

A CRITICAL STUDY ON ENERGETIC LEAKAGE CONTROL IN WATER SUPPLY NETWORK: A NEGLECTED ASPECT OF ENVIRONMENTAL ENGINEERING

Engr. A. N. Iroegbu; M. Alozie; and Dr. G. N. Chima

Abstract

In this critical study on energetic leakage control in water supply networks, procedures and guidelines developed for uncertainty analysis in the modeling and operation of water distribution systems are presented. The proposed Monte Carlo model analyses the propagation of initial uncertainty in demand through a water supply model anti its influence on calculated flows. The procedure is supposed to reduce uncertainty and facilitate the decision-making process by setting up bounds against which operational data (metered flows) can be compared and checked for validity and reliability.

Introduction

Since the ongoing privatization of the private and public enterprises, the water companies have been under increasing pressure to reduce the level of leakage. Substantial efforts have been made to improve the operational management and general reliability of the water supply systems. As a result, the water companies have started to collect large amounts of data to control the use of water in their systems. However, this data according to Bukar (1992); Okereke (2000), is still not fully used to produce the required level of information. Furthermore, the acquired data, very often are not validated and processed.

Traditionally, leakage assessment is based on a rather simplistic method of water balance rather than taking advantage of extensively studied water supply network models (Water Resource Commission (WRC), 1994). The problem which leakage engineers encounter according to Okereke, Udeagu and Eze (2000), is two fold:

- (i) Leakage is impossible to measure on a regular basis.
- (ii) The majority of domestic consumers are not metered in Nigeria.

Therefore, the leakage level obtained through a water balance analysis is based on estimations of these two components. The use of water supply network models in the operational management of some water companies is still rather limited despite their ability to reliably represent the system (Tabesh & Burrows, 1995). On the other hand, water supply network models are considered from a deterministic point of view only where the parameters and the state variables are treated as constant values at a certain snapshot of time. However, a water supply system operates with a constantly present uncertainty of factors such as *demand, leakage and physical characteristics of the network*.

Therefore, in trying to model a system with these uncertain input sets, the calculated output will be uncertain as well. The water supply network model output (pressures and flows) is a function of the input data (demand) and a number of parameters (e.g. friction factors, diameters) that are essentially either *stochastic processor or random variables*. Moreover, consumer demands as well as flows and pressures are monitored only at a limited number of points, which collectively does not provide an overall picture of the system's behaviour.

The study presented here is part of a larger project on the reduction of uncertainties and improvement of data accuracy for robust on-line monitoring and leakage detection in water supply systems. The research was initialed in order to provide improvements in data processing and analysis procedures that will be beneficial to the water companies in Nigeria. The final goal is to provide appropriate techniques for an automatic data checking procedure for the on-line validation and verification of telemetry data which can be used to reduce uncertainty and facilitate the decision making process. The use of a water supply network model is suggested as a support tool in the process of every-day operational management. By sampling from original probability density functions that correspond to a level of consumption (nodal demands), the proposed Monte-Carlo model analyses the propagation supply model and its influence on calculated (lows).

Water Consumption Variability

The preparation of input data sets was based on the analysis of probability density functions. Thus, the stochastic nature of water demand can be analysed not only regarding frequency of water use in a given time interval, but its intensity and duration (Buchberger & Wu, 1995). It was therefore, very important to have a data set that covers all of these three aspects.

Data on water consumption of individual users was necessary to assess the temporal variability of the domestic component of water balance, since most of Nigerian consumers are currently not metered (Ofwat, 1999; Obradovic, 1998 and Okereke, 2000). A study of domestic use of appliances was available and this is described by Butler (1992). The study on appliances was essentially to examine the preliminary evidence on water consumption variability. A week of diary data on houses has been provided and analysed to examine the features of water consumption. The data set contains information on the following appliances; washing machine, toilet, bidet and dish washer.

When consumers were asked to participate in this study, it was extremely important to select houses with different number of occupants because it is obvious that water consumption varies significantly with this number (Martins, Seales & Edwards, 1994). The number of houses with the corresponding number of occupants is presented in table I below. Due to incomplete data records, 10 houses out of thirty-three were discarded at the beginning of data analysis.

