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Modeling and field work to investigate the relationship between the age and the quality of drinking water at customer's taps

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Abstract: It has been widely theorized that water age may be a useful indicator of the quality of water within drinking water distribution networks. However, there is limited evidence of model simulation results being related to empirical water quality (WQ hereafter) data to substantiate the theory. This paper presents the findings of investigations designed to determine if there was an observable relationship between mean water ages calculated using a WQ simulation model, and measured WQ in two live distribution networks.

The age of water in all pipes was calculated using Aquis hydraulic and WQ modeling software. Historic regulatory WQ data was examined to determine if there was a relationship between general WQ and calculated water age within the networks. A more detailed study was then undertaken in one network by translating model locations that were representative of the spread of water age into real world locations. WQ samples were taken intensively from these sites and analyzed for a range of aesthetic, physical, chemical, and bacteriological parameters indicative of general WQ.

Some relationship between the calculated mean age of water and the general WQ in the network was demonstrated. Analysis that considered calculated water age and associated WQ along unperturbed flow routes through the network produced a stronger relationship. Given that regulatory WQ within the study networks as reported to the Drinking Water Inspectorate (DWI) was 99.9% compliant, this relationship was deemed noteworthy.

CE Database headings: water age, WQ, distribution networks, customer's taps, modeling

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INTRODUCTION

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When drinking water is transferred through distribution networks the quality often deteriorates. The mechanisms causing deterioration are complex, involving numerous interactions between the water and the asset materials that comprise the pipe networks; and physical, chemical and biological reactions that occur within. In the UK, failures include a consistent number of bacteriological samples and, despite extensive conventional investigation and expansive intervention, UKWIR (2006) reported that, in many cases, the cause of these failures could not be explained. The Drinking Water Inspectorate (DWI) recommended that water companies should look deeper into the problem in an effort to obtain an understanding of the reasons for the failures, and have advocated the use of calibrated hydraulic and WQ models (Rouse, 2000).

It has been theorized that the time water spends in a distribution network influences WQ; for example, taste and odor, corrosion rates, material precipitation, discoloration, disinfection by-product formation and biological activity (AWWA, 2002). Water age is not directly measurable, but can be estimated as a mathematical approximation, and residence time can be measured using tracer techniques (Skipworth et al., 2002, DiGiano et al., 2005, Rubulis et al. 2010). These methods are potentially useful surrogates for general WQ, but the relationship between simulated water age and empirical WQ data has not been proven in practice.

This paper first presents the findings of an evaluation of the calculated age of water within two distribution networks, and how this relates to the underlying WQ characteristics as represented by historic regulatory sample results. This is followed by a presentation of the results of a more detailed investigation in one of the networks. A number of customer taps were used to access water volumes with a spread of different calculated ages. WQ samples were taken intensively from these locations and analyzed for standard regulated parameters in line with water industry standard quality assurance practice and methods (Eaton et al. 2005). The results were evaluated to determine whether there was any relationship between the calculated water mean age and measured WQ at the customer taps.

SCIENTIFIC BACKGROUND

Potable WQ

Specific effects of water age on WQ have been documented. Older water was shown by Burlingame (1995) to be more corrosive to iron pipes. Mutoti et al. (2007) showed that the release of iron was a function of the water chemistry and the hydraulic flows within the network.

Increased water temperature promotes bacteriological activity, initiates new reactions, increases the rates of existing reactions, and pushes the reaction equilibrium towards by-product formation (Haas et al. 1984, Reilly and Kippin 1983, Chung et al. 2003, Toroz and Uyak 2005); for example, the formation of trihalomethanes (THMs).

Low flow network areas provide more time for corrosion products to be taken into solution, and for temperature gradients to affect the bulk water volumes. Rossman et al. (1994) and Wu et al. (2005) highlighted that older water may have little or no residual disinfectant due to substance decay and reactions with network materials resulting in reduced biocide efficiency and promoting additional biological activity that could give rise to unpleasant tastes and odors.

Similarly, turbidity may be generated by the sloughing of biological material and organisms from the pipe walls into the bulk flow increasing the probability of failed regulatory bacteriological samples (Ohashi and Harada 1994; Peyton and Characklis 1993; Picioreanu et al 2001; Rittmann 1982; Stoodley et al 2001; McCoy and Olsen 1985). Sekar et al. (2012) suggest bacterial composition and numbers, over short durations, are governed by the interaction of the bulk water and the biofilm influenced by network hydraulic conditions.

As this brief review highlights, the reactions and interactions within water distribution networks are kinetic in nature and therefore governed by time. No single WQ measurand can be directly associated with calculated water age at the current time. However, it is often theorized that water age has the potential to act as a surrogate indicative of general WQ.

Modeling WQ

1-Dimentional hydraulic simulation of distribution networks is well established and has age functionality generally based on substance transport and tracking algorithms. The Lagrangian time-based approach used in EPANET tracks the fate of discrete parcels of water as they move along pipes and mix together at junctions between fixed-length time steps, Liou and Kroon, (1987) and Rossman, (2000).

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It is possible to superimpose WQ algorithms on this hydraulic basis, but it is a complex task. Some studies have successfully used network models to predict chlorine decay (Rossman et al. 1994, Chambers et al. 1995, Hua et al., 1999), although with considerable effort in pipe specific calibration of wall and bulk reaction coefficients, and generally when chlorine concentrations were high.

Basha and Malaeb (2007) presented a highly accurate Eulerian–Lagrangian Method (ELM) for solving the unsteady advection-dispersion reaction equation using a non-uniform grid distribution and interpolation scheme that was especially effective in pipes with low flow velocities. ELM demonstrated improved advection and dispersion calculation for fluoride and chlorine modeling but still required accurate pipe wall coefficients to be manually input.

EPANET-MSX, a recent EPANET extension, enables modeling of complex reactions between multiple chemical and biological species in both the bulk flow and at the pipe wall (Uber, 2009). Examples include the auto-decomposition of chloramines, the formation of disinfection by-products and biological re-growth (Quiroz-Centeno et al. 2010, Andrade et al. 2010, Alexander and Boccelli, 2010, Rubulis et al. 2010).

Machell et al. (2009) described a method of characteristics approach utilized in Aquis. This method allows identification of the different age mixes contributing to the mean age, and tracking of maximum water age volumes that are “lost” using other methods.

It is currently quite difficult to model many WQ parameters directly because of the complexity and variability of the reactions, and the non-availability of the required reaction coefficients and other essential data components. However continued development of understanding and modeling functionality will eventually make this possible.

Whilst not a real WQ parameter, water age is a potentially useful, and practicably calculable, surrogate. However, as with all simulations, the accuracy of calculation is directly related to the quality, and the level of calibration, of the model being used. For this work, all-pipe Aquis models built to UK industry specification/calibration were provided by the collaborating water company. Calibration was to +/- 1m pressure, and +/- 10% flow using measured 15-minute values. No account was taken of weekend or seasonal effects and service reservoirs, i.e. storage tanks (SR hereafter) were assumed completely mixed. Tracer studies were not possible within the scope of the work.

In the United Kingdom, standards of hydraulic model performance have been recommended, along with criteria for extended period simulations (Water Authorities Association, 1989). Most models are calibrated using pressure data only, and it is interesting to understand what value such models can be for WQ modeling if applied as-is.

AIMS AND OBJECTIVES

This study was designed to determine how measured WQ relates to the calculated age of water within a network. The aims of the study were to: identify pipes containing water volumes of different age; evaluate historic regulatory WQ sample data; determine if there was a relationship between calculated water age and measured historic WQ data; undertake a program of sampling at locations where water volumes demonstrated different ages; analyze the samples for a range of physical, chemical and bacteriological parameters and determine if there was a relationship between WQ and age of water; paying special attention to bacteriological parameters.

METHODOLOGY

The work was undertaken in two distinct phases.

Phase 1 Methodology: Regulatory WQ and mean water age

Distribution networks within two water supply systems were selected for a comparative study of long term regulatory WQ data, and calculated water age. Both networks were large and complex, comprised of a number of interconnected District Metered Areas (DMA hereafter). Each network was served by two SRs; one at the inlet, and a second within the network.

Network1 was primarily urban, comprised of 8 DMAs. The hydraulic model contained 3881 pipes and 200 loops. Network2 had 15 DMAs a high proportion being rural. The hydraulic model contained 9073 pipes and 376 loops. Although network2 had more than twice the number of pipes, both networks had a similar cross section of pipe materials and diameters; the dominant material being iron (~70%). Network2 contained more uninterrupted runs of single pipes. Figure 1 presents the geometric layout of the networks with mean age of water superimposed as color bands.

Modeling methods were used to determine the mean age of water within both networks as Machell et al. (2009); using a repeating 24-hour flow and pressure profiles for boundary conditions.

Results for pipes with no flow were removed from the data set. Stagnation in dead ends is known to impact on WQ, but this can mostly be resolved by flushing, and was not the subject of this study. All sample points used in this work were on pipes with a measurable flow so that any deterioration in water quality is (most probably) attributable to travel time through the network (as opposed to stagnation mechanisms)".

Accurate water age can only be obtained after all the water in the modeled pipes has been replaced (Machell et al 2009). A 20-day simulation was found to ensure stable representative age values. Average, mode, 95th percentile, and highest mean ages for each network were calculated. Calculated water age values were exported to Excel and sorted into ascending order. This work investigated the *distribution* of water ages, not absolute values so results were allocated to "age bins", each 4 hours wide, starting at 1-4 hours increasing to 132-172 hours, representing the complete spread of water ages in the networks.

Water at inlets was assigned an age of "0". Age profile histograms were created, and potential WQ sample points (SP hereafter) for phase 2 identified. Six years of historic WQ data was collated, and average parameter values derived. Regulatory failures of WQ parameters within each network were normalized by the total number of samples taken in each network to enable comparison, and to determine if there was a simple high level relationship between the water age profiles and the general WQ within the networks.

Phase 2 Methodology: WQ at customers taps and mean water age

In phase 2, a more detailed analysis was undertaken in network2 which was found to have a wider range of water ages and poorer WQ. Network2 was split naturally by two SRs; Figure 2. The outlet of SR1 was assumed to have an age of 0.0 hours. The outlet of SR2 had a calculated age of 41 hours (travel time from SR1 plus the average residence time in SR2.

SRs have the potential to affect WQ by mechanisms different to those found in pipes, principally due to relatively large volumes and small surface areas, and complex internal hydraulics; in particular mixing. In order to reduce the computational complexity of modeling the tank, it was assumed that SR2 could be accounted for by an average residence time, analogous to a large pipe, but with the potential for distinct reaction and interaction effects.

Age calculations were used to find a series of sample sites distributed across the full range of ages in the network. 11 such areas were identified in the model, and were translated into real world locations using geographical information system (GIS) mapping. Domestic properties at each of the 11 locations were identified and external sample taps were installed to standardize sampling technique and minimize customer inconvenience. Figure 2 shows the locations of the SPs. The network inlet SR is (SP1), and the second SR (SP8). Table 1 shows the calculated mean water age at each SP.

