Make a Water Main Wider and the Water in It Grows Older

— widening a branch main fourfold from 100 to 400 mm lengthens the time the water spends in it from **8.7266** to **139.6263** hours, exactly sixteenfold — the boundary diameter at which chlorine still meets the limit is **303.6676** mm — [Paper 576]

Yuuki YAMAGISHI (山岸 勇輝)
Yamagishi Complexity Torus Lab, Japan
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— *From thinking to syncing.* —

Abstract

Water mains are often chosen “wide, to leave a margin” for future demand and for fire fighting.What this paper shows is that at the same flow the time water spends in a pipe grows as the square of its diameter, and the disinfecting chlorine runs out along the way in proportion.No new theorem or law is claimed. First, the residence time is proportional to the square of the diameter——a fourfold diameter gives exactly 16.000000 times the residence (Section 3). **Second, chlorine lasts only so long——chlorine decaying at first order takes 80.4719 hours to fall from 0.5 to the limit of 0.1 mg/L** (Section 2). **Third, and this is the core.Through 300 mm the chlorine at the outlet is 0.1039 mg/L, above the limit; through 400 mm it is 0.0306 mg/L, below it——the boundary diameter is 303.6676 mm, and one step wider leaves the tap short of chlorine** (Section 3). **Fourth, the narrow side has room to spare——100 mm gives a residence of 8.7266 hours and 0.4199 mg/L at the outlet; 200 mm gives 34.9066 hours and 0.2488 mg/L** (Section 3). **Fifth, consumption at the wall does not change the direction——the exponent of decay goes as $k_b D^2 + 4k_w D$ and grows with the diameter** (Section 4). **Sixth, the separator is whether the diameter is set by the everyday flow or by a rare maximum——a pipe sized for the maximum flows too slowly on ordinary days** (Section 5). **Keywords**: water main, residence time, residual chlorine, water supply, pipe diameter.

Scope of this paper (scope note): No new theorem or law is claimed——velocity and residence time in a pipe and first-order decay of chlorine are all standard.The numbers are representative——a bulk decay rate of chlorine of 0.02 per hour, 0.5 mg/L leaving the works, a limit of 0.1 mg/L at the tap, a branch 2 km long and a daily mean flow of 0.5 L/s.The flow is held at its daily mean——real flow varies greatly through the day, and at night the residence grows longer still.A single pipe is considered——mixing in the network, loops and storage tanks are not included.Consumption at the wall is shown only in direction——no rate for it is given.Neither the effect of temperature on decay nor disinfection by-products are treated.It is not said that pipes should be narrower——a diameter able to meet fire fighting and future demand is needed; then chlorine must be topped up on the way or flow created by other means, which is as far as this paper goes.Relation to earlier papers: Paper 557 showed that the pressure angle that strengthens a tooth points against the angle that smooths the drive——the same shape here: the diameter that secures capacity points against the freshness of the water.Paper 346 showed that a half-life is a property of the substance only for first-order reactions——bulk decay of chlorine is first order, so the time from 0.5 to 0.1 is the same 80.4719 hours from wherever it is counted.Paper 300 showed that sharing a root is decidable——"the water grows older" and "the chlorine falls below the limit" come from one root, the residence time.What is added is setting out residence and outlet chlorine for different diameters at one flow and confirming that residence grows as the square of the diameter ratio, finding the diameter **303.6676** mm at which the outlet sits exactly at the limit and checking both sides of it at 300 and 400 mm, showing in the form of the formula that consumption at the wall does not change the direction, and placing the separator on the flow that sets the diameter.

1. Notation and the Question

Setting: when a flow Q passes through a pipe of diameter D and length L, the velocity and the time the water spends in the pipe (the residence time) are

$$v = \frac{4Q}{\pi D^2}, \qquad t = \frac{L}{v} = \frac{\pi D^2 L}{4Q}.$$

With chlorine decaying at first order, the outlet concentration is $C = C_0 e^{-kt}$.

Observation 1.1

water mains are often chosen "wide, to leave a margin".A wide pipe resists flow less, holds pressure more easily and can meet the large flows of fire fighting——leaving a margin is usually thought of as the safe choice.

Question: at the everyday flow, what happens to the water in a wide pipe?

2. How Long Chlorine Lasts

Computation 2.1: with a bulk decay rate of 0.02 per hour, 0.5 mg/L leaving the works and a limit of 0.1 mg/L at the tap.The longest residence before reaching the limit is $t_{\max} = \ln(0.5/0.1)/0.02 = \mathbf{80.4719}$ hours (at that time the concentration returns exactly to 0.1, to 10^{-12}).

> **Observation 2.2**
>
> because the decay is first order, the time is the same from wherever it is counted.Paper 346 showed that a half-life is a property of the substance only for first-order reactions——bulk chlorine is such a case, and the 80.4719 hours from 0.5 to 0.1 do not depend on whether they are counted from the inlet or from halfway.

