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Preliminary Estimation of Spatial and Temporal Synchronization of Water Demands in the City of Tripoli

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Abstract: Water supply systems represent an essential component of the infrastructure in urban populations worldwide. Water distribution systems are designed by sizing system components so that they meet current and future demands to be provided at minimum required levels of water pressure and quality. The sizing of pipelines is highly dependent on the amount of water demands allocated to distribution nodes of the system under consideration. The current demand allocation practices normally imply that there is perfect spatial synchronization among the aggregated demands, which is not essentially the case in practice. However, the way users react in real-world systems highly depends on many factors that differ from one user to another such as social habits and financial constraints. Recent studies anticipated that low levels of spatial demand synchronization can result in significant savings of the capital cost of water supply systems. In this paper, an investigation on the actual demand spatial synchronization is carried out using field measurements of diurnal demand patterns for different users in a residential area located in the city of Tripoli. Results showed that users react independently and the correlation is far away from the perfect case.

Key words: water demand synchronization, demand cross-correlation, diurnal demand pattern

1. Introduction

The performance of a water distribution network, whether it is an existing or newly designed, highly depends on an accurate estimation of water demands such that estimated demands during the design stage could be considered similar to those evaluated in the constructed network. This similarity can ensure that the network is properly sized at an acceptable cost and acceptable levels of pressures during peak and off-peak periods. Accordingly, it is crucial to obtain an accurate picture of how the demands are distributed and allocated to nodes before a water distribution network is built or rehabilitated. This requirement is challenging to simulating networks for extended periods as it becomes essential to represent spatial patterns of demand across network nodes for peak and off-peak periods.

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The effect of the spatial correlation of demands on the hydraulic performance and cost of water distribution networks have been an active subject among a number of researchers. A chance-constrained optimization model developed by Tolson et al. [6] was applied to a simple network. The study showed that, for a fixed level of hydraulic reliability, network cost increases with the level of cross correlation between demands. Additionally, the results of Tolson et al. pointed out that a higher level of cross correlation between network demands has the effect of producing larger fluctuations in nodal pressure accompanied with more frequent low-pressure failures. The results of Tolson et al. were confirmed by Kapelan et al. [5] and Babayan et al. [1] by the development and testing of multi-objective evaluation models to the New York tunnels problem under correlated demands. Both studies showed that correlated demands increases a network cost at a fixed level of hydraulic reliability.

Filion et al. [3, 4] extended the previous study by conducting a systematic correlation analysis to gain a better understanding of the relationship between correlated demands, network cost, and hydraulic performance. The results of these studies showed that, in systems without tank storage, the level of cross correlation between nodal demands is proportional to variability of nodal pressures. In other words, higher levels of cross correlation between nodal demands result in a larger variation in pressure or the standard deviation of nodal pressures is sensitive to the level of demand cross correlation. Network cost is also found to be sensitive to the level of cross correlation between demands at a fixed level of hydraulic reliability. Accordingly, higher levels of demand correlation produce a higher network cost if a desired level of hydraulic reliability is to be maintained against larger pressure fluctuations.

Filion et al. [4] investigated the cross correlation between demands in an existing system by analyzing the cross correlation in the residential demand data collected in the city of Milford, Ohio. A periodic regression model was used to isolate the deterministic and the random noise components from the residential demand data collected in Milford. The main findings of this study were: 1) Both residential demand and its deterministic, diurnal component had a positive and moderate to high correlation, while the random noise component of demand had a low level of correlation for the cases investigated; 2) Increasing the time step length (from 600 s to 3,600 s) did increase the strength of the correlation in residential demand and its deterministic, diurnal component; 3) Both residential demand and its deterministic, diurnal component were more strongly correlated during weekend periods than during weekday periods.

The aim of this paper is to investigate the cross correlation of demand in a real system. To do this, indoor residential demand data were collected from 20 single-family residences in the city of Tripoli, Libya. Then, the collected data were analyzed for cross correlation in an attempt to answer an important question: how strongly cross-correlated indoor, residential demands within the city of Tripoli are? To the best of the authors' knowledge, this question has not been investigated or explored yet.