Two WQ samples were taken from each sampling point morning and afternoon, at different times each day, for 5 days; generating 130 samples in total. This method took account of potential WQ changes brought about by overnight stagnation and peak morning demand, and to ensure representative daily average values. All samples were taken by a specially trained sampling officer using UK water industry standard methods.

Sample analysis was carried out by a United Kingdom Accreditation Service (UKAS) accredited water analysis laboratory for a number of standard aesthetic, chemical, and bacteriological WQ parameters (tables 2 and 3), plus temperature and Heterotrophic Plate Counts (HPC) 2-day at 37°C, and 3-day at 22°C respectively. The parameters were chosen because they were all indicative of WQ changes brought about by the various physical, chemical and biological reactions, interactions and mechanisms thought to occur in distribution networks. Metal results were total, not filtered. The UK standard suite of biological parameters was extended to include HPC 5-day at 37°C and 7-day at 22°C in an attempt to gain a more in-depth view of bacteriological activity. This approach also captured data about slower growing organisms not accounted for in standard regulatory sampling. Also, because of the high quality of water in UK networks, parameters such as coliforms and E-coli are rarely present in any WQ samples. The water age/WQ relationship was explored by considering calculated age and WQ results at each sample location.

RESULTS AND DISCUSSION

Phase 1 Mean Age and Regulatory WQ

Figure 3 shows the calculated mean age distribution for each network. The number of pipes is expressed as a log value in order to be able to see the low numbers involved at higher age values. Although the number of pipes containing water with the highest age volumes is low, there is potential for the volumes contained within them to be appreciable. The majority of the water in network1 was found to have a mean age of less than 24 hours, with a maximum mean age of 122 hours. The majority of the water in network2 was found to have a mean age of less than 100 hours old; with a maximum mean age of 463 hours.

Historic regulatory WQ sample results were acquired for each network, imported into Excel, and then subjected to basic statistical analysis. Tables 2 and 3 present the statistical summaries for 6 years of samples for networks 1 and 2 respectively. Chlorine >0.05, indicates the number of samples that had a measurable concentration of free and total chlorine. From the regulatory data it is clear that WQ in both networks was of a very high standard. The current England and Wales average compliance figure is 99.96% of samples. Both networks compared favorably with this figure. From comparison of the values shown in tables 2 and 3 it can be seen that Network2 generally performed less well than network1. Table 4 presents a summarized comparison of water age and quality failures for each network. From this it can be seen that network2, which contained water volumes with higher ages than network1, had slightly poorer WQ, as evidenced by higher failure rates for coliforms, clostridia, turbidity and manganese.

Comparison of historic WQ and mean age distributions

Network1 was found to have a narrow water age profile, while network2 displayed a broader profile; figure 3. Historic data showed that, in general, the quality of water in network1 was excellent with very few regulatory failures. Network2 was very good; with only a small number of regulatory failures. One parameter that stood out in network1 was manganese, but investigation revealed that the manganese results were almost certainly due to legacy treatment issues; deposited manganese being disturbed by infrequent network hydraulic events.

It is clear from Table 4 that network2 had a broader age profile and poorer WQ; arguably providing evidence of a relationship between the two. The age analysis appears to have the same right tail distribution as the overall water age; including averages of less than 24 hours. The statistics suggest that the water age distribution for the failed samples is similar to that of the satisfactory samples and do not demonstrate significant difference in water age. However, figure 3 shows that a number of pipes in network2 contain water that is much older than any pipe in network1. It is hypothesized that these volumes have the potential to detrimentally influence WQ in this network.

Phase 2 WQ at customer's taps and mean age

WQ sample data

In Phase II, 130 samples per week were collected; 30x more intensive than the regulatory sampling in Phase I. No positive detections were observed for coliforms, Ecoli, faecal streptococci or clostridium perfringens. The mean values for other WQ parameters, with standard deviation error bars for plus and minus one standard deviation, were plotted against SPs ordered by increasing calculated mean water age. This information can be seen for the most informative parameters in figures 6 to 14 by ignoring the flow route lines).

Although temperature tended to be erratic, the underlying trend appeared to increase with increasing mean water age. pH appeared to exhibit some randomness; two sites in particular had elevated pH values. Conductivity increased across the first five sample sites then decreased over the next three points until the second SR after which it stabilised. Within error bars, it could be observed that colour and turbidity were stable across all sites. Within error bars the underlying trend for free and total chlorine appeared to follow the latter stages of an exponential decay curve but two points in particular, 12-18 hrs and 41 hrs (SR2), showed an unexpected deviation for both free and total chlorine. Both 2-day and 3-day HPC appeared constant except for a sudden increase at the next to last SP. It could be argued that, within error bars, the trend is constant with low values. Within error bars 5-day and 7-day HPC were also relatively stable, both counts showing a very similar pattern (albeit an order of magnitude different) and an unexpected increase at point 32-37 hrs.

The inlet SP shows slightly elevated residuals for all 3 metals, and there is no dominant trend for the other SPs. Aluminum concentrations were appreciable higher than iron or manganese and thought to be a function of the legacy of the water treatment plants which originally used aluminum salts in the coagulation stage.

The results demonstrated *some* relationship between calculated mean water age and WQ. Underlying trends in pH (if 2 unusual peaks were ignored), temperature, 7-day plate counts, and iron (if 2 unusual peaks were ignored) suggested that there might be an increase with increasing mean water age, but unexplained deviations were present. Free and total chlorine exhibited an inverse relationship; decreasing with increasing mean water age (again, if unexplained peaks are ignored). Unusual peaks in all HPCs may be attributed to these points being located on a long pipe, remote from the rest of the network, leading to the ends of the system. However, these points do not constitute dead ends in the traditional sense, as water is being drawn further along the pipes past these points, albeit at very low velocity. Also, one SP was located at a property which (it was determined later) was not occupied for a few weeks prior to the sample program, thereby creating a stagnant service pipe which, although flushed correctly for sampling, could have affected WQ.

Flow Routes

Effects on, for example, iron and manganese are likely to be significantly different where pipe material is predominantly metallic or non-metallic. Legacy effects of water treatment inadequacies that allowed aluminum floc and manganese to enter the network may also have played their part. Flocs and oxides could have settled in interstitial spaces between corrosion products. These deposits could have been disturbed by unusual networks flow events generated, for example by burst pipes. Such events would give rise to increased residuals and turbidity (Boxall and Saul 2005; Vreeburg and Boxall 2007; Husband and Boxall 2011).

Further data interpretation was therefore undertaken looking at the data in relation to SPs located along specific, unperturbed, flow routes through the network in order to determine whether this influenced the patterns observed in the data. As an example, figure 4 shows the asset data from the network inlet at SP1 to SP13; displaying dominant lengths of pipe, material, diameter and year(s) laid to highlight the different size, age and lengths of pipes comprised of different materials, as well as mean water age (in dd:hh:mm format). The large increase in age along the final two lengths of the route is due to large diameter low flow conditions; thought to be a legacy of the creation of DMA structure from large open systems. Hydraulic model results were used to identify specific flow routes to each WQ SP. These are displayed in schematic form in figure 5, together with indication of the total route length and material composition grouped as either plastic (predominately uPVC and HPPE) or iron (cast and ductile).

Less informative parameter results are described, then figures 6 to 14 show SP average WQ values for the more informative parameters plotted against mean water age order by increasing age category. Data points are linked with lines to capture the unperturbed flow routes shown in figure 5. Hence, each plot is essentially in 2 sections; SPs fed directly from SR 1 (dashed lines) and those fed from SR 2 (solid lines). As stated previously, water age is only a potential surrogate for WQ not a direct measurand. Water age was therefore allocated to “age bins”, and the WQ associated with each age bin was compared not the absolute numerical values, x axis.

All plots use linear axis scales with the exception of HPC; which have logarithmic y axes. The use of the logarithms of the values rather than the actual values reduces the wide range to a more manageable size and the values of “y” are easier to see on the figure; especially where they are less than 10. A logarithmic scale could also arguably be justified on the basis that unconstrained population growth theoretically follows an exponential trend. As a further aid, where error bars are large, their extremities have purposely been allowed to go off scale.

With the exception of point 2 to 4 on route1, pH increases slightly with increasing water age along the flow routes. This increase in pH may be the result of sorption reactions with pipe wall and accumulated materials (Machell 1988); it may also be driven by corrosion mechanisms reducing water; $2H_20 + 2e^-$ -----> $H_2 + 2OH^-$ producing hydroxide ions that act as a base. The change in pH was generally less in pipes supplied from SR1; except for route 1 which also has a greater percentage iron pipe that the other SR1 routes. Of the SR2 routes, 7 has significantly less iron pipe but does not display a marked difference in pH behavior.

If route3 point 76to82 is regarded as abnormally low, that within error bars the tendency is for conductivity to increase with increasing water age along all routes. There is clear grouping between all routes originating from SR1 and those via SR2. Conductivity increase is most likely due to charged corrosion products; the effect was more pronounced in pipes supplied from SR1 than those supplied by SR2; the opposite of the effect for pH. This change is potentially temperature related as the routes beyond SR2 also have the highest temperature increase. There are no apparent changes that associate with pipe material.

Within error bars color could be considered stable along all flow routes; although there is an apparent small increase along all pipe routes. All pipe routes from SR1 show an increase in color. There is a small increase to SR2 followed by larger increases along all pipes routes after the SR. The lower increase between SR1 and SR2 compared to the increase along all other pipe routes is probably due to the trunk main being ductile iron and comparatively low retention time leading to low pipe wall contact time.

Within error bars turbidity could be considered very stable along all flow routes. Turbidity decreased between SR1 and SR2 indicating some particulate accumulation. Accumulation was also evident along routes 3, 4, 5 and 7. Routes 2, 6 and 8 experienced slight increases in turbidity, and route1 showed a decrease over the first 3 points then an increase at the final point; probably caused by proximity to the end of a long cast iron pipe. 93% of route 1 pipes were iron, and the final pipes before the last SP were cast iron laid 87 years ago and were subject to low flow velocities. The final SP on route 8 displayed the highest rise in turbidity, and this point was where the highest age water in the network was found. This lack of clear association of turbidity to either water age or pipe material highlights the complexity of interacting processes involved in discoloration. It is suggested that the critical information missing here may pertain to hydraulic disturbances that would have removed old material and allow for new accumulation; Boxall and Saul (2005), Husband and Boxall (2011).

From figure 6, it can be seen that temperature increases with increasing water age along all flow routes. The different pipe routes demonstrate a range of temperature increases; the largest being route 7 and the lowest route 4. Temperature increase has been reported previously, Machell and Boxall (2011), Rajani et al (1996), and will be dependent upon the difference between bulk water and local ground temperature. There is a comparatively low increase in the trunk pipe to, and within, SR 2 compared to all other pipe routes. This is likely to be due to the low surface to volume ratio of the large diameter pipe and the SR reducing the capacity for heat transfer from the surroundings. The results are typical for the time of year the study took place; the water absorbing heat via the pipes from the warm ground. Variability in the amount of temperature increase is probably due to local effects such as depth of cover and ground surface cover.

