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Calculation of the mean residence time in distribution systems from tracer studies and models

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ABSTRACT

The residence time of water within the distribution system (DS) is a key parameter to characterize the extent of disinfectant loss and disinfectant by-product formation. While hydraulic models include calculation of a parameter referred to commonly as 'water age', the expense of development and calibration has restricted their availability. Chemical tracer studies provide a less expensive alternative way to estimate water age even if these may need to be repeated to capture the seasonal range of water demand. This research presents a technique to calculate the 'mean residence time' (MRT) from tracer studies by applying well-known principles from chemical reactor engineering. A numerical experiment was first performed using a pipe network from a case study. A negative step input of a conservative chemical to a case study DS was simulated using the EPANET model. The response curves at a series of nodes were predicted by the water quality sub model of EPANET from which the MRT_{model} values were calculated. MRT_{model} values were close to the average water age as predicted by the hydraulic sub model of EPANET. Actual tracer studies were conducted in the distribution systems of Raleigh (serving 250,000) and Durham (serving 190,000), North Carolina. MRT_{field} values were calculated from tracer response data at a series of sampling stations. A highly skeletonized hydraulic model was available for the Raleigh DS to generate a predicted average water age. The MRT_{field} values at 12 stations were consistently higher than average water age, most likely because the hydraulic model was too highly skeletonized. The tracer study in the Durham DS showed the use of two or more tracers to calculate an MRT_{field} that was weighted by the percentage contribution of water from each of two water treatment plants.

Key words | distribution systems, tracers, water age, water quality models

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INTRODUCTION

The distribution system (DS) is a large and complex reactor in which many important changes occur in finished water quality. Disinfectant residual is lost by oxidation reactions in both the bulk water and on the surface of pipes. Disinfection by-products (DBPs), most notably the regulated trihalomethanes and haloacetic acids, continue to form by reaction between the residual disinfectant (if free chlorine is used) and DBP precursors that are present in the finished water. However, as disinfection residual disappears because of oxidation reactions, bacterial regrowth can also occur and this also has been shown to cause biodegradation of haloacetic acids. To quantify the extent of these reactions as well as others of interest, the residence time of water within the DS must be known. Residence time can be predicted by a hydraulic model of the DS or measured experimentally with a tracer test. Better knowledge of water residence time allows water utilities to decide the location of sampling stations where disinfectant residuals may be lowest or where DBPs may be highest in accordance with the proposed EPA Stage 2 Disinfection/Disinfection By-products Rule (US EPA 2003).

Hydraulic and water quality models of the DS such as EPANET (Rossman *et al.* 1994; Rossman 2000) include a

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subcomponent for calculation of the temporal variation in water age at any location within the DS. Practical and reliable applications, however, require a significant investment in time and money for calibration and verification of such models, especially in large and complex distribution systems. In particular, water age may not be determined satisfactorily unless most pipes are represented in the model and demand is distributed accurately among the nodes of the network.

Chemical tracer studies are suggested for calibration of hydraulic models (Grayman & Clark 1998). They can also be used independently to obtain estimates of residence time to different locations within the DS. However, a standardized methodology for the conduct of tracer studies and interpretation of the resulting data has not been put forth. Moreover, comparisons between residence times obtained from tracer studies and computer modelling have not been widely published. An additional concern is the design of a tracer study when water enters the DS from more than one water treatment plant (WTP). Depending upon the design and operation of the DS, the water at any location in the DS can be a blend of waters from these multiple sources. If the same chemical tracer is used at all treatment plants, it is impossible to distinguish the contributions of water from each source during a tracer test.

The objectives of this research were to: (1) propose a simple, quantitative method to calculate the mean residence time (MRT_{field}) from field tracer studies; (2) compare the MRT_{model} with water age as calculated by EPANET; and (3) demonstrate a multiple tracer technique to maximize the information gained in DS served by more than one WTP. These objectives were met with the aid of tracer studies conducted in the DS of Raleigh and Durham, North Carolina.

DEVELOPMENT OF MEAN RESIDENCE TIME

The MRT derives from the well-known theory of exit-age distribution that is used to characterize reactor behaviour in environmental systems (Weber & DiGiano 1996). The most common type of tracer study in a DS consists of a step input of a conservative chemical in the finished water. The response to this stimulus is a change in the tracer concentration at any location within the DS. Eventually, the concentration at each location will reach the new tracer concentration introduced into the finished water as the step input. In classic reactor engineering, the 'F curve' is constructed from the data points by dividing the concentration at the measurement location by the concentration of the step input to create a fractional concentration, F. It represents that fraction of the step change in input tracer concentration that has arrived at the measurement location up to time, t.

The most typical tracer study consists of turning off the fluoride feed such that the fluoride concentration decreases abruptly to the background concentration in the finished water. Thus, the tracer study is initiated by negative rather than positive step input, so that the tracer concentration must decrease with time. The longer the time for each water parcel to arrive at a sampling point from the WTP, the longer it will take for the tracer concentration to decrease, that is, the slower the response to the tracer input.

The MRT at any point in the DS is given by:

$$MRT = \sum_{0}^{n} t_i \Delta F_i\,(t) \tag{1}$$

where i is the i-th water sample, t_i is the time elapsed from the beginning of the negative step input, $\Delta F_i(t)$ is the change in fractional concentration, F_i, of the tracer over the time interval between samples and F_i is defined by:

$$F_i(t) = \frac{[Tracer]_{Before} - [Tracer]_{t_i}}{[Tracer]_{Before} - [Tracer]_{After}} \tag{2}$$

where the subscripts 'Before' and 'After' designated the tracer concentrations before and after the negative step input, respectively. In effect, $F_i(t)$ is a weighting function to account for the fractional composition of 'new water' (after introduction of the negative step input) that has mixed with the 'old water' (before the introduction of the negative step input). Accordingly, $F_i(t)$ increases from 0 to 1 over the course of the tracer study as depicted in Figure 1 and the area above the F curve is the MRT. The derivation of Equation 1 from the residence time distribution

