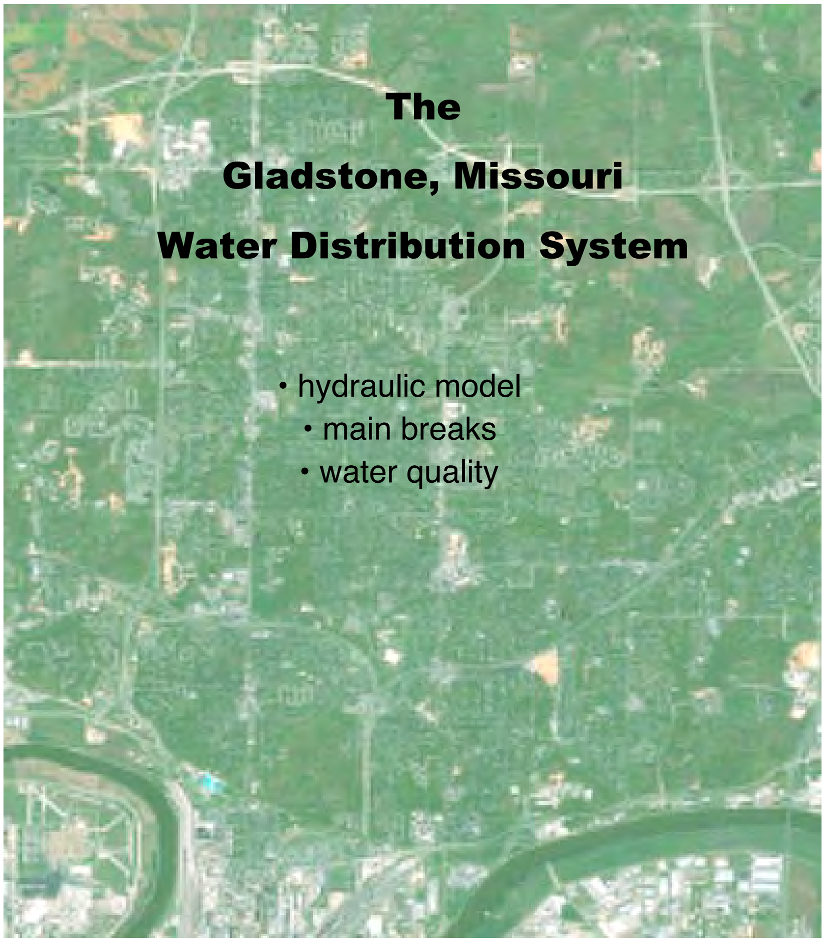
The Gladstone, Missouri Water Distribution System

- hydraulic model
- main breaks
- water quality



submitted

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H$_2$O'C Engineering
2401 Tahoe Court
Columbia, MO 65203-1444
(877) 22-WATER
www.h2oc.com

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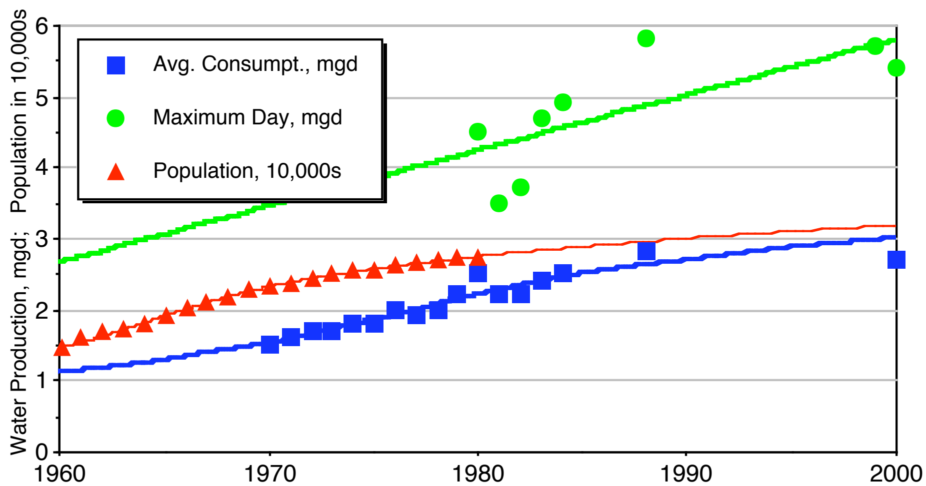
Summary

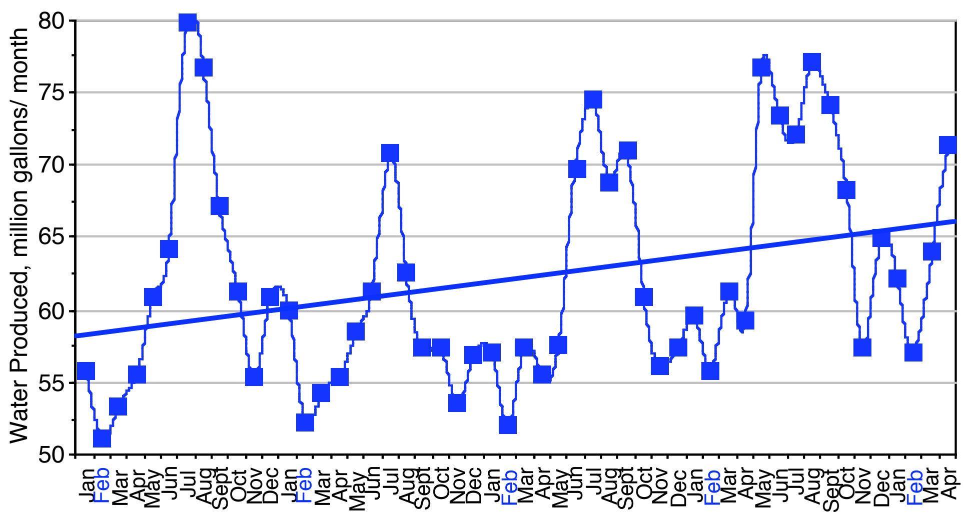
The current study of the Gladstone water distribution system was undertaken to address periodic water quality complaints of cloudy and discolored water. These consumer complaints are generally voiced after main flushing or main breaks have resuspended matter which has accumulated in the inverts of the distribution mains. Recommendations are made for water treatment modifications which should minimize the amount of these accumulations.