Table I: Number of Houses Monitored with Corresponding Number of Occupants

Occupants	Number of Houses
1	6
2	8
3	3
4	8
5	3

Additionally, not all the appliances were present in all the houses. A shower was present in 61% of houses, a washing machine in 68% and a bath in 97%. For the development of input data files for the Monte Carlo Simulation, it was assumed that each appliance was present in 100% of properties. This is reasonable from the point of view that the data set was too short to represent the whole population of one-Town Melcring Area (TMA) and absence of some of these appliances was more probable than today. Butler (1992), on his research in United Kingdom compared an average ownership in the study sample and his results showed that they agree to the acceptable level.

Frequency of Usage

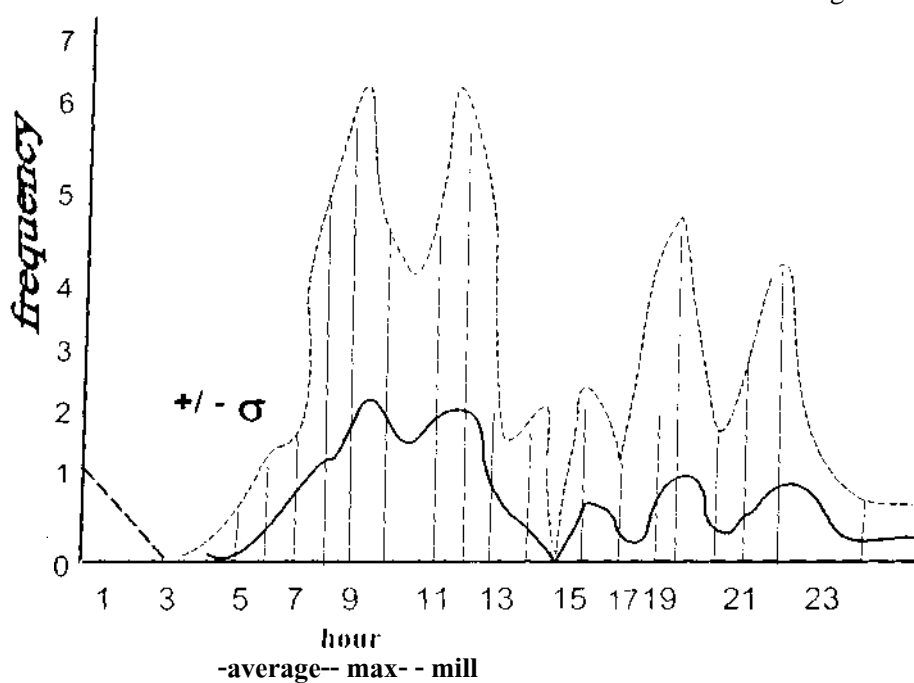
Firstly, the frequency of usage of appliances was analysed on an hourly basis for all properties, not taking into account the number of occupiers. The number of events was counted for every hour and every day of the week.

The major conclusion on the frequency drawn was that a Poisson distribution should be used for modeling of data that represents the number of occurrences in a given unit of time or space, which here correspond to a number of uses per hour. The idea of applying a specific probability density function is similar to Buchberger and Wu (1995), who hypothesized that the flows can be modeled as a Poisson rectangular pulse process. This assumption was examined here using the chi-square test for every appliance. The major modification introduced here is that frequency of use of each appliance is modeled with Poisson distribution, rather than the total water consumed in every property.

An example from the data analysis for the bath is shown below. Figure I represents the sum of usage for all houses over 24 hours as it was recorded in the study. As can be seen in the figure, for every hour, most of the data lie in the range of one standard deviation. Following the conclusion made; water appliance usage is variable not only with time but at a certain time of the day leads once again to the conclusion that a standard water usage pattern does not exist in reality.