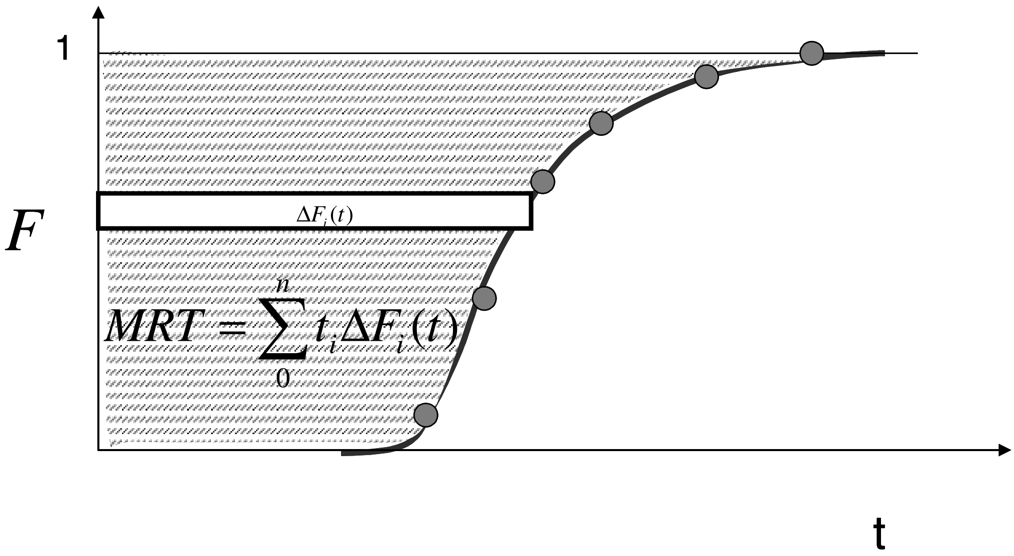

Figure 1 | Determination of MRT from tracer data where F is determined from Equation 2 and t is time elapsed from start of tracer input.

theory is available (Weber & Di Giano 1996). Implicit in the mean residence time calculation are the effects of temporal variations in water demand, blending of water that occurs at pipe junctions and other important operational parameters such as filling and emptying of storage tanks.

While the MRT method is appealing for its simplicity, it strictly applies to analysis of step input of tracer. However, an instantaneous decrease (i.e. a step decrease) is difficult to achieve if the addition point of fluoride is ahead of the clear well. In this situation, the clear well serves as an equalization tank that smoothes the step decrease into an exponential decay function. Even though the step assumption is not valid, the fluoride concentration pattern will decrease with time at each sampling point in the distribution system so that an F curve can be plotted and the MRT can be calculated. As will be shown for a practical application of a tracer study in a DS, the F curves resulting from a step decrease and an exponential decrease are very similar.

This research also includes a comparison of MRT with water age, as calculated within EPANET and other commercial pipe network models by accounting for the travel time from sources, inputs and mixing at nodes, and interaction with storage tanks (Rossman 2000). Water age is dynamic because of temporal variations in water demand that change the local water velocity at any node, and thus the residence time of water parcels at each node throughout the day. However, repetition of the same daily demand pattern over many days leads to a quasi-steady state condition of periodic age variation from which an average water age is calculated by the model.

EXPERIMENTAL METHODS

Tracer Study in Raleigh, North Carolina

The DS for Raleigh, was selected to test the MRT concept because both a network model and a fluoride tracer study were available. This DS serves about 250,000 customers and the average water demand is about $159 \times 10^3\ m^3\ day^{-1}$. The fluoride feed was turned off on 21 September 1998 and measurements of fluoride concentration were made at 20 stations over a 5-day period. Of these stations, nearly complete F curves (i.e. F increasing from 0 to near 1) were obtained in 5 days of sampling at 12 stations. The location of the stations is provided in Figure 2.

A hydraulic network model was developed for the Raleigh distribution system in 1992 by Pitometer

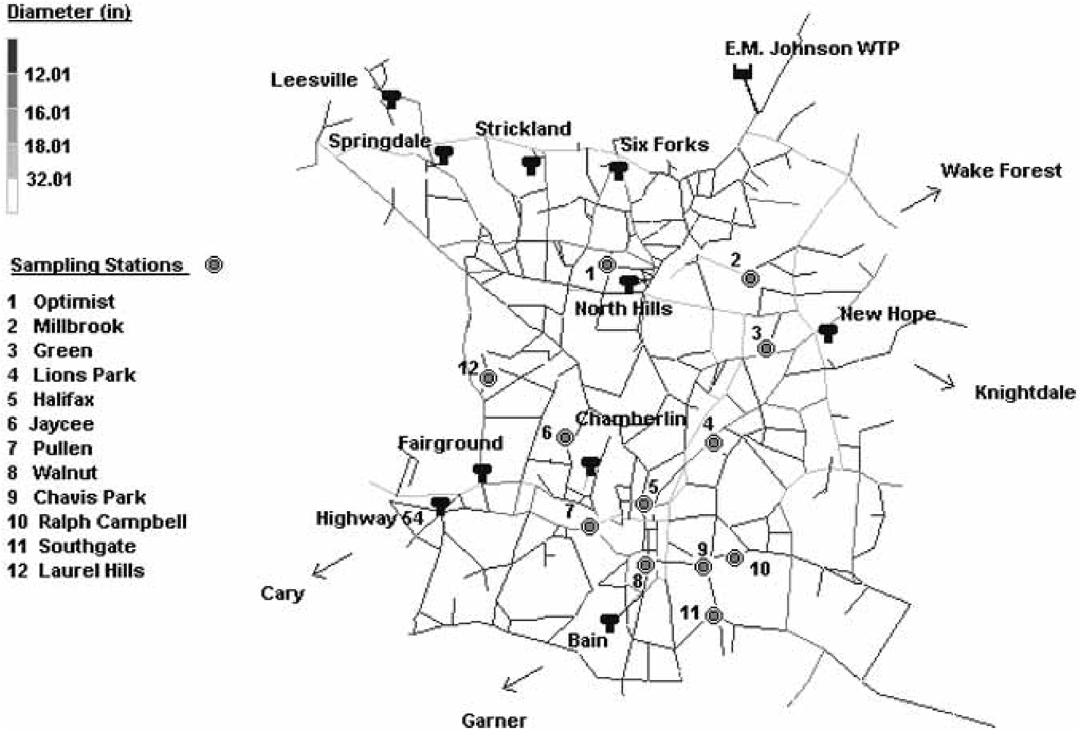

Figure 2 | Skeletonized DS pipe network in Raleigh, North Carolina, showing location of water storage tanks and sampling stations.