The results of the study suggest that cross correlation analysis should be carried out to accurately model network for better hydraulic performance and to achieve more cost-effective designs. More importantly, these results are still preliminary and further investigations need to be conducted to find out how representative such findings are for real systems.

The paper is organized as follows: the methodology of cross correlation analysis is described. The correlation index used to measure the cross correlation of residential demand is presented. Then, the collected demand data is analyzed for cross correlation. The paper concludes by placing the correlation results into the context of the accuracy network modelling.

2. Material and Methods

The method of study was first started by instantaneously collecting data for residential water demands in a residential area at the East part of the city of Tripoli, Libya. Twenty single-family houses were randomly selected and numbered from 1 to 20. The reason for selecting this area was that the houses equipped with metering devices, which are not the case in different areas of the city. For the purpose of collecting continuous data with high-resolution of time intervals, recording video cameras were installed on the service pipe for each house within the month of October 2017. The recording process lasted for 24 hours and carried out simultaneously for all sample houses. Then, these indoor residential demand data were converted into single rectangular pulses with one hour time interval each by aggregating the water demand consumed within this selected interval. The water demands were averaged and demand multipliers were calculated with respect to the average demand. A diurnal demand pattern that relates the demand multiplier to the corresponding time interval was determined for each house. To visually investigate the cross correlation among all sets of residential houses, all demand patterns were plotted together. The cross correlation was quantified by calculating the correlation coefficients for recognized minimum, maximum, and average time shifts of peak multipliers. This is to demonstrate how strongly water demands are cross correlated. Finally, all demands were aggregated to explore whether such demands could be represented by a single pattern or not.

3. Concept of Cross Correlation

Since this paper uses the idea of cross correlation, a brief explanation and definitions on the concept of cross correlation is described. The term cross correlation defines the interdependence between two spatial variables *X* and *Y*, at a particular point of time. When applied to water distribution systems, *X* might represent the value of demand at a particular node, and *Y* represents the value of demand at an adjacent or distant node. The degree of interdependence, or correlation, between *X* and *Y* is measured by the coefficient of cross correlation, or the average product of normalized pairs of deviations of *X* and *Y* from their respective mean values μ_X and μ_Y, such that

$R = (1/m) \sum (x_i - \mu_X))\sum(y_i - \mu_Y)/s_X\, s_Y$ for all $i \in [1,m]$ (1)

where *R* is cross correlation coefficient of demand between *X* and *Y*; and s_X and s_Y are respectively standard deviations for *X* and *Y*. Equation (1) indicates that the covariance of *X* and *Y* is calculated with *m* pairs of x_i , y_i values. When the values of the demands *X* and *Y* are large or small at the same time (peaks are synchronized), the product of their respective deviations in Eq. (1) is positive and they are said to be positively correlated. Similarly, when large *X* values occur with small *Y* values or vice versa (Peaks are in distant), the product of their respective deviations in Eq. (1) is negative and they are said to be negatively correlated. In case their covariance is zero, *X* and Y are said to be independent and no high–low relationship exists.

4. Results and Discussion

The collected indoor demand data of the selected houses were converted into diurnal demand patterns as described previously. Fig. 1 shows a combination of all demand patterns each represents an indoor demand of the corresponding house. Interestingly, all demand patterns are characterized by having 5 peaks of demand. The highest demand peak has a multiplier of 6.2, while the lowest peak has a multiplier of 2.5. This difference could be attributed to the size of family members that significantly differ from one house to another. Clearly, demand peaks suggest classifying the patterns into two groups. The first group (Fig. 2) appears to have synchronized peaks and thus the cross correlation among them is strong. The synchronization is not only among the peaks but also among zero demand periods. The similarity of the demand patterns herein suggests that such families have similar daily activities but different family sizes. The peaks of the second group (Fig. 3) are shifted in different times throughout the day time indicating that the cross correlation among this group is weak. The time shifts of peaks suggest that the family members have different daily activities among the group. Additionally, the patterns of this group refer to the absence of zero demand periods. This might be attributed to that the members of such families have night and day work shifts.

