Accounting for infiltration - a more explicit approach

By G. M. HEYWOOD, MA, MSc, DIC, MCIWEM*

(Paper presented at CIWEM Metropolitan Branch meeting, 22nd April 1997)

ABSTRACT

Two methods have been developed to enable account to be taken of the variability of infiltration in estimating the frequency of flooding and overflow events within high infiltration catchments. The methods are of benefit in planning and design, and provide a first step in assessing the economic benefits of remediation measures.

The first method (**infiltration modelling**) uses a time series approach to characterise the dependence of infiltration on rainfall and seasonal variations, and hence derive a long term volume-frequency relationship. The second method (**prediction of spill frequency**) uses this relationship alongside conventional hydraulic modelling to estimate the return period of flooding or overflow.

The two methods are illustrated by **a case study** in which the frequency of capacity exceedence was estimated for a major wastewater transfer scheme.

Key Words: Combined Sewer Overflow; flooding; infiltration; return period analysis; sewerage.

INTRODUCTION

Infiltration to sewerage is an issue of increasing concern within the water industry due to a growing awareness of the operational and capital costs associated with its collection and treatment, and its impact in terms of increased risk of flooding, Combined Sewer Overflow (CSO) operation, and sewer collapse.

The estimation of the return period of an undesirable occurrence such as flooding or CSO operation is a cornerstone technique in sewerage planning and design. Return period analysis is used to assess the adequacy of the current system and in the optimal design of hydraulic improvements. In simplified terms, the return period is traditionally derived by:

(i) assuming a constant base flow (including domestic, industrial and infiltration components);

(ii) using a hydraulic model to predict the response of the catchment to a range of storms of known return period; and

(iii) identifying the most frequently occurring storm for which the model predicts the undesirable occurrence.

---

* Engineering Analyst, Tynemarch Systems Engineering Ltd, Abinger House, Church Street, Dorking, RH4 1DF, Telephone 01306 742772, Fax 01306 742276.

The predicted return period of the occurrence is then trivially derived from the return period of this storm.

This approach is adequate where *either* the base flow is small relative to the storm flow component, *and/or* the base flow component can be taken to be constant over the period of interest. However, where base flow and storm flow components are comparable in magnitude (as may be the case in partially separate systems), and where base flows vary significantly during the year, the traditional approach will not provide an adequate estimate of the return period.

In this latter situation, flooding or overflow will often be the result of a combination of high infiltration and heavy rainfall. Determining the return period of the undesirable occurrence is a non-trivial statistical problem. There are three main technical challenges:

(i) It is necessary first to derive a volume-frequency relationship for the catchment infiltration. This will require the separation of infiltration from other flow components, which is particularly difficult to achieve during rainfall.

(ii) It is then necessary to be able to associate return periods with combined rainfall and infiltration events. This is non-trivial since infiltration cannot be assumed to be independent of rainfall, and hence conditional probability relationships are required.

(iii) The final objective is to associate a return period with an undesirable occurrence such as flooding or overflow. This cannot be derived from the return period of a single combined event considered in (ii), but rather it is necessary to sum probabilities over a continuous range of combinations of events which trigger the occurrence.

WHAT IS INFILTRATION?

Infiltration is defined as "ground water entering a drain or sewer through broken or porous pipes, or through defective joints"[(1)]. In many catchments infiltration has been found to be highly variable in quantity. Infiltration volumes have been shown to be strongly correlated with groundwater levels[(2),(3)], tide levels[(4)], and rainfall[(5),(6),(7),(8),(9),(10)]. The latter has been termed rainfall-induced infiltration, which is distinct from inflow in that it is of groundwater origin and generally exhibits a slower response, typically taking several days to decay following a rainfall event. At coastal sites, infiltration is likely to be influenced by groundwater, tides and rainfall in varying degrees.

The need to exclude rainfall runoff from estimates of infiltration means that most estimation methods make use of flow data recorded during dry weather. These methods can fail to take account of peaks in rainfall-induced infiltration occurring during extended wet periods. The characterisation of these peaks is particularly important when there is concern regarding events which involve a combination of storm conditions and high infiltration.