Associates with WaterMax software. This model was calibrated in 1993 and was only intended for use as a planning tool for hydraulic capacity (Cruickshank 1993). Of the approximately 1,760 km of pipes in the distribution system, only 576 km of pipes having a diameter equal to or greater than 30.5 cm are included. This represents a 32% skeletonization of the system. There are 10 storage tanks with a total capacity of about 105.8×10^3 m^3 in the DS; their locations are provided in Figure 2; there are four pressure zones. Demand was also updated from 1992 to 1997 to reflect an increase in water consumption due to the new residential developments.

The existing network model in WaterMax format was converted into a format compatible with EPANET version 2 (Rossman 2000). The calibration procedure consisted of adjusting some of the parameters in the dataset until the water level in each of the 10 storage tanks predicted by the model matched the level observed on 21 September 1998, the start date of the fluoride tracer study. Details of the calibration procedure are presented elsewhere (DiGiano et al. 2002). The time patterns of wholesale customer as well as small retail demand were adjusted as part of the calibration effort. The pipe roughness coefficients were not changed from those in the original WaterMax configuration because new field data for pressures and velocities were unavailable. Three discharge pumps at the WTP had to be adjusted within the data file to match measurements from flow meters at the plant. Given the unavailability of billing records and land use maps, the 'small retail' water demand (i.e. the average demand for commercial and residential use smaller than 379 m^3 day^{-1}) was equally distributed among the nodes of the network within each pressure zone. A more accurate approach would have been to examine building permits issued between 1990 and 1997 and then to adjust the demand upward to reflect changes from 1997 to 1998 using factors applied equally to all nodes in a pressure zone. Whether this approach would have led to better predictions of the system conditions for September 1998 (pressure and velocity in the pipes, water level fluctuations in the tanks, etc.) cannot be stated conclusively without considering the importance of large demands by eight wholesale customers.

The following drawbacks of the Raleigh DS model are readily acknowledged: (1) calibration efforts have been outdated since 1993; (2) field data to update the roughness coefficients, water demand allocation and daily pattern of water demand were unavailable; (3) water demand has been redistributed since 1993; (4) system changes have occurred owing to replacement of pumps and storage tanks; and (5) skeletonized models do not capture the water age accurately (Clark & Grayman 1998; Walski 2000; Walski *et al.* 2001). Nonetheless, the modelling exercise was considered useful because it provided a rough comparison between the MRT measured from the field tracer study (MRT_{field}) and water age calculated from EPANET. Moreover, the model was also used as a stand alone tool to compare the MRT with water age. That is, a numerical experiment was performed in which F curves were generated by the model at locations in the DS in response to a tracer input. In this way, the F curves were used to calculate MRT from the modelling results (MRT_{model}) for comparison with water age. Whether the model truly represents the Raleigh DS is not essential for this comparison.

Tracer Study in Durham, North Carolina

The population served by the DS in Durham is about 190,000 with an average daily demand of 121×10^3 m^3 day^{-1}. The total length of pipe is similar to that in Raleigh (about 1,760 km). At the time of the tracer study, a water quality DS model was not available. The DS is supplied by the Brown and Williams WTPs. There are two pressure zones and three elevated storage tanks. The location of these WTPs, and those of the nine sampling stations used in the tracer study are provided in Figure 3.

A unique tracer study was developed to determine simultaneously the percentage contribution to flow from each WTP at each sampling station and the flow rate weighted average of the MRT_{field}. The tracer study consisted of a switch from ferric chloride to alum as the coagulant at the Brown WTP on 15 April 1999. Alum was in continuous use at the Williams WTP during the same study period. Measurements were made of the decrease in Cl^- and increase in SO_4^{-2} concentrations in the finished water of the Brown WTP and at stations within the DS; the measurement technique was ion chromatography as conducted at the Brown WTP laboratory. The fluoride feed at the Brown WTP had also been turned off several weeks before the tracer study in order to reach background concentration prior to the tracer study. The fluoride feed at the Williams WTP was turned off on 15 April 1999 simultaneously with the switch in coagulants at the Brown WTP. Measurements of the decrease in F^- concentration were made electrochemically by an ion-specific electrode. The responses to all three tracers (Cl^-, SO_4^{-2} and F^-) were used to measure the MRT_{field} from both WTPs at each of 10 stations in the DS. This permitted calculation of a weighted average of MRT_{field} based on the percentage of water arriving from each WTP at each sampling station. The percentage contribution of water from each WTP at each station was also calculated from the concentrations of each tracer chemical compared with those entering the DS from the two WTPs under steady-state feeding conditions that existed prior to the tracer study.

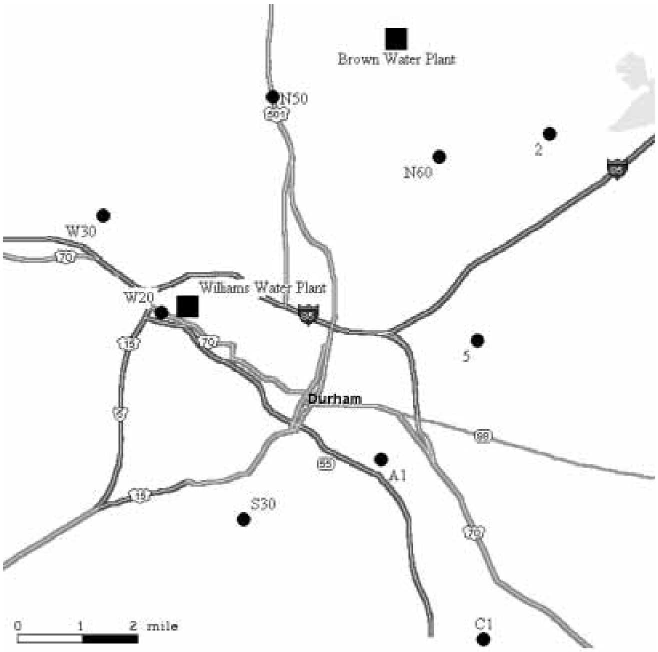

Figure 3 | Location of two WTPs and sampling stations in the Durham DS.