Additional evaluations were conducted to determine the causes and remediation of main breaks. To assist in this effort, a distribution system hydraulic model was developed to predict the system pressures, flows and travel times. Additional recommendations were derived from the results of these analyses.

I Water Production, Consumption, and System Losses

Prior to the water quality and main break analyses, an evaluation was conducted of the Gladstone annual and seasonal water use. In addition, a determination was made of the system water losses. The results are shown graphically below.



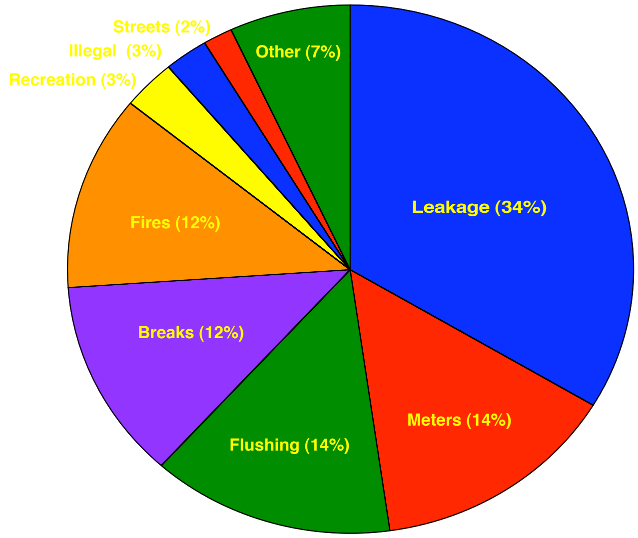


Water Loss

Lost or unaccounted-for water is water that is pumped from the treatment plant into the distribution system but is not sold to customers.

Water can be lost to leakage, breaks, fire-fighting, flushing, illegal or unmetered connections, inaccurate meters, or other causes.

The pie chart (right) from AWWA shows an estimate of the breakdown of the fate of lost water. Others use a 'rule of thumb' that 65% of lost water is due to leakage.



An AWWA Distribution and Plant Operations Division survey, conducted in 2001, gathered data from 43 state agencies on maximum standards for 'unaccounted-for' water. Of these, one state utilized a standard of 25%; four states, 20%; thirteen states, 15%; and ten states, 10%. The report lamented the inconsistent assessment, lack of data and minimal performance expectations for a *"potentially growing problem."*

An estimated 6 billion gallons per day of treated drinking water is lost, primarily, due to leakage during distribution. This volume would meet the combined daily demands of New York, Los Angeles, Chicago, Houston, Philadelphia, Phoenix, San Diego, Dallas, San Antonio and Detroit.

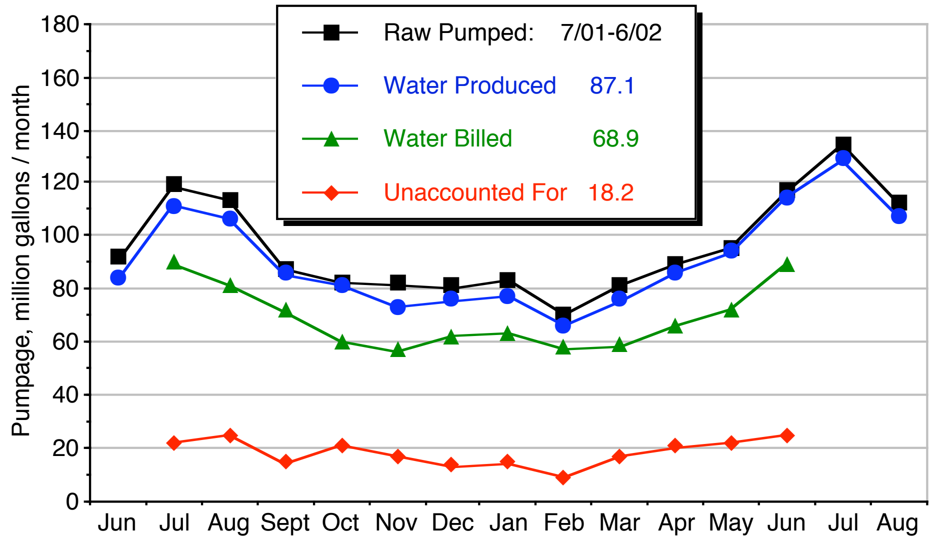
Case Study: Reduction in Water Losses

Several decades ago, the Village of Morton, Illinois embarked on a long-term program for reducing their amount of unaccounted-for water. Over a period of twenty years, the Village systematically reduced its water loss from in excess of 20% to less than 5%. As a by-product of the reduced loss of treated water, the steadily-growing community (population 18,000) has not had to expand its treatment facilities during this period. The indirect savings from *deferred capital investment* may have exceeded the direct benefit from reductions in unaccounted for water.

These savings were achieved through the employment of a hydraulic model, main looping and pipe replacement, a leak detection program, adequate financing and aggressive management of a program to reduce water loss.

