Utility flushing programs for managing treated water quality – How does distribution system flushing impact water quality that customers experience? (MSU Fall '22)

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Case URL
https://www.learngala.com/cases/flush-msu-fall22

Overview

Utility flushing programs are low-barrier opportunities to monitor and improve water quality after treatment.

Summary

Drinking water utilities routinely flush water from the distribution system to maintain integrity of the infrastructure and improve water quality for customers. Almost all utilities around the world conduct some form of flushing in their distribution system at least once per year. Flushing programs are one of the few ways water providers can easily and non-invasively monitor and manage the health of distribution pipes and integrity of distributed water quality. More than that, in an industry largely hidden from the public eye, flushing activities place water professionals in the physical spaces where the people they serve can see them and the work they do to ensure safe drinking water. On the surface, flushing water from the system may seem like a fairly simple operation. However, as you will see in this module flushing induces complex interactions between hydraulic flow, the distribution system environment, and water quality. It can be a powerful tool for distribution system and water quality management, but also can be difficult to control and achieve desired results. This module provides a foundation of how distribution system flushing works to impact water quality. A case study from collaborative research with the City of Ann Arbor provides a jumping off point to learn about what is going on down in the pipes to cause changes in water quality. By the end of the module, you will reflect on the mixed results observed in Ann Arbor's program to think about what may have been the cause and what solutions may help optimize their program.

Learning objectives

- Define distribution system flushing and its goals
- Understand how flushing impacts the distribution system environment
- Understand how flushing and the distribution system environment impact water quality
- Apply key concepts of flushing to help troubleshoot mixed results from a real flushing program

Introduction to flushing

What is distribution system flushing?

Have you ever seen red water come out of your faucet? Did it make you wonder if your tap water was safe to drink?

Water quality issues like discolored water are a major concern for tap water users. Red water is one of the most common examples of water quality issues that can occur to drinking water after it is treated, but before it reaches your faucet.

Water providers conduct distribution system flushing to help prevent these and other kinds of water quality issues. Coincentally, flushing can also cause these kinds of issues, as well.

Website Url
https://www.wilx.com/content/news/MSU-Students-concerned-over-water-in-dorm-hall--564061111.html

Caption
What does flushing water from distribution system pipe mains look like?

Website Url
https://www.youtube.com/watch?v=A4GDmlcthNg

Website Url
https://ipf.msu.edu/notices/campuswide-red-water-notice

Flushing water from hydrants or valves in the street (aka "blowoff valves") is a long-standing practice° among water utilities used to ensure the integrity of the physical infrastructure, hydraulic supply, and water quality.

This module focuses on flushing for the purpose of maintaining safe drinking water quality. We will review the different types of flushing methods and explore what is actually happening underground in the pipes during flushing to impact the water quality.

- Flushing mains (https://awwa.onlinelibrary.wiley.com/doi/10.1002/j.1551-8833.1927.tb13484.x)

FLUSHING MAINS

CHAIRMAN PATTON: On calling for a show of hands, I find that we are about evenly divided on whether to flush during the day or during the night.

MR. LYON: We do not flush during the day except on the main street.

MR. NELSON: In most cases we do our flushing in the daytime.

CHAIRMAN PATTON: Do you isolate the mains being flushed? I will ask you to hold up your hands if you are in the habit of isolating the mains when they are being flushed. That is to flush one main with the side lines cut off so that you can flush straight through. Those who do this please hold up your hands.
(Seven hands.)

CHAIRMAN PATTON: Evidently the rest of you do not.

Caption
Excerpt from a 1927 American Water Works Association meeting where different utilities are discussing their flushing programs.

Photo credit
American Water Works Association

Types of flushing programs

TWO OVERARCHING APPROACHES

There are two general approaches to flushing: conventional and unidirectional.

Conventional flushing

This type of flushing requires the least amount of planning, coordination, and resources. It is a common approach for utilities because it is easy to perform.

For the most part, the system is left alone other than conducting the flush at the desired location.

The main benefit of conventional flushing is achieving bulk water turnover, which you will learn more about later.

A few specific forms of conventional flushing include:

“Spot flushing” is where a fire hydrant or blowoff valve is flushed as desired and then staff move on to the next location or other work.

“Dead end flushing” consists of spot flushing specifically at the ends of dead-end lines.

“Automatic flushing stations” (aka “auto-flushing”) consist of locations that are flushed repeatedly at designated times or continuously using an automated device.

Unidirectional flushing (UDF)

This type of flushing requires much more planning and coordination than conventional.

It involves creating a single flow path (aka “flow path isolation”) for water to travel into the flushed pipe, achieved by closing valves that lead to/from other paths.

This flushing is also typically conducted at sequential locations starting closer to a treated water reservoir and working outward. This helps to ensure that pipes connected to the one being flushed have already been cleaned, known as creating a “clean water interface”.

The main benefit of UDF is being able to remove more accumulated matter from the insides of pipes (and with more control), which you will learn more about later.

A few specific forms of unidirectional flushing include:

“Strict UDF” involves meticulous planning to ensure that there is only one isolated flow path into the flushed outlet and to ensure that all pipes from potential upstream paths (closer to the treatment plant or reservoirs) have already been flushed.

“Quasi UDF” creates an isolated flow path into the flushed outlet, but doesn not necessarily ensure that all upstream pipes have already been flushed.

“No discharge UDF” is any type of unidirectional flushing that captures the water being removed and returns it back into the system after filtration. As a result, this method produces no water waste from the flushing.

This table from a recent Water Research Foundation funded project° provides a convenient overview of these different flushing methods.

- Use of Flushing as a Corrective Action Under the Revised Total Coliform Rule (https://www.waterrf.org/research/projects/use-flushing-corrective-action-under-revised-total-coliform-rule)

Classification of flushing techniques		
	Technique	**Description**
Conventional Flushing	Spot Flushing	Select hydrants or blow-offs are manually flowed at a relatively low rate. Lack of valve manipulation allows water to originate from numerous pipe segments and flow in multiple directions.
	Dead-End Flushing	Similar to spot flushing, but hydrants are located on dead-ends which results in single flow path for the immediate pipe segment.
	Automatic Flushing Stations	Similar to spot or dead-end flushing, but flushing is achieved with an automated device as opposed to man-power.
Unidirectional Flushing	Strict UDF	Flushing starts at a clean water interface and progresses in an organized manner through an area using sequential runs. Uses high flow rates and velocities.
	Quasi UDF	Hybrid of conventional spot flushing and strict UDF. Local valving provides local flow control, but upstream sources are not pre-cleaned.
	Zero-Discharge UDF	Valving is used to isolate sections of main. Water is recirculated (pumped) through a closed loop system. Deposits are filtered out.

Photo credit
WRF/Hill et al, 2018.

Conceptualizing the flush

WHAT HAPPENS WHEN WE FLUSH?

What we see on the street makes flushing look simple, but what is happening underground is far more complex.

The animation below shows a bird's eye view of that complexity unfolding durin flushing at a dead-end pipe.

As you watch, take note of the…

direction of flow (arrows)

water quality (color of water)

accumulated material along pipe walls

*Consider replaying the video a couple of times or on slower speed. Some of the changes happen quickly.

View the animation

Website Url
https://youtu.be/3bnjr1B4Ty4

Flushing intervenes on the distribution system environment in two ways:

Bulk water turnover

Removal of accumulated material

Bulk water turnover

Flushing removes water residing in the local pipe and replaces it with water from connected pipes.

Typically, we expect that water being flushed out of the target pipe segment is older and more degraded than the water coming in from nearby pipes. As a result, flushing ideally removes water of worse quality and replaces it with incoming water of better quality.

For example, residents along a dead-end street may normally have water with low chlorine residuals. A flush event can leave them with water that has higher chlorine residuals and therefore less risk of microbiological contamination.

Removing accumulated material

There are various substances (for example: sediments, corrosion scales, & microorganisms) that accumulate along the walls of drinking water pipes. Many of these substances can degrade treated drinking water before it reaches customers.

For example, many substances can react with the disinfectant residual (typically free chlorine or chloramine) that helps keep the water safe from microbiological contamination while it travels to customers. Reduction in disinfectant residual levels increases the risk that water reaching cutomers will be unsafe to consume.

Elevated flow rates induced by flushing can disturb accumulated material, mobilizing it into the water and flushing it out of the system. Sometimes, high flow rates can disturb material in nearby pipes (seen in the animation), which may cause unintended issues. We will revist this later in the module.

Overall, we expect that removing accumulated material from the pipes will improve future water quality by removing the main sources of degradation acting on water as it travels through the system.

A real scenario from Ann Arbor

Troubleshooting Ann Arbor's flushing

In this module, you will learn about some mixed results that the City of Ann Arbor experienced during their annual conventional flushing program and think about what could be done differently in the future.

Like most real scenarios, there will not be enough information to have a definitive answer to the mixed results – only guesses informed by knowing how flushing works and thinking critically about the data you are seeing.

Water Treatment in Ann Arbor

The Ann Arbor drinking water treatment plant treats a mixture of 15-20% groundwater and 80-85% surface water using lime softening, coagulation, flocculation, settling, ozonation (primary disinfection), single and dual-media filtration (granular activated carbon, some on top of sand), and chloramination (secondary disinfection).

The treatment plant promotes the formation of monochloramine as the disinfectant residual and limits nitrification by

using a chlorine to ammonia mass ratio of 4.75-5.0 (i.e. 4.75:1.0 to 5.0:1.0 mass ratio)

maintaining the finished water pH > 9 and alkalinity > 50 mg/L as $CaCO_3$

providing a monochloramine residual > 3.0 mg/L as Cl_2 in the finished water and > 1.5 mg/L as Cl_2 in the distribution system

flushing the distribution system

Additional details on the drinking water treatment process can be found on the City of Ann Arbor's website. The treatment plant serves approximately 125,000 residents, corresponding to about 26,000 customer connections, and produces an average of 14 million gallons (around 53,000 m^3) per day.

> **Website Url**
> https://www.a2gov.org/departments/water-treatment/about/Pages/default.aspx

Annual summer dead-end flushing program

As part of its strategy to manage distribution system water quality, the City of Ann Arbor conducts repeated conventional flushing in selected locations throughout the summer and early fall. The process consists of weekly flushing at sites (mostly dead-ends) in order to address:

aesthetic issues (i.e. discoloration or off-putting odor and taste)

low chloramine residuals (< 1.5 mg/L as Cl_2)

elevated nitrite levels (> 0.1 mg/L as N) from microbiolical nitrification

Sixteen locations in the Ann Arbor distribution system were flushed from June through October, 2020. Flushing occurred each week between 7am and 3pm and each location was flushed individually for 10 to 90 minutes.

Sampling and parameters of interest

Each sampling location, a fire hydrant or blow-off valve, was flushed for 10 to 60 seconds before taking a "start-of-flush" (SOF) sample. This step ensured the sample represented the quality of water in the distribution system main rather than in the hydrant barrel or blow-off valve lines.

An "end-of-flush" (EOF) sample was also taken just before closing the outlet.

Many utilities only collect data on visual discoloration during flushing programs, often measuring the amount of time it takes for the flow stream to visually run clear (aka "time to clear"). Utilities find this measure helpful as an indicator of having removed material that could cause aesthetic issues for nearby customers.

Ann Arbor was interested to pilot a more quantitative approach to water quality monitoring during flushing, which included measuring total chlorine, nitrite, and turbidity levels for each sample.

Overview of monitored parameters

Total chlorine

Measured to represent the amount of chloramine disinfencant residual in the water. The disinfectant residual protects the water from microbial contamination as it travels from the treatment plant to customers. The parameter is also one of the most widely used indicators of overall water integrity – when disinfectant residuals are lower it demonstrates that the overall quality of water has degraded. Drinking water providers aim to keep disinfectant residual levels as close as possible to the finished treated water leaving the treatment plant, and at least detectable in any water reaching customers.

