both durations. As discussed earlier, a single curve cannot be applied to all durations, but the original curves from the combined data set may be adjusted using the rato of these "single" curves. That is, the same ratio of frequency factors observed for daily and monthly data has been applied to hourly and 10 minute data. Table 4.5 gives details of the adjustment.

Table 4.5 Adjustment factors based on rainfall durations 1 day to 1 month.

	RETURN PERIOD (YEARS)					
	1	2	3	5	10	20
Jeddah Growth Curve	0.29	0.80	1.18	1.61	1.82	1.95
Combined Growth Curve	0.46	0.93	1.23	1.34	1.45	1.53
Ratio	0.63	0.86	0.96	1.20	1.25	1.27
x Ratio of Means (=1.1)	0.70	0.95	1.06	1.32	1.37	1.40

4.23 Applying the final row of Table 4.5 to Table 4.2 and plotting as frequency curves the 5-year depth was found to be consistently above a smooth line through the other data points. Consequently, a reduced factor was applied. These final values were then plotted for durations up to 6 hours (see Fig. 4.3) and the storm data of Appendix 2 added. From this the fit was judged adequate, and the intensity-duration frequency data presented in Table 4.6 compiled. While the analysis has obvious shortcomings, the final values may be used with some confidence up to the 5 year return period.

Table 4.6 Jeddah rainfall intensities (mm/hr) at selected return periods.

Return Period (years)	Duration (mins)								
	2	4	6	10	20	30	60	120	180
1	46	43	40	36	27	21	11.5	6.0	4.1
2	79	75	72	66	53	42	26	14.5	10.3
3	104	99	94	86	68	55	36	21.5	15.5
5	141	133	126	114	90	73	49	29.5	20.8
10	180	170	162	148	120	100	65	38	26.7
20	217	205	195	177	144	116	74	43	29.8

Rainfall Profile

4.24 Depth-duration-frequency curves define only a total depth of rain in a given duration and not its distribution through that duration. In the U.K. version of WASSP a standard profile (the 50% Summer) is used to distribute the depth in time. This profile was adopted because:

(a) it was available - there was good short period data available from which a range of typical profiles had been derived, and

(b) it combined with the average value of the urban catchment wetness index, UCWI (used in runoff volume estimation) to give accurate estimates of the T-year peak discharges - peakier profiles, higher discharges, lower UCWI, lesser discharges.

For overseas use suitable profile information may not be available and likewise UCWI values. Anyway the dependence of percentage runoff on UCWI would not generally be appropriate since it is based exclusively on U.K. data. Where profile data are available sensitivity tests of a range of profiles, perhaps in combination with typical antecedent conditions, could be carried out to find a combination which matches observed T-year discharges. Where no profile data are available either the existing 50% summer profile may be used or one derived from depth-duration statistics. In climates similar to the U.K. the first alternative might be suitable. However, in Jeddah the use of depth-duration statistics would seem the only sensible solution. This might be thought to give a "worst case" storm with the T-year depth in each critical duration. Use of a typical storm can, however, give greater than T-year depths in sub-intervals. On balance the effect can probably be ignored.

4.25 Depth-duration statistics may give the depth in critical durations, but it still remains to decide on the form of profile - symmetrical or not. Urban flooding generally follows intense convective rainfall which is conventionally considered to have a skewed profile, with higher intensities at the start of the storm. Several standard profiles mirror this characteristic. However, the U.K. version of WASSP uses a symmetrical profile, and there would seem little justification to change. When a synthetic profile is being used it may as well be synthetically symmetrical! (Note exactly the same argument applies to the use of constant runoff factors - they may as well be synthetically constant.)

4.26 One advantage of using a synthetic profile based on depth-duration-frequency statistics is that only one duration need be considered - a long one. Storms of all other durations will be contained within it. However, this ignores the effect of an areal reduction factor. Bigger factors will apply to the longer durations, and thus longer storms will be (slightly) more intense. Thus using WASSP in the conventional way a 60 minute storm may surcharge upstream pipes designed to pass a 15 minute storm. A single suitable duration should, therefore, be selected at the outset.

4.27 For Jeddah, Appendix 1 suggests most storms are of duration 2-3 hours. This is supported by the compression in the frequency analysis for durations above 120 minutes. A 2 or 3 hour duration would, therefore, seem appropriate, with the longer duration recommended here in view of the size of the drainage area involved. Table 4.7 gives profiles for different return periods.

Table 4.7 Rainfall profiles for Jeddah

Return Period in Years

(Mins)	1	2	3	5	10	20
5	0.6	1.8	4.8	6.0	6.6	8.0
10	0.6	3.0	5.4	6.0	8.4	8.0
15	0.6	3.0	6.6	8.4	9.0	9.0
20	0.6	4.0	7.2	10.2	12.0	10.2
25	1.2	4.0	8.4	12.6	13.8	15.6
30	1.2	4.8	9.6	15.0	16.8	16.8
35	1.8	6.0	11.4	18.0	22.8	24.0
40	1.8	9.6	16.8	21.6	28.2	28.8
45	3.0	12.0	21.0	30.0	38.4	43.8
50	7.8	20.4	30.6	48.6	54.0	60.6
55	22.2	41.4	54.6	81.0	96.6	106.8
60	33.0	64.2	81.6	118.8	149.4	180.0
65	33.0	64.2	81.6	118.8	149.4	180.0
70	22.2	41.4	54.6	81.0	96.6	106.8
75	7.8	20.4	30.6	48.6	54.0	60.6
80	3.0	12.0	21.0	30.0	38.4	43.8
85	1.8	9.6	16.8	21.6	28.2	28.8
90	1.8	6.0	11.4	18.0	22.8	24.0
95	1.2	4.8	9.6	15.0	16.8	16.8
100	1.2	4.0	8.4	12.6	13.8	15.6
105	0.6	4.0	7.2	10.2	12.0	10.2
110	0.6	3.0	6.6	8.4	9.0	9.0
115	0.6	3.0	5.4	6.0	8.4	8.0
120	0.6	1.8	4.8	6.0	6.6	8.0

Areal Reduction Factor and Areal Filter

4.28 No data are available to define real reduction factors in Jeddah, but their effect is generally small and factors probably vary little from place to place. The existing U.K. factor might reasonably be used in Jeddah. By the same reasoning the same filter adopted in the U.K. version may be used (the filter after all is derived from the areal reduction factor). An interesting point does arise though, why not apply the areal reduction factor to the depth-duration-frequency curves before deriving the profile? In this way the filter would not be required. This indeed is done when depth-duration-frequency curves are used to derive estimated maximum precipitation. However, it should not be done with WASSP. When areal reduction factors are applied at minute intervals to a depth-duration curve, they may just yield an inflexion, giving an inverted peak to the rainfall profile. This indeed happended when the filter was first derived for U.K. data, and is why the filter parameter was set to a lower limit of 1/3.

