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EFFECTS OF DOMESTIC STORAGE ON DEMAND PATTERNS

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EFFECTS OF DOMESTIC STORAGE ON DEMAND PATTERNS

by

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1. INTRODUCTION

It is claimed[1] that the provision of cold water storage in domestic water supplies produces four benefits, as follows:

(a) provision against interruptions of the supply caused by repairs to the main, etc;
(b) good protection against back siphonage risks;
(c) reduction of the maximum demand rate on the mains;
(d) limitation of the pressure on the distributing pipes and fittings connected thereto, reducing noise and waste of water and enabling lighter and therefore cheaper piping to be used.

The purpose of this study was to investigate (c), that is, to determine whether the presence of individual domestic storage has any effect on the peak demand rate for a large group of consumers, and, in doing so, to answer the following questions:

(i) would a change to a European type all-pressure plumbing system produce increased peak demand rates ?
(ii) could better use be made of individual domestic storage to reduce peak demand rates ?

No attempt was made to determine whether the type of plumbing system affects the total quantity of water used by individual households.

2. UK AND EUROPEAN PLUMBING SYSTEMS

There are two basic types of plumbing system used in the UK. They are often referred to by the plumbing trade as the South of England system and the North of England system respectively, although there is no strict geographical dividing line for their use.

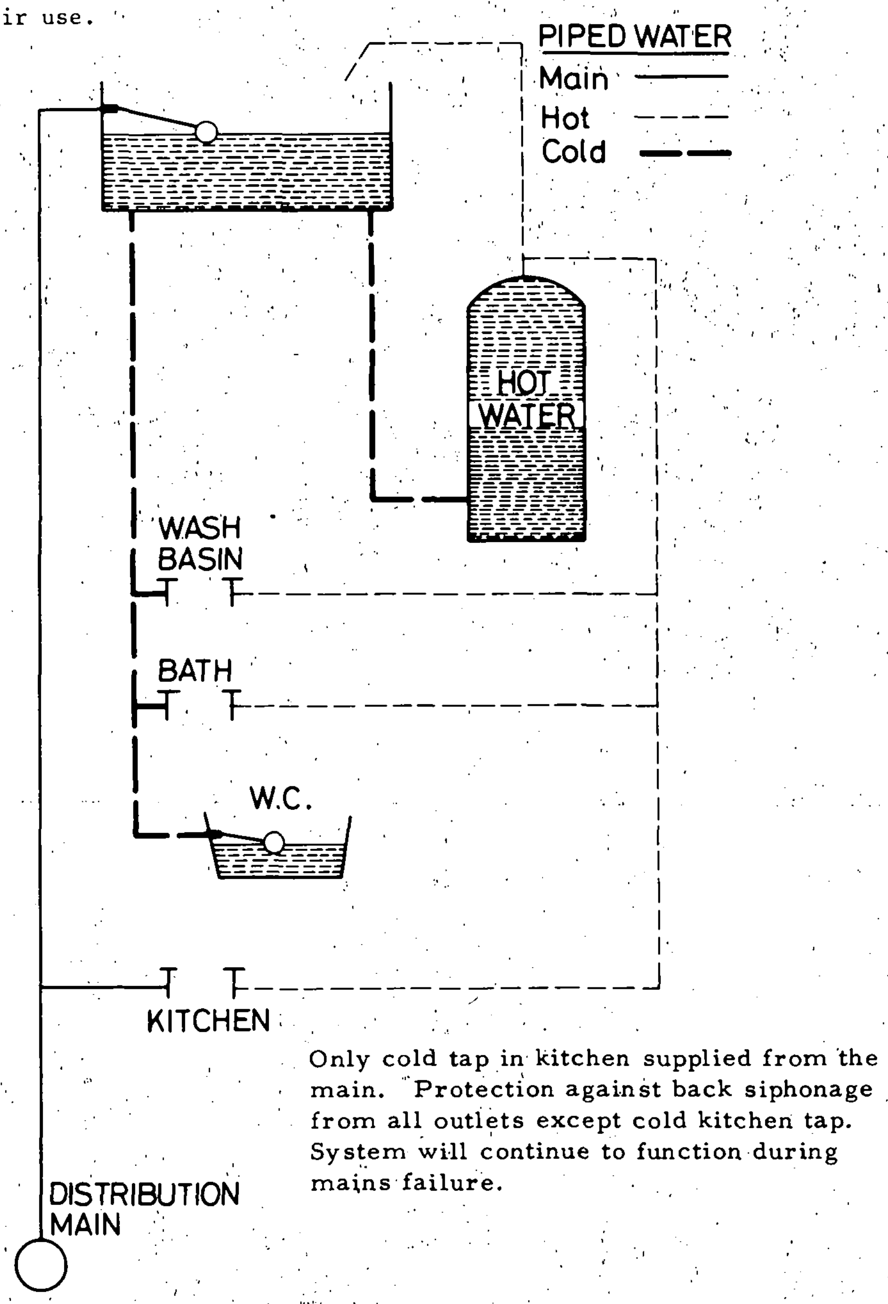


Fig. 1. South of England plumbing system

In the South of England system (Fig. 1) all the water used within the house goes through the storage tank, except for the cold supply to the kitchen which is taken directly from the main. In the North of England system (Fig. 2) all cold taps and the W.C. are supplied directly from the main and only the hot water system is supplied from the storage tank. In general terms, the South of England system has a stored volume of about 230 litres (50 gallons) and the North of England system 115 litres (25 gallons).

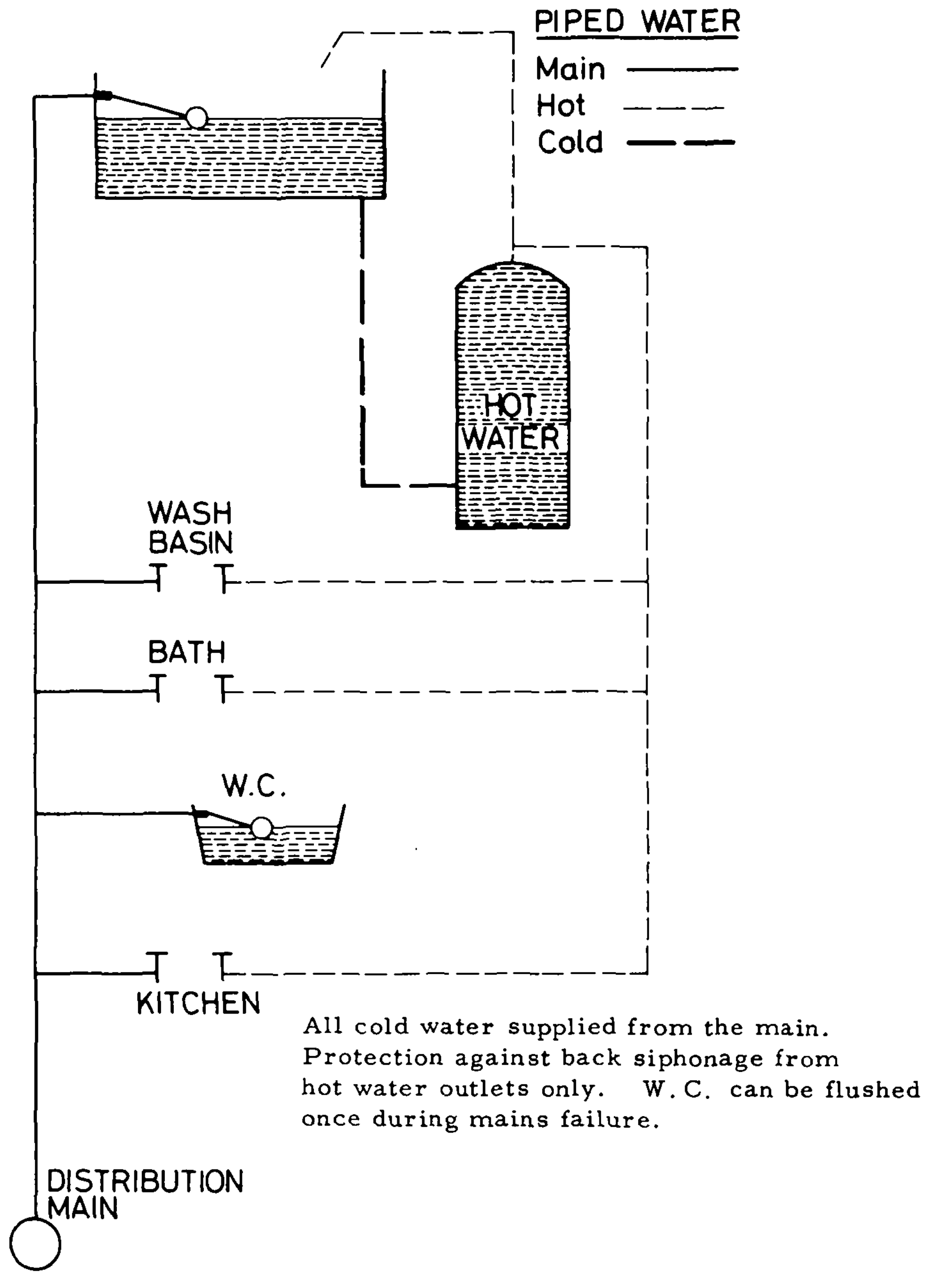


Fig. 2. North of England plumbing system

For the purpose of this study, a European all-pressure system was assumed to have all outlets (hot, cold and W.C.) supplied directly from the main and to have a W.C. flush cistern rather than a W.C. flush valve. The system is shown diagrammatically in Fig. 3.

It was also assumed that the European system would provide the same quantity and flow rate at each outlet within a house, as the storage systems. This is equivalent to saying that a change of plumbing system does not affect the way in which a consumer uses water, that is, the consumer uses water at the same rates and at the same time with all three systems.

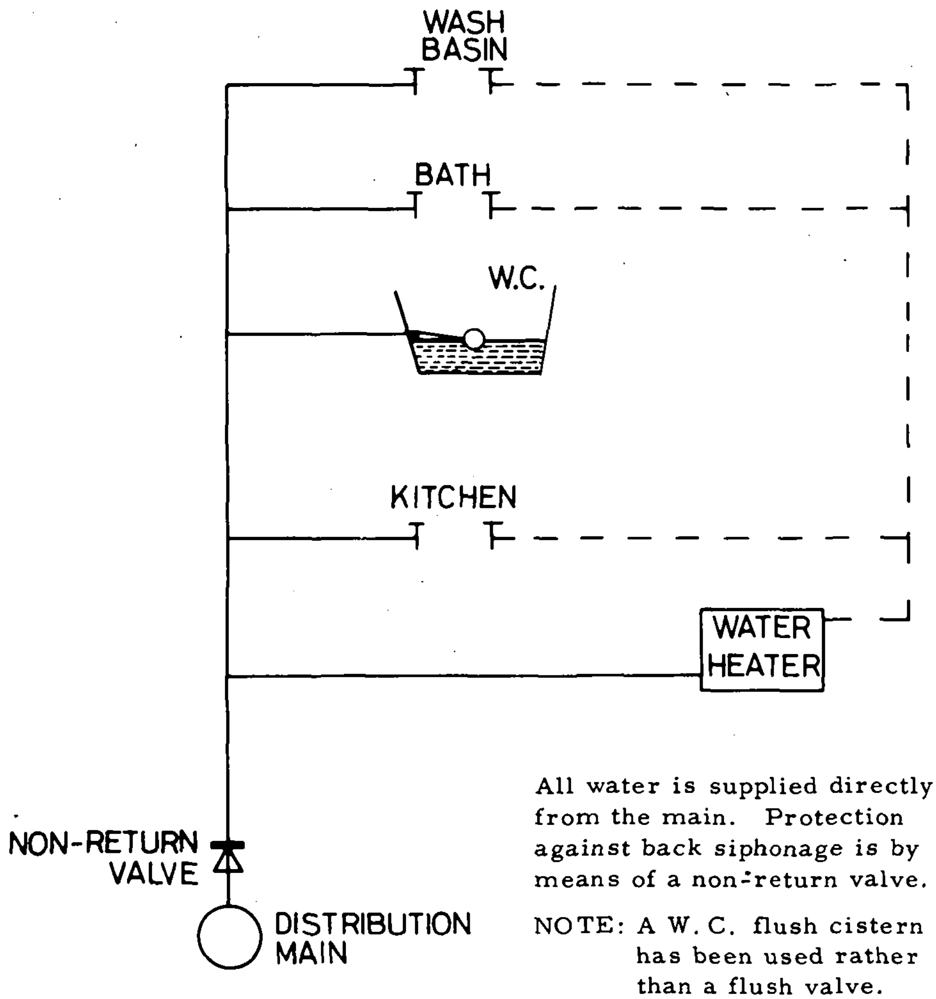


Fig. 3. Diagrammatic representation of a European plumbing system

Provided that the pressure within the distribution system is sufficient to supply the demands, its actual value does not enter into demand calculations. 'Sufficient' in this case, means a head of water equal to:

the height of highest outlet above the main	+	the head-loss along the service pipe at the required flow rate

If the pressure falls below this value, then the flow rate at the outlets will be reduced and the systems are no longer comparable. At this point failure is said to have occurred since the consumer can no longer obtain the flow he desires. A pressurised system does not necessarily require a high pressure to work satisfactorily. Consequently in practice, the diameter of the service pipe supplying the European system may need to be larger than 15 mm to prevent premature failure of the system.

In most instances, as the pressure is gradually reduced, failure of the European system will occur before failure of the storage system and it may not be possible to design an effective pressurised system for use in an area of low and fluctuating pressure.

3. METHOD OF ANALYSIS

If the demand rate, duration and starting time of every water use were known for each consumer, the corresponding flow rates through the service pipe could be calculated for a particular plumbing system. These individual flow rates could then be summed to produce the flow pattern for a group of consumers. Total demand for a group of consumers can be said to depend upon two factors, the individual rates of flow of water through the service pipe and the diversity of use. The diversity of use, or diversity factor as it is often called, takes account of the fact that different numbers of people are using water at different times of day. As no satisfactory statistical model of this diversity has yet been developed, it was decided to calculate the diversity for each of the study areas and to use this for predicting the effects of changing the plumbing system.

The method used for the analysis was to assume the same water use sequence for all consumers, and then to calculate the corresponding individual flow pattern through the service pipe, taking into account the existing plumbing system. Using this individual flow pattern and a measured flow pattern for a group of consumers, the number of consumers starting to use water at a particular time was calculated. The individual flow pattern was then changed, corresponding to a change of plumbing system, and the new patterns were combined using the starting times previously calculated. The resultant is a predicted group demand pattern corresponding to the new plumbing system.

4. DATA COLLECTION

Data were collected for the flow rates into three areas of domestic consumers. The areas chosen were existing waste meter areas that could remain isolated during the day without seriously reducing the pressures in any part of the network. The flow measurements were made with waste-water meters installed in the single main which supplied each area, and were recorded over a two-week period. Measurements were also made of flow rates into some individual houses and from various types of outlet. These measurements were used in conjunction with the data published by Webster[2] to determine a typical individual use sequence. Measurements were also made of the maximum draw-down level of domestic storage tanks over a four-week period.

5. ANALYSIS OF DATA

The flow data collected from the three study areas were in the form of traces on charts with each chart covering a 24-hour period. The charts showed that the rate of flow into each area started to rise at about 05.00 h and had reached a peak by 09.00 h. The flow then reduced for the rest of the day but produced secondary peaks around midday and in the evening. (A typical flow pattern for a day is shown in Fig. 7(a), page 12.) It is possible to consider the flow pattern as being made up of two components. The first consists of an overall flow rate which changes slowly with respect to time and is the major component of the flow at any instant. The second is a higher frequency component of random amplitude within a band of ± 0.5 litres/sec.

Readings were taken from the charts at 10-mm intervals, corresponding to 15 minutes, and put on to punched cards suitable for subsequent analysis by computer.

Analysis of the data collected showed that the peak flow rate occurred between 08.00 and 09.00 h on weekdays but occurred during late morning, lunch time or early evening at week-ends. In all three areas, the largest daily quantity of water was used on Sundays and the smallest quantity on Thursdays. The time at which the week-day peaks occurred could vary by as much as three-quarters of an hour between one day and the next, and on some days two peaks, of equal height, were measured. Typical results are shown in Table 1.

The measurements of domestic storage tank levels showed that on average the tanks were not drawn down more than 30 mm unless the bath was used; in such cases the level fell by about 100 mm. The maximum drop in level recorded was 280 mm. This was measured in a house with two bathrooms which are often in simultaneous use. The surface area of all the tanks measured was 0.54 m^2 (6 ft^2).

The rates of flow into individual houses showed a regular use pattern in the morning on weekdays, but were much more varied at other times of the day and at week-ends.

Table 1. Measurement of flow

	Quantity (litre)	Peak flow rate (litre/sec)	Peak to average ratio
Area No. 1			
Monday	169 644	4.60	2.23
Tuesday	168 800	4.50	2.20
Wednesday	165 424	4.70	2.34
Thursday	162 892	4.55	2.30
Friday	177 662	4.60	2.14
Saturday	198 762	4.90	2.03
Sunday	209 734	5.40	2.12
Area No. 2			
Monday	252 800	4.90	1.67
Tuesday	237 000	4.90	1.79
Wednesday	236 210	4.80	1.76
Thursday	230 680	4.61	1.72
Friday	232 260	4.50	1.67
Saturday	240 950	4.90	1.75
Sunday	269 390	5.00	1.60
Area No. 3			
Monday	256 533	6.06	2.04
Tuesday	244 650	6.01	2.12
Wednesday	256 533	5.55	1.87
Thursday	232 767	6.06	2.25
Friday	248 844	6.06	2.10
Saturday	252 339	6.06	2.07
Sunday	262 824	6.69	2.26

6. SIMULATION OF PEAK DEMAND PERIOD

With a South of England plumbing system it is impossible to produce a flow through the service pipe of high rate and short duration. The randon fluctuations in flow rate measured for the groups of consumers must, therefore, have been produced by water uses made at the kitchen tap. Similarly, it can be argued that the gradually changing flow into each area is largely produced by the demand for water taken through the storage tank.

For the purpose of this study, it was assumed that all individuals had the same water-using sequence after getting up in the morning. The sequence used is shown in Fig. 4 and consists of flushing the toilet, washing, and then cleaning teeth. It was also assumed that a use was made from the kitchen tap at some time before 09.00 h.

The flow pattern corresponding to this sequence of use with a South of England plumbing system was calculated and is shown in Fig. 5. For the calculation it was assumed that the storage tank and W.C. were both fitted with Portsmouth type ball valves to B.S.1212[3]. The flow characteristic for such a valve[4] is shown in Fig. 6. It can be seen that once the tank level has drawn down by about 40 mm the ball-valve is fully open and any further drop in level does not result in a higher inflow rate.

The rate of flow of water into each study area started to increase at 05.00 h and it was assumed that all users were out of bed by 09.00 h. This period 05.00 to 09.00 h was assumed to represent the peak period, and for the analysis was divided into 10-second periods. The flow rate for each period was calculated from the measurements made at 15-minute intervals, assuming a linear relationship between readings. The individual flow pattern was similarly divided into 10-second periods. It was assumed that the flow rate was constant within any 10-second period.