Gladstone 'Unaccounted for' Water: 7/01 - 6/02

(Water Produced - Water Billed = 20.7% Unaccounted)



Area	Billing Cycle	Water Billed	/2		Water Billed	Water Produced	Unaccounted For	Unaccounted For
		thousands of gal			millions of gal	millions of gal	millions of gal	as % of production
East	Jun Jul 01	99129	49564.5	Jul 01	89.6595	111.3	21.6405	19.44
West	Jul Aug 01	80190	40095	Aug 01	81.123	106	24.877	23.46
East	Aug Sep 01	82056	41028	Sep 01	71.3765	85.5	14.1235	16.51
West	Sep Oct 01	60697	30348.5	Oct 01	59.894	80.9	21.006	25.96
East	Oct Nov 01	59091	29545.5	Nov 01	56.5345	73.1	16.5655	22.66
West	Nov Dec 01	53978	26989	Dec 01	62.1735	75.4	13.2265	17.54
East	Dec 01 Jan 02	70369	35184.5	Jan 02	62.908	77	14.092	18.30
West	Jan Feb 02	55447	27723.5	Feb 02	57.4745	66.1	8.6255	13.04
East	Feb Mar 02	59502	29751	Mar 02	58.4775	75.4	16.9225	22.44
West	Mar Apr 02	57453	28726.5	Apr 02	66.0385	86.3	20.2615	23.47
East	Apr May 02	74624	37312	May 02	71.8485	93.4	21.5515	23.07
West	May Jun 02	69073	34536.5	Jun 02	89.0565	114	24.9435	21.88
East	Jun Jul 02	109040	54520	Jul 02				
averages		71588			68.8	87.03	18.15	**20.65**

Based upon water production and water billing numbers for the period July 2001 to June 2002, Gladstone's unaccounted for water was estimated at 20.7%. The Missouri Rural Water Association publishes water loss data from 29 Missouri water systems with more than 2,500 service connections. These systems report water losses ranging from 3% to 35%, with an average of 14.3%. Only four of the twenty-nine utilities reported losses greater than 20%.

High distribution system pressures may be a major factor in Gladstone's greater than 20% water loss and excessive number of main breaks. Whereas many systems commonly maintain a target system pressure around 60 psi, Gladstone maintains far higher pressures, often exceeding 100 psi.

Estimates of water loss as a function of pressure may be made using the Hardy Cross pipe equation, $H=kQ^{1.85}$. A 20 psi reduction in system pressure from 100 to 80 psi should reduce current water losses by about 11.4% (from 20.7% to 18.3% annually). In practice, field studies by Hoag (US HUD, 1984) showed that a 30 psi reduction in pressure resulted in a 6% reduction in water loss due to leakage.

While the magnitude of the *overall* water savings is indeterminate, additional reductions in water loss will accompany reductions in the number of main breaks. Fewer breaks are expected due to a lessening of hydraulic transients (surge or water hammer) and progressive metal fatigue at reduced pressure. Over time, still other water loss reductions *and energy savings* should accompany the replacement of mains which are so severely encrusted with calcium carbonate and iron deposits that frictional head losses in these pipe sections are excessive. Perhaps, the most important benefit of replacing those mains whose carrying capacity has been seriously reduced over the years is the direct savings in electrical costs for pumping.

If, over time and by various combined measures, including main replacement, Gladstone's water loss could be reduced by one-half (to 10%), an average of 9.1 million gallons of lime-softened water per month might be saved. This would translate into a treatment plant operational cost savings of approximately $7,200 per month ($86,000/year).* Again, at lower pressures, the costs associated with main breakage should decrease.

**The cost of water production was determined from the City of Gladstone Water Production Reports from June 2001 to August 2002. Extreme fluctuations from month to month (from $285 to $1235/MG) were moderated by using fourteen months of cost data to develop an average monthly production cost figure of $791 per million gallons.*

Water Rates

Even though the cost of lime softening and recarbonation make the finished water at Gladstone relatively valuable (softened drinking waters are more costly than unsoftened waters), in comparison to other Missouri municipalities, Gladstone's water rates are low. According to 2002 data published by Missouri Rural Water Association, the average cost for 5,000 gallons of water from a municipal system is $21.06, whereas Gladstone's rate is $15.75 or 75% of the state average.

II Treated and Distributed Water Quality

Water Quality Concerns

While complaints regarding water quality are routinely detailed in Gladstone, a review of complaint records showed that over 80% are specifically related to *suspended matter* and *color*. This is consistent with the observed deposition of iron oxides and calcium carbonates in the distribution system. The distributed water is not corrosive and does not appear to develop tastes and odors. The disinfectant residual is persistent. While aesthetically undesirable, the periodic suspension of accumulated solids should not constitute a health concern.

Improvements to the filtration process and adjustment of finished water pH for stabilization with respect to calcium carbonate should address most of the water quality complaints. However, the existing encrustations and loose deposits in the distribution system will most likely continue to contribute color and sediment to the water.

The following discussion relates to an evaluation of filtration plant performance data leading to recommendations for improved filter performance.

Gladstone Filter Performance - 5/1/98 to 4/30/99

Filter	Effluent Turbidity , ntu	Average/Maximum Head Loss, feet
1	0.56	- / -
2	0.57	3.04 / 9.42
3	0.50	2.79 / 8.59
4	0.57	2.00 / 5.90

From the turbidity data available, an estimate can be made of the weight of dry solids passing through the filters and entering the clear well and distribution system during the period, 5/1/98 to 4/30/99. This estimate is based on the assumption that 1 ntu of turbidity is roughly equivalent to 1 mg/l of suspended solids. This assumption relates to the historical origin of the turbidity measurement. Therefore, 0.55 mg/l (ntu) average filtered water turbidity x 8.34 pounds / million gallons x 2.8 mgd average daily flow x 365 days/year would result in **4,688** pounds of solids released to the distribution system.

In addition, the subsequent post-precipitation of calcium carbonate would add to the quantity of material deposited on surfaces and in the inverts of distribution mains.

Iron Removal

Iron averaged 0.57 mg Fe/l in the filter influent and 0.15 mg Fe/l in the filter effluent, for an average 74% removal by the filters. Since the iron is present in the form of a ferric hydroxide precipitate, both in the filter influent and effluent, percent iron removal is one measure of filtration efficiency. New, properly-graded filter media might be expected to achieve removals in excess of 90% of all particulate matter.

Since the MDNR secondary MCL for iron, based on aesthetic concerns over discolored water, is 0.3 mg Fe/l, Gladstone normally meets this standard in their finished water. However, further reductions in treated water iron concentrations will reduce the potential for its progressive accumulation and subsequent re-release from encrustations and deposits that bring the orange-brown iron precipitates to public attention.