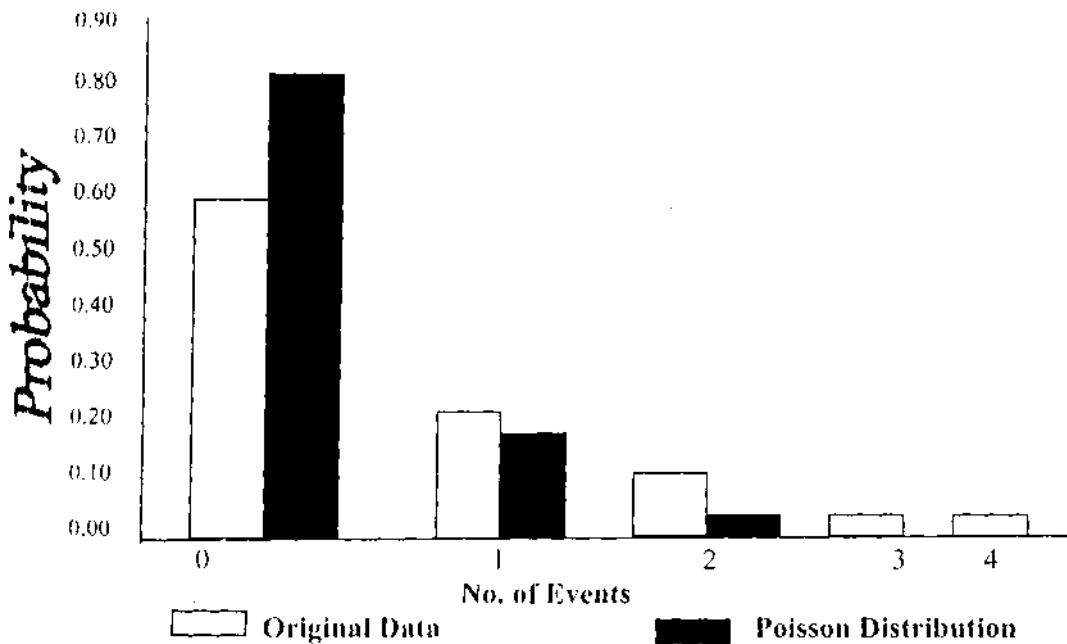
Figure I: Frequency of Bath Usage for all Households Per Hour

Evidence for the Poisson discrete distribution is shown in figure 2 below. From the original data



set, the number of uses of every appliance were counted on a daily basis and then averaged. The chi-square test result confirms (he lit of the Poisson distribution to the average number of uses per day for rare events. However, to apply the Poisson distribution for modeling the set of events, they must be independent which is considered reasonable to assume taking into account the time interval used for (he network modeling. *In addition, this is the reason why the fitness of the Poisson distribution was inadequate for certain appliances on a daily basis.*