The number of consumers starting to use water in each 10-second period was calculated as follows:

If Q_1, Q_2, Q_3 ... Q_i represents the measured flow rate for the group of consumers in each 10-second period i, and q_1, q_2, q_3 ... q_j represents the calculated flow rate for an individual consumer in each 10-second period j, and N_i represents the number of people starting to use water in each period i, we have:

$$Q_1 = N_1 q_1$$

$$Q_2 = N_1 q_2 + N_2 q_1$$

$$Q_3 = N_1 q_3 + N_2 q_2 + N_3 q_1$$

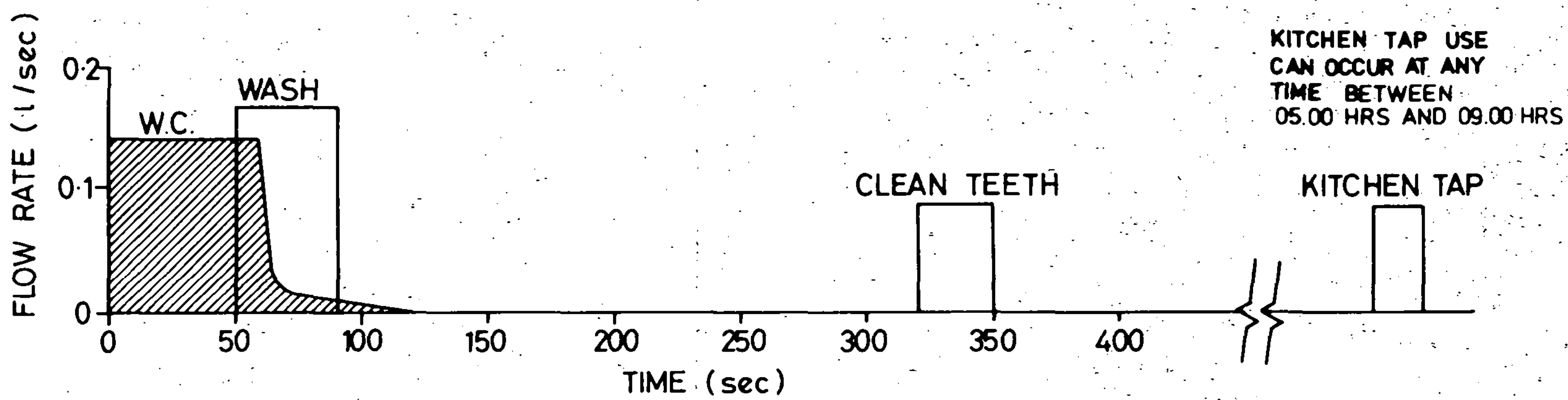


Fig. 4. Assumed sequence for the use of water

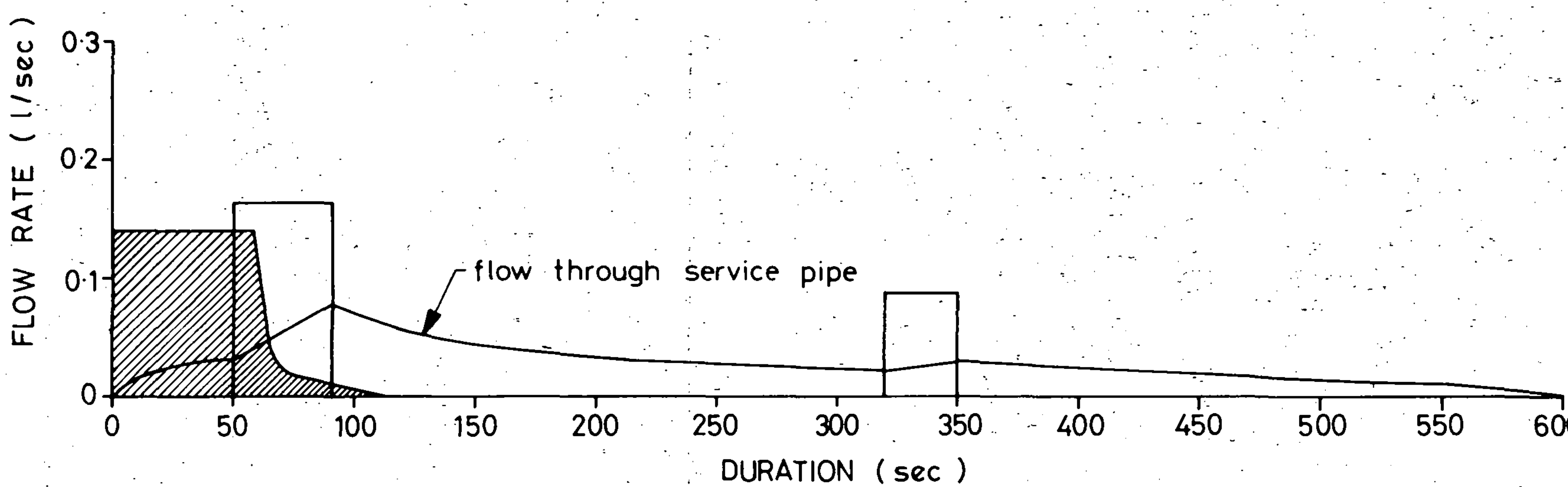


Fig. 5. Calculated flow through service pipe for South of England plumbing system using the demand sequence shown in Fig. 4.

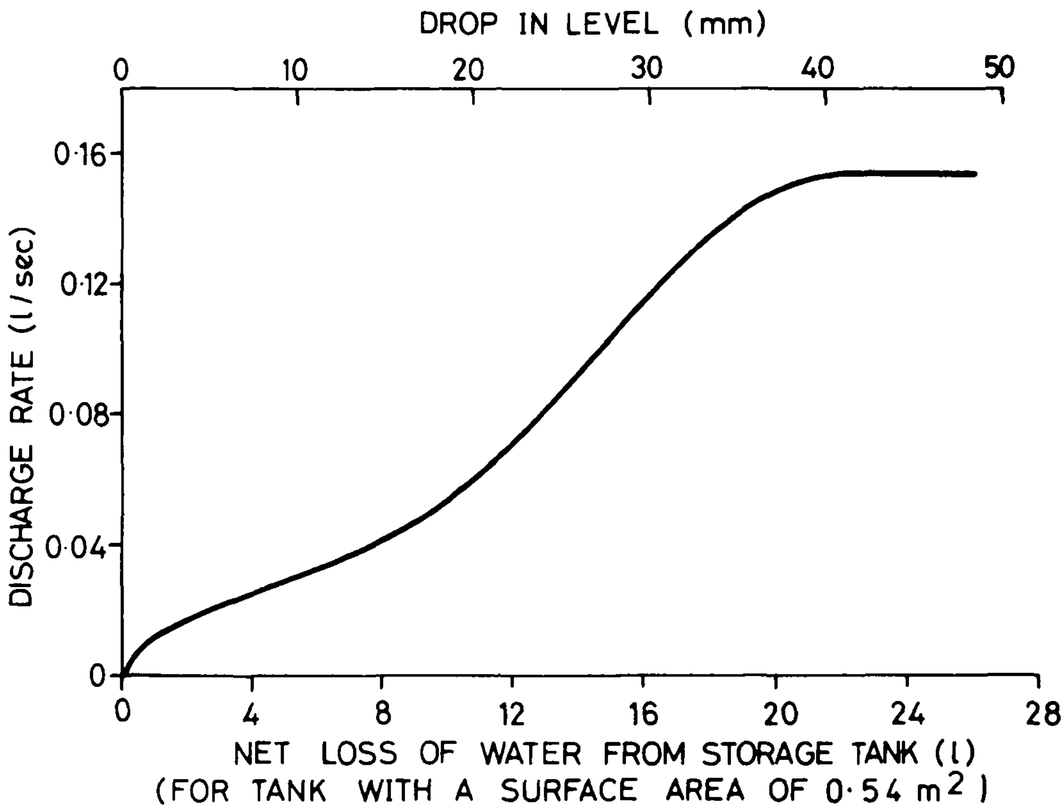


Fig. 6. BS 1212 Portsmouth ball-valve characteristics

$$Qi = \sum_{j=1}^{n} N_{(i - j + 1)} q_j .$$

The values of N_i were taken to the nearest integer, or zero if negative.

The kitchen tap uses were added as a set of random demands.

Figs 7(a) and 8(a) show two typical flow patterns measured in two different areas where all the houses were fitted with South of England plumbing systems. Figs 7(b) and 8(b) show the measured flows excluding the kitchen use. It can be seen that the rate of change of flow is assumed to be constant between any two of the readings taken at 15-minute intervals.

The simulations of these measured curves are shown in Figs 9(a) and 10(a). The simulations excluding the kitchen tap use are shown in Figs 9(b) and 10(b). It can be seen that there is a very good fit between measured and simulated curves in both areas and these are typical of the results obtained with other data. Integrations of the measured and simulated curves to yield total quantity of water used agreed to within 10 litres.