Alternatives for Improving Distributed Water Quality

Based on the evaluation of plant performance, several recommendations can be made for reducing the passage of suspended matter (turbidity) through the plant plus the deposition of solids in the distribution system mains. These include:

- Reduced filter flow rates for reduced turbidity
- Reduced throughput between backwashes
- Replacement of encrusted and enlarged filter media
- Construction of additional filters to increase filtration capacity to allow reductions in filter flow rates
- Reduced pH for improved calcium carbonate stability and reduction in post-precipitation

Turbidity Reductions

Filtered water turbidity (averaging 0.55 ntu in 1999) should be reduced to monthly average levels that are consistently in the range of 0.1 to 0.4 ntu. This should reduce the amount of solids passing directly into the clearwell and distribution system by one-half or more.

Reduced Filter Run Time between Backwash

Turbidity reduction will be accomplished by several means. An immediate reduction in average filtered water turbidity can be achieved by limiting filter operation between backwash (filter run times) to a maximum of 96 hours. In this regard, the AWWA/ASCE Manual on Water Treatment Plant Design (3rd Edition, 1990) reports that “rapid sand filters are generally operated with run lengths between 12 and 72 hours, typically with 24 hour runs.” The Manual also advises that “long filter runs make washing a filter much more difficult because of particulate matter compaction in the filter media.”

Individual filters which suffer excessive head losses (greater than 4 feet) or allow the consistent passage of turbidity in excess of 0.4 ntu may have to be backwashed more frequently than 96 hours. For example, Gladstone's 1998/1999 water treatment plant records show that Filter #2 routinely exhibited head losses in excess of 4 feet. This was generally accompanied by high turbidities and may indicate increase in media size, encrustation of the underdrain system, extensive mudball formation and/or filter blockage.

In the absence of sufficient capacity to store and reclaim backwash water, Gladstone's filters should be operated for 96 hours or until filtered water turbidities exceed 0.4 ntu. When a filter effluent exceeds 0.4 ntu prior to a 96-hour filter run, the filter should be backwashed even if the backwash water must be wasted.

Tailored Reductions in Filter Surface Loadings

In the long term, improvements in finished water turbidity should result from a reduction of the surface hydraulic loading on Gladstone's filters. Reducing filter loadings from 4 towards a conservative 2 gallons per minute per square foot (gpm/sf) should result in further lowering and stabilization of the turbidity in the filter effluent. At some lime softening plants, similar flow rate reductions are employed on older filter beds to compensate for filter turbidity removal performance that has degraded with age.

In-house tests should be made with each of the four filters currently in operation to directly observe the effect of reduced hydraulic loading (to 2 gpm/sf) on turbidity removal through a 96 hour filter cycle as compared with the filters operated at normal (4 gpm/sf) loadings. If the lower hydraulic loadings result in markedly improved turbidity reductions, consideration should be given to routinely decreasing filter flow rates as well as the time between backwash.

Reducing flow rates on older filters will ultimately require the construction of additional filters that, presumably, could be initially operated at 3 gpm/sf. With surface areas of 348 sf, the four existing filters each provide filtration capacity as shown in the following table.

Four Existing Filters

flow rate	production per filter	plant nominal capacity	plant firm capacity
gpm/sf	*MGD*	*MGD*	*MGD*
2	1.0	4.0	3.0
3	1.5	6.0	4.5
4	2.0	8.0	6.0

The addition of additional, identical filters would have the following effect on plant capacity.

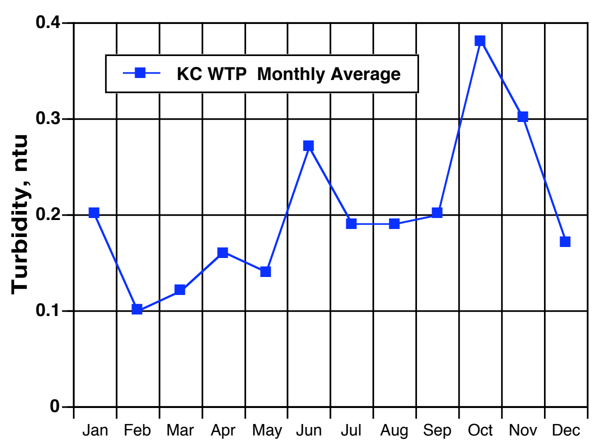
Five Filters

flow rate	production per filter	plant nominal capacity	plant firm capacity
gpm/sf	*MGD*	*MGD*	*MGD*
2	1.0	5.0	4.0
3	1.5	7.5	6.0
4	2.0	10.0	8.0

Six Filters

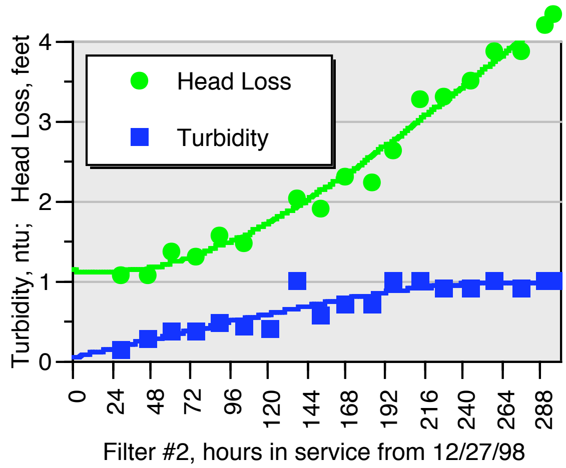
flow rate	production per filter	plant nominal capacity	plant firm capacity
gpm/sf	*MGD*	*MGD*	*MGD*
2	1.0	6.0	5.0
3	1.5	9.0	7.5
4	2.0	12.0	10.0

Reduced monthly average turbidity levels should be more consistent with the turbidities achieved at the Kansas City water treatment plant (annual average turbidity 0.20 ntu as opposed to 0.55 ntu for Gladstone) as well as at other regional water plants that also practice lime softening. The plot at right illustrates the monthly average finished water turbidity at the Kansas City plant for the year 2000.