INFILTRATION MODELLING

INFILTRATION MODELS IN THE LITERATURE

A number of attempts have been made to construct a model which adequately characterises groundwater and rainfall-induced infiltration:

- Lutz[5] proposed a graphical approach which involved fitting an exponential decay curve to the rainfall-induced infiltration flow component.
- Newport[6] adopted an equivalent time series approach and included a complementary model for the runoff component. A simple correction is made to take account of seasonal variations in groundwater levels and soil moisture deficits.
- Males and Turton[11] proposed the use of time series models based on either groundwater levels or rainfall.
- Huber and Dickinson[12] incorporated a model based on multiple linear regression within their Storm Water Management Model (SWMM) software.

MODEL DESCRIPTION

The infiltration model described here is a development of the approach proposed by Newport[6], developed to reproduce more accurately the seasonal variations observed in the case study catchment. The model is used to separate the domestic/industrial, rainfall runoff and infiltration components, and in particular to characterise the infiltration flow component and its dependence on rainfall and seasonal variations. The model is calibrated using wastewater treatment works flow records, and can then be used to derive a long term volume-frequency relationship for infiltration flows.

The flow Q (m^3/d) arriving at the point of interest on a given day is modelled as:

$$Q = D + R + I \tag{2.1}$$

where D, R and I are the domestic/industrial, runoff and infiltration components respectively, all expressed in m^3/d.

The domestic/industrial component D is expressed as:

$$D = P.G + E \tag{2.2}$$

where P is the contributing population, G (m^3/h.d) is the per capita flow returned to sewer, and E (m^3/d) is the trade effluent flow.

The runoff component R is expressed as:

$$R = 10.C.S.A.\mathrm{r(n)} \tag{2.3}$$

where C is a dimensionless runoff coefficient, S is a seasonal correction factor (also dimensionless), A (ha) is the area of the sub-catchment contributing to the point of interest, and $\mathrm{r(n)}$ (mm) is the rainfall on the current day.

The seasonal correction factor S is given by:

$$S = B.\sin\left\{\frac{2\pi(\mathrm{n}-\mathrm{x})}{365} - \frac{\pi}{2}\right\} + 1 \qquad (2.4)$$

where B is a dimensionless calibration constant indicating the amplitude of the seasonal variation, n is the current date measured in days from a chosen start date, and x is a constant indicating the phase of the seasonal variation.

The infiltration component I is then given by:

$$I = K + 10.F.S.A.\mathrm{i(n)} \qquad (2.5)$$

where $\mathrm{i(n)}$ is expressed in mm as:

$$\mathrm{i(n)} = \sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{r(j)}.\exp\left\{-\frac{\mathrm{n}-\mathrm{j}}{H.S+1}\right\} \qquad (2.6)$$

or alternately,

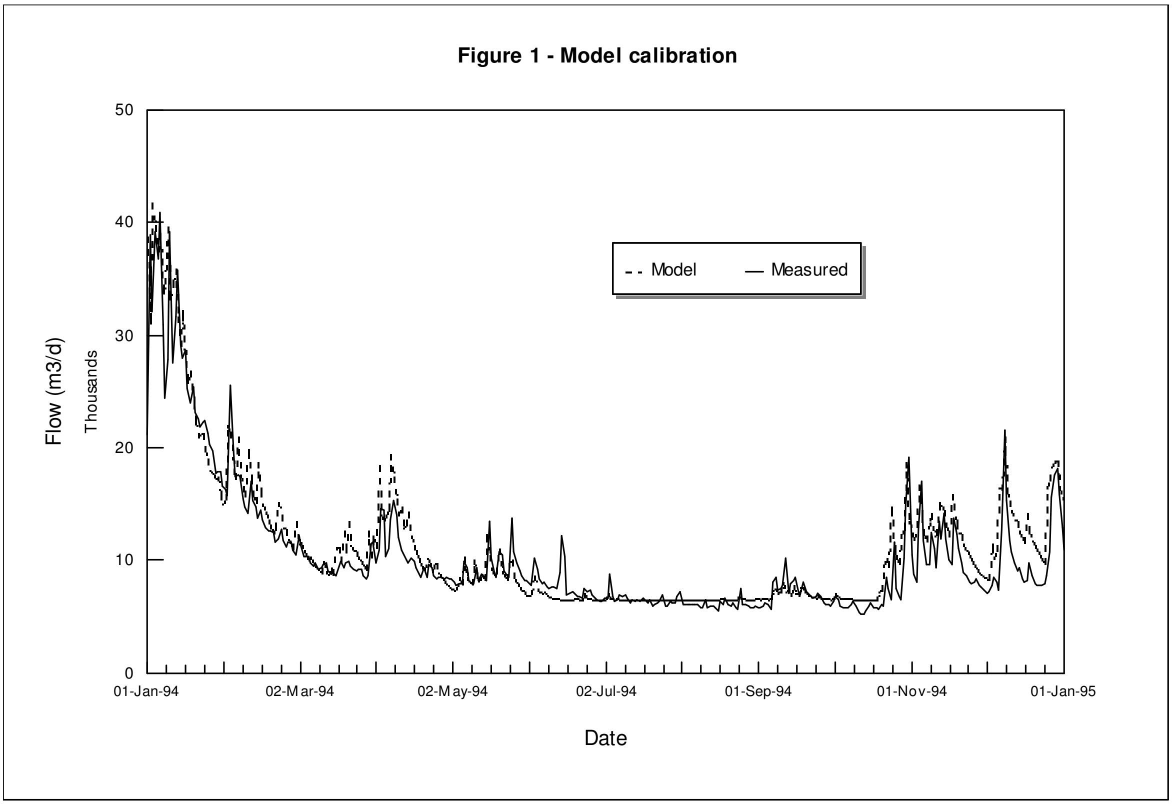
$$\mathrm{i(n)} = \mathrm{i(n-1)}.\exp\left\{-\frac{1}{H.S+1}\right\} + \mathrm{r(n)} \qquad (2.7)$$