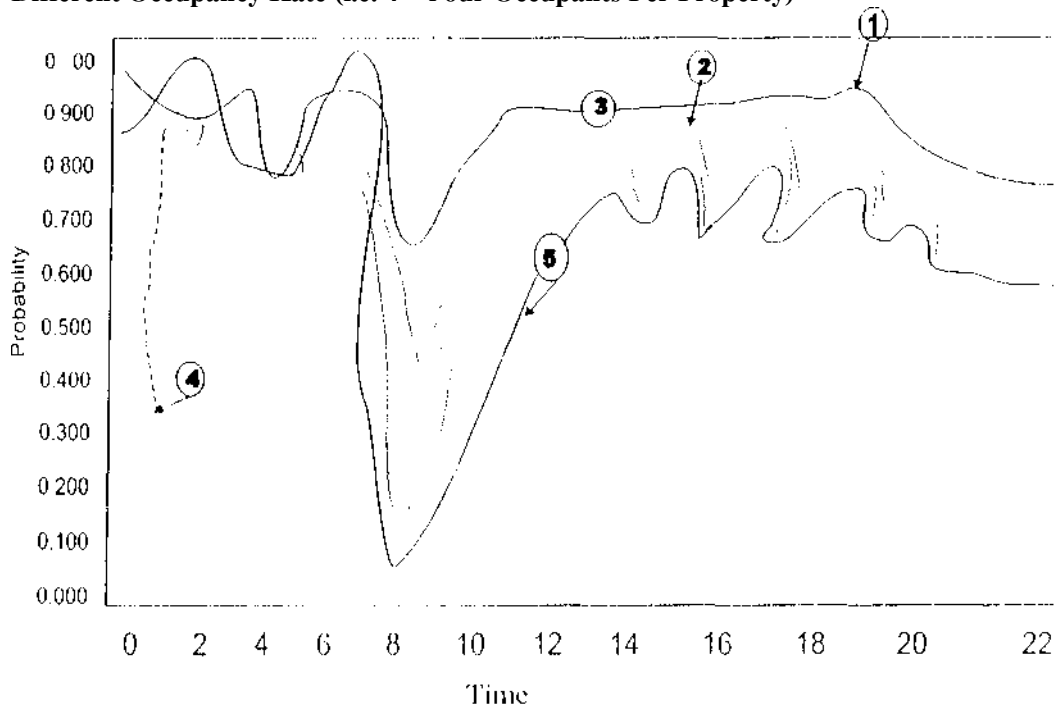
Figure 2: Probability of Bath Usage



Secondly, the data have been analysed in detail looking at the number of occupants and probability of their use over 24 hours on an hourly basis. Using the averaged values from the houses with the same occupancy as mean values for the Poisson process, the probability was derived. One of the disadvantages of this data set is that it was not possible to derive any information on the weekly variation of water usage, since only one week of data was available. Also, no seasonal trend could be detected. Therefore, all days of the week have been considered without any difference, although it is clear that people's behaviour changes significantly during the weekend. It must be stressed that the purpose here was to develop a methodology, which can be later applied within a water company using probability functions specific for a particular (own and a day of the week, rather to derive a standard water usage pattern.

Finally, Poisson distributions were derived for every appliance, hour of the day and occupancy rate. Probabilities for the same number of uses per hour (zero uses in figure 3), similar pattern for every occupancy rate can be recognized, which gives us a confirmation for data consistency and applicability for future prediction of demand. Similar graphs have been produced for all appliance and all occupancy rates.

Figure 3: Probability of Zero' Use Per Hour of the Washing Basin Over 24 Hours and Different Occupancy Kate (i.e. 4 = 1 our Occupants Per Property)



Duration and Flows

Research assistants were used and they were also asked to record the duration of the use of the appliances. To examine the variability of flows, all appliances had to be calibrated.

It is not expected that data collected in the form of histogram can fit to certain probability distribution function. It is a rather complex process, which in the first place depends on the appliance nature. For example, the duration of bath use is very likely to be within longer periods and with a very low probability of occurrence. The advantage of the Monte-Carlo simulation is that it allows the usage of discrete distributions without knowing the statistics (mean and standard deviation) as described by Rubinstein (1981).

Model Development

The model is based on the fact that consumption could take any value within the limits gained from the consumption measurements. Using Monte-Carlo simulation, a water supply network model is

repeatedly simulated. For every simulation, demands attached to nodes are changed in order to perform different scenarios. For every scenario the possible usage of appliance is taken into account

and frequency, duration and intensity of the use attached to individual homes. In this way, the scope of all events (flows), which can be expected during the regular daily operation of the system, is derived. The statistical analysis of outputs gives (Iroegbu, 2005), the limits, which correspond to the first standard deviation (high and low limits) or second (high-high and low-low limits) over 24 hours of operation.

Monte-Carlo Simulation

Once the discrete probability mass functions for the frequency, duration and intensity (flow) are established, the Monte-Carlo random number generator samples from the original cumulative probability functions to match the level of consumption for a particular hour. For the random number generation procedure, a modified algorithm for the inverse transform method (Rubinstein, 1981; Fishman, 1996), is used. As described above, Poisson random number sampling was used for the simulation of number of occurrences per hour. For the duration and flows, the original distributions were used.

It is very important to stress here that, since some appliances have a very short duration of usage, the preparation of input data had to be done on a one-minute basis. This also highlighted the uncertainties involved in the analysis of influence of temporal smoothing deployed when deriving demand patterns.

A water supply system is usually represented with the set of nodes linked with linear elements (pipes, valves and pumps). The nodes represent physical junctions of pipe or points of any change that can occur on the linear elements. Reservoir and tanks are also modeled as nodes. The operation of the system is described by the set of curves defining water consumption, pump characteristics and the set of rules controlling the functioning. The interaction between the physical characteristics of its elements and the state variables describing their behaviour is defined by the set of equations satisfying the mass and momentum conservation law. In general, the system of equations is non-linear and regardless which numerical method is deployed, the solution is found through an interactive process. Many authors (experts), discussed the methods for efficient solution and comparative study of these methods can also be found in the literature (Ivetic, 1996 cited in Jankovic - Nisic, Makosimovic & Graham, 2000; Martinez & Izquierdo, 1994 cited in Jankovic - Nisic, Makosimovic & Graham, 2000; Salgado, Todini & O'Connell, 1987).