3. Diameter and Residence

Computation 3.1: a branch 2 km long carrying a daily mean of 0.5 L/s, with only the diameter changed.

diameter	velocity	residence	outlet chlorine
100 mm	**0.063662** m/s	**8.7266** h	**0.4199** mg/L
150 mm	**0.028294** m/s	**19.6350** h	**0.3376** mg/L
200 mm	**0.015915** m/s	**34.9066** h	**0.2488** mg/L
300 mm	**0.007074** m/s	**78.5398** h	**0.1039** mg/L
400 mm	**0.003979** m/s	**139.6263** h	**0.0306** mg/L

> **Observation 3.2**
>
> residence grows as the square of the diameter.Widening from 100 to 400 mm, fourfold, lengthens the residence $\mathbf{16.000000}$ times, matching the square of the ratio to 10^{-9}——the same water flows more slowly by as much as the cross-section has grown.

Observation 3.3

this is the core.Through 300 mm the outlet chlorine is 0.1039 mg/L, above the limit; through 400 mm it is 0.0306 mg/L, below it——both sides of the boundary were checked. The diameter at which the outlet sits exactly at the limit is 303.6676 mm, where the residence returns exactly to the maximum of 80.4719 hours (to 10^{-9}). One step wider “to leave a margin” leaves the tap short of chlorine.

Observation 3.4

the narrow side has room to spare.At 100 mm the residence is 8.7266 hours and 0.4199 mg/L remains at the outlet——the margin in width is eating the margin in chlorine.

4. Consumption at the Wall

Observation 4.1

in a real pipe, chlorine is consumed at the wall as well as in the water.Including the wall, the decay rate becomes $k_b + 4k_w/D$, faster in narrow pipes.Yet the exponent of decay along the pipe is

$$\left(k_b + \frac{4k_w}{D}\right)\frac{\pi D^2 L}{4Q} = \frac{\pi L}{4Q}\left(k_b D^2 + 4k_w D\right),$$

and both terms grow with the diameter.That chlorine falls further the wider the pipe does not change.

5. The Separator

Observation 5.1

the separator is whether the diameter is set by the everyday flow or by a rare maximum.A pipe sized for the maximum (fire fighting, future demand) flows too slowly at the everyday flow——the same pipe is enough on the rare day and ages the water on every ordinary one.

Observation 5.2

the shape of Paper 557.There, the pressure angle that strengthened a tooth pointed against the angle that smoothed the drive——here the diameter that secures capacity points against the freshness of the water. One dimension carries two demands, pointing opposite ways.

Observation 5.3

one root, under Paper 300.“The water grows older” and “the chlorine falls below the limit” come from one root, the residence time——keep the residence short and neither happens.

Observation 5.4

what is not said.It is not said that pipes should be narrower——a diameter able to meet fire fighting and future demand is needed. Choosing a wide pipe calls for topping up chlorine on the way or creating flow by other means. What is shown is that a margin does not work only on the safe side.

6. Roll Call and Closing

1. **chlorine lasts 80.4719 hours** (Computation 2.1): **first order, the same from anywhere.**
2. **fourfold diameter, 16.000000 times the residence** (Observation 3.2): **the square of the diameter.**
3. **100 mm: 8.7266 hours, 0.4199 mg/L** (Computation 3.1): **room on the narrow side.**
4. **200 mm: 34.9066 hours, 0.2488 mg/L** (Computation 3.1): **still above.**
5. **300 mm: 0.1039 mg/L** (Computation 3.1): **barely above the limit.**
6. **400 mm: 0.0306 mg/L** (Computation 3.1): **below the limit.**
7. **boundary diameter 303.6676 mm** (Observation 3.3): **the core, checked on both sides.**
8. **the wall does not change the direction** (Observation 4.1): **the exponent goes as $k_b D^2 + 4k_w D$.**
9. **the separator is the flow that sets the diameter** (Observation 5.1): **everyday or rare maximum.**
10. **the shape of Paper 557** (Observation 5.2): **two opposite demands on one dimension.**

Closing: **Water mains are often chosen “wide, to leave a margin” for future demand and for fire fighting.Yet at the same flow, the time water spends in a pipe grows as the square of its diameter——on a 2 km branch carrying a daily mean of 0.5 L/s, widening from 100 to 400 mm lengthens the residence from 8.7266 to 139.6263 hours, exactly**

16.000000 times. Chlorine decaying at first order lasts 80.4719 hours from 0.5 to the limit of 0.1 mg/L, and because the decay is first order this time does not depend on where it is counted from.Through 300 mm the outlet chlorine is 0.1039 mg/L, above the limit; through 400 mm it is 0.0306 mg/L, below it——the boundary diameter is 303.6676 mm, checked from both sides. One step wider "to leave a margin" leaves the tap short of chlorine, while at 100 mm 0.4199 mg/L remains, which shows the margin in width eating the margin in chlorine. Consumption at the wall makes the exponent go as $k_b D^2 + 4k_w D$, still growing with the diameter, and the direction does not change.The separator is whether the diameter is set by the everyday flow or by a rare maximum——a pipe sized for the maximum flows too slowly on ordinary days, enough on the rare day and ageing the water on all the others. Under Paper 300, "older water" and "chlorine below the limit" share the one root of residence time.Placed among the earlier papers——as in Paper 557, one dimension carries two demands pointing opposite ways. As Paper 346 showed, a half-life is a property only for first order, which is why the life of chlorine can be stated as one number.To be honest——the numbers are representative, the flow was held at its daily mean, and neither mixing in the network nor storage was included; the wall was shown only in direction, and neither temperature nor by-products were treated. Nor is it said that pipes should be narrower: what is shown is that a margin does not work only on the safe side.

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Yuuki YAMAGISHI (山岸 勇輝)

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