Estimation of Infiltration from Long Term Flow Records

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Introduction

This paper describes the analysis of more than 5 years of sewage flow and rainfall records for a catchment in which particularly high flows occur for long periods during the winter.

The aim was to determine how infiltration varied through the year. However, the analysis indicated that, even during dry weather, sewage flows were strongly influenced by the amount of rain that had fallen during the preceding weeks and months. Seasonal variations were also evident but appeared to have only a secondary effect on sewage flows.

The techniques that were developed have demonstrated similar effects in several other catchments. This paper provides one such example and describes further analysis to show the relationship between the daily peak and average flows in that catchment during dry weather.

Catchment A

Southern Water engaged Montgomery Watson (now MWH) to carry out a feasibility study for a wastewater treatment works (WwTW) close to the south coast. Since effluent discharged from the WwTW was believed to affect the quality of bathing waters, revised consent standards would be imposed due to the Bathing Water Directive.

As well as more stringent treated effluent standards, a limit of 3 spills per bathing season would be imposed on storm tank discharges. This paper describes how the level of infiltration during the bathing season was determined and how the required storm tank capacity was calculated.

Catchment A serves several villages that are linked by a system of gravity sewers, pumping stations and rising mains. It is a relatively flat catchment with permeable ground.

The catchment model

It was expected that the sewerage system model that had been developed for the drainage area plan (DAP) could be used to determine the storm tank capacity. The model was adjusted to allow for the projected 2010 flow to full treatment (FFT) and was run against the 4 times per year summer design storm to determine the likely volume of overflow to the storm tanks. The results were surprising. No spill was indicated, even for much more severe design storms!

It was then realised that the model did not include infiltration. However, when it was used for the DAP, the model had included the relatively large allowances for infiltration that allowed it to simulate flooding that had actually been recorded in the catchment.

Flooding was only a problem in the catchment during the winter. Therefore, it would not be appropriate to use the winter level of infiltration to determine the amount of overflow during the bathing season. Consequently, attention turned to establishing the appropriate level of infiltration that should be allowed for this purpose.

DWF and Infiltration

Infiltration is generally assumed to be a constant component of the dry weather flow (DWF) in a sewerage system.

The following definition of DWF was provided by the Institute of Water Pollution Control (IWPC) in its 1975 Manual of British Practice in Water Pollution Control:

"The average daily flow to the treatment works during seven consecutive days without rain following seven days during which the rainfall did not exceed 0.25 mm on any one day."

During such periods, there should be no surface runoff. Therefore, in addition to the sewage that is discharged into the system, only groundwater infiltration should remain. Infiltration also represents the majority of the minimum night-time flow in most sewerage systems.

Flow data

Southern Water provided flow data that had been gathered by their telemetry system since 1 January 1996. This included the daily minimum, average and maximum values of the total inlet flow and the FFT at the WwTW.

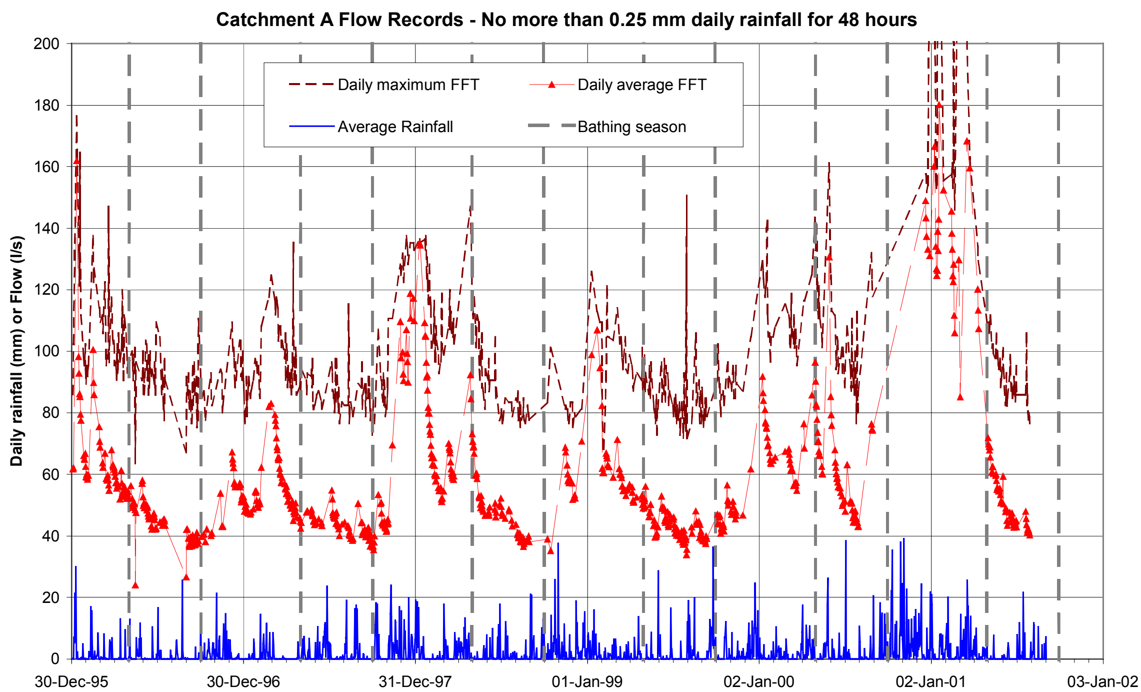
Since all the flow is pumped to the inlet works, the maximum and minimum recorded flows are strongly influenced by the operation of pumps. For example, the flow falls to zero if none of the pumps operate for a long enough period during the night.

