Probabilistic analysis and evaluation of nodal demand effect on transient analysis in urban water distribution systems

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Abstract

The implementation of nodal demands in current transient modelling and analysis in the urban water distribution system (WDS) is usually based on steady-state conditions or empirical-based approximations, lacking for appropriate evaluation and scientific guidance of the nodal demand effect on transient modelling and analysis for accurately reproducing transient responses. This paper develops a probabilistic analysis and evaluation framework based on Monte-Carlo simulation (MCS) and global sensitivity analysis (GSA) methods for prior-known evaluation of transient nodal demand effect in WDS. An expression of the demand impact factor (DIF) is firstly proposed for indicating the influence of nodal demand effect based on a

Lagrangian nodal demand model and implemented in the developed evaluation framework. Parameter sensitivity analysis is then conducted to evaluate the relevance and importance of DIF to transient modelling and analysis in WDS. The results indicate that the DIF is highly relevant to the inherent attributes and initial steady state of the system, which can thus be used to facilitate the prior-known evaluation of the importance and influence of nodal demand effect in WDS. To demonstrate the application procedure and the applicability of the proposed probabilistic method, a realistic WDS is adopted for numerical investigation. The application results and analysis confirm the effectiveness and improvement of the developed method in this study on the guidance of accurate transient modelling and analysis under the influence of nodal demands in WDS.

Authors' Keywords: Water distribution system (WDS); transient; nodal demand; probabilistic analysis; demand impact factor (DIF); sensitivity analysis

Introduction

Hydraulic transient or waterhammer, which is usually caused by the fast change of flowrates in the fluid conveying system, has become one of crucial issues encountered in practical systems. For urban water distribution system (WDS), transient theory and practice have been developed for many decades (Ghidaoui et al. 2005). To date, many different methods and tools have been proposed, which are proved to be effective and useful, for the analysis and evaluation of transient pipe systems in the literature (e.g., McInnis and Karney 1995; Brunone et al. 1995; Ramos et al. 2004; Vítkovský et al. 2006; Duan et al. 2009; Brunone and Berni 2010; Lee et al. 2013). With these methods and tools, appropriate devices and pipeline construction schemes could be designed appropriately for the protection of the system under potential transient conditions. In practical applications, however, clear discrepancies of transient responses between numerical simulation results by these methods/tools and field data by measurements were observed commonly in previous studies, especially for realistic and complex pipe networks (e.g., McInnis and Karney 1995; Stephens 2008; Duan et al. 2010; Ebacher et al. 2011; Meniconi et al. 2014; Duan 2015; Rathnayaka et al. 2016). This may be due to: (1) the inaccuracy of current physical models such as unsteady friction or turbulence model for representing the mechanism and process of transient events; and (2) the perceived imperfect representation of realistic networks in transient models (e.g., system skeletonization). These two aspects of research progress and achievements are discussed in details as follows.

In the literature, many researchers have made substantial progress and achievements on improving the transient modelling accuracy and applicability (e.g., Vardy and Brown 1995; Brunone et al. 1995; Silva-Araya and Chaudhry 1997; Axworthy et al. 2000; Ramos et al. 2004; Zhao and Ghidaoui 2006; Duan et al. 2009, 2010, 2012; Kim 2011; Lee et al. 2013; Meniconi et al. 2014). Meanwhile, different uncertainties and influence factors commonly exist in practical WDS, which may affect greatly the applicability and accuracy of transient modelling and analysis. As a result, such system influence factors, if they are not well represented and calibrated, may be wrongly attributed to the inaccuracy or inadequacy of current models and methods (Duan et al. 2010; Duan 2015, 2016). One potential source involved among these influence factors is the nodal demand transformation during system skeletonization, which may be easily overlooked and irrationally aggregated for transient applications. Therefore, it is necessary to investigate the importance and impact of such nodal demand uncertainty resulted from the skeletonization to the transient modelling and analysis, which is the scope of this study.

In the context of steady-state flow model, nodal demand is treated as a conceptualized attribute of connection node in WDS, which represents a collection or aggregation of all water consumptions along the pipelines connecting to that node in order to reduce the complexity of the steady model. With the state of the art of hydraulic modelling, the nodal demand is usually considered as pressure-dependent demand or head-driven demand, such as the parabolic head-discharge and the standard orifice-based model proposed in the literature (Gupta and Bhave 1996; Ang and Jowitt 2006; Zheng et al. 2013; Diao et al. 2015). While under transient conditions, this steady-state based inherent relationship between demand and pressure, e.g., represented by the head-driven demand model, is still assumed to be valid and commonly adopted in previous studies and application works for transient modelling and analysis. Particularly, McInnis and Karney (1995) raised the relevant question in terms of nodal demand representation/simulation effect on transient behaviors, in which they attempted three demand models, including a constant demand model, an orifice-based demand model (or head-driven demand model) and a distributed pipe flux demand model. Thereafter, Karney and Filion (2003) implemented consumptive demand concept and their results indicated the potential importance of nodal demand representation to the accuracy of transient analysis. Among these different treatments, the head-driven demand model has been thought to be most suitable one, and thus widely used for transient modelling and analysis in the literature (Jung et al. 2009; Ebacher et al. 2011; Rathnayaka et al. 2016). Consequently, the head-driven demand model is also adopted herein as the basis for the evaluation of nodal demand effect on transient analysis in this paper.

In addition to the nodal demand simulation, the transformation of demand consumption nodes in complex and large-scale WDS, which is usually in conjunction with the aggregation and/or skeletonization operations of the system, is another common factor that may affect the accuracy and efficiency of hydraulic modelling (steady and transient). Currently, the steady-state based system skeletonization including demand node transformation method has been widely used for transient situations, which has raised many cautions from the researchers in this field (e.g., Walski et al. 2004; Jung et al. 2007; Edwards and Collins 2013; Gad and Mohammed 2014; Meniconi et al. 2015; Haghighi 2015). Despite of the common use of this approximate treatment in practice, it has been demonstrated in previous studies that the accuracy of the transient modelling and analysis could be greatly affected due to inappropriate transformation of demand nodes during system skeletonization in realistic WDS (McInnis and Karney 1995; Ebacher et al. 2011; Rathnayaka et al. 2016). Unfortunately, so far there is not yet a general guidance on such demand node transformation and system skeletonization for accurately reproducing transient responses. On this point, it is practically important to investigate the impact of nodal demand transformation during system skeletonization operations on transient responses in WDS, which is also the objective of this study.

This paper intends to characterize the nodal demand effect on transient response and wave propagation in pipe networks, in order to develop an applicable evaluation method to predict and quantify the nodal demand effect on transient modelling and analysis prior to the application of demand node transformation involved within system skeletonization for transient modelling and analysis, which is thus termed as prior-known evaluation of nodal demand effect in this paper. To this end, an expression of the demand impact factor (DIF) is firstly derived in this study based on a Lagrangian model, which is used as the key parameter later in the evaluation process of transient modelling and analysis. A probabilistic analysis and evaluation framework based on the Monte-Carlo simulation (MCS) and global sensitivity analysis (GSA) is then developed for the prior-known evaluation of the influence range and importance of nodal demand effect from the nodal demand transformation for system skeletonization to transient analysis in the system. To validate the proposed method and demonstrate the application procedure, a realistic WDS is adopted for the numerical investigation. Finally, the results and findings of the study are discussed for the guidance and implications of transient modelling and analysis under the influence of the nodal demands in practical WDS.

Models and Methods

The one-dimensional (1D) waterhammer model has been widely developed and used for practical transient modelling and analysis in WDS, which is adopted in this paper for the numerical study, with the model details referred to the classic references (e.g., Chaudhry 1987; Wylie et al. 1993; Ghidaoui et al. 2005). In this section, the transient nodal demand model and the expression of nodal demand effect in pipe networks as well as the analysis and evaluation methods are briefly introduced as follows.

Transient Nodal Demand Model and Demand Impact Factor

Partial transmission and reflection of pressure waves at pipe connection nodes (i.e., nodal junctions) is known as the typical characteristics of transient flows in pipe networks, such that the transient signal becomes progressively complicated due to various wave superimpositions in WDS (Chaudhry 1987; Ferrante et al. 2009). The pressure change (transmitted or reflected transient pressure) at a node boundary for different incident pressure waves can be generally expressed in the Lagrangian form as (Wood et al. 2005)

$$\Delta H^{t} = \sum_{k=1}^{N} S_k \Delta H_k^{t-} \tag{1}$$

where ΔH^{t} represents the instantaneous pressure change at the node (i.e., immediately after the wave reflection/transmission); ΔH_k^{t-} indicates the incident pressure wave from the *k-th* connected pipe-section before the wave arrives the node; N is the total number of connected pipe-sections at the node; $t-$ indicates the ultimate instant before the overlap/superposition of different incident waves; $S_k = (2A_k/a_k) \big/ \sum_{l=1}^{N} (A_l/a_l)$ is the transmission coefficient at the node for *k-th* pipe section (Chaudhry 1987); A is pipe sectional area; and a is wave celerity. In the literature, Eq. (1) is useful and commonly applied to evaluate transient wave-junction interaction in pipe fluid systems. However, Eq. (1) is only valid and applicable to the system conditions of no external flows through the node (i.e., without nodal demand) and no energy dissipation at the nodal junction. For the case of external flows at the node, Eq. (1) can be extended accordingly in this study, and the final result is,

$$\Delta H^{t} = \sum_{k=1}^{N} S_k \Delta H_k^{t-} - \frac{1}{g\sum_{l=1}^{N}(A_l/a_l)} \Delta q^{t} \tag{2}$$

where Δq^{t} is the nodal demand change during the pressure waves transformation at the node; and g is the gravitational acceleration. As a result, Eq. (2) is a Lagrangian form of general nodal demand model for transient analysis, which characterizes the pressure change resulting from the nodal transformation of pressure waves. Particularly, Eq. (2) considers both effects of nodal demand changes and incident wave transmissions/reflections, and thus can give a general and accurate description of the pressure change at a demand node than original Eq. (1).

To better analyze the influence of the nodal demand effect, the expression of Eq. (2) can be further re-written in following form:

$$\Delta H^t = \Delta H^t_{psd} - \Delta H^t_q \tag{3}$$

where $\Delta H^t_{psd} = \sum_{k=1}^{N} S_k \Delta H_k^{t-}$ represents the pressure change part due to the superposition of incident waves at node, which is defined as pseudo pressure surge in this study; and $\Delta H^t_q = \Delta q^t \Big/ \left(g \sum_{l=1}^{N} \left(A_l / a_l \right) \right)$ is the pressure change part resulted from the nodal demand change, which is defined as the node pressure disturbance in this study. With this separation, Eq. (3) clearly demonstrates that the pressure change at a demand node is actually the pressure head difference between the pseudo surge and the node disturbance, and therefore, explains the attenuation effect of nodal demand on transient pressure wave as widely evidenced in the literature. Consequently, the ratio of the nodal disturbance and pseudo surge from Eq. (3) is defined as the demand impact factor (DIF) in this study,

$$E^t = \frac{\Delta H^t_q}{\Delta H^t_{psd}} = \frac{1}{g \sum_{l=1}^{N} \left(A_l / a_l \right)} \frac{\Delta q^t}{\Delta H^t_{psd}} \tag{4}$$

which actually characterizes the effect of nodal demand on transient wave propagation. Meanwhile, considering the head-driven demand model in transient analysis (Mcinnis and Karney 1995; Jung et al. 2009), in which the relation between the nodal demand (q) and pressure (H) is taken as $q = C_q H^{\alpha}$, the nodal demand model in a Lagrangian form and the DIF could be refined as follows:

$$\Delta H^t = \Delta H^t_{psd} - \frac{C_q}{g \sum_{l=1}^{N} \left(A_l / a_l \right)} \left[\left(H^{t-} + \Delta H^t \right)^{\alpha} - \left(H^{t-} \right)^{\alpha} \right] \tag{5}$$

$$E^t = \frac{C_q}{g \sum_{l=1}^{N} \left(A_l / a_l \right)} \frac{\left(H^{t-} + \Delta H^t \right)^{\alpha} - \left(H^{t-} \right)^{\alpha}}{\Delta H^t_{psd}} \tag{6}$$

where C_q is an "equivalent orifice" emitter coefficient of nodal demand; α is exponential index; H^{t-} is the prior transient pressure at the node before the overlaps of all incident pressure waves. Note that the exponential index α is variable depending on many factors, e.g., pipe material, orifice shape, surrounding soil, etc. Besides, this orifice-based relation assumption is subjected to system uncertainties in practice, e.g., the "equivalent orifice" scale for actual demands may change in different time-scale of transient conditions, the micro-transients generated by opening and closing valves at home may introduce disturbance to the nodal demand model. However, the exponential index α is usually taken as 0.5 for practicability and simplicity consideration, with the orifice emitter coefficient $C_q = q_0 / H_0^{\alpha}$, in which q_0 and H_0 are the initial nodal demand and pressure, respectively (McInnis and Karney 1995; Jung et al. 2009; Ebacher et al. 2011).