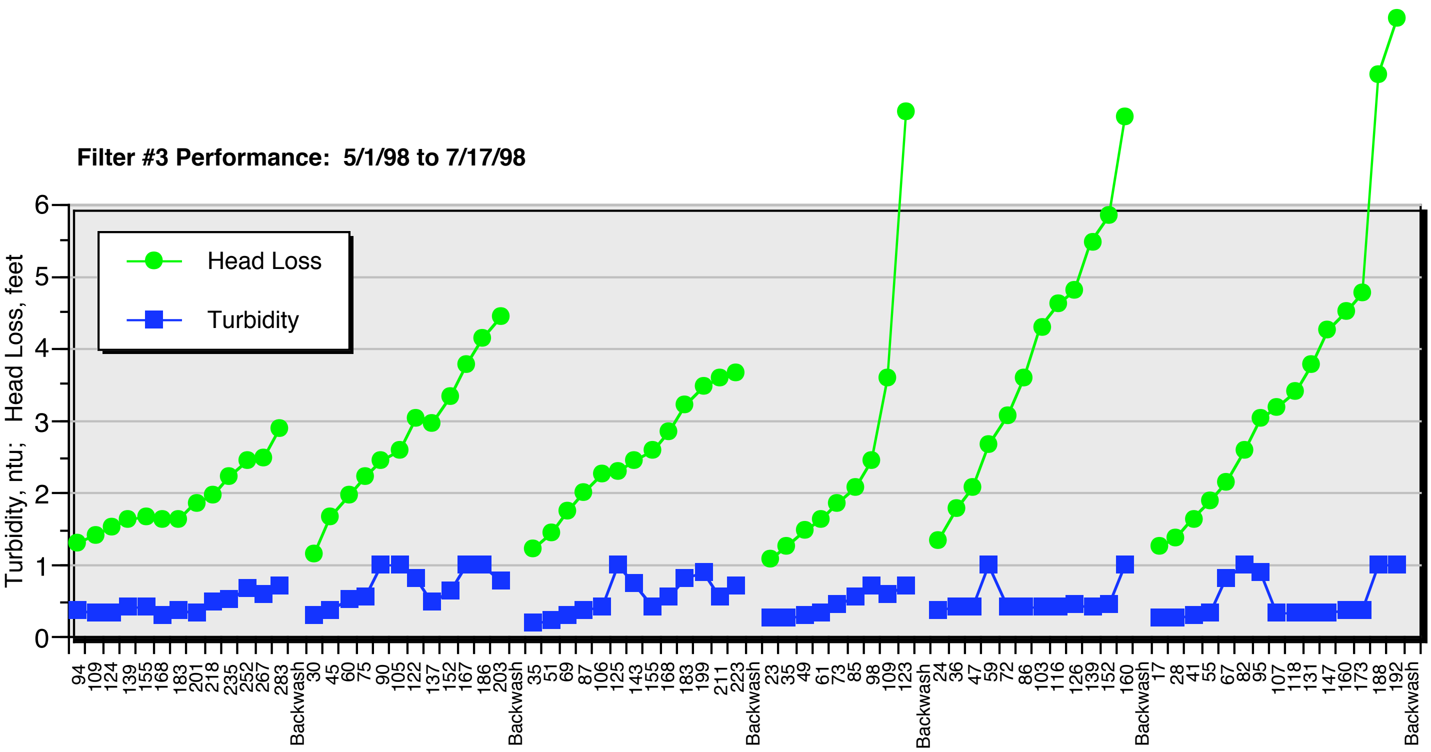


Also, at these reduced turbidity levels, iron concentrations in the Gladstone finished water should be further reduced to less than 0.05 mg Fe/l. The removal of ferric oxides will reduce the apparent color of the water in the distribution system. This apparent color may be most obvious to consumers during periods when mains are being flushed and sediments suspended from main inverts.

Individual filters which suffer excessive head losses (greater than 4 feet) or allow the consistent passage of turbidity in excess of 0.4 ntu may have to be backwashed more frequently than 96 hours. For example, 1998/1999 records show that Filter #2 routinely exhibited head losses in excess of 4 feet. This was generally accompanied by high turbidities and may indicate encrustation of the underdrain system, mudball formation or filter blockage.



Filter #3 Performance: 5/1/98 to 7/17/98



Filtration cycles during 1998/1999 sometimes exceeded 200 hours. Several terminal head losses were well in excess of 6 feet. Commonly, toward the end of the filtration cycles, filtered water turbidities reached 1 ntu. While acceptable from a regulatory standpoint, these turbidities indicate the routine passage of solids through the filter.

Assessment of Condition of Filter Media

Media from both the surface and a one-foot depth within a filter was examined. The samples were washed with hydrochloric acid to remove the calcium carbonate buildup. This caused a decrease in weight and volume of over 60%. Both samples were found to contain primarily anthracite intermingled with a small amount of sand.

Cleaning the media required a large amount of strong acid and generated noxious gases. If the media was cleaned within the filters, the acid would attack the concrete and piping, and a substantial amount of additional media would need to be purchased to make up for the lost volume. Due to chemical and media costs, potential health hazards, and likely damage to the plant, replacement would be safer and more cost-effective than cleaning.

For these reasons, the media should be simply be replaced rather than acid-treated.

Additional Filters to Increase Plant Hydraulic Capacity

There are several current concerns related to the condition and capacity of Gladstone's four existing filters. First, the media in each filter has grown to the point where media replacement is clearly required.

In addition, the impaired filter particle removal performance may be partially related to the progressively-increasing hydraulic loadings placed on aging filters. These increases in filter loadings have occurred due to increased system demands and new uses for treated water in Gladstone.

To accommodate lower filter loadings and more frequent backwash, additional plant filtration capacity will be required.

Deposition of Calcium Carbonate During Treatment and Distribution

If calcium carbonate supersaturation is not largely arrested in the filtered water prior to discharge to the distribution system, post-precipitation will result in the formation of both loose deposits in the invert of the transmission mains and hard deposits on pipe walls. Once hard deposits have formed, only physical removal techniques, such as main flushing and pigging have been found to be effective in mitigating the problem.

Calcium Carbonate Saturation Index

Higher pH waters generally experience less corrosion of mains and household plumbing. Where calcium carbonate has been observed to form a uniform coating on piping, corrosion is retarded. For many years, it has been considered appropriate to adjust finished water pH so that the water is slightly supersaturated with calcium carbonate. Hopefully, a uniform, thin deposit of calcium carbonate is will form a hard, protective scale on interior pipe walls.