Nitrite

Measured as an indicator of a particular type of undesirable microbial growth that typically occurs during warmer months in systems that use chloramine as the disinfectant residual. There are several groups of microbes, called "nitrifiers", that grow by making use of available organic nutrients and ammonia in the water. The chloramine compound is made up of chlorine and ammonia. When chloramines degrade, the ammonia becomes available for microbial growth, which then causes more chloramines to degrade and so on. This process can accelerate quickly when microbes grow exponentially in optimal conditions. The nitrite that is produced by nitrifiers tends to build up in drinking water systems. Nitrite then becomes an indicator of nitrification activity, but also of microbial growth more generally during warmer months.

Turbidity (aka "flushing-induced turbidity")

When measured during flushing activities, it is a measure of the amount of material accumulated on pipe walls that is mobilized by the flush. As a result, the flushing-induced turbidy serves as an indicator of pipe conditions rather than a measure of water quality (i.e. normal turbidity).

Results: Water quality improvements during flushes

Water quality and pipe conditions almost always improved during each flush.

Total chlorine (cl2_tot) levels either remained high or increased (improved)

Nitrite (nitrite_ppm) levels either remained low or decreased (improved)

Flushing induced turbidity (turb) levels remained low or decreased (improved)

These plots show a comparison of start-of-flush parameter levels versus end-of-flush parameter levels at two different sites. Boxplots represent data from all flushes conducted at the site (between 10–20 depending on the site).

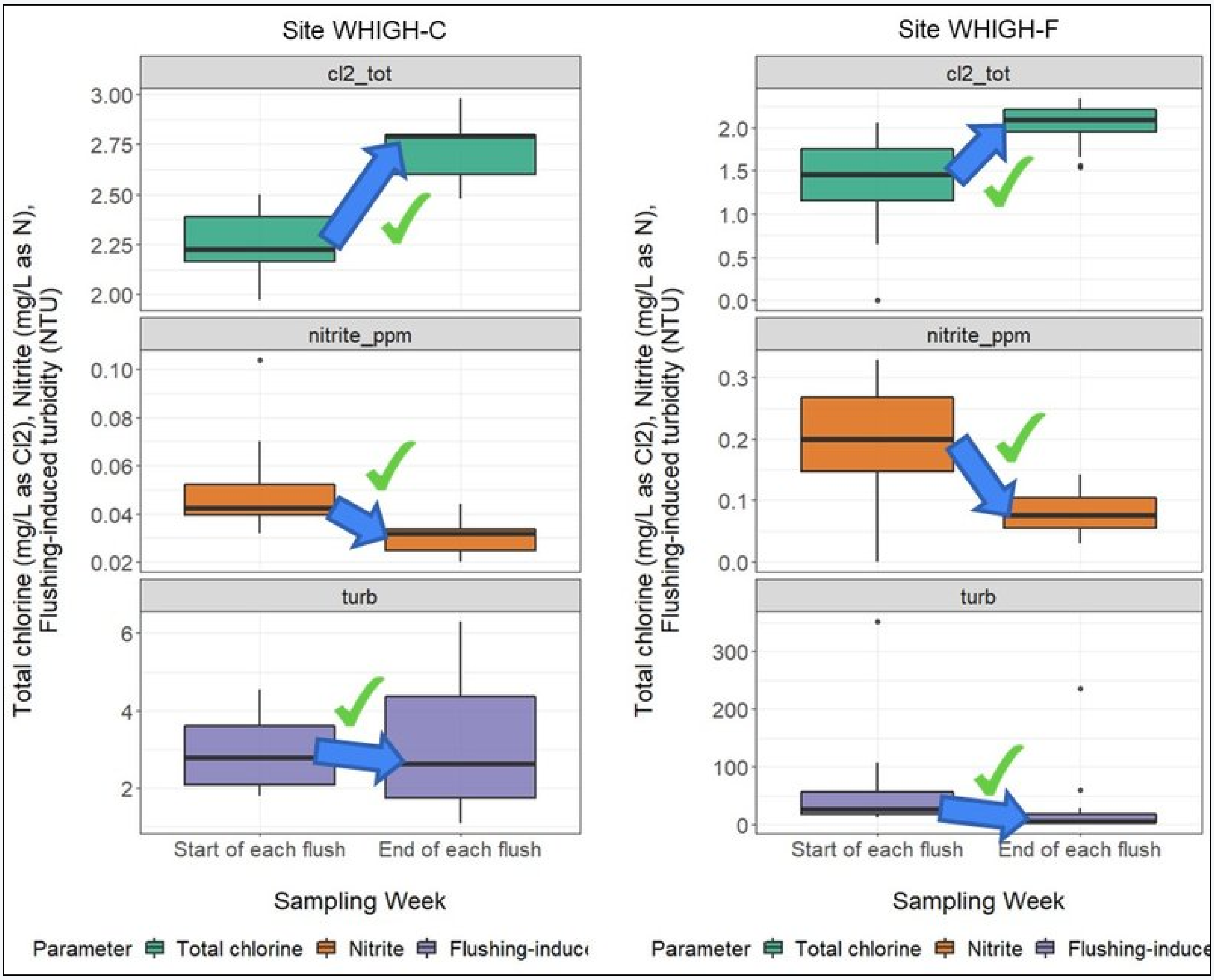


Image description for accessibility

Overall, the water quality at the start of flushes was better than the water quality at the end of flushes.

Caption

Overall, the water quality at the start of flushes was better than the water quality at the end of flushes.

Results: Water quality improvements over time

All three measured parameters improved, or remained good, over time at many sites.

However, at some sites the total chlorine and nitrite did not improve over time as desired, despite large reductions in accumulated material that were expected to reduce future degradation.

Take a moment to view these mixed results below and use any knowledge you already have about flushing to think about what may be causing the different results.

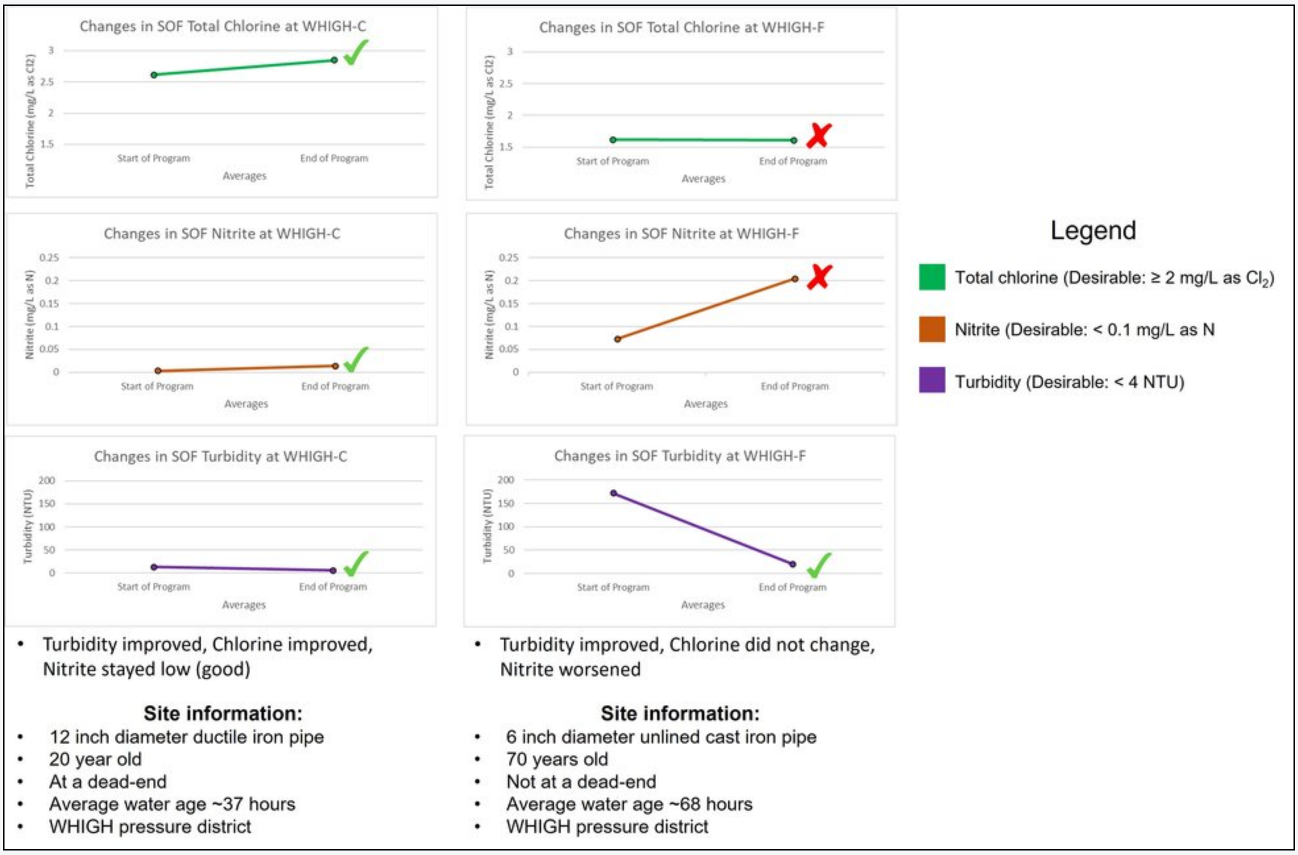


Image description for accessibility

At one site (WHIGH-C) flushing removed turbidity (accumulated material) while total chlorine improved and nitrite remained low (good). At another site (WHIGH-F) flushing removed even larger amounts of turbidity, but total chlorine did not improve and nitrite worsened.

Caption

At one site (WHIGH-C) flushing removed turbidity (accumulated material) while total chlorine improved and nitrite remained low (good). At another site (WHIGH-F) flushing removed even larger amounts of turbidity, but total chlorine did not improve and nitrite worsened.

Looking ahead

By the end of this module, you will revisit these mixed results and reflect on what may be happening with the City's flushing and what kinds of changes might improve it.

For now, let's dive into the specific ways that flushing works to impact water quality.

Bulk water turnover

The main idea – refreshing the local water quality

One of the primary effects of flushing is removing water that resides in the pipe segment being flushed and replacing it with water that resides in connected pipes nearby. This is called bulk water turnover.

Typically, we expect that water residing in the segment being flushed is older and more degraded than the water that is moving into the area.

As a result, flushing ideally removes water of worse quality and replaces it with incoming water of better quality. Where residents along a dead-end street may normally have water with low chlorine residuals, a flush event would leave them with water that has higher chlorine residuals and less risk of contamination.