As chlorine travels through a distribution system, chemical reactions, mostly with organic materials, occur within the bulk water volume; giving rise to a chlorine demand that is evidenced by a decaying residual. Once the bulk water demand is satisfied, chlorine decay brought about by reactions with pipe walls and other materials within the system, continues. Compared to the amount of organic material in the bulk volume, the potential surface area of pipe walls and deposited materials can be very high; especially where corrosion products are present Borch et al. (2008). Machell (1988) measured the surface area of manganese dioxide in UK distribution networks to be 300m^2.gm^{-1}. Our results support and confirm these findings.

Figures 7, 8 and 9 show free, total and combined chlorine respectively. With the exception of point 3 on route 1 (labeled anomalous), free and total chlorine dissipate rapidly along all flow routes; probably due to high pipe wall surface area and reaction coefficients. In contrast, while travelling from the inlet to SR2, combined chlorine demonstrates a small increase, and free chlorine an equivalent decrease, showing that the free chlorine is reacting with ammonia or amines derived from organic matter before dissipating completely. The decay of both free and total chlorine in between network inlet and the outlet of SR2 is less than for any other pipe. This suggests that the combination of relatively low surface areas and residence time in these assets is related to low chlorine consumption, confirming that pipe wall effects are greater than bulk water decay effects.

HPC 2-day@37 and HPC 3-day@22 results, within error bars, follow the same trend and could be regarded as relatively stable, showing only a slight increase at the points where the oldest water is found. HPC 5-day@30 results within error bars, is stable but shows an underlying tendency to increase slightly along most flow routes. The greatest increase is along route 4 and lowest along route 5. HPC 7-day@22 shows a very similar pattern to HPC 5-day@30. The most pronounced increase occurs along route 4, with smaller effects along routes 1, 7 and 8 (ignoring the SR component of routes 7 and 8). The lowest increase is along route 5; this is the same as for HPC 5-day@30.

However, when potted with logarithmic y axis, HPC 5-day@30 show straight line relationships along all but one route, and highlights approximately an order of magnitude increase along all routes; figure 12. This log plot also highlight that there is little differentiation between SR effects and pipe effects.

Similarly, log HPC 7-day@22 increases by an order of magnitude with increasing water age along most routes, although the trend is not as strong or as clearly linear as for HPC 5-day@30; figure 13. If the 23to28hours point on route 3 is regarded as abnormally high, and the 2to4 hours point route 1 as abnormally low, log plots of HPC 7-day@22 produce relatively straight lines along most routes with

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increasing water age suggesting the relationship with water age is there, but possibly being influenced by other factors. No clear trend in association to pipe vs. SR, or in association to pipe material is evident, possibly suggesting that HPC counts are a bulk water (planktonic phase) dominated process.

From figure 14 it can be seen that iron concentrations demonstrate route dependant decreases and increases. Iron initially decreases along route 1, where the pipes are plastic, but then there is an increase at the final point, which is situated on a long cast iron pipe towards the end of the network; a similar pattern was observed for turbidity. Route 3 with the lowest percentage iron pipe material of all the routes shows a significant iron increase with water age. This is converse to what might be expected and different to the behavior observed in route 1. Iron decreased along routes 2 and 4; which both have over 40% plastic pipe. In transit between the two SRs, where the flow velocity was low, both iron and turbidity decreased indicating some particulate accumulation. After SR 2 there was an increase in iron along routes 6, 7 and 8. Routes 6 and 8 are predominately iron, while 7 was 25% plastic. However route 5 with 98% iron pipe showed no change in iron after the SR. Overall there is a complex process of iron accumulation and release that, as with turbidity, is not fully explained by consideration of water age, flow routes and pipe material.

Aluminium residual generally decreases along most routes, suggesting overall trends for aluminium deposition within this network, with this generally occuring as a function of age. As with condutivity, colour, clorine, temperature and to some extent iron there is a difference between the rate of decrease through the trunk main and SR2 than through the pipes. Aluminum decreased along all routes except 1 which decreased initially then increased again, and 8 which increased after leaving the second SR. Both increases are difficult to explain, though one potential explanation is that previously settled aluminum floc in the network was disturbed. Routes 1 and 8 also demonstrated increase in iron concentrations, as did route 3, route 8 also showed increase in turbidity.

Other than for route 3, which shows an unusual pattern, manganese is general very stable within error bars. Manganese was stable with a very slight decrease along all routes except 1, 3, 6 and 8. 1 and 8 are the two routes that have shown increases in iron, manganese and turbidity demonstrating dependence of the processes affecting these parameters. While these routes have high percentage of iron pipe, routes 5 and 6 have the overall highest percentage iron and confusing trends, including increasing concentrations, where seen for route 3 which is 60% plastic.

DISCUSSION

Considering WQ in the networks was of an extremely high standard, (99.8% against regulatory standards) to observe any change in any parameter as water age increased was deemed of interest.

Phase 1: showed historic regulatory WQ within both networks was high; a small number of failures attributable to poor water treatment in the past. Network2 had a broader age profile and poorer WQ; arguably providing evidence of a relationship between water age and general WQ, but not to any specific WQ parameter.

Phase 2: When customer tap WQ was related to only mean age there was appreciable scatter. This was resolved to some extent by considering specific unperturbed flow routes. Within the limitations of the data set it was observed that: overall increases occurred for pH, conductivity, temperature, color, and HPC 5 and 7-day along all routes; there was an overall decrease in free and total chlorine along all routes; an overall decrease in aluminum along all but one route; some increase in HPC 2-day, HPC 3-day along some routes; and turbidity, iron and manganese showed some route dependent increase and decrease.

Route 8 (6.7km pipe, 99.6% iron, 0.4% plastic) had the greatest detrimental effect on WQ, and route 5 (6.6km pipe, 98% iron and 2% plastic) the least. The relationship between water age and WQ appears stronger when data is plotted along specific flow routes, but not strong enough to say that water age alone could fully describe the drivers of change. However, this was to be expected as age is only a surrogate, not a true WQ parameter. A number of WQ parameters showed differentiation at SR2; for example temperature, which increased more after SR2 than before it, and chlorine which demonstrated little change in combined residuals along routes from SR1, but after SR2 combined residuals increased indicating that chlorine was having time in SR2 to react with ammonia or organic material. Large increases in age along some pipe lengths was due to large diameter / low flow conditions thought to be a legacy of the creation of DMA structure from large open systems. This problem may be exacerbated In the US where networks are generally larger diameter pipes relative to the UK due to firefighting regulations. Low flows were also seen to occur on long mains leading towards the extremities of the networks.

HPC exhibited some correlation to water age; in particular, for 5-day counts. No clear trend in association to pipe vs. SR, or in association to pipe material, possibly suggests that HPC counts are a bulk water (planktonic phase) dominated process. Despite this, the most widely applied routine test in most of the UK is 2-day and 3-day HPC. However, when investigational sampling is required (in response to an illness complaint for example) 5-day and 7-day counts are also done as these provide extra information about slower growing organisms. It is feasible that other trends may have been revealed by more advanced microbiological analysis techniques however, the aim here was to utilize industry standard metrics.

Routes 1 and 8 were consistently poor performers in terms of concentration increases for multiple parameters, and had high percentages of iron pipes. However, routes 5 and 6 which had the highest percentage of iron performed well, and route 8, which had the highest percentage plastic pipes, exhibited some poor performance. This seems to indicate that it is more the actual condition of individual pipes, along with the interaction of plastic and metallic pipes, water age, and treatment legacy that influences overall WQ behavior.

In summary; tentative trends of variable quality and consistency between WQ parameters and water mean age were present in the data. A dominant feature of many plots is the distinctly different aging / WQ deterioration for flow up to, plus residence time within, SR 2, than within the pipe routes. This clearly shows that pipe wall effects cause more WQ deterioration than the bulk water effect, and reflects the pipe or tank surface area to water volume ratio being much greater in pipes.

Operational application

Water age has been shown to be useful; both for overall network evaluation in phase 1, and for the specifics of network performance, phase 2. However, as only two networks were studied the findings are not definitive. It is clear that knowledge of water age alone is not sufficient to describe changes in specific parameters, with many exhibiting behavior dependent upon interactions with network assets along specific flow routes. Water age does however, seem to offer merit as a catch all surrogate to overall WQ.

While the modeling approach is transferrable to any network, the age calculation results will reflect the degree of calibration of the hydraulic base model. There are a number of ways this knowledge can be practically applied. For example:

- Knowing where older water volumes are located within a network could be used to promote investigational sampling / monitoring programs to determine when proactive flushing should be undertaken to prevent WQ from deteriorating to the point customer complaints or regulatory WQ failures occurring.

- Depending upon the topography of a network, it may be possible to regularly re-route or change the velocity of water flows in specific pipes using valve operations, to prevent water aging excessively.

- It may also be possible to use the data to determine a network specific preferred highest water age; i.e. a “sell by” date. An absolute ‘use by’ date will be unlikely because it is anticipated this value will vary for networks with different raw water and water treatment process types, as well as for networks with different mixes of pipe and other asset materials and condition.

- Water age calculation on its own can indicate where poorer WQ might be found. Better understanding of WQ deterioration can be formed if this is interpreted with asset and asset condition information. GIS systems often already hold this data and automation of the model build process is improving.

- Water age could be used to extend and improve current investigation processes for failed regulatory WQ samples. This in turn would allow the strengthening of investigational evidence for presentation to regulatory bodies, and provide the wherewithal to increase “due diligence” as applied to distribution network operation.

CONCLUSIONS

This paper has explored the theorized association between mean water age, calculated using one-dimensional simulation software, and high quality water in two distribution networks. Underlying trends demonstrated some relationship between calculated mean water age and general WQ measurements, but no specific parameters exhibited ideal relationships. This is perhaps not entirely surprising as water age is a potential surrogate to WQ in general rather than any specific parameter.

More detailed analysis, that considered flow along specific unperturbed flow routes, revealed that most of the WQ parameters exhibited a stronger relationship to the calculated water age. However, consideration of the dominant pipe materials along these routes did not lead to further understanding of WQ changes, in particular the relative amounts of iron or plastic pipe were not a substantive factor.

Overall the study shows that water age together with flow routes, reservoir effects, the condition of individual pipes, the interaction of plastic and metallic pipes and treatment legacies all influenced overall WQ. This study has shown that while water age cannot be used to represent any specific WQ parameter, if consideration is given to the routes water follows through a network, it is a useful surrogate for WQ in general, with the potential to enable companies to predict where poorer quality water might be manifest. This in turn could guide investigational WQ sampling and capital investment planning.