It is also worthy of noting that the defined DIF above can be easily incorporated into numerical schemes for transient modelling, such as the commonly used Method of Characteristics (MOC). For example, an explicit method is applied in this study to calculate transient pressure (i.e., the pseudo pressure, $H_{psd}^{t} = H^{t-} + \Delta H_{psd}^{t}$), by assuming that the nodal demand at current calculation time step is same as that at previous time step. As a result, the instantaneous DIFs for all the demand nodes in the pipe network from this MOC-based scheme can then be assessed by Eqs. (3) and (4).

Probabilistic Analysis and Evaluation Framework

The application of the above transient nodal model and DIF analysis in practical WDS usually subjects to different variations and uncertainties (e.g., due to demand node transformations in different levels of system skeletonization), such that the influence of nodal demand effect on the transient analysis for a specific system is usually either overestimated or underestimated. Therefore, it is necessary to systematically analyze the nodal demand effect in WDS based on the transient nodal model and the DIF defined above in this study. To this end, four following parameters related to the nodal demand effect, i.e., demand coefficient (C_q), connected attribute ($\sum_{l=1}^{N}\left(A_l/a_l\right)$), pseudo surge ($\Delta H_{psd}^{t}$) and prior pressure ($H^{t-}$), are considered for the parametric analysis in this study. The framework for probabilistic analysis and evaluation of nodal demand effect on transient analysis is developed in this study, as shown in Fig. 1. Within the framework, the Monte-Carlo simulation (MCS) and the global sensitivity analysis (GSA) methods are utilized for parameter sensitivity analysis, in order to explore the stochastic characteristics of the nodal demand effect and the inherent sensitivity of the DIF with respect to different parameters (Duan et al. 2010; Duan 2015, 2016); then a prior-known evaluation method is developed based on the results of sensitivity analysis to facilitate the practical implication of nodal demand transformation in transient modelling and analysis.

For MCS, a total number of 100,000 runs for each analysis is conducted for MCS to obtain enough results for statistical analysis (Tung et al. 2006). For GSA, both the elementary effect method (also termed as Morris screening method) and the variance-based method (also termed as Sobol' method), which are frequently employed in the field of hydrosystems (Neumann 2012; Song et al. 2015), are utilized for sensitivity analysis. These two GSA methods are combined and adopted in this study by taking advantages and characteristics of the low computational cost and qualitative ability for the elementary effect method and the robustness and quantitative ability for the variance-based method. For this purpose, the Matlab/Octave toolbox – Sensitivity Analysis for Everybody (SAFE), which is an open source program developed by Pianosi et al. (2015), is adapted and incorporated in the probabilistic framework used in this study.

Parameter Sensitivity Analysis

Prior to the application of the proposed nodal demand model and the defined DIF, it is important and necessary to systematically analyze the dependence of the nodal demand effect on different parameters in practical water pipe systems based on the proposed probabilistic and sensitivity analysis methods (MCS and GSA), so as to develop an efficient and prior-known evaluation method for better transient modelling and analysis in the realistic and complex WDS.

System Conditions and Parameters

Among the four parameters considered in this study, the first two, i.e., demand coefficient (C_q) and connected attribute ($\sum_{l=1}^{N}\left(A_l/a_l\right)$), are static ones, which are relevant to the inherent attributes and initial steady state of the system condition, and thus can be prior-known before the transient analysis and probabilistic evaluation; and the other two, i.e., pseudo surge (ΔH_{psd}^{t}) and prior pressure (H^{t-}), are dynamic ones which are time-dependent and fluctuating with the transient conditions, and thus have to be updated at each transient step for the calculation. In terms of uncertainties, the variation ranges of the factors associated to these parameters, including nodal demand, wave speed, topological structure and external exciter, are quite extensive in actual pipe networks, such that the variability for each of these four parameters becomes relatively large and scattered. In this study, the variation ranges of the two dynamic parameters (ΔH_{psd}^{t} and H^{t-}) are statistically estimated from rules of thumb in practical network models and projects. For instance, the general steady-state of networks gives a reference of intermediate value for prior pressure; the pressure sustaining capacity of pipe sections and the vapor pressure indicate the upper and lower limitations respectively for prior pressure; the combination of the potential surge by the Frizell-Joukwosky's equation and the general steady-state of networks can present a rough conjecture of the variation range for pseudo surge. The ranges of the two static parameters (C_q and $\sum_{l=1}^{N}\left(A_l/a_l\right)$) are extracted from the previous applications in the literature, with the details summarized in Table 1.

Furthermore, to fully utilize and better generalize the methodology and analysis results of this study, the variation ranges of the two static parameters are extended artificially with certain extents so that most typical cases of practical WDS can be covered from the current analysis. As a result, two sets of the variation ranges of parameters, termed as general and extended ranges respectively, are used and analyzed in this study, as follows:

- Demand Coefficient (C_q, $m^{2.5}/s$): General range: [1.0E-8, 1.0E-3]; Extended range: (0, 0.01)
- Connected Attribute ($\sum_{l=1}^{N}\left(A_l/a_l\right)$, $m \cdot s$): General range: [1.0E-6, 1.0E-3]; Extended range: (0, 0.01)
- Pseudo Surge (ΔH_{psd}^{t}, m): [-100, 0) ∪ (0,100]
- Prior Pressure (H^{t-}, m): [-10, 100]

It is also noted that a uniform distribution is assumed for all these four parameters for parametric analysis in this preliminary study, which is however not preventing the extension of the developed methods herein to other possible situations in the future study.

MCS-Based Results

With the MCS-based analysis for the above variation ranges of parameters, the profiles of cumulative density function (CDF) of the DIF for the general and extended ranges are shown in Fig. 2. It can be concluded that: (1) the distributions of the obtained DIF results for the general and extended range cases are very similar (nearly on top of each other), indicating the trends with a high density of low DIF and a sparse density of high DIF. Specifically, both results reveal about 96.7% realizations with the DIF below 10.0% and only about 1.6% realizations with the DIF over 20.0%; (2) the percentage of the DIF above 10.0% for both the general and extended cases is around 3.3% with the maximum DIF approaching to 100% (99.9% in this study). Consequently, these results indicate that the nodal demand effect has little impact on transient propagation for most cases, but it cannot be roughly overlooked as the relatively high DIF still exists for some extreme cases, which needs further analysis.

Figure 3 shows the detailed distributions of the obtained DIF with respect to the four parameters under the situation of general variation ranges, corresponding to MCS results and local variation results, respectively. Note that for a distinct illustration, the local variation for each parameter refers to the DIF results calculated through its variation range with other three parameters kept constant. According to the MCS results (scatters in the figures), the rankings of the relevance between the DIF and the four parameters are as follows: connected attribute, demand coefficient, prior pressure and pseudo surge, which indicates the DIF of demand node has significant relevance to the static properties (connected attribute and demand coefficient), but has little relation to the dynamic characteristics (pseudo surge and prior pressure). Similar result can also be obtained from the local variation calculations shown in Fig. 3.

Furthermore, the correlations between the DIF and different parameters can also be evaluated qualitatively from the local variation results in Fig. 3. Precisely, for the two static parameters with relatively high relevance, the demand coefficient is positively correlated with DIF while the connected attribute is negatively correlated with DIF. However, the correlations of the two dynamic parameters with little relevance are found to be either positive or negative depending on the system conditions and evaluation cases such as the pressure exponent α in Eq. (5) and the transient states. For example, for the selection of $\alpha = 0.5$ as adopted in this study, the prior pressure is negatively correlated with DIF when $H^{t-} \geq 0$ and positively correlated with DIF when $H^{t-} < 0$. Therefore, according to the analysis results herein, it is necessary and critical to analyze and confirm the variation properties of different system factors or parameters prior to the evaluation and analysis of the nodal demand influence.

GSA-Based Results

The MCS-based results above have provided the relevance between the DIF and different parameters, indicating the different important extents and rankings of the four parameters to the evaluation of the influence of nodal demand. In this section, the GSA is used to evaluate the sensitivity of the DIF to each of these parameters, with aiming to understand the dependences of the DIF on different factors and thus their influences to the transient analysis. Table 2 presents the GSA results with the elementary effect method and the variance-based method respectively. With the combined analysis of the results by these two methods, the sensitivity of the DIF can be systematically evaluated: (1) μ^* and S give qualitative and quantitative measures, respectively, of the importance of each parameter to the model output (DIF); and (2) σ estimates the nonlinearity and/or interactions between these input parameters, and S_T indicates the total effect of each parameter to the model output, which can be used to determine which of these parameters can be fixed for simplicity (factor fixing) during the transient analysis and nodal demand influence evaluation (Neumann 2012; Song et al. 2015).

According to the GSA results in Table 2, the importance orders of the input four parameters for both general and extended range cases by both analysis methods are as follows (see μ^* and S in the table): connected attribute, demand coefficient, prior pressure and pseudo surge. This result confirms again the previous MCS-based analysis of the relevance results between DIF and input parameters. The sums of first order sensitivity indices (i.e., S) in Table 2 explain 74.7% and 82.8% of the total variances for the general and extended ranges respectively, which demonstrates about 20% left for non-linear variance and parameter interactions, which indicates that the nodal demand model is non-linear or non-additive. Meanwhile, by referring to σ values in Table 2, the major contribution of the nonlinearity or non-additivity of the model is mainly due to the parameter of connected attribute for both general and extended range cases. Therefore, from this perspective, it can be concluded that the connected attribute factor is most crucial for the evaluation of nodal demand effect on transient analysis.

In addition, the two static parameters, connected attribute and demand coefficient, are the two significant influence factors with a cumulative contribution (S) of 73.8% for the general range and 81.4% for the extended range, which means these two parameters account for the vast majority in the variation of the DIF. For the two dynamic parameters, which are prior-unknown to the analysis, a total contribution of 17.7% and 14.3% to the sum of S_T is obtained for the general and extended ranges, respectively. On this point, it is preferable and acceptable to fix these two dynamic parameters to evaluate the transient model outputs in order to achieve the prior-known evaluation. The detailed influence of fixing these factors to the evaluation of nodal demand effect is discussed in the next section.

Prior-known Evaluation of Nodal Demand Effect

The MCS and GSA results above have indicated the uneven distribution characteristics of the DIF with variations of the four input parameters, in which the two static parameters, especially connected attribute, may have an overriding total contribution (over 80%) in the variation of DIF result. Therefore, the prior-known evaluation for the nodal demand effect with these two static parameters only is analyzed in this section for its accuracy and validity. For simplicity, the ratio of the two parameters (demand coefficient and connected attribute) is utilized for the prior-known evaluation of their relative importance. Two estimations of the evaluation results (range and value) are conducted for this analysis.