5. Percentage runoff

5.1 The surface runoff of rainfall varies considerably over a catchment depending on the degree of impermeability of the surface, antecedent wetness, soil characteristics and other features. One way of determining the volume of runoff is to assign appropriate runoff factors to the areas contributing to each pipe in the sewer network. Alternatively, the percentage runoff from the whole catchment may be fixed and the runoff from various surfaces determined according to some specified rule. The U.K. version of WASSP adopts this latter approach by defining the percentage runoff from a regression equation based on data collected from urban catchments in the U.K. The regression equation includes such variables as the percentage impervious area, a soil index and an urban catchment wetness index. The runoff is distributed between the impervious and pervious areas such that if the runoff can be generated by less than 70% of the impervious area no runoff is assumed to come from the pervious area. If more than 70% is required the excess runoff above that generated by the 70% of the impervious area is distributed equally between the impervious and pervious areas.

5.2 A way of defining the percentage runoff for Jeddah is to make use of the curve number method devised by the Soil Conservation Service (SCS) of the United States Department of Agriculture; SCS(5). In this method the percentage runoff from a given area is defined by:

$$PRO = \frac{100Q}{P} = \frac{100}{P}\frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad (1)$$

where Q is the runoff in inches
P is the rainfall in inches
and S is the sum of the potential maximum retention (S') and the initial abstraction (Ia) (in inches)

5.3 To apply the curve number method to Jeddah, the soil must be classified into one of four groups: deep well drained; moderately well drained; moderately poorly drained; and poorly drained. Some guidelines for this classification are given by the SCS(5). Some soil particle analyses were obtained from Jeddah, showing quite a variability, with some free draining sands, but some sands badly clogged with clay particles. Overall the water table is high. In these conditions, the soil has been classified as moderately well drained, corresponding to a curve number 86 (for fallow or bare soil). The SCS recommend a value 98 for impervious areas. Corresponding values of S for pervious and impervious areas are 1.6279 in. and 0.2041 in. respectively. It now follows that for an area with percentage paved area X% the percentage runoff is given by:

$$PRO = \frac{100}{P}\quad \frac{(P - 8.27)^2}{(P + 33.08)}\quad 1 - \frac{X}{100} + \frac{(P - 1.04)^2}{(P + 4.15)}\quad \frac{X}{100} \qquad (2)$$

where P is measured in mm. For a graphical representation of Eq 2 see Fig. 5.1.

5.4 Also shown in Fig. 5.1 are some relationships attributed to Hoad (reference unknown, USA 1950 approx.). He gives three equations, for desert, "improved" desert and impervious areas.

$$PRO = \frac{0.3t}{t+20} \quad \text{or} \quad \frac{0.5t}{t+20} \quad \text{or} \quad \frac{t}{t+8} \qquad (3)$$

where t is rain duration in minutes. The equations are asymptotic to 30%, 50% and 100% respectively. Hoad's equations relate PRO to main duration, while the SCS equation uses rain depth. In order to compare the equations the two year depth-duration curve from Fig. 4.3 has been adopted. The agreement is remarkable, and gives support to the use of Fig. 5.1 in Jeddah.

5.5 The graph, however, should only be used as a guide; intuitively the values are rather high. For instance, for a 180 minute storm of three years return period, giving from Fig. 4.3 a rainfall depth of 46.5mm, percentage runoff of 40, 59 and 80% values closer to intuition. However, since with a storm profile derived from depth-duration-frequency statistics the half hour storm is contained within the three hour storm, the longer duration and the higher percentage runoff will always give the worst case. It is difficult to make a firm recommendation, but it is probably better to adopt percentage runoff figures from the depth of rainfall expected in a duration near to the time of concentration for the catchment. This indeed is probably the way Hoad intended his equations to be used.

5.6 Theoretically and practically the definition by the engineer of a percentage runoff from the whole catchment to the pipe in question is very attractive. Eq 2 above is an estimate of that percentage runoff for Jeddah. Obviously confirmation of Eq 2 or its revision in the light of recorded data would be extremely valuable and this gives urgency to the collection of data from the surface water pumping station on Sewer 71. As such data is not yet available and there remains some doubt about Eq 2 the software permits the approach of either Eq 2 or the specification of separate runoff factors for each area contributing to a pipe.

5.7 If a percentage runoff for the whole catchment is specified then the runoff is distributed between two types of surface. Rather than refer to these surfaces as paved and pervious it is preferable to label them as quick response and slow response. The road surface beneath which a sewer is constructed will be regarded as generating the quick response runoff, whereas the remaining area will generate the slow response runoff. A similar rule to that in the U.K. version is used to distribute the runoff between the surfaces except that the 70% is replaced with a value defined by the user in the Program Control Data (PCD) file.

5.8 If factors are used for each individual contributing area, whether fast or slow response, then the percentage runoff for the whole catchment is set to zero by the user. In this case an individual contributing area is multiplied by an appropriate factor depending on an index supplied by the user. There are two indices, one each for the fast and slow response surfaces, and either index can take the values 1, 2, 3 or 4. (If an index is left undefined it takes the default value of 1.) The actual values of runoff factor for each value of the indices are given in Tables 5.1 and 5.2.

Table 5.1 Fast response index

Index	Description	Runoff Factor
0, 1	High quality surfaced roads with gulleys approximately 50m apart	1.0
2	High quality surface roads with gulleys 100m or more apart	0.9
3	medium quality paved roads	0.85
4	Poor quality/improved roads	0.8

Table 5.2 Slow response index

Index	Description	% Impermeable	Runoff Factor
0	Default value		1.0
1	High density housing	50	0.55
2	Medium density housing	33	0.45
3	Low density housing and industrial development	17	0.35
4	Open area	0	0.25

5.9 The values for the runoff factor for the slow response areas correspond approximately to values which can be deduced from the SCS equation for a 2 year storm event with a duration of 140 mins, and therefore a depth of 30mm.

6. Depression storage

6.1 Without any rainfall-runoff data the determination of depression storage is similarly a matter of conjecture. We anticipate that typically depression storage will be a function of surface type and slope. Therefore, we have increased the U.K. values as shown in Table 6.1.