K (m^3/d) is the constant component of infiltration, F is a dimensionless coefficient analogous to C in equation (2.3), and ($H.\log_e 2$) is the time in days for the exponential decay function to decrease by one half.

CASE STUDY APPLICATION

The model was implemented within a PC spreadsheet application, and applied to a separately sewered coastal catchment in the UK, in which infiltration was known to be large and variable. Flows from the catchment were to be transferred to a neighbouring catchment for treatment prior to discharge, as part of a scheme to improve bathing water quality. The existing outfall was to be retained for use as an overflow when the transfer pumping rate was exceeded. The Client required an estimate of the frequency with which this could be expected to occur to allow an application to be made for an intermittent discharge consent.

The model was calibrated using daily flows recorded at the catchment wastewater treatment works during 1994, and locally recorded daily rainfall data. The early months of 1994 included unusually high volumes of infiltration, providing confidence in the calibration of the model for these conditions. Figure 1 presents the measured and modelled daily flows for 1994 using the calibrated model. These show reasonable agreement particularly at high flows. The model was verified by comparing the measured and modelled flows for the remainder of the period for which measured flow data were available.



The calibrated model was then used to derive estimates of total daily flow and infiltration for the 22-year period for which daily rainfall data were available. Whilst the calibration parameters were not changed, other input parameters were revised in order to reflect catchment populations and other base flow parameters predicted for the transfer scheme design horizon. The model results are presented in Figure 2 for a two year sample period.