The Newton - Raphson method was used for the linearization of the equations. This method was first introduced by Marlin and Peters (1963) and it is based on an iterative process for the solution of linearised equations. *The reason why this method is used is that it is relatively easy for programming and the solution can be found after a small number of iterations.* Developing the mass conservation law into Taylor series expansion and combining both of the equations, the researcher came to the set of linear equations (Ivetic, 1996 cited in Jankovic-Nisic, Makosimovic & Graham, 2000).

The Gauss Seidel method was used for the solution of the set of equations modified with successive over relaxation (Chapra & Capale, 1998), in order to accelerate the convergence to the solution. Since the Gauss-Seidel method is the most commonly used method and it is described widely in the literature (Chapra & Canale, 1998; Press, Teukolsky, Vetterling & Flannery, 1992), it will not be described here in detail because of the targeted page of this article.

Test Network

An example has been composed to examine the propagation of uncertainty and its influence on a model's state variables. The topology (Table 2 and Table 3) and schematic of the network (Figure 4) are enclosed. The network is created from two reservoirs, 6 nodes and 9 pipes. Fourty properties were attached to each of the nodes marked with I in column Qb (see Table 3).

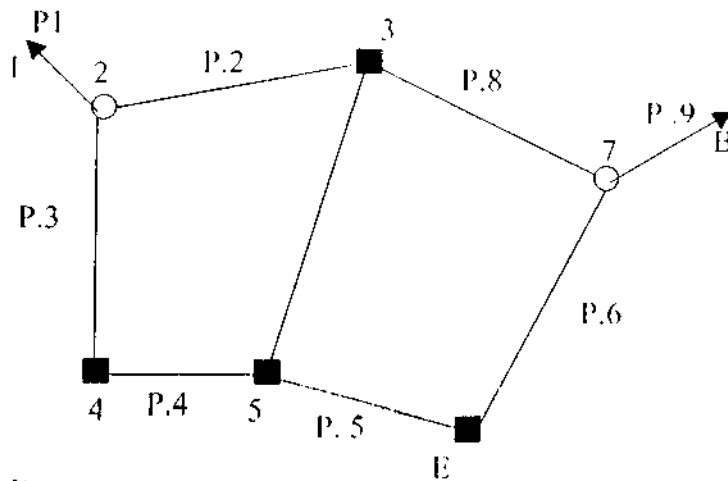
Table 2: Topology of the Nodes (There is (no) Consumption Pattern Attached to This Node)

Nodes		
No (-)	Z (1m)	Qb* (l/0)
1	217	0
2	170	0
3	160	1
4	150	1
5	150	1
6	150	1
7	150	0
8	197	0

Table 3: Topology of the Pipes

Pipes					
No (-)	From Node	To Node	L (m)	D (mm)	K (mm)
1	1	2	100	75	0.3
2	2	3	350	75	0.3
3	2	4	250	75	0.3
4	4	5	350	75	0.3
5	5	6	200	75	0.3
6	6	7	200	75	0.3
7	3	5	250	75	0.3
8	3	7	250	75	0.3
9	7	8	250	75	0.3