The FFT is measured by a flume and is understood to be more reliable than the measurement of total inlet flow. Since all flow goes to treatment during dry weather, the two flows should be the same during periods when the level of infiltration can be assessed. Therefore, the analysis was based on the recorded average daily FFT.

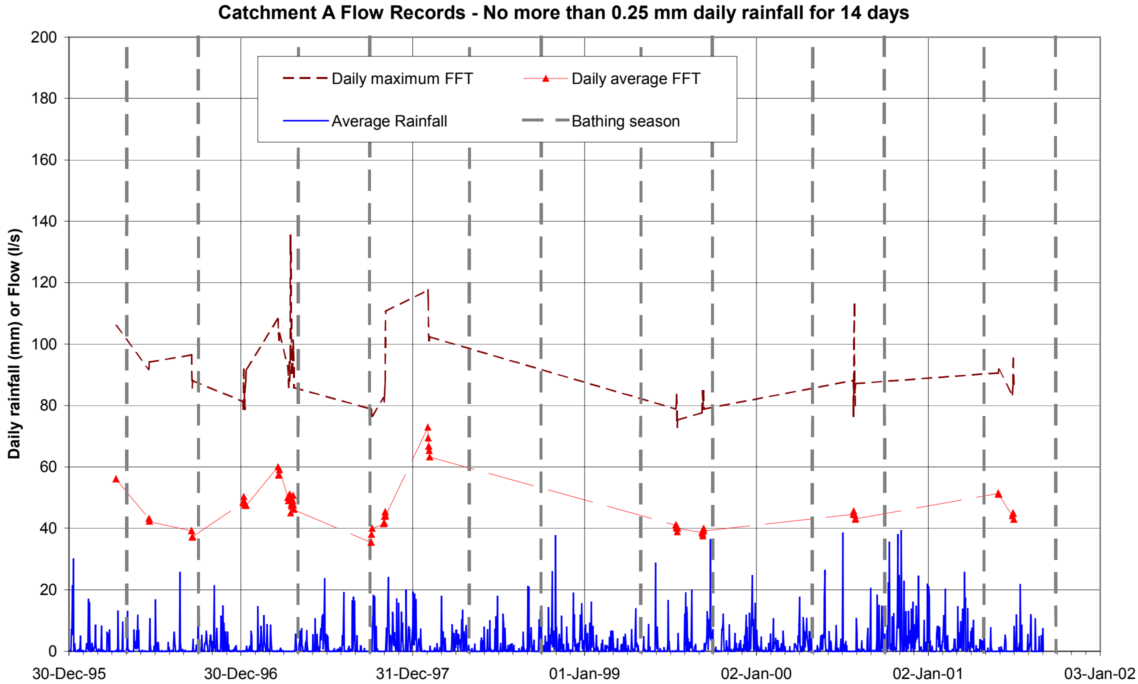
Rainfall data

The EA provided rainfall data from three local automatic rain gauges. The average of the three rain gauge readings was taken to indicate rainfall in the catchment and a dry day was taken to be one on which the average reading did not exceed 0.25 mm.