Table 6.1 Depression storage for fast response areas

Slope	Depression storage (mm)
mild (1 in 50)	1.0
medium (1 in 30) 1 in 50)	0.75
single (1 in 30)	0.5

The values in Table 6.1 are assumed to apply to all fast response surfaces. However, depression storages for the slow response areas are obtained by multiplying the values in Table 6.1 by 4.0.

7. Surface routing

Impervious areas

7.1 Surface routing in the U.K. version of WASSP uses two non-linear reservoirs, one for roofs and one for paved/pervious. The pervious response is not considered explicitly but lumped with the paved area (which was considered adequate for U.K. conditions). The non-linear reservoir is a relatively sophisticated model, requiring considerable computer effort to solve the equations. For more general application it is probably better to change to a simpler surface routing model allowing greater flexibility. A suitable alternative would be the linear reservoir, particularly in a quasi-linear formulation where the delay time depended on average storm intensity. This model indeed came a close second to the non-linear reservoir in an international workshop held at the Institute of Hydrology and organised by Kidd(4). In the report from that workshop an equation is given for the delay time based on length and slope. Subsequently more data has been collated and an equation on area and slope would now be preferable. Such an equation has been derived. A full description of the model is given in Kidd(4) and only a brief description is given here.

7.2 The linear reservoir is given by the equations:

$$\frac{dS}{dt} = i - q \qquad (4)$$

$$S = Kq \qquad (5)$$

where S is storage, t is time, i is rainfall input, q is outflow and K is the only model parameter, the delay time. The model has an impulse response given by:

$$U = \frac{1}{K} e^{-t/k} \qquad (6)$$

7.3 Solution may be by finite differences on the differential equation or by unit hydrograph techniques. Although the model is popular its linearity has been considered a drawback and several members have proposed quasi-linear forms where K depends on average rainfall intensity. Theoretical work has shown K should vary with $\bar{I}^{-0.39}$, where $\bar{I}$ is the maximum average rainfall intensity over a 10 minute period (in mm/min). In this case the storage equation may be written:

$$S = C\ \bar{I}^{-.39}\ q \qquad (7)$$

Table 7.1 Results of the U.K. sub-catchment analysis

Sub-catchment	Slope (%)	Length (m)	Area (m^2)	Cmin x(mm/min)$^{+.39}$
301	0.5	12.0	176	4.631
311*	0.5	12.0	196	3.285
2032*	3.1	25.0	320	1.674
2033*	3.0	10.6	90	2.241
2042*	2.4	25.0	450	1.659
2051*	2.2	45.0	346	2.891
1952	2.0	30.0	417	3.057
2061*	1.7	16.3	283	2.847
2062*	0.9	50.0	393	3.356
4175*	2.1	9.3	291	1.230
4176*	0.9	27.0	326	6.164
4177*	2.3	32.1	335	2.046
4276	3.3	8.6	82	1.133
4277*	4.1	6.1	78	1.563
4376*	3.1	10.6	306	1.958
4377*	2.3	13.2	413	2.281
4476*	1.6	10.2	277	1.896
4477	1.9	10.1	279	1.792
101	0.6	13.4	36	1.076
104	0.7	8.5	18	0.928
105	1.4	13.4	36	0.731
2161	0.8	20.0	240	1.819
2162	1.0	45.0	572	1.540
2150	2.1	45.0	763	4.046
2141	1.1	30.0	215	2.501
2142	1.3	28.0	145	2.085
2144	0.9	38.5	165	2.195

* These are the subcatchments used by Kidd(4)

7.4 Using data from 27 catchments from the surface response archive held at Institute of Hydrology, values of C were optimised and related to catchment characteristics. The model was solved by unit hydrograph techniques, having first converted the impulse response to a one minute response. Mean rainfall intensity $\bar{I}$(mm/min) was calculated over the most intense 10 minute period of each storm. The optimum C values for each catchment are given in Table 7.1, together with the catchment length, slope and area.

7.5 Using this data base, a repression equation was derived for C on slope and area.

$$C = 0.37 S_{\ell}^{-.278}\ A^{.374} \qquad \left\{C \text{ in min } \left(\frac{mm}{min}\right)^{+.39}\right\} \qquad (8)$$

where S_ℓ is slope % and A is area (m^2). This equation has a correlation coefficient of 0.69 and a factorial standard error of 1.44. Although this was the optimum equation, an equation in $A^{1/3}$ is frequently seen in the literature. For this reason a second equation was derived following the $A^{1/3}$ term.

$$C = 0.393\ S^{-.264}\ A^{.333} \tag{9}$$

The factorial standard error of this equation was also 1.44, showing it is only slightly sub-optimal, and may be adopted with negligible error. Although some of the catchments in Table 7.1 contained pervious areas their contribution is considered to be small and the equation is recommended for impervious areas. No separate equation for roof areas is proposed.

8. Sewered sub area model

8.1 The analysis of large sewer networks is made complicated by the considerable amount of data which has to be collected and prepared for parts of the network which are not of immediate interest. To reduce the amount of effort involved and to confine attention to the main trunk sewers, say, of a given network the U.K. version of WASSP includes a model to define the runoff from a sewered sub-area of the catchment without modelling the sewer network there in detail. This conceptual model is simple to apply and can be used for ares up to 150 ha or larger.

8.2 At this stage no such model has been developed for the overseas version of WASSP. However, the U.K. version of the sewered sub-area model is included and could be updated at a later time.

9. Rainfall-runoff frequency relationship

9.1 A key feature of the U.K. version of WASSP is the attempt to identify the return period of flow with the return period of design rainfall depth for a specified urban catchment wetness index. In the absence of rainfall-runoff data this exercise cannot be repeated and therefore the traditional assumption has to be made that the return period of flow is approximately the same as the return period of rainfall.

10. Amendments to the Program Users Guide (U.K. verion) for WASSPOS

10.1 Two main amendments to the U.K. version of the Program User's Guide are required, namely those dealing with the contributing areas and the event data.

10.2 Contributing areas

Ignore Sections 3.5.3 and 3.5.4. Replace these sections with the following:

3.5.3(a) Fast and slow runoff response

The whole of the area contributing to a particular pipe is viewed as being made up of two types of surface: one having a fast and the other a slow runoff response. In general the paved road surface along the pipe should be regarded as having the fast runoff response and the remainder of the area as having the slow runoff response. For this reason the surface with the fast runoff response will be referred to below as the "paved" area and the surface with the slow runoff response will be regarded as the "permeable" area. The size of the area with the fast runoff response is defined as a percentage of the total contributing area to the nearest percent. The programs then calculate the size of the area with the slow runoff response as the difference between the total area and the area with the fast runoff response.