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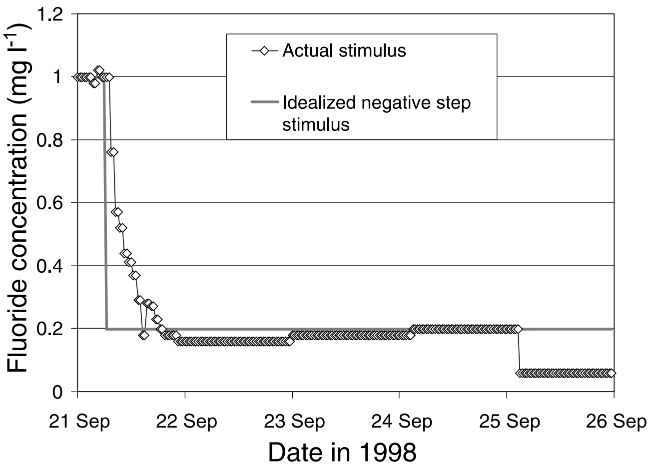

Figure 4 | Actual pattern of fluoride tracer concentration at leaving the clearwell of E. M. Johnson WTP in Raleigh and the idealized, negative step input used for comparison in the EPANET model.

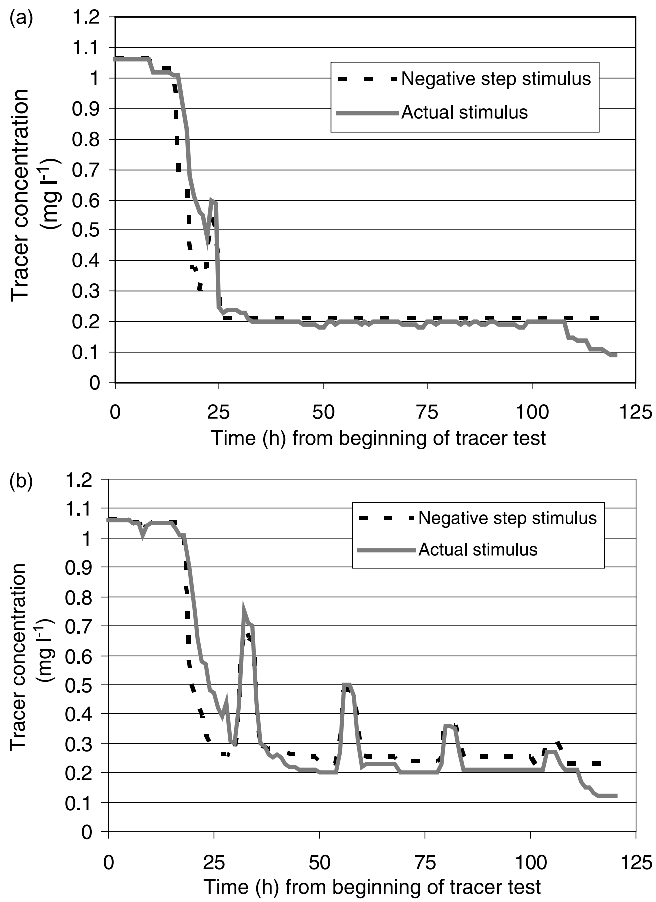

Figure 5 | EPANET predictions of tracer response at (a) Lions Station and (b) Laurel Station for simulations of both a negative step stimulus and the actual stimulus pattern at E. M. Johnson WTP in Raleigh.

RESULTS

Calculation of MRT_{model} from tracer response prediction by EPANET

F curves predicted by EPANET at selected sampling stations in the DS were used to calculate the MRT_{model} according to Equation 1. The area above the F curve was found by fitting a smooth tracer response curve through the experimental data and calculating the area above the F curve by the simplified trapezoidal rule:

$$Area = \sum_{i=0}^{i=N} \frac{\Delta F_i}{2}(t_i + t_{i+1}) \tag{3}$$

This formula works well, for the F curves increase monotonically. However, a few of the F curves had small segments in which F declined. The ΔF_i values for these segments were set equal to zero.

As shown in Figure 4, a step decrease and an exponential-like decrease in tracer input concentration were simulated within the EPANET model. The latter stimulus is referred to as the 'Actual stimulus' in Figure 4 because it was taken directly from the measurements of fluoride made at the exit of the clear well during the September 1998 tracer study. In residence time theory, the same result should be obtained either by introducing an ideal step or a pulse input in tracer studies (Weber & DiGiano 1996). However, the error introduced in analysis of residence time distributions, or more specifically, in calculation of the MRT by not achieving either of these ideal inputs, is rarely discussed. The EPANET model provided a convenient way to explore the effect of a non-ideal tracer input pattern on the MRT calculation.

For illustrative purposes, the tracer response predicted by EPANET for the two types of tracer input is shown in Figure 5a for Lions station and in 5b for the Laurel station in the Raleigh DS. Neither type of input gave a completely smooth tracer response curve at either

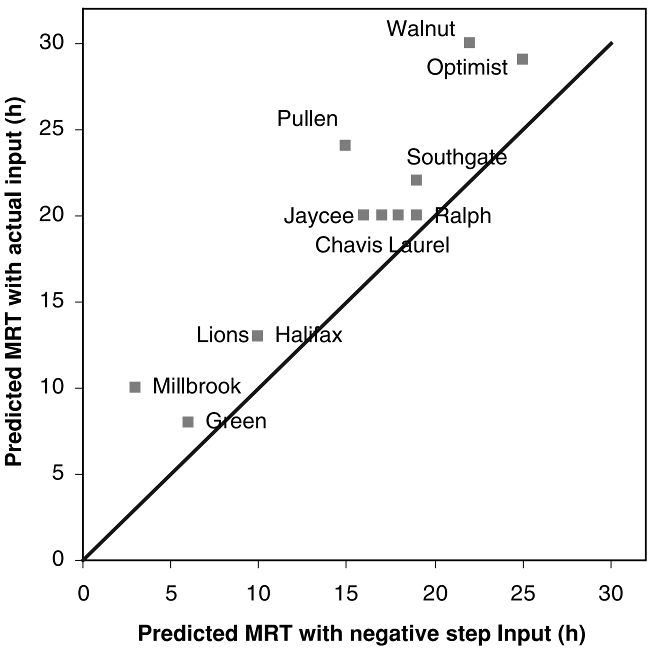

Figure 6 | Comparison of MRT (h) for actual and negative step input both predicted by EPANET for sampling stations in Raleigh DS.