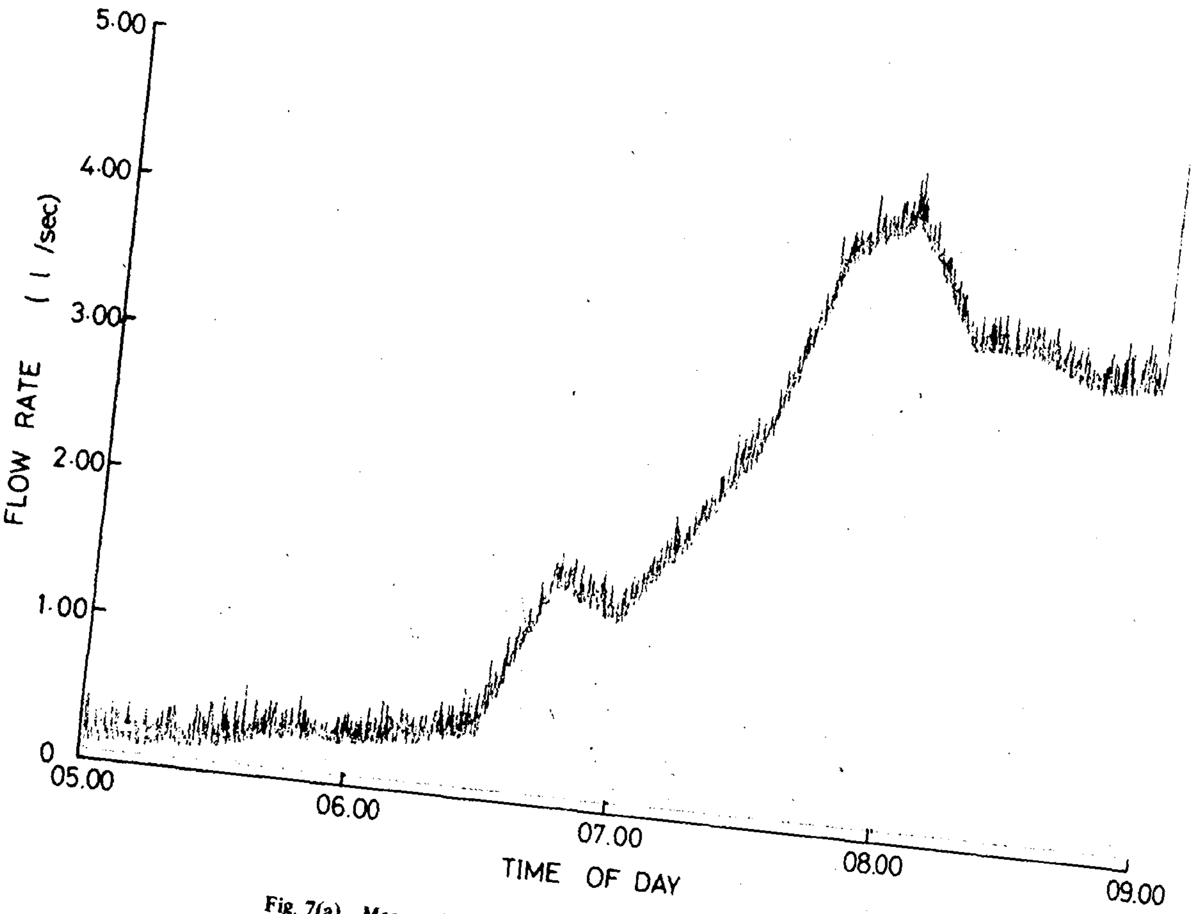


Fig. 7(a). Measured flow into area 1 including random kitchen tap use

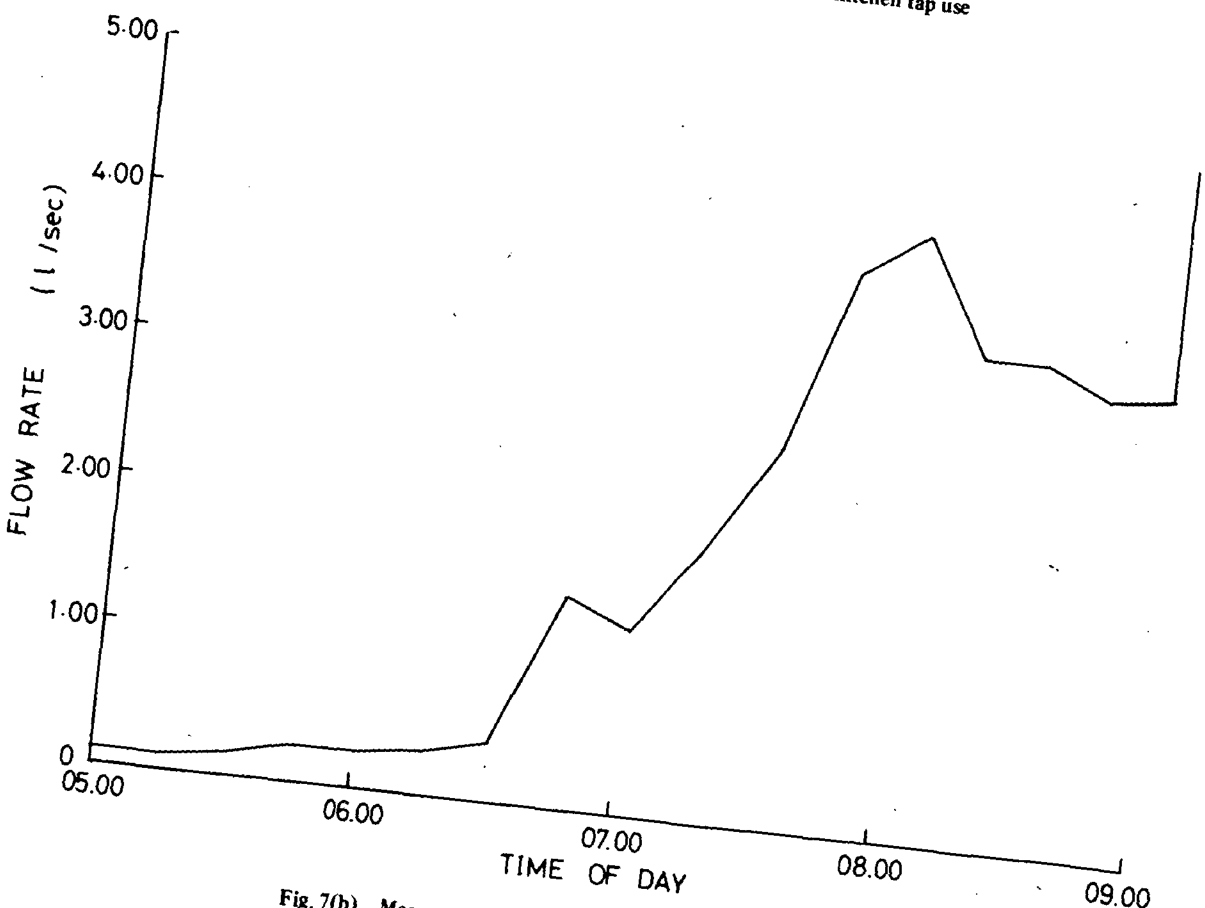


Fig. 7(b). Measured flow into area 1 excluding kitchen tap use

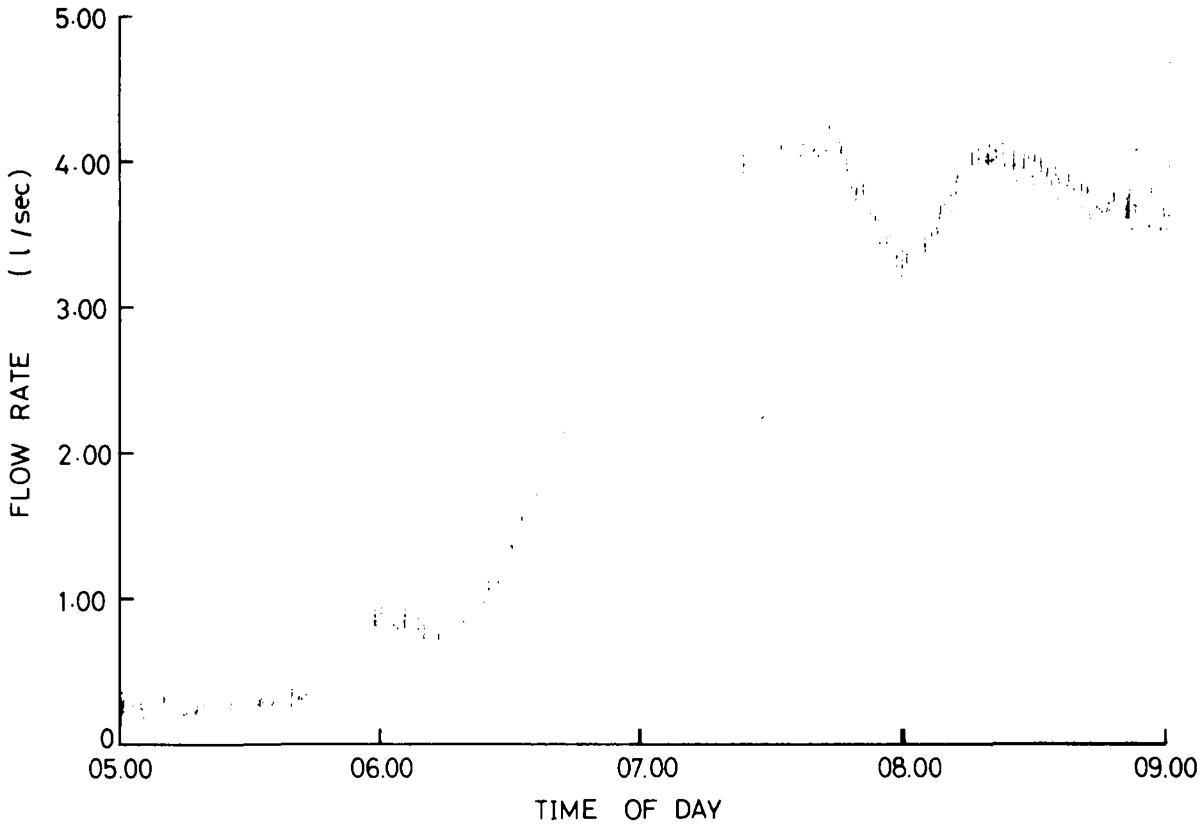


Fig. 8(a). Measured flow into area 2 including random kitchen tap use

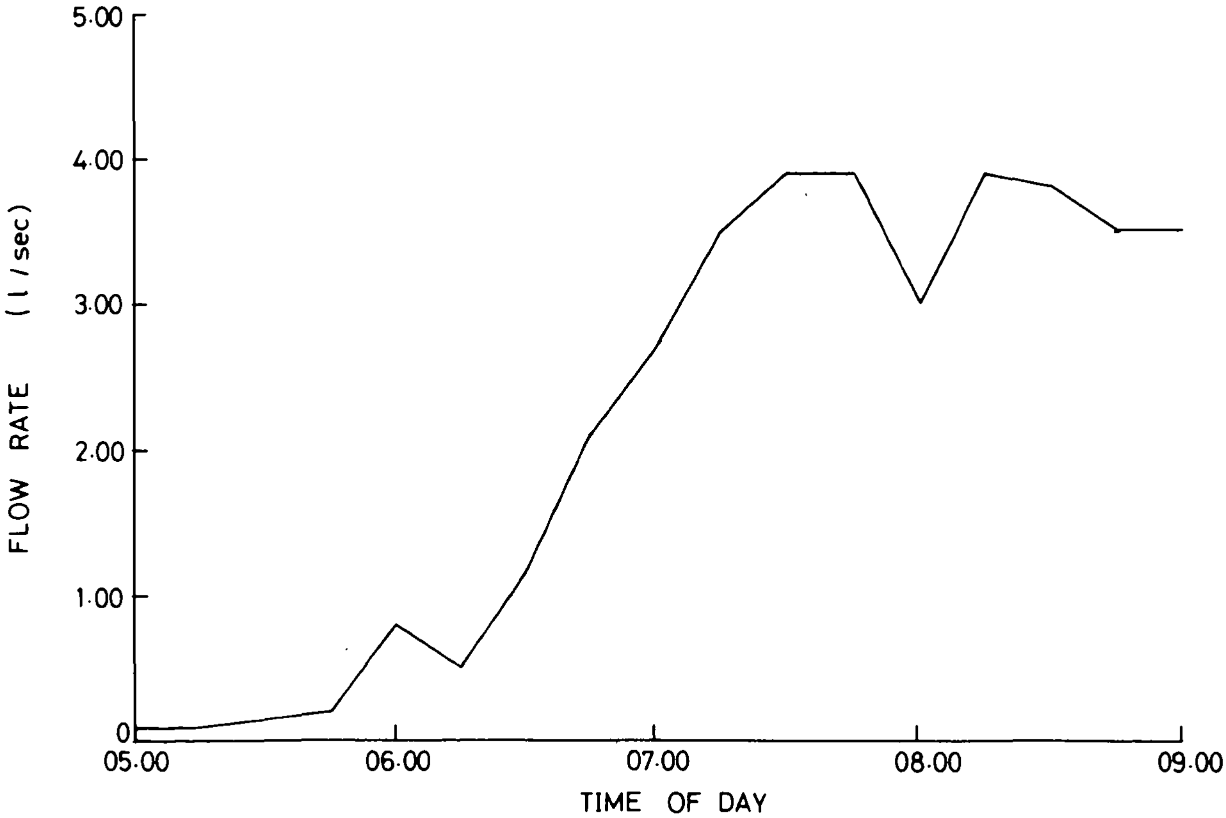


Fig. 8(b). Measured flow into area 2 excluding kitchen tap use

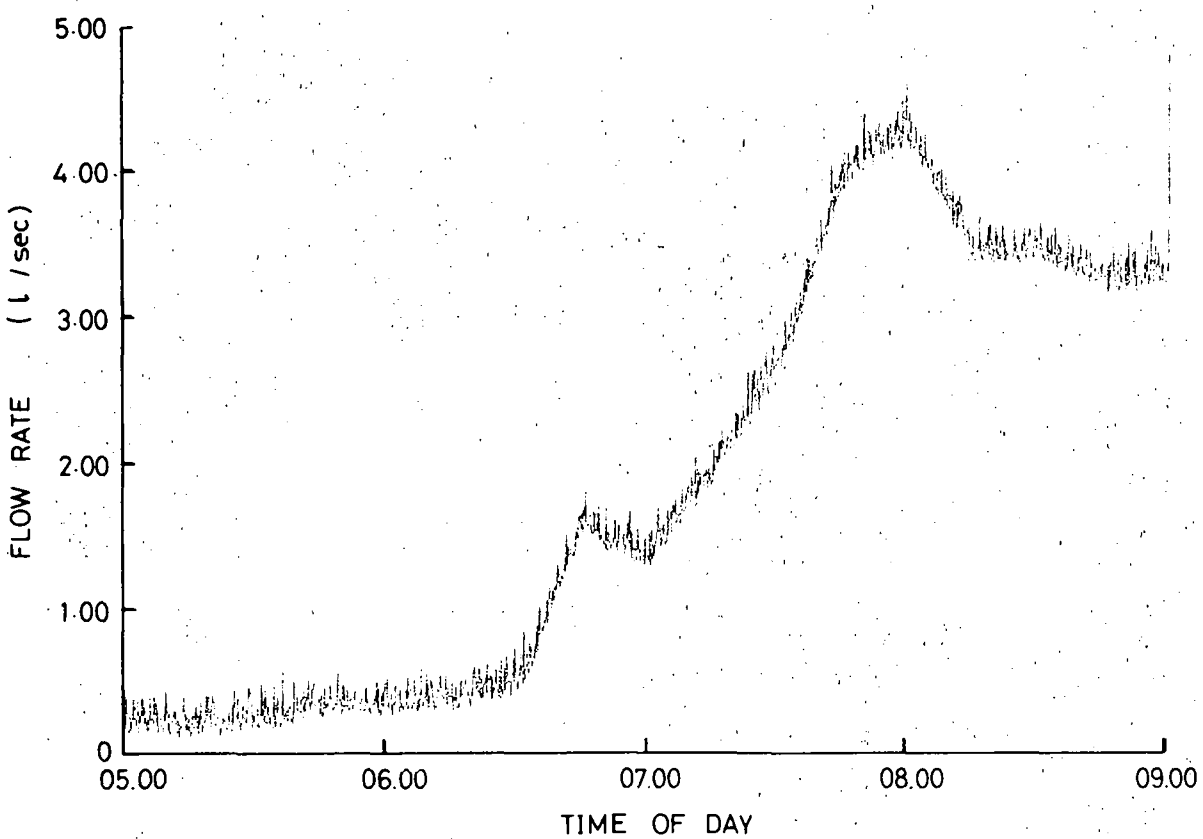


Fig. 9(a). Simulation of flow into area 1

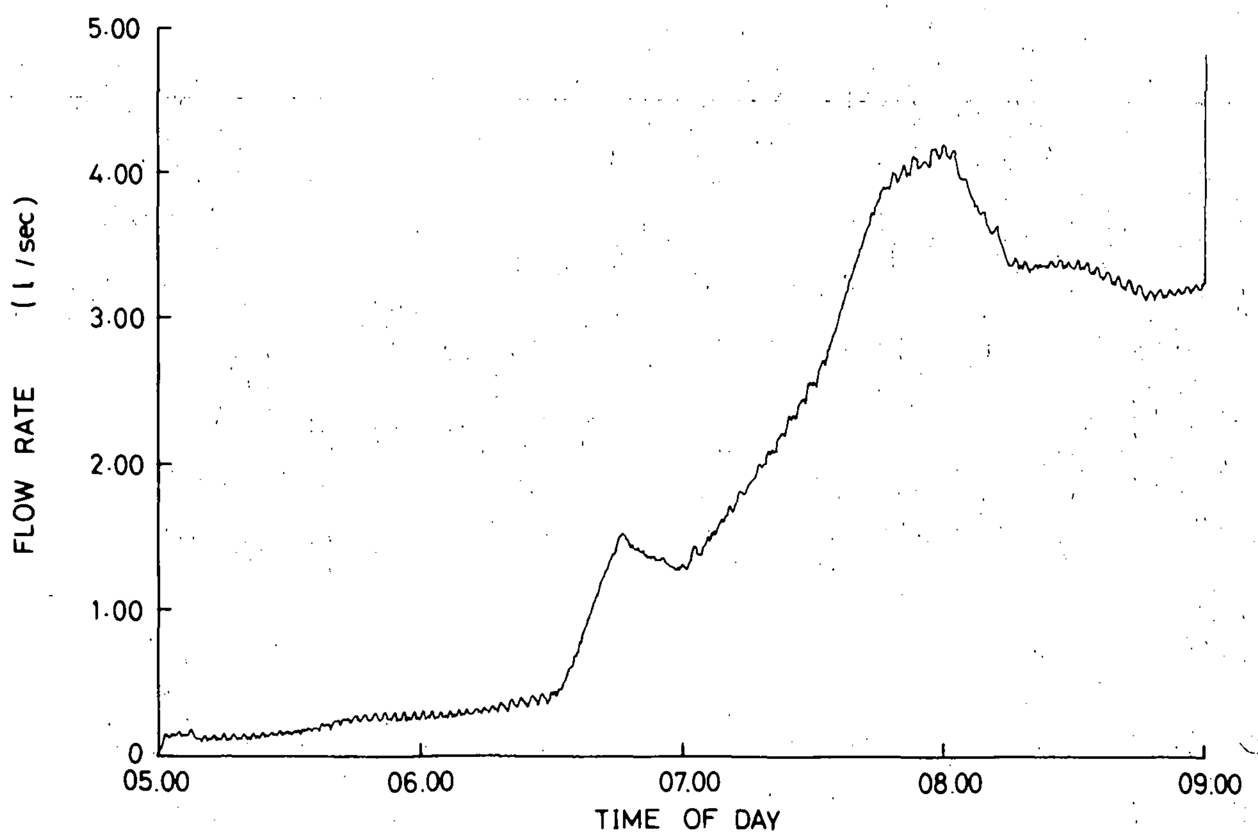


Fig. 9(b). Simulation of flow into area 1 excluding kitchen tap use

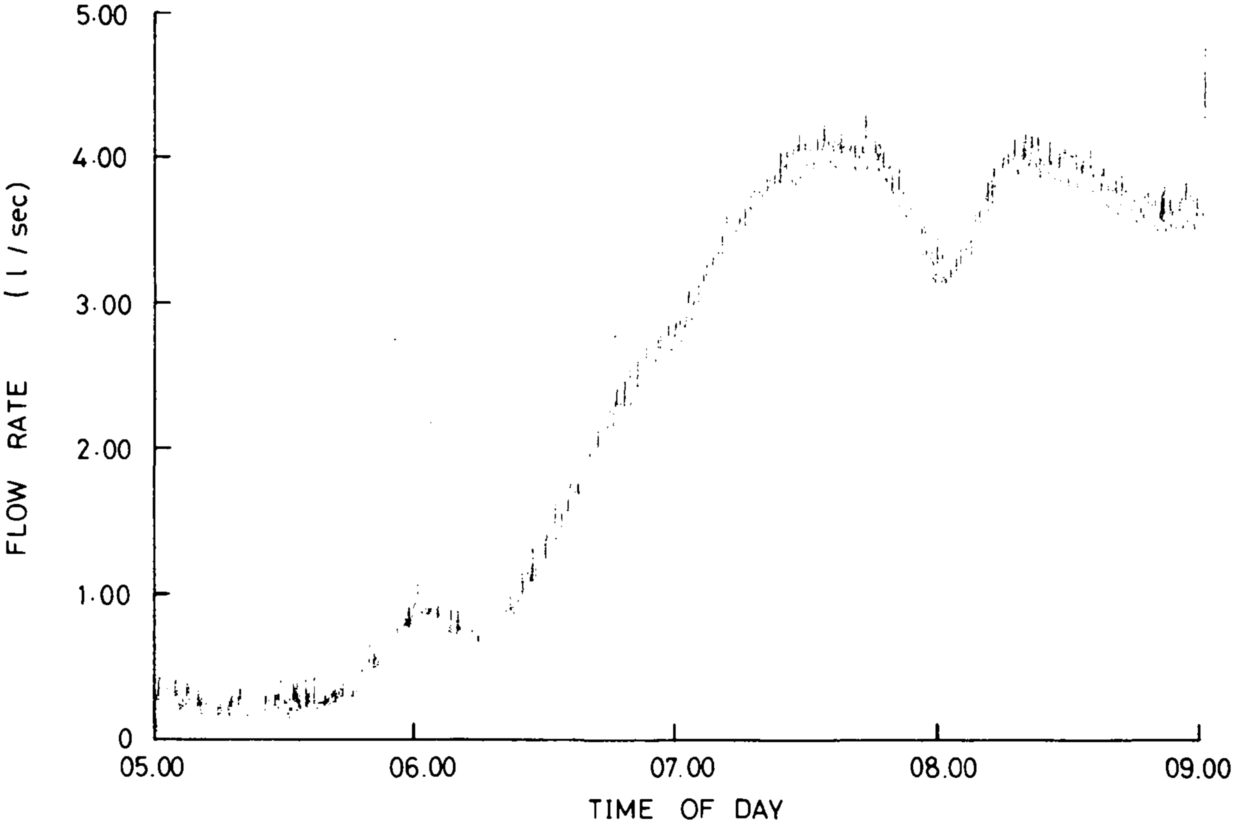


Fig. 10(a). Simulation of flow into area 2

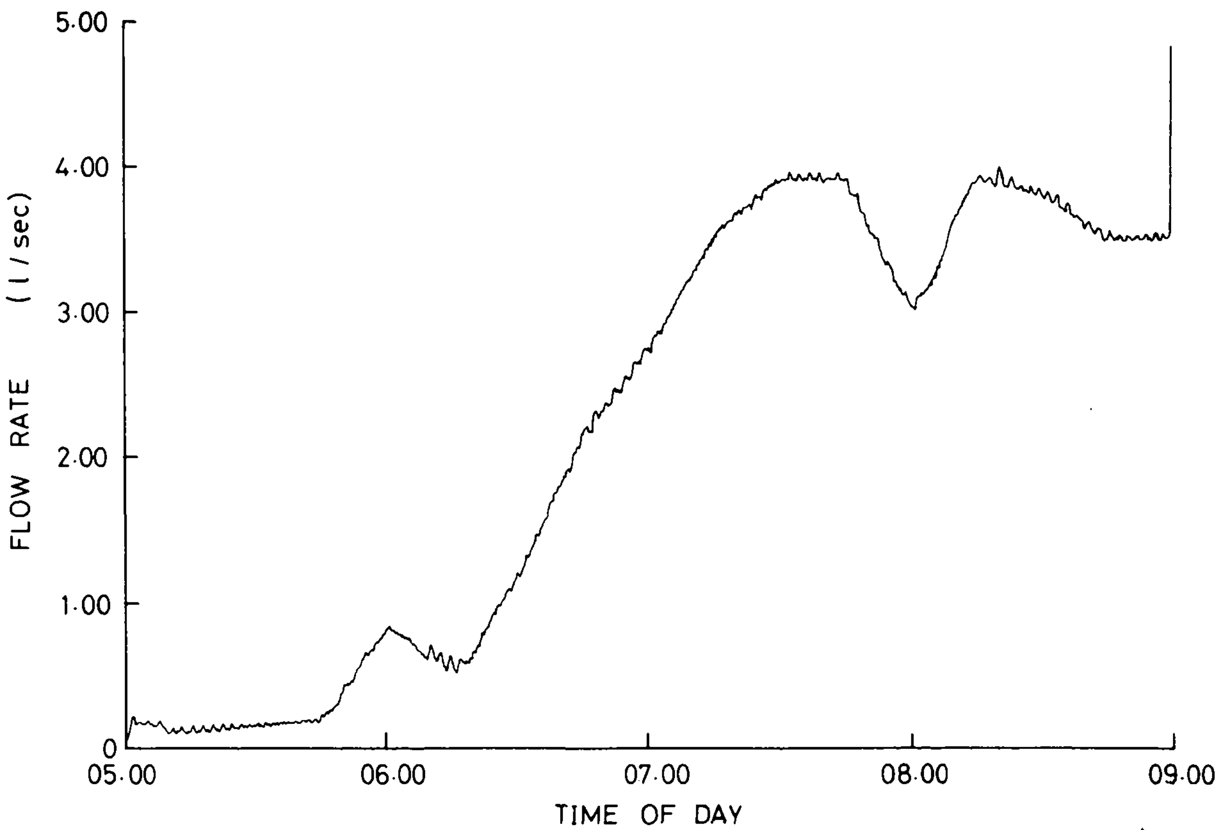


Fig. 10(b). Simulation of flow into area 2 excluding kitchen tap use

7. PREDICTED DEMAND PATTERNS

The flow pattern for an individual household with the same use sequence but with a European plumbing system was then calculated and is shown in Fig. 11. Comparison of Figs 4, 5 and 22 shows the effect of storage on the flow pattern for a single consumer. A comparison of peak and average flow rates, ignoring the kitchen tap use, is given in Table 2.

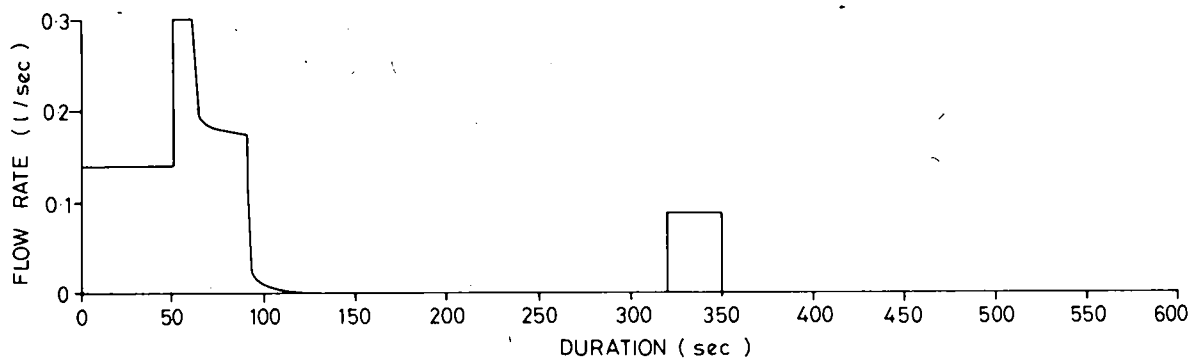


Fig. 11. **Calculated flow through service pipe for plumbing system with no storage (calculated for the use sequence shown in Fig. 4)**

Table 2. Effect of storage for single consumer

	Peak rate (l/sec)	Duration (sec)	Mean rate (l/sec)
With storage	0.077	610	0.03
Without storage	0.30	140	0.13

The duration is the total time for which water is flowing through the service pipe. For the European system the duration is the sum of the two separate uses shown in Fig. 4.

It can be seen that the peak flow rate has increased by a factor of 3.9 and the mean flow rate by a factor of 4.3.

The overall effect of the change of plumbing system for the group of consumers was determined by adding the curves using the values of N_i previously calculated.

If P_1, P_2, P_3 ... P_i is the predicted flow rate for the group of consumers in any period i, and g_1, g_2, g_3 ... g_h is the calculated flow rate for a consumer with a European plumbing system in period h, then:

$$P_1 = N_1 g_1$$

$$P_2 = N_1 g_2 + N_2 g_1$$

In general:

$$P_i = \sum_{J = i}^{h} N_{(i - J + 1)} g_3.$$

The kitchen tap uses were then added as random uses as before.

The predicted demand curves of the two groups of consumers are shown in Figs 12(a) and 13(a). Comparison of these two curves with Figs 9(a) and 10(a) shows the effect of storage removal for a group of consumers. It can be seen that there is no overall increase in peak demand rate, although there is a slight change in shape. The European system produces a slightly higher rate of increase of demand and the peak flow rate is of longer duration, which gives the curve slightly steeper sides and a flat top. Figs 12(b) and 13(b) show the predicted demand curves for each area excluding the kitchen tap use. It can be seen that the European plumbing system produces fine-scale fluctuations in flow similar to those produced by the kitchen tap demand. In order to demonstrate that the fluctuations were not produced by the large peak in the particular demand sequence used, the use of the wash basin was delayed to produce the individual flow pattern shown in Fig. 14.

By combining these patterns in the same way as before, the curve shown in Fig. 15 was produced. It can be seen that there is very little difference between Fig. 13(b) and Fig. 15.