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Figure 1

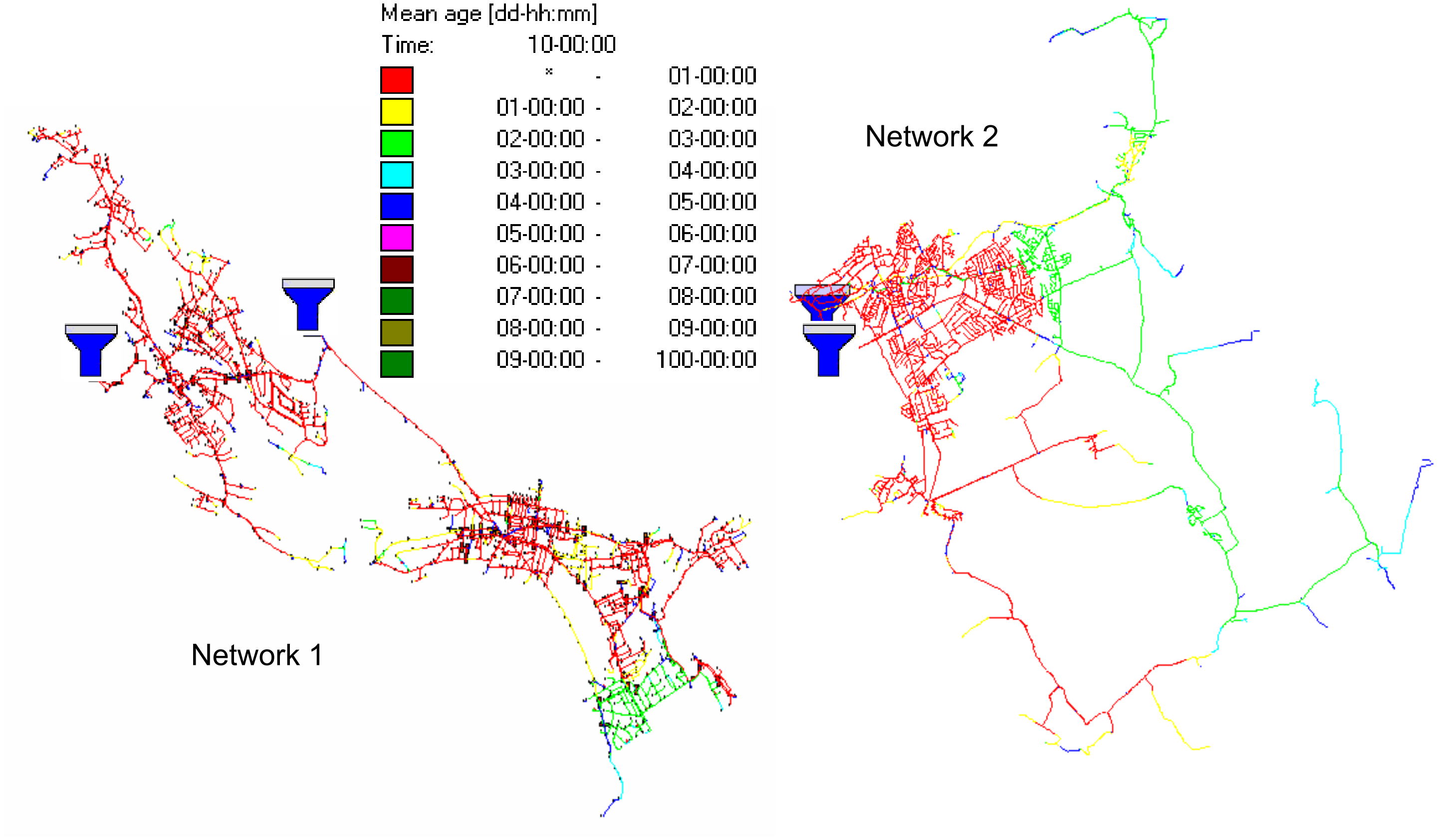

Figure 2

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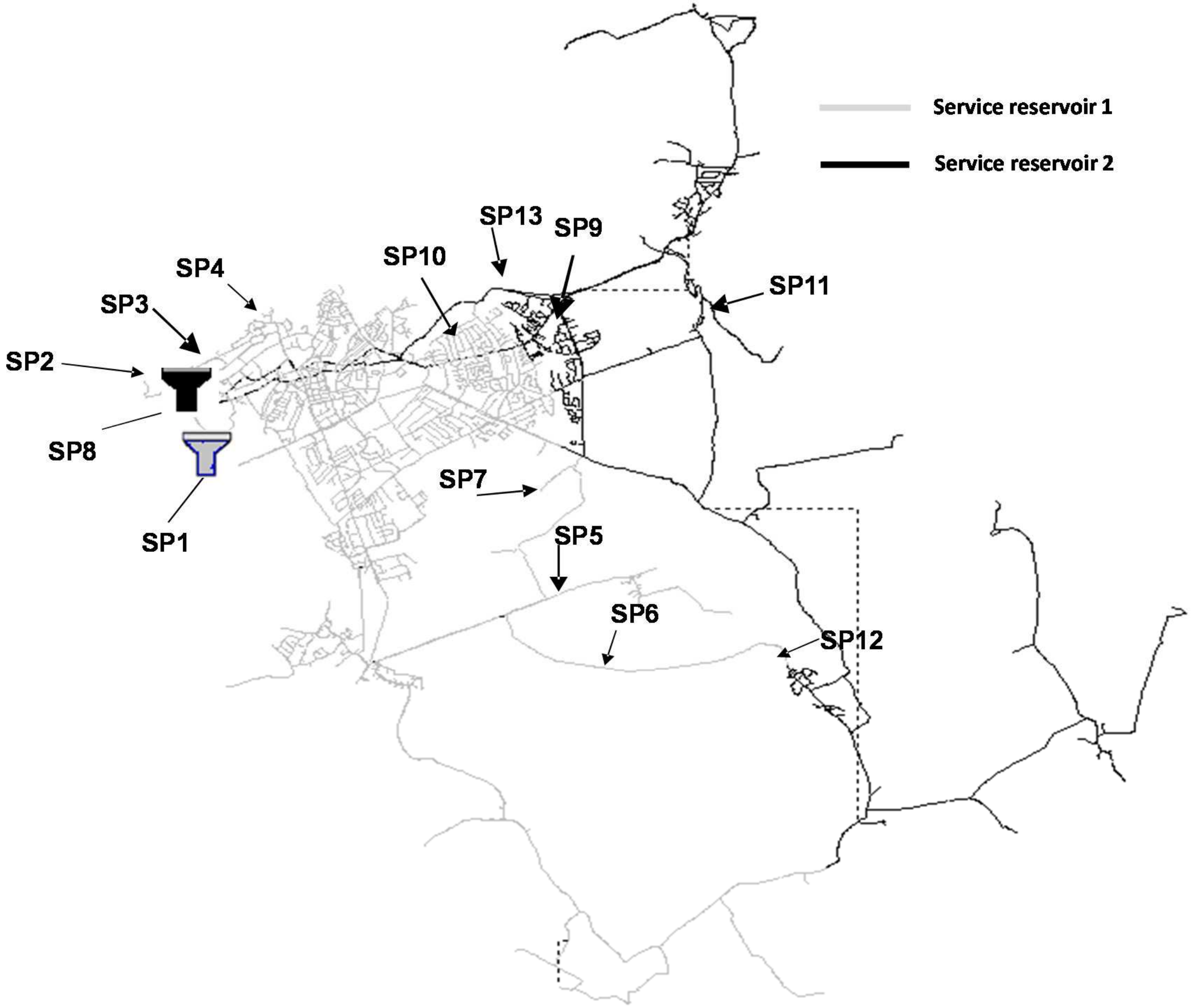

Figure 3

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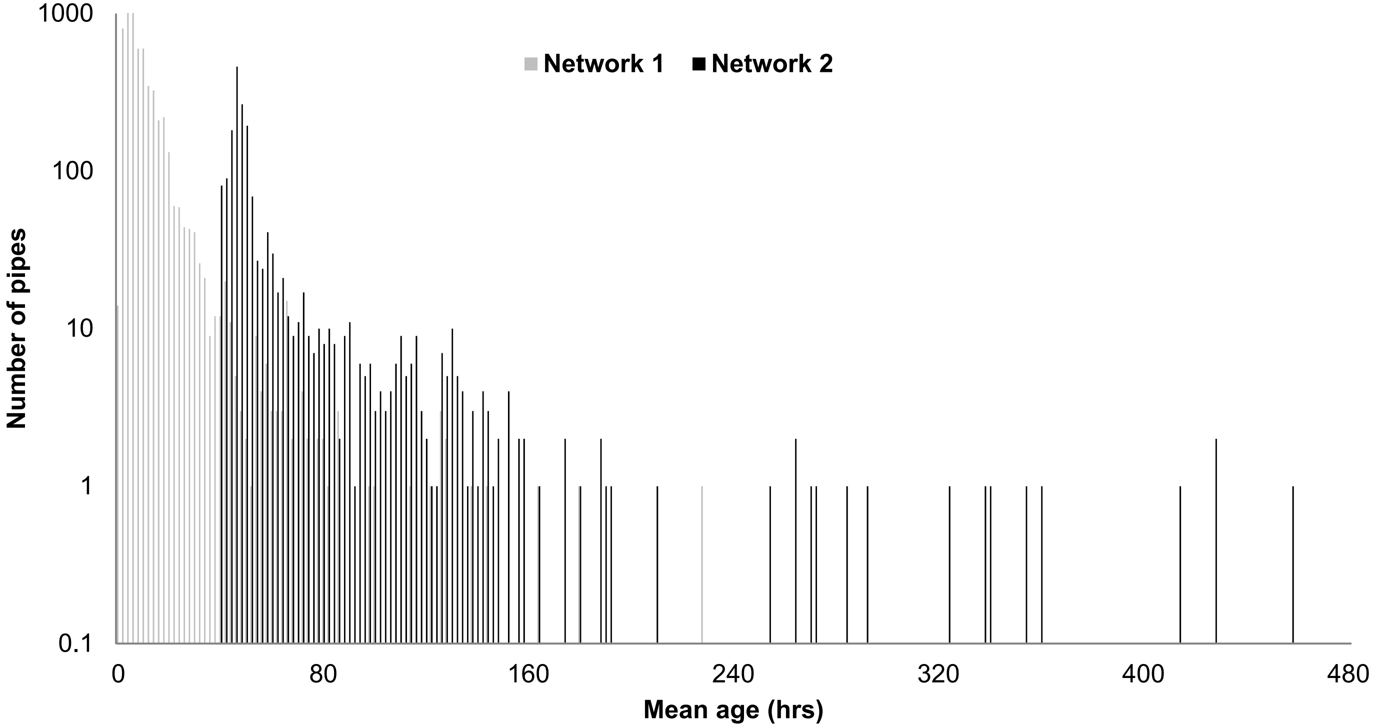