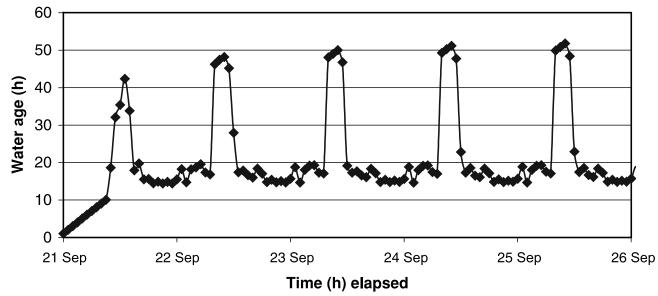

Figure 7 | EPANET simulation of water age at Southgate Station in Raleigh.

station as would be typically found when conducting a tracer study in an engineered reactor under steady flow conditions. Instead, the pattern is jagged, particularly because of many factors that affect the transport of tracer to any location, including mixing at pipe junctions and release of tracer when water enters the DS from storage tanks in response to variations in water demand. Nevertheless, the predicted tracer response at either station is not significantly affected by the assumption used for the type of tracer input function.

The predicted response curves were then used to calculate F curves by Equation 2 and subsequently, the MRT_{model} was calculated by Equation 1. The MRT_{model} values are compared for the two types of tracer input in Figure 6. Perfect agreement would correspond to a line with a slope of 1. These results indicate that the MRT_{model} for the actual input concentration pattern of the tracer was consistently somewhat larger than the MRT_{model} for an idealized, negative step input. Nevertheless, a strong linear correlation (0.93) exists between the two MRT_{model} values.

Comparison of MRT_{model} and water age

The water age predicted by EPANET at one of the sampling stations of the Raleigh network for a 5-day simulation is provided in Figure 7. The initial water age of zero and the gradual increase in the maximum water age as simulation time progresses are both artefacts of the initializing condition used in the EPANET model wherein water parcels all have a water age of zero. As the 24-hour pattern of water demand repeats itself day after day, the effects of water storage in tanks and elsewhere in the DS on water age begin and the model eventually leads to a quasi-steady state pattern of water age. At most sampling nodes, water age reached a maximum at around 9:00 a.m. when the DS has a peak in demand and the storage tanks drain to meet this demand. The water parcels that were held in the storage tanks during the night are released into the network and, hence, contribute to increase the age of water in the pipes of the DS. Simulations with EPANET were extended from the 5-day period in Figure 7 to 20 days. These showed very little further difference in the 24-hour cyclical pattern. Therefore, the last 24-hour cycle in Figure 7 was used to report the minimum, maximum and average water age (this value is calculated by EPANET).

The MRT_{model} as calculated from EPANET (with the actual tracer input from September 1998) is compared in Table 1 with the average, minimum and maximum water age. With the exception of the two stations with the lowest water age (Millbrook and Green), the MRT_{model} and the average water age are in good agreement. The discrepancy at the two lowest water age values may be due to inaccuracy in the MRT_{model} calculation if too few data points on the F curve were included in Equation 1; that is, the shape

Table 1 | Comparison of MRT_{model} from simulation of actual tracer stimulus in EPANET with predictions of average, maximum and minimum water age

Station	MRT_{model} (h)	Average water age (hours)	Maximum water age (h)	Minimum water age (h)
Walnut	30	28	75	10
Southgate	22	23	53	15
Ralph	20	22	47	15
Pullen	24	19	36	8
Optimist	29	26	34	8
Laurel	20	22	62	13
Chavis	20	21	52	12
Millbrook	10	3	4	2
Lions	13	11	13	7
Jaycee	20	18	20	15
Halifax	13	11	13	9
Green	8	3	5	3

of the F curve may not have been captured completely during the relatively rapid rise to F = 1. The results also indicate that the MRT calculation obviously cannot capture the daily variations in water age, which in the absence of a hydraulic model is a disadvantage.

Comparison of MRT_{field} and MRT_{model}

The EPANET model was used to generate predicted fluoride concentrations at the sampling stations used in the September 1998 tracer study from which MRT_{model} values were calculated. Agreement between predicted and measured fluoride tracer responses was quite variable as is illustrated by the results given in Figures 8 and 9; data for other stations are available elsewhere (DiGiano *et al.* 2000). The disparity between predicted and measured values of the fluoride tracer concentration resulted in disparity between MRT_{model}, as predicted by EPANET, and MRT_{field}, as calculated from measured tracer response data. Figure 10 shows that the MRT_{field} values are generally longer than the MRT_{model} values; moreover, the correlation coefficient between them is less than 0.3.

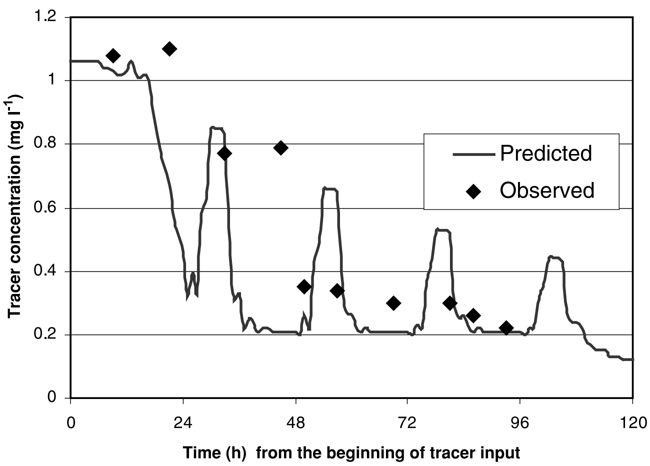

Figure 8 | Fluoride concentration at Walnut Station in Raleigh as predicted by EPANET and actually measured during tracer study of September 1998.