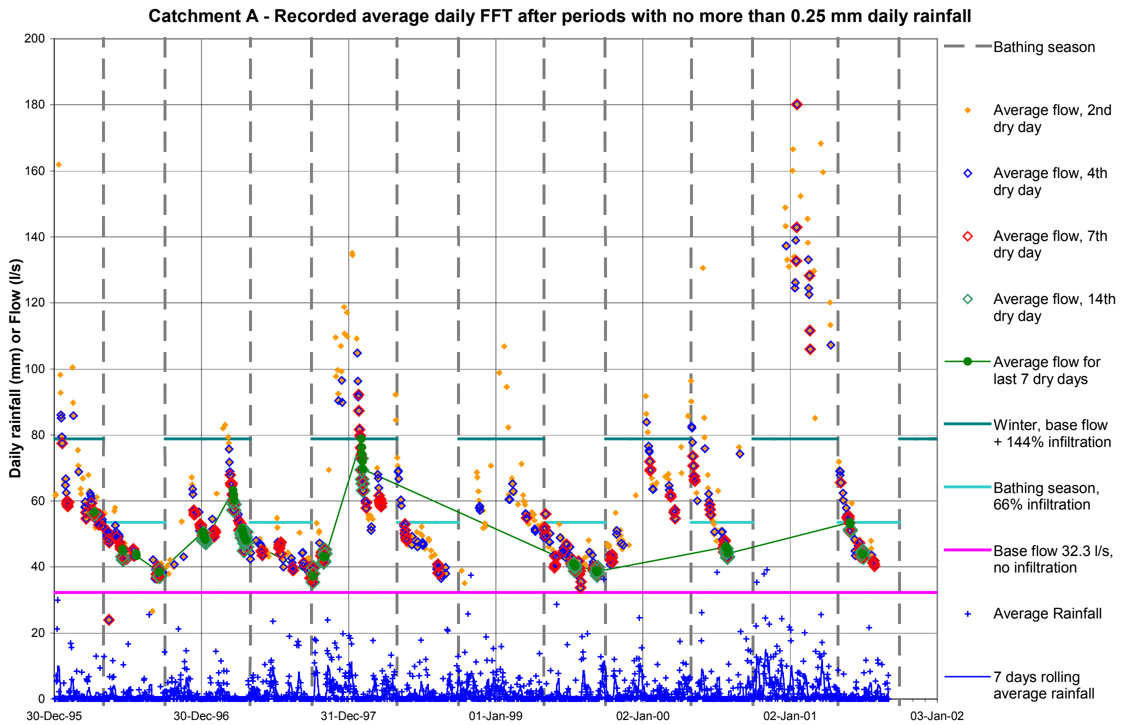
Since the rain gauge readings are taken at 09.00 GMT the following morning, they need to indicate two consecutive dry days to ensure that the FFT recorded on a particular day was not affected by rainfall before 09.00 GMT. The following graph shows the maximum and average FFT recorded on such dry days.



As the previous graph indicates, the FFT varied considerably, even on days when the weather had been dry since 09.00 GMT the previous day. The FFT continued to fall as periods of dry weather became more prolonged and, as the following graph shows, the recorded FFT did not fall to a constant value even after 14 dry days.



During several of the winters, the longest dry period was not as long as 14 days. Nevertheless, the previous graph does indicate that the flow recorded after prolonged dry periods was generally lower during the bathing season than during the winter. The following graph shows the average FFT recorded after periods of 2, 4, 7 and 14 dry days.



The graph clearly indicates that the FFT continued to fall as periods of dry weather became more prolonged. This was particularly evident during the winter, spring and early summer, especially in the long dry period early in 1998.

DWF

The previous graph indicates the average flow for the last 7 days of each 14 dry day period. This is the DWF calculated broadly in accordance with the IWPC definition, the exception being that the *"seven consecutive days without rain"* have been taken as days on which rainfall did not exceed 0.25 mm.

The graph clearly indicates that, at least for Catchment A, DWF does not have a constant value but exhibits a distinct seasonal variation.

There is not likely to be much seasonal variation in the amount of sewage discharged into the sewerage system, nor a significant amount of surface runoff after 7 dry days. Therefore, the variability of DWF must be due to variations in the amount of groundwater that infiltrates into the sewerage system. This can be expected to vary as the ground water level varies and is likely to become most severe when ground water rises up to the level of the shallowest pipelines, including the private drains that connect individual properties to the public sewers.

Sewage base flow

The amount of sewage discharged into the sewerage system, excluding rainfall induced runoff and groundwater infiltration, has been termed the sewage base flow. This was estimated by multiplying the total catchment population of 18,600 that was given in the DAP by an assumed sewage flow of 150 l per person per day. This gives the estimated 32.3 l/s sewage base flow that is shown on the previous graph.

Infiltration

The difference between the FFT and the sewage base flow indicates the amount of inflow and infiltration. After prolonged dry periods, when inflows from surface runoff should be absent, this should indicate the level of groundwater infiltration alone.

