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TIME SERIES RAINFALL

RECENT CASE STUDIES AND RESEARCH DEVELOPMENTS

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1. INTRODUCTION

In many investigations of sewer system hydraulic performance it is necessary to gain insight into the behaviour of the system under day to day rainfall conditions. Representative Time Series Rainfall (TSR) sequences, suitable for use with WASSP and appropriate to a number of UK regions were developed for this purpose[1] and these have received fairly widespread use in drainage area studies over the last two years. These rainfall series, which each represent a 'typical' year, have proved especially useful when investigating the spill characteristics of existing storm sewer overflows (SSOs) and in planning upgrading schemes featuring SSO rationalisation.

The series have also been used in a number of other applications, including:

- estimation of pollutant loadings to receiving waters (from both SSOs and surface water sewers),
- pump station optimisation studies,
- design of headworks storage in coastal sewer systems,
- design of detention tanks to reduce SSO discharges,
- assessment of storm overflow compliance with EC Bathing Waters requirements.

It is important to remember that the existing series do not contain any particularly extreme events, i.e. greater than approximately one year Return Period. It has been recognised, however, that many applications will demand assessment of more extreme historic events in addition to the day to day TSR events.

Such applications may include

- assessment of frequency of storm discharge to bathing waters following system upgrading,
- design of storage tanks.

2. RAINFALL REQUIREMENTS FOR STORAGE DESIGN

In-system storage may be considered an appropriate solution to a range of hydraulic and pollution problems. Storage tanks have been used for

- flow attenuation to prevent downstream flooding,
- flow attenuation to reduce discharges from downstream overflows,

- flow balancing at treatment works,
- retention of pollution at overflows.

The most appropriate volume for a storage tank depends on the functional requirements of the tank and on the nature and quality of the receiving watercourse. It is normally acceptable to have tanks installed for the prevention of pollution of inland watercourses spilling several times per year whereas similarly frequent spillage of tank overflows to bathing waters may be considered unacceptable. Tanks with a flood relief function may require to fill only very rarely, for example once in five years or more.

Each requirement demands different design criteria and hence rainfall input to arrive at a satisfactory tank volume. The two case studies described below provide examples of:

(i) storage designed using a 'typical' annual series and
(ii) assessments of system performance and storage requirements using a longer record of local data, including extreme historic events.

3. CASE STUDY 1 - DUNFERMLINE DEVELOPMENT AND APPLICATION OF AN ANNUAL SERIES

A major criticism of the existing rainfall time series developed for use with WASSP has been that the data from which the series were derived was only available for a few locations.

To provide more applicable data for eastern Scotland a series was developed using data from a gauge located at Falkirk. Charts from a syphon recording raingauge at this location had been converted into one minute interval rainfall data similar to that used in earlier studies. Data from other sites were considered, the nearest being at Bishop Auckland and Newcastle. However it was felt that, although the rainfall variation would probably be similar for all three sites, they were so distant that the resulting series would be little better than the original north east region series.

The basic data from Falkirk was filtered, giving a statistically reliable 'average' year from which rainfall events can be selected. This series is in effect an east of Scotland series which can form the basis for series at other locations within this area. It was transferred to Dunfermline (approx 30km away) by using a simple ratio of SAAR values for the two sites.

The full 'average' year contains innumerable trivial quantities of rainfall of which only a relatively limited number form significant events. The depth and intensity criteria for separation of events will be determined by the use to which the series is to be put. The particular requirement in this case was for storm pollutant retention tanks and events were extracted by applying the following rules:

Minimum intensity	1.50mm/h
Minimum depth	2.00mm
time between events	25 min.

These criteria resulted in identification of 22 events for Dunfermline. For micro-WASSP however, this number of events would result in undue run times and a PCD file was prepared using the 10 greatest rainfalls (see Table 1). Some modification of the data was necessary to reduce the duration of the events to 480 minutes, a restriction of the version of micro-WASSP used in this study. Standard equations for API5 and UCWI were applied, with the series data being used for the former and monthly average Dunfermline SMD values for the latter.

DUNFERMLINE SEWER SYSTEM

The sewer system of Dunfermline comprises two main branches, the Tower and Lyne Burn sewers. The two branches are relatively steep for most of their length, however in the area of their confluence gradients are flat, a factor which restricts rehabilitation options. The system causes severe pollution of the local water course, the Lyne Burn which is Class 2[2] for most of its length reducing to Class 4 close to the confluence with the Forth estuary. In addition to the poor pollution performance parts of the system surcharge badly.