An index may be used to distinguish between different types of fast response areas. This index, referred to as the "paved index", is defined in Table 3.0(a).

Table 3.0(a) Paved index

Index	Description
0	100% runoff, or default value
1	High quality surfaced roads with gulleys approximately 50m apart
2	High quality surfaced roads with gulleys 100m or more apart
3	Medium quality paved roads
4	Poor quality paved roads

A similar index, termed the "permeable index", may be used to distinguish between high, medium and low density housing, industrial and open areas. This index takes the values given in Table 3.0(b).

Table 3.0(b) Permeable index

Index	Description
0	100% runoff, or default value
1	High density housing
2	Medium density housing
3	Low density housing and industrial areas
4	Open area

Items 17, 18, 19, 20 and 21 in Table 4.5 describing the input on record 4 of the complete pipe data need corresponding amendment as follows:

Item number	Description of input	Column numbers	Format
17	Fast runoff response (or paved) area as a percentage of the total area (Section 3.5.3(a))	62-64	Integer
18	Flooded area as percentage of total area (Section 3.5.5); if zero or left blank flow does not return to the manhole and is lost to the system, if = -1 the manhole is pressurised and no flooding occurs	65-67	Integer
19	Index defining the fast runoff response or "paved" index (see Section 3.5.3(a), Table 3.0(b))	69	Integer
20	Index defining the slow runoff response or "pervious" index (see Section 3.5.3(a), Table 3.0(a))	70	Integer
21	Ground slope index (Section 3.5.6; see Table 3.1); if zero or left blank the built-in value of 1 is used; if = -1 then the linear reservoir coefficients in the surface runoff model are read from the PCD file and over-ride the built-in values	71-72	Integer

Please note that items 1 to 16 and item 22 remain as specified in the U.K. version of the Program User's Guide.

10.3 Event data

Ignore Sections 7.5.2, 7.5.3 and 7.5.8. Replace these sections with the following:

7.5.2(a) Volume runoff data

The volume runoff at the outfall is fixed by the user who specifies a percentage runoff for the whole catchment area, or is generated internally by the software or is determined by the software as the cumulative effect of separate runoff factors as defined by the user for the different surface types of the individual contributing areas.

If a percentage runoff, PRQ is specified, the distribution of runoff between the fast and slow response areas is affected by the choice of percentage runoff coefficient, PRC. This coefficient is defined such that if all of the runoff may be generated by less than PRC/100 of the total of the fast runoff response (or "paved") area, then it is assumed that there is no contribution from the slow response (or "pervious") area. If, however, the runoff volume is generated by an area greater than PRC/100 of the total "paved" area then the volume generated from areas in excess of PRC/100 of the total "paved" area is distributed between the "paved" and "pervious" areas.

This distribution is done by the computer such that X% additional "paved" area is used together with X/(1 - PRC/100)% of the "pervious" area, and X is determined to achieve the correct volume at the outfall.

If the percentage runoff is not used then the runoff factors for the individual areas are defined by the values of the "paved" and "pervious" indices given in Table 7.1(a) and 7.1(b):

Table 7.1(a) Paved area runoff factors

Index	Runoff factor
0, 1	1.0
2	0.9
3	0.85
4	0.8

Table 7.1(b) Pervious area runoff factors

Index	Runoff factor
0	1.0
1	0.55
2	0.45
3	0.35
4	0.25

7.5.3(a) Linear reservoir storage coefficients

The linear reservoir storage coefficients may be defined within the programs without any action being taken by the user. The user may, however, override these values by specifying his own values for the fast and slow runoff response areas. The specified values are then used for all areas and are treated as constants.

Table 88 needs replacing as follows:

Table 8.8 Input on record 22 - Surface runoff parameters

Item number	Description of input	Column numbers	Format
1	Percentage runoff (Section 7.5.2(a)); if = 100 and percentage runoff coefficient is zero or left blank then runoff factors are used for individual areas; or if zero or left blank and percentage runoff coefficient is zero or left blank then the percentage runoff is calculated from the SCS method	1-10	Decimal
2	Percentage runoff coefficient (Section 7.5.2(a)) recommended value -70; if zero or left blank and percentage runoff is zero or left blank then runoff factors are used for individual areas or percentage runoff is calculated from the SCS method	11-20	Decimal (1)
3	Antecedent condition index (Section 7.5.4)	30	Integer
4	Storage coefficient for paved areas (Section 7.5.3(a)); if zero or left blank the storage coefficient is determined by the programs	31-40	Decimal (3)
5	Storage coefficient for pervious areas (Section 7.5.3(a)); if zero or left blank the storage coefficient is determined by the programs	41-50	Decimal (2)

Ignore Table 8.11

11. Conclusions

A new version of WASSP appropriate for use in climatic conditions other than the UK has been developed. In particular, a version has been developed for Jeddha, with particular attention given to:

a) the analysis of existing rainfall data; and

b) the generation of an alternative surface runoff model based on the linear reservoir concept

The documentation for WASSP has been updated to take into account the alterations made to the software.

The complete lack of any suitable runoff data for Jeddah and other locations in Saudi Arabia makes it imperative for this and other storm drainage projects that effort should be put into storm runoff data collection. An opportunity does exist in Jeddah to collect such data from the surface water pumping station serving a catchment in the centre of the city. If data on pumped volumes can be acquired for observed rainfall events it should be possible to determine the percentage runoff for the remaining areas of the city with more confidence.

12. Acknowledgements

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13. References

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APPENDIX 1: JEDDAH STORM DATA

Date	Depth (mm)	Duration (min)	Source
21.11.59	26	95	2
29.12.62	55	180	2
07.04.63	25	105	2
08.11.65	38	380	2
09.11.67	28	60	2
17.04.68	56	110	3
	88	604	2
14.12.68	33	50	2
	40	139	3
05.01.69	45	205	2
22.01.69	76	137	2
	79	202	3
11.01.70	36	180	2
04.02.71	48	360	1
	52	540	1
	74	720	1
	83	1080	1
03.11.72	40	30	3
	83	170	1
13.12.77	55	60	1
17.02.78	57	45	1
	67	115	1
16.01.79	80	300	1

Data Sources given in order of priority.

1 - observers notes on monthly recordings sheets
2 - El-Sayed and Enani (1979)
3 - Watson Saudi Arabia (1974)

Note:
- Recording sheets not available at the time of this study for 1959-1970.
- El-Sayed and Enani table gives depth in total storm duration only.
- Watson Saudi Arabia information used for shorter duration information only.