Range Estimation

The MCS-based results in Fig. 3 can be interpreted through the distribution of obtained DIF with respect to the ratio of two static parameters for range estimation. For illustration, the envelope lines for different probabilistic confidence levels are plotted in Fig. 4. Particularly, the confidence levels of 99%, 95% and 90% in the results of Fig. 4 refer to different options with high probabilities of the range estimation for the DIF corresponding to an arbitrary specified ratio of these two chosen static parameters, while the confidence level of 10% denotes untrusted range estimation for the DIF with low probability. From Fig. 4, the range estimation can be easily conducted by engineers with knowing only two static parameters in advance. For instance, for the case of the ratio below 1.0, the demand effect is below 1.8% with 99% probability and below 1.0% with 90% probability, which indicates a minor effect of the nodal demand; while for the case of the ratio above 30.0, the demand effect is above 10.4% with 90% probability (or below 10.4% with 10% probability), which indicates relatively large effect of the nodal demand. Meanwhile, a positive correlation between the ratio of these two static parameters and the DIF result can be observed for all confidence levels, indicating that the demand nodes in WDS with a great ratio value (e.g., large demand) are supposed to have great influence, while those with a minor ratio value (e.g., nodes connected with large diameter pipe sections) tend to have little influence on the transient behavior and analysis in the pipe system.

Value Estimation

The GSA results and analysis have suggested to fix the two dynamic parameters (with relatively small contributions) for the prior-known evaluation of the nodal demand effect. In this section, the influence and accuracy of the suggested factor fixing is systematically analyzed. On the basis of the proposed probabilistic framework in this study, the analysis process and procedure are shown in the flowchart in Fig. 5. The statistical results of the deviations of the factor fixing process for any fixed values versus the original values are calculated and shown in Fig. 6.

In more details, Fig. 6 plots the probability envelopes of the estimation errors of the factor fixing for the two confidence levels (i.e., CL = 99%, 95%). In the figure, the envelope of a specific estimation error contour indicates a certain range of value estimation below the estimation error under the specific confidence level. On one hand, the result of Fig. 6 demonstrates that the closer the fixed value is to the original value, the lower the estimation error for both confidence levels and both dynamic parameters is, which also means the more accurate the value estimation is. This result is unsurprised since the error of such factor fixing is mainly due to the difference between the fixed and original values of these two parameters. On the other hand, the result of Fig. 6 also demonstrates that the envelope range is becoming narrower when it approaches to the origin point (0, 0), which indicates a tougher selection of the fixed value for value estimation around zero values. However, when the restriction of value estimation is relaxed, e.g., the confidence level is changed from 99% in Fig. 6(a, b) to 95% in Fig. 6(c, d), the estimation errors become minor (below 5%) through the whole parameter ranges, which is consistent with the former GSA-based results for the two dynamic parameters.

Consequently, with this prior-known evaluation method, the influence range and importance of each nodal demand in transient models can be predicted and quantified from the range and value estimations respectively with the two static parameters only (demand coefficient and connected attribute), thus the nodal demand effect (DIF) on transient modelling and analysis can be properly evaluated before any nodal demand transformation in WDS. The results and findings of the prior-known evaluation method and also the sensitivity analysis of the nodal demand effect in this study may become useful guidance and tool to practical transient applications such as complex system skeletonization and transient wave propagation analysis. The accuracy and applicability of the proposed methods and procedures are further verified and validated through the numerical application of a realistic pipe network in the following study.

Numerical Application and Results Discussion

Description of WDS

To demonstrate the application procedure and verify the applicability of the proposed methodology in this study, a realistic WDS of the Modena Network (MOD) in Italy from Bragalli et al. (2012) under different hypothetical transient conditions is used for the analysis. This MOD consists of 317 pipes, 268 nodes (in which 245 are demand nodes) and 4 reservoirs, with the pipe network sketched in Fig. 7. As for transient analysis, the 1D waterhammer model coupled with the MOC scheme is applied to the original MOD model for transient simulation, in which the discrete vapor cavity model (DVCM) is adopted for cavitation simulation if necessary (Wylie et al. 1993). For simplicity and illustration, a common wave speed of 500 m/s is assigned for all pipes and only the quasi-steady state friction factor is included for the friction formula (actually it was found that the final results have nothing to do with such factors). The transient conditions for all numerical studies are induced by simultaneous closure of the three virtual control valves with an operation duration of 2.0 s (i.e., Exciters 1, 2, and 3 in Fig. 7), so as to generate extensive pressure fluctuations in the system. These three exciters are located at pipes no. 123, no. 259 and no. 227 respectively as shown in Fig. 7. Note that these hypothetical conditions of transient generations and system parameters and operations are mainly used to illustrate the application procedures and demonstrate the applicability of the proposed methods in this study, so as to explore and discuss quantitatively later the potential influence of nodal demand to transient modelling and analysis in WDS.

Probabilistic Analysis and Evaluation of Nodal Demand Effect

The effect of nodal demand on transient response and wave propagation in this system can be qualitatively analyzed by the nodal demand model in Eq. (5) and the proposed DIF in Eq. (6) in this study. For demonstration and analysis, the results of transient pressure components and the DIF for the node no. 28 in Fig. 7 are retrieved and plotted in Fig. 8. The result shows clearly the time-dependent DIF profile for describing the nodal demand effect on transient wave propagation. Particularly, the DIF value at the node no. 28 is between 30% and 60%, which indicates relatively large influence of this nodal demand effect on the transient response in this system.

Meanwhile, the result comparison of Fig. 8 reveals that: (1) the variation trend of the DIF is opposite to that of transient pressure (see Figs. 8 (a) and (c)); and (2) the DIF increases with the downsurge (i.e., negative pressure wave) and decreases with the upsurge (i.e., positive pressure wave) (see Figs. 8 (b) and (c)). This variation trend may be explained by the negative correlation between the DIF and the two dynamic parameters (prior pressure and pseudo surge) as observed and analyzed previously in this study.

Figure 9 shows the relevance between the ratio of two static parameters and the level of demand effects (indicated by the mean values of DIF during transient process). The result of this figure indicates that the nodal demand effect is increasing with the ratio of the two static parameters, which conforms to the positive correlation between the ratio and the DIF observed previously in Fig. 4. Combining the former analysis results of MCS and GSA, it can be concluded that the ratio of demand coefficient and connected attribute can be largely used as an indicator of nodal demand effect with positive correlation, since the two dynamic parameters provide little relevance to the DIF and also small impact on the sensitivity of the nodal demand effect. Therefore, these two dynamic parameters in this studied system can be fixed so as to conduct the prior-known evaluation of the nodal demand effect for the whole WDS.

The results of the range and value estimations by the prior-known evaluation method and the originally actual simulation are plotted in Fig. 10 for comparison. Note that the upper and lower limits of the estimated ranges are selected with 90%

and 10% confidence level respectively, and estimated values are calculated by taking the initial pressure as the prior pressure and a constant value of 5.0 m as the pseudo surge. From Fig. 10, the actual ranges of the DIF for all the demand nodes (with 8 exceptional nodes marked in this figure) are enveloped by the estimated ranges with a 90% or higher confidence level. This result implies that the range estimation is feasible to evaluate the nodal demand effects in a realistic network. In addition, for the 8 exceptional nodes in Fig. 10, a common feature is observed that all of them are very close to the downstream of the transient exciters (as marked in Fig. 7). Actually, the reason for the extensive ranges of DIF at these locations may be attributed to the downsurges (negative waves) at the downstream of transient exciters refer to the negative correlation for the two dynamic parameters with DIF at general transient states, e.g., the variation trend for node no. 28 as shown in Fig. 8. Meanwhile, the drastic pressure fluctuations at these locations may also result in the possibility of extensive DIF.

Furthermore, Fig. 10 demonstrates that the estimated value by the factor fixing agrees well with the actual value by the simulation, which indicates the effectiveness and accuracy of the estimated value from the static parameters only as an indicator of demand effect level. From this perspective, the factor fixing result by the probabilistic analysis and evaluation is useful and accurate for practical transient analysis of the complex WDS.

Further Applications and Practical Implications

The prior-known evaluation results of nodal demand effect obtained by the probabilistic framework developed in this study become useful to guide the transformation of demand nodes during both the system construction and transient analysis for complex pipe networks, such as system skeletonization with consideration of demand aggregation or reallocation (Zheng et al. 2013; Diao et al. 2015). For an illustration of the usefulness and effectiveness of the proposed method and procedure, the prior-known evaluation is conducted and applied to the transformation of demand nodes herein for skeletonization purpose for the Modena network as shown in Fig. 7.

The results of three scenarios with different guidance levels of skeletonization for the studied pipe network are selected and shown in Fig. 11, including: (1) demand nodes of estimated range below 5% with 90% confidence level, i.e., the ratio of the two static parameters is below 4.3 obtained from Fig. 4, are allowed to be skeletonized and the others are kept as original, which is termed as the case of "DIF < 5%" in Fig. 11; (2) similar scenario as (1) but with estimated range below 10% (i.e., the ratio is below 8.8), termed as the case of "DIF < 10%" in Fig. 11; (3) a traditional skeletonization scenario without any specific guidance from the above analysis, termed as the case of "No guide" in Fig. 11. As a result, the levels of skeletonization for this studied network are about 37.7%, 50.4% and 63.8% respectively for these three scenarios as indicated in Fig. 11. Specifically, with the traditional guideless skeletonization way (without the DIF guidance), the complexity of the network is greatly reduced with significant demand reallocations and over simplification which may cause potentially large risk of deviations of transient analysis from the original transient results. With the guidance results by the prior-known evaluation method in scenarios (1) and (2), the nodes with high demand effects (large DIF values) have been largely kept as original, and only those with relatively small impact have been simplified and reallocated, and thus the influence of the system skeletonization to the transient analysis can be greatly reduced.

To inspect the detailed influence of skeletonization and effectiveness of the prior-known evaluation, the results of transient pressure traces at the downstream of exciter no. 3 are retrieved from the analysis process and shown in Fig. 12, which reveals clearly the much larger difference/error of the traditional guideless scenario for the demand transformation and system skeletonization than the two guidance ways by the prior-known evaluation. As for the initial steady state, the guideless skeletonization has caused the difference (error) at about 1.5 m of the pressure head from the original/actual value, which is much large than those from the two guided results (e.g., 0.0 m for scenario (1) and 0.2 m for scenario (2)). As for the transient analysis, all the three scenarios have generated increasing deviations with transient evolution time from the original model. However, the errors of the two DIF guidance scenarios (“DIF < 5%” and “DIF < 10%” in the figure) are still within an acceptable range (e.g., on average about 0.4% and 2.8% of initial steady state pressure, respectively), while that of the guideless case attains to over 15.0%.

To further highlight and analyze the influence of different skeletonization levels, maximum differences of pressure profiles for the 97 selected nodes (which are included for all the scenario results) are plotted in Fig. 13. This comparison confirms again that the guided skeletonization scenarios may produce much smaller errors than the traditional guideless way. Meanwhile, for the guidance results, the accuracy of the system skeletonization is decreasing with the estimated range of DIF. From this perspective, the MCS and GSA based prior-known evaluation of nodal demand effect is useful and effective to the complex system skeletonization, and thus to better guide the practical transient modelling and analysis of WDS.

Consequently, the skeletonization with guidance of prior-known evaluation proposed in this study may provide selectable and predictable schemes to the modelers with different error levels of demand node skeletonization for the transient modelling and analysis. It is also noted that both the guided and guideless skeletonization schemes may cause the change of waveforms (shift and attenuation) during the transient analysis as shown in Fig. 12 (zoomed part), which is conforming to the results in Edwards and Collins (2013). This difference may be ascribed to the aggregation of demand nodes during the skeletonization process.