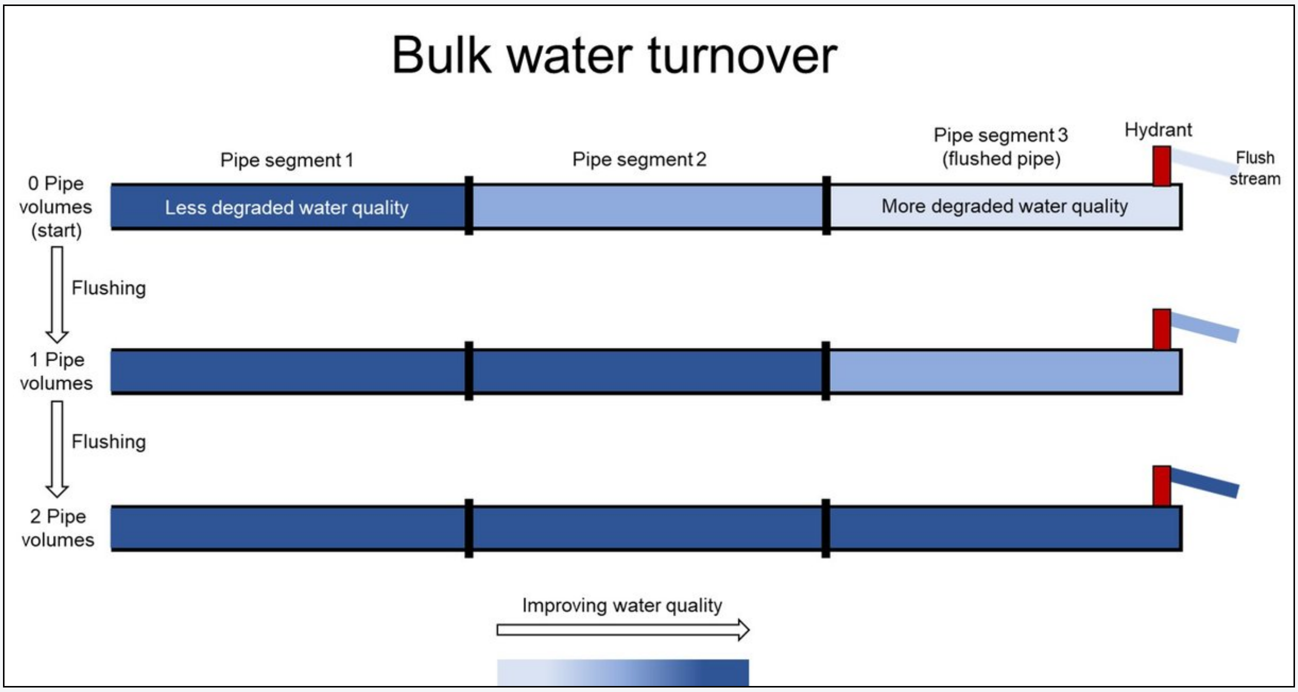


Image description for accessibility
Ideal bulk water turnover where better quality water from nearby pipe replaces older and more degraded water in the flushed pipe segment.

Caption
Ideal bulk water turnover where better quality water from nearby pipe replaces older and more degraded water in the flushed pipe segment.

Understanding turnover

Turnover is the amount of water that is replaced in the target pipe segment.

It is commonly measured as number of pipe volumes – which refers to how many times the total volume of water in the target pipe segment was fully removed and replaced.

If interested, see this example calculation of turnover from a dead-end flush.

Example calculation

Suppose we flush a pipe segment of interest at *50 gallons per minute for 10 minutes* – flushing a *total of 500 gallons* of water out of the system.

If the segment of pipe being flushed is 100 ft long and 8 inches (0.67 ft) in diameter, then the total volume of water the pipe can hold is calculated as

$$\text{Volume} = \pi * r^2 * L = 3.14 * (0.67/2)^2 * 100 = 34.9 \text{ cubic ft} = 261 \text{ gallons}$$

*So our bulk water turnover from the flush was

$$\frac{500 \text{ gallons flushed}}{261 \text{ gallons in the pipe}} = \mathbf{1.9 \text{ pipe volumes}}$$

Image description for accessibility
An example calculation of turnover from a dead-end flush

Caption
An example calculation of turnover from a dead-end flush

Visualizing bulk water turnover

The link below contains a hydraulic model simulation of a flush at a distant dead-end pipe segment.

For the sake of thinking about bulk water turnover by itself, let's ignore any effects on accumulated matter that would come from a 1000gpm conventional flush conducted in the video.

Focus instead on the "movement" of water through different pipes by following the water age changes throughout the network.

The model in the video shows pipes colored by water age, where lighter colors are lower water age (younger/fresher water) and dark red is the highest water age (older/stagnated water).

Reflect on the following questions as you watch:

In which pipes do you expect to see the water age change first?

What can you see about the flow of water by watching the changing water ages?

Does water "flow" as you expect?

Did water age change in all pipes near the flush site?

Watch the hydraulic simulation video from around 5:28–7:15 timstamp.

> **Caption**
> Hydraulic model simulation of a hydrant flush.
>
> **Website Url**
> https://youtu.be/SmFe0QYiljo?t=328

Does bulk water turnover always improve local water quality?

Whether bulk water turnover improves the quality of water in the flushed pipe depends on:

the quality of water in nearby pipes

the flow path(s) induced by flushing

whether accumulated matter in nearby pipes is disturbed

Keep this in mind moving forward, we will explore these points in more detail in a later segment!

How long can it last?

Limited impact of bulk water turnover

The impacts on local water quality specifically from the effect of bulk water turnover are only temporary!

Why only temporary?

The new water brought in by flushing arrived quickly through elevated flow rates. As a result, it spent much less time degrading on its way to the outlet than usual.

However, as soon as regular demand patterns resume after flushing, the water will once again travel as slowly as it did before flushing. Soon, the typical water age patterns will return to the flushed pipe, marking the end of any beneficial water quality changes caused specifically by bulk water turnover.

How long can it last?

Imagine that we flush the entire volume of water sitting in a dead-end section of pipe. Suppose we flush water into the pipe 10 times faster than it would normally travel – water that normally takes 300 minutes (5 hours) to arrive at the outlet only takes 30 minutes to arrive during the flush.

The water now in the flushed pipe has spent 4.5 hours less than usual traveling and degrading.

Just after flushing, normal flow rates return based on local consumption patterns. It will take the usual five hours for new water entering the pipe to fully replace all the water just brought in from flushing.

So, within five hours the effect of the bulk water turnover is gone and we have returned to our normal distribution system pattern!

Water residence times

The amount of time it takes for one volume of water to pass through a section of pipe is called the water residence time. This amount of time is inherently dependant on water flow that is dictated by demand patterns.

Under the same flow rate, a longer section of pipe has a longer water residence time than a shorter section of pipe. Similarly, considering the same length of pipe, a higher flow rate results in a shorter water residence time than a lower flow rate.

In a real distribution system, any particular pipe segment does not have a constant residence time – it changes according to changing flow rates / demands. We know that water demand changes over the course of a day and even differs by season. Therefore, the amount of time it takes for water to travel from pipe entry to exit (i.e. one pipe volume) varies based on the daily and seasonally changing flow rates.

*So, we can reasonably guess that the improvement from bulk water turnover will last only as long as the water residence time that follows the flushing.

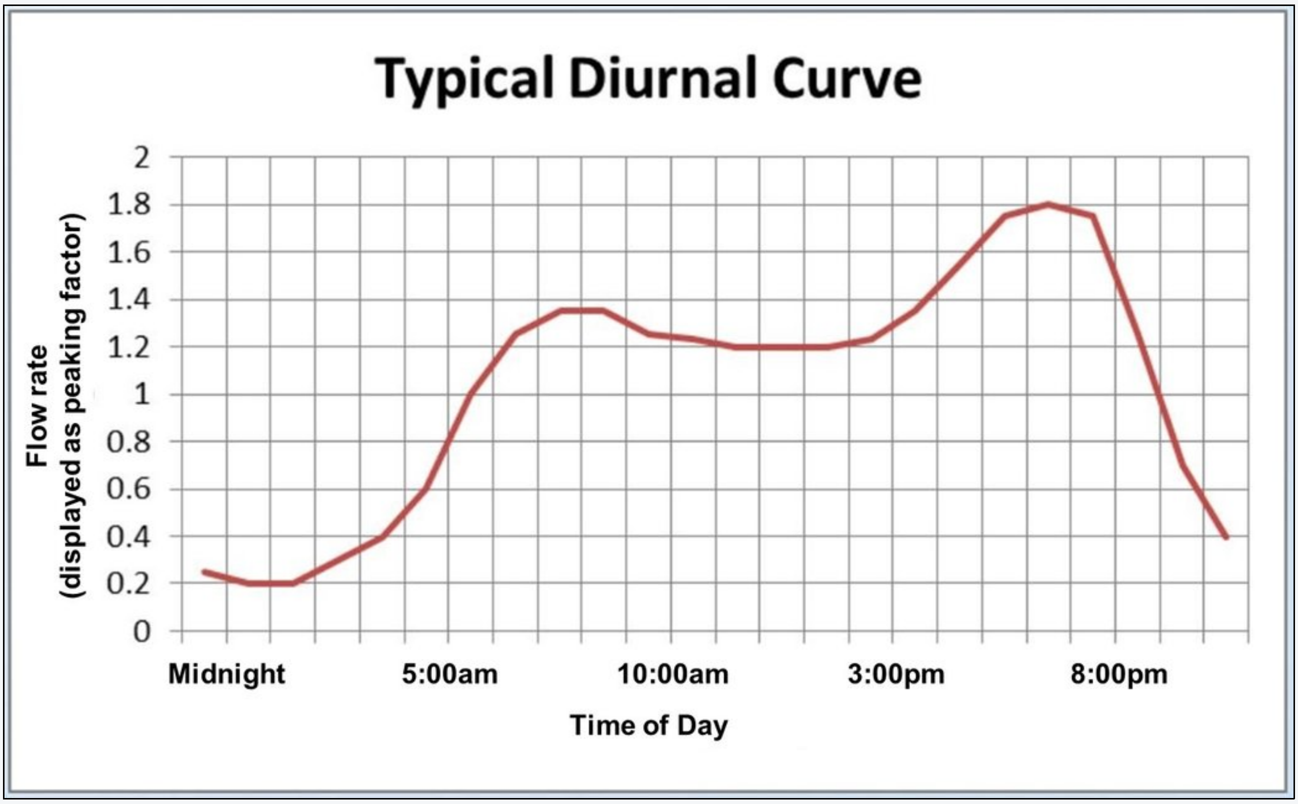


Image description for accessibility
Water demand changes over the course of a day.

Caption
Water demand changes over the course of a day.

Auto-flushing

As you might have guessed, this limited duration of impact is one of the reasons why implementing an automatic flushing device can be so useful.

Programming an auto-flush device to operate at frequent enough intervals, or even continuously, can help keep water ages lower (i.e. reduce stagnation) on a continuous basis so that nearby customers experience a baseline improvement in their water quality – not just immediately following the flush.

Material accumulation

Accumulated material – the sources of degradation

One of the main reasons that water quality degrades after treatment is because of interactions with matter that accumulates in distribution pipes.

Drinking water in the distribution system is in constant interaction and exchange with the pipe environment. As water travels though the pipes, different substances in the water settle or attach to pipe surfaces, while substances on pipe surfaces also detach and (re)join the passing bulk water. In addition to this material exchange, the bulk water and the pipe environment physically and chemically interact in ways that change one another.

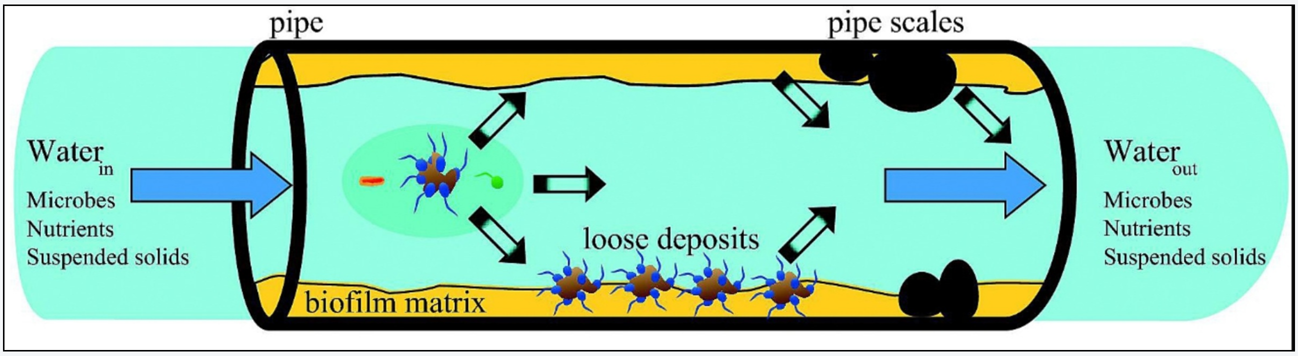
These exchanges and interactions can degrade water quality, causing changes that could:

cause displeasing aesthetic experiences for customers

increase the risk of contamination during its travel to customers

contaminate the water in a way that could directly harm people

In contrast to achieving bulk water turnover, removing accumulated material has the potential to impart longer lasting improvements to water quality at a flushed location.



