Study on the impacts of peaking factors on a water distribution system in Germany
K. Diao, M. Barjenbruch and U. Bracklow

ABSTRACT
This paper aims to explore the impacts of peaking factors on a water distribution system designed for a small city in Germany through model-based analysis. As a case study, the water distribution network was modelled by EPANET and then two specific studies were carried out. The first study tested corresponding system-wide influences on water age and energy consumption if the peaking factors used at design stage are inconsistent with ones in real situation. The second study inspected the possible relationship between the choice of peaking factors and budgets by comparing several different pipe configurations of the distribution system, obtained according to variety of peaking factors. Given the analysis results, the first study reveals that average water age will increase if peaking factors estimated at design stage are larger than real values in that specific system, and vice versa. In contrast, energy consumption will increase if peaking factors defined for system design are smaller than ones in real case, and vice versa. According to the second study, it might be possible to amplify peaking factors for design dramatically by a slight increase in the investment on this system. However, further study on budget estimation with more factors and detailed information considered should be carried out.

Key words | budget, modelling, peaking factors, water age, water demand,
water distribution system

INTRODUCTION
The peaking factors are the ratio of the maximum flow during some specified time interval to the average flow (Mays 1999), which are used to estimate the peak flow regarded as a crucial factor in the design of a water utility’s production, distribution capacity and in customer metering (AWWA 2004). Thus far, however, how to define peaking factors reasonably is still a disputable issue given the uncertainties in the magnitudes of maximum and average daily flows. As Johnson (1999) concluded, “It has been confirmed that the design guidelines generally recommended conservative peaking factors (Turner et al. 1997), which are probably in excess of actual values (Wild 1997)”. As a result, water distribution networks are usually in overcapacity conditions in the design when the fire hydrants are not in use, which consequently increase the capital cost of a system dramatically since the pipeline network in the water supply system accounts for around 75% (WSAA 1999a) of the total investment (Burn et al. 2002). In addition to the capital cost which is a function of pipe diameter and laying conditions, the present worth of energy costs included in the distribution system costs is also affected by pipe sizing (Walski et al. 2005). Therefore, it is essential to study how to define peaking factors carefully on which the pipe sizing depends, so that considerable savings can be achieved in expense on pipelines. However, there are only a few studies concentrating on peaking factors, most of which focus on more accurate estimations of peaking factors (Johnson 1999; Booyens & Haarhoff 2002; Surendran et al. 2005; Zhang 2005).
Literature review

The prerequisite for setting peaking factors correctly is to have a clear picture of their significant properties first. In general, peaking factors are highly related to the number of consumers, the service areas, and the duration of peak flow of a water distribution system.

As concluded by Johnson (1999) based on several researchers’ studies:

Peaking factors tend to increase with a decrease in the number of consumers. This is majorly oriented by simultaneity of consumption. Barrufet (1985) found that peaking factors increase from a constant 1.5 for more than 100,000 consumers to as much as 98 for a two-person apartment. There is also a strong inverse linear relationship between the number of inhabitants in a building and the peaking factor (Tessendorf 1980) as well as between flow and pressure. The shorter the duration of measured peak flow, the larger the peaking factor (Johnson 1999).

Again, Mutschmann & Stimmelmayr (2007) stated that “Peak factors are greater in smaller water supply areas”. This is because smaller coverage areas usually mean less water users. As a result, the variation of water demands is more difficult to predict.

“For drinking water supply systems, there is no authoritative calculation method for the choice of appropriate peaking factors, and therefore these factors have to be estimated according to records or even empirically.” Zhang (2005) commented, “Moreover, as water use varies greatly with location, varying regions often have their own methods for estimating the peak demands in their systems.”

Zhang (2005) introduced two examples in America:

Georgia Minimum Standards for Public Water Systems (2000) presented a relationship between peak instantaneous demand and the number of connections, which can be well approximated ($R^2 > 0.999$) with the following expression,

\[ Q_p = 43.40C^{0.54} \]  

where $Q_p$ is the peak instantaneous demand (L/min) and $C$ is the number of connections. Equation (1) holds for the $C$ value of less than 500 only. In the US Bureau of Reclamation Design Criteria (2002), the peak instantaneous demand is expressed as

\[ Q_p = 18.19N^{0.5} + 3.41N + 22.36 \]  

where $N$ is the number of houses.