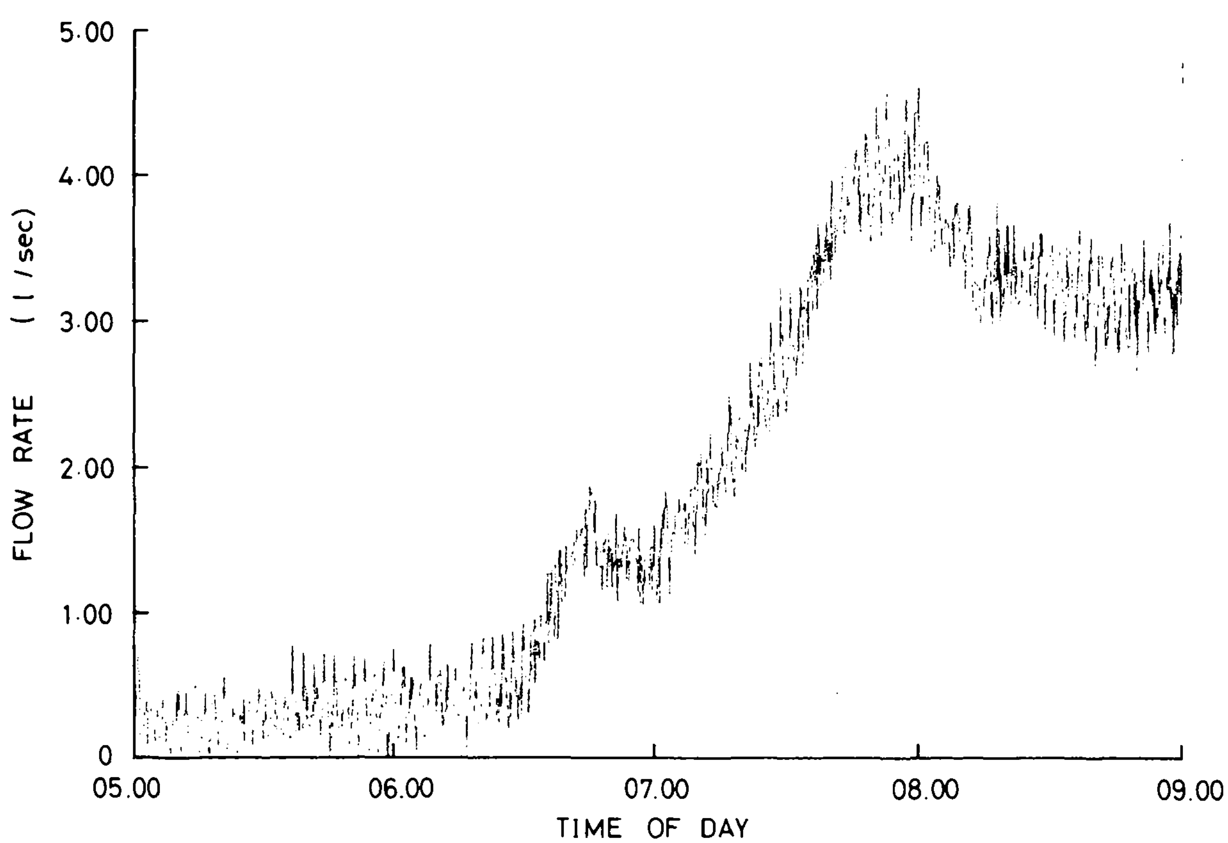


Fig. 12(a). Predicted flow into area 1 – European plumbing system

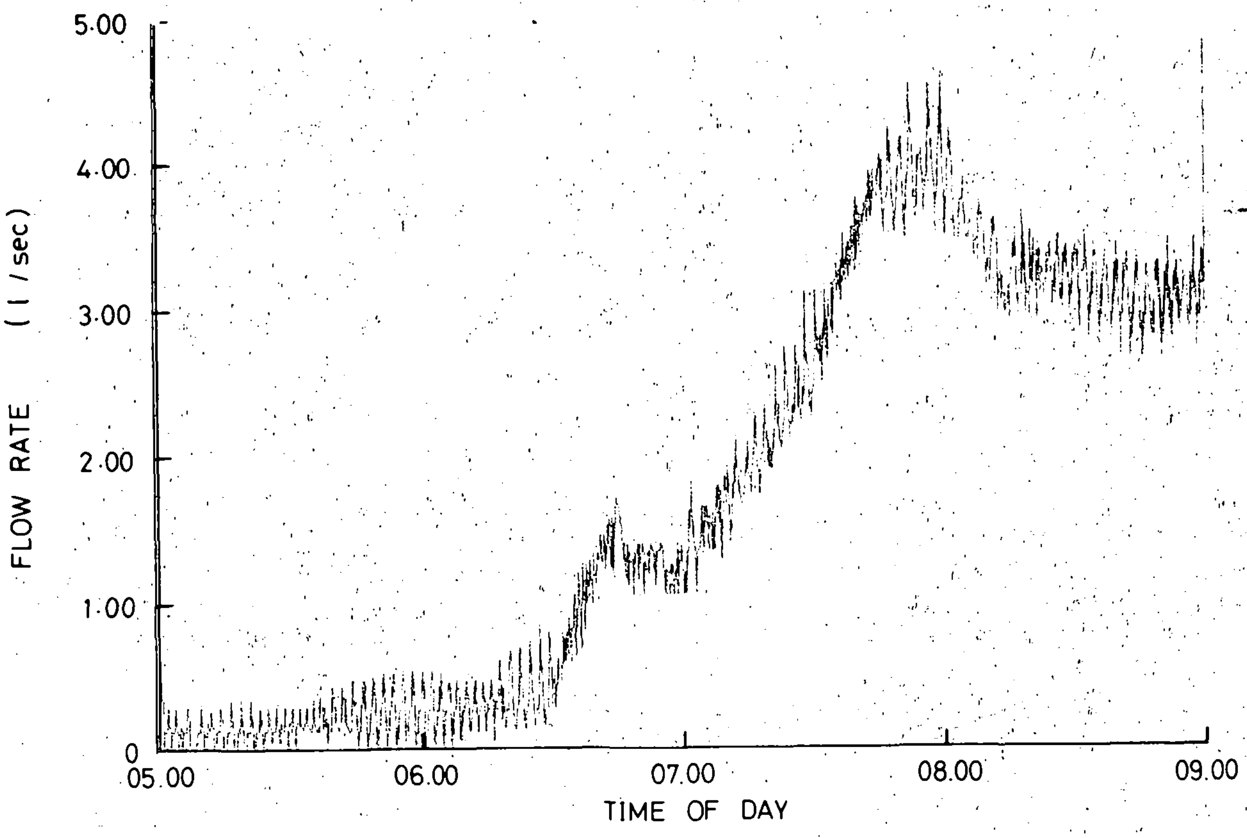


Fig. 12(b). Predicted flow into area 1 excluding kitchen tap use – European plumbing system

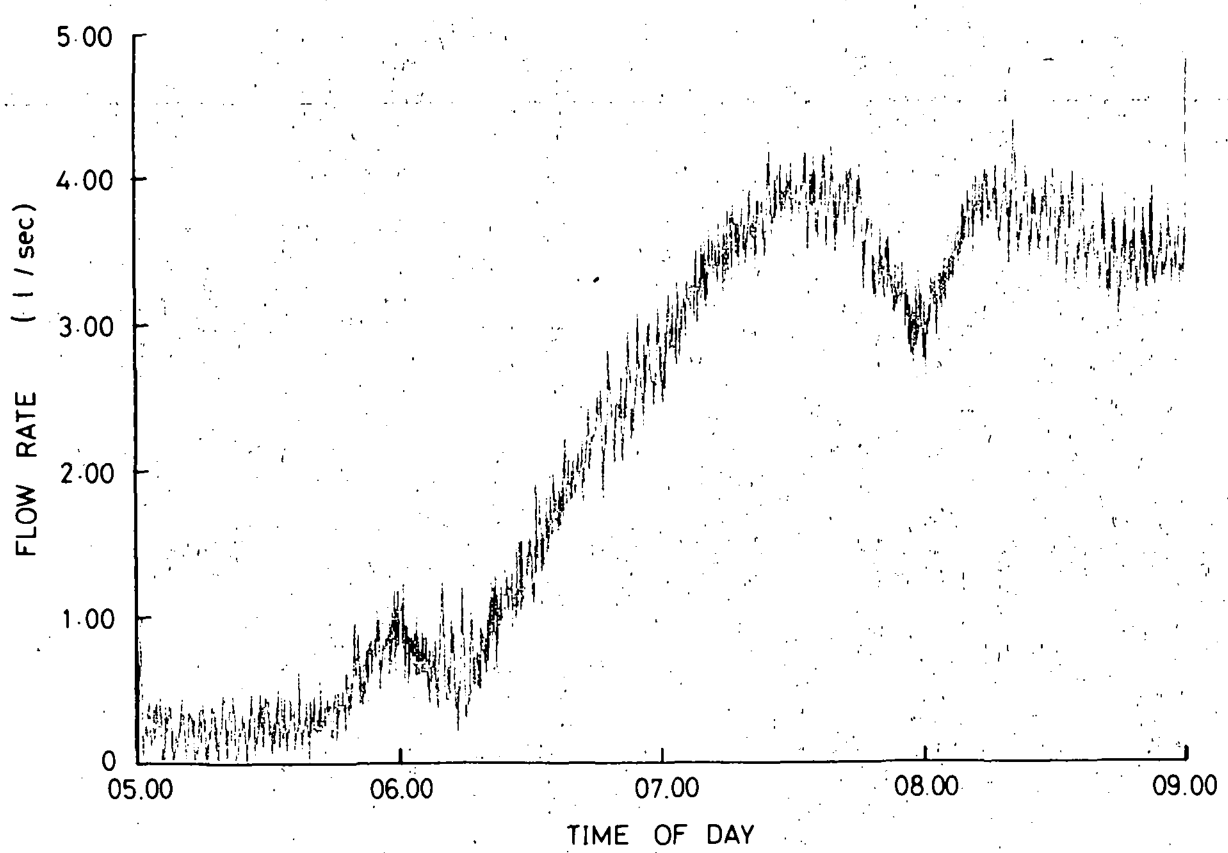


Fig. 13(a). Predicted flow into area 2 – European plumbing system

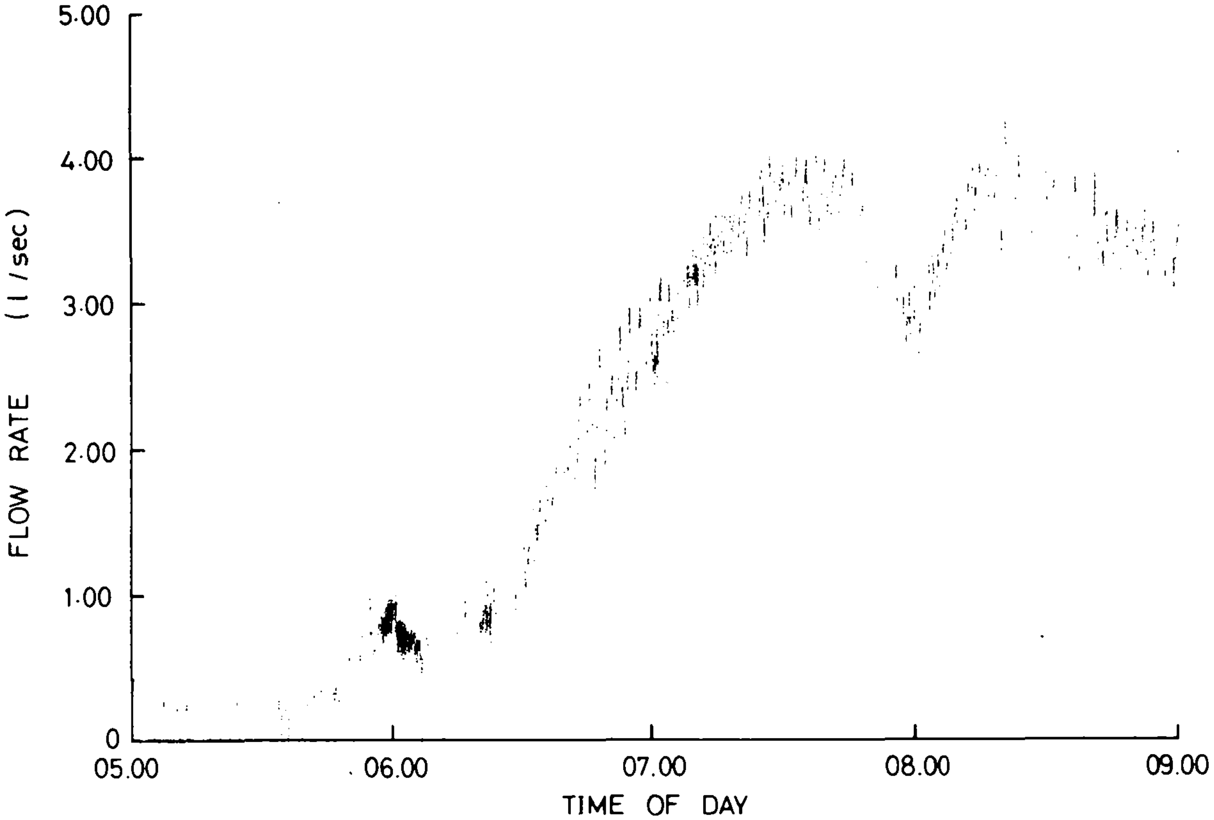


Fig. 13(b). Predicted flow into area 2 excluding kitchen tap use – European plumbing system

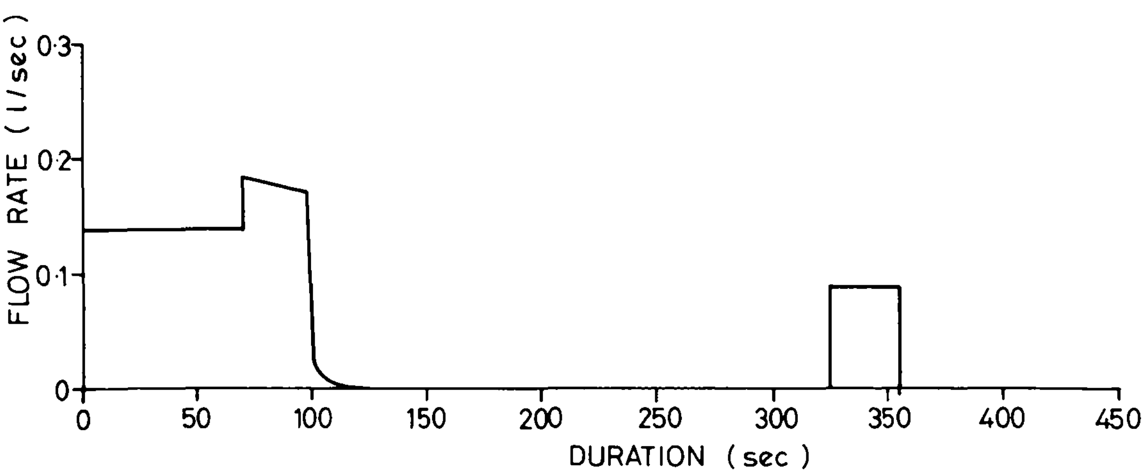


Fig. 14. Calculated flow using modified use sequence

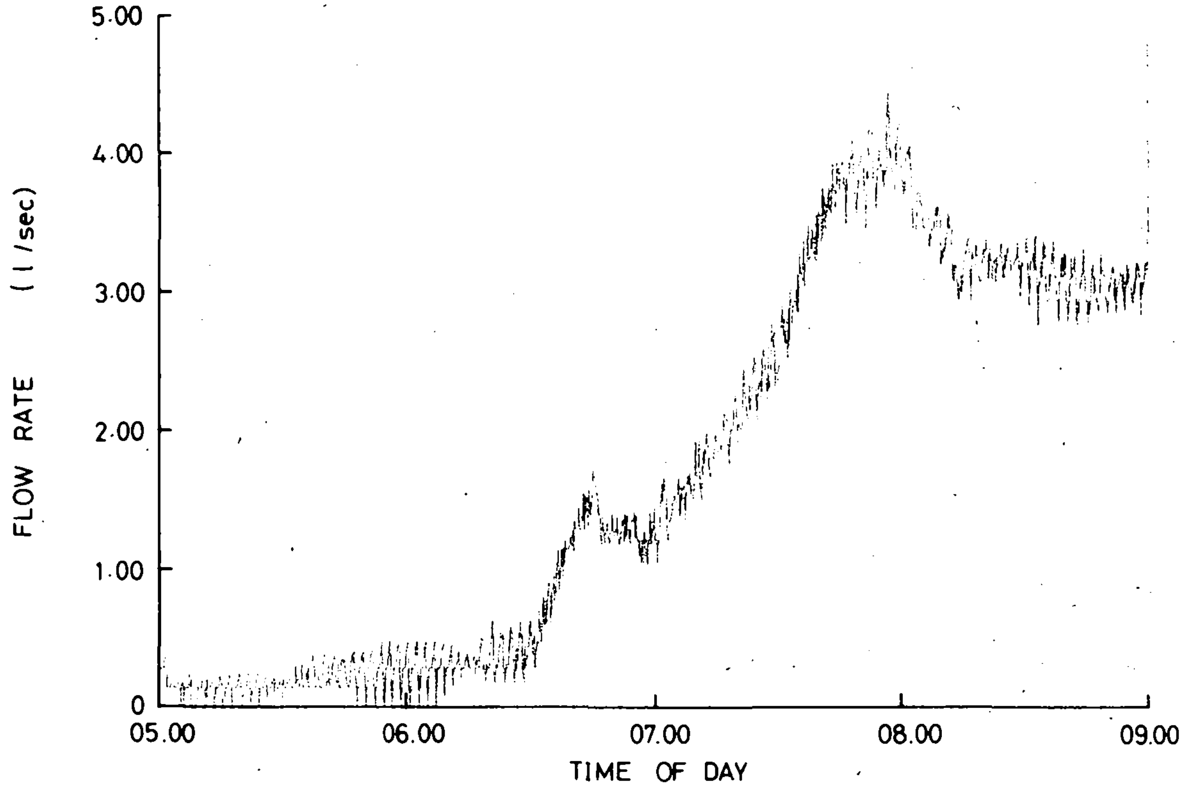


Fig. 15. Predicted flow into area 1 using modified use sequence shown in Fig. 11 and excluding kitchen tap use

8. REDUCTION OF PEAK DEMAND RATE

The possibility of reducing peak demand rate was investigated by studying the effects of two different types of plumbing system. The first utilised a modified ball-valve characteristic and the second allowed the tank to draw down a fixed amount before refilling.

8.1. MODIFICATION OF BALL-VALVE CHARACTERISTIC

The flow characteristics for a standard half-inch Portsmouth type ball-valve are shown in Fig. 6. It can be seen that once the level of water in the tank has dropped more than 40 mm, the ball-valve is fully open and there is no restriction of the flow into the tank other than the hydraulic resistance of the piping. If the ball-valve of each consumer was modified so that it only allowed water to flow through at the average daily demand rate for that consumer, then the flow rate for a group of consumers would be constant over 24 hours. In practice, obviously, such a system would be impossible to operate but it would be possible to restrict the flow rate to some low value and allow the storage tank level to rise and fall during the day.

Fig. 16 shows a modified ball-valve characteristic where the flow rate is restricted to 0.01 litre/sec (8 gal/h) until the level has dropped 400 mm; after this point the valve behaves normally and is fully open after a further drop of 40 mm. In practice, it will be necessary to determine the tank size and inflow rate to fulfil certain requirements, but for the time being, it is assumed that the tank is sufficiently large to meet all requirements.

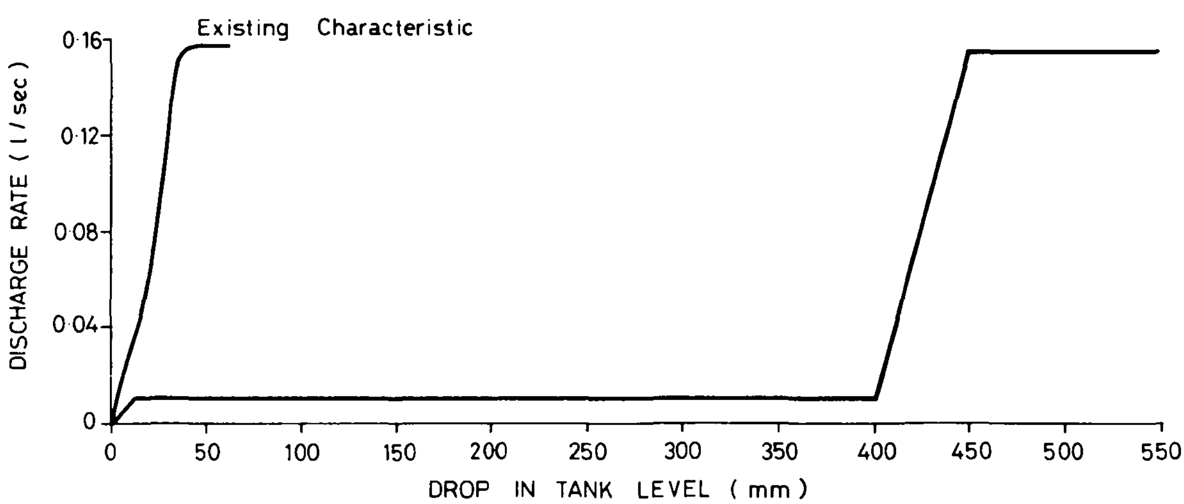


Fig. 16. Modified ball-valve characteristic

If the storage tank in any house fills at a rate of 0.01 litre/sec, the filling time for the use shown in Fig. 4 will be approximately 30 minutes. If an individual with this particular use sequence occupies the bathroom for, say, 15 minutes, then it is possible that a second person could use water within the house before the tank had refilled from the first use. Under these circumstances the flow through the distribution pipe would not increase to 0.02 litre/sec, but would remain at 0.01

litre/sec for one hour. It is necessary, therefore, to know in how many houses people begin to use water within 30 minutes of each other, and to take these into account when predicting the rate of demand for the group of users. This again presents the problems of a statistical model of diversity outlined in Section 3.