The graph indicates that, with the exception of one (possibly erroneous) data point early in 1996, the recorded flows on dry days always exceeded the estimated 32.3 l/s sewage base flow. However, the FFT did occasionally fall quite close to this value. Every year for which the flow records were complete, the FFT on dry days towards the end of the summer fell below 40 l/s, indicating that the level of infiltration would have been less than 25%.

The highest DWF occurred during the period ending 1 February 1998, when the average flow for the previous 7 days was 78.8 l/s. Therefore, in addition to the assumed sewage base flow, there would have been 46.5 l/s of infiltration. This corresponds to 144% of the sewage base flow. Horizontal lines on the graph during winter periods indicate this level of infiltration.

Taking a similar approach for the summer periods, the maximum DWF was indicated on 31 May 2001. The average FFT for the previous 7 days was 53.5 l/s, indicating 21.2 l/s or 66% of infiltration. The graph includes horizontal lines during bathing seasons to indicate this level of infiltration.

The records also indicate much higher levels of infiltration during shorter periods of dry weather, particularly after the very wet weather during the winter of 2000 / 2001. Whilst these periods were not long enough to comply with the definition of DWF, they did extend for at least 7 days, after which the flow in the sewers should have included little if any surface runoff.

The highest recorded flow after 7 dry days was 142.9 l/s on 18 January 2001, indicating around 110.6 l/s or 342% of infiltration. This is very similar to the total amount of infiltration that was included in the hydraulic model when it was used for the DAP.

The graph clearly indicates that the level of infiltration into the sewerage system is not constant. Whilst it does exhibit seasonal variation, it is influenced much more significantly by the amount of rainfall that occurred during the preceding period.

Flow model

Due to the unexpected variation of FFT, even after long dry periods, flow variations were investigated in more detail. This led to the development of a model that demonstrates the relationship between rainfall and FFT.

Individual components of the modelled flow are generated by applying factors to the total rainfall recorded in the following periods:

- The current two days (i.e. the sum of the rain gauge readings taken on the morning of the day for which the flow is being modelled and on the following morning)
- The preceding two days
- The preceding three days (i.e. the remainder of the current week)
- The preceding week
- The remainder of the current month
- The preceding month
- The month before that (i.e. 2 to 3 months ago)

Individual graphs were created for each of the components listed above. A composite flow was then created from a base flow (set equal to 32.3 l/s) plus the sum of the individual rainfall related components. The factors applied to the rainfall components were adjusted until the composite flow graph matched the recorded daily flow to treatment.

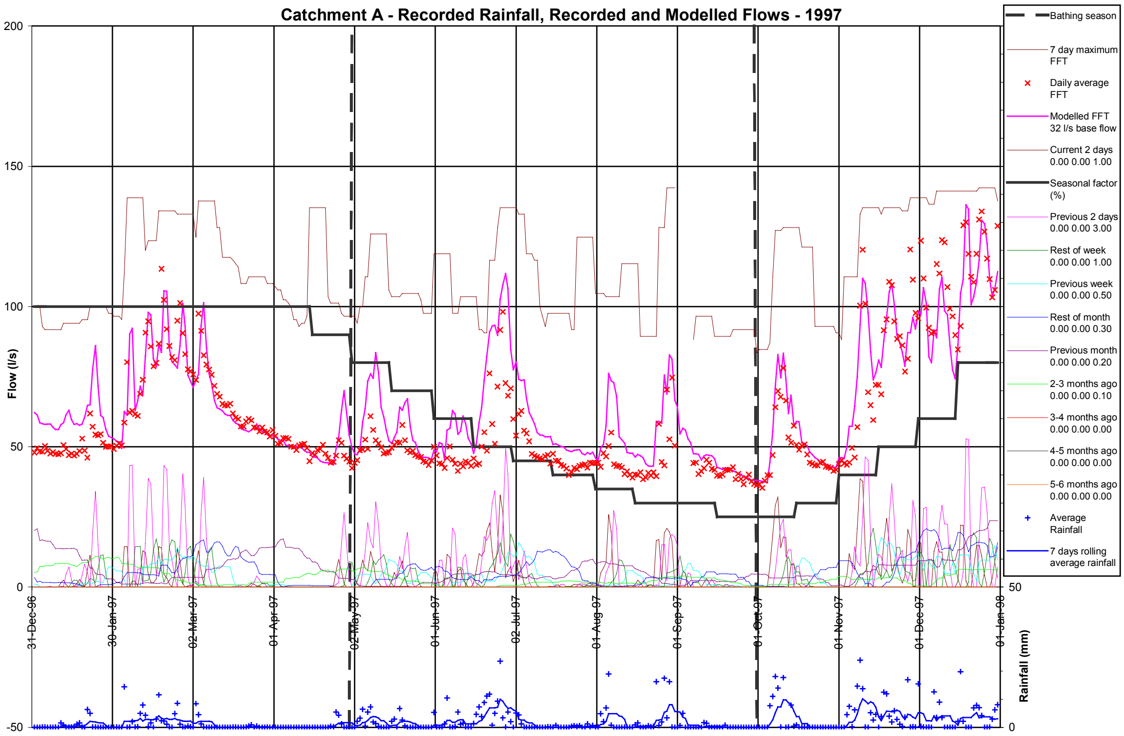
When the model was calibrated to match the flows in the winter and spring, it over-predicted summer and autumn flows. Therefore, a seasonal factor was also included. This was set equal to unity from January to April, falling to a low of 0.3 in August and September before rising again to unity in January. This allowed the modelled flow to match the recorded flow remarkably accurately throughout the year.