Summary and Conclusions

This paper investigates the nodal demand effect on transient analysis in urban water distribution system (WDS). The transient nodal demand model in a Lagrangian form and the demand impact factor (DIF) are firstly derived to express qualitatively the influence of nodal demand effects to transient analysis in WDS. A probabilistic framework, including a parameter sensitivity analysis based on MCS and GSA methods, is then developed for a prior-known evaluation of transient nodal demand effect, so as to facilitate the practical implication of nodal demand transformation in transient modelling and analysis. The parameter sensitivity analysis results indicate that the DIF is mostly sensitive to the static parameters (demand coefficient and connected attribute) in the system and the dynamic parameters (prior pressure and pseudo surge) can be used approximately as fixing factors, which sets the foundation of range and value estimations for the prior-known evaluation of nodal demand effect with the static parameters only.

A realistic pipe network from the literature is adopted to validate the procedure and effectiveness of the proposed method. The analysis and evaluation results confirm the applicability of the ratio of demand coefficient and connected attribute as an indicator of nodal demand effect and the feasibility of the prior-known evaluation method to evaluate the nodal demand effects in a realistic network. According to the application results for the guidance of demand transformations within complex system skeletonization, it is demonstrated that the accuracy of the guided system skeletonization by the prior-known evaluation method can be much higher than traditional skeletonization way, which is however decreasing with the estimated range of the DIF of nodal demand effect in the system. The results and findings of this study may provide useful guidance to the transient modelling and analysis of complex pipe networks in practice. It is also noted that, with the existence of various uncertainties and complexities in practical pipe systems, more applications and further validations of the developed assessment method and framework in this study are required in the future work.

Acknowledgments

This work was partially supported by the grants from: (1) the Hong Kong Research Grant Council (RGC) under projects no. 25200616 and no. T21-602/15-R; (2) the Hong Kong Polytechnic University under projects no. 1-ZVCD and no. 1-ZVGF; and (3) the National Science and Technology Major Project (2014ZX07406003).

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Table 1. Summary of WDS models from the literature

WDS model	Node	Pipe	Parameter Range (with 95% confidence)		Sources or References
			Demand Coefficient ($m^{2.5}/s^{-1}$)	Connected Attribute ($m \cdot s$)	
Richmond_standard	865	949	(3.67E-7, 5.31E-5)	(2.23E-6, 1.07E-4)	Benchmark of ECWS, Zyl and Ernst (2001)
Exeter Network	1891	3032	(6.41E-6, 0.0018)	(0.91E-5, 5.51E-4)	Benchmark of ECWS, Wang et al. (2015), Farmani et al. (2004)
Modena Network	268	317	(3.62E-6, 0.0014)	(1.74E-5, 1.47E-4)	Benchmark of ECWS, Wang et al. (2015), Bragalli et al. (2012)
Wolf-Cordera Initial Model	1782	1985	(2.56E-5, 7.63E-5)	(2.03E-5, 3.24E-4)	Benchmark of ECWS, Lippai (2005)
BWSN_Network_2	12523	10551	(5.91E-7, 6.03E-5)	(2.25E-6, 3.24E-4)	WDSA2008-BWSN, Ostfeld et al. (2008)
C-Town/D-Town	388	432	(4.03E-6, 2.60E-4)	(5.04E-6, 5.88E-4)	WDSA2010-BWCN, Ostfeld et al. (2012) WDSA2012-BWNII, Marchi et al. (2013) WDSA2014-BBLAWN, Giustolisi et al. (2014)
E-Town	11063	13896	--	(4.91E-6, 4.41E-4)	WDSA2016-BWNDMA, Online source[1]
Example 7	381	469	(3.08E-5, 3.92E-4)	(2.03E-5, 3.24E-4)	Exported from samples of WaterGems V8i
Example 8	1321	1122	(1.80E-7, 1.06E-4)	(5.04E-6, 0.0055)	Exported from samples of WaterGems V8i
Haining Network (simplified)	2120	2331	(1.21E-6, 4.16E-4)	(8.73E-6, 0.0019)	Owned by the local water utility of Haining city, China
Jinan Network (full-scale)	51892	45602	(3.30E-8, 2.23E-4)	(3.47E-6, 0.0025)	Owned by the local water utility of Jinan city, China

1. Abbreviations: ECWS, the Centre for Water Systems at the university of Exeter; WDSA, the conference of Water Distribution Systems Analysis; BWSN, the Battle of Water Sensor Networks; BWCN, the Battle of Water Calibration Networks; BWNII, the Battle of Water Networks II; BBLAWN, the Battle of Background Leakage Assessment for Water Networks; BWNDMA, the Battle of Water Networks DMAs.

2. The "C-Town/D-Town" case includes three referred sources with nearly identical models, thus gathered together with the maximum range of parameters.

3. The wave speeds for all these models were assumed as 915 m/s to get a general range of connected attribute, as this wave speed is proved to obtain realistic transient pressure fluctuations for a network with its major pipe materials as metal pipes (Farmani et al. 2004; Svindland 2005; Rathnayaka et al. 2016).

4. All the ranges of parameters are trimmed with 95% confidence to exclude the excessive values in order to indicate the general ranges of parameters.

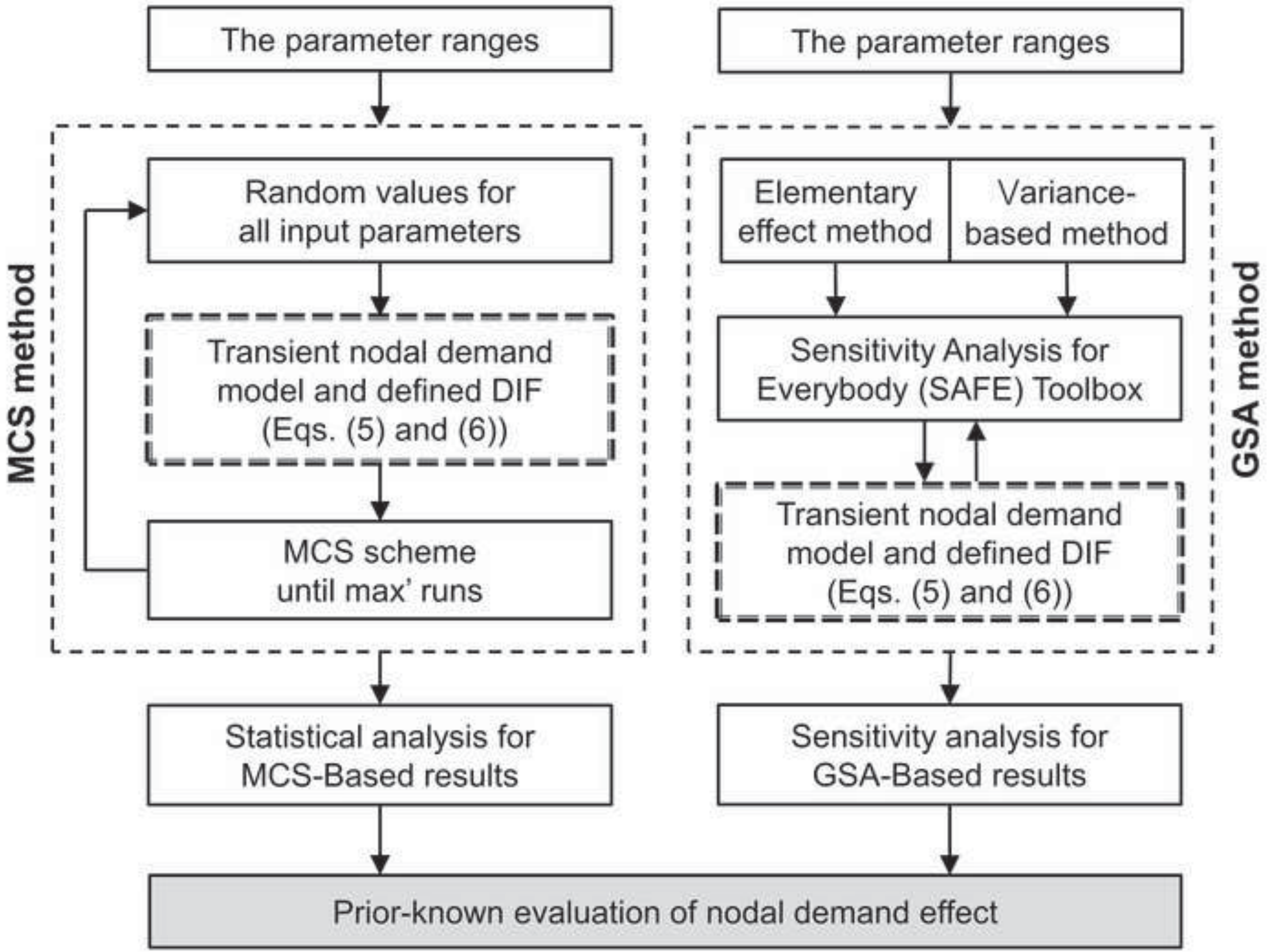
[1]Available at: https://wdsa2016.uniandes.edu.co/index.php/battle-of-water-networks.

Table 2. GSA-based results for different parameters by the elementary effect method and the variance-based method

Parameter	General range				Extended range			
	μ^*	σ	S	S_T	μ^*	σ	S	S_T
Demand Coefficient	0.036	0.080	0.042	0.292	0.036	0.085	0.032	0.124
Connected Attribute	0.103	0.877	0.696	0.934	0.110	0.976	0.782	0.930
Pseudo Surge	0.028	0.156	0.003	0.089	0.027	0.103	0.003	0.064
Prior Pressure	0.034	0.216	0.006	0.175	0.033	0.170	0.011	0.112
Sum			0.747	1.490			0.828	1.230

Note: Elementary effect method: $\mu^*$is the mean of absolute elementary effects; σ is the standard deviation of elementary effects. Variance-based method: S is the first order sensitivity index; S_T is the total sensitivity index.

Fig 1



The parameter ranges
MCS method
Random values for all input parameters
Transient nodal demand model and defined DIF (Eqs. (5) and (6))
MCS scheme until max' runs
Statistical analysis for MCS-Based results
The parameter ranges
GSA method
Elementary effect method
Variance-based method
Sensitivity Analysis for Everybody (SAFE) Toolbox
Transient nodal demand model and defined DIF (Eqs. (5) and (6))
Sensitivity analysis for GSA-Based results
Prior-known evaluation of nodal demand effect