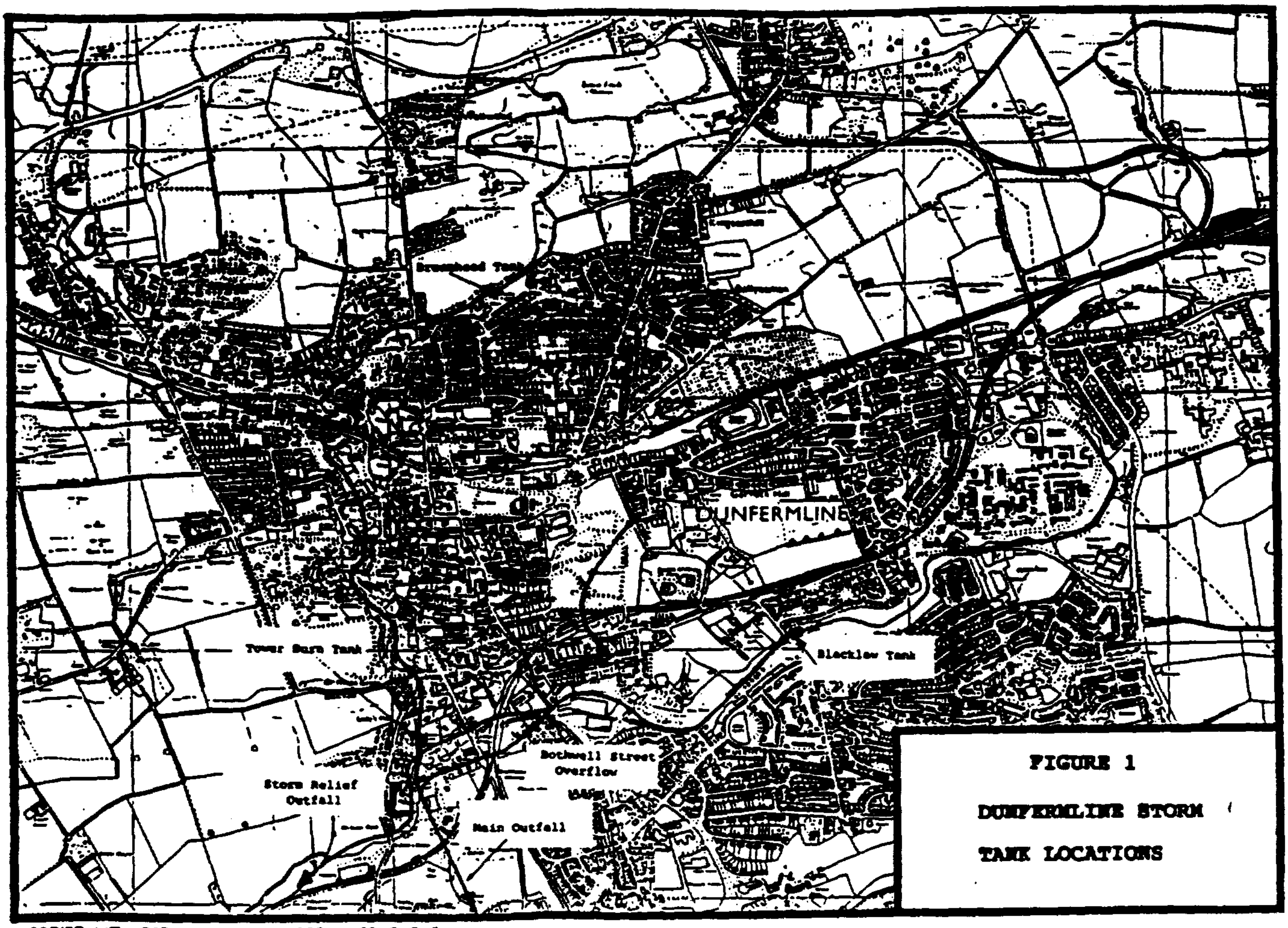
The Tower Burn branch has a conventional tree structure and is laid for part of its length in a stream bed. This leads to excessive infiltration and surcharging in the lower reaches and sewer renewal is being undertaken to rectify both of these problems. An offline tank was constructed at Broomhead (see Figure 1) in 1985 to reduce pollution from an intermediate overflow. This tank was sized according to the standard practice of 80 litres/head[3].

The main Lyne Burn system comprises two parallel interconnected pipes nominally for separate foul and storm flows respectively. In the 1960s the single combined system was surcharging badly and a storm relief sewer was constructed in parallel. The twin pipes are interconnected by at least 10 low side weir overflows and other cross connections. As a result the relief sewer carries excessive quantities of foul sewage, yet with the number of cross connections there is no obvious simple solution to control the resulting pollution. In addition the Towerburn system contributes combined storm sewage to the relief sewer via two low side weir overflows. The Lyne Burn receives excessive foul discharges from the relief outfall resulting in the watercourse being of Class 4.

STORM TANK SIZING

To reduce the number of storm sewage discharges into the relief sewer two new storage tanks are to be constructed. Performance requirements for these tanks have been difficult to specify due to the complexities of the system and because any one of the series of improvements under way will only have a marginal effect on the stream quality. In Scotland, consent must be obtained from River Purification Boards for discharges, however in this case where no new discharges will result and pollution is reduced, the river board has only advisory powers.

In view of the complexities of the system, a rather blunt approach has been adopted for tank sizing. WASSP models for parts of the system above each tank have been developed and verified in the normal manner. For the Tower Burn the WASSP model was used with design storms to evaluate new pipe sizes for the surcharging section referred to above and the model for the renovated system was run with the TSR.



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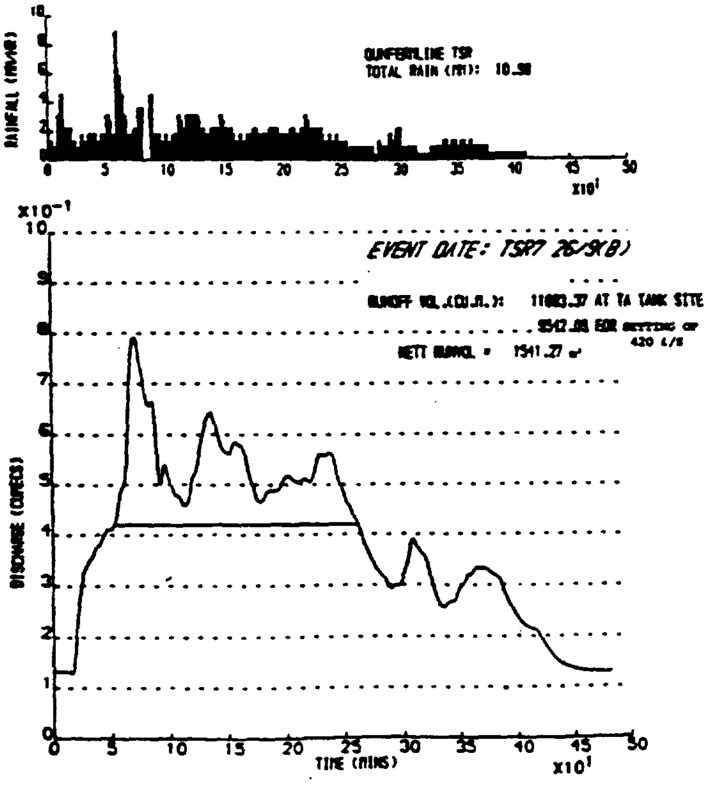