Study objective

This paper aims to explore this issue from another perspective by testing impacts of peaking factors on water distribution systems based on a case study in Germany. For this purpose, two types of analysis are carried out respectively. The first study is to test corresponding system-wide influences on water age and energy consumption if the peaking factors used at design stage are inconsistent with ones in a real situation, since different peaking factors result in different demand patterns and consequently affect behaviour of a network system. The second study is trying to inspect the possible relationship between the choice of peaking factors and budgets by comparing several different pipe configurations of the distribution system obtained according to variety of peaking factor selections. Analysis results of these two studies could provide decision-makers with more reference information for water distribution system design and operation management.

Defining peaking factors

The peaking factors are calculated as the ratios of discharges for various conditions (Walski et al. 2003). For this study, the daily peak factor and hourly peak factor are considered.

Daily peak factor

The daily peak factor $f_d$ is defined as the ratio of the maximum day demand $Q_{d,\text{max}}$ to the average day demand $Q_{d,\text{avg}}$ (Mutschmann & Stimmelmayr 2007):

\[ f_d = \frac{Q_{d,\text{max}}}{Q_{d,\text{avg}}} \]
and
\[ Q_{d,\text{avg}} = \frac{Q_a}{365} \]  \hspace{1cm} (4)

where \( Q_a \) is the average annual demand, m\(^3\).

**Hourly peak factor**

The hourly peak factor \( f_h \) is defined as the ratio of the peak hour demand \( Q_{h,\text{max}} \) on the day with maximum daily demand \( Q_{d,\text{max}} \) to annual average hourly demand \( Q_{h,\text{avg}} \) (Mutschmann & Stimmelmayr 2007):

\[ f_h = \frac{Q_{h,\text{max}}}{Q_{h,\text{avg}}} \]  \hspace{1cm} (5)

where
\[ Q_{h,\text{avg}} = \frac{Q_{d,\text{avg}}}{24} = \frac{Q_a}{365 \times 24} \cdot \text{m}^3/\text{h} \]

**Peaking factors estimation**

The original peaking factors of this case study were determined officially based on standards developed by the DVGW (Deutsche Vereinigung des Gas- und Wasserfaches e.V.—Technisch-wissenschaftlicher Verein = DVGW German Technical and Scientific Association for Gas and Water). DVGW technical standards that provide the basis for the trouble-free design, construction and operation of gas and water systems in Germany are set by DVGW German Technical and Scientific Association. As acknowledged, rules for technical matters regarding the regulation of the DVGW are documented in the law, for energy economy and the decree for drinking-water (DVGW German Technical and Scientific Association for Gas and Water 2009). Three worksheets taken from DVGW standards are involved in this study (see Table 1), including two methods for peaking factors estimation.

<table>
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<tr>
<th>Index</th>
<th>Title</th>
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<tr>
<td>W 400-1</td>
<td>Engineering rules for water supply systems; part 1: design</td>
<td>2004</td>
</tr>
<tr>
<td>W 410</td>
<td>Water demand—characteristic and influencing values</td>
<td>2007</td>
</tr>
<tr>
<td>W 405</td>
<td>Provision of fire water through the public drinking water supply</td>
<td>1978</td>
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**Method A: Mutschmann & Stimmelmayr (2007)**

The first approach taken into account for estimating peaking factors for this case study is provided by Mutschmann & Stimmelmayr (2007) on the basis of DVGW-Worksheet W 400-1 (2004), since the water distribution system in this project is designed for a small city in Germany. According to this method, both the peak day demand and peak hour demand depend on the population, and can be resolved by Equations (6) and (7) respectively. In addition, the diagrams indicating these relationships are provided in Figures 1 and 2.

\[ f_d = -0.1591 \cdot \ln E + 3.5488 \]  \hspace{1cm} (6)

\[ f_h = -0.75 \cdot \ln E + 11.679 \]  \hspace{1cm} (7)

**Method B: DVGW-Worksheet W 410 (2007)**

This method uses formulae given in the latest draft of DVGW-Worksheet W 410 (2007). Similarly, the two peaking factors are also a function of the population, see Equations (8) and (9). Figure 3 illustrates the dependence of the peaking factors on the population in this case.

\[ f_d = 3.9 \times E^{-0.0752} \]  \hspace{1cm} (8)

\[ f_h = 18.1 \times E^{-0.1682} \]  \hspace{1cm} (9)

Using peaking factors calculated based on a region’s own method is preferable, since these factors could vary significantly among regions. For instance, an hourly peaking factor

\[ E \text{—population} \]
factor of 2.3 could be applied to a residential area with 4,000 households in summer (Burn et al. 2002) according to Australian Code (WCWA 1986; WSAA 1999b), see Figure 4. For similar population estimated by assuming 2.6 person per household, however, the value computed through method A introduced in the DVGW standard is about 4.74.