Fig. 4 shows a diurnal demand pattern after aggregating all of the demand patterns. This is a common practice in network modeling to represent all users with a single pattern. In real systems, such pattern can be obtained by installing a metering device at the pipe emerging from the supplying source. Expectedly, the demand peak in the aggregated demand pattern is attenuated to 2.3, which reflects averaging the peak demands among all of the patterns. This is because single demand peaks are not synchronized and, when superimposed, the contribution of low peaks to high peaks attenuates the aggregated peak. The five peaks of demand are visible after demand accumulation. This suggests that users of such houses have similar daily activities during peak times. However, they differ in periods with zero demand that is evident from the absence of such periods in the aggregated pattern.

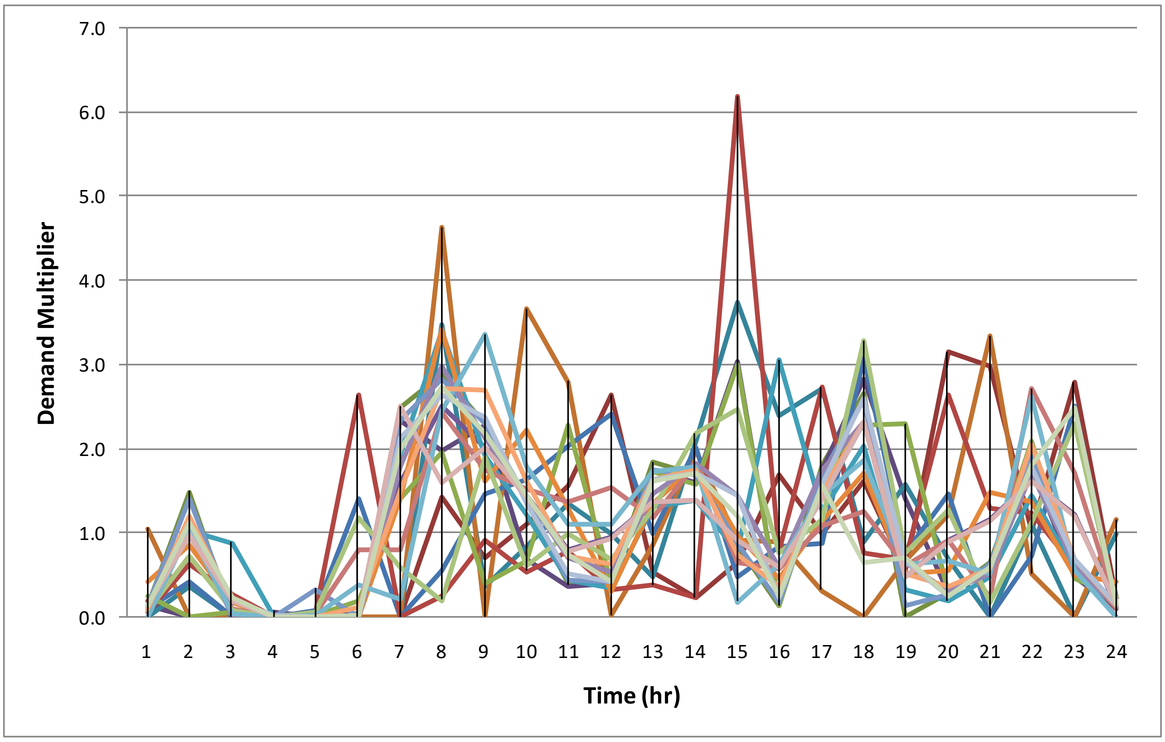

Fig. 1 Diurnal demand patterns for all samples.