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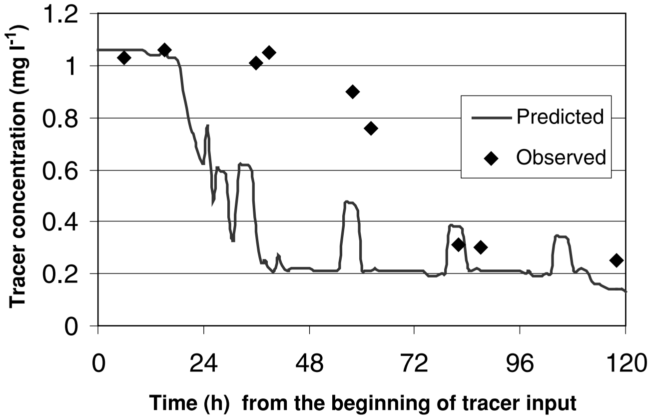

Figure 9 | Fluoride concentration at Southgate Station in Raleigh as predicted by EPANET and measured during tracer study of September 1998.

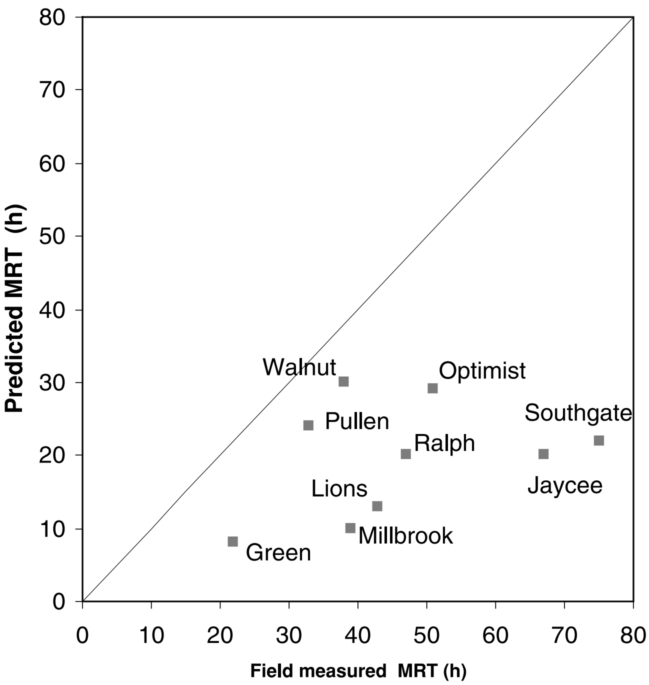

Figure 10 | Comparison of MRT_{model} (h) with MRT_{field} (h) from Raleigh tracer study.

The most likely explanation for lack of agreement between MRT_{field} and MRT_{model} is that the DS model did not include all pipe segments through which a chemical constituent is transported. In this particular skeletonized version of the DS, the EPANET model did not include pipes less than 30.5 cm where most of the sampling stations were located. A skeletonized version of the DS should predict shorter travel times because fewer pathways for water movement have been included (Clark & Grayman 1998; Walski 2000; Walski *et al.* 2001). Shorter travel time leads to a more rapid decrease in fluoride concentration than would be measured at corresponding sampling stations in the DS and thus shorter MRT_{model}. Notwithstanding the admitted inadequacy of a skeletonized model, lack of agreement between MRT_{field} and MRT_{model} could also have been due to out-of-date information about DS; inadequate calibration due to lack of data; valves that were improperly specified as open when they were closed or vice versa; and inaccurate specification of water demand within each pressure zone.

The results above serve to emphasize that skeletonized models should not be used for water quality modelling because the locations of greatest concern are those with the longest travel time, which would be underestimated. Instead, skeletonized models are used in master planning such as to determine location of low pressure areas and expansion of a DS to service more customers (Walski *et al.* 2001). The drawback to inclusion of all pipes for more accurate water quality predictions, however, is the cost of data entry and robust calibration.

Tracer study for two WTPs in Durham, North Carolina

The patterns of increase in sulfate and decrease in chloride concentration entering the DS from the Brown WTP as a result of the switch in coagulants are presented in Figure 11. Ideal positive and negative step inputs were not achieved owing to the equalization effect of the clear well. The fluoride concentration remained at background because the fluoride feed had been turned off weeks in advance of the tracer study. The corresponding patterns of chloride, sulfate and fluoride concentrations entering the DS from Williams WTPs are illustrated in Figure 12. Because the coagulant remained as alum, the concentrations of chloride and sulfate remained relatively constant. The fluoride concentration decreased in response to turning off the fluoride feed in a pattern that is fairly close to a negative step input.

Illustrative responses to the three tracer inputs are given in Figures 13 and 14 for two stations in the DS

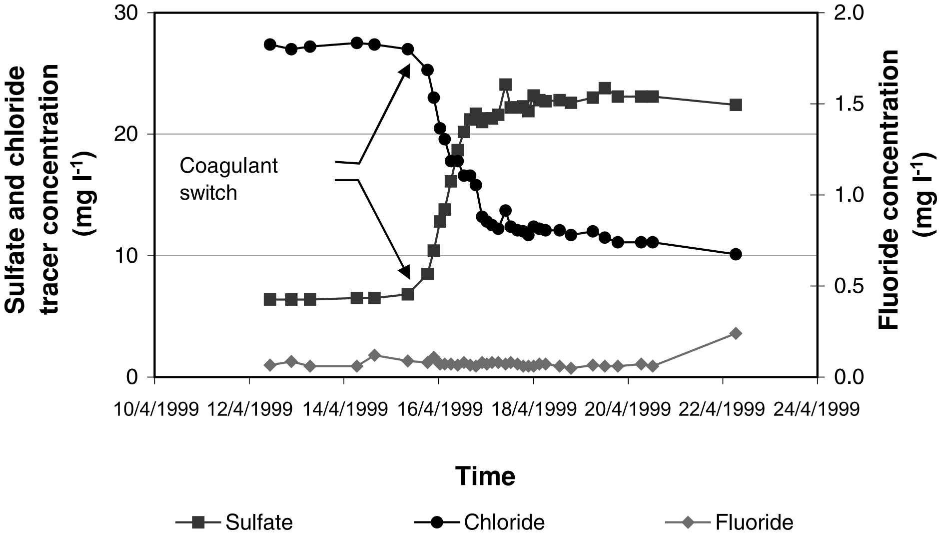

Figure 11 | Tracer concentrations in the finished water at the Brown WTP in Durham.