Alternately, excessive oversaturation with calcium carbonate results in the formation of large quantities of pipe encrustations which increase frictional losses and decrease water throughput. The additional operational costs for pumping and main cleaning may be very significant. In particular, the pumping costs are hidden and not generally attributable to encrusted mains.

Of the many indices available, only saturation index (SI) is widely used. This index indicates whether the water is saturated (SI=0) or supersaturated by a factor of ten (SI=+1) or one hundred (SI=+2). Commonly, a finished water SI of 0 to +1 is recommended to promote deposition to aid in corrosion control.

From APHA Standard Methods, 20th edition, 1998; Method 2330B, pages 2-30 to 2-33.

$$SI = pH_{\text{finished water}} - pH_{\text{calcium carbonate saturation}}$$

At a temperature of 15 °C, and for a water with a total dissolved solids concentration of 200 mg/l, the ionic strength of Gladstone's finished water is estimated as 200/40,000 = 0.005 g-moles/l and pf_m = 0.033. The simplified version of Equation 2 was used to calculate pH_s.

$$pH_s = pK_2 - pK_s + p[Ca] + p[Alk] + 5pf_m$$

$$pH_s = 10.43 - 8.43 + 3.26 + 3.07 + 5 \cdot 0.033$$

$$pH_s = 8.5$$

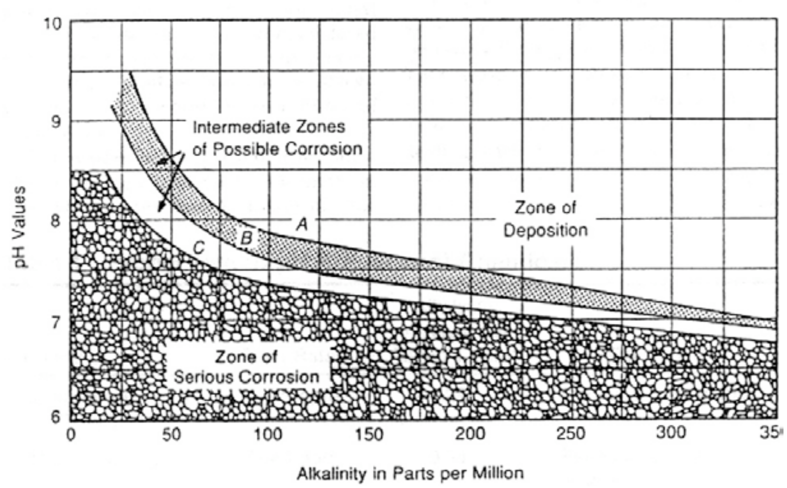
Using data for Gladstone finished water, the pH of calcium carbonate saturation is calculated as 8.5.

During the early decades of lime softening in Gladstone, finished water pH exceeded 10. During that period, calcium carbonate deposition appears to have occurred progressively throughout the Gladstone distribution system. Currently, the finished water pH should be (and is being) adjusted to 8.5 to help preclude further accumulation of solids in the distribution system. This requires the application of additional carbon dioxide.

The application of additional carbon dioxide prior to filtration should also reduce the solids loadings on the filters. This will extend the service life of the filter media.

For the month of April 1999, Gladstone's finished water in the clear well had an average pH of 9.3, resulting in an SI value of +0.8. On June 17, the average pH in six distribution system samples was 8.6. This decrease is most likely attributable to the precipitation of calcium carbonate within the distribution system.

Baylis Curve



The Baylis Curve illustrates the degree of saturation of water with calcium carbonate based on pH and alkalinity. For Gladstone's finished water, pH has been in the range of 9.3 and alkalinity approximately 50 mg/l as calcium carbonate equivalent. This would indicate that calcium carbonate is well within the "Zone of Deposition".

Pipe Encrustation

Severely Encrusted 2" Pipes

Encrusted 8" Pipe

Pipes that had been removed from service showed varying degrees of encrustation. Generally, the smaller pipes exhibited more encrustation, presumably due to greater surface area and lower flows. Some 2" pipes appear to have only a small fraction of their rated flow capacity available. Since smaller pipes break more frequently, selection of larger pipe may help reduce breakage rates in the system.

Clean 12" Pipe

Despite the severity of encrustation in some smaller pipes, the ruptured 12" main (right) showed none whatsoever.

The hard scale (encrustation) on many pipes appears to be composed of iron and calcium carbonate deposited from the lime-softened water. There is little evidence of tubercle or pit formation resulting from corrosion on the interior of the pipe.

Removing Sediments from Mains

Flushing, Swabbing, Pigging

Physical removal processes are facilitated by the formation of a ‘soft’ scale which is readily dislodged from pipe surfaces. Flushing is most commonly used to scour and suspend solids in distribution mains. However, the effectiveness of flushing depends on the peak velocity of water which can be achieved. Whereas design flow velocities are in the range of 2 to 5 feet per second, scouring velocities fall in the broad range of 2 to 10 fps depending upon the pressure available at the hydrants or blowoffs. Higher velocities increase the potential for water hammer during startup and shutdown.

For unidirectional flushing, efforts are made to progressively achieve velocities up to 6 fps by opening multiple upstream hydrants. Once the sediment is disturbed, substantial quantities of treated water may have to be used to completely remove the suspension of dislodged solids without creating nuisances and generating consumer complaints.

While more labor intensive, swabbing and pigging are highly effective techniques for removing scale, debris and slime from water mains. However, the utility of this technique may be limited in Gladstone due to the previous design practice of using undersized valves in the pipe grid. With valves openings smaller than the pipe diameter, the swabs and pigs would be in danger of getting stuck in the mains.

Removing hard scale encrustations from pipe can be accomplished in two general ways: physical removal (flushing, swabbing, pigging) and chemical removal. While flushing is almost universally practiced on a routine basis, more costly and labor-intensive physical removal processes force swabs and pigs through the water main in an effort to dislodge/scrub/abrade solids from the pipe wall.