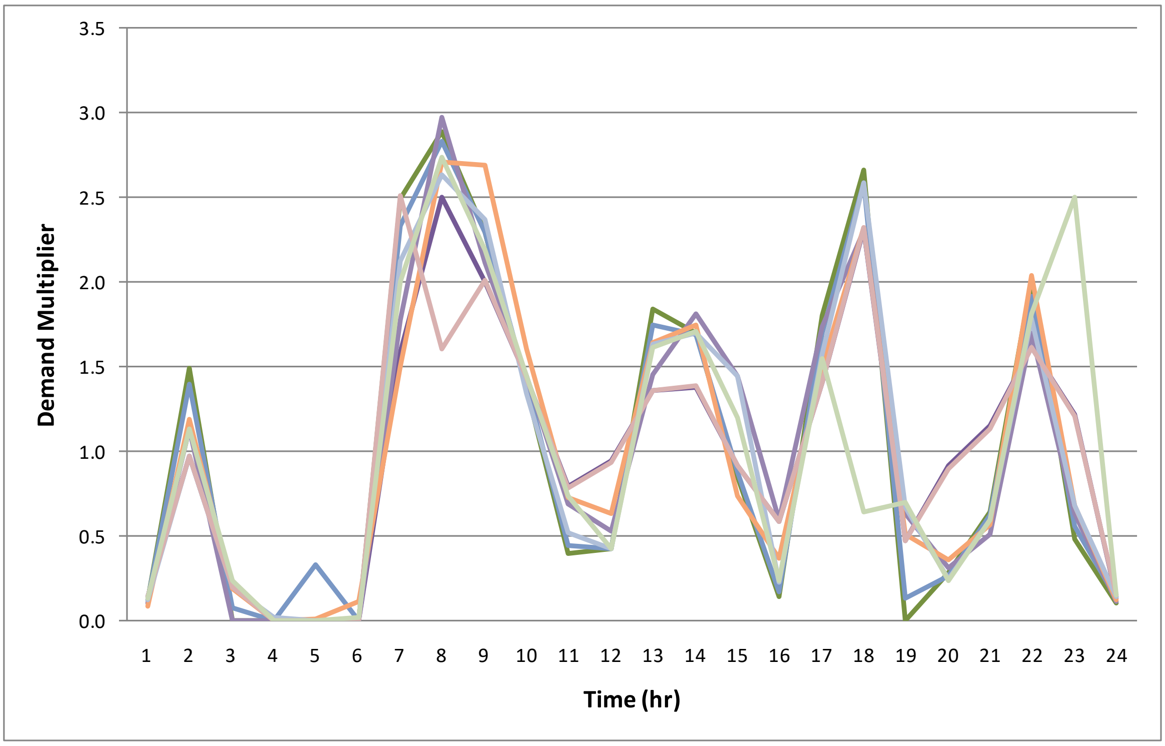

Fig. 2 Group 1 of Diurnal demand patterns.