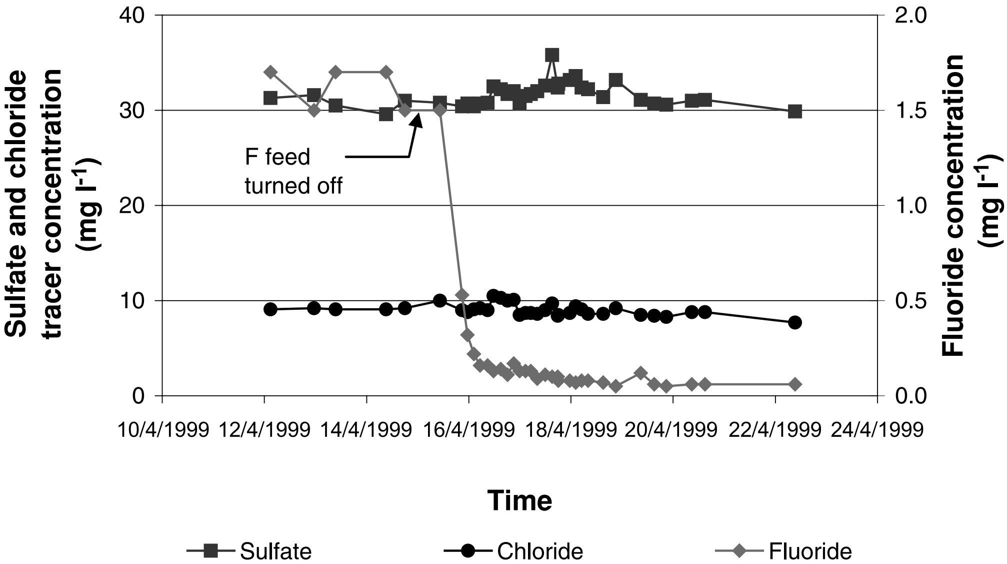

Figure 12 | Tracer concentrations in the finished water of the Williams WTP in Durham.

before and after the start of the tracer test; data for other stations are available elsewhere (DiGiano *et al.* 2000). In general, the response curves showed relatively smooth changes in tracer concentration that reflected the change in either the fluoride concentration or the shift in coagulant at each WTP. This pattern would suggest that the percentage contribution from each WTP at each station remained about the same over the 7 days of observation.

The calculation of percentage contribution from each WTP at each station was determined from concentrations of Cl^- and SO_4^{-2} at each station during the steady state period just prior to the tracer study (14 April 1999). At that time, $FeCl_3$ was the coagulant at the Brown WTP

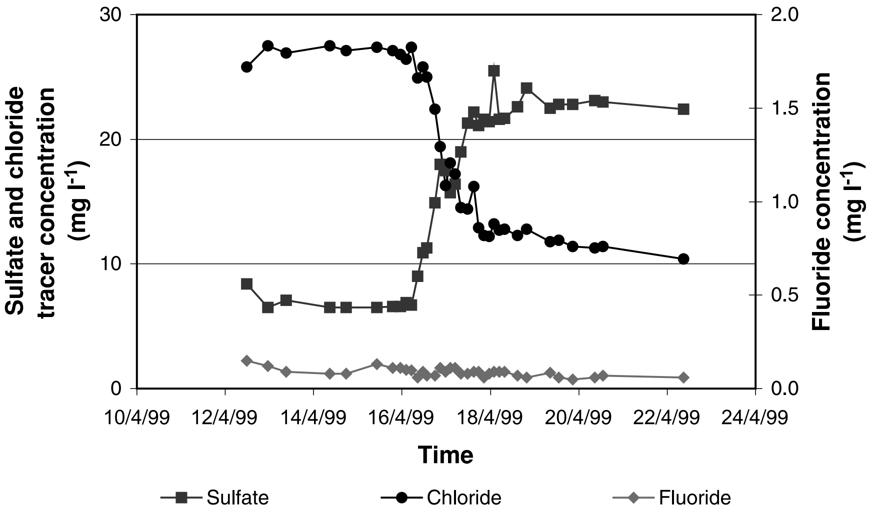

Figure 13 | Tracer responses at Station A1 in Durham.

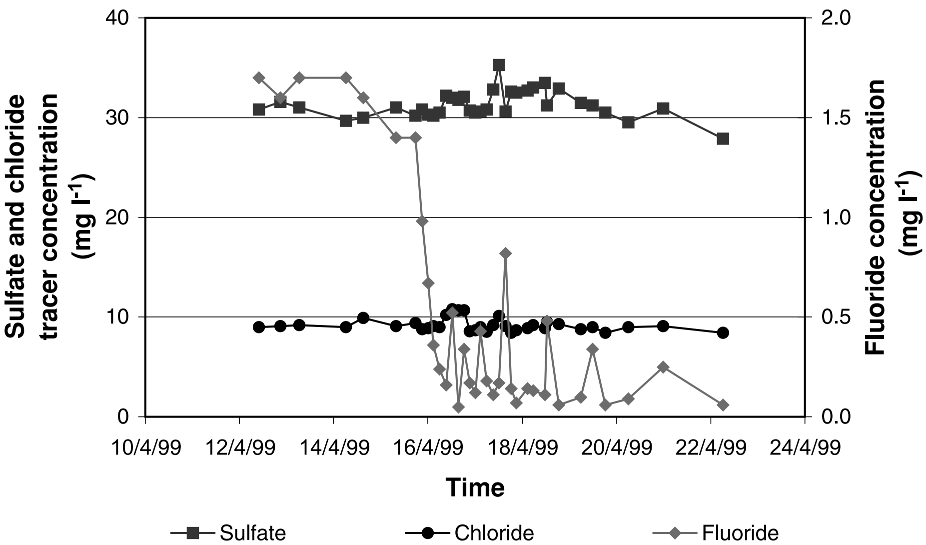

Figure 14 | Tracer responses at Station W20 in Durham.