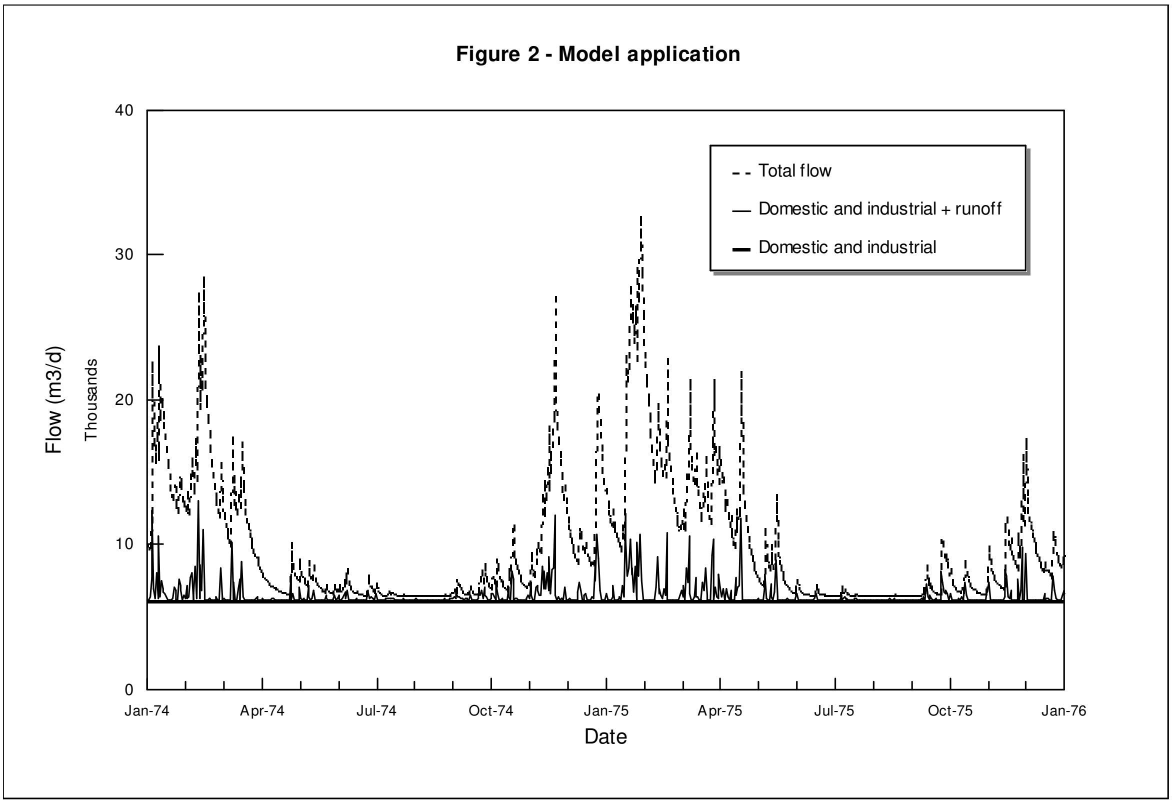
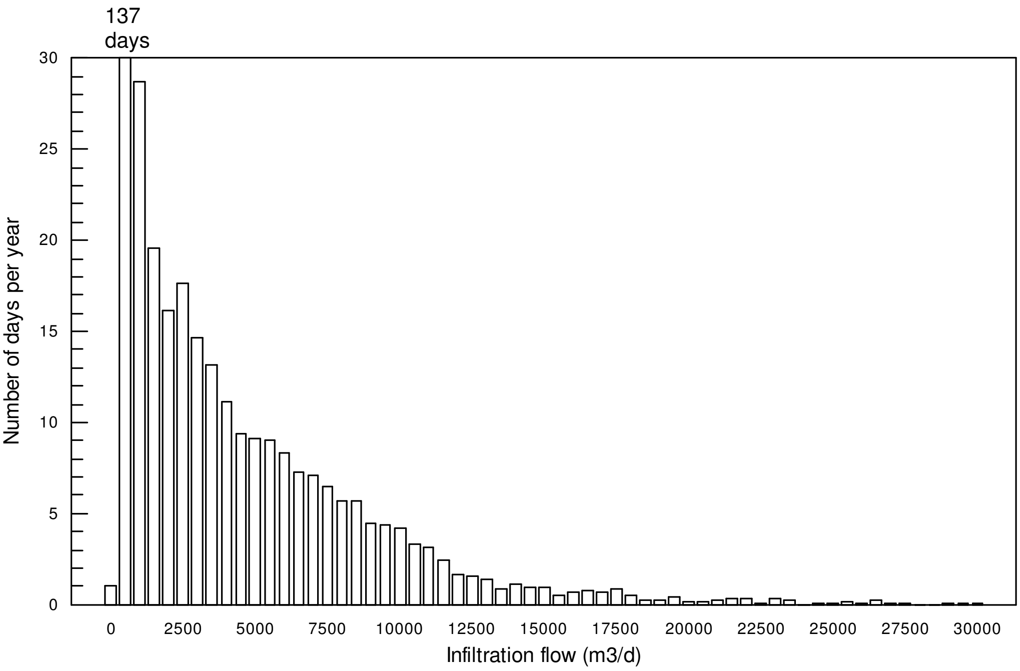


Figure 3 shows the distribution of predicted infiltration volumes for the 22 year modelling period. The results have been normalised to give the number of days expected to experience infiltration within each flow band in a typical year.