FIGURE 2 Example TSR hydrograph - Towerburn Tank

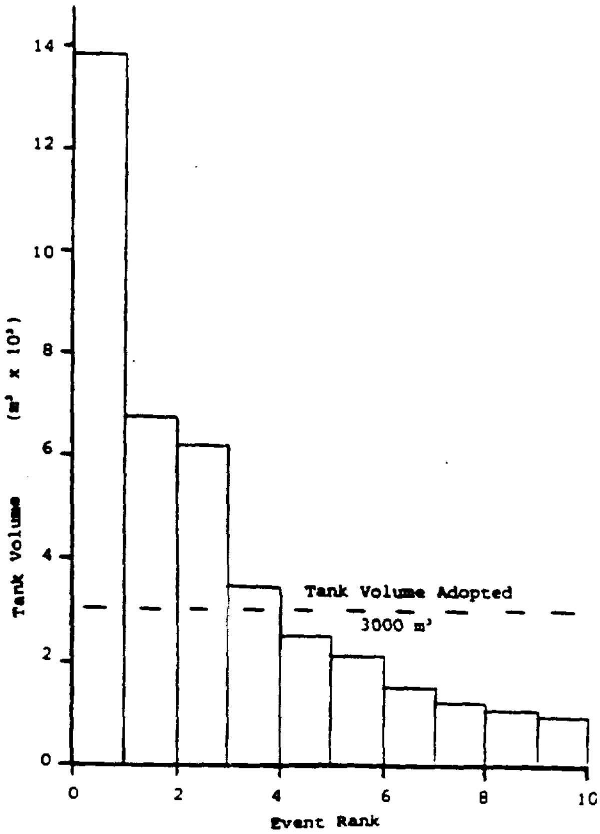


FIGURE 3 Towerburn Tank - Volume required for greatest events in annual series

The 10 most severe storms in the series were used for simulation, a tedious process on micro-WASSP. The output from WASSP was run through a short routine to determine the volume of flow above the overflow setting for each event. This approach is very simplistic and will overestimate the volume for an online tank, but it is reasonably appropriate for offline tanks. A plot of a typical TSR output hydrograph with the tank volume required for that event is shown in Figure 2. The results of this exercise were used directly to determine the volume for the offline Tower Burn tank. Table 2 details the flows and volumes resulting from the TSR runs and was used for tank sizing. Figure 3 shows the ranked volumes necessary for each event and enables the influence of a variation of tank volume to be evaluated. The volume selected from this information was 3,000 cubic metres giving an anticipated four spills per year.

Table 1 - Time series rainfall summary
Dunfermline

Event no	START DATE	START TIME (hhmm)	END DATE	END TIME (hhmm)	Duration (min)	Depth (mm)	Average Intensity (mm/h)
1	31 Mar	1 - 54	31 Mar	9 - 53	480	17.65	2.21
2	11 Jun	8 - 2	11 Jun	16 - 1	480	12.63	1.58
3	24 Aug	17 - 53	24 Aug	20 - 45	172	6.56	2.29
4	19 Sep	22 - 10	20 Sep	6 - 13	479	34.48	4.29
5	23 Sep	11 - 30	23 Sep	19 - 30	480	21.40	2.68
6	26 Sep	14 - 49	26 Sep	22 - 43	473	20.84	2.64
7	26 Sep	23 - 14	27 Sep	6 - 12	412	11.08	1.59
8	3 Oct	17 - 30	3 Oct	21 - 21	230	6.85	1.79
9	24 Oct	0 - 0	25 Oct	8 - 8	479	14.76	1.82
10	3 Nov	14 - 25	3 Nov	18 - 45	261	7.30	1.68

Events have been selected on the basis of:

Minimum intensity (mm/h) : 1.50
Minimum depth (mm) : 6.50
Time between events (min) : 25

Table 2 - Summary of TSR outputs for Toverburn tank

EVENT	RAINFALL DEPTH (mm)	PEAK FLOW TANK SITE (m^3/s)	TOTAL RUNOFF VOLUME (m^3)	RUNOFF VOLUME AFTER SETTING DEDUCTED (m^3)
31/3	17.58	0.907	14909	3461
11/6	12.49	1.197	11666	2528
24/8	6.52	0.723	8010	1344
19/9	34.43	1.524	25545	13808
23/9	21.32	1.082	17690	6207
26/9	20.77	1.234	17418	6694
26/9	10.98	0.794	11083	1541
3/10	6.80	0.858	8216	1010
24/10	14.66	0.880	13230	2174
3/1	7.21	0.921	8497	984

4. SYNTHESIS OF RAINFALL SERIES USING HOURLY DATA

As mentioned above there are few sites in the UK which have an adequate record of 1-minute rainfall data and this necessitated the development of relatively crude regionalisation procedures[1]. There are, however, over 200 stations having long records of hourly rainfall data available from the Met. Office. This pool of data offers potential for:

- improved regionalisation
- extension of the series beyond 1 year to examine more extreme events
- examination of antecedent conditions prior to extreme events (e.g. likelihood of storage being partly full prior to the design storm).

Clearly the blocks of hourly data cannot be used in conjunction with WASSP as they stand and a disaggregation procedure is required to distribute the rainfall depth within the hour. Such a procedure has recently been developed by WRc with assistance from Newcastle University.

The details of this profile generation model are beyond the scope of this paper and are available elsewhere [4, 5], however an outline description of its capabilities and application is appropriate here.

A sensitivity analysis, based upon volumes spilled at SSOs in a number of test catchments indicated that rainfall data at 5 minute intervals gave virtually the same precision as data at 1 minute intervals. It was therefore decided that disaggregation of profiles to a 5 minute time base was appropriate.