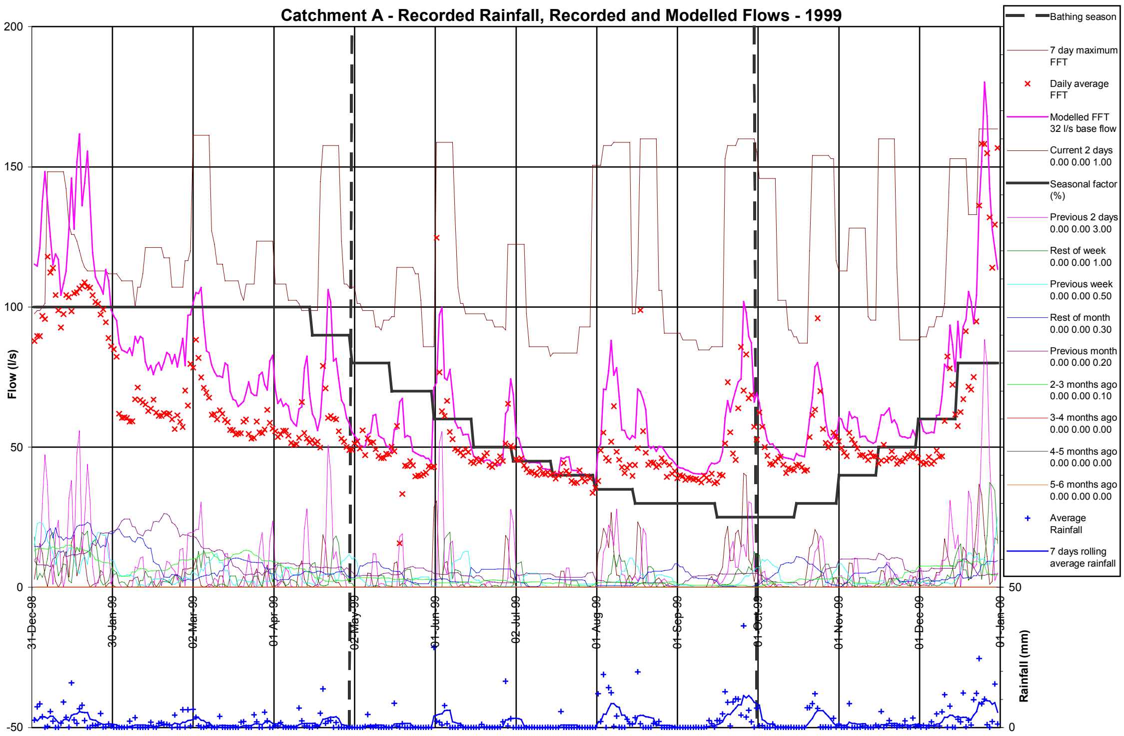
The model was developed from the flow and rainfall data provided between 1 January 1996 and 31 July 2000. Complete rainfall data was available for this period but there were several gaps in the flow data.

Graphs were produced for each year and the model was calibrated to provide a reasonable fit between the modelled and recorded flows without seriously underestimating the FFT.

The following graphs for 1997 and 1999 indicate how accurately the modelled flow fitted the recorded FFT.