APPENDIX 2: FREQUENCY DATA FROM COMBINED KHULAYS-AZIZIYAH-USFAN RECORD AND FROM JEDDAH

Combined Record: Depths in mm — JEDDAH

Rank \ Duration (mins)	10	20	30	60	120	180	360	720	1 Day	1 Month	$\ln(T)$	1 Day (Jeddah)	1 Month (Jeddah)
20	26.0	35.6	46.6	64.0	64.0	67.4	67.4	67.4	67.4	75.4	3.6	88	125
19	19.6	31.6	36.6	46.8	59.4	61.0	61.0	61.0	67.2	72.2	2.6	86	102
18	15.8	30.6	36.6	44.2	52.6	56.0	56.0	56.0	61.0	70.8	2.1	83	99
17	15.0	27.4	32.4	41.2	49.6	53.0	53.4	53.4	56.0	70.0	1.76	80	93
16	14.8	25.2	32.2	41.2	46.8	52.8	53.4	53.4	53.4	67.4	1.51	79	83
15	14.0	25.2	30.2	39.2	43.4	50.4	52.8	52.8	53.4	66.4	1.31	67	75
14	13.4	23.4	25.4	37.8	41.2	45.0	45.2	50.0	52.8	63.0	1.15	56	67
13	13.0	20.4	25.4	36.4	40.0	42.0	45.0	50.0	52.8	59.2	1.00	55	56
12	11.8	18.8	24.8	32.6	35.4	35.6	39.0	45.2	45.2	56.8	0.88	45	55
11	11.6	17.0	23.0	26.2	30.6	33.6	38.0	38.0	38.0	53.4	0.77	40	46
10	11.4	17.4	20.4	26.2	30.4	32.2	35.6	35.6	37.4	48.8	0.67	38	40
9	11.4	17.2	20.2	22.8	27.6	30.4	35.2	35.2	35.6	43.4	0.58	36	38
8	11.4	16.2	20.2	22.6	27.0	27.0	33.2	34.6	35.2	40.6	0.49	28	34
7	11.2	16.6	19.6	22.0	24.2	24.6	27.0	27.0	27.0	40.2	0.42	25	33
6	10.2	16.0	19.0	20.6	23.2	24.4	27.0	27.0	27.0	35.8	0.35	24	33
5	10.2	15.8	18.8	20.4	22.8	23.6	26.2	26.2	26.2	35.6	0.28	22	29
4	10.0	15.0	17.0	20.0	22.6	22.8	23.6	23.6	23.6	33.4	0.22	22	25
3	8.8	15.2	16.2	19.0	22.0	22.6	22.8	22.8	22.8	30.6	0.16	20	20
2	8.8	12.6	15.6	17.6	17.6	17.6	22.6	22.6	22.6	30.6	0.10	20	20
1	8.0	12.0	15.0	17.6	17.6	17.6	17.6	17.6	17.6	26.6	0.05	20	18
MEAN	12.8	20.4	24.8	30.9	34.9	37.0	39.1	40.0	41.1	51.0		46.7	54.5
S.D	4.2	6.6	8.5	12.5	14.0	15.3	14.5	14.8	15.9	16.3		25.4	31.8