A series of rules was developed to allow synthesis of rainfall profiles within each hour. These were based upon an extensive analysis of 1-minute rainfall data series for a number of sites in Southern Britain. A programme was developed to allow realistic distribution of observed rainfall depths within each hour according to a number of criteria, principally:

- location (eastern or western UK)
- season
- total rainfall during the event

- duration of event
- maximum hourly intensity during the event
- position of hour considered within the event
- depth of rain during the hour considered.

Rainfall distributions also include a considerable random element and this was maintained within the methodology by basing the distribution structure upon observed rainfalls.

Figure 4 shows a rainfall profile generated by the model compared with the true observed 1-minute data and hourly intensities. Obviously the rainfall depth observed during a single event may be distributed according to any number of profiles and this will have implications for the volume of spill predicted at an overflow or the size of tank required to store excess flows. The "Rainfall Profile Generator" model was therefore assessed by applying it to WASSP models of 3 test catchments using

(i) an annual series of observed 1-minute rainfall data

compared with

(ii) 5-minute data generated from hourly totals given by the same series.

These tests confirmed that, over a number of events, the generated profiles gave virtually the same total SSO spill volume and spill frequency as the 1-minute observed data. During individual events, however, the spill could be considerably under or over predicted although the volume was within ± 10% for about half of the events, with very good predictive performance for the more extreme events. Figure 5 illustrates how the model performed for one year of data in the Great Harwood test catchment (pop 12,500).

Techniques for applying the methodology are being refined but the basic steps may be summarised as:

(i) Obtain a record of hourly rainfall and daily SMD data from the Met. Office for the site considered. This is available on diskette at a cost of about £50 per station year.

(ii) Screen significant rainfall events from the record using depth and duration criteria.

(iii) Apply the profile generation software to the selected events, thereby generating 5 minute sequences.

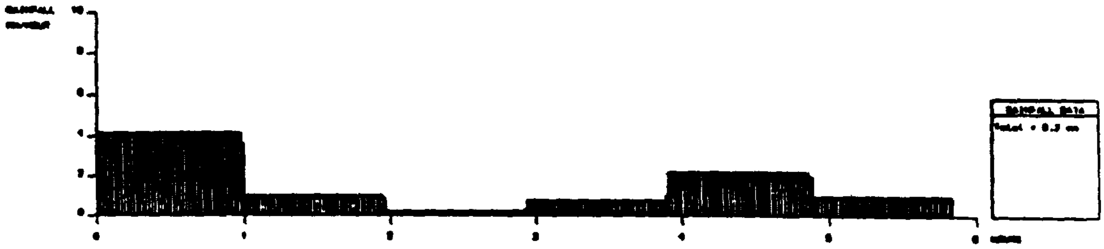
(iv) Calculate UCWI from SMD and rainfall data for each event.

The whole procedure has been computerised, allowing generation of WASSP input files for any number of events automatically selected from the record.

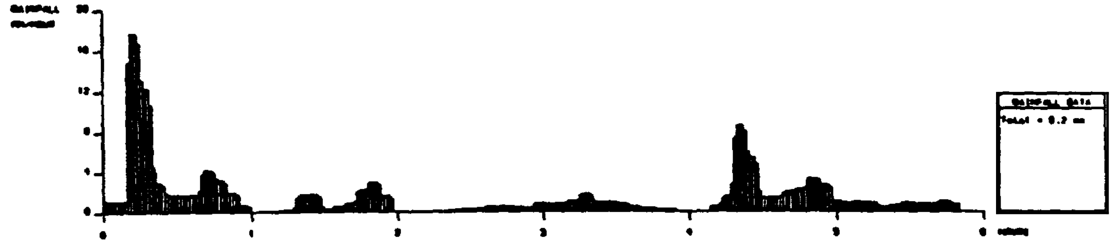
To summarise, the procedure allows selection of events of any magnitude from a long, local record of hourly data and prepares realistic rainfall profiles in WASSP format. Each event is accompanied by observed antecedent conditions, therefore it is unnecessary to assume a design UCWI value.

FIGURE 4 Example rainfall profile generated from hourly data

(a) Observed data at 1 minute intervals



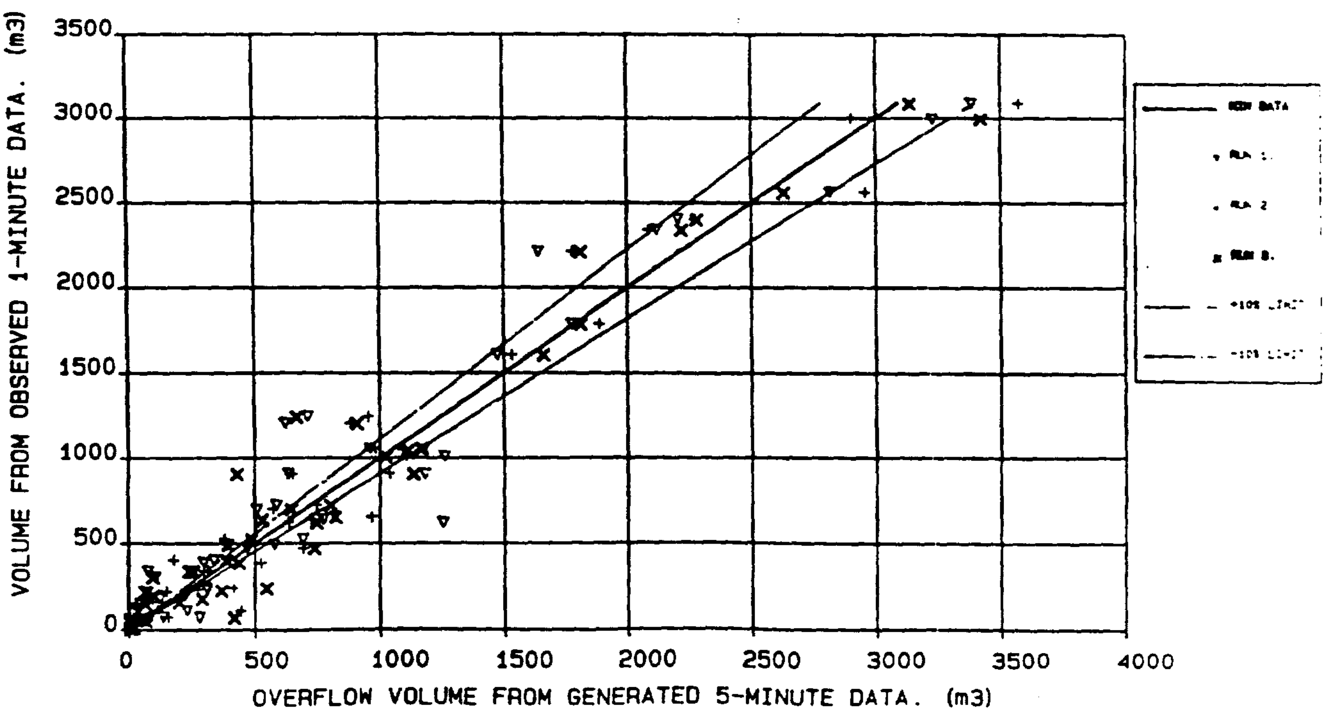
(b) Observed data for same event at hourly intervals
(standard Met. Office format)



