Short communication

Degree of utilisation – The reciprocal of the peak factor. Its application in the operation of a water supply and distribution system

EH Johnson

Stewart Scott, PO Box 25302, Monumentpark 0105, Pretoria, South Africa

Abstract

The degree of utilisation provides both a technical and economic connotation to the analysis of peak (load) factors. It is the reciprocal of the peak factor and should be measured within specified time-intervals that will provide realistic values for the specific purposes of a particular analysis of a water supply and distribution system. This paper briefly reviews some previous studies on peak factors and suggests a method of examining peak factors and their associated degree of utilisation in terms of probability theory in an attempt to provide greater insight when analysing the optimal investment level required in water infrastructure. The application of this concept is specifically relevant, although not restricted to, the operation of water supply and distribution systems for short time horizons.

Low degrees of utilisation indicate the uneconomical practice of maintaining excess capacity to accommodate a short interval of peak demand. The application of probability theory is used to indicate the recurrence interval of peak events as well as to provide a useful intuitive method for improving a water system's degree of utilisation through operation and control procedures.

Introduction

The shortcoming of most water demand forecasts is that they produce average consumption values. However, it is the maximum or peak load (flows) which is used in the application of fundamental hydraulic sizing and design techniques for water engineering infrastructure.

The simplest form of the peak factor is a ratio of maximum or peak flow to average flow. A more comprehensive method is to express the peak factor as a function of average flow in the form of a linear or logarithmic expression. Tessendorff (1972) considered that a peak value which occurs only very seldom and which is only of very short duration provides no useful basis for hydraulic design. Therefore the duration and the frequency of peak-flow intervals must be taken into account in addition to the peak flow rate and the period of observation. The magnitude, duration and frequency of flow peaks are not amenable to theoretical predictions and must therefore be assessed by field measurements.

Tessendorff (1972) recommended different time-intervals for the various sections of the pipe network where the load should be considered constant. These time-intervals are:

For consumer installation lines	: 15 s
For service lines	: 2 min
For supply lines (and distribution systems)	: 15 min
For mains and feeders	: 30 min

Due to the technical limitations of the chart-scanning equipment used for Tessendorff's project, the limit of accuracy of the flow interval was 20 s. However, the use of a shorter time-interval would result in unrealistically high values being determined.

☎ (012) 347-1018; fax (012) 347-7379; e-mail edgarj@ssi.co.za

Received 20 May 1998; accepted in revised form 20 August 1998.

The consequences of design flows being exceeded are generally not catastrophic for the water network as a whole, but occurrences such as a drop in supply pressure may prevail for a short period whilst the peak flow for a particular pipeline is being exceeded or the reserve storage of a service reservoir is encroached upon (Johnson, 1987). In the United Kingdom, however, it is a requirement that the number of failures (i.e. below a particular specified pressure threshold) occurring in the supply pressure must be recorded (Newsome, 1991). Cognisance should be taken of the possibility that smaller items within the water network, such as water meters, can be damaged when design flows are exceeded.

The degree of utilisation is determined by dividing the average flow (load) during a certain period by the maximum flow (load) for which the installation (i.e. pipe, pump station, etc.) was designed or can accommodate and expressing it as a percentage.

The reciprocal of the peak factor is therefore the degree of utilisation and it is important to know this degree of utilisation when the economic use of the distribution network is to be determined. The closer the degree of utilisation is to unity (or 100%), the lower is the excess capacity that needs to be maintained just to accommodate short intervals of peak demand and therefore the more profitable is the installation (Tessendorff, 1972).

It would appear from some literature that most water supply and distribution systems have a low degree of utilisation in the order of 30 to 50% (Tessendorff, 1972) (Johnson, 1987).

This paper provides a brief review of some previous studies on peak factors, and suggests a method of examining peak flows and their associated degree of utilisation in terms of probability theory in an attempt to provide greater insight when analysing the optimal investment level in water infrastructure. The application of this concept is specifically relevant in the operation of water supply and distribution systems for short time horizons, although it can also be applied in the planning stage of projects to establish the effect on existing water infrastructure of delaying the installation of new water infrastructure.

Peak factors

Peak factors tend to increase with a decrease in the number of consumers. Barrufet, (1985) found that peak factors increase from a constant 1.5 for more than 100 000 consumers to as much as 98 for a two-person apartment.

A peak factor function established for a city from its 29 years of records of annual average daily demand and maximum daily demand of the year was $Q_{max} = 1.5840Q_{ave}$-0.7480 with a correlation coefficient of 0.9924 (Johnson, 1987). This is approximately equal to a peak factor of 1.58.

The shorter the duration with which peak flows are measured, the greater is the peak factor. There is also a strong inverse linear relationship between the number of inhabitants in a building and the peak factor (Tessendorff, 1980) as well as between flow and pressure.