METHODS

A water distribution network designed for a small city in Germany was modelled by EPANET (Rossman 2000) as a case study in order to explore the impacts of peaking factors on a real water distribution system and therefore achieving valuable outcomes contributing to decision-making on peaking factors determination.

Case study description

The layout of the case study water distribution mains is a looped network with 5 rings (Figure 5).

With regard to the city, it consists of a new town, an old town and a settlement, including utilities such as sanatorium, public swimming pool, school, sports field, industry, as well as a waste water treatment plant. The population of the city is around 20,300, and the total area of the city is about 200 ha.

Peaking factors of this water distribution system are calculated in accordance with method A, which are 1.97 for $f_d$ and 4.24 for $f_h$ respectively. The original planning scheme resulting from that is used as the benchmark for all the
following analysis. Peaking factors acquired from method B are also utilized as members of test data. Fire flow is taken into account during design stage by adding a demand of 192 m$^3$/h at node $h$. During a fire fighting period, a minimum pressure of 15 m at each node is guaranteed as required by W 405.

Model-based analysis

Two specific analyses are described in this section in order to illustrate the effects due to selecting different peaking factors.

Study one: water age and energy consumption

Study one is to test corresponding system-wide influences, resulting from various maximum day demand patterns that are determined by different peaking factors, on water age and energy consumption of the distribution system. Results of this study illustrate how the system may respond if peaking factors estimated at design stage are inconsistent with ones in a real operating situation. The analysis scenario is chosen on the maximum day as it is the typical condition concerned, on which the peak flow is specified according to peaking factors.

Water age is regarded as a reliable surrogate for water quality, as more generally chemical processes that can affect water quality in a distribution system occur over time. The water age analysis (Walski et al. 2003) reports the cumulative residence time for each parcel of water moving through the network. The initial age of water entering a network from a source is considered to be zero. The algorithm the software uses to perform the analysis is a specialized case of constituent analysis, in which constituent concentration growth is directly proportional to time, and the cumulative residence time along the transport pathways in the network is numerically summed.

Considering energy consumption, power usage for pumping is investigated since it is the determining factor for addressing energy costs that is the largest operating expense of many water utilities next to infrastructure maintenance and repair costs (Walski et al. 2003).

Study two: budget analysis

The economic comparison of design alternatives is a key element of the final choice. Nevertheless, the economic issue in itself is the most debatable part of the entire project (Trifunović 2006). For this reason, the second study explores impacts of peaking factors estimation on budgets.

At this stage, the corresponding changes on pipes delivery and laying costs as well as energy consumption of various planning schemes generated through using different groups of peaking factors are examined. Without modifying the network layout however, the replanning only adjusts pipe configuration wherever necessary. The reference for calculating costs of delivery and laying is cited from Mutschmann & Stimmelmayr (2007) (Table 2).

Admittedly, the cost considered in this task is only a small part of the total investment, whereas, the tendency of budget variation with respect to different peaking factors can also be indicated to some extent from this analysis.

Five groups of peaking factors are specified for this test. At the planning stage, the hydraulic analysis and fire flow analysis are both carried out for each case based on model simulation in order to ensure the pipe configurations are well designed. Then budgets were calculated according to the network layouts of the five cases. Comparisons are implemented on costs of pipe layering and delivery as well as energy consumption.

It is worth noticing that, within the two analyses, the role of buffering reservoirs is not considered since this research focuses on exploring system-specific impacts of peaking factors on the water distribution system without

Table 2 | Costs of delivery and laying

| Ductile cast iron pipe, with Tyton (a trademark) joint, purchase quantity over 10 t, delivery and laying |
|---------------------------------------------------|---------------------------------|-----------------|----------------|----------------|----------------|----------------|----------------|
| DN                                                | 80                             | 100              | 150            | 200            | 250            | 300            | 400            | 500            |
| Weight (kg/m$^3$)                                 | 15.1                           | 18.5             | 27.3           | 37.4           | 49.5           | 62.7           | 94.2           | 128.9          |
| Delivery and Laying (€/m)                         | 33                             | 38               | 55             | 75             | 95             | 115            | 175            | 250            |
|                                                   | *Weight per meter including sockets. |
considering all possible influencing factors. However, further study, looking at more contributing factors and their importance, will be in progress.