Caption
Transfer of different matter through different methods from bulk water to the pipe environment and vice-versa.

Photo credit
Liu et al, 2017.

One example related to the Ann Arbor case study

Many types of accumulated material work to degrade chloramine disinfectant residuals. Nitrifying microorganisms are one particularly important part of the accumulated matter in chloraminated systems. As nitrifying microorganisms grow more actively in warmer months, chloramine residuals substantially decrease while nitrite levels increase. This relationship is a double-edged sword – low chloramine levels increase the risk of microbiological contamination, while high enough nitrite levels can be lethal to babies (shortness of breath and blue-baby syndrome).

Another example related to the Flint Water Crisis

Corrosion buildup on pipe walls and its detachment or dissolution into the water can result in public health disasters. In Flint, the corrosiveness of the new drinking water supply and lack of protective chemicals caused lead to leach from the metal pipes. Lead was then carried into the water along with iron corrosion that detached from pipe walls. Customers noticed the aesthetic issues from iron in the water, but it was the imperceptible lead levels carried alongside the iron that was the public health issue.

Material accumulates in all drinking water pipes

All pipes undergo accumulation of matter over time, regardless of pipe material.

See for yourself!

Take a look at this video of the inside of a distribution system pipe main in the United Kingdom. Water is flowing toward the camera and the camera disturbs material attached to the wall as it moves along the pipe. (Watching at 2x speed may be helpful)

Caption
A camera inserted into a drinking water distribution system main observes and disturbs accumulated material.

Website Url
https://youtu.be/uJzx9vUXeGo

Accumulation processes

Accumulation processes

Understanding how material accumulates in the pipes is critical to understanding how flushing acts to remove it (or not).

Material buildup occurs through a relatively complicated series of processes that results in a wide range of substances all mixed up in different structures on the pipe surface. Some of those materials are loosely settled on pipe surfaces (aka “loose deposits”), while other materials are strongly adhered to pipe walls (e.g. corrosion scales, biofilms).

For visual reference, see this illustration of material buildup and this image of real material buildup (with annoations).

Overall, the types of matter, how they build up, and how much matter accumulates depend on:

pipe material

water quality

flow hydraulics

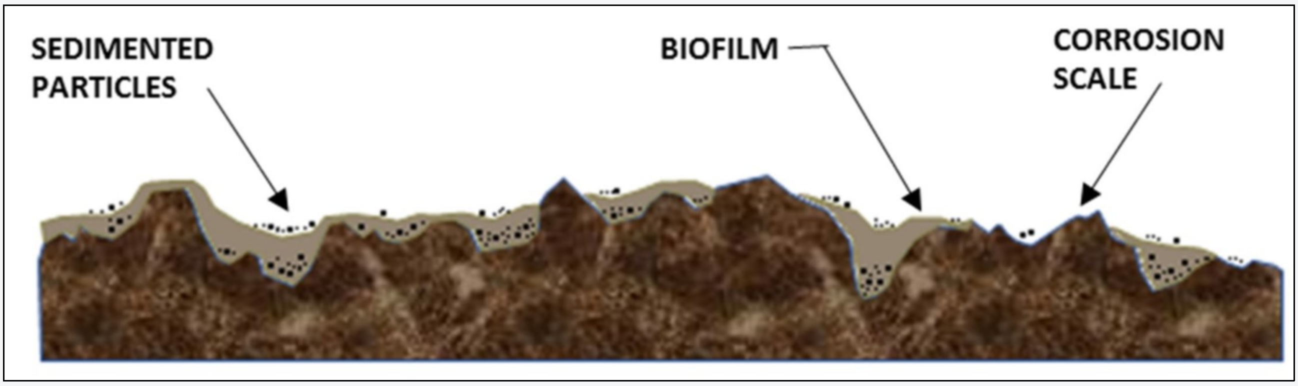


Photo credit
WRF/Hill et al, 2018

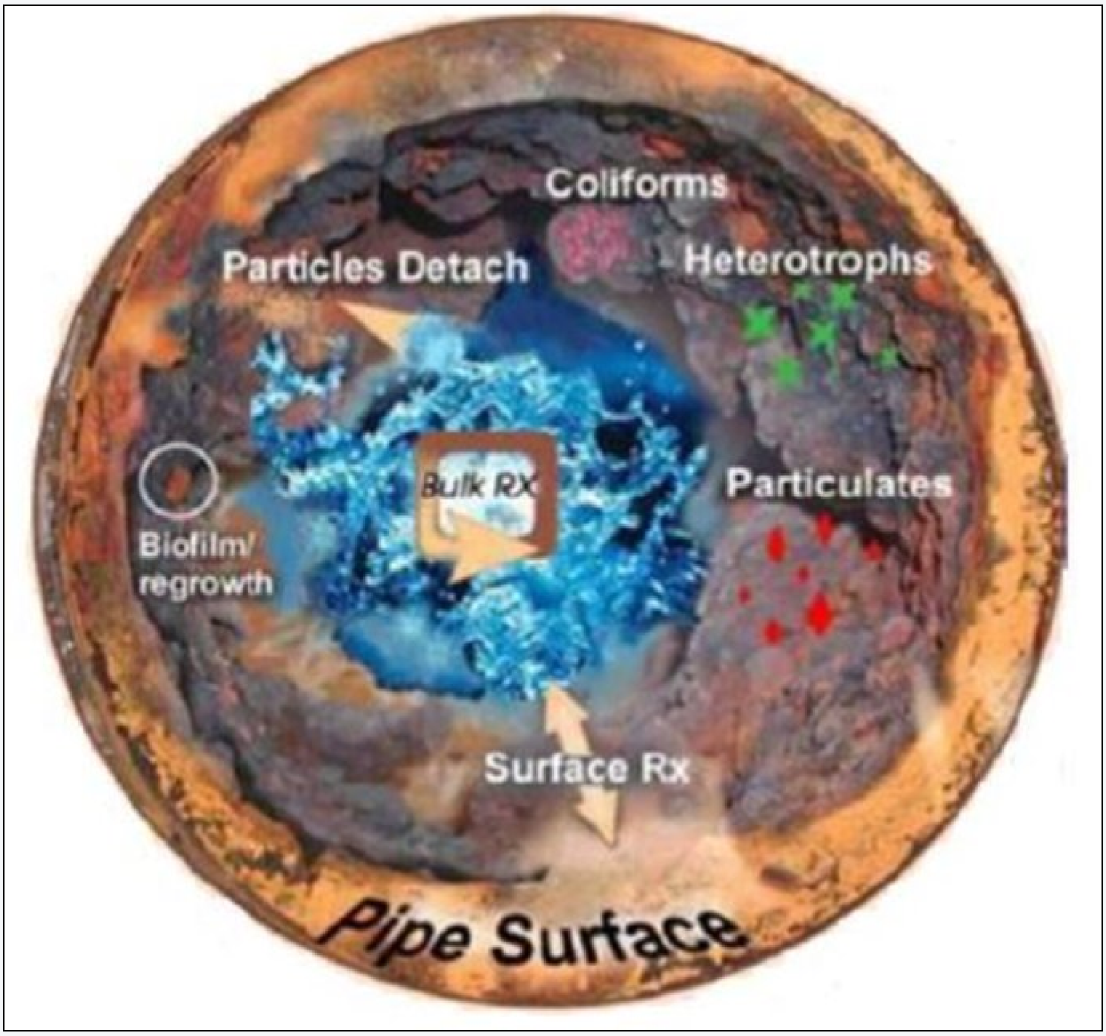


Photo credit
Confluence Engineering, LLC.

1. Pipe materials

Different pipe materials and pipe linings (cast iron, ductile iron, cement, asbestos, plastic) influence the types and amounts of material buildup that occurs in pipes.

Pipe materials with rougher surfaces are more likely to catch matter transported by the bulk water flowing by. These surfaces also have large amounts of surface area, which provide a great environment for microbial growth and corrrosion processes (in metal pipes) to take place. Finally, rough surfaces can result in higher head losses and lower flow conditions, which can also support greater material accumulation.

The chemical makeup of different pipe materials is also connected to material buildup. The pipe material chemically interacts with bulk water and other accumulated materials that can shape what kind of material accumulates and how much.

Unlined cast iron pipes are particularly influential on material accumulation in distribution systems because of their rough surfaces and chemical makeup. These pipes react with bulk water to form corrosion scales and provide micro-nutrients that many microorganisms can use to grow. Tuberculation in cast iron pipes is a complex accumulation of corrosion, minerals, and microorganisms that we will explore more in the next module segment.

Non-metal pipes, or metal pipes with non-metal liners, have smoother surfaces and no metal that can corrrode, which result in less overall accumulation of matter.

However, films of microorganisms (biofilms), sediment, and inorganic matter still often form on the pipe walls over time, as shown in this large cement transmission main in the United Kingdom.

Caption
Large transmission main with a buildup of microorganisms and particles on the pipe walls.

Photo credit
PODDS, UK Sheffield

2. Water quality

Different qualities of the bulk water interact with pipe walls and existing accumulated material in ways that can cause further accumulation, but also some material removal.

Below are just a handful of water quality parameters that can play a role in material accumulation.

Also important to note is that flushing relies on physical forces to disturb and move material from pipes, but key changes in water quality (such as pH) can also lead to mobilization of large amounts of accumulated material from pipe surfaces. This is often known as “chemical destabilization.”

Temperature

In general, higher water temperatures support faster reaction rates, more optimal microbial growth conditions, and help to dissolve more material into the bulk water.

Therefore, in higher temperatures you can expect more buildup of corrosion and more microorganisms. At the same time, you can also expect more sediment and minerals to dissolve from pipe surfaces into the bulk water.

pH

The pH (acidity/corrosiveness) of the bulk water plays a complicated role in material accumulation. Each drinking water system has its own optimal pH to keep different chemical compounds, reactions, and accumulated materials in balance.

In general, however, the pH can:

affect the amount of matter that dissolves into or precipitates out of the bulk water

better support or inhibit microbiological growth

influence the reactivity of bulk water with the pipe environment

cause changes in concentrations or forms of some chemicals in the water

Disinfectant residual

Free chlorine or chloramine (chlorine + ammonia) help prevent harmful microorganisms from contaminating the water before it reaches customers. Chlorine compounds react with many types of accumulated matter.

Dissolved oxygen

Bulk water flowing through drinking water systems tend to be saturated with dissolved oxygen – that is, dissolved oxygen is abundant. Yet, there are also micro-environments in the distribution network where there is little to no dissolve oxygen (an anaerobic or anoxic space).

For example, clusters of sediment buildup or large pipe wall scaling can create small anoxic environments. Oxygen is an essential substance for corrosion reactions and for many microorganisms to grow. On the other hand, only some chemical processes and microbial growth occur in the anoxic regions.

Organic carbon

The amount of (assimilable) organic carbon in the system is a major source of nutrients for microorganisms. Many microorganisms need carbon from their environment to grow.

Natural organic matter

There are many small substances of organic matter that make it through the treatment process into the distribution system. These substances contain carbon and nitrogen, two of the most important nutrients for microbial growth. Natural organic matter can also react with disinfectant residuals (e.g. chlorine or chloramine) to form unwanted compounds like ammonia and disinfection byproducts.

3. Flow hydraulics

Bulk water flow rates are directly involved in shaping how material accumulates, which in turn influences the types and amounts of material that exist in the pipe environment. As water flows, it exerts shear forces on pipe surfaces and existing material buildup.