The peak factors used by water engineering practitioners in South Africa originate from the "Blue Book" (Department of Community Development, 1983) and "Red Book" (Department of Planning, Provincial Affairs and Housing, 1991) guidelines. Peak factors established from flows recorded with the aid of electronic data loggers and water meters reveal that the design guidelines generally recommend conservative peak factors (Turner et al., 1997). It was also confirmed in another project at the coast that the peak factors given in the design guidelines are probably in excess of actual values (Wild, 1997).

Another study undertaken within a developing community recommends the following summer peak factors (Van Schalkwyk, 1997):

- House connection water distribution. Peak factor of 1.5 (degree of utilisation 66.7%)
- Yard connection water distribution. Peak factor of 1.35 (degree of utilisation 74.1%)
- Street tap distribution system. Peak factor of 1.2 (degree of utilisation 83.3%)

In 206 American towns the ratio of annual peak factors of monthly, daily and hourly water demand was found to be 1.4; 1.62 and 2.57 respectively (Tessendorff, 1972), which translates to a degree of utilisation of 71.4%; 61.7% and 38.9% respectively.

Degree of utilisation

The degree of utilisation provides both a technical and economic connotation to the analysis of peak (load) factors. It also provides greater insight into as well as more scope for growth in the analysis of the performance of hydraulic systems, with specific reference to their operation and control, than can be achieved through the analysis of peak (load) factors alone.

The larger the peak factor the lower is the degree of utilisation. For example, a peak factor of 1.5 is equivalent to a degree of utilisation of 66.67% while a peak factor of 5 would be equivalent to a degree of utilisation of only 20%. The interval for which the degree of utilisation has been derived must also be stated, i.e. "mean annual degree of utilisation based on the hourly load" or "peak degree of utilisation" for the peak value actually reached and the capacity held available (Tessendorff, 1972).

The degree of utilisation can therefore be defined as follows:

$$\text{Degree of utilisation (specifying the period)} = \frac{100}{\text{peak factor or function}} \text{ (per cent)}$$

The degree of utilisation is closely related to the profitability of a water authority as it indicates the actual utilisation level of the particular infrastructure. Low degrees of utilisation imply that very large capacities must be maintained within pipelines just to accommodate short intervals of peak demand (Tessendorff, 1972). Probability theory can therefore be used to indicate the recurrence interval of these peak events as well as the associated effects of improving (increasing) the particular part of the system's degree of utilisation.

Application of probability theory

The peak factor based on the maximum 15 min flow and average daily flow from a reservoir for 120 months has been analysed here to illustrate how the degree of utilisation together with the probability theory can be used to evaluate possible alternative design and operational criteria. The 15 min time-interval was selected in order to be consistent with the previously mentioned time-intervals recommended by Tessendorff (1972).

The peak factors were first ranked from largest to smallest and the return period and percentage probability were determined from the following formulae (Wilson, 1979):

$$\text{Return period (Tr)} = \frac{(n + 1)}{m}$$

where:
m = event ranking
n = total number of events

$$\text{probability} = \frac{100}{Tr}$$

A chi-square test is used to determine how accurately the normal distribution curve fits the peak factors. This is undertaken in order to determine whether probabilistic concepts can be used to describe the degree of utilisation/peak factors. The data were then distributed into categories with the number within each category determined, i.e. observed frequency (0) in Table 1 and illustrated in the form of a histogram in Fig. 1.

The area under the standard normal curve was then determined to establish the expected frequency (E) of the flow values if the distribution is normal.

The chi-square test was then undertaken to determine the agreement between the observed (0) and expected (E) frequencies. This is done because the assumption is that the sampling distribution of chi-square is approximated very closely by the chi-square distribution (Spiegel, 1972).

The following formulae were used:

$$Z = (X - \bar{x})/s \qquad \text{(Spiegel, 1972)}$$

where:
Z = standardised variable
$\bar{x}$ = mean
s = standard deviation
X = peak factor value