Indications of how an inflow of 0.01 litre/sec might affect the demand rates of the two groups of consumers are shown in Figs 17 to 20. Figs 17(a) and 18(a) show the predicted flow rate assuming that no two people in any one house start to use water within 30 minutes of each other. Whereas Figs 19(a) and 20(a) are based on the assumption that after 07.30 h, 10% of demands are followed by a second demand beginning 15 minutes after the start of the first demand. Figs 17(a), 18(a), 19(a) and 20(a) exclude kitchen tap use whereas 17(b), 18(b), 19(b) and 20(b) do not. It can be seen, by comparing these curves with the simulated ones shown in Figs 9 and 10, that restricting the inflow rate to 0.01 litre/sec has produced a smoother curve of less steep gradient, but has not reduced the peak rate of flow.

In general, as the flow rate into a storage tank is reduced the probability that all of the tanks in a group will be filling at the same time is increased. When this inflow rate is reduced to the mean rate for the group, the probability becomes unity and all the tanks are filling all the time. As the inflow rate approaches the mean, there is a good chance that all the tanks will be simultaneously filling at some period during the day. If the mean flow into the tanks is restricted to less than the value q, where:

$$q = \frac{\text{existing peak flow rate}}{\text{number of houses in the group}}$$

then the peak flow will be reduced regardless of the number of tanks filling at any instant. Values of q together with the mean flow rate for each of the study areas are given in Table 3. It can be seen from Table 5 that the inflow rate must be very close to the mean flow rate before peak reduction is certain to occur.

Table 3. Calculated number of people starting to use water in each 10-second period – area 1

Area	N	Limit of q (litre/sec)	Mean flow (litre/sec)
1	442	0.009	0.005
2	790	0.005	0.004
3	699	0.007	0.004

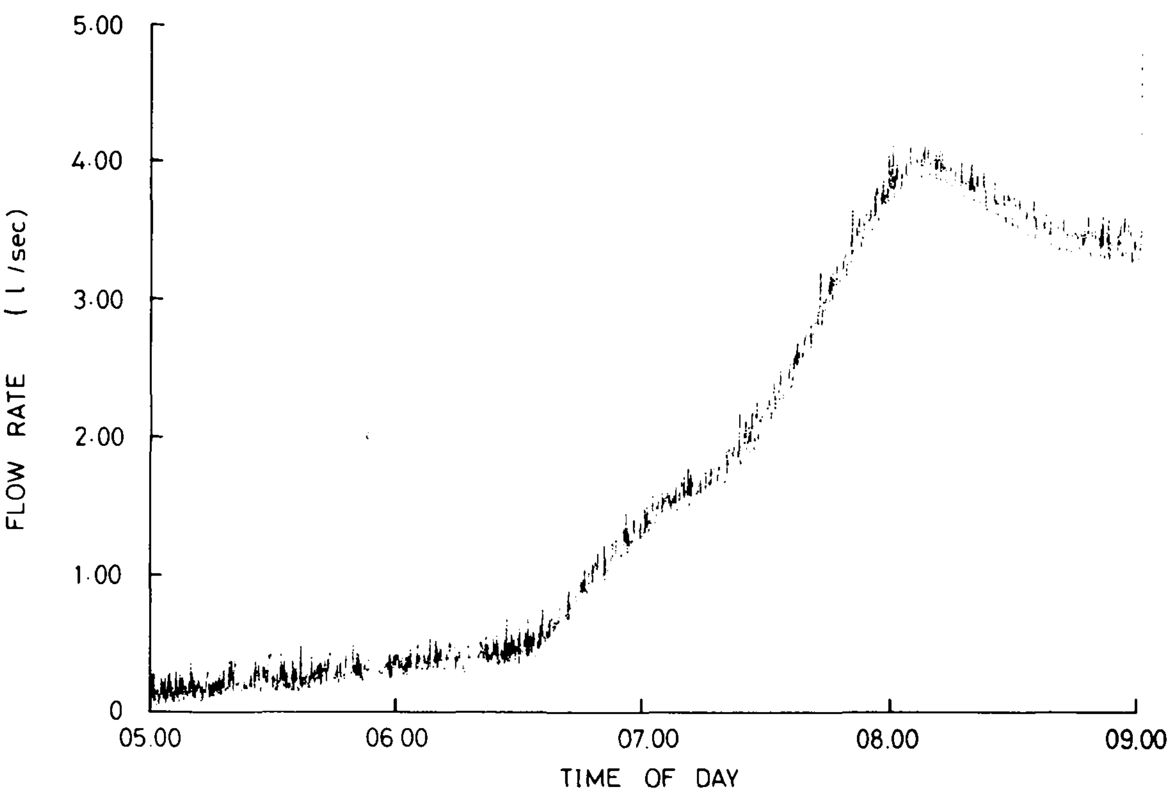


Fig. 17(a). Predicted flow into area 1 with tank inflow rate restricted to 0.01 litres/sec (assuming the start of water uses within a single house are at least 30 minutes apart)

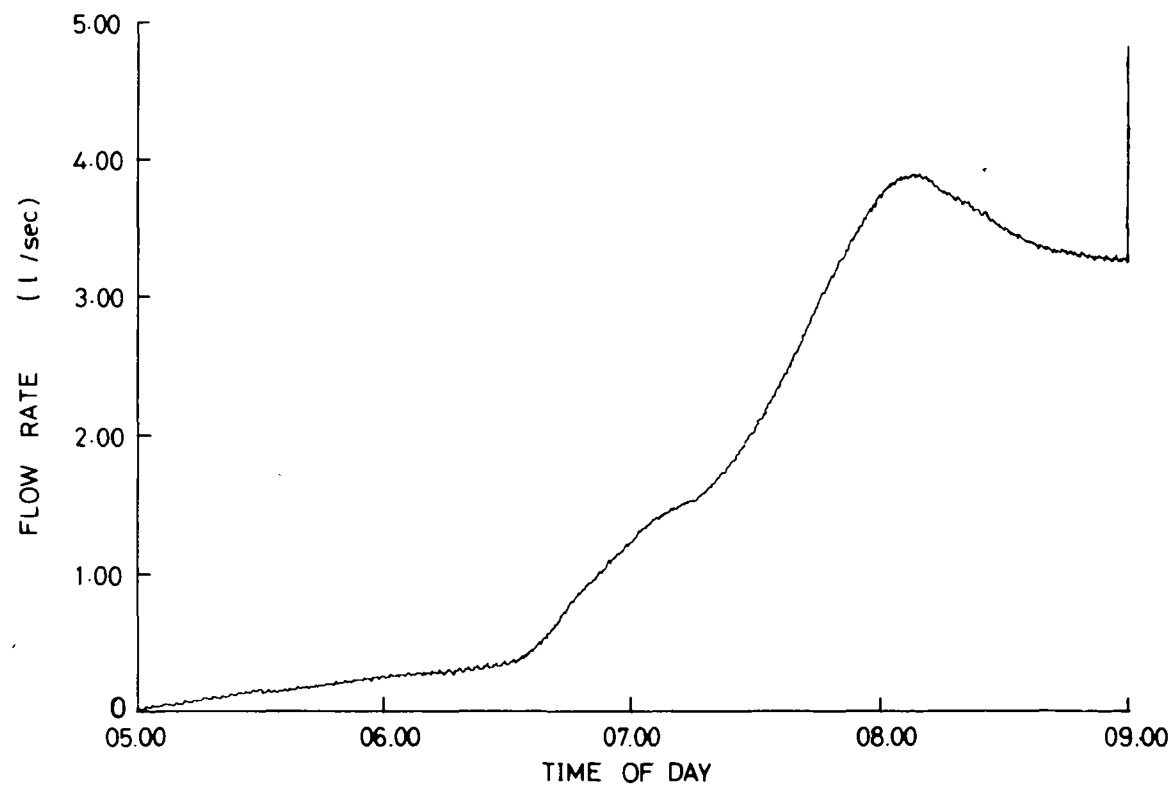


Fig. 17(b). Predicted flow into area 1 with tank inflow rate restricted to 0.01 litres/sec excluding kitchen tap use (assuming start of water uses within a single house are at least 30 minutes apart)

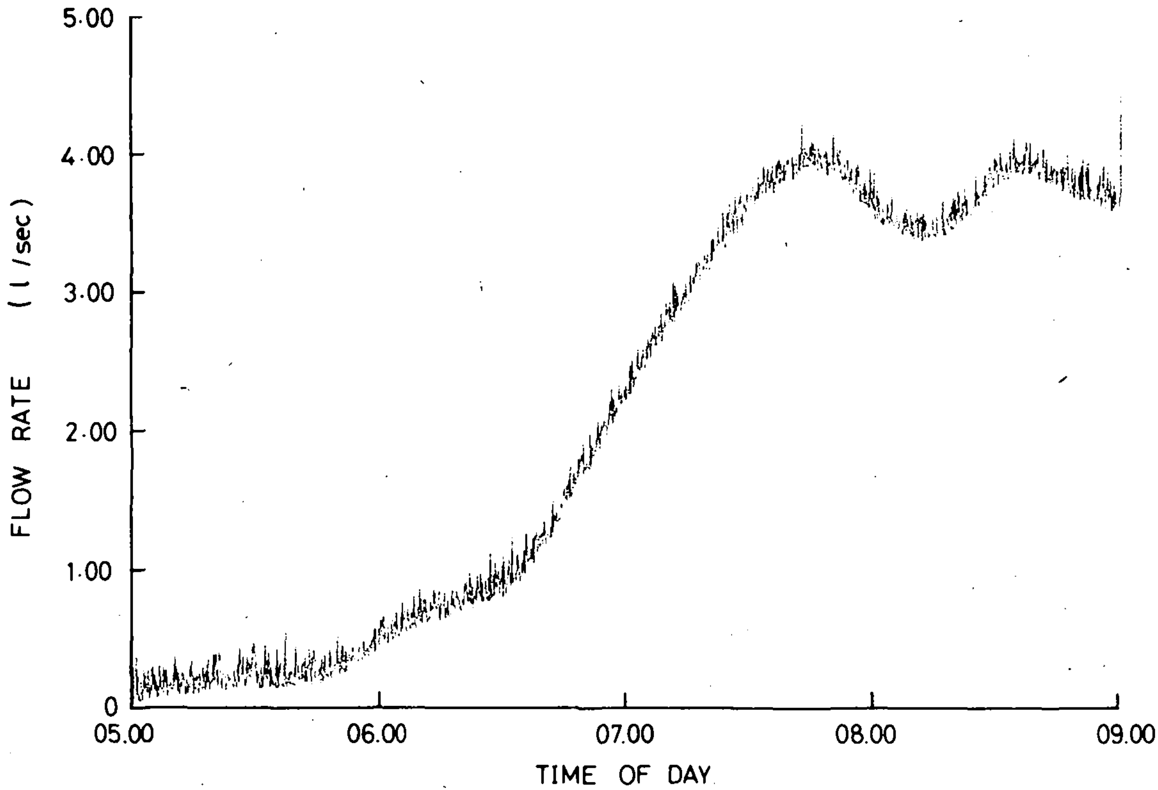


Fig. 18(a). Predicted flow into area 2 with tank inflow rate restricted to 0.01 litres/sec (assuming the start of water uses within a single house are at least 30 minutes apart)

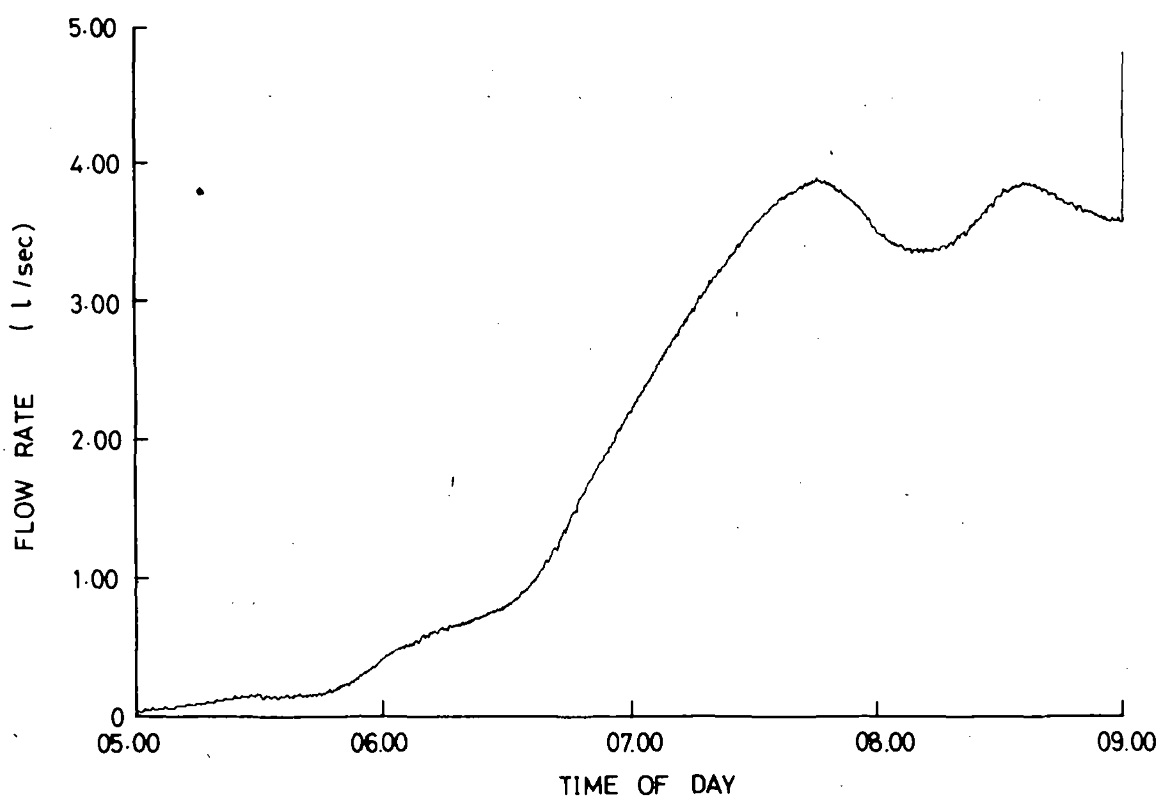


Fig. 18(b). Predicted flow into area 2 with tank inflow rate restricted to 0.01 litres/sec excluding kitchen tap use (assuming start of water uses within a single house are at least 30 minutes apart)

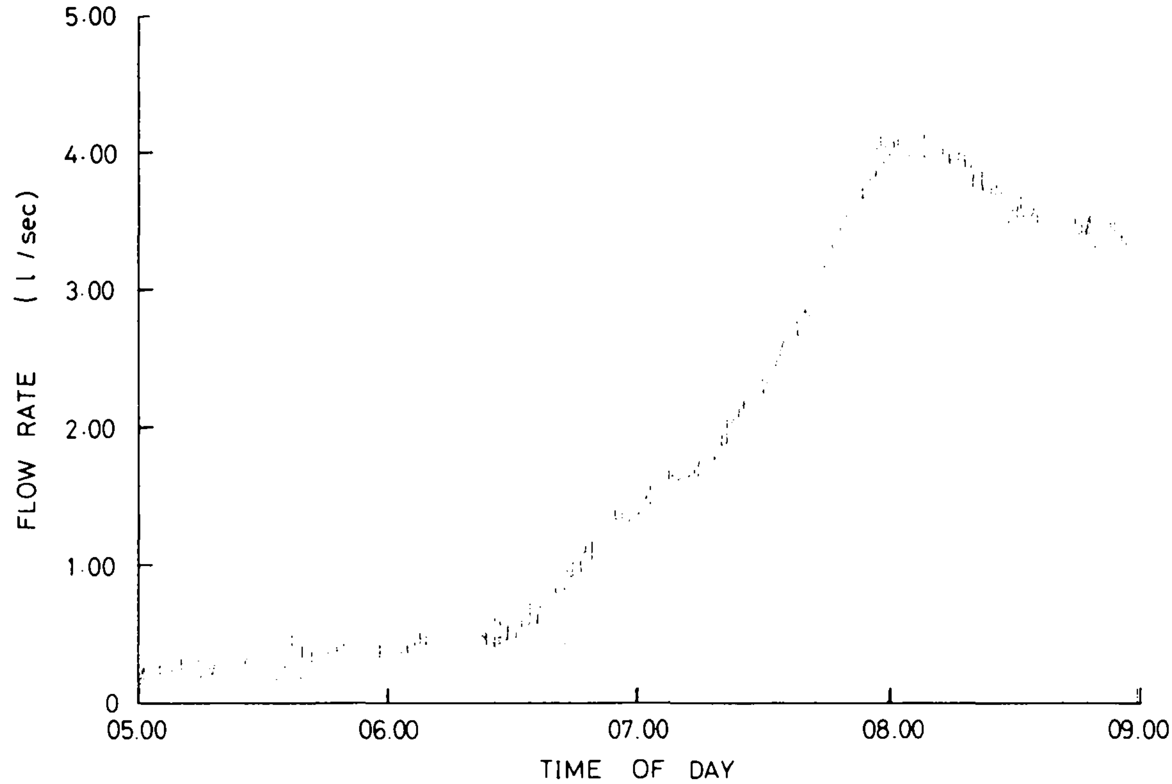


Fig. 19(a) Predicted flow into area 1 – tank inflow rate restricted to 0.01 litres/sec (assuming 10% of the uses have a second use starting 15 minutes after the first)

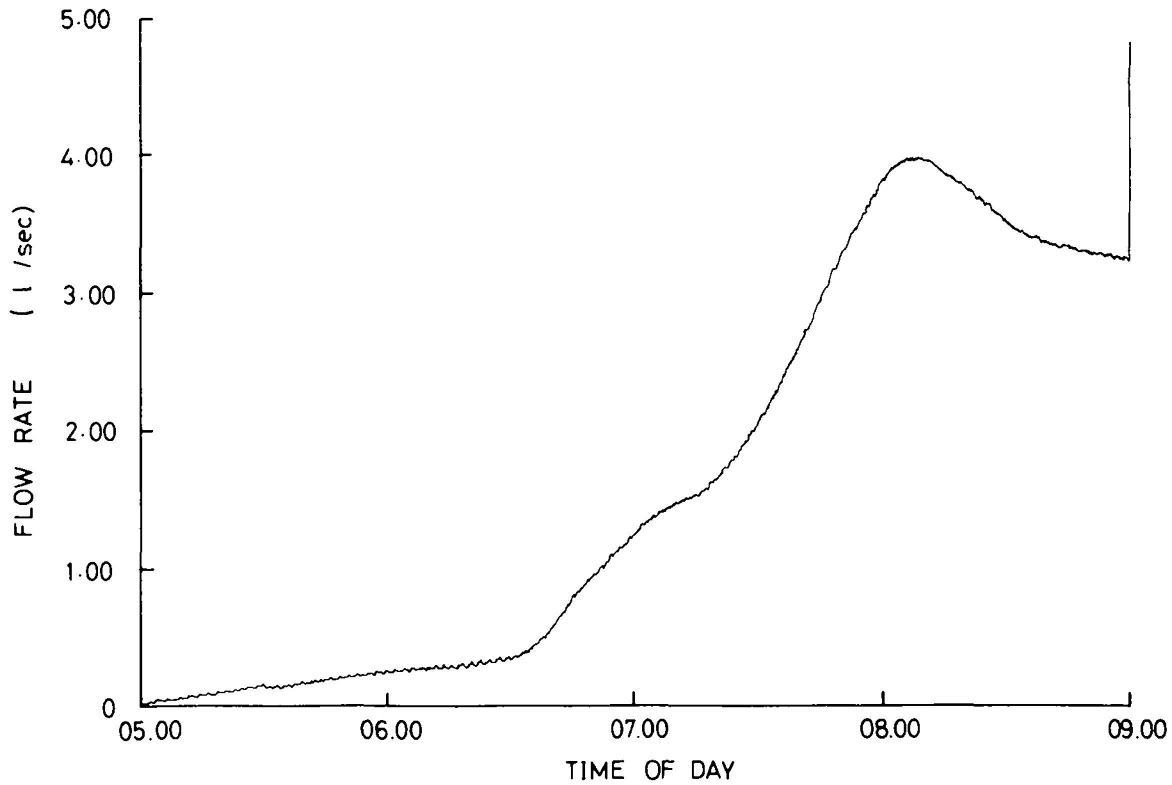


Fig. 19(b). Predicted flow into area 1 – tank inflow rate restricted to 0.01 litres/sec – excluding kitchen tap use (assuming 10% of the uses have a second use starting 15 minutes after the first)