Using Proprietary Chemical Formulations

Chemical removal processes change the water quality such that it will dissolve the solids in the pipe. Most of these processes employ proprietary phosphate formulations (polyphosphates) purport to ‘loosen’ and gradually detach scale, layer by layer, from the pipe wall. The effectiveness of the wide variety of formulations offered for this purpose is widely debated. From the quantity, hardness and density of the carbonate scale observed on Gladstone’s mains, it appears doubtful that a low dosage chemical additive would suffice to remediate the extensive scaling that has already occurred.

Pending a clear demonstration of the effectiveness of polyphosphate formulations, such treatment is not recommended.

III Distribution System Operations

The experience of system operators should be drawn upon, and a distribution system operational protocol should be established. Ideally, this protocol should minimize main breaks due to pressure surges, minimize residence time of water in the system, maximize turnover of water reservoirs, and optimize pressures in all areas of the system.

System Pressures

The MDNR Design Guide for Community Public Water Supplies establishes acceptable system pressures as follows:

> *The minimum working pressure in the distribution system should be 35 psi and the normal working pressure should be approximately 60 psi. When static pressures exceed 100 psi, pressure reducing devices should be provided on mains in the distribution system.*

Multiple Pressure Zones

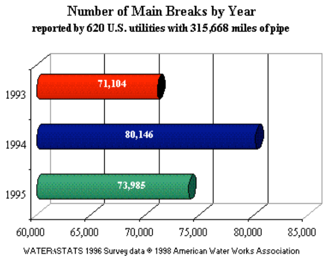
Currently in draft form, the MDNR Design Standards for Community Water Systems states:

> *Areas with elevation differences of more than one hundred-fifty (150) feet should be divided into multiple pressure zones so that each zone has pressure between thirty-five (35) and one hundred (100) pounds per square inch gage (psig). Multiple pressure zone systems should have separate storage facilities for each zone and should be equipped so that water can be transferred between zones with pump stations and pressure control valves.*

Elevations within Gladstone's water distribution system range from 810' to 1030' msl, a difference of 220', which represents a difference in hydrostatic pressure of 95 psi. However, 90.5% of the distribution system is within the elevation range from 851' to 1000'. The remainder breaks down as: 2.4% of the system below 850'; 7.1% above 1000'.

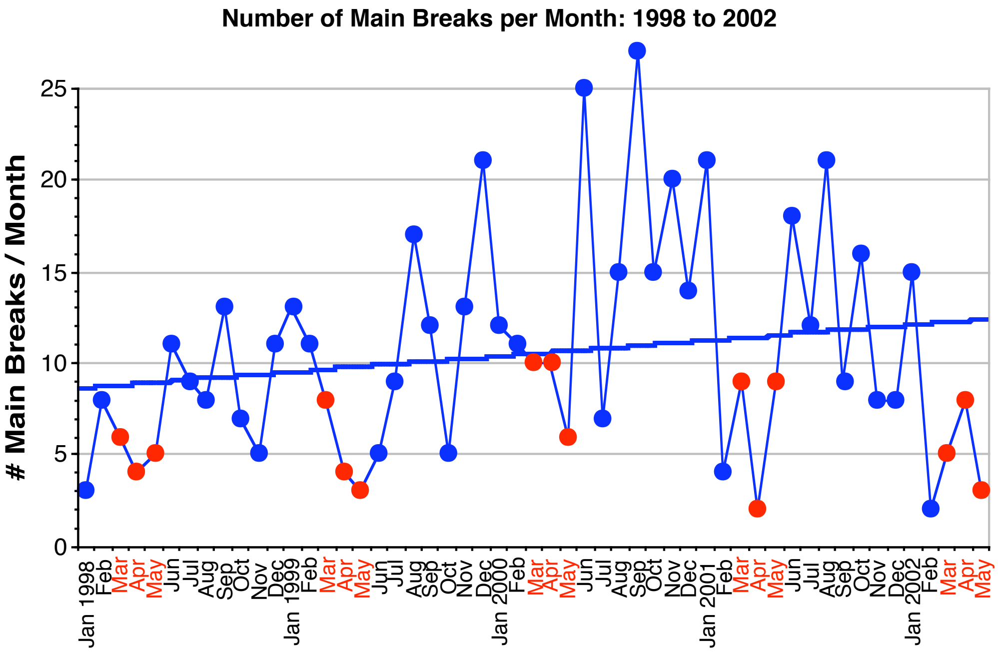
Consideration should be given to the possibility of establishing a separate pressure zone for the southeast portion of the distribution system. This would involve the installation of several pressure reducing valves (PRV) at a cost of $3,000 to $4,000 per valve. Additional modifications may be necessary to secure MDNR approval.