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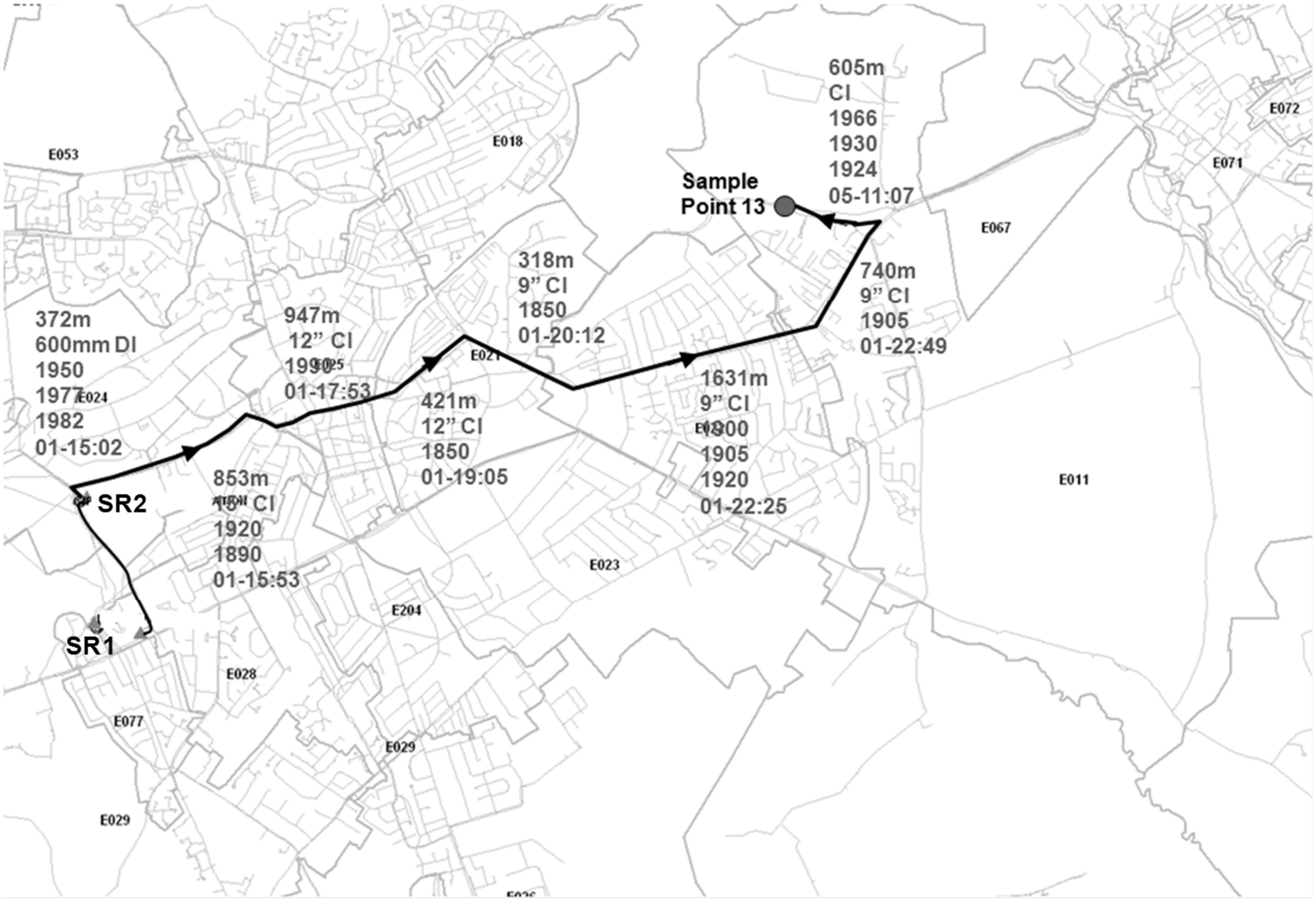

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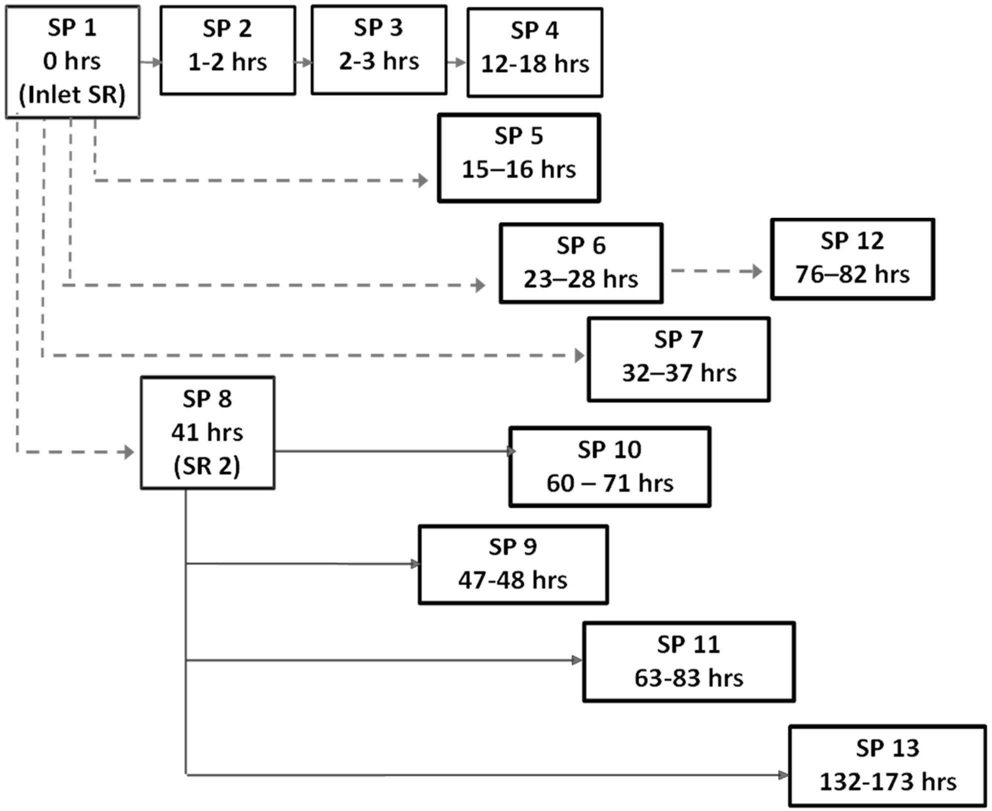

Route	Pipe length	% Iron	% Plastic
1	3783	93.4	6.6
2	7253	56.0	44.0
3	10862	39.4	60.6
4	10301	59.2	40.8
5	6626	98.0	2.0
6	7237	100.0	0.0
7	14541	74.7	25.3
8	6668	99.6	0.4

Figure 6

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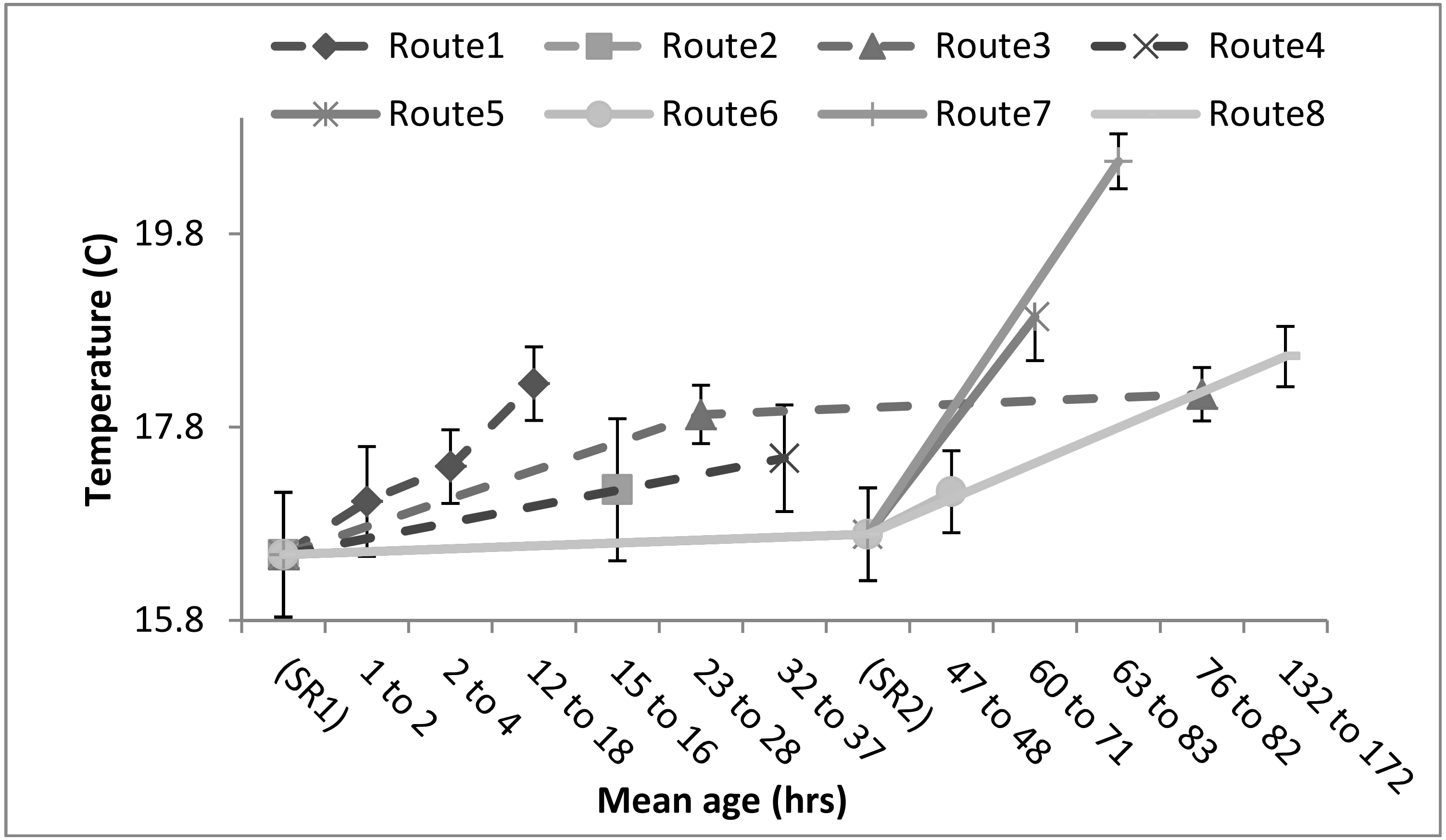