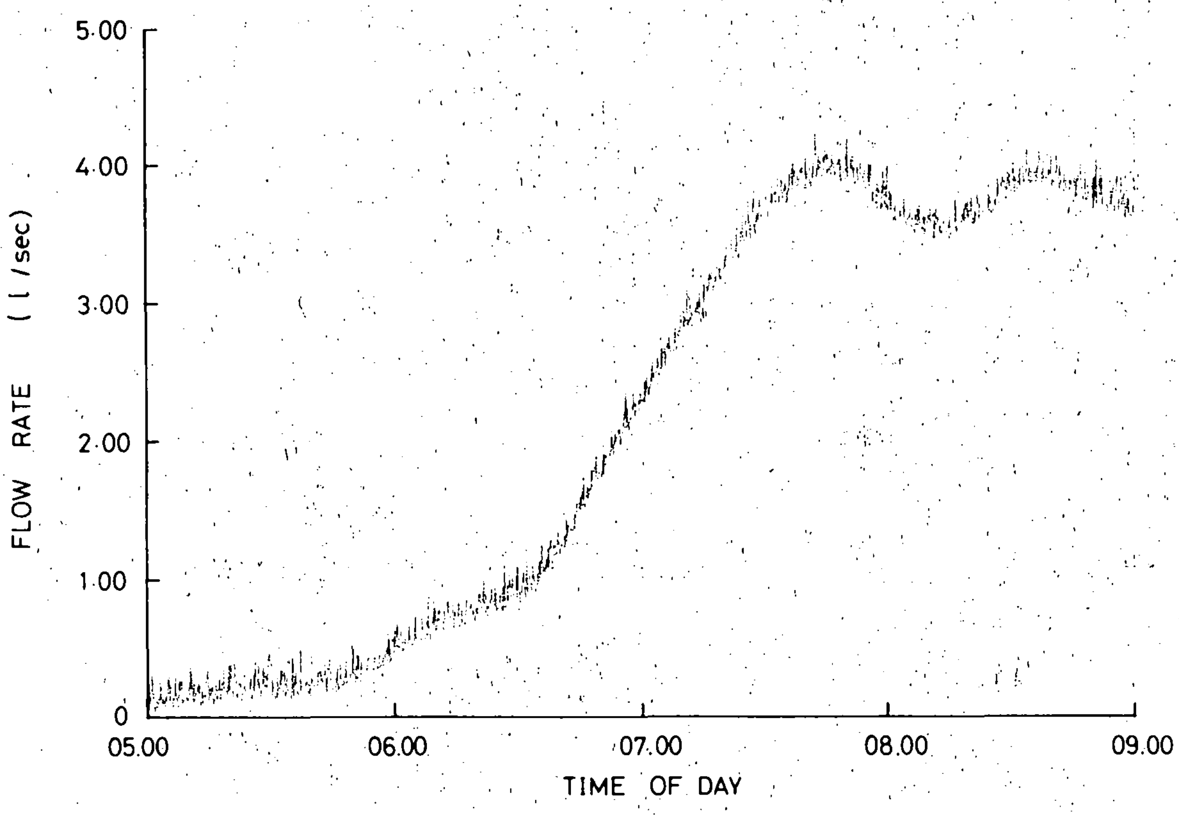


Fig. 20(a). Predicted flow into area 2 – tank inflow rate restricted to 0.01 litres/sec (assuming 10% of the uses have a second use starting 15 minutes after the first)

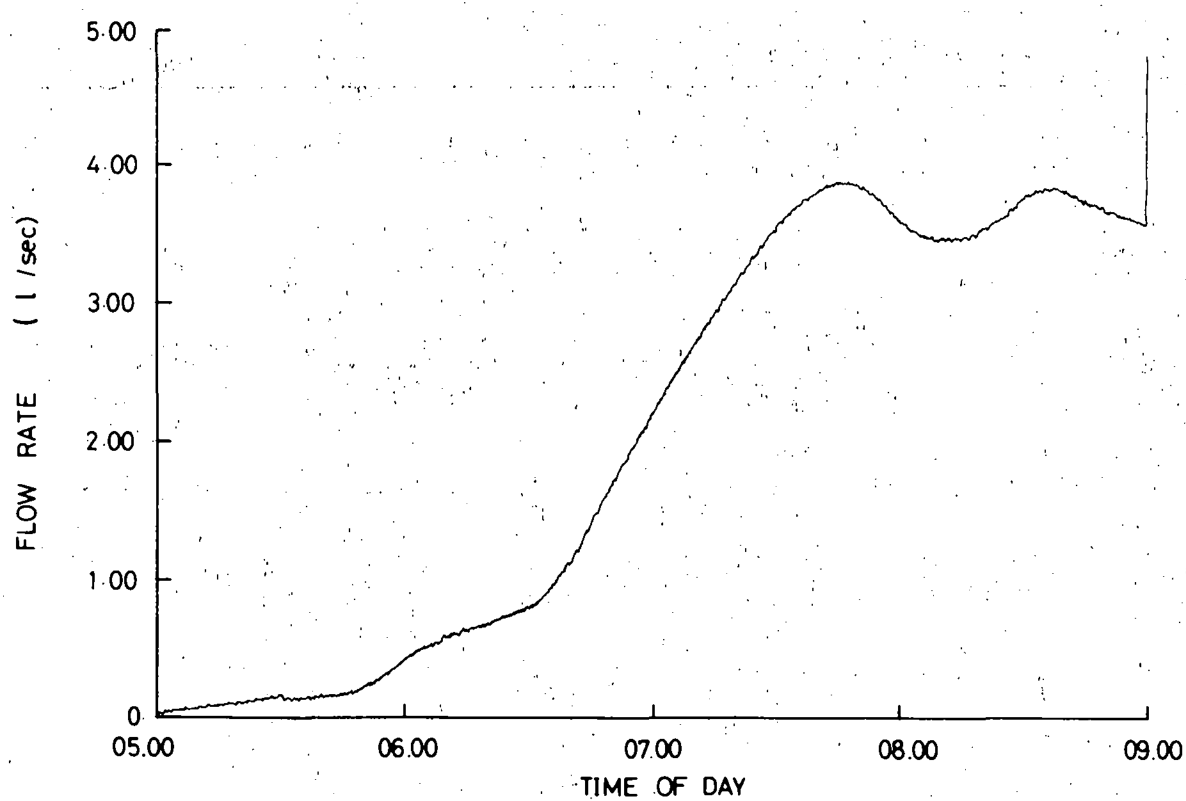


Fig. 20(b). Predicted flow into area 2 – tank inflow rate restricted to 0.01 litres/sec – excluding kitchen tap use (assuming 10% of the uses have a second use starting 15 minutes after the first)

8.2. DELAYED TANK REFILLING

The second method of peak reduction investigated consisted of allowing the storage tank to draw down a fixed amount before starting to refill at the normal rate. With this type of system it is possible that some consumers would not draw any water from the main during the morning peak period if their tanks had filled the previous evening. Consequently, this type of system could reduce the peak flow rate and, at the same time, provide an approximate way of metering, since counting the number of refills and multiplying by the volume of the tank gives the quantity of water used less any used whilst the tank was refilling.

If such a system was installed, it would only be possible for the tank to start filling whilst water was drawn from it.

If q_t is the quantity of water drawn from the tank in some small time period Δt, then the probability of the tank starting to fill in period Δt is

$$q_t/C$$

where C = capacity of the tank.

For a group of N consumers, the expected number of consumers whose tanks start to fill in period Δt is

$$\frac{1}{C}\sum^{N} q_t = \frac{Q_t}{C}$$

where Q_t is the total quantity of water drawn from storage by the group of N consumers in time period Δt.

The expected number of tanks filling in period Δt depends upon the time it takes to fill the tank and the number of tanks starting to fill in that period.

If L = the rate of flow into the tank whilst it is filling, then the time taken to fill is given by C/L, ignoring any water consumed whilst the tank is filling.

The expected number of tanks filling at the end of period Δt is given by:

$$\frac{1}{C}\int_{T_o}^{T_1} Q_t dt = \frac{1}{C}\times G$$

Where G is the total quantity of water taken from storage in time C/L for the group of N consumers the expected flow rate at time T_1 is given by:

$$\text{expected flow rate} = \frac{G}{C}\times L$$

Fig. 21 shows part of a demand curve for the water taken by N consumers. The quantity consumed can be calculated from the mean flow rate for period

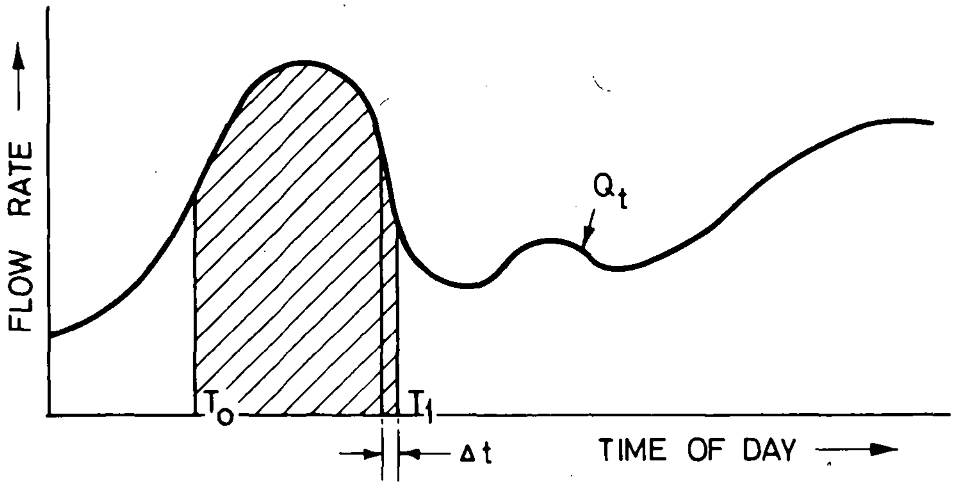
$T_1 - T_o \times T_1 - T_o$, or:

$$G = M \times \frac{C}{L}$$

Where M = mean flow rate for period C/L, substituting into the equation for expected flow rate, we have:

$$\text{expected flow rate} = \frac{M}{C} \times L \times \frac{C}{L} = M$$

Therefore the expected flow rate at time T_1 is the mean of the rate for the previous period C/L.



$$\int_{T_o}^{T_1} Q_t \, dt = G = \text{shaded area of graph}$$

If M = mean flow rate for the period $T_1 - T_o$

then $G = M(T_1 - T_o)$

Curve represents the total flow of water into an area of N users minus the water used from the kitchen tap.

Fig. 21. Storage tank emptying/refilling cycle

With this plumbing system it would be necessary to have a fairly high filling rate L to prevent the system running out of water.

If L is taken as 0.14 litre/sec, then, on average, each tank in the study areas would have a filling time of about 35 minutes during each day. Figs 22(a) and 23(a) show the predicted demand patterns for areas 1 and 2 taking the filling duration as half an hour, and Figs 24(a) and 25(a) show the predicted demand pattern for a filling time of one hour. Figs 22(b) to 25(b) are as Figs 22(a) to 27(a), but excluding any use from the kitchen tap. It can be seen that in each case the peak would occur at a later time and would be of lower magnitude than the measured peaks (Figs 9(b) and 10(b)). Table 4 shows the percentage reduction in peak flow rate for each area. Delayed tank filling has less effect in area 2 because the peak recorded there was of longer duration than that of area 1.

Table 4. Calculated number of people starting to use water in each 10-second period – area 2

Filling time (min)	% Reduction in peak Area 1	Area 2
30	6.1	2.0
60	12.7	4.0

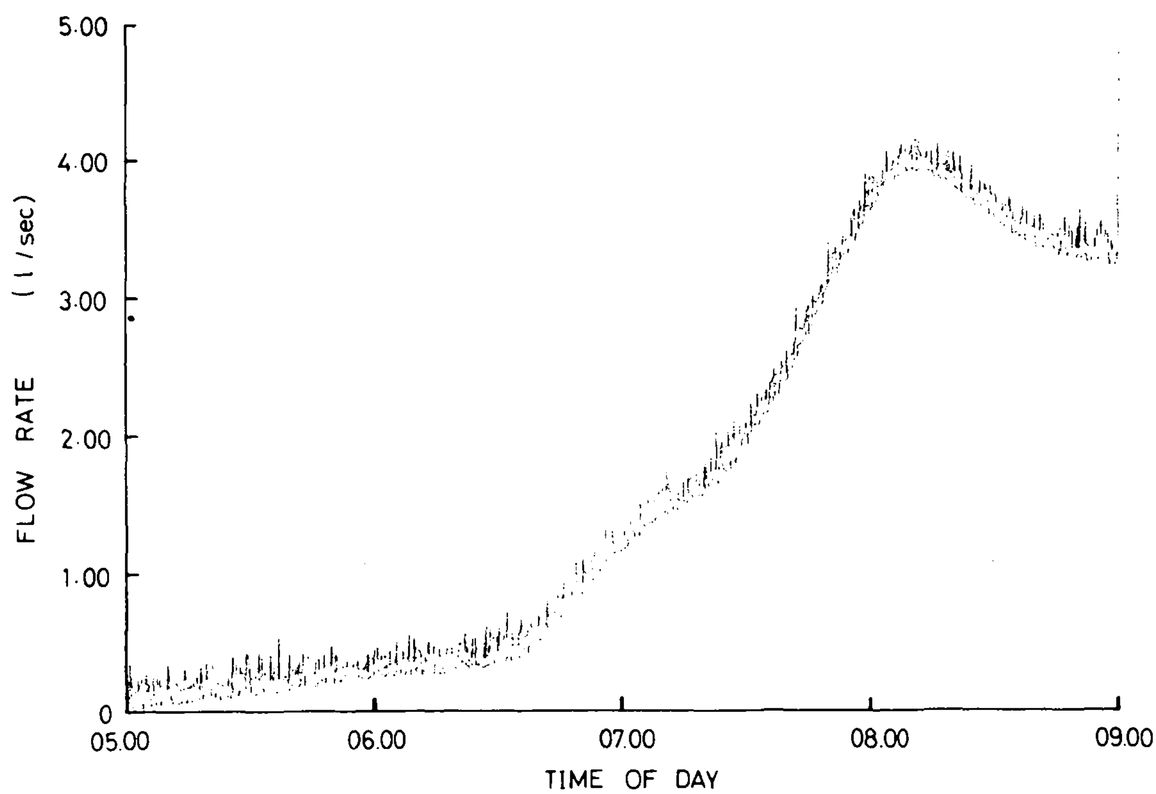


Fig. 22(a). Storage tank emptying/refilling cycle. Predicted flow into area 1 – filling time 30 minutes

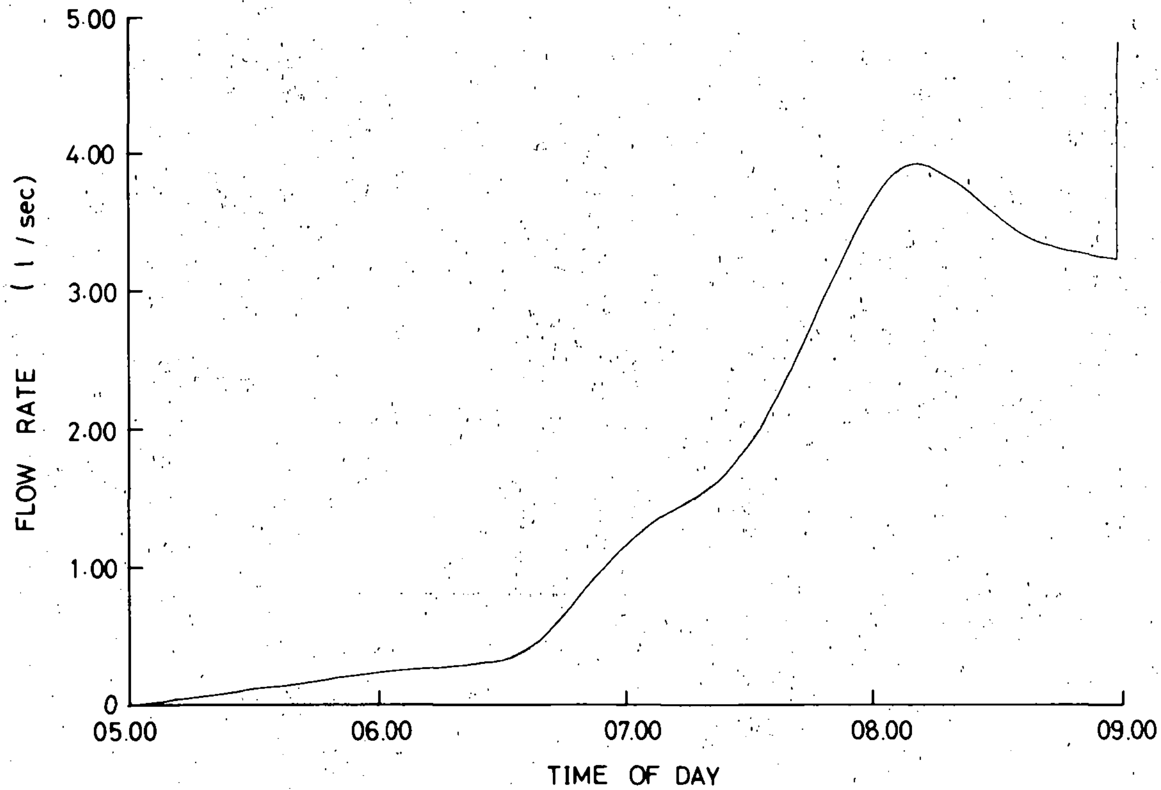


Fig. 22(b). Storage tank emptying/refilling cycle, excluding kitchen tap use. Predicted flow into area 1 – filling time 30 minutes

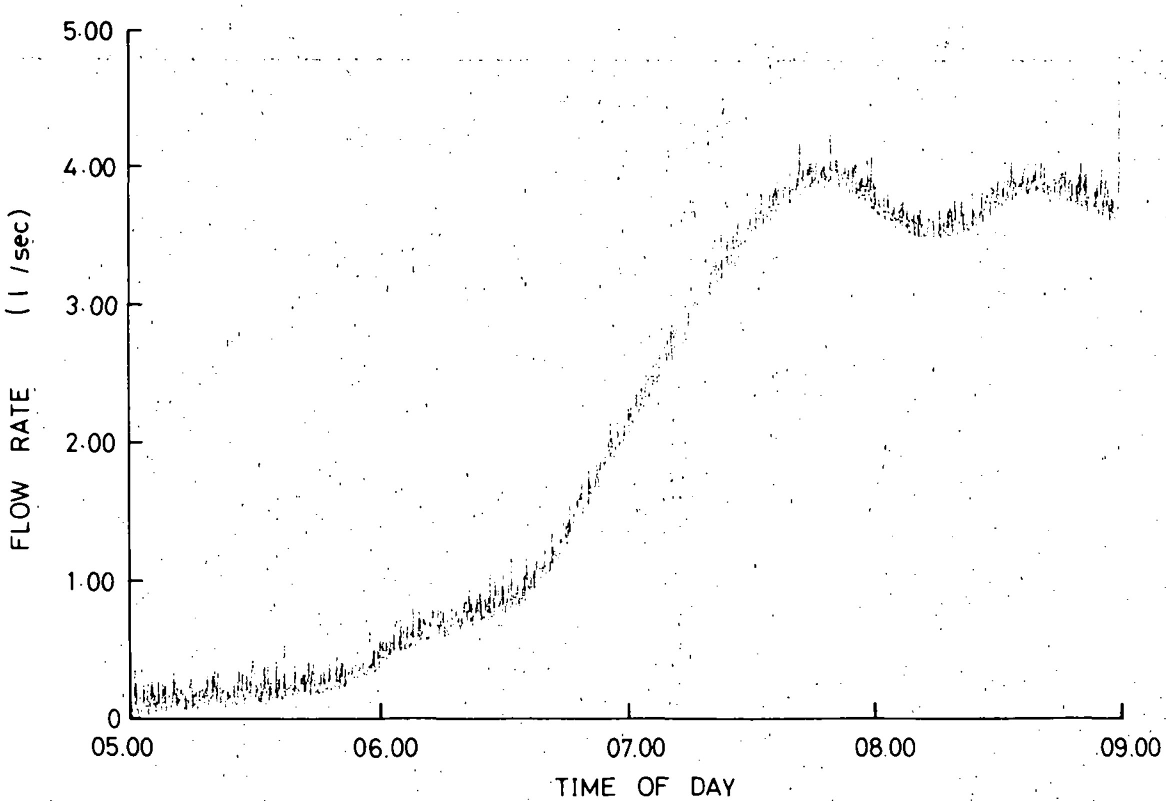


Fig. 23(a). Storage tank emptying/refilling cycle. Predicted flow into area 2 – filling time 30 minutes