Water flow exerts a shear force on the pipe surfaces, and rougher parts of the surfaces experience a larger portion of the force. Those shear forces can pull loosely settled material and forcibly detach more strongly adhered material into the bulk water.

Higher flow rates

Higher flow rates are more likely to prevent material from settling on and attaching to pipe surfaces. On the other hand, they also make some nutrients and water quality conditions (e.g. Dissolved Oxygen) more available and accessible (from constant refreshing). In high-flow pipe environments, accumulated material that remains on pipe surfaces has stronger ability to resist detaching under higher shear forces.

Lower flow rates

In general, lower flow rates allow more material to settle out of bulk water and onto pipe surfaces. They also provide more time for water to fully react with already accumulated material and pipe surfaces, but the refresh rate of nutrients and conditions is slower. Pipes with low water flow rates are prone to accumulate more loosely settled material than pipes with higher flow rates due to lower shear forces. As a result, much of the material that accumulates in low-flow pipes may be easily mobilized.

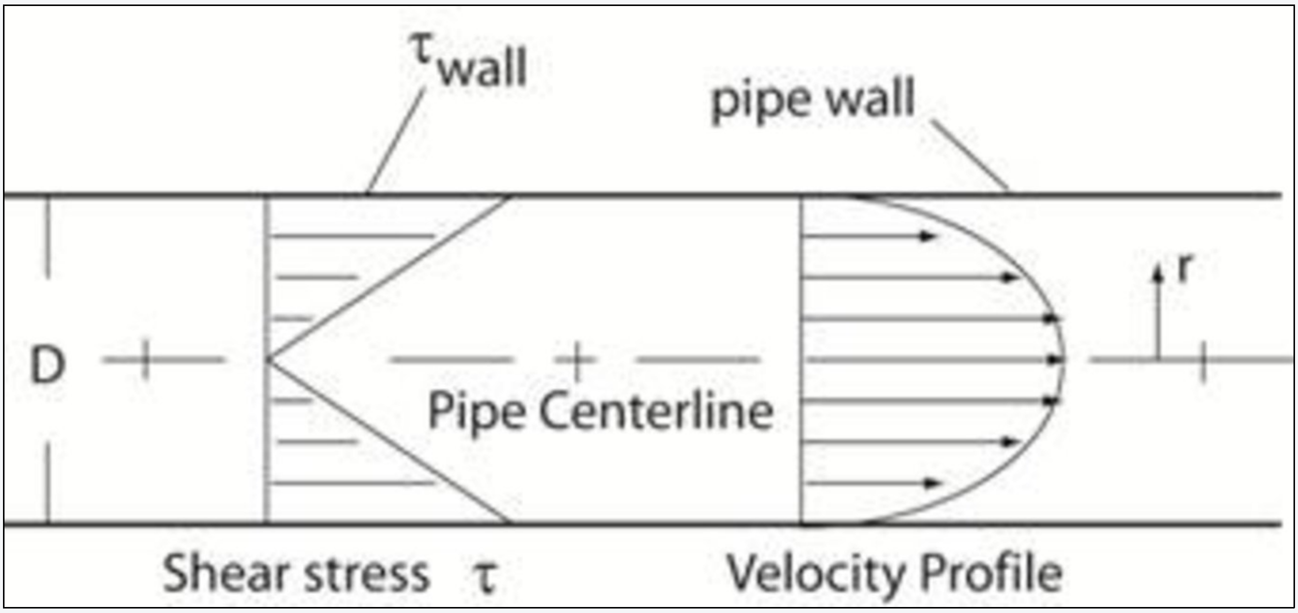


Image description for accessibility
Shear stress exerted on pipe walls corresponds to the velocity profile from water flow. Higher shear forces occur closest to pipe surfaces (where velocity is lowest).

Caption
Shear stress exerted on pipe walls corresponds to the velocity profile from water flow. Higher shear forces occur closest to pipe surfaces (where velocity is lowest).

Photo credit
http://abe-research.illinois.edu/faculty/dickc/Engineering/xmplaminara.htm

A model of layered buildup influenced by hydraulics

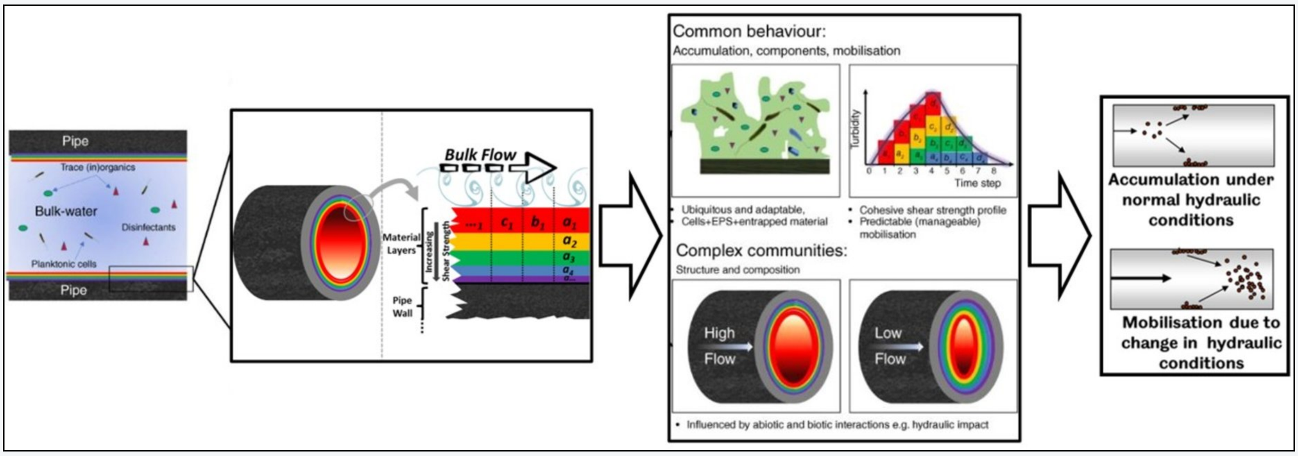
Researchers have created a model that helps explain and visualize some of the material accumulation processes in pipes. The model below was created from many years of field work alongside distribution system operators and technicians at utilities in the United Kingdom.

The Prediction of Discoloration in Distribution Systems (or PODDS) model demonstrates how adhered matter builds up in layers along pipe walls according to hydraulic conditions.

In fact, the typical patterns of water flow that are driven by nomal changes in demand throughout a day / month / season all work to shape the accumulation or release of matter within the system.

This buildup of matter based on cyclical flow rates is also known as pipe “conditioning.” The number of layers and their abilities to resist mobilization at different shear forces are unique in pipes with different flow profiles.

As you might imagine, different types of material are more or less likely to exist in different layers based on their abilities to resist detachment.



Caption
Matter inside of pipes accumulates according to the regular cycles of flow and is disturbed by flow rates that exceed typical maximum levels.

Photo credit
PODDS, UK Sheffield

Types of material

Types of accumulated material

The matter inside pipes is not all the same. It can consist of:

organic matter

inorganic matter

microorganisms

In addition, the origin of those substances can be both external and internal to the pipe environment. Some examples include:

small organic matter particles that make it through the treatment plant

activated carbon from filtration at the treatment plant escapes with the bulk water

minerals precipitate out of the water under the right conditions

microorganisms grow from other microorganisms that were already in the system

corrosion builds up on pipe walls from interfacing with the bulk water

Some substances are symbiotic with or support the presence of other substances.

For example, natural organic matter often provides nutrients for microorganisms to grow. Similarly, microorganisms that rely on small amounts of metals to survive tend to grow alongside corrosion buildup along pipe surfaces.

Finally, some special structures with complex mixtures of accumulated matter form in the pipes such as the following:

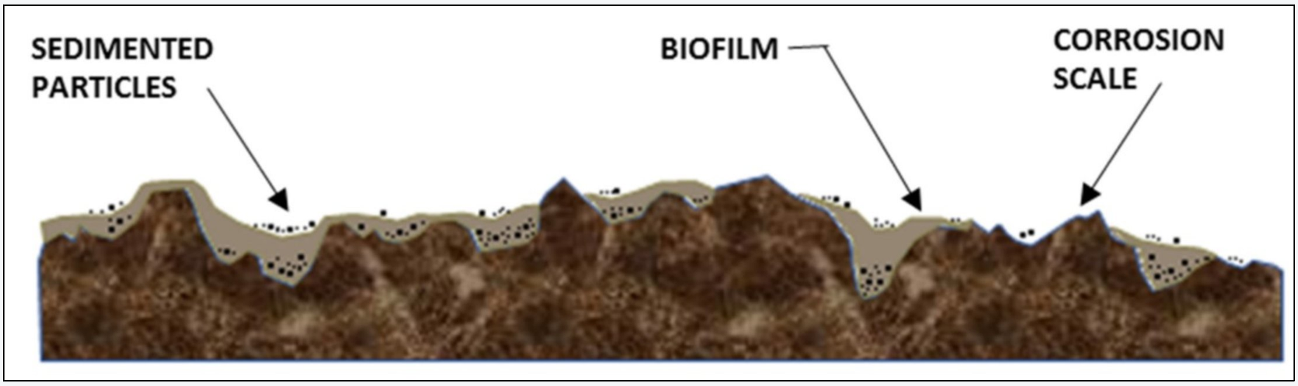
Loose / “soft” deposits

Material that settles on pipe surfaces and remains loosely connected to other material or pipe walls is often called “loose deposits” or “soft deposits” or “sedimented particles”.

These deposits can include all types of matter – organic and inorganic substances as well as microorganisms.

Loose deposits are much easier to mobilize than adhered matter – they are often mobilized and redeposited even during typical demand pattern fluctuations.

They are especially common at or near areas of low flow, such as dead-end pipe sections where they can remain fairly undisturbed.



Caption
Note the top layer of buildup called "sedimented particles", which are also known as "loose deposits" or "soft deposits". This layer is easily mobilized by hydraulic changes.

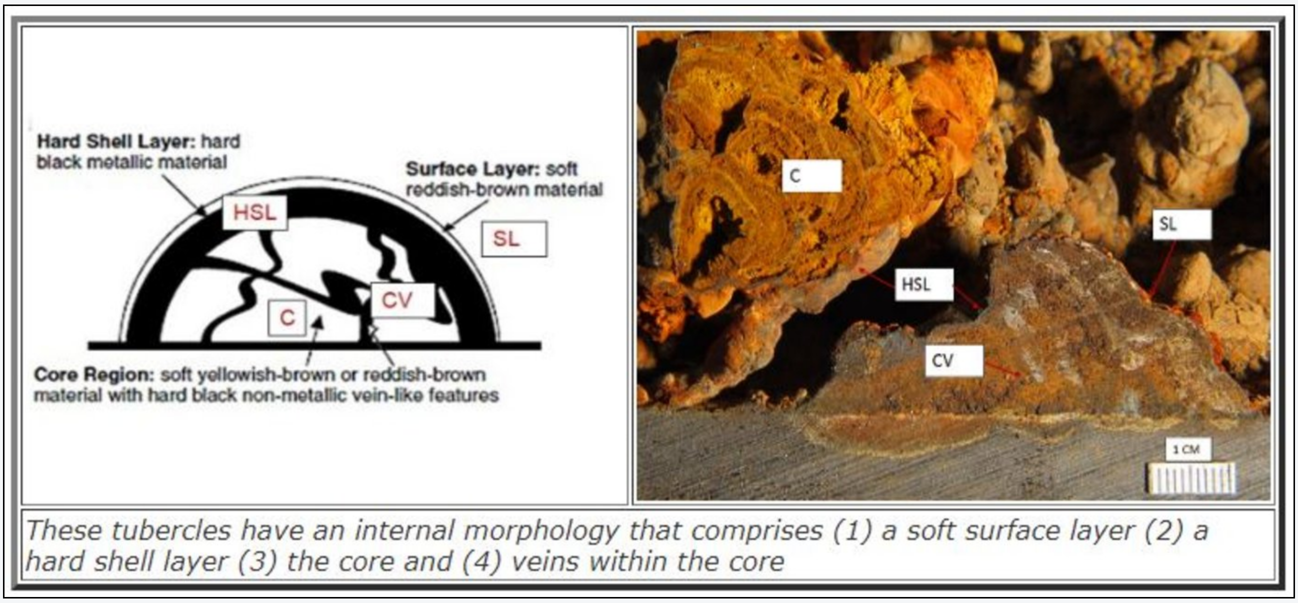
Tubercles

Unlined cast iron pipes support a special type of material accumulation called tuberculation, where structures called "tubercles" form.