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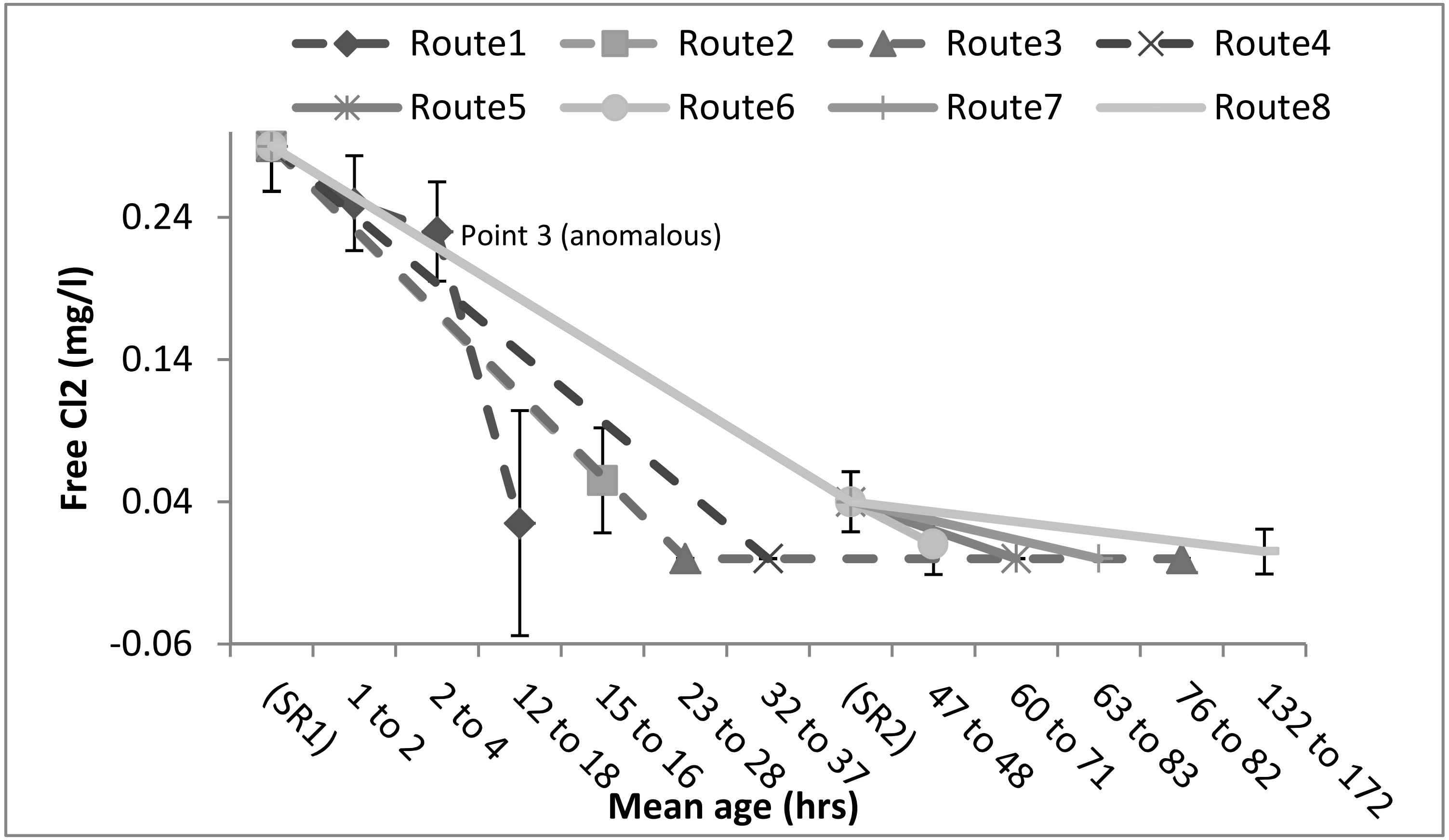

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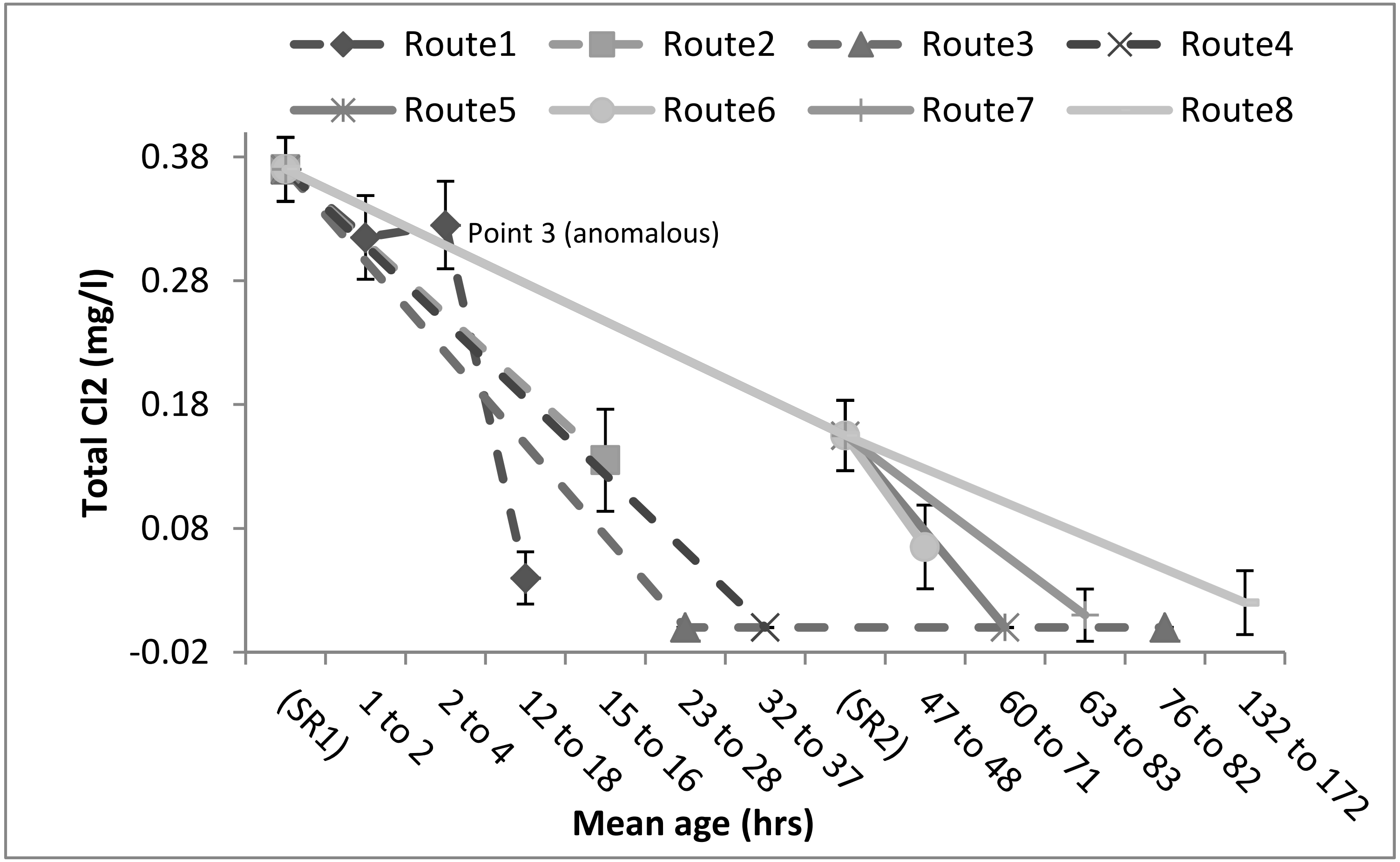

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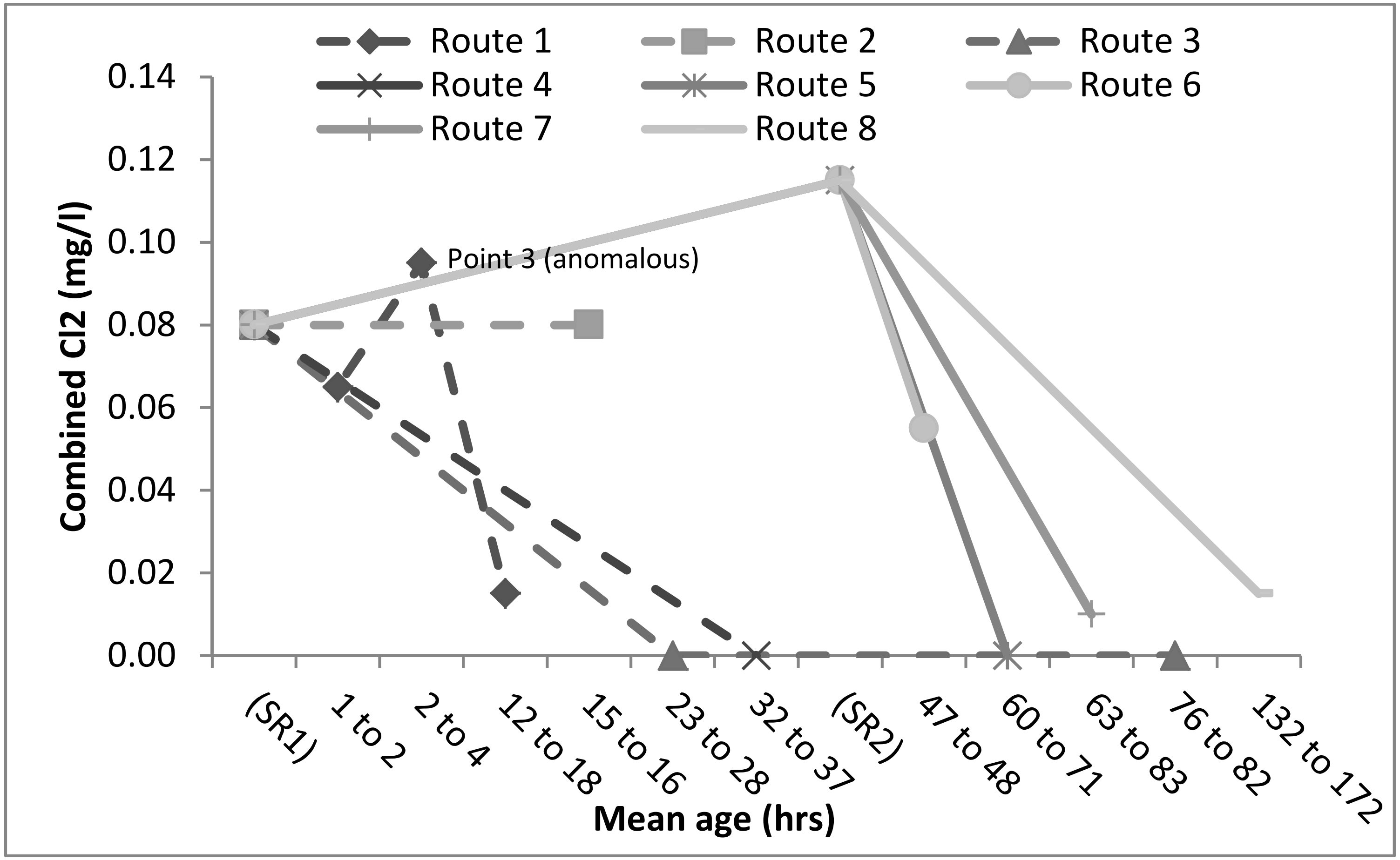