Figure 4: Schematic of the Network – Nodes with Attached Demands



Results

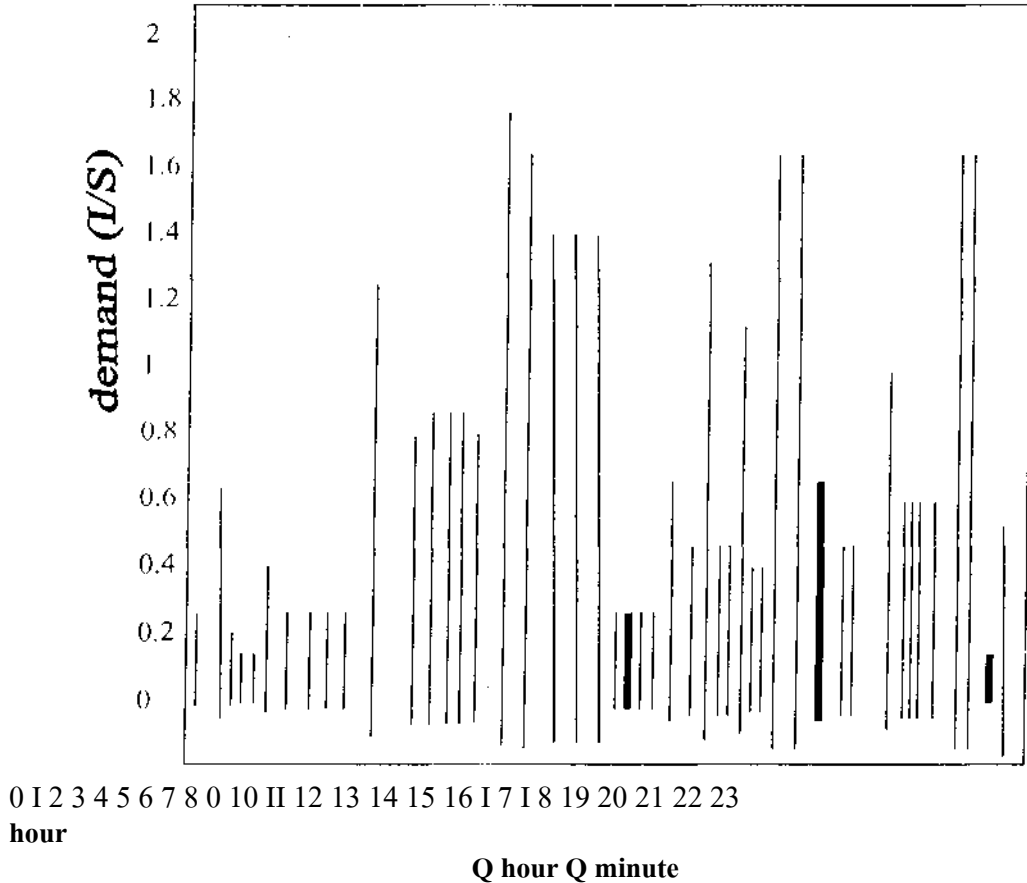
As was outlined above, the development and establishment of patterns for consumer demands require the estimation of demand allocation and its variability. The hydraulic simulator was built to support the initial hypothesis about the representation of water demands and propagation of its uncertainty through the model. The Monte – Carlo simulation was used to assess the propagation of uncertainty. The influence of the number of properties attached to a node of the network model is examined here as part of the analysis of input uncertainty. Taking into account the number of people in the houses and the variability of use of appliances described in the data section, the generalization and targets achieved can be summarized as follows:

- (i) The frequency of use of appliances is recognized to follow the Poisson distribution.
- (ii) Rare events show good fitness even on a daily basis while the others on an – hour basis.

The use of water is recognized as an intermittent stochastic function rather than standard continuous as it is used in all network models.

Figure 5 shows one possible scenario of use of water on a one minute basis (Q minute). When the demand pattern was derived and further averaged on an hourly basis (Q hour), the ratio between the real and average demand in peak hour is shown to be significant.

Figure 5: Comparison of Oiiie-Mimite and Average Pattern for Five Houses

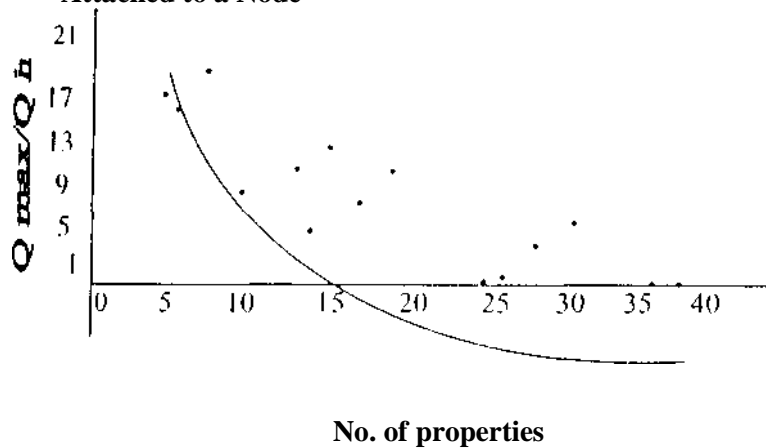


For the peak hour, the ratio between maximum and average demand tends to decrease as the number of attached properties; it is a function of uncertain use of water and occupancy rate in properties. Therefore, the trend line in figure 6 is only this played to show the tendency. The conclusions that can be drawn are twofold:

- 1) Estimation of water balance on a TMA level depends on a TMA size.
- 2) The more properties are attached to one node, the more likely the flow in the mains is to be smoothed.

These conclusions raise the question of, “how many properties can be attached to a node so that the simplification of the network does not influence calculated flows in Pipes?”

figure 6: The Ratio Between maximum and Average Demand Against Number of Properties Attached to a Node

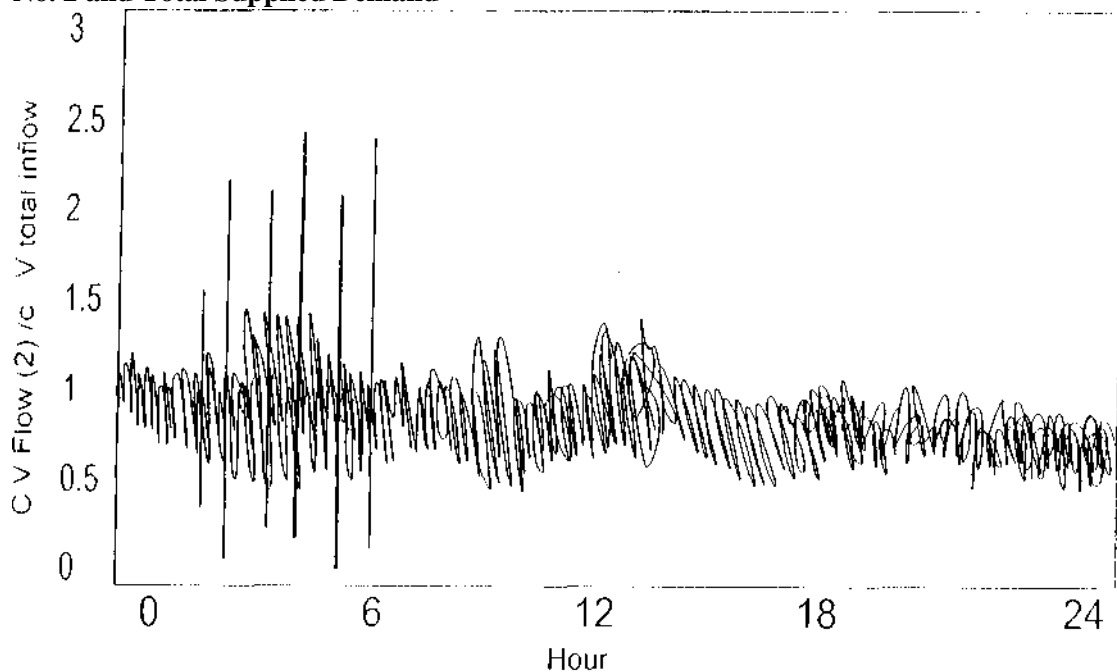


After a hundred iterations performed, the results for flows were statistically analyzed, for every pipe, the high and low confidence limits on one minute basis were built. As a measure of uncertainty, the coefficient of variance has been considered. *When the coefficient of variance is plotted against time, it can be seen that the uncertainty has its minimum at night. However, the coefficient of variance itself is not a relative measure of uncertainty.*

Conclusion

The uncertainty in outputs must be considered relatively to the uncertainty in inputs. The same conclusion was made by Lei (1996), when he first introduced a sensitive coefficient, the ratio between coefficient of variance of the outputs and inputs for the analysis of sensitivity in parameters. Parallel to that, the ratio between flow in a single pipe and total water supplied is analyzed and shown in figure 7.