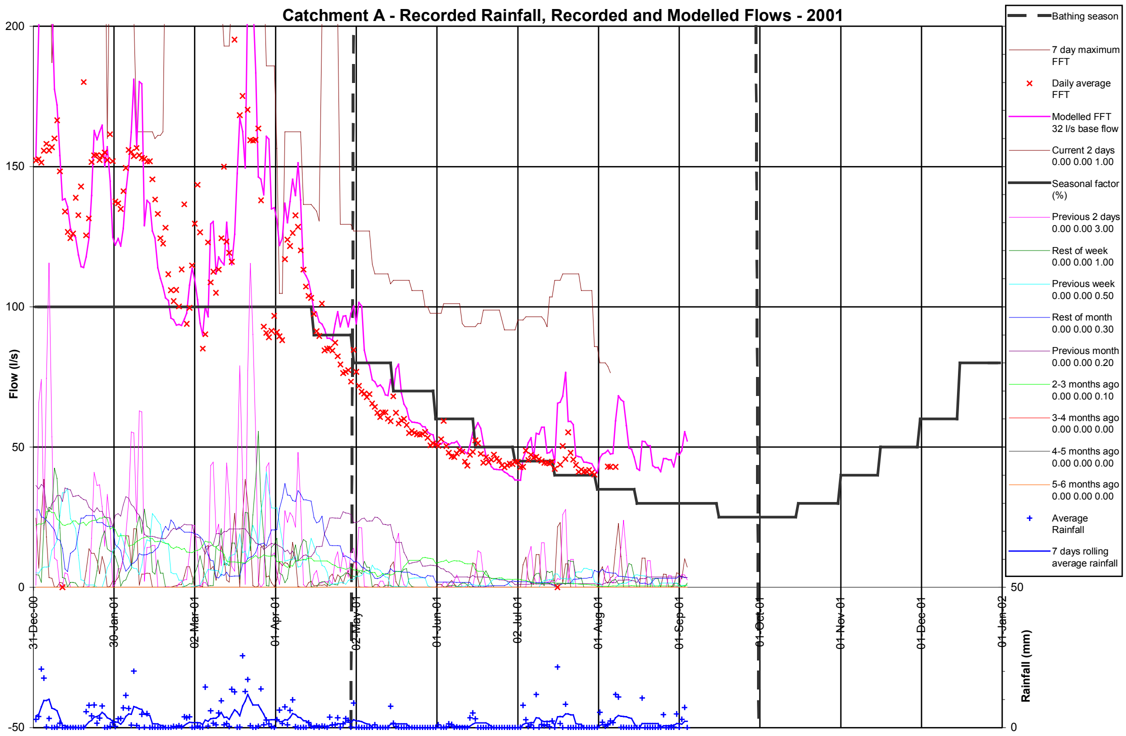
The graphs also indicate the individual components of the modelled flow. These clearly indicate the influence of much earlier rainfall towards the end of long dry periods. In particular, the periods between March and April 1997 and between September and October in both years illustrate the need to include components in the modelled flow that are based on the amount of rain that fell on the catchment as much as 3 months earlier.





Only flow data up to the end of July 2000 was used to calibrate the model. However, the model was used to project the flow during the following period from the rainfall data.

The following graph shows the FFT that the calibrated model projected for 2001 and the recorded FFT data that was provided later. It illustrates the remarkably accurate match that the model achieved between the projected and actual FFT.



Required storm tank capacity

The WwTW inlet flow records were used to estimate the storm tank volume that would have been required to limit the number of spills to less than an average of 3 per bathing season.

The peak inlet flow recorded on all days was compared with the peak FFT of 142 l/s that had been projected for the catchment in 2010. During both the 1996 and the 1998 bathing seasons, this was only exceeded on three and two days respectively. Thus, if the peak FFT had then been 142 l/s, the limit of 3 spills per bathing season would not have been exceeded during those two years, even if there had been no storm tanks.

For 1997 and 1999, the fourth largest peak daily inlet flows were 179 l/s and 190 l/s. However, the average inlet flows on those days were only 69 l/s and 79 l/s respectively. Therefore, only a relatively small storm tank volume would have been required to store the peak flows in excess of 142 l/s so that they could be treated when the incoming flow reduced. For example, in 1999 the excess flow reached a maximum of 48 l/s. If this excess had averaged 30 l/s for 2 hours, 108 m^3 of sewage would have overflowed to the storm tanks. Since this is far less than the capacity of the existing storm tanks, they would not have spilled.