Fig 2

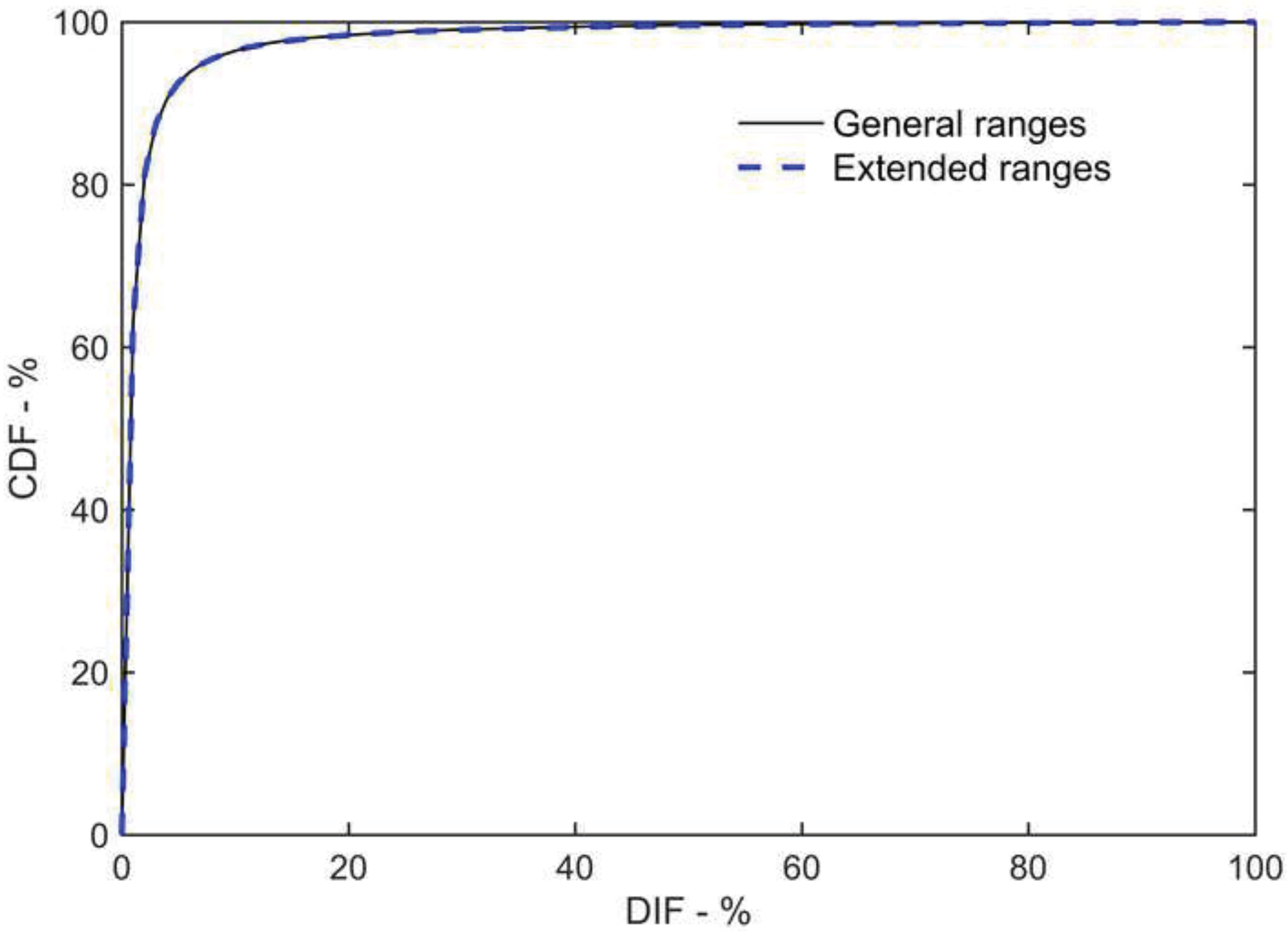

100
80
60
40
20
0
CDF - %
0
20
40
60
80
100
DIF - %
General ranges
Extended ranges

Fig 3

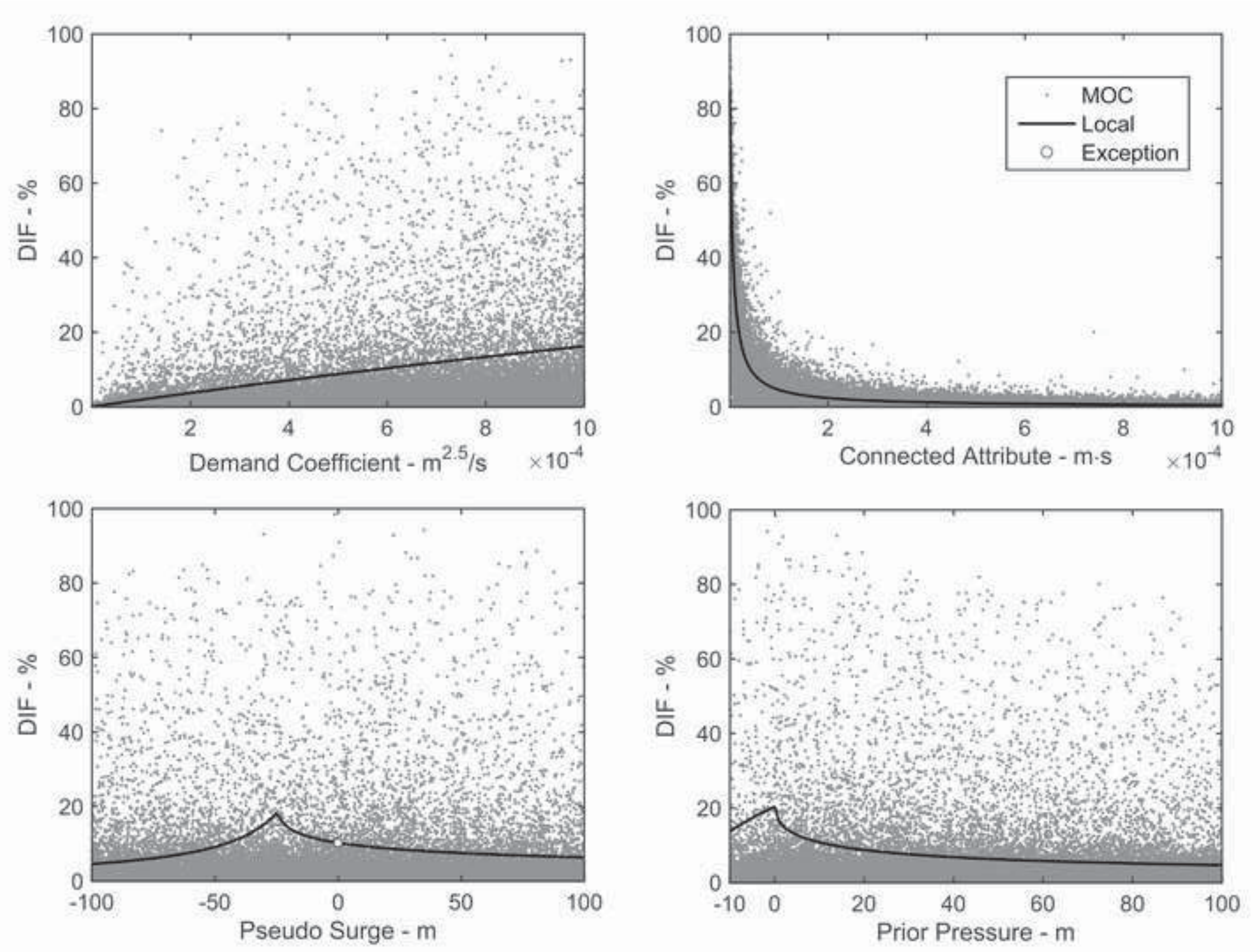

DIF - %
100
80
60
40
20
0
2
4
6
8
10
Demand Coefficient - m^2.5/s
×10^-4
DIF - %
Connected Attribute - m·s
×10^-4
MOC
Local
Exception
DIF - %
-100
-50
0
50
100
Pseudo Surge - m
DIF - %
-10
0
20
40
60
80
100
Prior Pressure - m

Fig 4

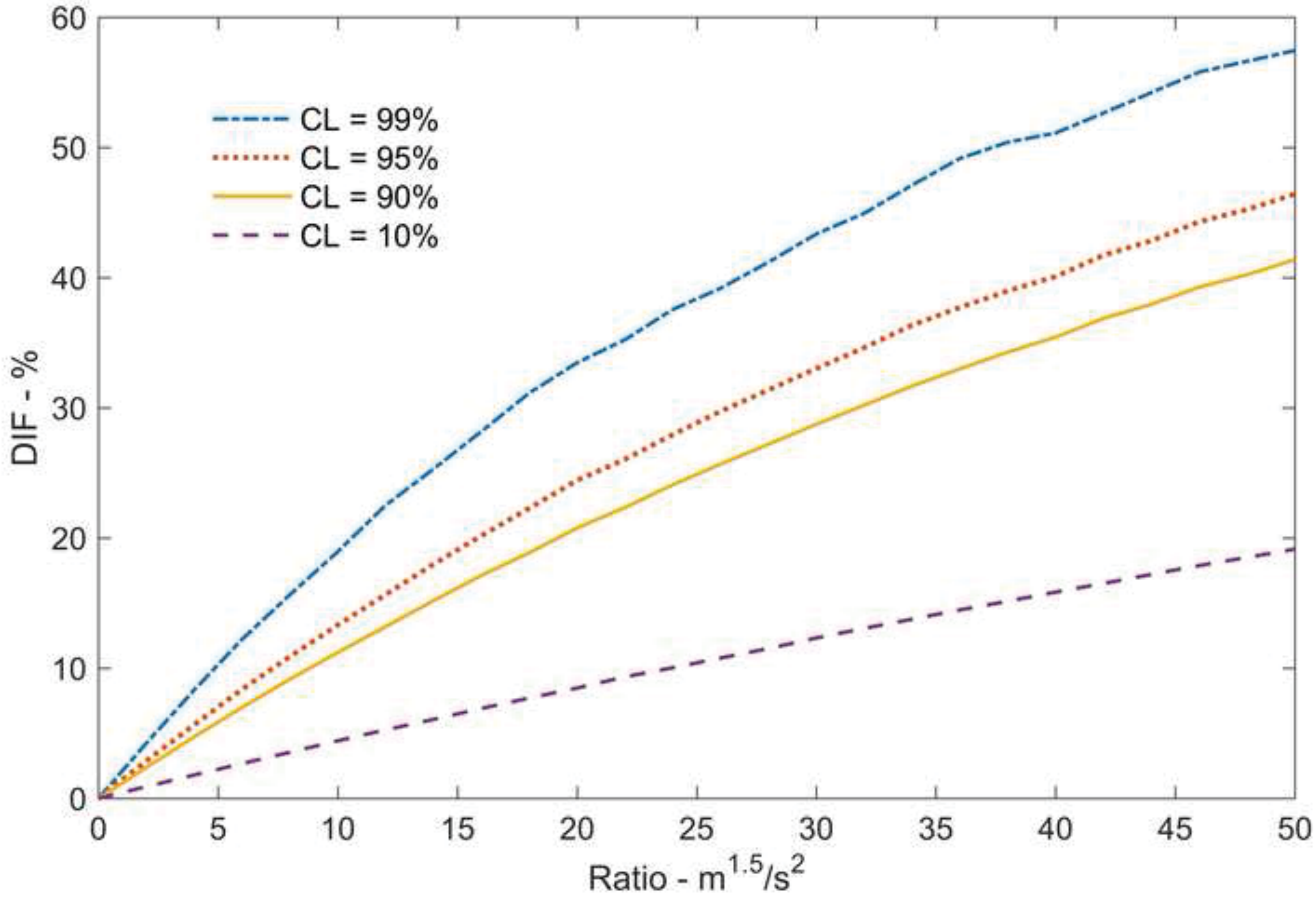

CL = 99%
CL = 95%
CL = 90%
CL = 10%
DIF - %
Ratio - m^1.5/s^2
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45
50