PREDICTION OF SPILL FREQUENCY

STATISTICAL BASIS

The infiltration volume-frequency relationship derived above is now used to specify a set of hydraulic model analyses, and the results used to estimate the return period of flooding or overflow. This estimation is not straightforward since the occurrence of the undesirable flooding or overflow event is dependent upon rainfall, infiltration and baseflow, and these components are non-independent.

The problem is simplified initially by restricting attention to situations where the undesirable event may be assumed to occur if and only if the flow arriving at a given location exceeds a known figure. For example overflow occurs if and only if the flow Q arriving at the transfer pumping station exceeds Q_{max}.

The statistical basis for the method is described below. The notation used is similar to that used previously, but flows referred to are instantaneous flows measured in l/s rather than daily mean flows in m^3/d.

The random variables Q, D, R and I are defined as follows:

Q = the peak flow arriving at the point of interest on a given day (l/s).

D = the domestic/industrial flow component of the peak flow occurring on a given day (l/s).

R = the runoff component of the peak flow occurring on a given day (l/s).

I = the infiltration component of the peak flow occurring on a given day (l/s).

It is assumed that the components D, R and I together constitute the whole of the peak flow arriving at the point of interest on the given day. Thus:

$$Q = D + R + I \tag{3.1}$$

We are concerned with the event denoted by ($Q > Q_{max}$), the event that the peak flow Q arriving at the point of interest on a given day exceeds the flow Q_{max} at which the undesirable flooding or overflow occurs.

It should be noted that the random variables D, R and I are not independent for the following reasons:

- Both R and I are correlated with rainfall within the catchment.

- All three random variables are correlated with the time of day at which the peak flow occurs. R and I are correlated with time of day due to meteorological factors associated with convective rainfall. D is correlated with time of day due to regular diurnal variations in domestic and industrial water consumption.

- The three random variables are correlated with each other, since the three component flows will interact within the sewer network, e.g. a high value of I may constrict flows within the sewer network leading to a lower value of R.

Let $p_D()$, $p_R()$ and $p_I()$ be probability density functions for the random variables D, R and I respectively. For example, the probability that R lies within the range (r_1, r_2) may be expressed as:

$$\mathrm{P}(r_1 < R < r_2) = \int_{r_1 < r < r_2} p_R(r).dr$$

If D, R and I were independent then we could write the probability of ($Q > Q_{max}$) as:

$$\mathrm{P}(Q > Q_{max}) = \iiint_{\substack{d,r,i: \\ d+r+i \\ >Q_{max}}} p_D(d).p_R(r).p_I(i).dd.dr.di \tag{3.2}$$

However, since D, R and I are not independent, it is necessary to define conditional probability density functions in the form $p_{X|Y=y}()$, the probability density function of the random variable X given that the random variable Y takes the value y.

We can then express $\mathrm{P}(Q > Q_{max})$ as:

$$P(Q > Q_{max}) = \iiint_{\substack{d,r,i: \\ d+r+i \\ >Q_{max}}} p_D(d).\, p_{R|D=d}(r).\, p_{I|(D=d \cap R=r)}(i).\, dd.\, dr.\, di \qquad (3.3)$$

In order to reduce the data requirements of the method, a conservative simplifying assumption was made, allowing an upper bound on this expression to be calculated. The assumption is expressed as follows:

> *An upper bound on (3.3) can be obtained by assuming that on a given day the peak flow occurs at the same time as the daily peak of domestic and industrial flow, and that an upper bound on this quantity is given by $3(P.G+E)$.*

In the assumption, P is the contributing population, G (l/s) is the mean per capita flow to sewer and E (l/s) is the mean trade effluent flow. The multiplier on the expression ($P.G+E$) may be adjusted to take account of the known characteristics of the catchment.