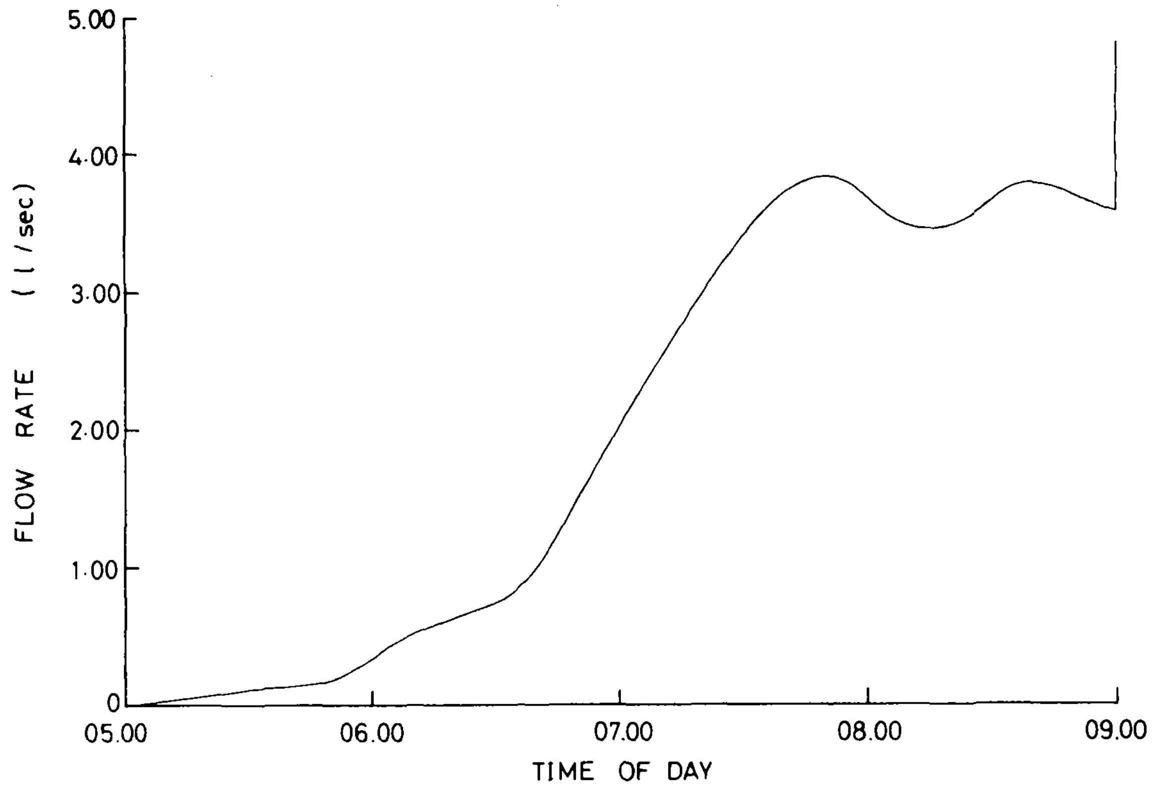


Fig. 23(b). Storage tank emptying/refilling cycle, excluding kitchen tap use. Predicted flow into area 2 – filling time 30 minutes

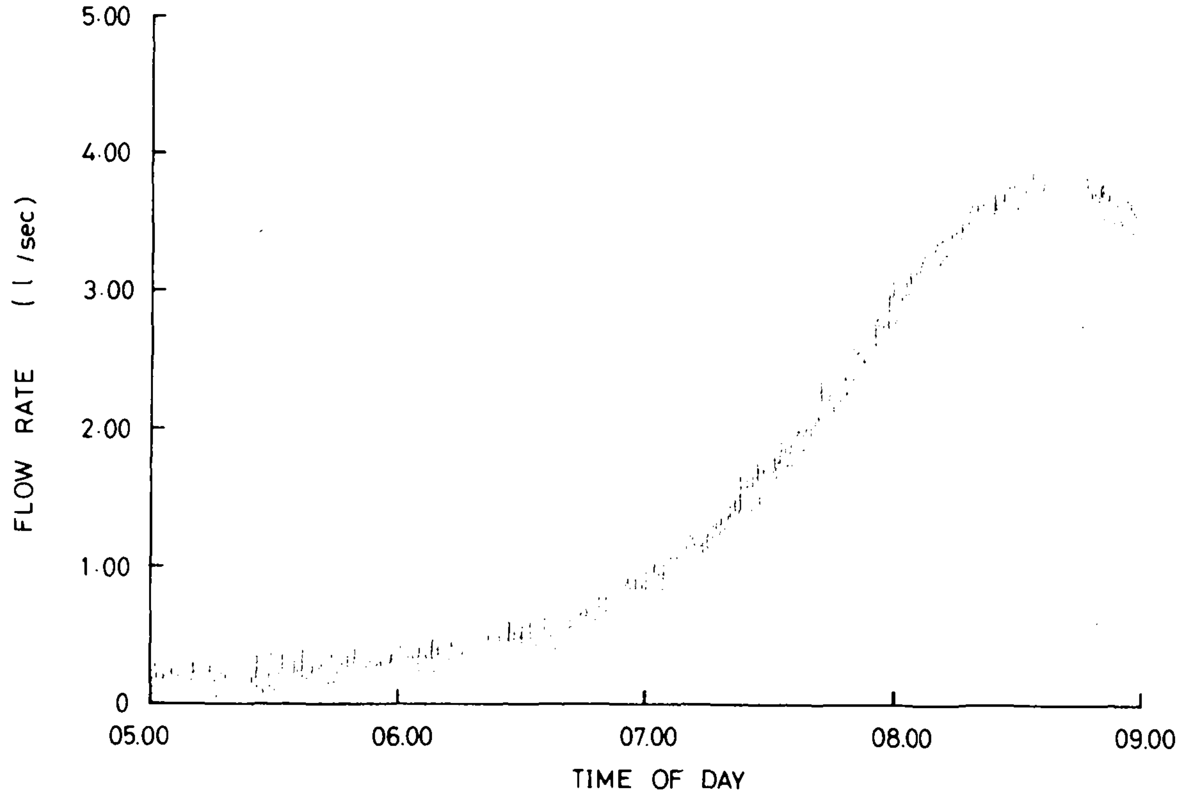


Fig. 24(a). Storage tank emptying/refilling cycle. Predicted flow into area 1 – filling time 60 minutes

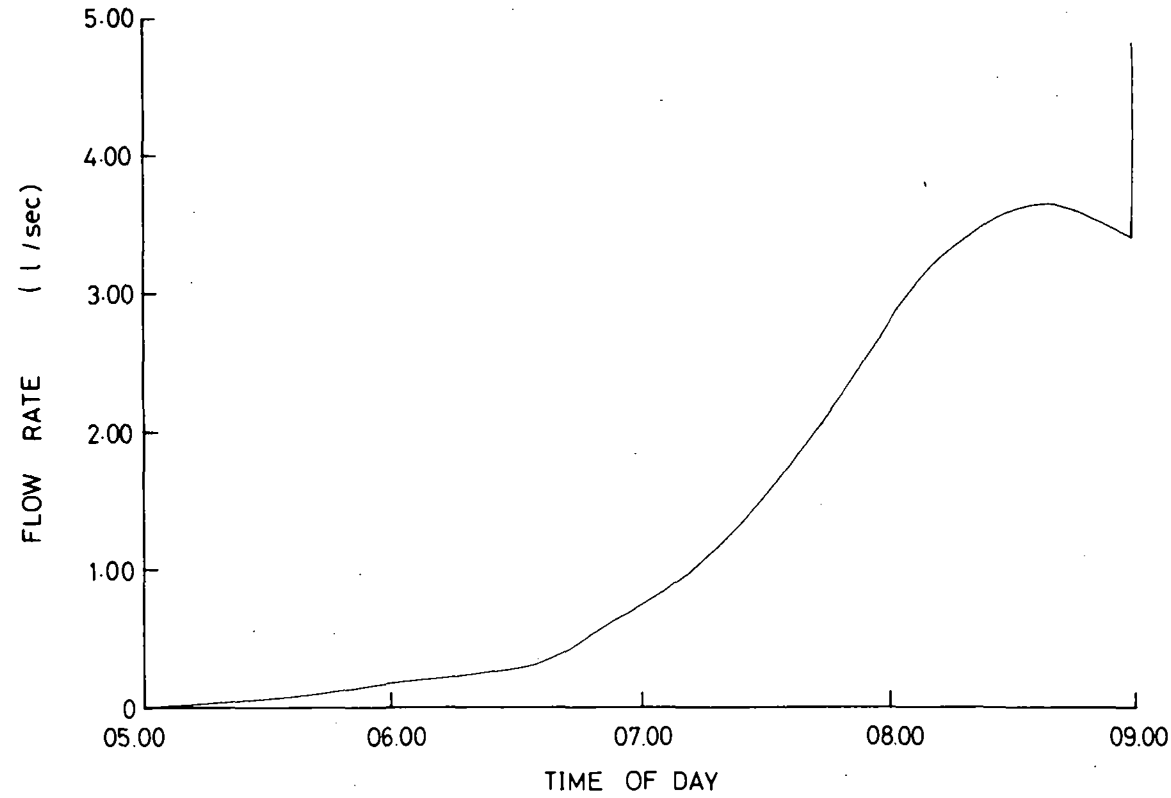


Fig. 24(b). Storage tank emptying/refilling cycle, excluding kitchen tap use. Predicted flow into area 1 – filling time 60 minutes

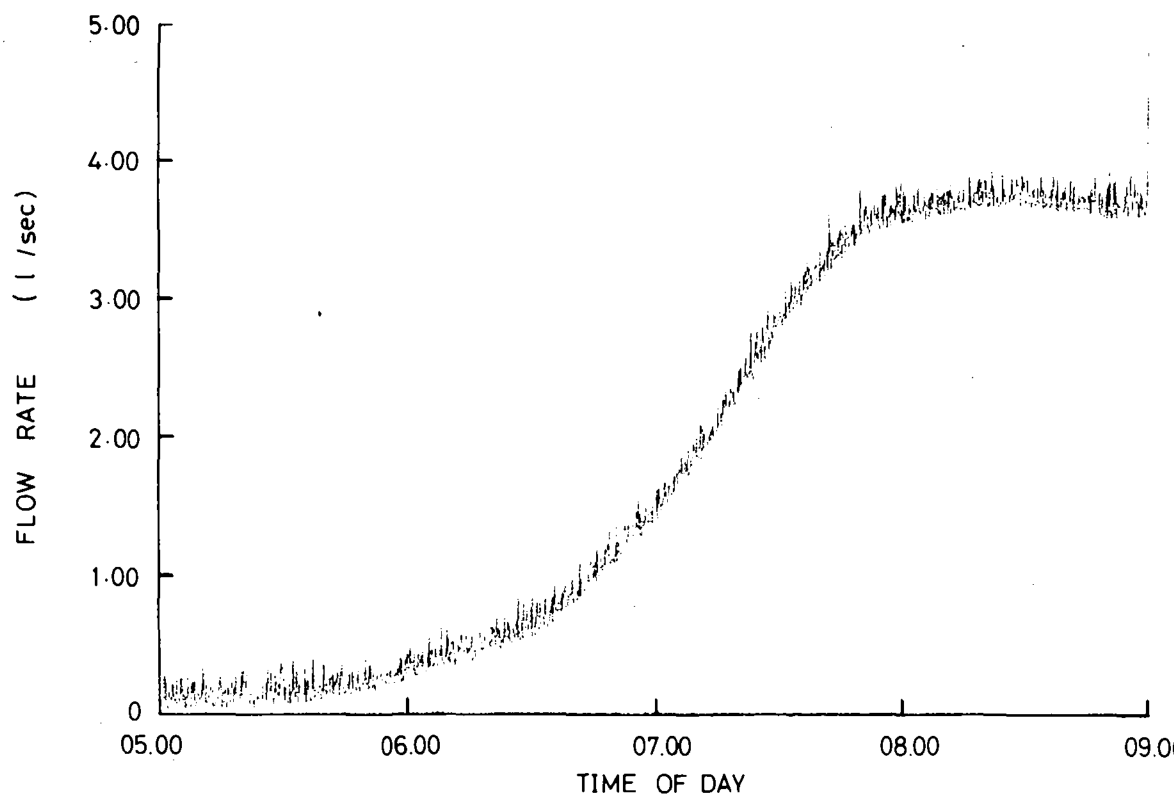


Fig. 25(a). Storage tank emptying/refilling cycle. Predicted flow into area 2 – filling time 60 minutes

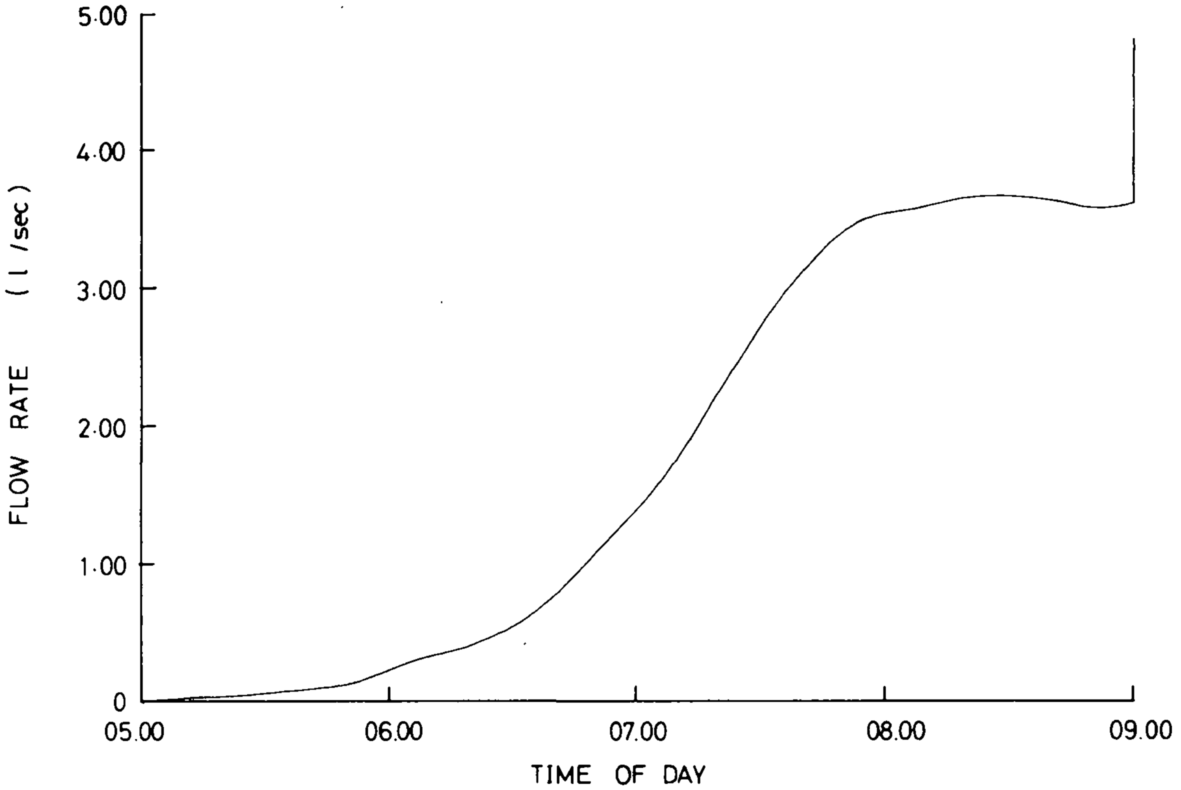


Fig. 25(b). Storage tank emptying/refilling cycle, excluding kitchen tap use. Predicted flow into area 2 – filling time 60 minutes

9. DISCUSSION

The results obtained from the analysis were surprising and unexpected. The original aims of the project were to assess the likely increase in peak demand rate, resulting from the removal of storage, and it had not been considered that this increase could be minimal. However, with the benefit of hindsight, it is not too difficult to understand the reasons why individual storage has little effect on peak demand rates, for a large group of consumers. The following is an attempt to explain these reasons in non-mathematical terms.

For a single house with storage, the rate of demand on the distribution system is reduced wherever the rate of flow through the service pipe into the house is less than the rate of use within the house. The ratio between the two can be defined as the reduction ratio.

$$\text{Reduction ratio} = \frac{\text{rate of demand within a house}}{\text{rate of flow through service pipe}}.$$

It can be seen that the reduction ratio will be high whenever the rate of demand within the house is high and the flow through the service pipe is low. Consequently for any particular demand, the reduction ratio will be greatest before the ball-valve is fully open. The fact that the level in the tank falls below the level of the float when, say, filling a bath, has no influence on the reduction ratio.

For a group of consumers, the flow rate at any instant will depend upon the number of houses with water flowing through the service pipes and the individual rates of flow. If these rates of flow are reduced, then the duration of the flow must be increased in order to supply the same quantity of water. Consequently, at any instant the number of consumers with water flowing through their service pipes will be increased and hence the total flow rate for the group tends to remain the same.

A group of identical demands is shown diagramatically in Fig. 26 as a series of blocks. Each block represents an individual water use. The height of each block q represents the flow rate and the length of each block T, the duration of the flow through the service pipe. The total height of the 'wall' represents the peak flow rate for the group of consumers and the times t_1, t_2, etc., the time at which each consumer starts to use water.

Fig. 27 shows the same set of demands. The start times, t_1, t_2, etc., are the same but the flow rates, q, are decreased and the duration, T, is increased so that total quantity of each use (area) is the same. It can be seen that no reduction in peak flow rate for the group occurs until some critical value of q is reached as in the last diagram of Fig. 27.