Fig 5

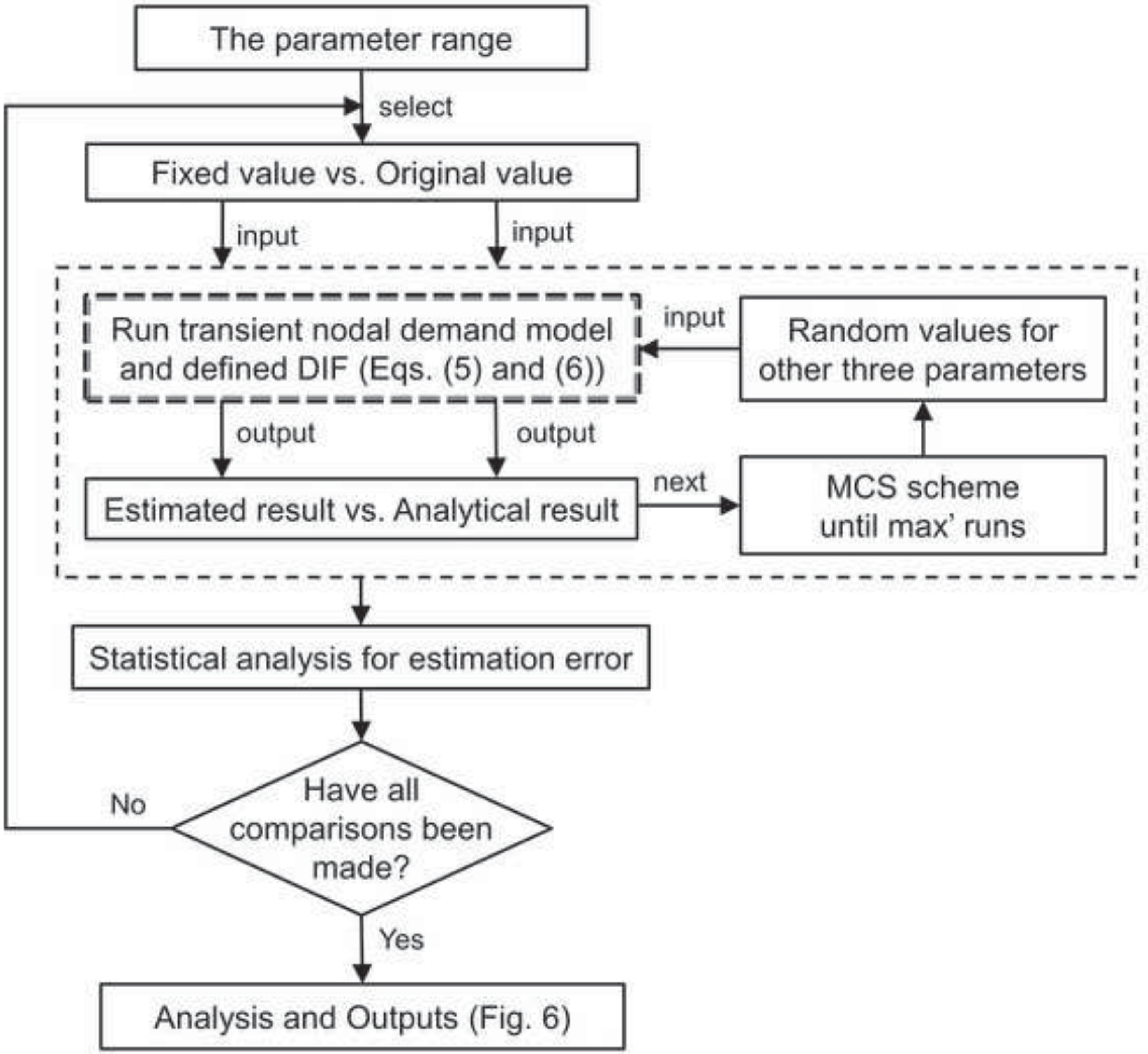

The parameter range
select
Fixed value vs. Original value
input
input
Run transient nodal demand model and defined DIF (Eqs. (5) and (6))
input
Random values for other three parameters
output
output
Estimated result vs. Analytical result
next
MCS scheme until max' runs
Statistical analysis for estimation error
Have all comparisons been made?
No
Yes
Analysis and Outputs (Fig. 6)