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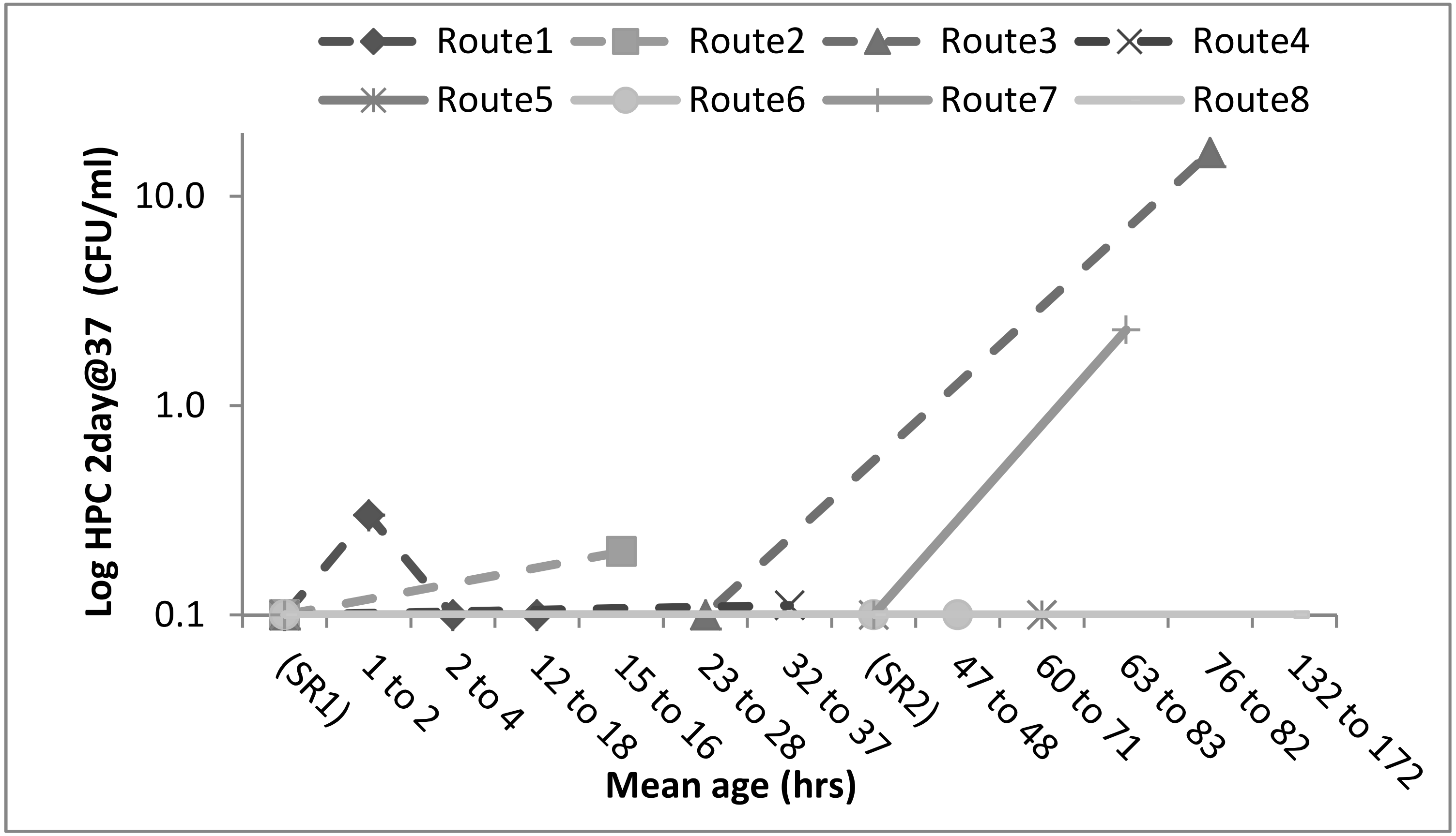

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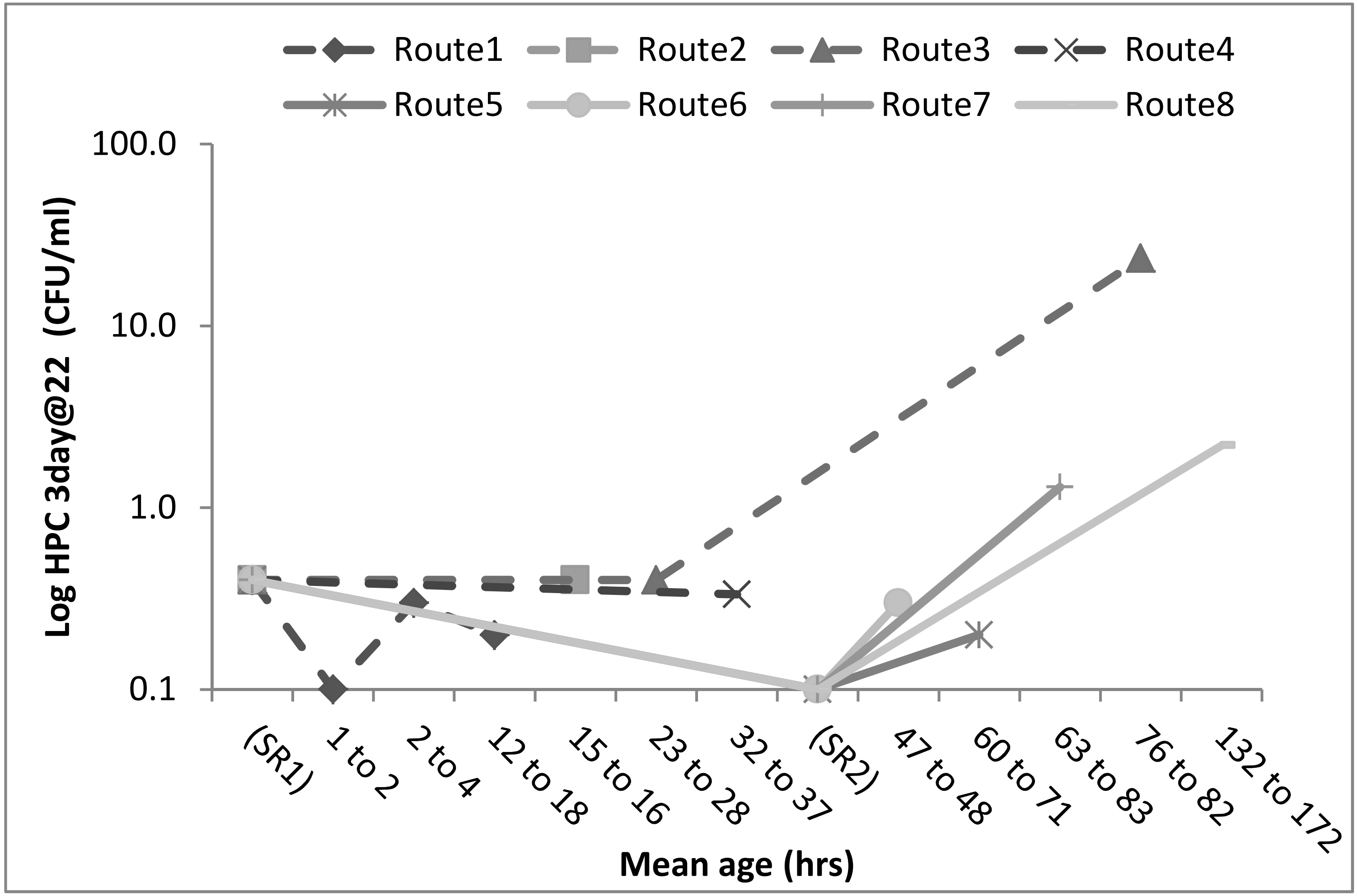

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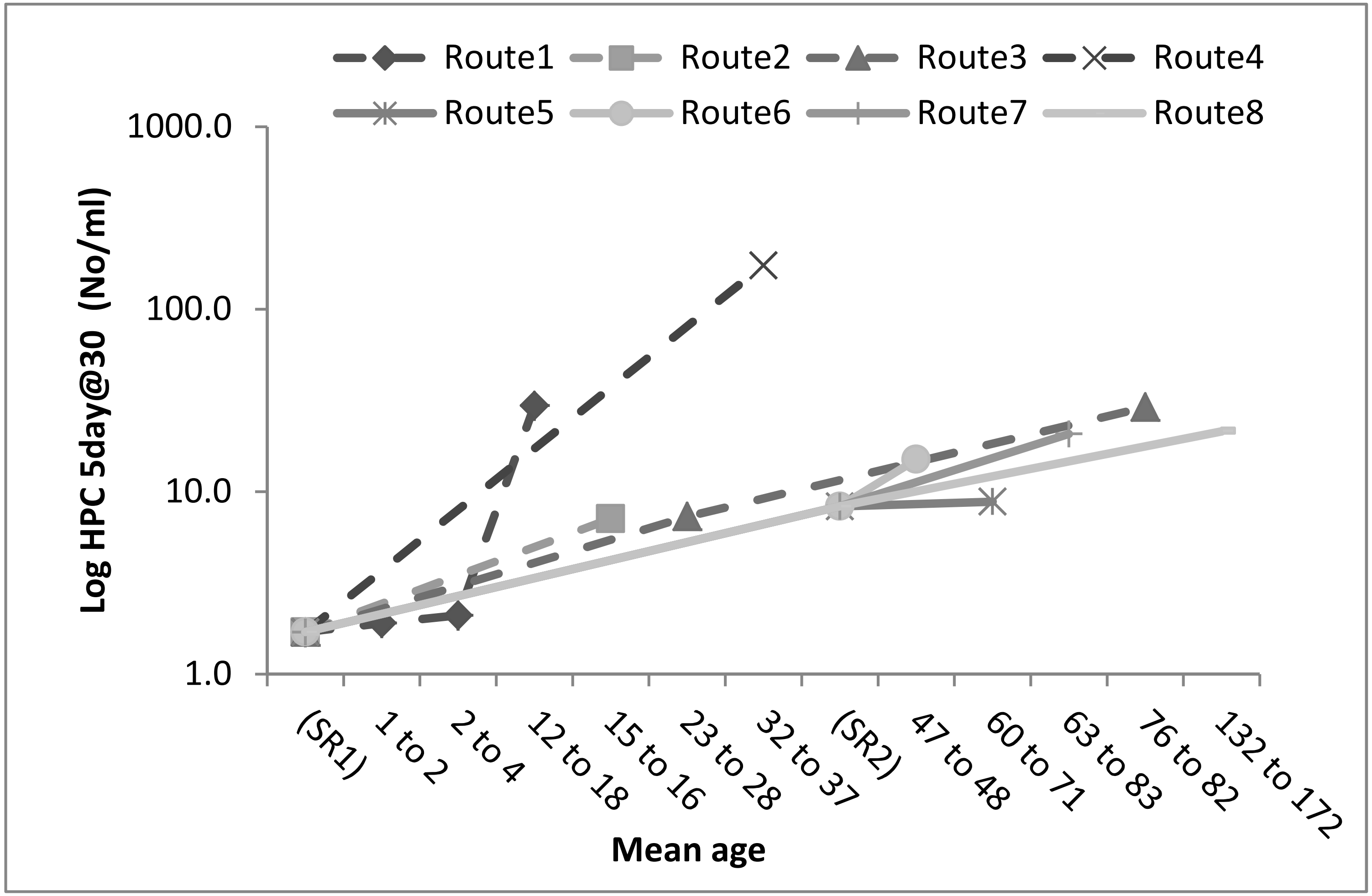