(c) Synthetic data at 5 minute intervals
(produced from hourly data)

FIGURE 5

COMPARISON OF OBSERVED AND GENERATED OVERFLOW VOLUMES.



5. CASE STUDY 2 - LYME REGIS

APPLICATION OF HOURLY RAINFALL DATA AND TSR

BACKGROUND

South West Water (SWW) are developing proposals to upgrade the severage system serving Lyme Regis in order to prevent flooding and to ensure compliance with EC Bathing Water Directives. The preferred option may require construction of a long sea outfall, headworks, storm outfall, on line storage tanks and reseverage. The cost of these works is considerable and an indication of the performance of these proposals is required to assess the impact on bathing water quality.

The proposed scheme would involve quite frequent operation of the storm sewage outfall. To quantify this, WRc produced a volume-frequency curve for discharges from the storm outfall.

CATCHMENT DESCRIPTION (See Figure 6)

The Lyme Regis catchment is a mainly combined system which serves a resident population of about 5,500. The summer population is projected to grow to 17,000 by the year 2031.

The catchment presently drains to a point near the River Lim and thence to sea via a short gravity outfall. The main trunk sewer is generally in poor structural condition and suffers infiltration from both river and sea. Hydraulic overloading of the system has been relieved by means of some 12 storm overflows to the River Lim and to the beach; it has been estimated that some of these currently operate up to 50 times per annum.

The upgrading option examined had the following principal features:

(a) Severage

* Replacement and enlargement of a number of sewers, particularly the main spine sewer running down the river valley.
* Separation of certain areas from the combined system.
* Elimination or resetting all overflows to the river.
* An in-line tank at Horn Bridge, capacity 250m³.
* An in-line tank at Cobb Gate, capacity 300m³.
* Connection of the effluent flow from Uplyme STW into the head of the system.

(b) Marine Treatment

* A headworks near the mouth of the River Lim with pumping capacity of 185 litres/second to the long sea outfall and 2000 litres/second to the storm outfall. Any flows exceeding 2000 litres/second would be spilled directly to the sea via an overflow at the headworks.

APPROACH ADOPTED

The method adopted for the study had three main elements:

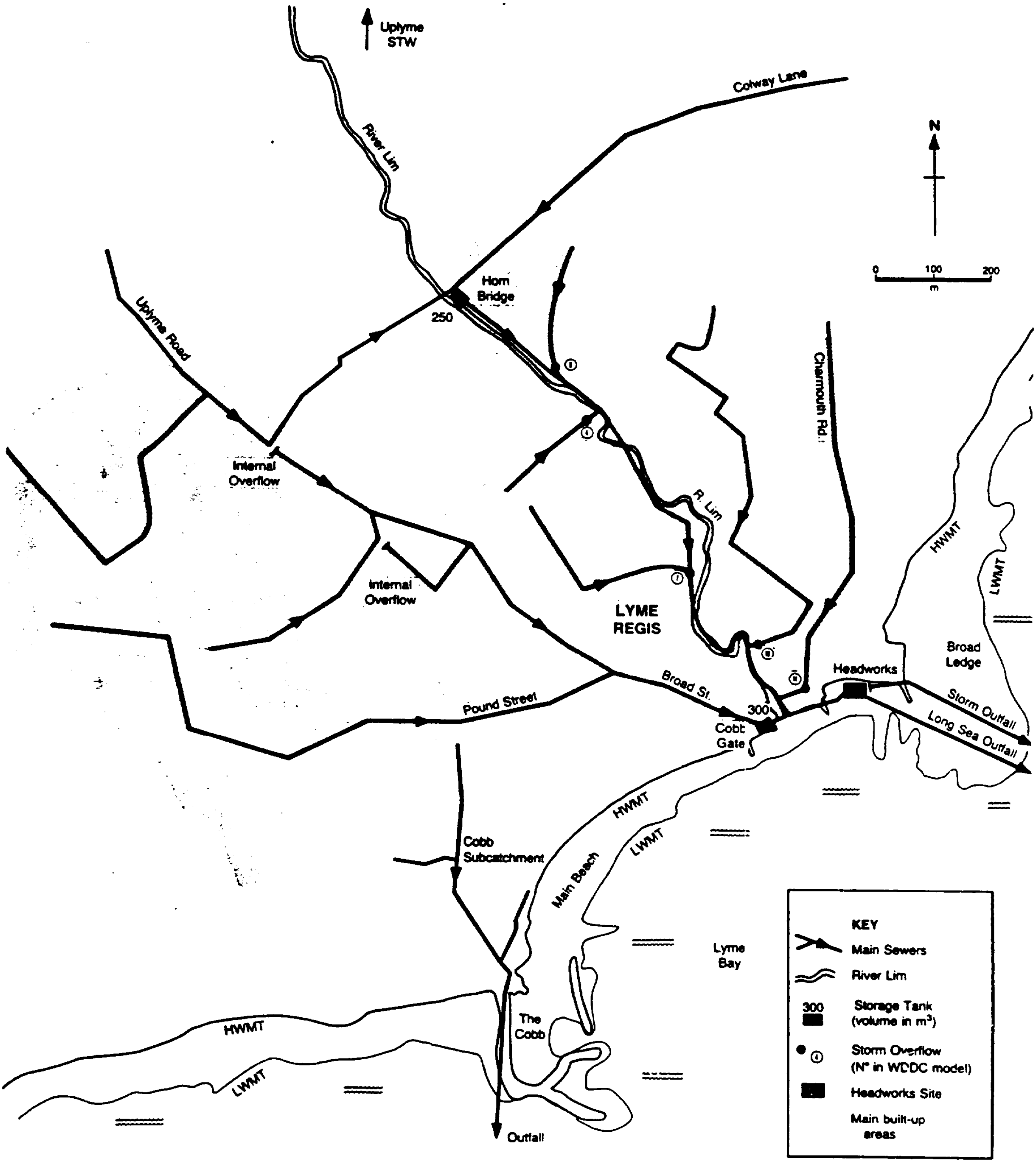


FIGURE 6 Lyme Regis sewerage system following upgrading

Step 1 - Rainfall Analysis

A 14 year local record of hourly rainfall data (1974-87) was obtained from the Met. Office. This was used to provide frequency estimates for historic (summer) storms of different depths, durations and intensities.

Step 2 - WASSP Analysis

This fell into two main areas:

(a) The Lyme Regis WASSP model was run for a number of design storms and also the 30 largest historic storms from the 14 year record to check the effectiveness of the reseverage proposals. This made use of the procedures outlined in Section 4.

(b) The response of the system, in terms of the volume of storm discharges to sea, was determined for a number of historic (summer) storm profiles taken from the existing Annual Rainfall Time Series [1]. A relationship was derived to explain this spill response in terms of the depth, duration and intensity of the rainfalls.

Step 3 - Probability Analysis

The relationship derived in Step 2(b) was used to estimate the storm discharge volumes for each of the 560 significant historic rainfall events defined in Step 1. The events were ranked by volume discharged and a volume/frequency curve produced.

In this way the average number of events per summer which would cause discharge to the storm outfall was calculated. In addition, probability analysis followed an estimate to be made of the number of such events likely in a "bad" summer (defined as having a probability of once in 20 years).

Sensitivity checks were carried out to see how this curve might be modified by changes in storage and pumping.

CONCLUSIONS

The principal conclusions from the analysis are shown in Figure 7 and 8 and are illustrated in the examples below.