Fig 6

Click here to download Figure Fig 6.tif

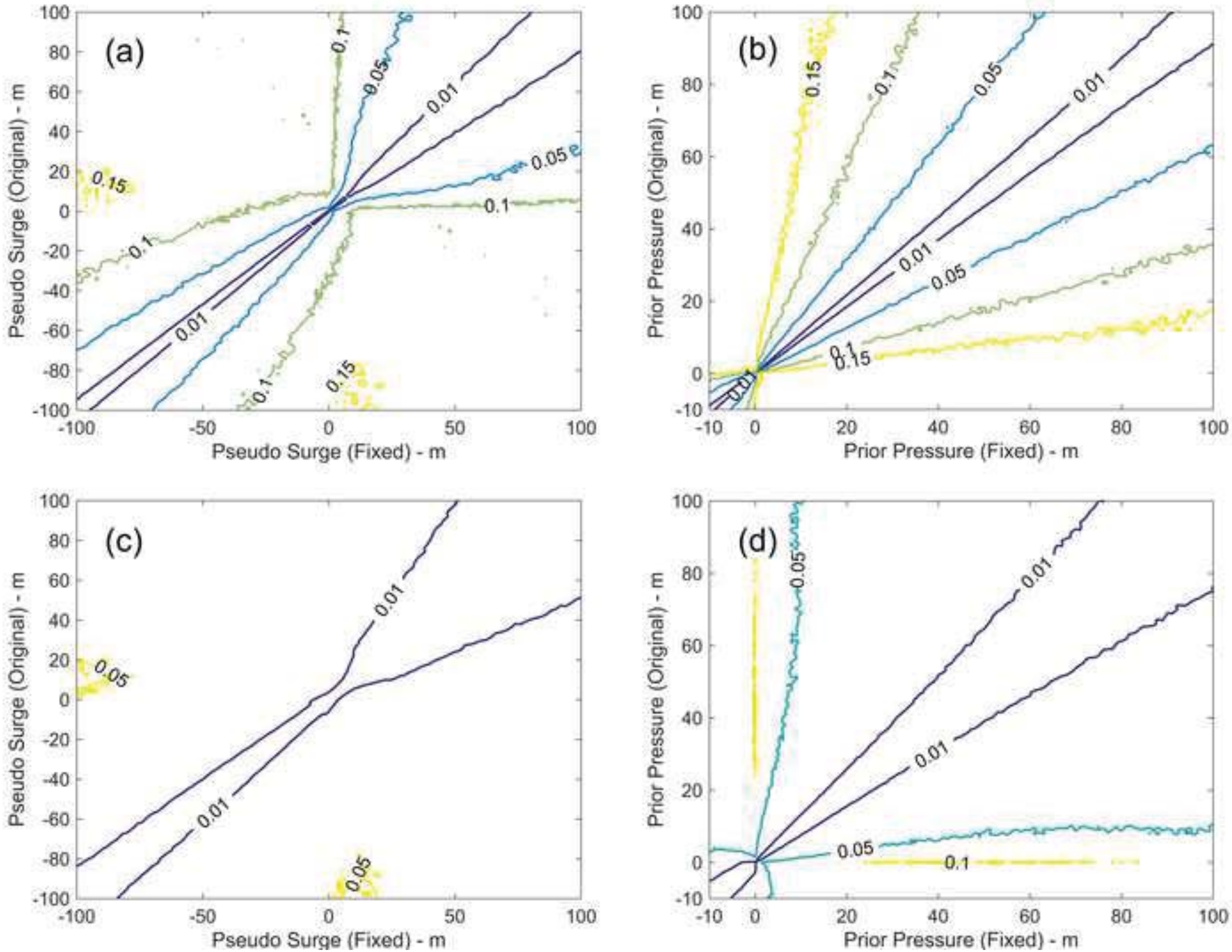


Fig 7

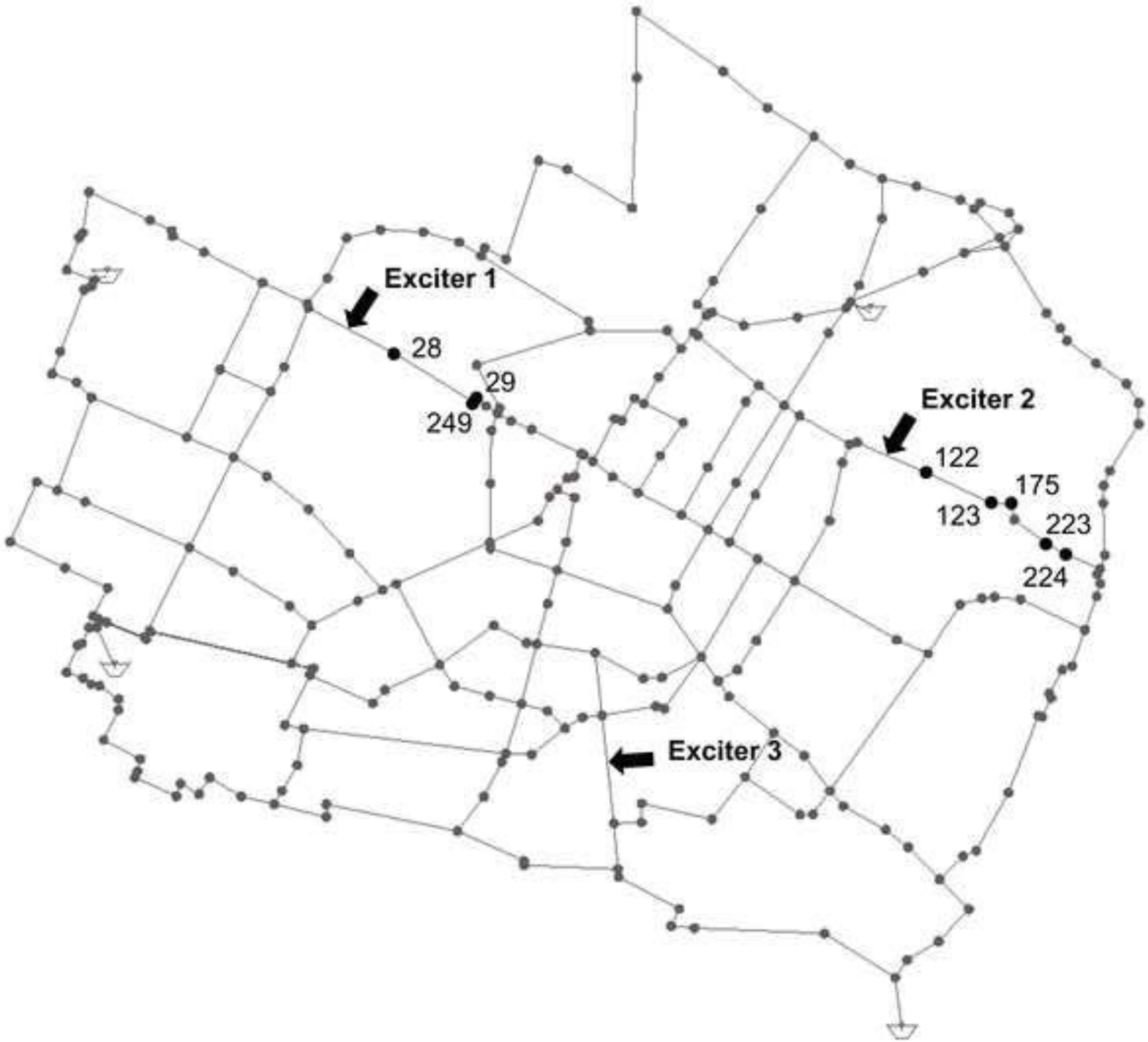


Fig 8

Click here to download Figure Fig 8.tif

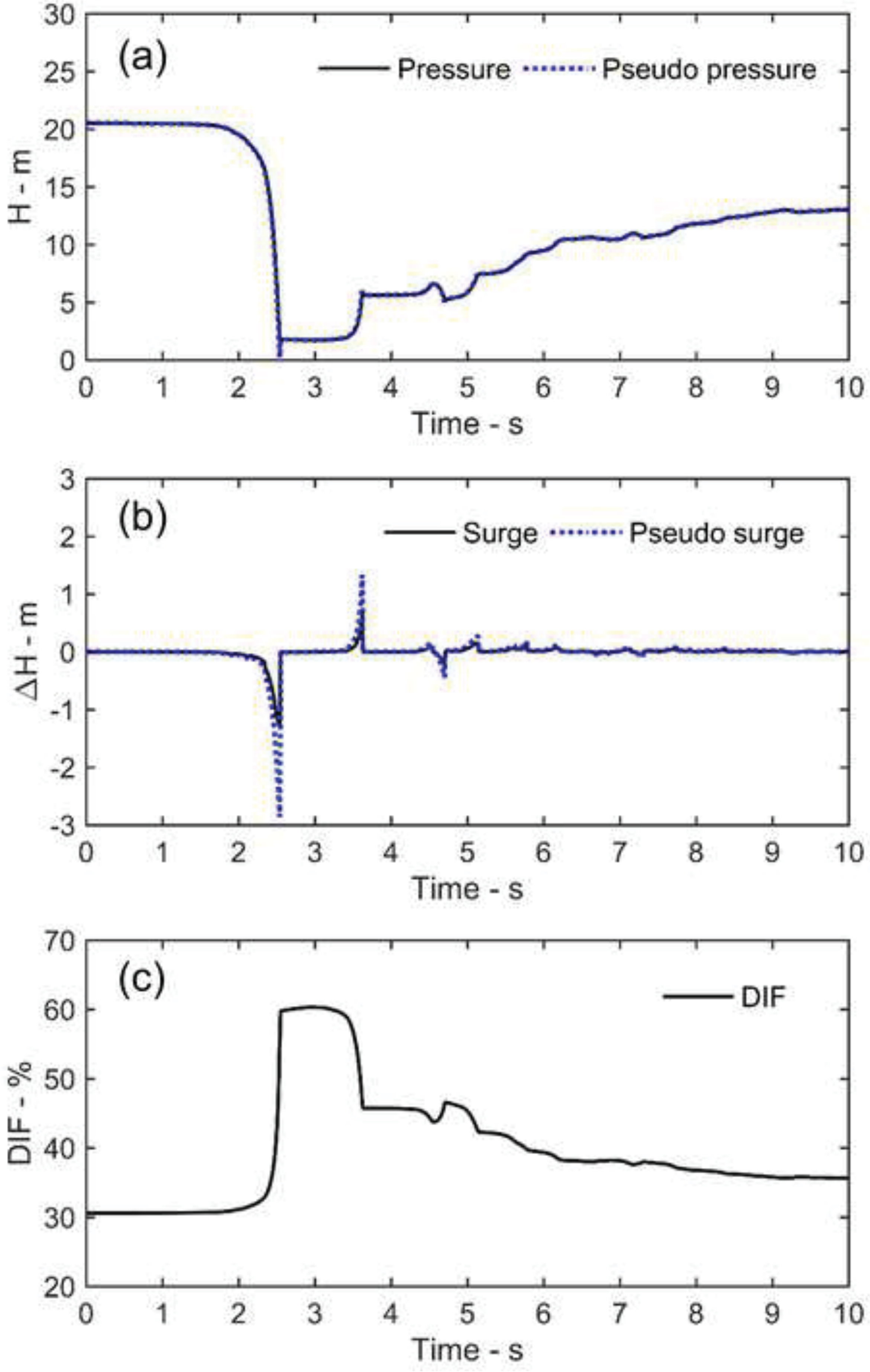
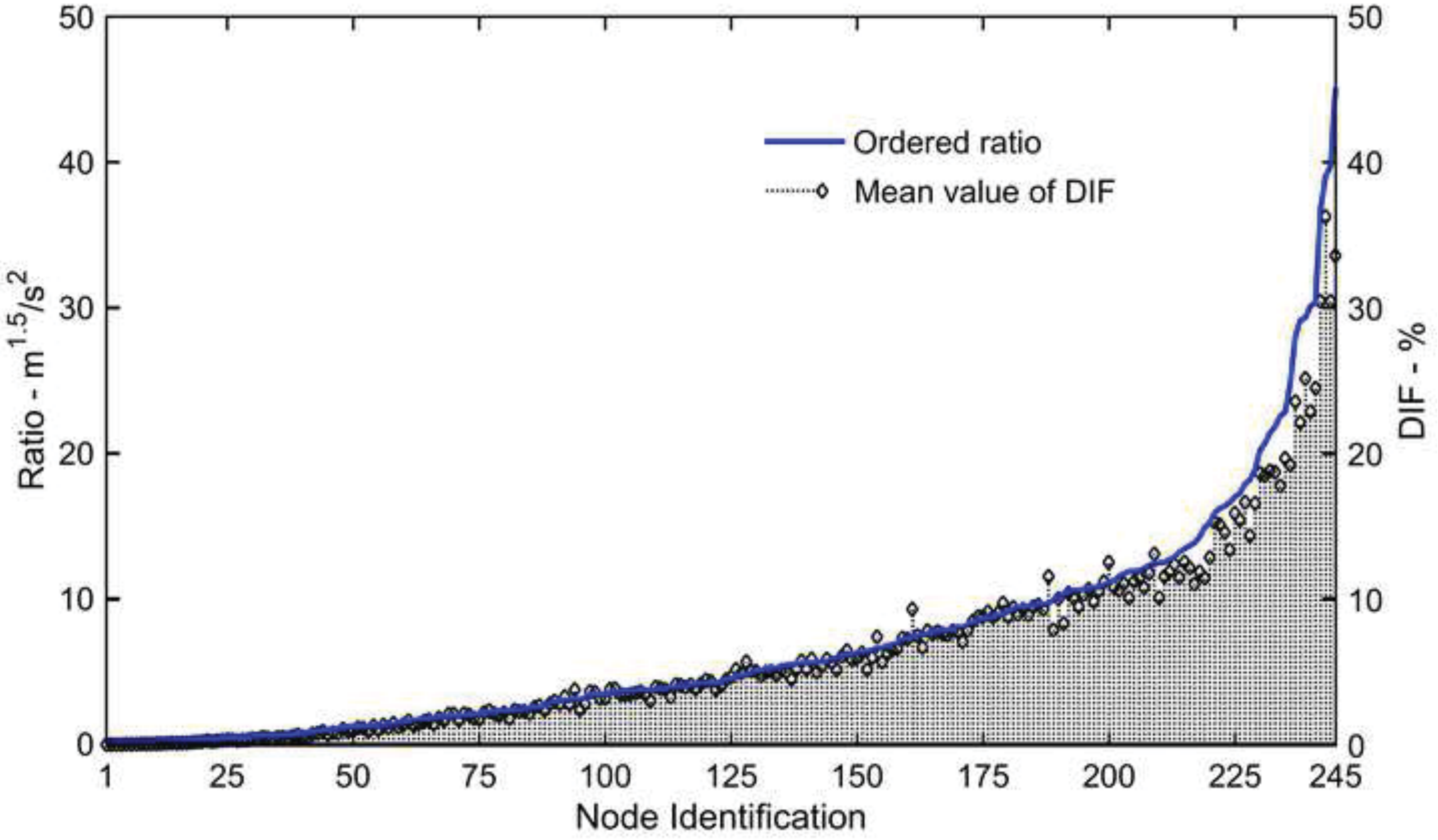


Fig 9



Ordered ratio
Mean value of DIF
Ratio - m^1.5/s^2
DIF - %
Node Identification
0
10
20
30
40
50
1
25
50
75
100
125
150
175
200
225
245

Fig 10

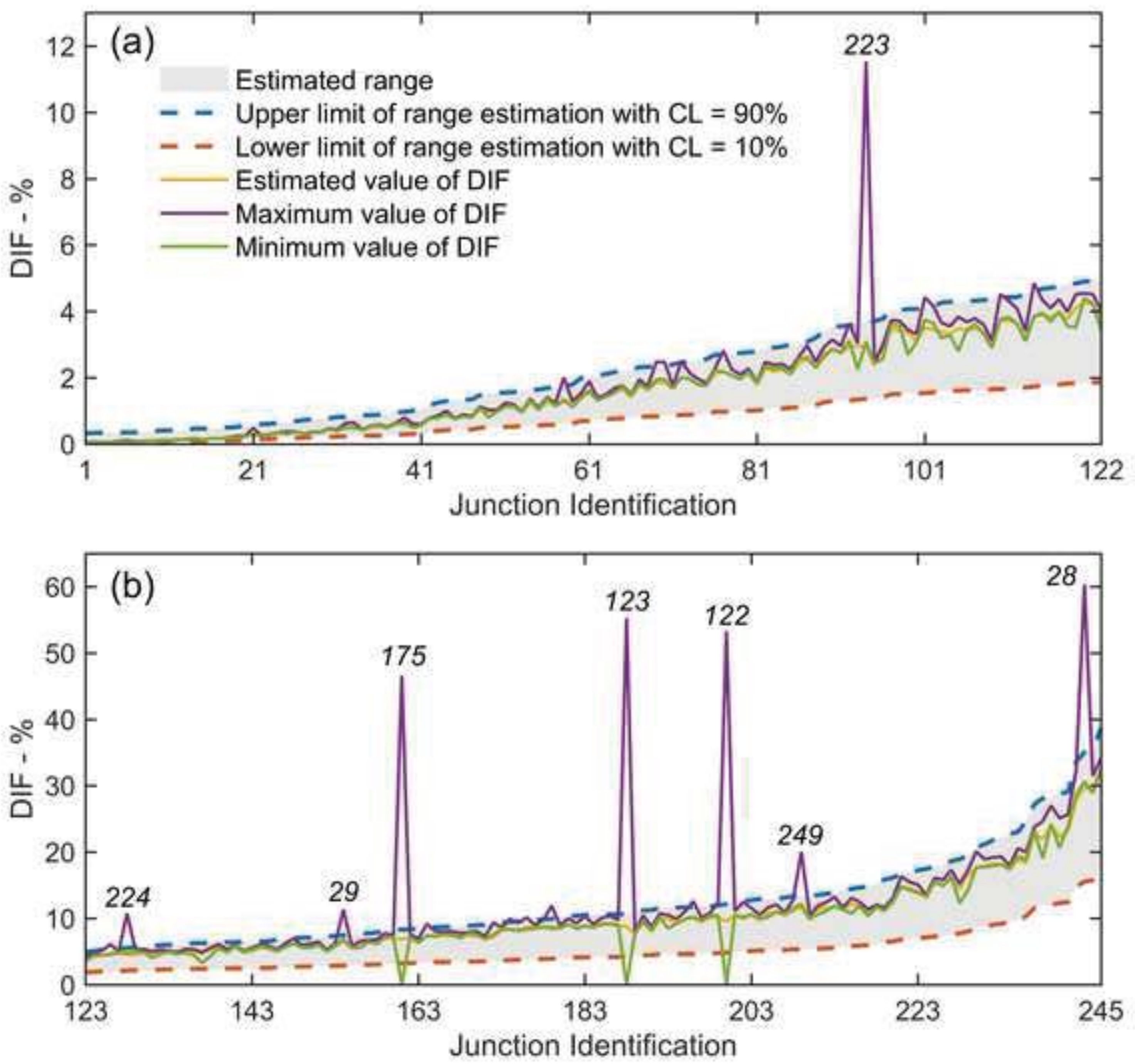
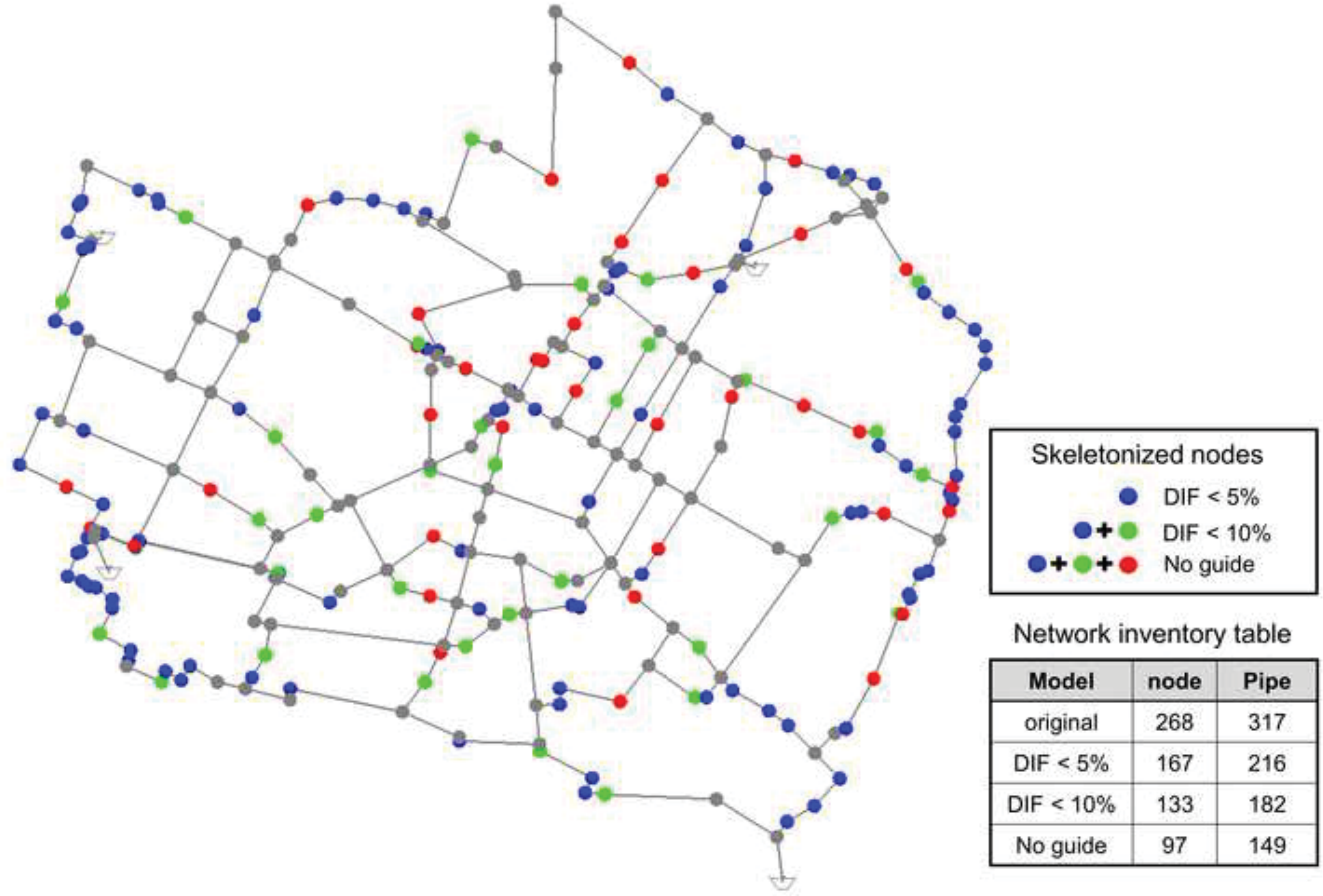