There were two significant storm events during the 2000 bathing season, one at the end of May and the other at the end of August, following which high inlet flows were recorded. The average daily inlet flow exceeded 142 l/s on the following 7 days during that bathing season:

Date	Average Inlet Flow (l/s)	Excess volume above 142 l/s (m^3)
27 May	145	240
28 May	228	7,430
29 May	161	1,630
27 August	207	5,640
28 August	205	5,400
29 August	197	4,720
30 August	200	4,970

Since it would not have been possible for the contents of the storm tanks to be returned for treatment on those days, spills would have occurred as soon as they were full. On 27 May, the storm tanks would have started to fill and, unless their total capacity exceeded 7,670 m^3, they would have overflowed on 28 May. They would have continued to overflow on 29 May and would probably also have overflowed on 30 May when the average inlet flow was 131 l/s.

Similarly, unless they had more than 5,640 m^3 of capacity, they would also have overflowed on 27, 28, 29 and 30 August. They would probably have continued to overflow after then but the flows recorded on the preceding and subsequent days were not provided.

For the projected 2010 population of the entire catchment, the usual allowance of 68 l per person would give a storm tank capacity of 1,447 m^3. Clearly, this would not have been sufficient to prevent spilling of storm flows on at least 6 days during the 2000 bathing season. However, the existing storm tank volume would have been more than sufficient to prevent any spills during the previous 4 bathing seasons and, averaged over these 5 years, the limit of 3 spills per bathing season should not have been exceeded.

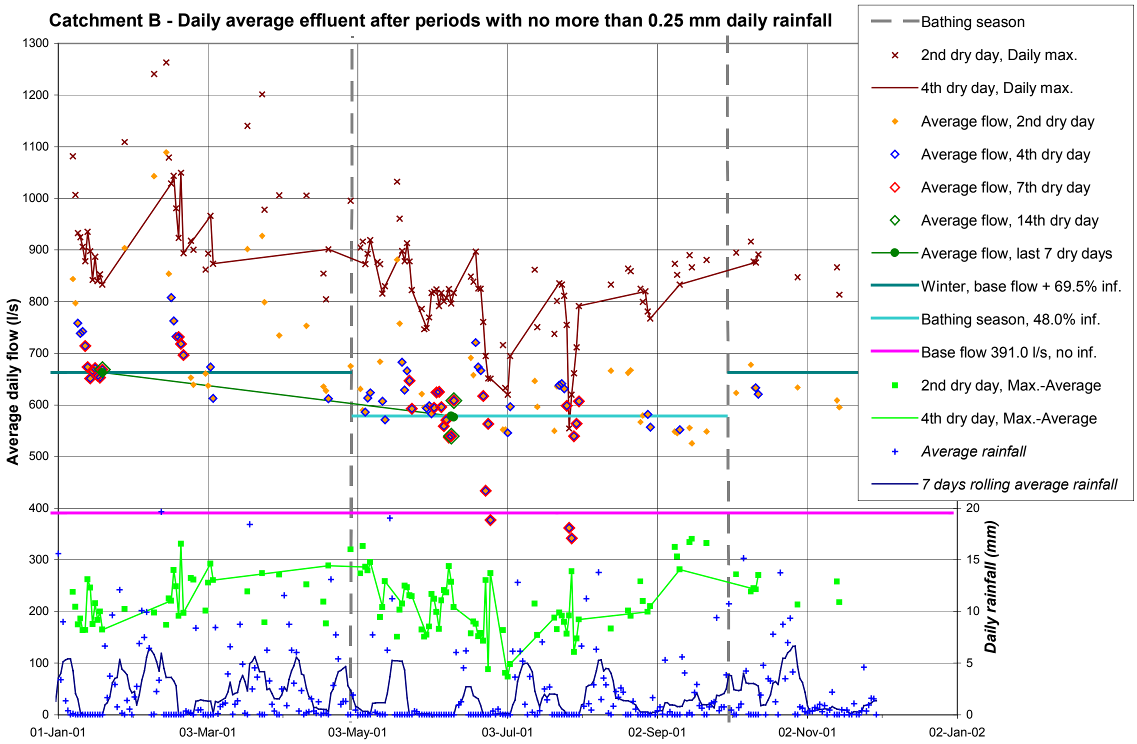
On this evidence, it was decided that there would be no need to provide additional storm tank capacity in order to satisfy the consent limit of 3 spills per bathing season.

Catchment B

The Trident West Alliance is currently designing WwTW enhancements for Catchment B, which covers a predominantly urban area in Thames Water's Western Region.

MWH used a technique based on that developed for Catchment A to confirm the DWF and FFT for which the WwTW is being designed. Maximum and average daily flows were obtained from the 2001 effluent flow records. From these, the flows on wet days were filtered out using daily rainfall records from two local rain gauges that were provided by the EA.