We can then use (3.3) to derive an upper bound on the probability of ($Q > Q_{max}$):

$$P(Q > Q_{max}) \leq \iint_{\substack{d=3(PG+E) \\ r,i:d+r+i \\ >Q_{max}}} p_{R|D=d}(r).\, p_{I|(D=d \cap R=r)}(i).\, dr.\, di \qquad (3.4)$$

To allow (3.4) to be evaluated in practice, it is necessary to partition the region over which the double integral occurs into a finite number of discrete intervals, defined in terms of the variables R and I. This will then allow the double integral to be expressed as a summation. We achieve this by first defining disjoint intervals $I_1, I_2, \ldots\ I_n$ which form a partition of the set of all possible values of I. Intervals $J_1, J_2, \ldots\ J_n$ are then defined such that r is in J_k if and only if there is a value of i in I_k such that $3(P.G+E) + r + i > Q_{max}$. This may be expressed mathematically as:

$$r \in J_k \Leftrightarrow \exists i \in I_k \text{ such that } 3(P.G + E) + r + i > Q_{max} \qquad (3.5)$$

Thus, if $I_k=[i_k,i_{k+1})$, then $J_k=(j_k,\infty)$, where $j_k= Q_{max}-3(P.G+E)-i_{k+1}$. The intervals I_k and J_k are shown schematically in Figure 4.

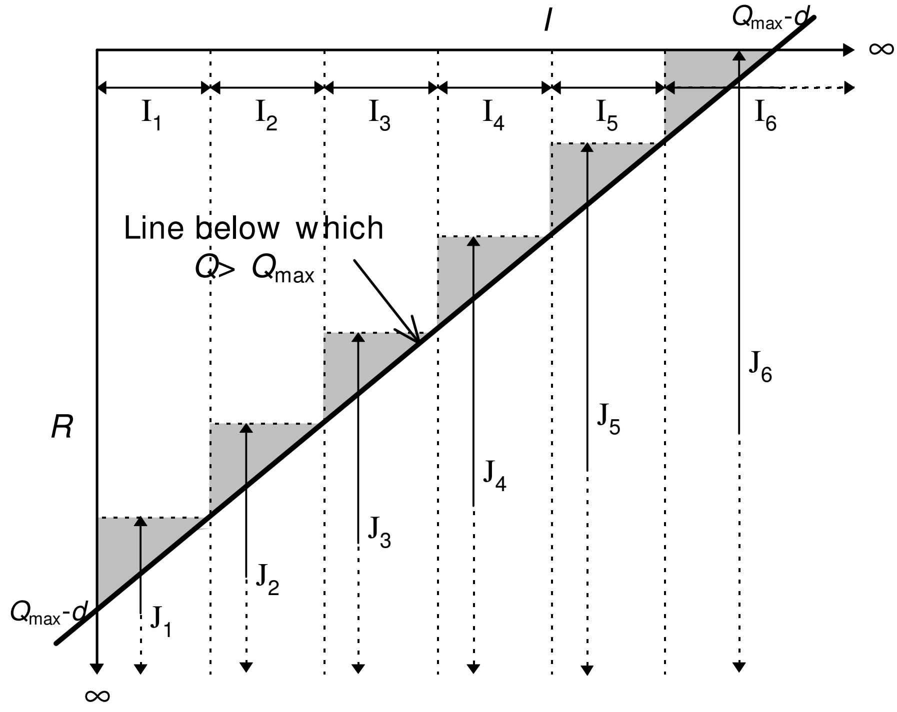


Figure 4

(3.4) can then be discretised to give:

$$P(Q > Q_{max}) \le \sum_{k=1}^{n} P(R \in J_k | D = d).P(I \in I_k | R \in J_k \cap D = d) \quad (3.6a)$$

where the notation $P(R \in J_k|D=d)$ represents the probability that R takes a value within the interval J_k, given that D takes the value d. This may be expressed in an alternative notation as:

$$P(Q > Q_{max}) \le \sum_{k=1}^{n} \left\{ \begin{matrix} P(R > Q_{max} - d - i_{k+1} | D = d) \times \\ P(i_k < I < i_{k+1} | R > Q_{max} - d - i_{k+1} \cap D = d) \end{matrix} \right\} \quad (3.6b)$$

where d=3($P.G$+E). The right hand side of (3.6) is always greater than the right hand side of (3.4), because of the inclusion of the area shaded grey in Figure 4, but the two expressions will approach equality as the number of intervals I_k increases.

The inequality (3.6) may then be used to estimate an upper bound on the probability of the undesirable occurrence, which in turn may be used to estimate a lower bound on its return period.

CASE STUDY APPLICATION

Analyses were performed using an existing verified WALLRUS hydraulic model of the case study catchment, in order to quantify the expected peak flows arriving at the transfer pumping station for a matrix of base flows and storm return periods.