and $Al_2(SO_4)_3$ was the coagulant the Williams WTP. In addition, the fluoride feed had been turned off at the Brown WTP but not at the Williams WTP. With three chemical tracers, it was possible to calculate the percentage contribution by:

$$\%\ Williams\ WTP = \frac{[F^-]_{Station} - [F^-]_{Finished\ Brown\ WTP}}{[F^-]_{Finished\ Williams\ WTP} - [F^-]_{Finished\ Brown\ WTP}} \times 100 \qquad (4)$$

$$\%\ Williams\ WTP = \frac{[SO_4^{-2}]_{Station} - [SO_4^{-2}]_{Finished\ Brown\ WTP}}{[SO_4^{-2}]_{Finished\ Williams\ WTP} - [SO_4^{-2}]_{Finished\ Brown\ WTP}} \times 100 \qquad (5)$$

$$\%\ Williams\ WTP = \frac{[Cl^-]_{Station} - [Cl^-]_{Finished\ Brown\ WTP}}{[Cl^-]_{Finished\ Williams\ WTP} - [Cl^-]_{Finished\ Brown\ WTP}} \times 100 \qquad (6)$$

Table 2 | Calculation of percentage contribution from two WTPs

				Calculated by F^-		Calculated by SO_4^-		Calculated by Cl^-	
Sampling station	F^- (mg l^{-1})	SO_4^- (mg l^{-1})	Cl^- (mg l^{-1})	Williams WTP	Brown WTP	Williams WTP	Brown WTP	Williams WTP	Brown WTP
Williams WTP	1.7	29.6	9.1						
Brown WTP	0.1	6.5	27.5						
N50	0.1	6.6	27.2	0	100	0	100	0	100
A1	0.1	6.5	27.5	0	100	0	100	0	100
5	0.1	6.5	27.4	0	100	0	100	0	100
C1	0.1	6.5	27.5	0	100	0	100	0	100
N60	0.1	6.6	27.6	0	100	0	100	0	100
2	0.5	6.6	27.8	19	81	0	100	0	100
S70	0.2	8.7	25.8	19	81	20	80	20	80
S30	1.6	30.2	10.1	87	13	83	17	83	17
W20	1.7	31.0	9.2	100	0	95	5	98	2

Each of these equations accounts for the concentration of each tracer when not added at the WTP. For example, the fluoride feed had been turned off at the Brown WTP but the concentration in source water must be included to calculate the percentage contribution from the Willams WTP correctly. The resulting values of percentage contribution from the three tracer calculations above are listed in Table 2. These show that the sampling stations nearest to each of the two WTPs receive water almost entirely from each respective WTP as expected. There was good agreement among the results calculated from the three different tracers.

The tracer response curves (e.g. Figures 13 and 14) were used to generate F curves (Equation 2) at each station. Because the F curves were specific representations of the tracer response from one of the two WTPs, MRT_{field} values were calculated for water originating for each of the two WTPs. The fluoride response data allow calculation of the MRT_{field} (Equation 1) for water arriving from the Williams WTP and the sulfate or chloride response data allow calculation of the MRT of water arriving from the Brown WTP. A weighted MRT_{field} was then calculated from the percentage contribution of water from each WTP. For example, if the water at a given station comprises 70% from Brown WTP and 30% from Williams WTP, and the MRT_{field} is 25 h for water from the Brown WTP and 40 h for water from the Williams WTP, the weighted MRT_{field} would be:

$$\text{Weighted } MRT_{field} = 25(h) \times 70\% + 40(h) \times 30\% = 29.5(h) \quad (7)$$

The percentage contributions from each WTP used in Equation 7 to find the weighted MRTs at each sampling station are given in Table 3; the weighted MRT_{field} values varied from 6 to 254 h.

CONCLUSIONS

The MRT is easily calculated from tracer data in the form of either a positive or negative step input at the WTP. In

Table 3 | Estimates of weighted MRT for stations in the Durham distribution system

	% Contribution		
Sampling station	**Williams WTP**	**Brown WTP**	**MRT (h)**
N50	0	100	6
A1	0	100	19
5	0	100	30
C1	0	100	34
N60	0	100	89
2	0	100	254
S70	20	80	55
S30	84	16	38
W20	99	1	14

the absence of a water quality simulation model for the DS, the MRT could be useful to locate areas where degradation in water quality occurs due to long residence times; this parameter could help to focus on more direct measures of system performance such as disinfection residual, DBP formation and bacterial indicators.

Numerical experiments with EPANET were used to show that tracer response predictions give an MRT_{model} that closely approximated the average water age that is calculated within EPANET. Because MRT is by definition an averaging procedure, the daily variations in water age due to filling and emptying of water storage tanks and changes in water velocity within pipes are not captured. Nevertheless, the value of the MRT is especially noteworthy when a complete hydraulic model of the DS is not available. The cost of developing such models and calibrating them is far greater than the cost to conduct tracer studies.

Although the MRT_{model} compares favourably with water age, the MRT_{field} values which were calculated from an actual fluoride tracer study in the Raleigh DS were much longer than MRT_{model} values as calculated from the tracer response curves predicted by EPANET. This discrepancy could have been due to the skeletonization of the DS (fewer than 35% of the pipes in the DS had been included), although limited calibration and assumptions about the daily water demand patterns could also be responsible.

Tracer response data that were unique to each WTP in the Durham system were obtained by shifting the coagulant of one WTP from ferric chloride to alum and simultaneously turning off the fluoride concentration at the other WTP. The percentage contribution of water from each WTP at each station in the DS was also determined from steady-state concentrations of chloride and sulfate before the switch when ferric chloride was used at one WTP and alum at the other.

The usefulness of the MRT calculation needs to be confirmed through more comparisons between tracer studies and network models. In particular, tracer studies are needed at sampling locations on pipes with small diameters that are already included in a well-calibrated network model. Based on these first results, however, the MRT calculation appears to offer a simple but effective alternative to network model estimates of water age that water utilities can calculate by conducting a tracer study without the need to develop and continuously upgrade a network model. The disadvantage to the MRT approach, however, is that the extent of information is limited by the number of stations at which tracer response data are collected. In contrast, a hydraulic simulation model of the DS, which includes all pipes, provides water age information at all locations. Even if a hydraulic model is available, tracer studies are still very useful for hydraulic calibration; in such applications, the opportunity also exists to calculate MRT values.

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Department City of Durham, North Carolina originally proposed the idea to use the dual tracer approach.

NOTATION

F = fractional concentration (dimensionless)

MRT_{field} = mean residence time (h) measured from tracer tests at sampling stations in a distribution system

MRT_{model} = mean residence time (h) calculated from tracer response curve at distribution system nodes predicted by EPANET with a tracer input pattern

t = time (h)

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