Tubercles are layers of buildup that grow out from the pipe wall and consist of a soft inner core, veins within the core, a hard outer shell, and a soft surface layer.

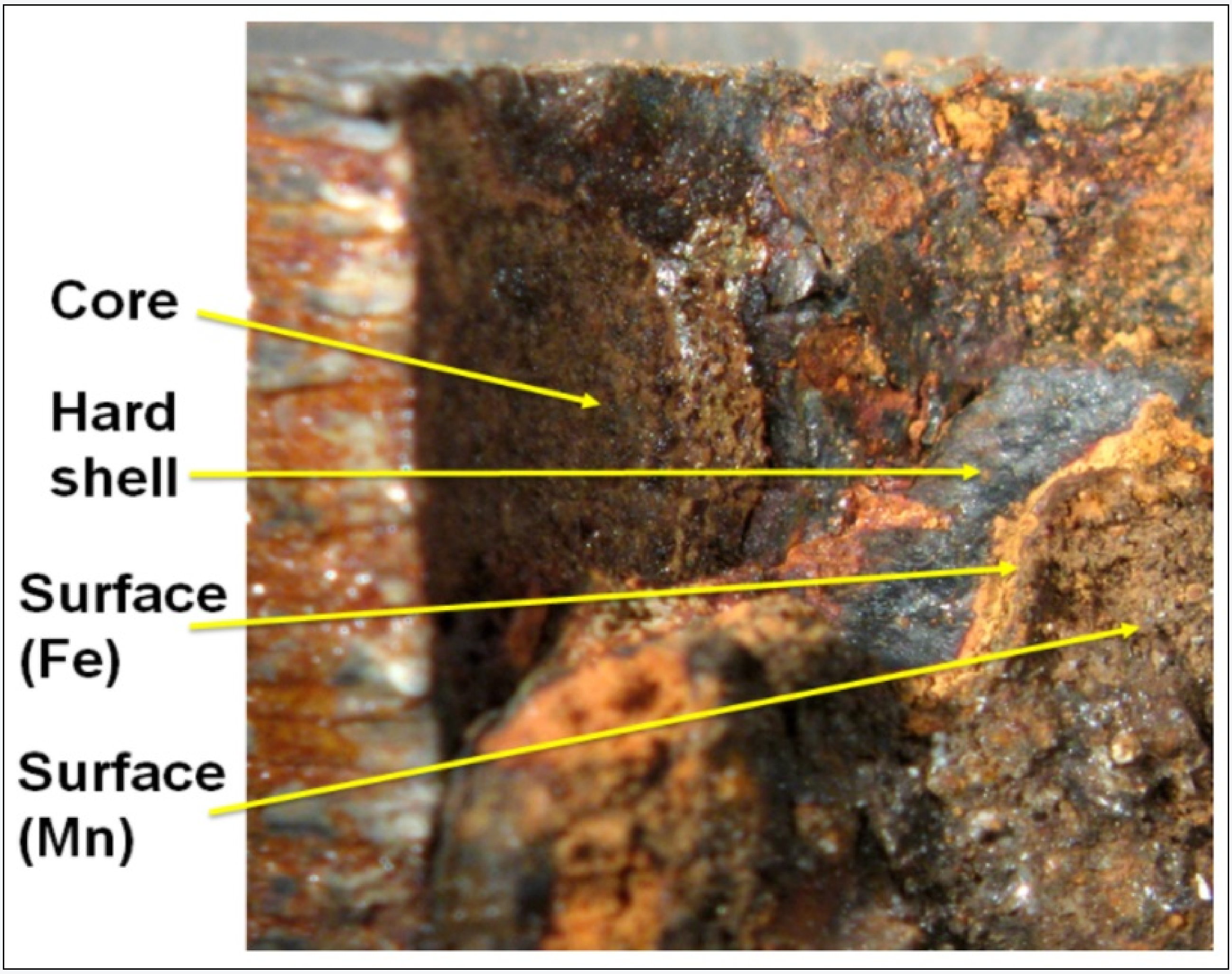
The inner core is a porous area that consists of minerals, corrosion, organic matter, and microorganisms. The outer shell has a hard surface and consists mostly of iron compounds, which makes the tubercles particularly resistent to mobilization or removal. Finally, the surface layer is a slightly softer layer that interfaces with the bulk water and serves as the corrosion front that continues to expand outward.

If you're interested, you can check out more information about tuberculation.



Caption
Three regions of a tubercle.

Photo credit
Gerke et al, 2008



Website Url
https://www.sedimentaryores.net/Pipe%20Scales/Fe%20scales/Tubercles%2002.html

Biofilms

One of the most important formations of accumulated material inside of pipes is the biofilm.

A biofilm is a group of microorganisms that have attached to the pipe wall and created a matrix of substances (called "extracellular polymeric substances" or "EPS") that act like a web to bond the microorganisms together with eachother and with different organic and inorganic matter.

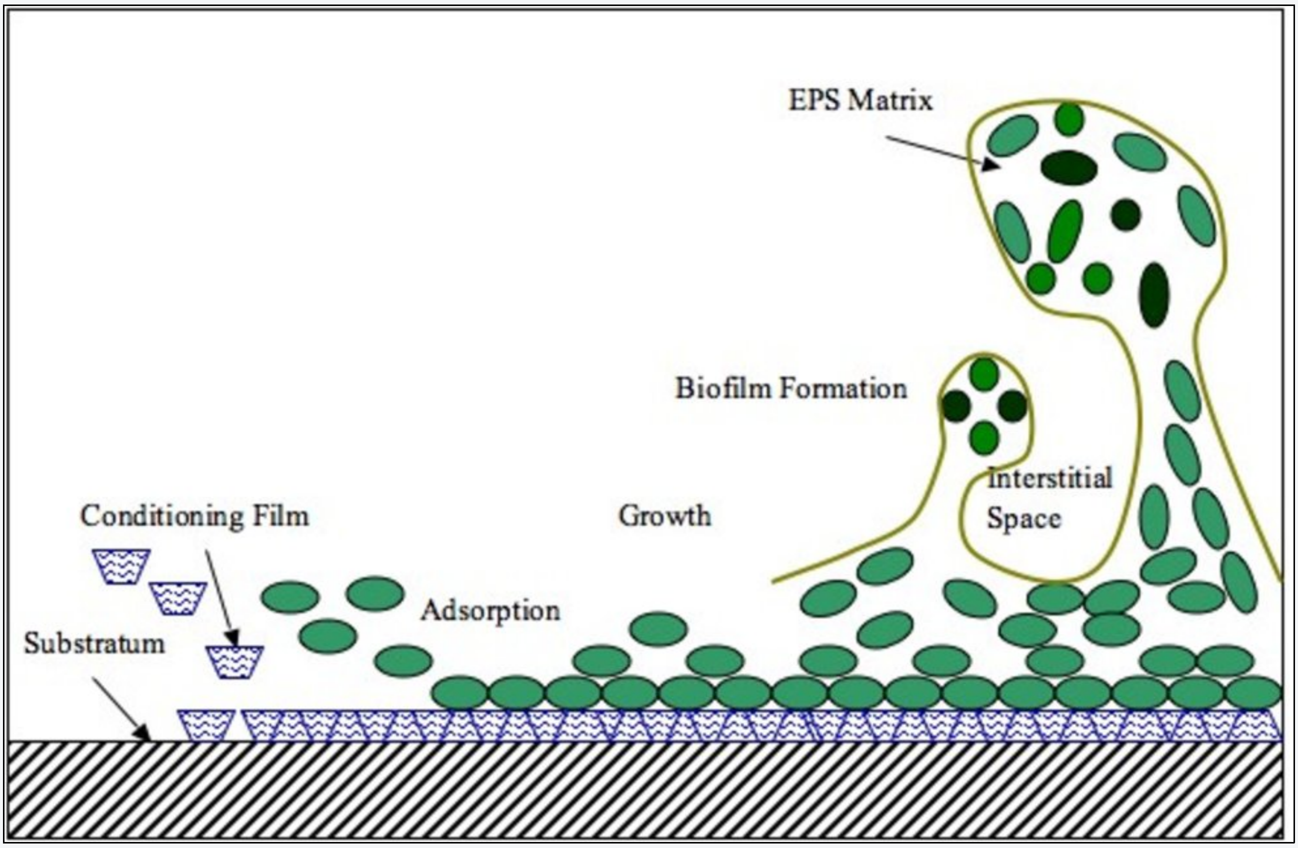
See this animation created from agent-based modeling thate visualizes the formation of a biofilm over time.

This biofilm created by the microorganisms encapsulates many different kinds of substances, not just other microorganisms. Within the biofilm there is often inorganic matter like corrosion particles and minerals containing other metals, as well as orgnic matter, all of which can serve as micro-nutrients for many microorganisms.

Due to their web-like matrix, biofilms are fairly resilient to detachment from elevated flow rates.

Some water quality changes can destabilize the biofilm, resulting in a weaker web that can more easily detach. In fact, many discoloration events (e.g. "red water" events) are often caused by the detachment of a biofilm that had entrapped large amounts of corrosion compounds. When the biofilm is released into the bulk water, the corrosion goes along with it.

We have only recently begun to understand the many different roles that biofilms play in the pipe environment.



Caption
Extracellular polymeric substances definition and depiction (wikipedia)

Website Url
https://en.wikipedia.org/wiki/Extracellular_polymeric_substance#:~:text=Extracellular%20polymeric%20substances%20(EPSs)%20are,physicochemical%20properties%20of%20a%20biofilm.

Caption
Computer simulation of different microorganisms attaching onto pipe walls and building up over time.

Website Url
https://www.youtube.com/watch?v=TLFpcMQJ62E

How you flush matters

THE WAY YOU FLUSH MATTERS

Neatly drawn out plans are always subject to change under real conditions in the field.

It may not be reasonable to expect that field work goes exactly as planned and it is important to how implementation of flushing work (not just the ideal design and planning) can impact the effectiveness of flushing programs.