$$X^2 = (O-E)^2/E \qquad \text{(Spiegel, 1972)}$$

where:
X^2 = chi-square
0 = observed frequency
E = expected frequency

TABLE 1
CHI-SQUARE TEST OF PEAK FACTORS

Peak factors	Categories (X)	Observed frequency(O)	Z	Area under normal curve	Areas	Expected frequency (E)	Chi-square
1.6-1.8	1.7	1	-1.8296	0.4663			
1.8-2.0	1.9	5	-1.4951	0.4326	0.0338	4.0540	0.2208
2.0-2.2	2.1	9	-1.1607	0.3771	0.0554	6.6533	0.8277
2.2-2.4	2.3	13	-0.8263	0.2957	0.0814	9.7738	1.0649
2.4-2.6	2.5	16	-0.4918	0.1886	0.1071	12.8518	0.7712
2.6-2.8	2.7	20	-0.1574	0.0625	0.1261	15.1263	1.5703
2.8-3.0	2.9	24	0.1771	0.0703	0.1328	15.9359	4.0807
3.0-3.2	3.1	11	0.5115	0.1955	0.1252	15.0277	1.0795
3.2-3.4	3.3	7	0.8460	0.3012	0.1057	12.6848	2.5477
3.4-3.6	3.5	4	1.1804	0.3811	0.0799	9.5840	3.2534
3.6-3.8	3.7	3	1.5149	0.4351	0.0540	6.4815	1.8701
3.8-4.0	3.9	3	1.8493	0.4678	0.0327	3.9236	0.2953
4.0-4.2	4.1	1	2.1838	0.4855	0.0177	2.1259	
4.2-4.4	4.3	1	2.5182	0.4941	0.0086	1.0310	
						Chi-square =	17.5817
						Degrees of freedom =	8.0000
					Acceptable at: 97.5409 % Confid.		

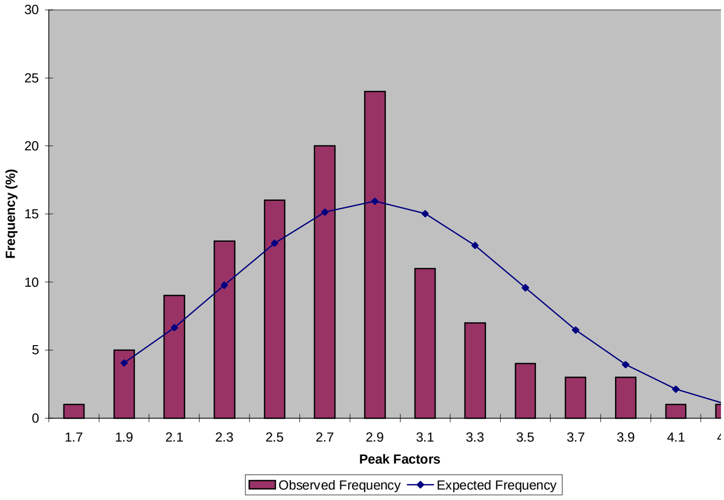

Figure 1
Frequency histogram

γ = k-l-m (Spiegel, 1972)

where:

γ = degrees of freedom
k = population parameters i.e. number of categories used
m = population parameters for samples i.e. two if standard deviation and mean are used plus if it is a sample of the total amount of data.

The relevant calculations are given in Table 1 which shows that the calculated chi-square value (17.582) is less than the critical value (from chi-square tables=20.1) and therefore the hypothesis can be accepted at the 99% confidence level (Spiegel, 1972).

In order to illustrate the application of this theory, say that the reservoir's outlet pipeline had a peak factor for a particular year of 2.6 with a recurrence interval of 1.52 months (66% probability) and this represents a mean monthly degree of utilisation of 38.5% (0.385) based on a 15 min load (See Fig. 2).

If this peak factor of 2.6 was restricted in an existing supply pipeline (say) to 2.32 the degree of utilisation could increase to approximately 43%. This could be achieved by a remotely controlled pressure-reducing valve with the consumer possibly having a 15 min reduction in supply pressure approximately once every six weeks. Alternatively, if the scenario was that a new pipeline was proposed, its installation could be delayed until the existing pipeline reached a particular degree of utilisation and associated recurrence interval that was considered acceptable by the water authority (e.g. a 15 min reduction in pressure once every 6 weeks).

A city's reservoirs storage could be used more efficiently should filling be undertaken slowly during the city's "off-peak" periods and thus reducing the overall peak load on the distribution system. It has been found that a "floating tank" policy, characterised by few pump changes and large reservoir depth excursions, is more economical than a policy where reservoir depths are brought to a maximum nightly (De Moyer, 1973).