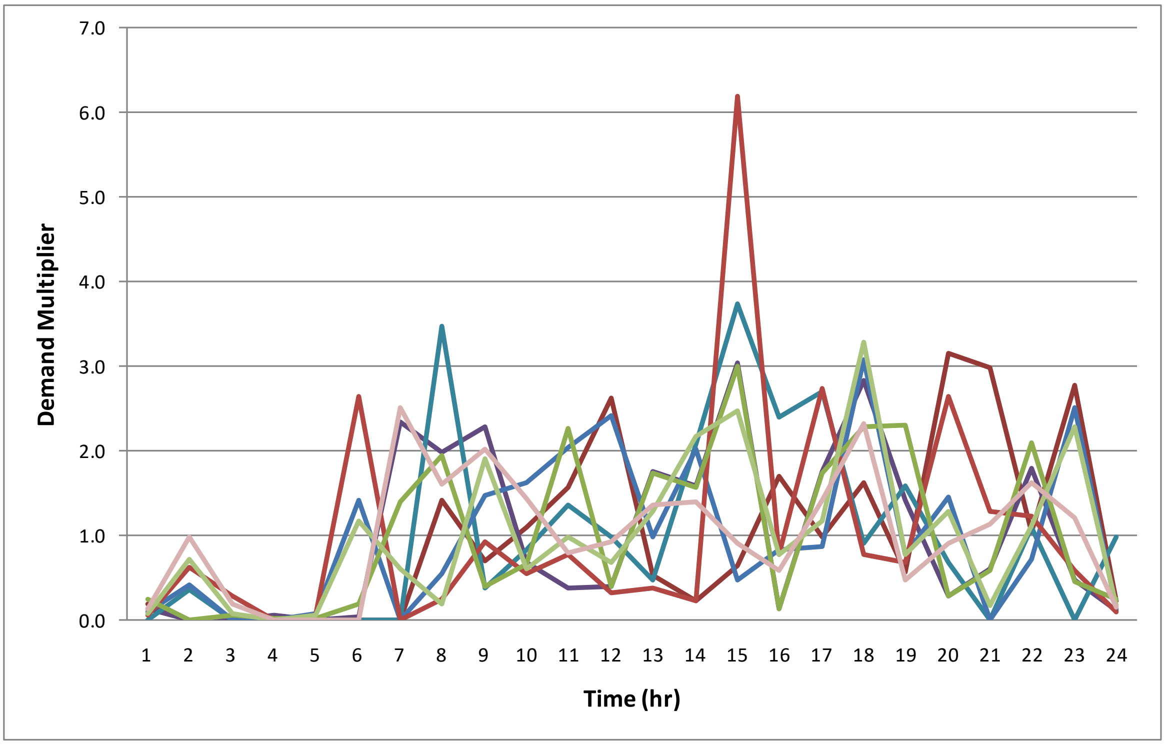

Fig. 3 Group 2 of Diurnal demand patterns.