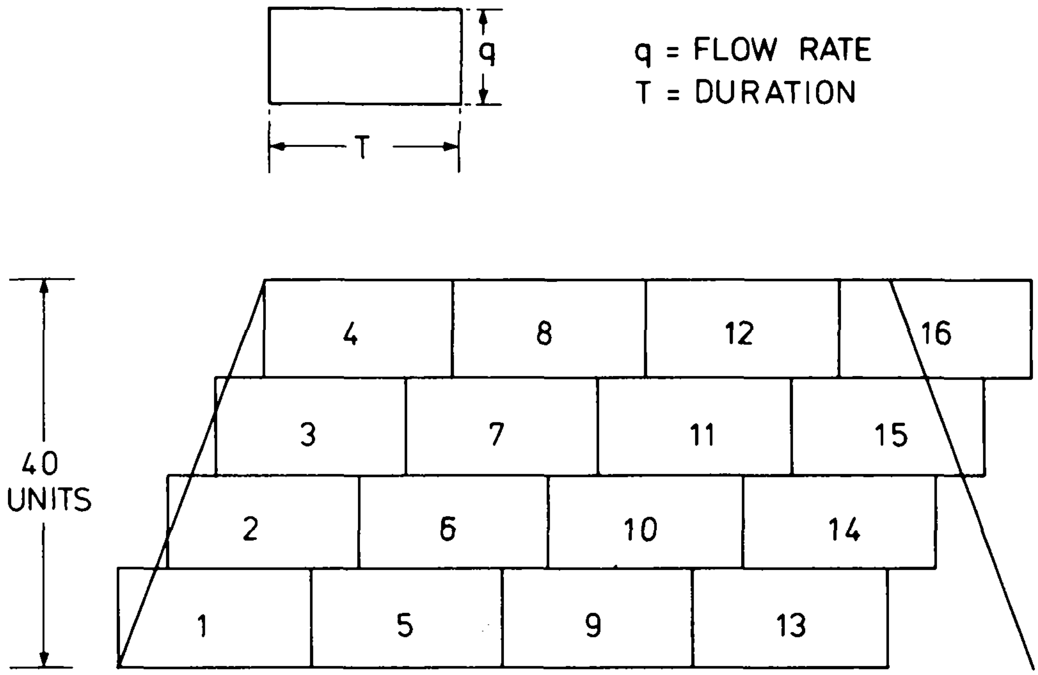


Fig. 26. Graphical representation of a group of consumers

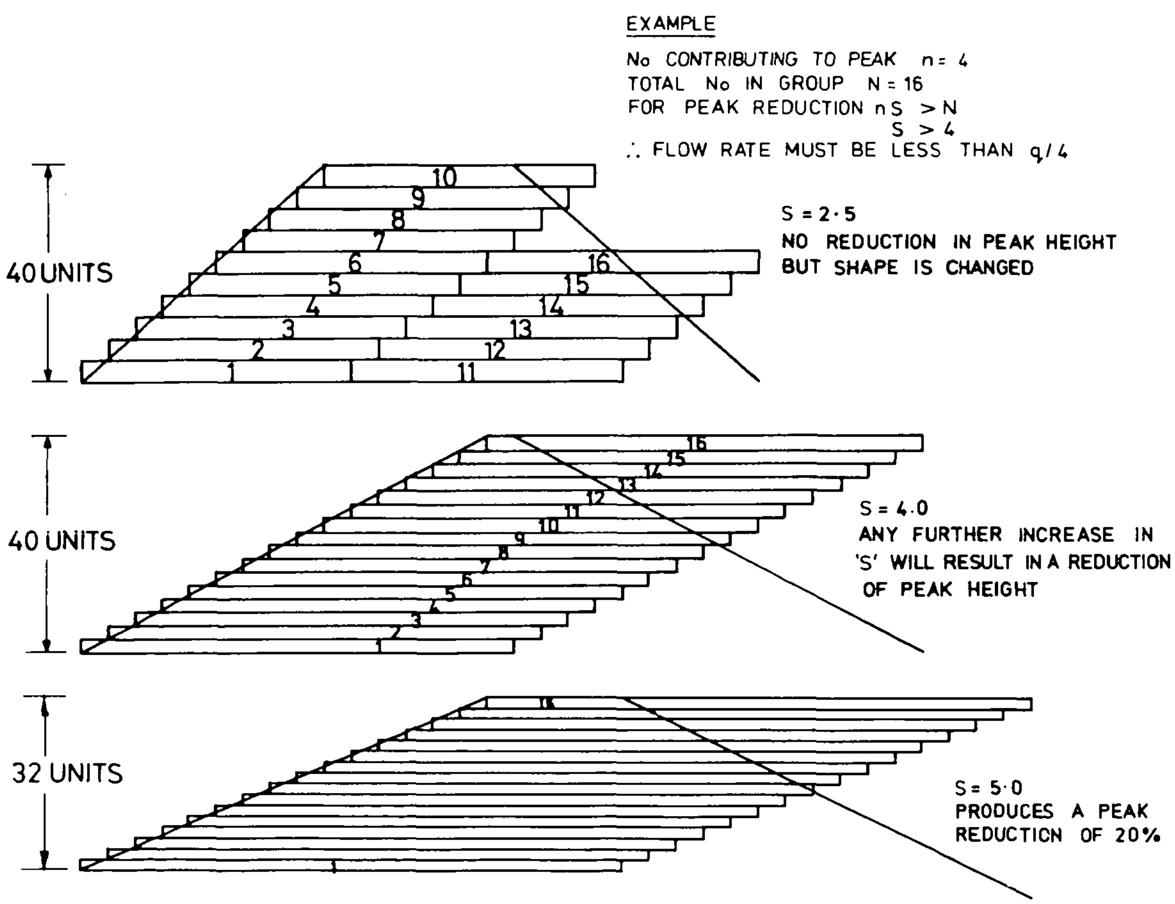


Fig. 27. Effect of restricting tank inflow rate

This greatly simplified example illustrates how a reduction in flow rate through service pipes of individual consumers does not necessarily result in a reduction of flow rate for a group.

The foregoing has demonstrated that the presence or absence of individual domestic storage has little or no effect on the peak demand rate for a large group of domestic consumers. As the size of a group is reduced, the storage has an increasing effect and has, of course, the greatest effect for a single consumer. The limiting size of group for which storage has no effect has not been precisely determined, but appears to be in the order of 1000 people or 300 to 400 houses.

10. PEAKS OF SHORT DURATION

Occasionally large demands of short duration are encountered which are produced by a relatively large number of people starting to use water in a short period of time and are consequently of low diversity. Demands of this type often occur after popular television programmes. The demand usually consists of flushing toilets, washing hands and making drinks. Fig. 28 shows a curve which was measured in one of the study areas at 01.00 h. Fig. 29 shows the simulation of the peak assuming that all consumers have the demand pattern shown in Fig. 30(a) with storage. Fig 30(b) shows the effect of removing storage for a single consumer and Fig. 31 shows the effect for the group.

It can be seen that the removal of storage results in a slightly higher peak flow rate. In practice the increase in flow rate will be less than that shown in Fig. 31, since an increase in flow will be accompanied by a reduction of pressure. It can also be shown that if the tank inflow rate is reduced or if the tank is allowed to draw down before refilling, a peak of this type would be further reduced.

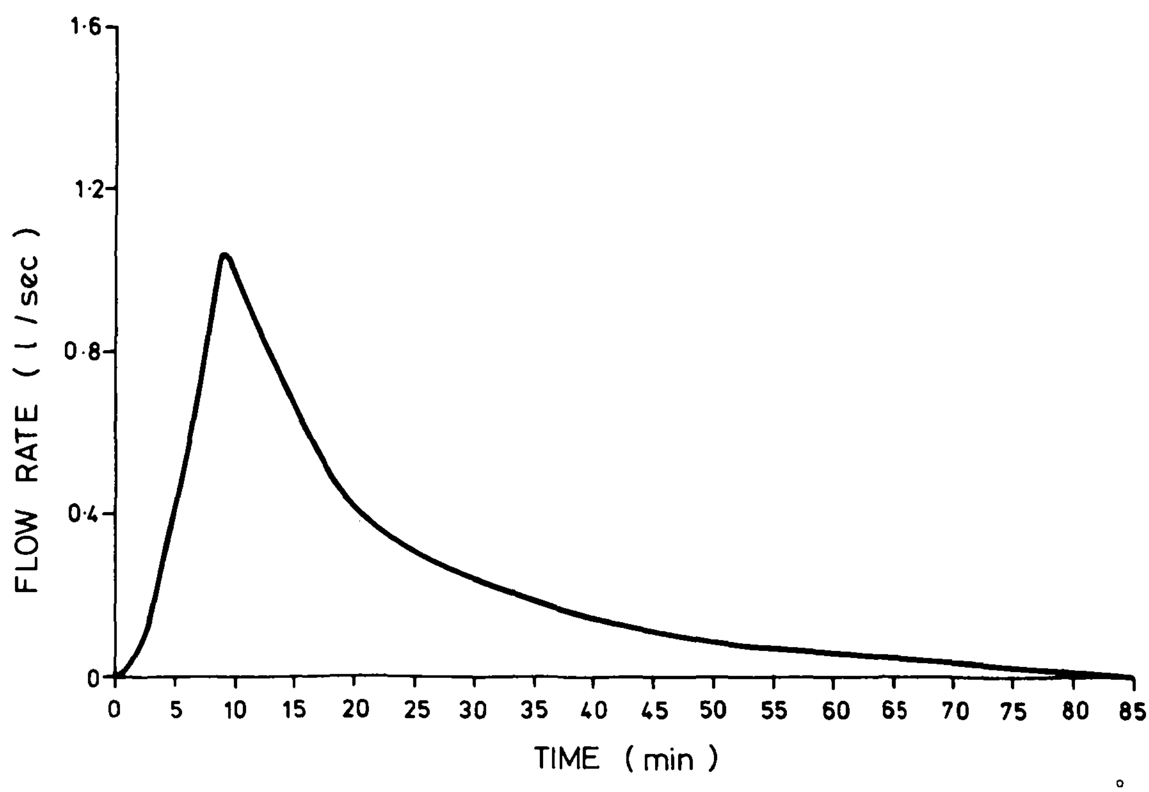


Fig. 28. Peak occurring at end of popular TV programme, measured at 01.00 h

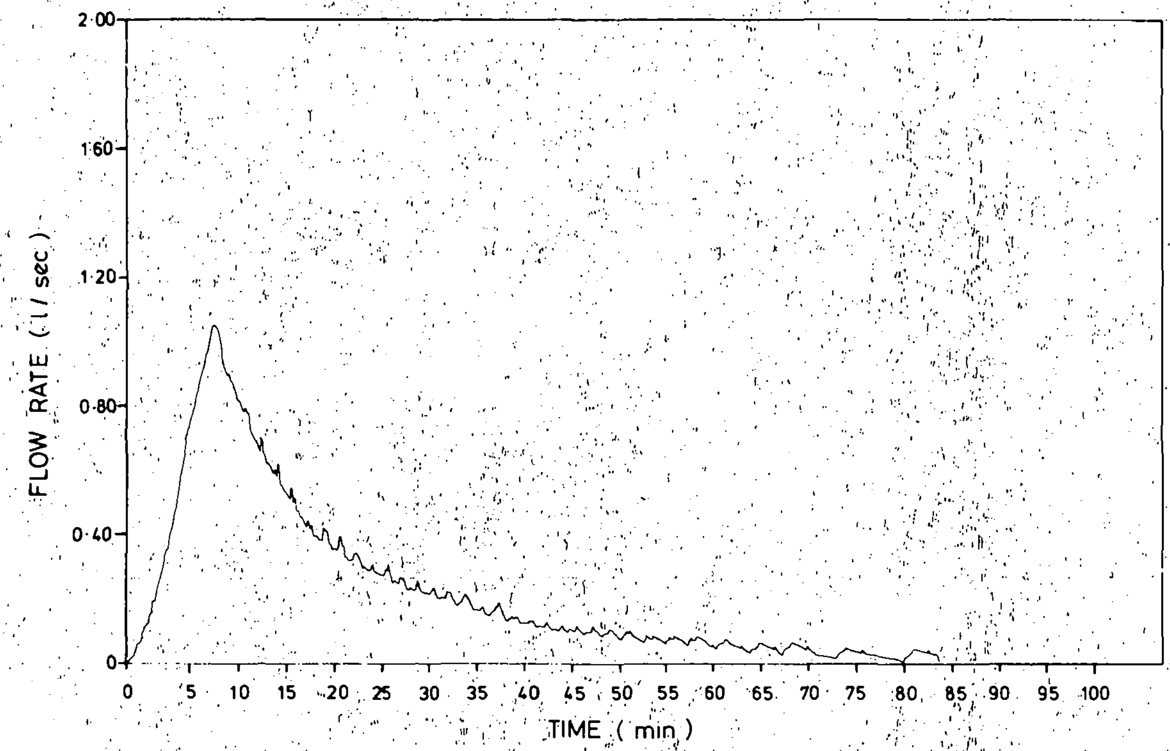


Fig. 29. Simulation of TV peak

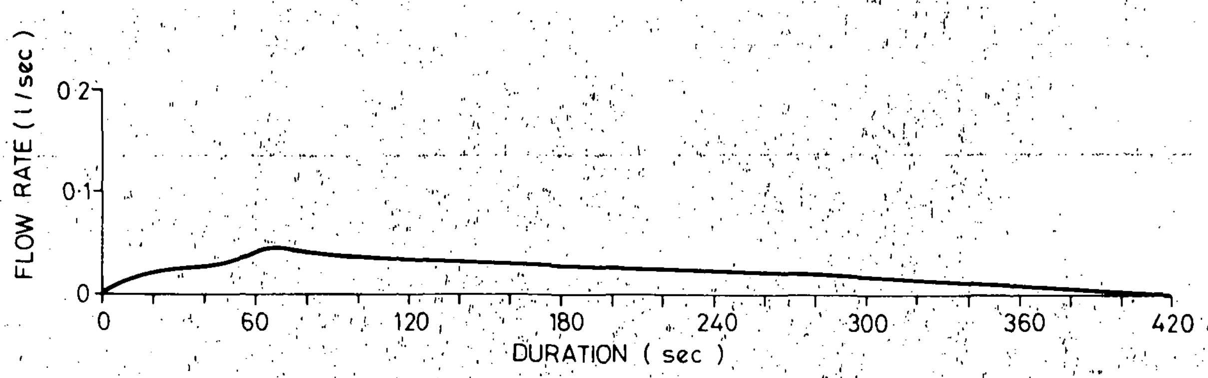


Fig. 30(a). Flow through service pipe with South of England plumbing system

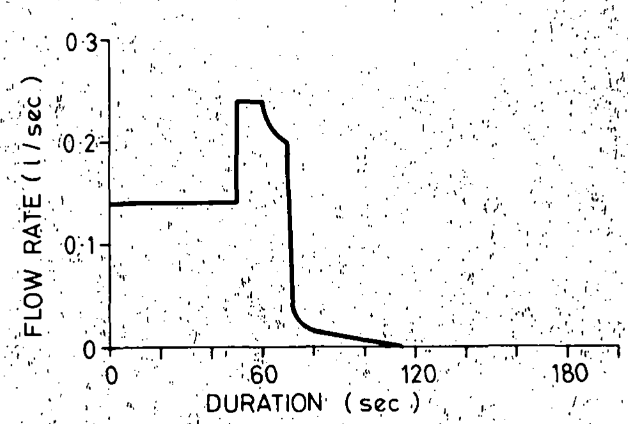


Fig. 30(b). Flow through service pipe with European plumbing system

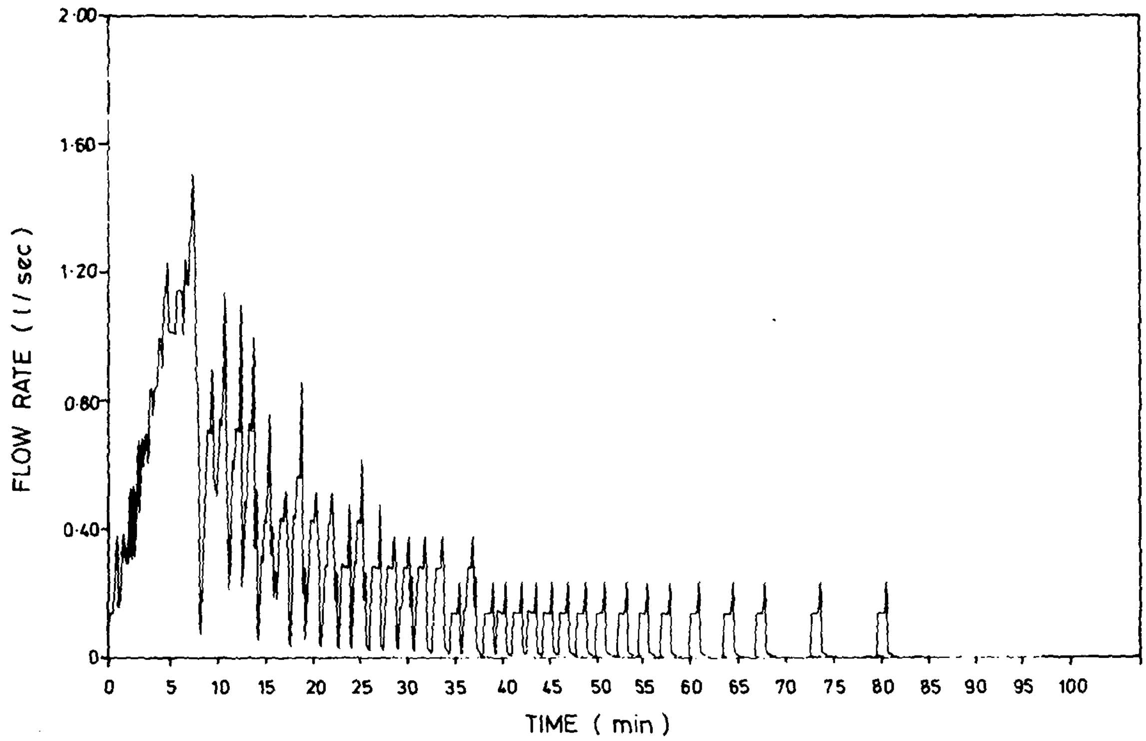


Fig. 31. Predicted TV peak with European plumbing system

11. THE THREE OTHER BENEFITS OF STORAGE

There are four benefits commonly attributed to the provision of storage; these are listed in the introduction. Whilst this report is concerned primarily with one of these, some opinions have been formed regarding the other three, and are mentioned briefly below.

It can be seen from Fig. 1 that if the pressure in the main was less than approximately 2 m head, all outlets, except the cold tap in the kitchen, would still be supplied with water, and all could be used normally. If the same conditions were applied to the system in Fig. 2, water could only be drawn from the hot taps and it would be impossible to flush the toilet more than once. Also, if the pressure in the main became negative with respect to atmospheric pressure then, none of the outlets, except the kitchen tap, could allow water to pass back into the main with the South of England system, whereas all cold water outlets in the North of England system are potential back siphonage hazards. Consequently items (a) and (b) listed in the introduction do not apply to a North of England system. However, this system is not generally considered inferior to the South of England system, and the importance of these items is therefore in some doubt.

The fourth benefit (d) listed in the introduction, namely limitation of pressure in distributing pipes, leading to reduction of noise and waste, and also allowing use of cheaper pipes, may be over-rated. Noise caused by a tank filling may be of longer duration, even if it is of less intensity. Waste may or may not be reduced with domestic storage; and it is common to use the same class of fitting on both inlet and outlet sides of domestic tanks.

A South of England plumbing system can provide an adequate service to consumers, even in areas with very low supply pressure and can even tolerate the head of water in the main falling below the level of the storage tank for short periods. Under these circumstances it would not be feasible to operate a European system.

12. CONCLUSIONS

From the results of this theoretical study, it would appear that the effect of introducing fully pressurised plumbing systems would not significantly change the requirements for main sizing or service reservoir capacity in order to cope with the normal daily usage patterns. The provision of individual domestic storage in its present form appears to have no effect on the normal morning peak flow rate produced by a large group of domestic consumers since they are waking and starting to use water at random times.

Storage does, however, reduce the peak flow rate of a demand caused by a number of people starting to use water within a few minutes of each other. Uses such as these would be encountered at the end of popular TV programmes. If storage was removed from domestic plumbing systems, then peaks of this type would be encountered more often. The fine-scale fluctuations in flow shown in Figs 12(b) and 13(b) demonstrate the ease with which peaks of short duration (in the order of a few seconds) are produced with a European system. In practice, European street mains are not significantly oversized by UK standards to cope with this effect.

Restriction of the rate of flow of water into domestic storage tanks does not significantly reduce the peak flow rate for a large group of consumers unless the inflow rate approaches the mean flow rate for the day. Daily fluctuations in the quantity of water used would make such a system difficult to work in practice.

Allowing the tank to draw down before starting to refill would also produce a slight reduction in peak demand, but the effect would be too small to warrant the increased complexity of the installation unless it was also used as a means of metering.

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