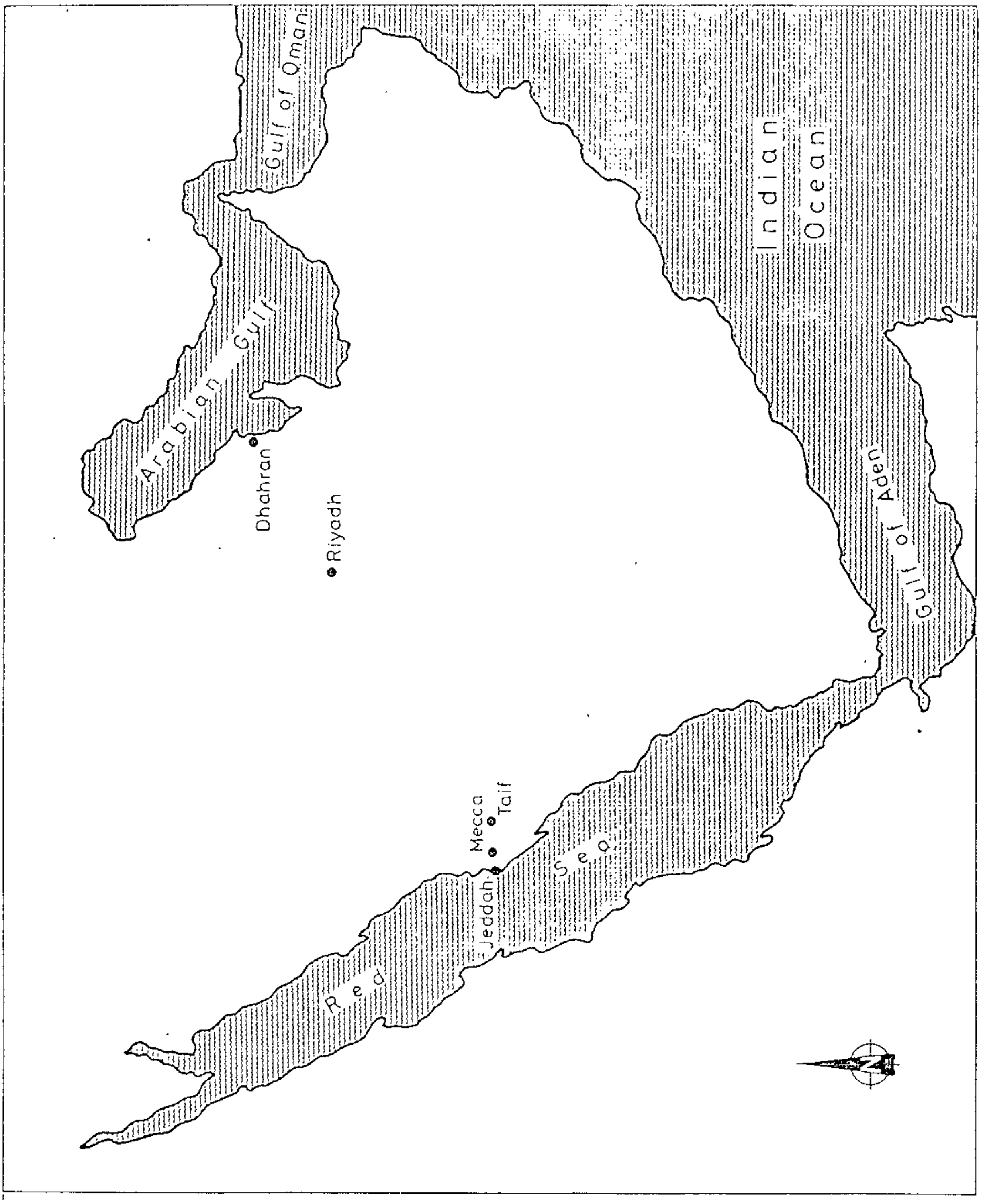

Fig 2.1 Location map

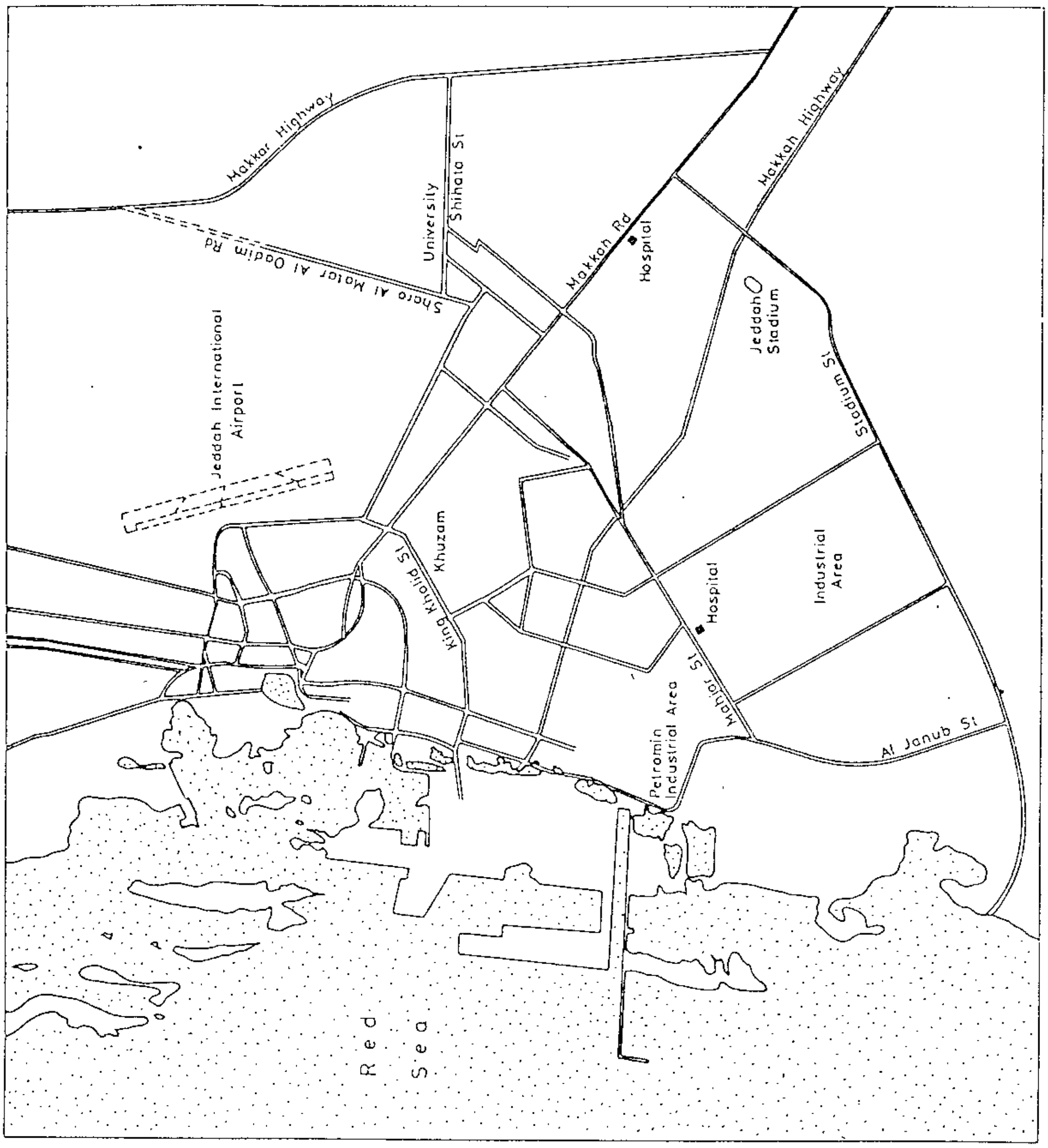

Fig 2·2 Study area

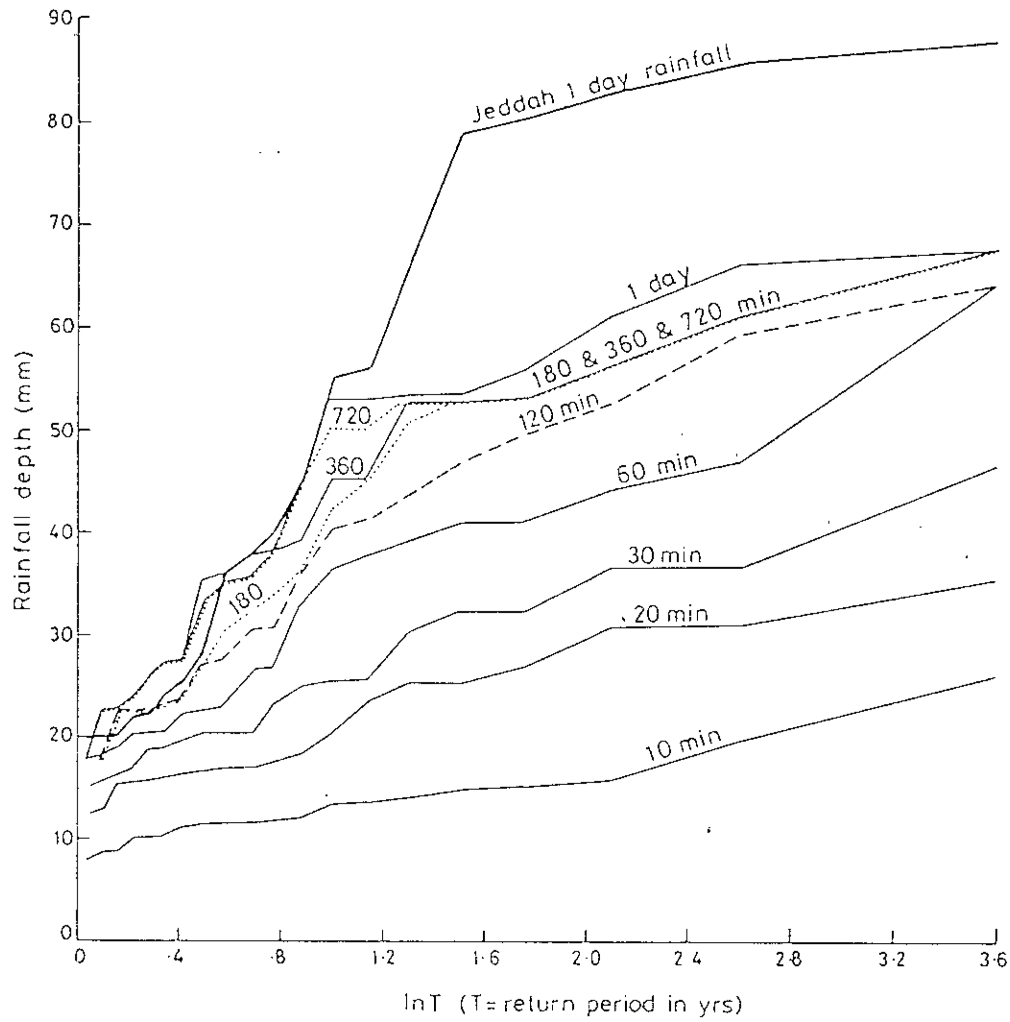