FIGURE 7 AVERAGE FREQUENCY OF STORM DISCHARGES PER SUMMER AS A FUNCTION OF HEADWORKS STORAGE AND DRY WEATHER FLOW

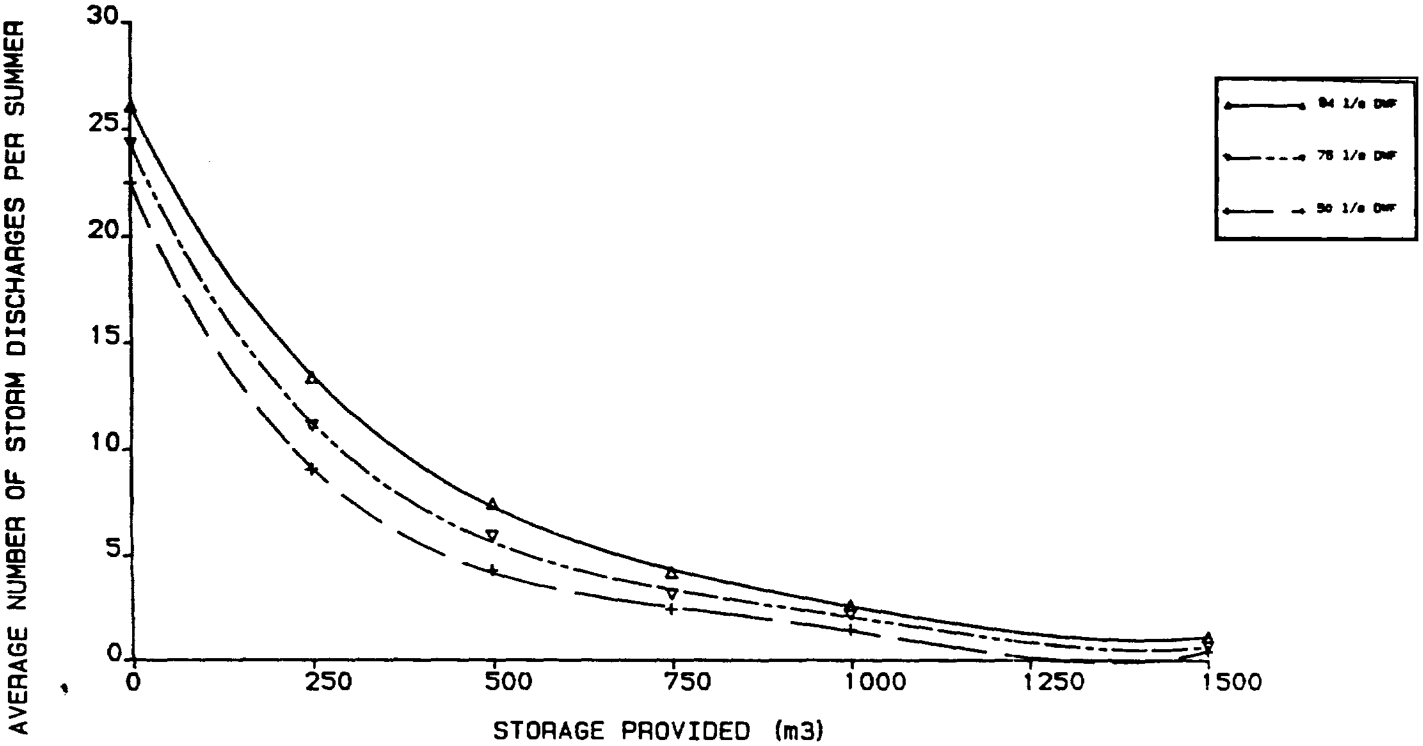
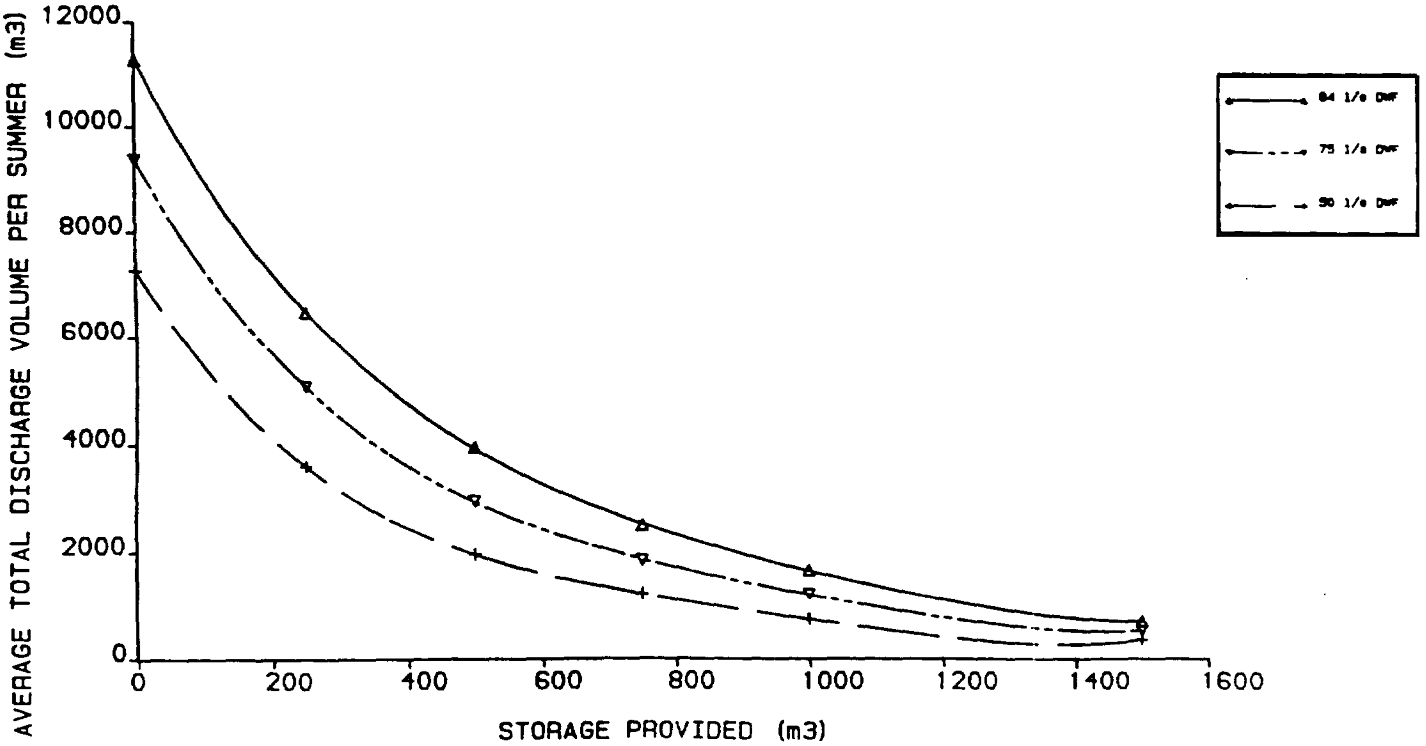


FIGURE 8 AVERAGE DISCHARGE VOLUMES PER SUMMER AS A FUNCTION OF HEADWORKS STORAGE AND DRY WEATHER FLOW



(a) STORM SEWAGE OUTFALL

ADDITIONAL STORAGE PROVIDED AT HEADWORKS (m^3)	OPERATION OF STORM SEWAGE OUTFALL
ZERO	24 discharges per summer on average, of which 6 would exceed 500m^3. In 1 summer in 20 there could be about 40 discharges.
250	11 discharges per summer, of which 3 would exceed 500m^3. In 1 summer in 20 there could be 17 discharges.
500	6 discharges per summer, of which 2 would exceed 500m^3. In 1 summer in 20 there could be 11 discharges.
Assuming proposed maximum pumping rate to long sea outfall of 185 litres/second and DWF of 75 litres/second.	

These results need to be considered in conjunction with marine hydrodynamic and dispersion models in order to predict dispersion of pollutants discharged from the main and the storm outfalls and hence the bacterial concentrations in the bathing waters. Initial indications are that such frequent storm discharge would be unacceptable and SWW are investigating options giving a much higher level of service, including increased pumping rates to the long sea outfall, together with provision of storage of up to 1500m^3 at the headworks.

(b) OVERFLOWS TO RIVER

Both design storms and extreme historic events indicated that storm discharges to the river from overflows and tanks are likely to occur less frequently than once in 5 years following system upgrading.

6. USE OF EXTREME HISTORIC RAINFALLS FOR DESIGN

Historic rainfall data is more widely used for the design of sewer systems overseas, particularly in Scandinavia and North America, than it is in the UK. This may be due in part to the widespread acceptance and ease of use of the synthetic design storms built into commonly used methods such as the Wallingford Procedure. It is now accepted, however, that series of historic data can be valuable in assessing sewer system performance under extreme events. It has also been concluded that, when designing sewer systems featuring ancillaries such as tanks, the engineer should consider use of rare historic storms as an alternative to synthetic design rains[5].