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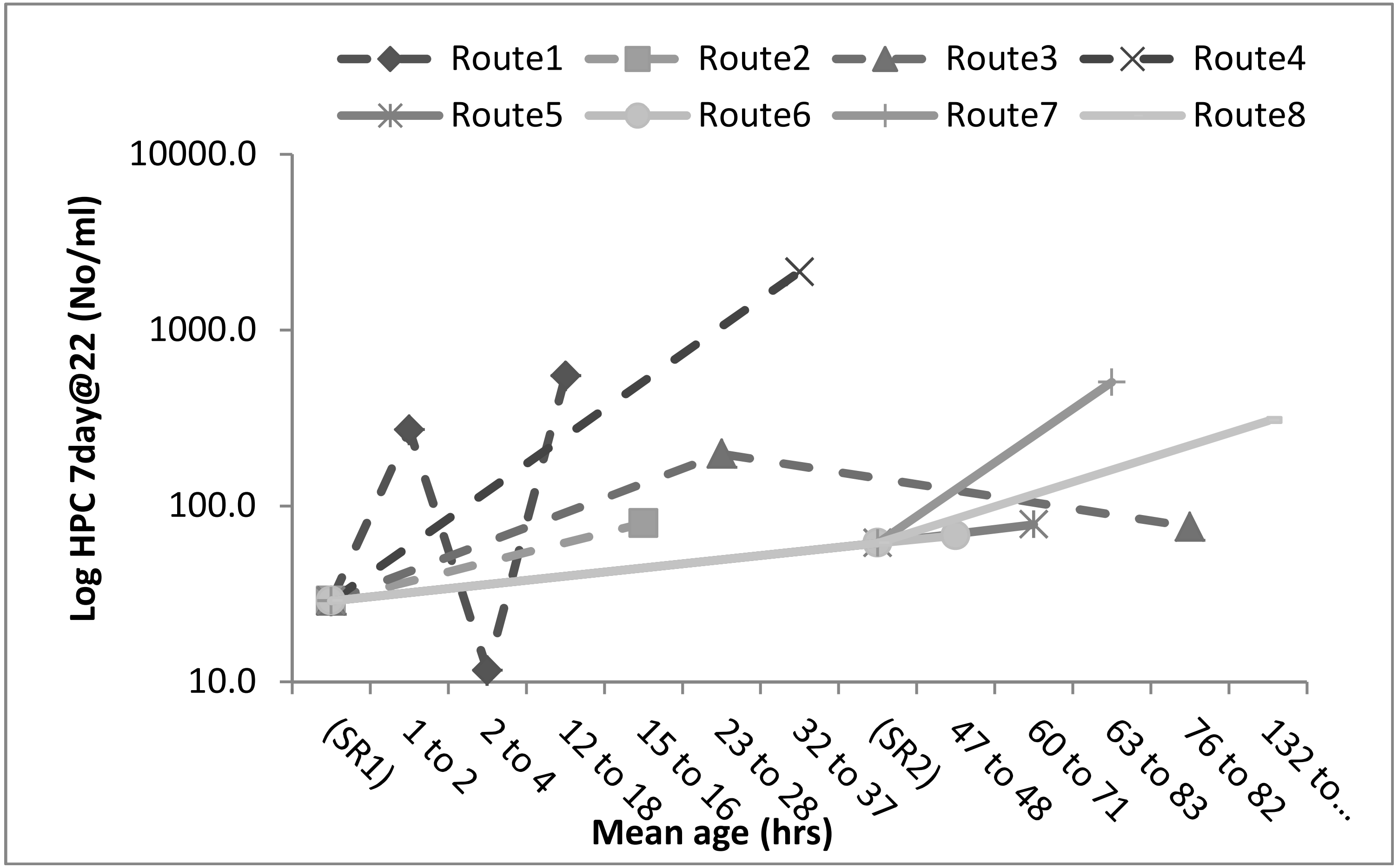

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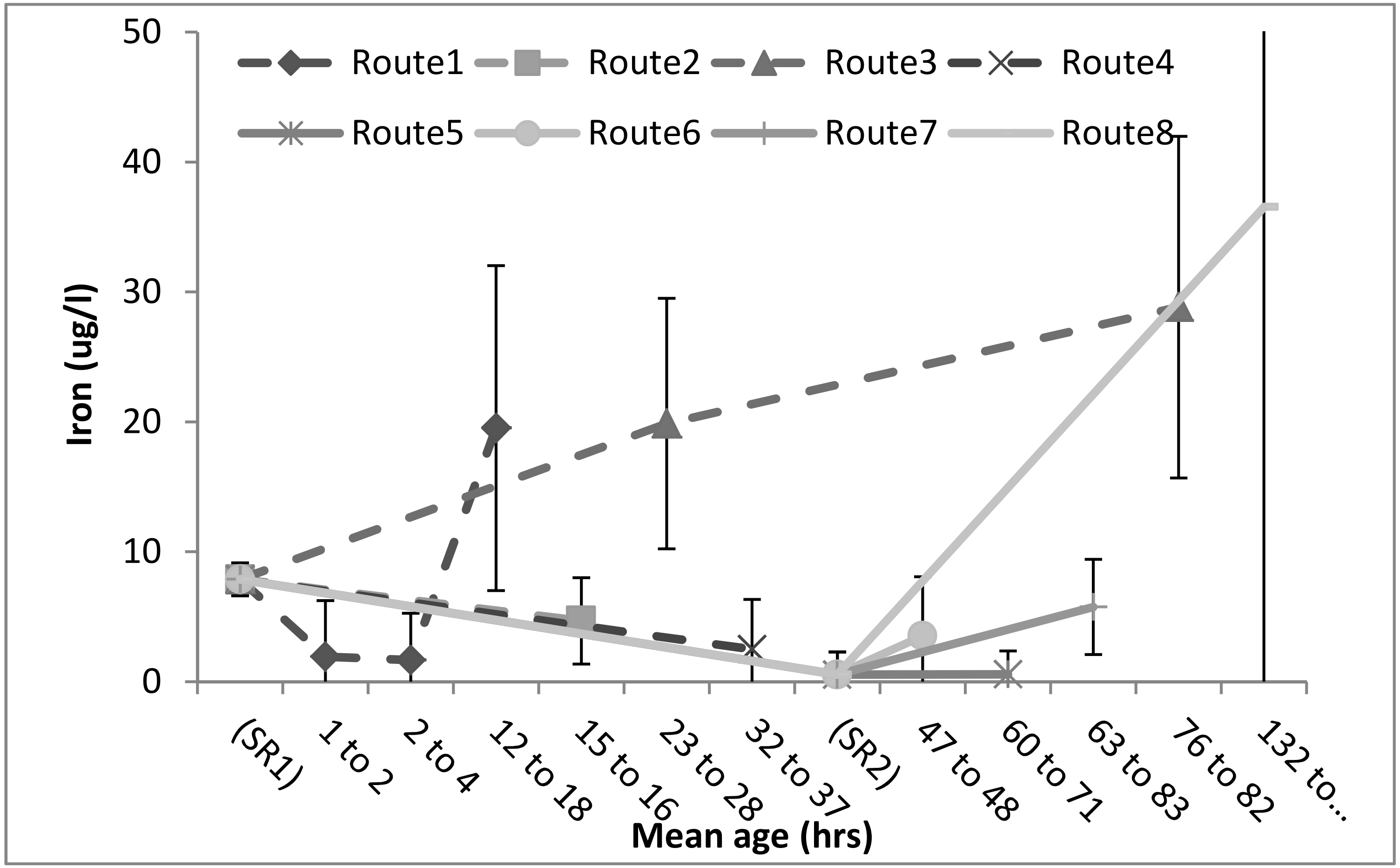

Table 1

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Sample point	Age bin (hours)	Sample point	Age bin (hours)
SP 1	0	SP 8	41
SP 2	2.1 to 3.6	SP 9	47 to 48
SP 3	1.6 to 2.2	SP 10	60 to 71
SP 4	12 to 18	SP 11	63 to 83
SP 5	15 to 16	SP 12	76 to 82
SP 6	23 to 28	SP 13	132 to 172
SP 7	32 to 37		

Table 2

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	pH	Conductivity 20c uS	Colour PtCo mg/l	Trubidity FTU	Chlorine		Coliforms no/100ml	Ecoli no/100ml	HPC 2d 37c	HPC 3d 22c	Clostridia no/100ml	Faecal streps no/100ml	Al total ug/l	Fe total ug/l	Mn total ug/l
					Free mg/l	Total mg/l									
No of samples	297	297	297	297	297	297	297	297	33	161	19	31	167	167	167
No with Cl2 > 0.05					104	196									
Max	8.90	333	5.10	0.48	0.35	0.50	8.00	0.00	4.00	879.00	0.00	0.00	158.00	245.00	24.20
Min	6.80	127	1.50	0.11	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	8.00	7.00	0.70
Mean	8.11	185	1.97	0.17	0.09	0.13	0.03	0.00	0.36	14.46	0.00	0.00	21.46	33.72	4.15
Standard deviation	0.34	35	0.53	0.06	0.06	0.09	0.47	0.00	1.03	84.17	0.00	0.00	17.85	33.86	4.30
No of regulatory fails	0	0	0	0	0	0	2	0	n/a	n/a	0	0	0	1	0

Table 3

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	pH	Conductivity 20c uS	Colour PtCo mg/l	Trubidity FTU	Chlorine Free mg/l	Total mg/l	Coliforms no/100ml	Ecoli no/100ml	HPC 2d 37c	HPC 3d 22c	Clostridia no/100ml	Faecal streps no/100ml	Al total ug/l	Fe total ug/l	Mn total ug/l
No of samples		774	1153	757	1375	1375	874	874	521	979	210	38	611	356	356
No with Cl2 > 0.05					833	1131									
Max	8.7	801	11	50	0.5	0.6	19	0	1820	801	2	0	151	112.38	23800
Min	6.7	124	0.7	0.08	<0.05	<0.05	0	0	0	0	0	0	7	5.1	0.70
Mean	7.06	195.14	1.12	0.47	0.14	0.21	0.07	0.00	5.39	129.79	0.01	0.00	37.94	18.99	660
Standard deviation	1.44	66.13	1.00	2.60	0.10	0.12	0.87	0.00	80.05	107.77	0.14	0.00	20.56	17.13	2858
No of regulatory fails		0		13	0	0	12	0	n/a	n/a	1	0	0	0	22

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	Parameter	Network 1	Network 2
Age analysis (Mean age in pipes (hrs)	Average	9.44	19.86
	Mode	5.28	2.68
	95th percentile	25.97	58.53
	Highest	122.00	463.00
Number of water quality failures	Coliforms	2.00	12.00
	Clostridia	0.00	1.00
	Turbidity	0.00	13.00
	Iron	1.00	0.00
	Manganese	0.00	22.00
Number of failures divided by number of samples	Coliforms	0.0067	0.0137
	Clostridia	0.0000	0.0048
	Turbidity	0.0000	0.0172
	Iron	0.0060	0.0000
	Manganese	0.0000	0.0618