The following graph indicates the wide variation of average flows, even on dry days. However, shortly after rainfall, the flow could have been increased by factors such as the sewerage system's slow response to rainfall and the emptying of storm tanks.



Although the effect was not as pronounced as in Catchment A, the average flow did tend to reduce as dry weather extended for longer periods. There were only two periods of 14 or more dry days. The one which ended on 19 January indicated a winter DWF of 668 l/s and the other, which ended on 11 June, indicated a lower summer DWF of 579 l/s.

The graph also indicates the estimated sewage base flow during 2001. This was calculated by multiplying the overall catchment population equivalent of 207,875 by the assumed sewage flow of 162.5 l per person per day to give a sewage base flow of 391 l/s.

The infiltration component of DWF represented 69.5% of the sewage base flow in the winter, reducing to 48% in the summer. The graph also indicates that the actual levels of infiltration often exceeded those that were estimated as a component of DWF.

Red symbols on the previous graph indicate the maximum flow that was recorded on dry days. During the period under consideration, the FFT was limited to 1250 l/s. However, this was only reached on two dry days, the maximum flow on 9 February being 1241 l/s and on 14 February being 1263 l/s.

The symbols representing the maximum flow on the fourth and subsequent dry days are joined up to indicate more prolonged periods of dry weather. The maximum FFT only exceeded 1050 l/s on seven dry days during the winter and these were all less than 4 days after rainfall.

Light green symbols indicate the difference between the maximum flow and the average daily flow on dry days. These show that the maximum flow never exceeded the average daily flow by more than 341 l/s. This difference occurred on 16 September and represented 87% of the sewage base flow. Thus, the sewage peaking factor never exceeded 1.87 during the period under consideration.

The lines that join up the symbols representing the flow difference on the fourth and subsequent dry days indicate that the maximum difference after more prolonged periods of dry weather was 331 l/s on 20 February. This represents 85% of the estimated sewage base flow.

Analysis of the 2001 effluent flow records has indicated somewhat higher levels of infiltration than had previously been estimated. However, when calculating the maximum flow that should be treated, this is offset by the much lower sewage peaking factor of less than 1.9 compared with the factor of 3 that is inherent in the 3DWF design FFT figure.

The flow records indicate that the set FFT of 1250 l/s was actually adequate for the period under consideration. This FFT figure could be derived by multiplying the estimated sewage base flow of 391 l/s by a factor of 3.2.

The analysis described above indicates that, for Catchment B, the most appropriate way of deriving the 3.2 multiplier would be to allow a sewage peaking factor of around 1.9 and a corresponding maximum infiltration level of 130% of the estimated sewage base flow. Alternatively, using the winter estimate of DWF, infiltration equal to 70% of the sewage base flow and a sewage peaking factor of 2.5 could be allowed. Both of these approaches would include an adequate allowance for increased flow due to the catchment's slow response to rainfall and would avoid overflows to the storm tanks on dry days.

The infiltration levels stated above are related to the sewage base flow, which includes trade discharges. However, infiltration is usually expressed as a percentage of domestic sewage. The 2001 domestic population was 181,779 out of the total equivalent population of 207,875 and the domestic sewage flow was 342 l/s out of the total base flow of 391 l/s.

Re-calculating the percentage infiltration on the basis of domestic sewage only, the estimated level of infiltration would be 80% of the domestic sewage flow within the winter DWF and 55% within the summer DWF. Similarly, the suggested infiltration design allowance of 130% of base flow would be equivalent to 150% of the estimated domestic sewage flow.

Summary

This paper has demonstrated that:

- infiltration should not be assumed to have a constant value, even as a component of the DWF that is calculated in accordance with the IWPC definition
- infiltration can vary seasonally and can be strongly influenced by preceding rainfall
- the amount of infiltration can be influenced by rain that fell as much as 3 months earlier
- the flow in a sewerage system can be modelled and predicted from rainfall records alone
- the storm tank volume necessary to satisfy a consent standard, such as 3 spills per bathing season, can be estimated from long term flow records
- the difference between the recorded peak and average daily flows, when compared with the estimated amount of sewage that is discharged into the sewerage system, indicates the sewage peaking factor
- for larger catchments, the sewage peaking factor can be significantly less than 3

Acknowledgements

I wish to thank Southern Water Services Ltd and Thames Water Utilities Ltd for allowing me to use their flow data to provide the examples given in this paper and the Environment Agency for providing the corresponding daily rainfall data.