For each base flow, the hydraulic modelling results were used to determine the storm return period corresponding to the lower boundary of the J interval described above. Logarithmic interpolation was used to estimate these return periods more precisely than was allowed by the number of WALLRUS analyses performed.

Interval:	$I_1 \rightarrow$	$\leftarrow I_2 \rightarrow$	$\leftarrow I_3 \rightarrow$	$\leftarrow I_4$
Infiltration:	123	173	223	
Base flow:	414	464	514	
Storm return period	**Peak flows in l/s (matrix of results of WALLRUS analyses)**			
1	546	587	625	
2		610	644	
5	593	639	670	
10	625		685	
20	658	679	708	
50	703	727		
Storm return periods corresponding to lower boundaries of J intervals				
(years)	12	4	1.5	
Interval	J_1	J_2	J_3	

Table 1 - Intermediate results (Solid line indicates boundary of event $Q > Q_{max}$)

The heavy black line in Table 1 corresponds conceptually to the line in Figure 4. It indicates the boundary of the region defined by ($Q > Q_{max}$), where in this case Q_{max} = 634 l/s. For example, considering the left-hand end of the black line (corresponding to a base flow of 414 l/s), we see that a storm return period of 10 years was estimated to give a peak flow of 625 l/s, less than Q_{max}, but a storm return period of 20 years gives a predicted peak flow of 658 l/s, greater than Q_{max}. Using interpolation, it was estimated that a storm of return period 12 years would generate a flow of Q_{max} = 634 l/s. This return period becomes the lower bound of the interval $J_1 = (12,\infty)$. In a similar manner, interval $J_2 = (4,\infty)$, and $J_3 = (1.5,\infty)$.

Inequality (3.6) can then be used to calculate an upper bound on the probability of transfer rate exceedence on a given day. The reciprocal of this probability is a lower bound on the expected return period of exceedence, a lower bound on the return period at which overflows from the transfer pumping station may be expected to occur.

CONCLUSION

Two methods have been developed which allow an estimate to be made of the return period of flooding or CSO operation within a high infiltration catchment. Although the theoretical background to the methods is complex, the methods may be applied relatively simply using available flow data and a conventional hydraulic model of the catchment. The case study illustrated how the approaches were used to estimate the frequency of operation of an overflow forming part of a major wastewater transfer scheme.

REFERENCES

(1) Glossary, Handbooks of UK Wastewater Practice, Second Edition, IWEM, 1993.

(2) Nogaj, R.J. and A.J. Holenbeck (1981) One technique for estimating inflow with surcharge conditions, J.WPCF, Volume 53, Number 4, Pages 491-496

(3) Nogaj, R.J. and G.A. Braam (1981) Selection of optimum storm frequency for sewer studies, J.WPCF, Volume 54, Number 10, Pages 1401-1407

(4) Martin, C., Quick, N.J., and Nott, N.A. (1982) Infiltration: Investigation, analysis and the cost/benefit of remedial action. In the Restoration of sewerage systems. Thomas Telford, 175-185

(5) Lutz, J.J. (1976) Comparing Inflow and Infiltration, Water and Sewage Works, May, Pages 68-69

(6) Newport, R. (1977) A strategy for investigating infiltration into sewers, WRc Conference, Opportunities for Innovation in Sewerage, Reading University

(7) Difilippo, J.D. (1977) Sewer system evaluation surveys in the U.S.A., WRc Conference, Opportunities for Innovation in Sewerage, Reading University

(8) Thorpe, A.D. (1977) Sewer sub-catchment inflow-infiltration analysis, WRc Conference, Opportunities for Innovation in Sewerage, Reading University

(9) Gaines, J.B. (1989) Peak sewage flow rate: prediction and probability, Journal of Water Pollution Control Federation, 61, No.7, 1241-1248

(10) McGregor, J.D., H.M. Klein and J. Lyons (1993) Municipal programme combines rainfall induced infiltration, Public Works, 124, No.11, 55-56

(11) Males, D.B. and P.S. Turton (1979) Design Flow Criteria in Sewers and Water Mains, Central Water Planning Unit, Technical Note No. 32

(12) Huber, W.C. and R.E. Dickinson (1988) Storm Water Management Model, Version 4, Part A: User's Manual, US Environmental Protection Agency ref. EPA/600/3-88/001a