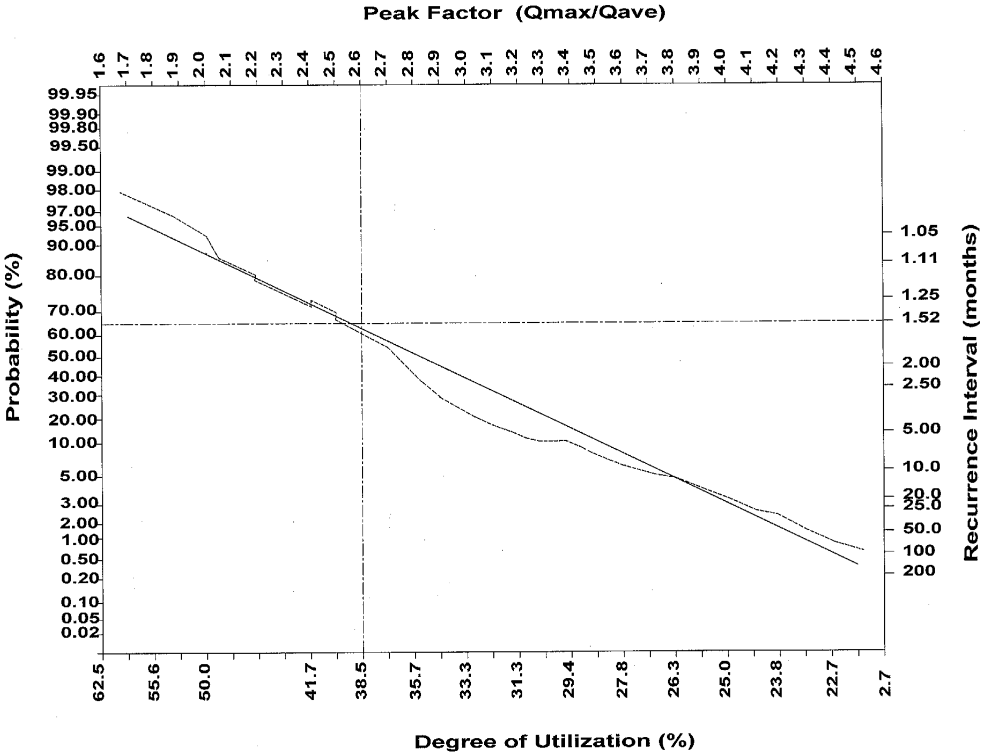

Figure 2
Degree of utilisation - probability graph

Closing comments

The degree of utilisation is the reciprocal of the peak factor and should be measured within time-intervals specified for different sections of the pipe network that will provide realistic values for the specific purposes of a particular analysis. The degree of utilisation is a more useful indicator when establishing the economic operational use of water infrastructure systems. Low degrees of utilisation indicate the uneconomical practice of maintaining excess capacity to accommodate short intervals of peak demand, e.g. a supply pipeline with a degree of utilisation of 40%, implies that 60% of its capacity is under-utilised.

Probability theory can be used to indicate the recurrence interval of peak events as well as the associated effects of changing the water system's degree of utilisation.

The operation and control of the water supply and distribution system can be optimised through the integration of various sensors (flow, pressure, level, etc.), local process controllers, alarms and a telemetry system together with a computer program that both provides the operator with operational options as well as undertakes automatic control decisions that improves the system's degree of utilisation. The intuitive concept detailed here could provide the impetus for further development of an algorithm for the computer program that will be a beneficial tool that assists the management of the operation and control of water supply and distribution systems.

References

BARRUFET A (1985) *Survey of Peak and Average Demand and their Interrelating Coefficients* (French). Water Supply Assoc. No. **6** 316-319.

DEPARTMENT OF COMMUNITY DEVELOPMENT (1983) Guidelines for the Provision of Engineering Services in Residential Townships (Blue Book). Prepared by the CSIR.

DEPARTMENT OF PLANNING, PROVINCIAL AFFAIRS AND HOUSING (1991) Guidelines for the Provision of Engineering Services and Amenities in Residential Township Development (Red Book). Unreleased guidelines prepared by the Division of Building Technology, CSIR.

DE MOYER R (1973) *A Statistical Approach to Dynamic Modelling and Control of Water Distribution Systems.* Polytechnic Institute of Brooklyn.

JOHNSON EH (1987) Flow Data Acquisition and Forecasting System for a Water Distribution Network. Laureatus Thesis, Port Elizabeth Technikon.

NEWSOME CD (1991) *Network Management - The Calder Experience. Advanced Technology in Water Management.* The Institution of Civil Engineers, Thomas Telford, London. 177-187.

SPIEGEL MR (1972) *Theory and Problems of Statistics in SI Units.* McGraw-Hill. 360 pp.

TESSENDORFF H (1972) Problems of peak demands and remedial measures. *Proc. 9th Congr. Int. Water Supply Assoc.* Int. Standing Committee on Distribution Problems: Subject No. 2. pp S10-S14.

TESSENDORFF H (1980) Peak demands - Results of the German research programme. *Proc. 13th Congr. Int. Water Supply Assoc.* Int. Standing Committee on Distribution Problems: Subject No. 5.

TURNER RH, FOWLER TG, MANSON NJ and STEPHENSON D (1997) Optimisation of Rand Water's Distribution System. Water Research Commission Report No. 488/1/97.

VAN SCHALKWYK A (1997) Guidelines for the Estimation of Domestic Water Demand of Developing Communities in the Northern Transvaal. Water Research Commission Report No. 480/1/96.

WILD RD (1997) The Performance, Selection and Optimum Replacement Interval of Water Meters. Dissertation for Masters Diploma in Technology. Port Elizabeth Technikon.

WILSON EM (1979) *Engineering Hydrology*. London: The MacMillan Press Ltd. 232 pp.