Fig 4·1 Frequency curves for combined record

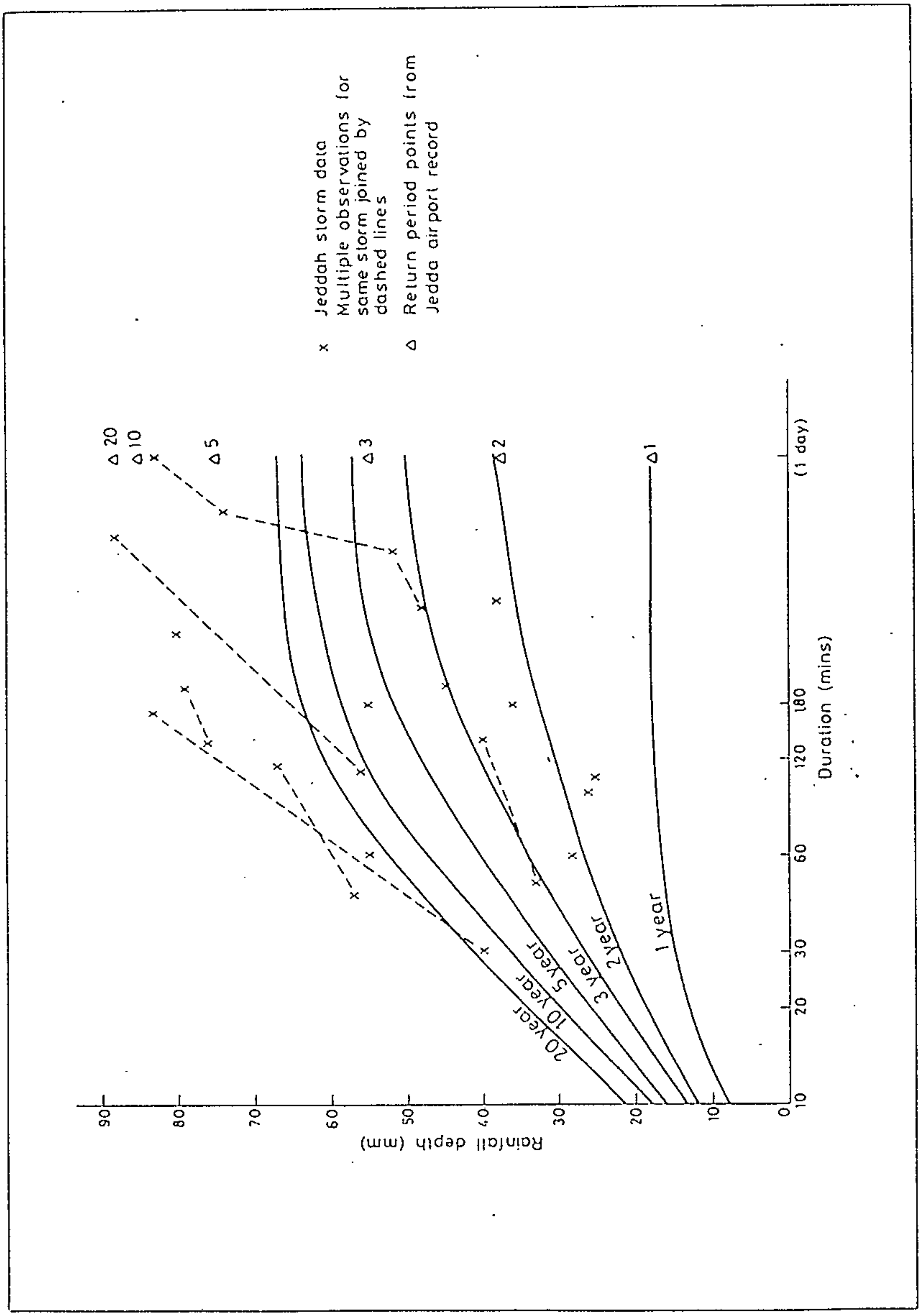

Fig 4·2 Depth-duration-frequency curves for combined record