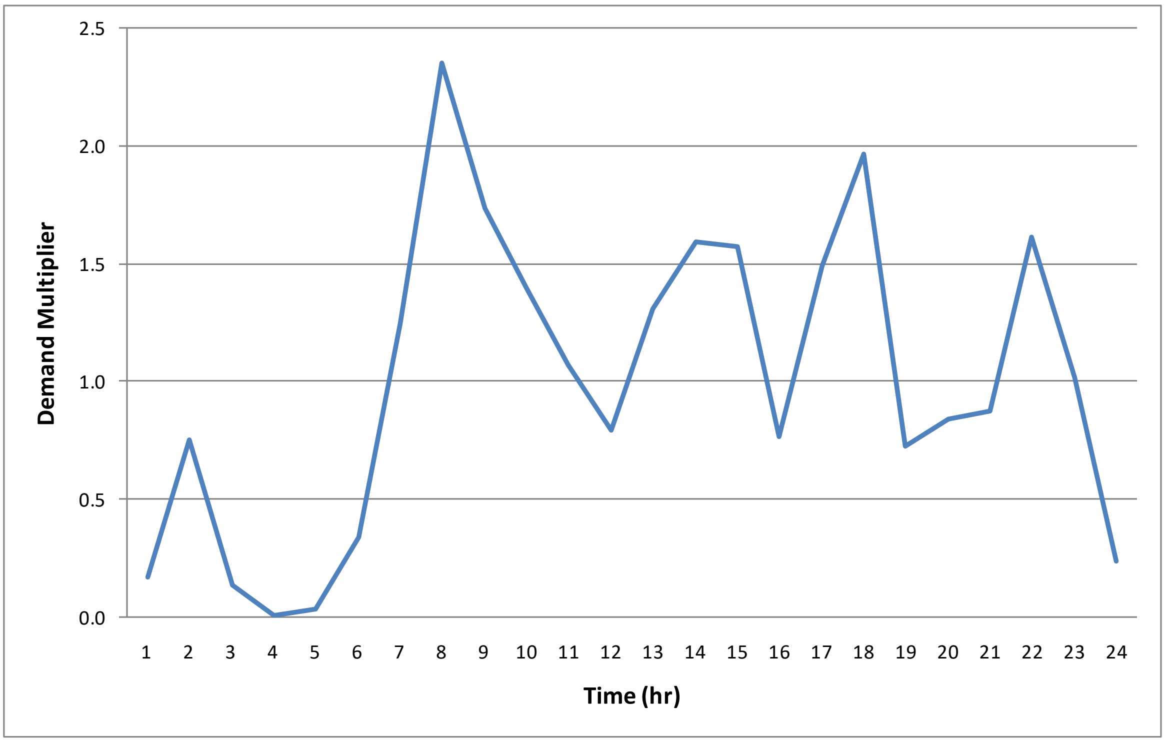

Fig. 4 Aggregated demand patterns

Table 1 shows the cross correlation analysis of the collected data of indoor residential demand for all of 20 cases. Each demand pattern was correlated to the rest of patterns and, due to lack of space, only minimum and maximum values of correlation coefficients were shown. For instance, R_1 shows the maximum and

Table 1 Cross-correlation coefficients of all demand patterns.

Coefficient of cross-correlation	Minimum value	Maximum value
R_1	-0.05798	0.56502
R_2	0.18221	0.98238
R_3	0.03826	0.89072
R_4	0.07811	0.69337
R_5	-0.04712	0.77694
R_6	-0.00754	0.74682
R_7	0.00954	0.55940
R_8	0.31127	0.65335
R_9	0.56935	0.99990
R_{10}	0.39383	0.83823
R_{11}	0.38379	0.90462
R_{12}	0.40217	0.97874
R_{13}	0.40284	0.86114
R_{14}	0.39202	0.59012
R_{15}	0.77759	0.97827
R_{16}	0.71514	0.89821
R_{17}	0.81264	0.95727
R_{18}	0.78781	0.89671
R_{19}	0.73415	0.73415

minimum values of correlation coefficient between pattern 1 and the rest 19 patterns. Obviously, the correlation in all cases is far from the perfect case among all of the patterns. Moreover, some correlation coefficients have negative values suggesting that there is no correlation at all. The weakest correlation was found between patterns 1 and 2 with minimum and maximum values of -0.05798 and 0.56502 respectively.

Interestingly, the perfect correlation does not exist herein and the nearest value is 0.9999 between patterns 1 and 9. These two patterns have correlation coefficients ranging from 0.56935 to nearly perfect correlation at 0.9999. Evidently, the correlation between patterns improves from This result has possibly two implications. First, the assumption that synchronization between network demands exists need to be reconsidered in network modeling. This means that applying a single peaking factor to all network demands in extended period simulation need to be re-evaluated. Further analysis is highly required to confirm such a conclusion. Second, should this is the case in real systems that demands are not strongly cross correlated (cross correlation coefficient is far away from the perfect case of +/-1.0), it may be necessary for water utilities to conduct a cross correlation analysis. This is to better increase the accuracy of network modeling for design and rehabilitation work. From economical viewpoint, increasing the accuracy between demands estimated in design stage and those observed in the real system could help utilities save design costs by building smaller pipe sizes and other network components. Additionally, establishing accurate demand patterns could help reduce the implications of underestimated design in avoiding low pressure zones.

5. Conclusion

This paper has focused on analyzing the cross correlation in indoor residential demand data collected in the city of Tripoli, Libya. The aim of the paper has been to investigate the answer to the following question: how strongly residential demands in the Tripoli system are cross correlated? To begin the answer to this question, continuous demand data was first collected from a residential area in the city. The demand data are then converted into diurnal demand patterns. The cross correlation coefficient is used to measure the cross correlation between residential demands. The preliminary finding suggests that cross correlation between residential demands is well away from the perfect case. This indicates that the assumption of synchronization between residential demands needs to be re-evaluated and thus cross correlation analysis should be carried out to accurately model networks in design and rehabilitation works. Further analysis is required using larger number of samples to confirm these preliminary results.

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