RESULTS AND DISCUSSION

Water age and energy consumption

As Figure 6 illustrates, in this specific water distribution network, the average water age decreases with increase of average water demand. The correlation between the change rate of demand (D) and the change rate of average age (A) is a monotonic decreasing curve. Namely, the demand drops when peaking factors chosen at design stage are lower than actual values in operation, and consequently slows down the overall velocity along pipes which leads to system-wide water age deterioration, and vice versa. In addition, another noteworthy point is the ratio of A to D. For this system, variation amplitudes of water age oriented by water demand reduction are apparently higher than its changing magnitudes due to demand increase. In particular when water demand declines to a certain degree, A is significantly larger than D. For instance, water age variation is near 70% when demand change reaches to about −50% (a ratio of 1.44). Nevertheless, in situation with a demand increase of 41.5%, water age response is not that sensitive as only −24% of A is witnessed (a ratio of 0.58).

Contrary to water age, energy consumption goes up with the rise of water demand (Figure 7). This is because the energy losses in the water network become larger as a result of increasing water flow transported. Similarly, variation amplitudes of energy consumption oriented by water demand reduction are apparently higher than its changing magnitudes due to demand increase as well. In terms of the ratio, the corresponding change rate of energy consumption (E) is always smaller than change rate of demand (D). For example, E is less than 18% when D is as high as 30%.

Budget analysis

With regard to pipe delivery and laying, two diagrams were created according to budget calculation results listed in Table 3. The diagram in Figure 8 demonstrates a definite increase of the investment as the peaking factors grow. It can be observed that probably the plot is comprised of two segments. At the first segment, the cost increase is almost linear with the increase of peaking factors. Yet it becomes rather limited at the second segment as the plot is nearly flat, especially between Case 3 and Case 4.

This fact indicates that the cost will not increase dramatically in some cases even though there is a comparatively greater change on peaking factors. As proved by the costs listed in Table 3, the budget of Case 4 is merely 2,000 Euros (0.22%) more than in Case 3. This small extra cost can lead to a remarkable improvement in the overall capacity of the water distribution system, by amplifying

<table>
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<th>Case</th>
<th>$f_h$</th>
<th>Cost (Euros)</th>
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<tr>
<td>1</td>
<td>2.2</td>
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<td>2</td>
<td>3.41</td>
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</tr>
<tr>
<td>3</td>
<td>4.24</td>
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<tr>
<td>4</td>
<td>5.5</td>
<td>905,100</td>
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<tr>
<td>5</td>
<td>6</td>
<td>927,300</td>
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</table>
Therefore, it could be feasible to increase the investment on piping slightly which in turn improves the capacity of a network significantly. However, attention should be paid to possible corresponding negative impacts on the system behaviour, water age in particular. Similarly, another research carried out by Todini (2000) also demonstrates that the performance of a water distribution system can be considerably improved with a slight increase in the cost. Even though the highlights of the two studies are different, as the performance evaluation in the latter study was based on an originally defined resilience index, both of the study results manifest the possibility of more efficient investment. However, further study should be done on this issue by testing more cases in order to acquire a larger amount of available statistics and then discover all the hints behind data.

**CONCLUSION**

In the study one carried out in this paper, negative effects on water age are observed if peaking factors used at design stage are larger than ones in real case, and vice versa. For instance, water age would increase by near 70% when demand is reduced by 50%. In contrast, energy consumption will increase if peaking factors defined for system design are smaller than ones in real case, and vice versa. For example, energy usage has an increase of 18% when demand is about 30% higher.

In terms of economic aspects, it might be possible to increase the investment slightly which in turn may improve the capacity of a network significantly, given the results of study two. However, attention should be paid to possible corresponding negative impacts on the system behaviour, especially water age as discussed in the first study.

As for the outlook, the first issue could be focused on how to achieve an overall evaluation of schemes derived from different peaking factors. However, since the planning of a water distribution system is a multi-objective program, which considers many factors such as hydraulic, water quality, economic aspects, operation and maintenance practices etc., the overall evaluation of a water distribution system is still impossible. With regard to the budget analysis, this issue is worth a further study. Various combinations
of peaking factors could be used to obtain more cases, which would provide a much larger amount of available data. Consequently, more valuable information hiding behind the data may possibly be revealed.

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REFERENCES