(a)
Estimated range
Upper limit of range estimation with CL = 90%
Lower limit of range estimation with CL = 10%
Estimated value of DIF
Maximum value of DIF
Minimum value of DIF
223
DIF - %
12
10
8
6
4
2
0
1
21
41
61
81
101
122
Junction Identification
(b)
224
29
175
123
122
249
28
60
50
40
30
20
10
0
123
143
163
183
203
223
245

Fig 11



Network inventory table

Model	node	Pipe
original	268	317
DIF < 5%	167	216
DIF < 10%	133	182
No guide	97	149

Fig 12

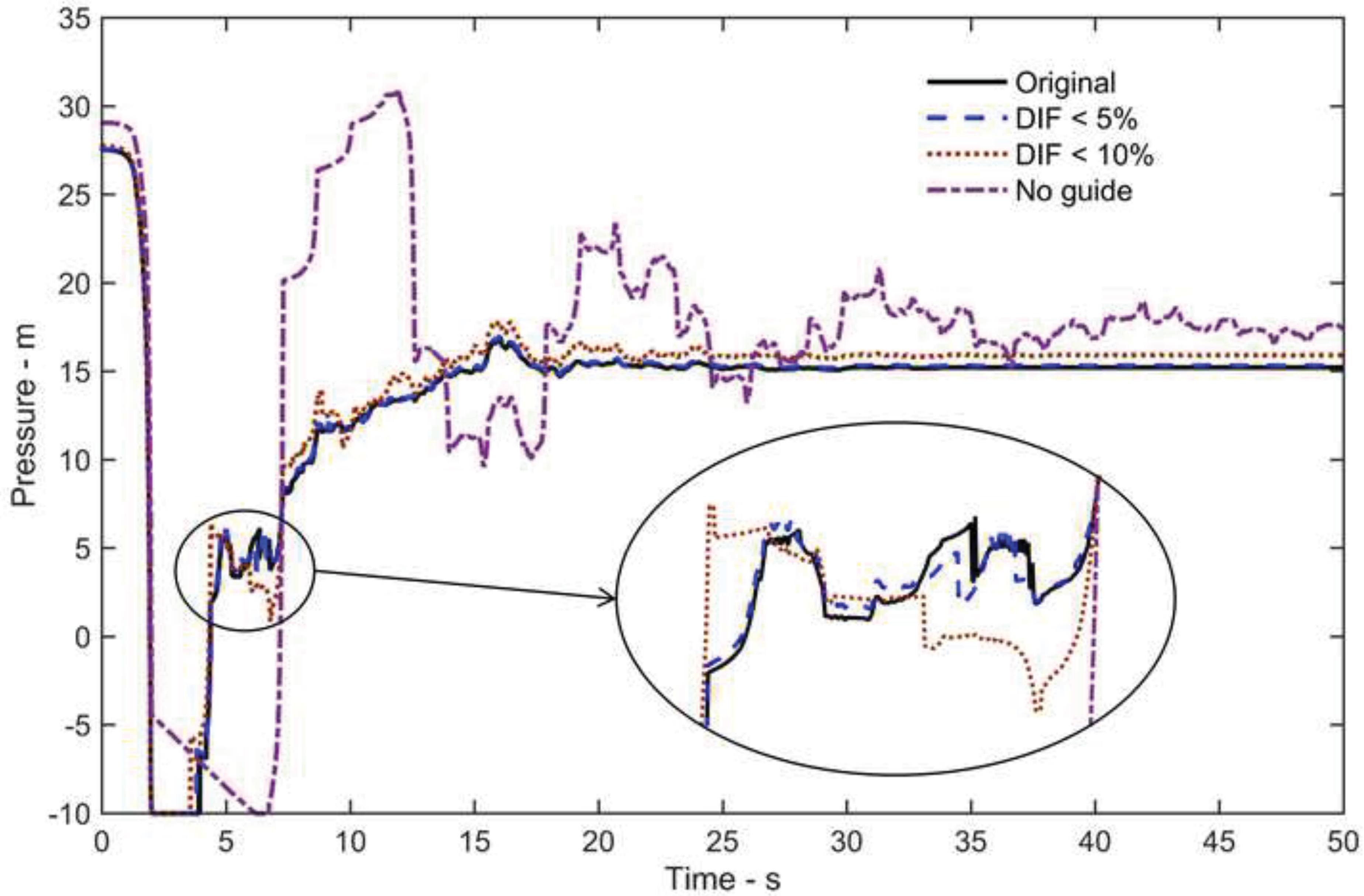

Original
DIF < 5%
DIF < 10%
No guide
Pressure - m
Time - s
35
30
25
20
15
10
5
0
-5
-10
0
5
10
15
20
25
30
35
40
45
50

Fig 13

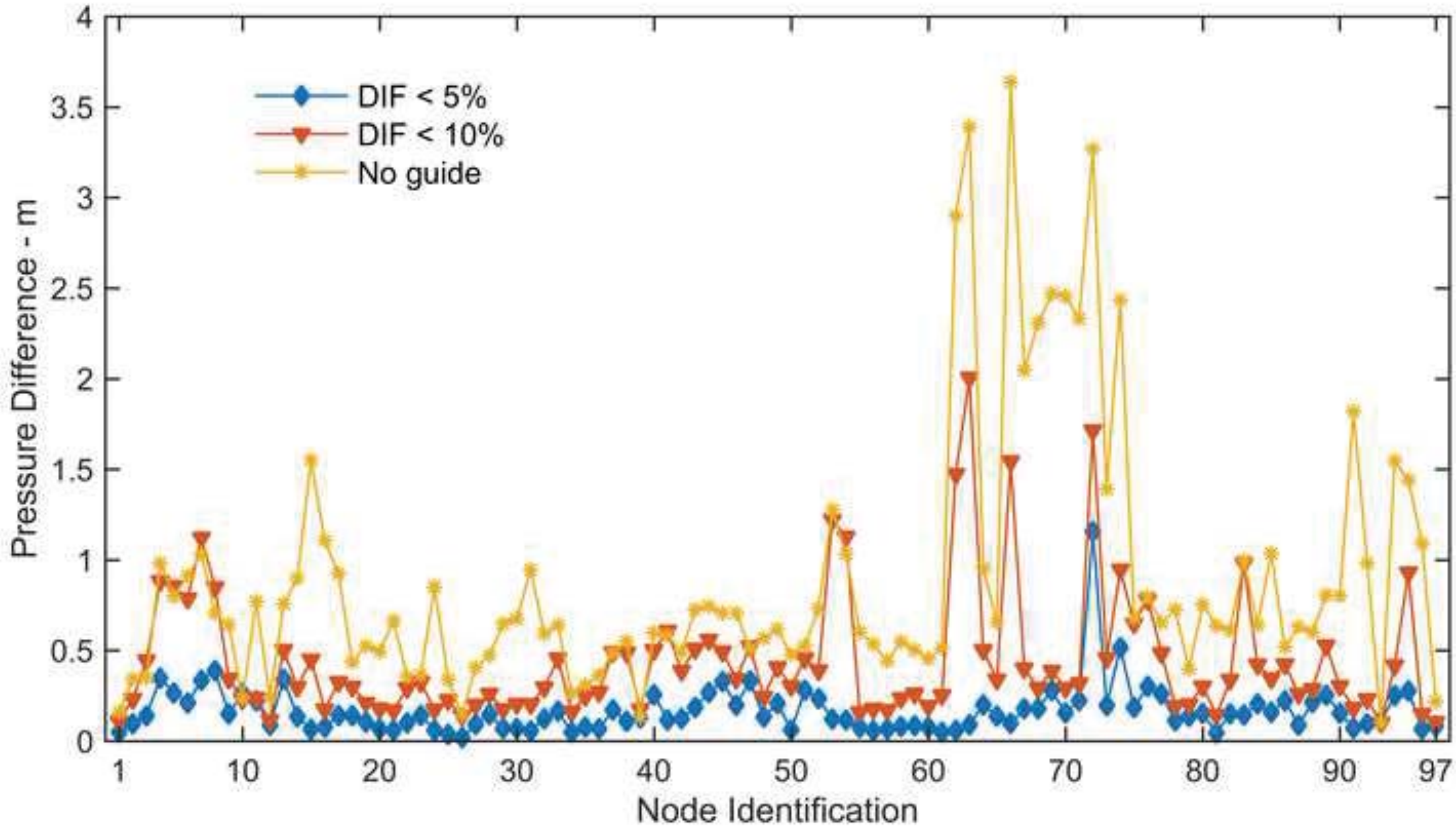

DIF < 5%
DIF < 10%
No guide
Pressure Difference - m
0
0.5
1
1.5
2
2.5
3
3.5
4
1
10
20
30
40
50
60
70
80
90
97
Node Identification

Figure Caption

Fig. 1. Flowchart of the framework for probabilistic analysis and evaluation of nodal demand effect

Fig. 2. CDF result for DIF with the general and extended variation ranges of relevant parameters

Fig. 3. Distributions of DIF with respect to different parameters within the general ranges (the scatters for the MCS results, and the lines for the local variation results)

Fig. 4. Probability envelopes of the range estimation for different confidence levels (CL)

Fig. 5. Flowchart of the deviation analysis for factor fixing process

Fig. 6. Probability envelopes of estimation errors for different confidence levels (CL) of factor fixing process: (a) and (b) for CL = 99%; (c) and (d) for CL = 95%

Fig. 7. Layout of the Modena network for analysis

Fig. 8. Results at node 28 for: (a) comparison of pressure and pseudo pressure; (b) comparison of pressure surge and pseudo surge; (c) the DIF of nodal demand effect

Fig. 9. Relevance between the ratio of two static parameters and the DIF of nodal demand effect for all the selected demand nodes in the test system

Fig. 10. Results of prior-known evaluation of demand effects for all demand nodes: (a) the first 122 nodes with relatively low ratios and (b) the other 123 nodes with relatively high ratios

Fig. 11. Skeletonization results of the Modena network for three scenarios

Fig. 12. Pressure traces for different skeletonization scenarios at the downstream of control valve (Exciter 3 in Fig. 7)

Fig. 13. Maximum differences of transient pressure traces between the guided skeletonization scenarios and the original model for all the demand nodes