In terms of impacts on water quality, there are five main factors to consider:

Flow rate

Flush duration

Time of day of flushing

Incoming flow path (path isolation)

Quality of incoming water (clean water interface)

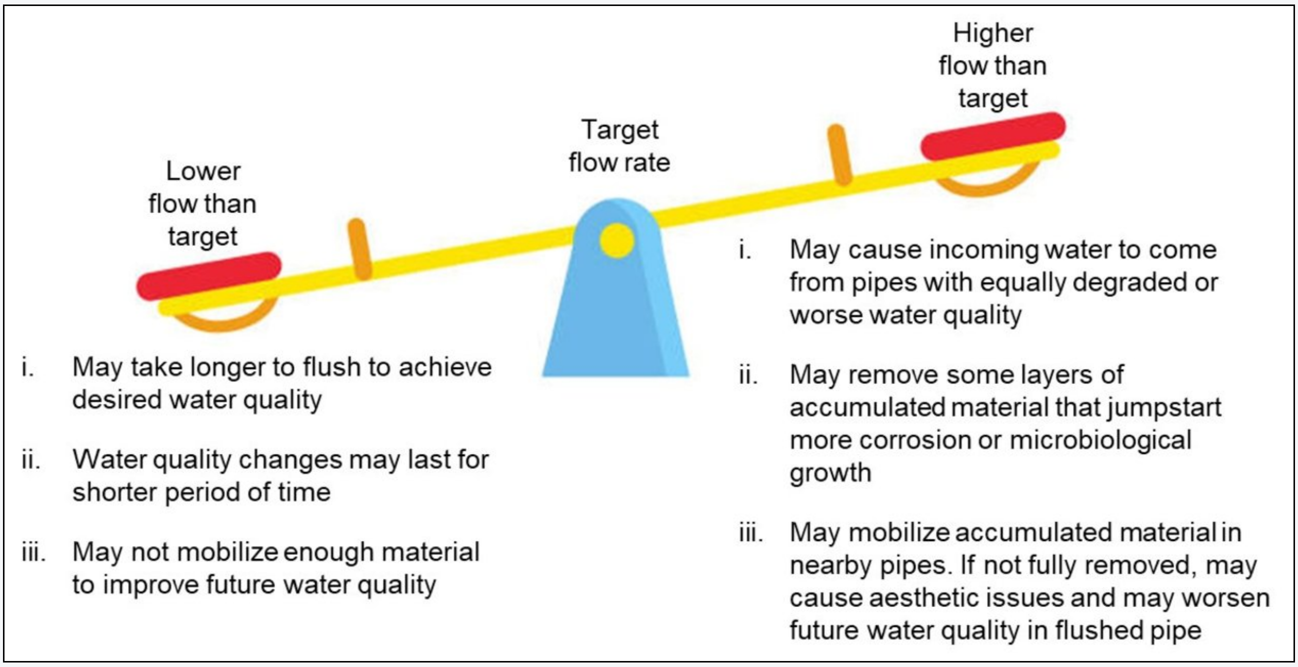
1. Flow rate

Achieving and maintaining the target flow rate during a flush is important to ensuring that the desired water quality impacts will be achieved, and to minimize the chance of unintentionally worsening water quality.

The chosen flow rate is associated with a desired amount of bulk water turnover and accumulated material removal.

Remember that bulk water turnover can help improve water quality in the short term, while material removal can help achieve long-term impacts.

Flushing at rates substantially higher or lower than the target may result in unintended consequences that could impact customer satisfaction and/or public health.



2. Flush duration

The amount of time that an outlet is flushed is important for achieving:

i) the desired amount of bulk water turnover ii) the complete removal of any material that is loosened by flushing

Amount of bulk water turnover

The flush duration, in combination with the flow rate, determines the amount of bulk water turnover that is achieved during the flush.

At minimum, the goal of bulk water turnover should be to replace at least one full pipe volume. This ensures that at least the entire volume of degraded water in the flushed pipe is removed.

There is a limit to the benefits of bulk water turnover. At a certain point, water quality will not improve any more and continuing to flush may become a waste of treated water.

Complete material removal

The flush duration is also important for ensuring that all of the accumulated material that is loosened by flushing is removed from the system. If the flush duration is too short, there may be a lot of material left in the bulk water that was brought into the flushed pipe, potentially causing aesthetic issues and additional water quality degradation.

When flushing aims to remove material from the pipe, best practices suggest to achieve three full pipe volumes of turnover to ensure complete material removal.

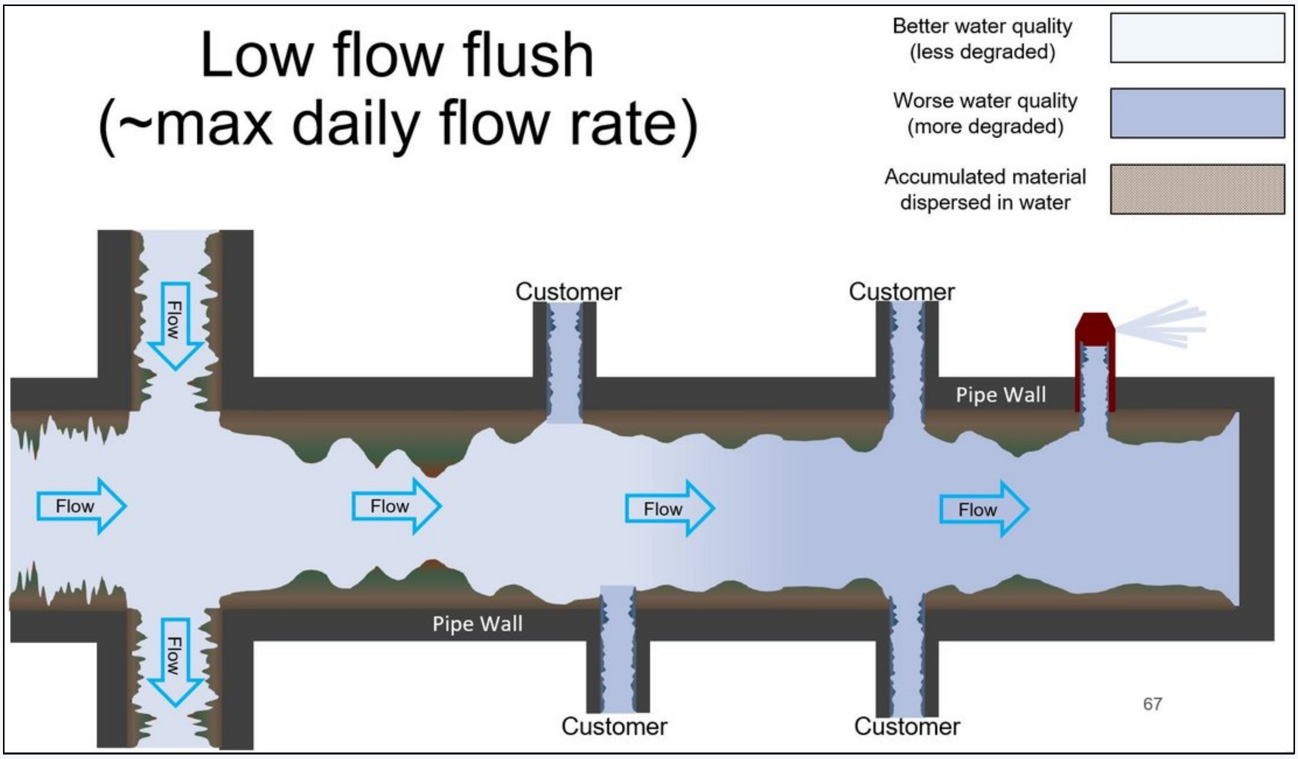


Image description for accessibility
Halfway through one full volume bulk water turnover at a dead-end pipe.

Caption
Halfway through one full volume bulk water turnover at a dead-end pipe.

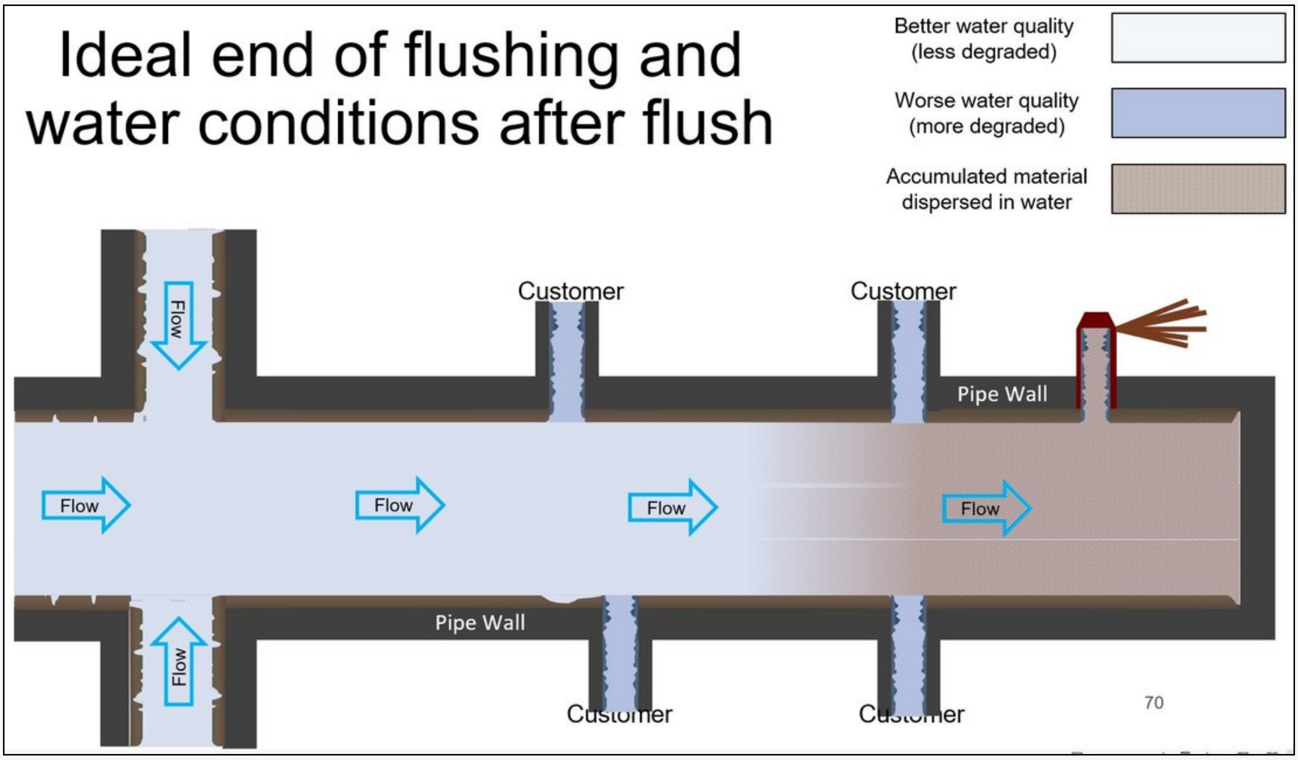


Image description for accessibility
Stopping the flush too early can leave a lot of mobilized material dispersed in the bulk water.

Caption
Stopping the flush too early can leave a lot of mobilized material dispersed in the bulk water.

3. Time of day of flushing

Water consumption patterns fluctuate over the course of the day, which changes the amount of time that water has to degrade in the system.

A water sample taken at 3am is likely to be much more degraded than a sample taken at 8am. Residential onsumption rates are very low over night compared to high water use is the morning hours.