Figure 7: Ratio Between Co-efficient of Variance of Flow for Pipe. No. 2 and Total Supplied Demand



A much higher uncertainty is reported at night, while during the daytime is almost always the same. The conclusion partly questions the use of night flows as a method for leakage assessment. Although the consumption is at minimum at night; it could have a much higher uncertainty involved

Recommendations

One recommendation would be that future work should concentrate on leakage assessment on a

daily basis.

Two, this uncertainty analysis can be used in many aspects of water supply system examination. It is necessary for (the state-estimation since the quality of the results highly depends on the reliability of the parameters (state variables).

Three, the limits derived can be used in on - line applications to control data from telemetry especially, in emergency cases where consumption have been taking part. The information is then stored for further calculations of amounts of water lost in the system. Moreover, the confidence grade can be assigned to every leakage calculation.

Further/Future Studies

There are several factors that can greatly influence the accuracy of leakage assessment using (the method described above. First of all, a more extensive data set is needed to assess the use of many other appliances, especially outdoor ones like garden sprinklers. In this case, it would be possible to assess seasonality by introducing appliances according to the month in a year. Another important issue that was neglected is that usage time can be extended if water is stored in a household water tank. Finally, the procedure has to be applied to real systems in order to examine the spatial distribution of uncertainty that is vulnerability of certain pipes to the uncertainty.

References

- Buchbrcger, S.G. and Wu, L. (1995). Model for instantaneous residential water demands. *Journal of Hydraulic Engineering* (121). (2) 232 - 246.
- Bukar, M. (1992). *Water supply inadequacies: problems and prospects of SWAs - NWRP Abuja: Launch Workshop.*
- Butler, D. (1992). Modeling the variation of domestic dry weather flows in sewer networks. *A Ph. D thesis*, University of London, London.
- Chapra, S.C. and Canele, R.P. (199X). *Numerical Methods for Engineers: With programming and software applications.* USA: McGraw-Hill, 292-298.
- Fishman, G.S. (1996). *Monte -Carlo concepts, algorithms and applications.* New York: Verlag. 153 - 156.
- Iroegbu, A.N. (2005). *Introduction to research methodology: A simplified version.* Owerri: Springfield Publishers.
- Jankovic - Nisic, B.; Maksimovic, G. and Graham, N. (2000). *Using a Monte-Carlo method for active leakage control in water supply networks.* Iowa, USA: hydroinformatics.
- Lei, J.I.I. (1996). Uncertainty analysts of urban rainfall-runoff modeling. *A Ph D. Thesis*, Department of Hydraulic and Environmental Engineering. Norwegian University of Science and Technology, Trondheim.
- Martin, D. W. and Peters, G. (1963). The application of Newton's method to network analysis by digital computer. *Journal of Institution of Water Engineers.* 17 115 129.
- Martin, L.; Scales, P. and Edward, K. (1994). *Surveying domestic water consumption.* United Kingdom: Anglican Water Services.
- Obradovic, D. and Lonsdale, I. (1998). *Public water supply: Data models and operational management.* New York: li & LN Spoil.
- O(wat(1999). *Report on leakage and water efficiency.* United Kingdom: Ol'wat.
- Okerekc, P. D. (2000). The water problem in old Imo state. National conference on Housing and Environment (CLLNACON) Owerri: Imo State University.
- Okerekc, P.A.; Udeagu, li.I. and fixe, G.U. (2000). *Water supply management in Nigeria: Examples in some states.* Owerri: M. Cajec Publications.
- Press, W.H; Tenkolsky, S.A.; Vetter!iny, W.T. and Flannery, B.P. (1992). *Numerical recipes in Fortran.*

United Kingdom: Cambridge University Press.

Rebinsteni, R. Y. (198 i). *Simulation and the Monte Carlo method*. New York: John Wiley & Sons.

Salgado, R.; Todini, G.; and O'Connell, P. G. (1987). Comparison of the gradient method with some traditional methods for the analysis of water supply distribution networks. In 13. Coulbeck and C.11 Orr (Eds.), *Computer Applications in Water Supply. I*. United Kingdom: Research Studies Press 38 62.

Tabesh, M. and Burrows, R. (1995). Investigation on aspect of water consumption and system leakage *in the United Kingdom*. /. *J. of Water Resources Engineering* 3(/). 35 - 46.

WRC(1994). United Kingdom Water Industry, UK: WRC, Managing Leakage Reports.