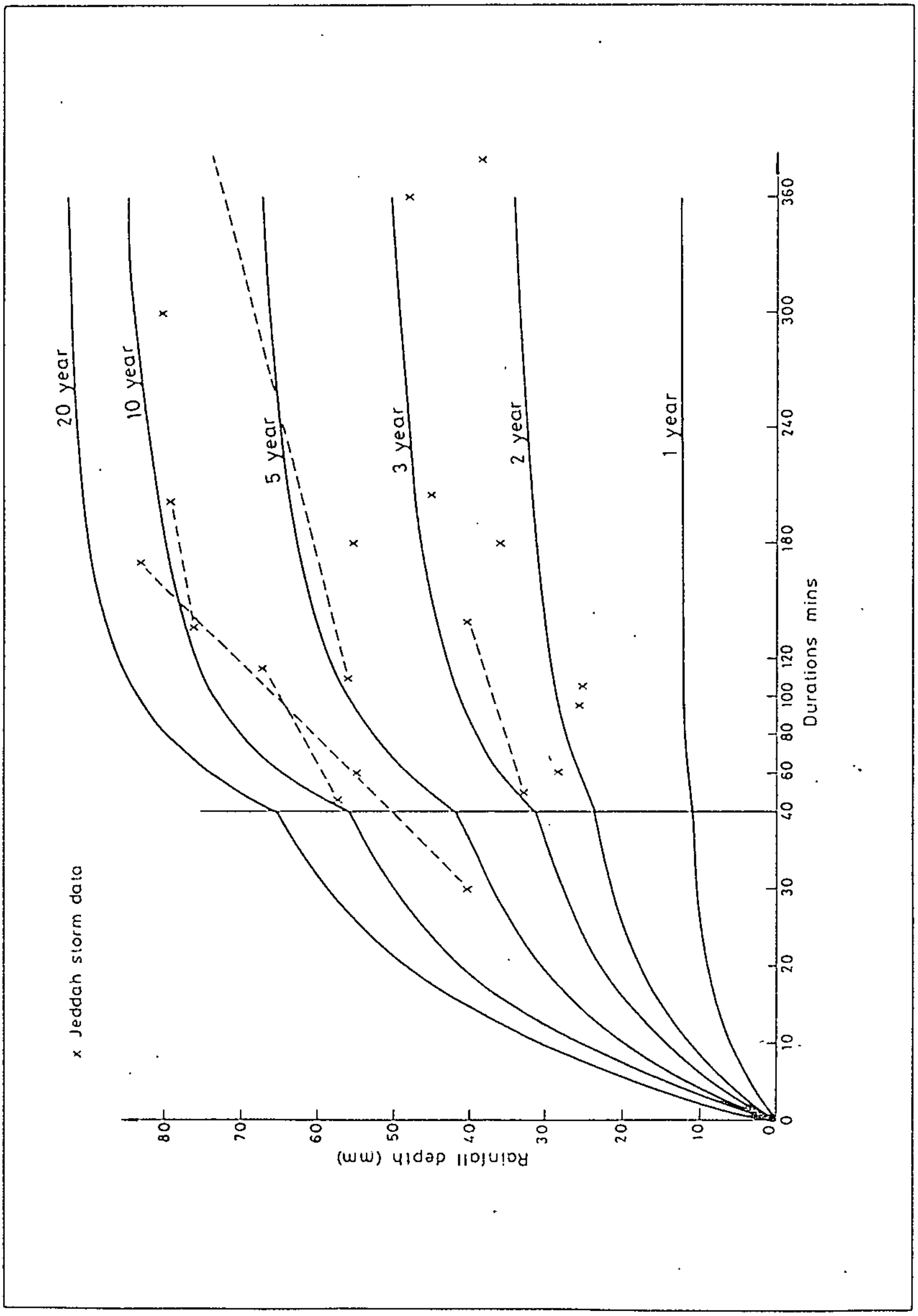

Fig 4·3 Final adjusted depth-duration frequency curves

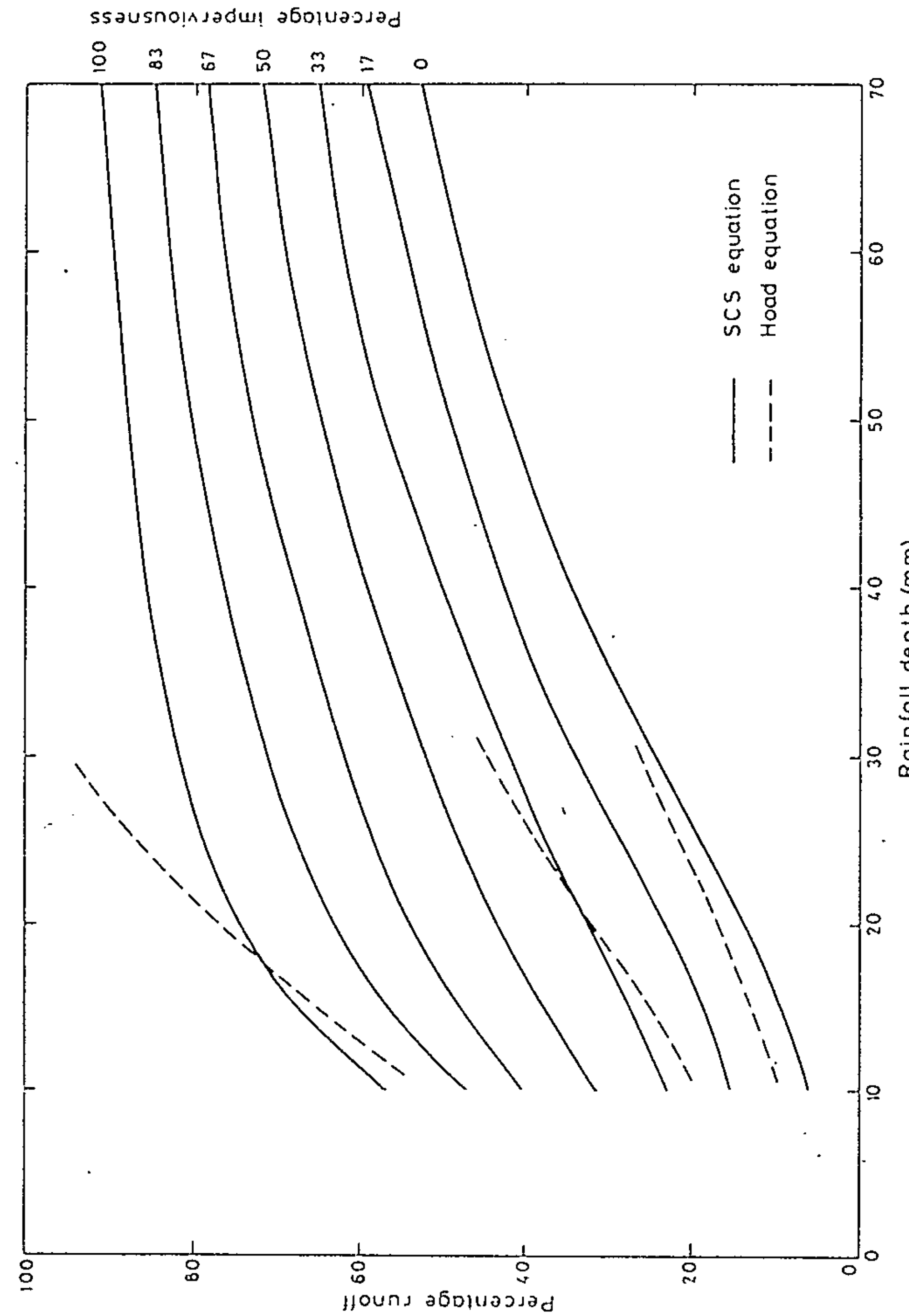

Fig 5·1 Percentage runoff for Jeddah