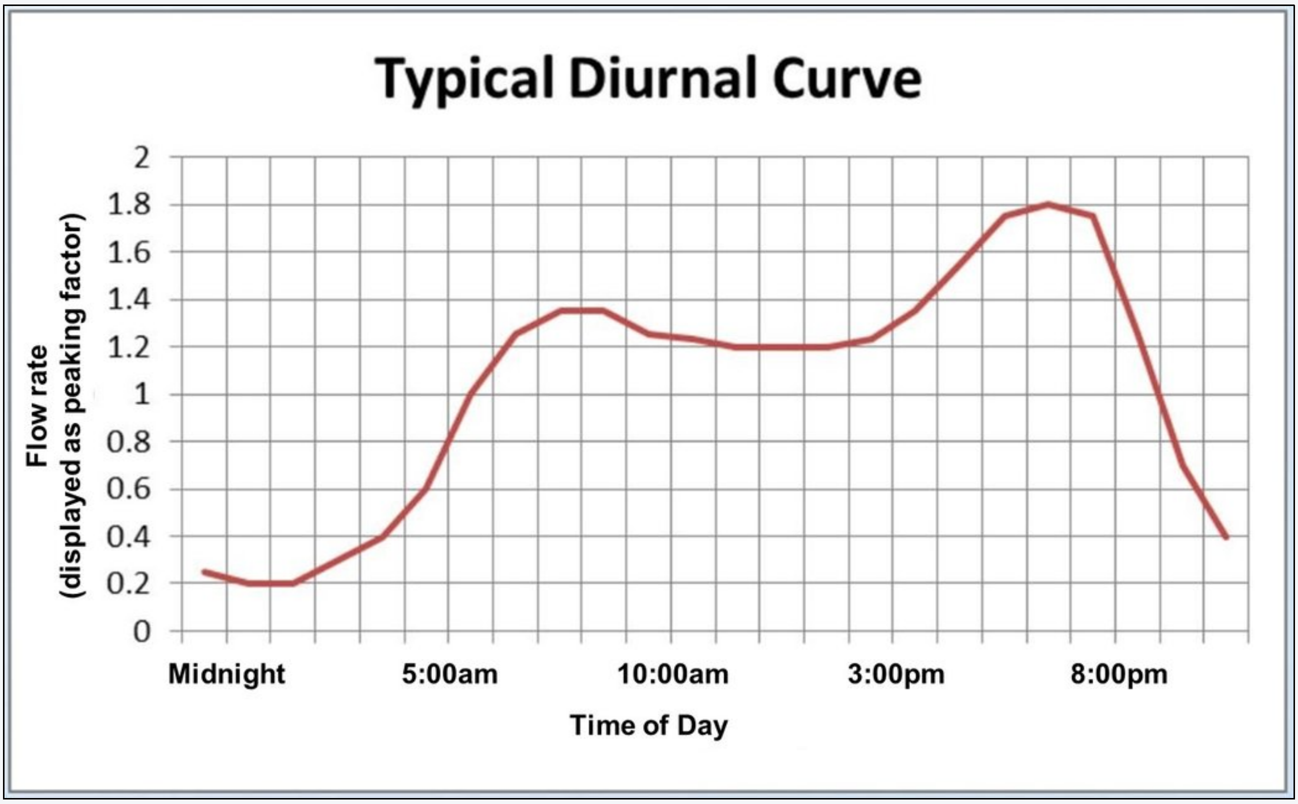


Image description for accessibility
Typical daily water use curve.

Caption
Typical daily water use curve.

4. Path isolation

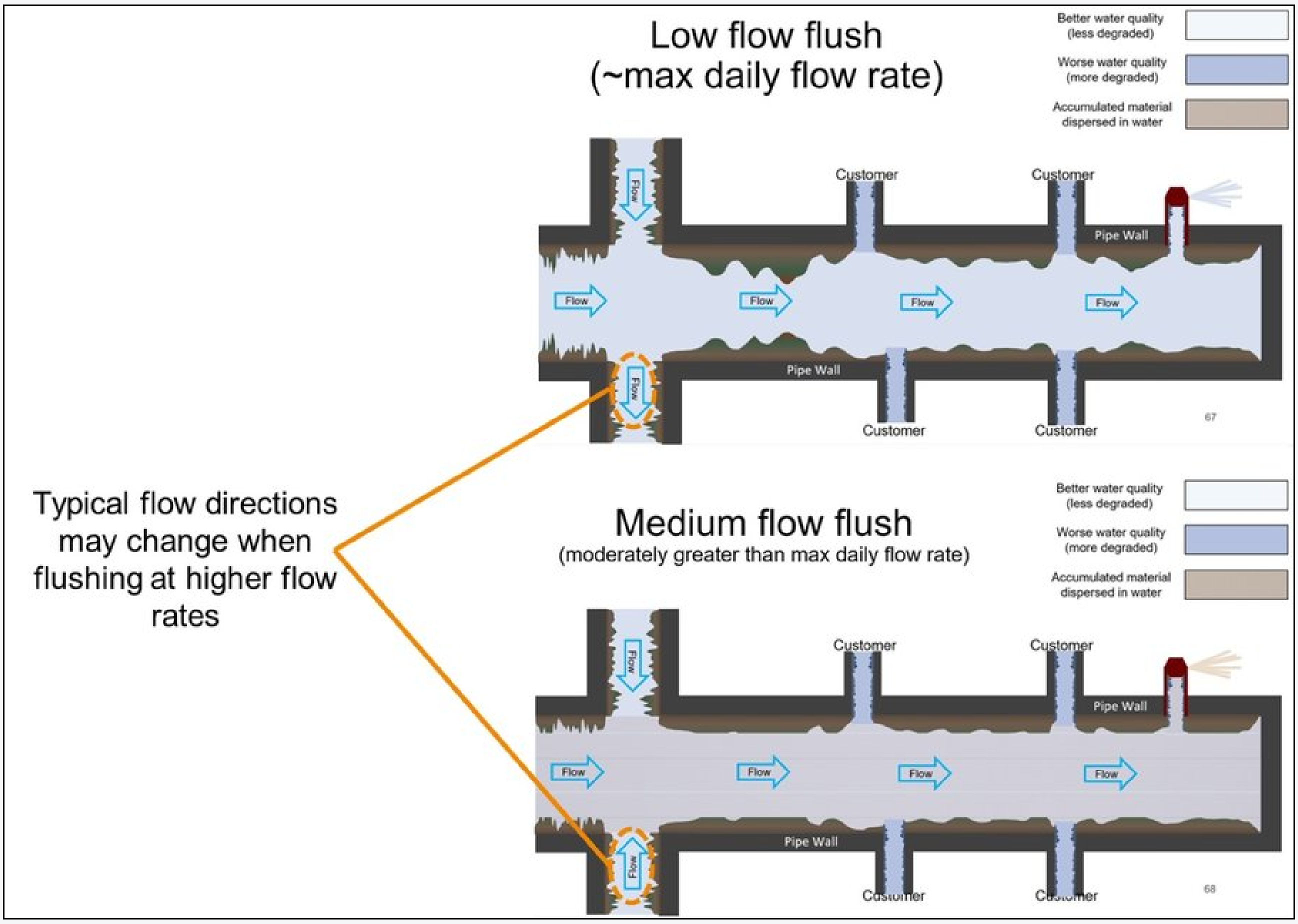
Flushing at rates higher than the daily maximum demand may change the typical flow paths that water travels toward the flushed outlet compared to normal system operation.

This could unintentionally result in bringing in water that is just as degraded (or even more degraded) as the water being replaced.

Higher flow rates may also unintentionally mobilize accumulated material in nearby pipes, which can cause aesthetic and other water quality issues if not addressed properly.

A single flow path into the flushed outlet can be created by turning valves. Isolating the flow path is the only way to know exactly which pipes will be impacted by a flush and where the incoming water has come from.

Path isolation usually requires more planning and multiple technicians in the field to turn valves before and after flushes. Conventional flushing methods (like Ann Arbor uses) typically do not isolate the flow paths, whereas unidirectional flushing is based around this strategy.



Caption
Flow directions might change as a result of higher flushing flow rates.

Photo credit
Flow directions might change as a result of higher flushing flow rates.

5. Clean water interface

Having a clean water interface means that the incoming water is known to have better quality and that accumulated material in nearby pipes has already been sufficiently removed.

In many cases, a clean water interface may be created by using flow path isolation and flushing sequentially from one pipe to the next. This ensures that the origin of the incoming water is known and that the water will not come with mobilized material from nearby pipes.

Without a clean water interface, it is more likely that

flushing may unintentionally mobilize material in nearby pipes and bring it to the flushed pipe

the incoming water may not be better quality than the water in the flushed pipe

Since ensuring a clean water interface typically requires flow path isolation and sequentially flushing pipe segments that lead to the target outlet, it is not usually a feature of conventional flushing and is almost always a feature of unidirectional flushing.

Revisiting Ann Arbor's mixed results

Reflect back on the scenario

Now that we have explored some of the important details about how flushing works, let’s think again about the mixed results from Ann Arbor’s program.

Consider the following reflection questions about the mixed results Ann Arbor saw from its flushing program:

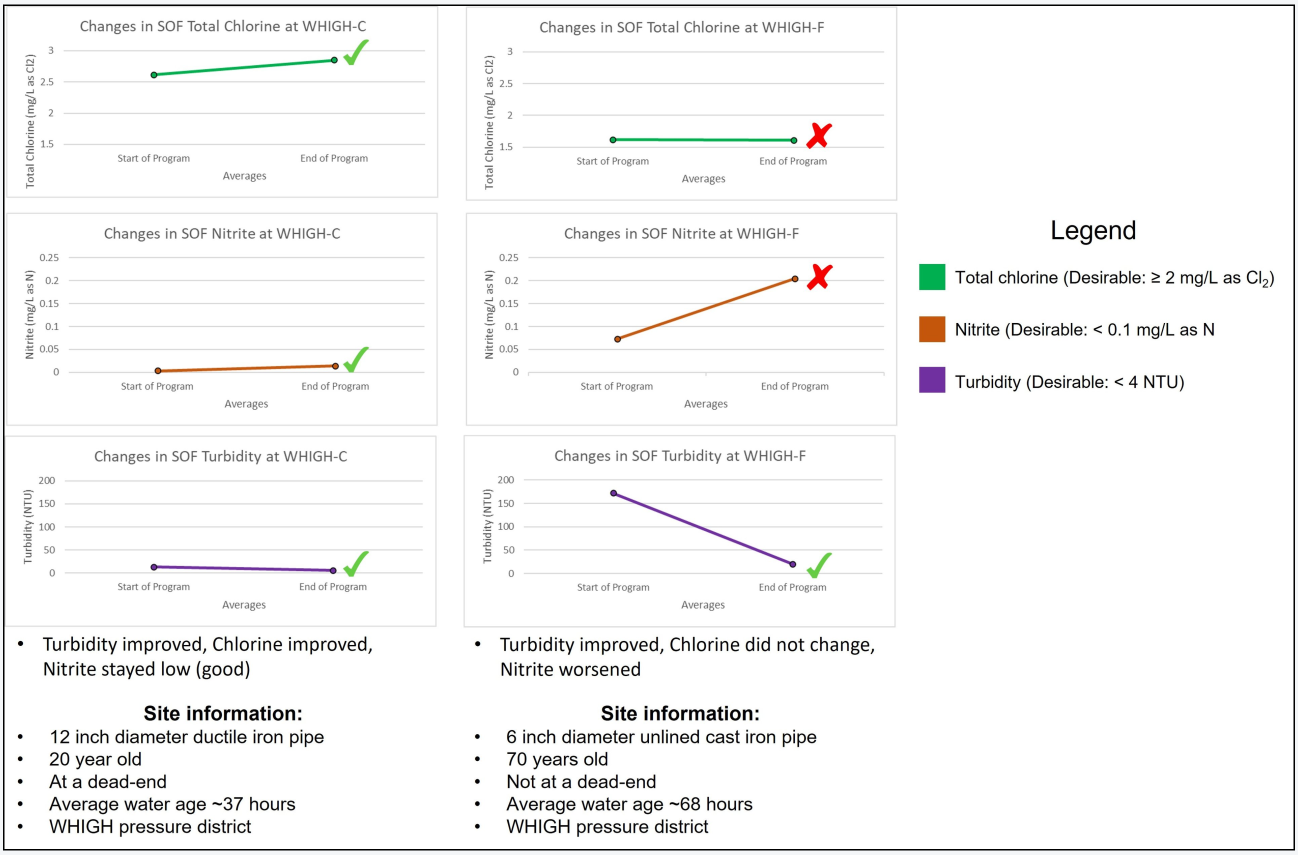
Do you have any new insights about why some sites did not improve?

Why would total chlorine and nitrite remain unimproved (or worsen) even though we clearly removed substantial amounts of accumulated matter from the pipe?

How would you go about trying to confirm your explanation?

Would you recommend any changes to the city's flushing program to overcome these mixed results in the future?

Review the mixed results



Post-module survey link (research participants only)

FOR RESEARCH PARTICIPANTS ONLY

If you are participating in the research study, please follow this link to take the post-module survey:

https://umich.qualtrics.com/jfe/form/SV_ePygZSGh33bKwU6