Design storms are usually developed for design of pipes carrying peak flows and the 50 percentile symmetrical summer storm in WASSP achieves this when used with the design UCWI. However, rainfall models based on I-D-F relationships may be formulated from incomplete observed storms and this can mislead the engineer who is primarily concerned with volumes rather than peaks of flow. Furthermore the temporal distribution of rainfall is very significant in determining tank performance and efficiency[6]; the critical shape of storm hyetograph (in terms of peakedness and timing of peak) will vary considerably from catchment to catchment.

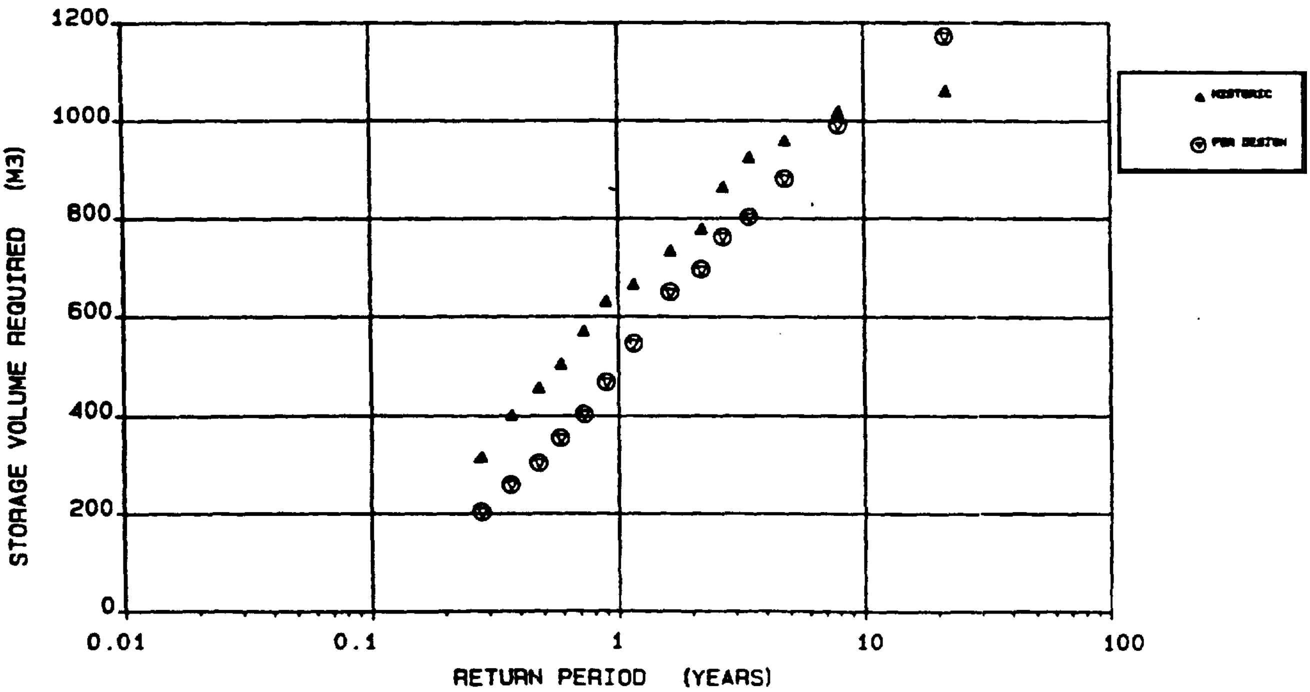
Recent work[7] has shown that historic storms sampled from a long record of 1-minute data can give significantly different results to synthetic design storms of equivalent return period. In this work the 48 most extreme events and their associated wetness parameter values were selected from 22 years of record from a site in SW England. These events were run with a WASSP model of medium sized test catchment and the volume of storage required to just contain the flow at one overflow location was calculated, assuming no spill and a maximum continuation flow of 6 DWF.

The storage volumes were ranked in descending order and assigned a plotting position and return period. Design storms of corresponding return periods and durations were also run with WASSP. The results showed that the WASSP design storms would consistently underestimate the required storage volume suggested by use of historic data typically by 10 - 20% at return periods of 2 - 10 years (see Figure 9). This finding is broadly in agreement with recent research carried out in Scandinavia[8].

Rare historical rainfalls will undoubtedly give valid results when used in a computer simulation program but are expensive and time consuming to run. Furthermore the assignment of a return period to a storm will require additional effort. The greatest problem precluding use of historical rainfall events however, is the availability to the engineer of adequate local data and it is anticipated that the procedures outlined in Section 4 will help to overcome this difficulty.

FIGURE 9

STORAGE VOLUMES DERIVED USING HISTORIC AND DESIGN RAINFALLS
(Volume required to prevent overflow assuming Formula A)



7. CONCLUSIONS

The existing annual series are based on limited data necessitating the development of a relatively crude regionalisation procedure.

Developing an acceptable annual series for the East of Scotland has been relatively straightforward although tedious.

Once developed, the series are easy to use and give an accurate indication of tank and overflow performance.

A newly developed rainfall profile generation procedure allows use to be made of local hourly rainfall records.

Historic rainfall records can be efficiently used to give an indication of the long term performance of sewerage upgrading works for extreme events.

Extreme historic storms should be considered as a valid alternative to synthetic storms when designing in-system storage.

8. REFERENCES

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DISCUSSION NOTES

Technical Session 1

Paper 1.2 Discussion

J.Packman ; I.H.

The Met Office have numerous rainfall stations and one can get an annual rainfall series from them. There was a proposal at one time to digitise the information at one-minute intervals , but nothing happened due to apparent lack of demand. Engineers should force the issue because the data is there.

R.J.Henderson ; W.R.c

The costs would probably be astronomical

J.Packman

How do you know ?

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