IV Main Breaks

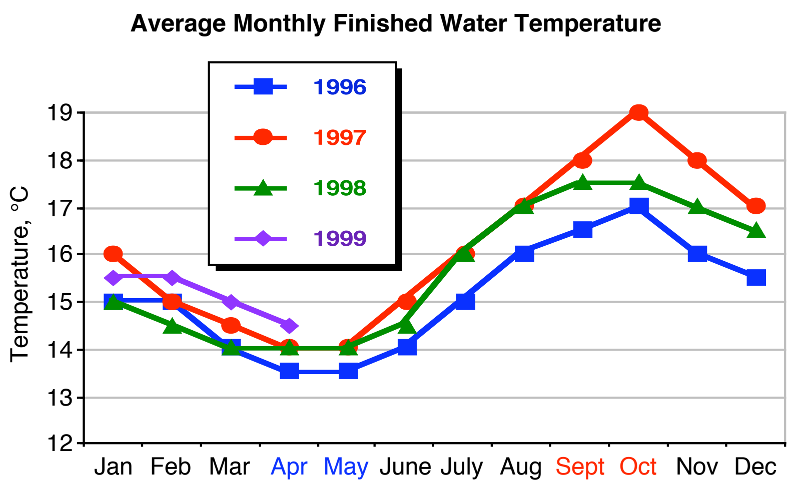


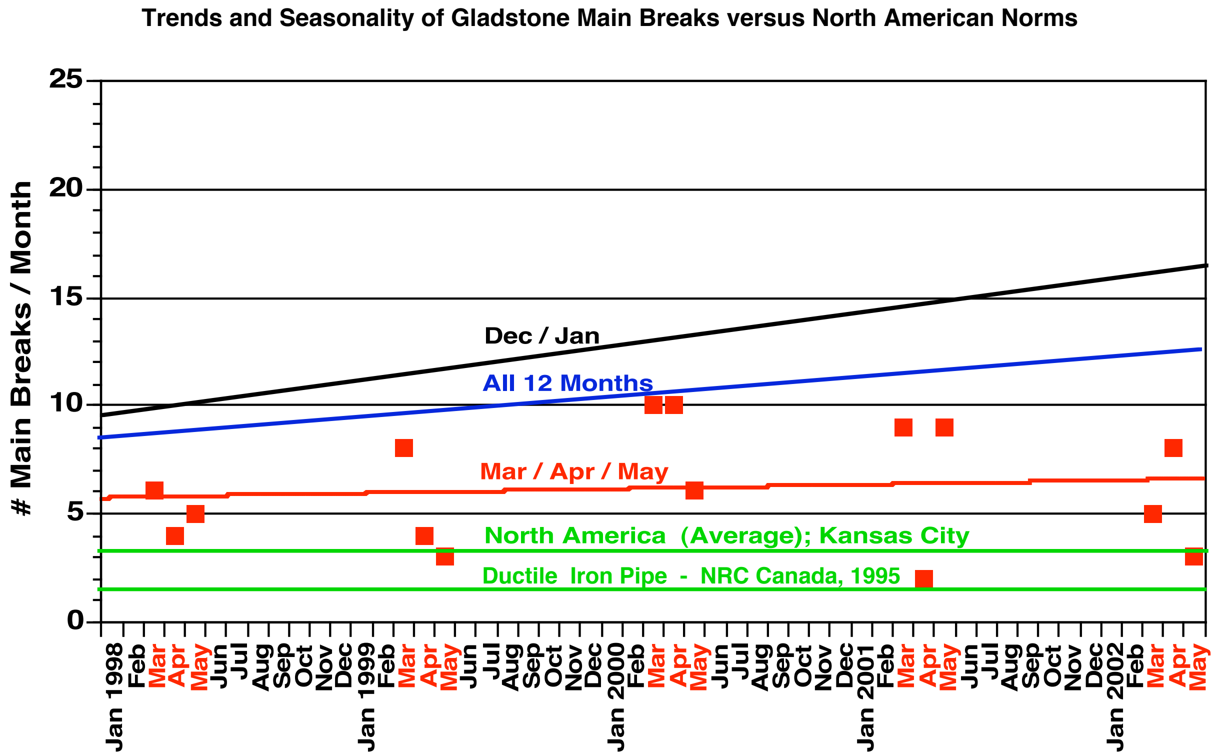
Gladstone has been plagued by an excessive number of main breaks — over four times the national average. This AWWA Waterstats data shows main breaks from 620 utilities over three years. The number of breaks averages 24 breaks per 100 miles per year. Gladstone averages over four times that rate: 100 breaks per 100 miles per year.

Seasonal Effects on Main Breakage



A plot of the number of main breaks per month in Gladstone (above) indicates that there is some seasonal relationship between the rate of breakage and distributed water temperature. The number of monthly breaks reported are consistently below Gladstone's average in March, April and May, the months when Gladstone's distributed water temperatures are lowest. During these months, the underground mains would be expected to be at their shortest due to contraction.





Gladstone Main Breaks versus North American Norms

Further examination of main repair data from 1998 to 2002 indicates that the rate of main breakage in Gladstone (blue trend line) has been increasing. This may be attributable to increasing pipe age and ongoing corrosion.

According to the Water Industry Database (AWWA,1992), the average pipe replacement rate for 794 utilities in the US is 0.5 percent of the total miles per year. At this rate, utilities will eventually have pipes with an average age of 200 years. A conservative design life for ductile iron pipe is 50 years. With approximately 130 miles of pipe in service, Gladstone should be replacing around 2% or 2.6 miles of distribution system piping per year. Due to low previous pipe replacement rates, this percentage should be still higher with priority given to pipes that have undergone repeated repair, are the oldest in the system, or have suffered the greatest degree of encrustation with calcium carbonate and iron.

While breaks occur randomly throughout the year, the peak rate in Gladstone is observed in December and January (black trend line). These are the months when the distributed water and ground temperatures decline most rapidly so that pipes contract. This contraction creates tensile stresses as pipe is restrained by the surrounding soil. Ductile iron pipe are more likely to break under tension since pipes with flaws or defects are much weaker in tension than in compression.

Alternately, at near-steady-state, low temperature (March, April, May), the rate of breakage is found to decrease markedly. During these months of low water usage, the main breakage rate more closely approaches the average reported for North America, in general, and Kansas City, in particular.

Whereas the previously cited data on main breakage in North America are for all types and classes of pipe, the Canadian data, tabulated below for reference, distinguishes between pipe materials.

The National Research Council of Canada determined that the most prevalent water main pipe material remaining in place is cast iron, representing 50% of the total Canadian water distribution network. The average break rate of this older cast iron pipe is 35.9 breaks/100 km/year. The mode of failure of cast iron pipe was 64% circular or circumferential.

Ductile iron pipe constituted 24% of the Canadian network and exhibited an average break rate of 9.6 breaks/100 km/year (or 1.3 breaks/100 miles/month). Holes and pits were present in 20% of the breaks, while the remaining breaks were longitudinal, joint or unclassified. In contrast to the circular breaks for cast iron pipes, ductile iron pipe failed mainly as a result of holes or pits.

The 21 Canadian cities data seem to suggest that ductile iron pipe develops pitting without debilitating its axial tensile strength. However, such a pit can reportedly increase the stress at the defect by more than three times the nominal stress (Ugural, A. C., and Fenster, S. K., 1985. Advanced strength of materials and applied elasticity. Elsevier, New York.)

PVC pipe represents 10% of the Canadian inventory and averages 0.7 breaks/100 km/year.

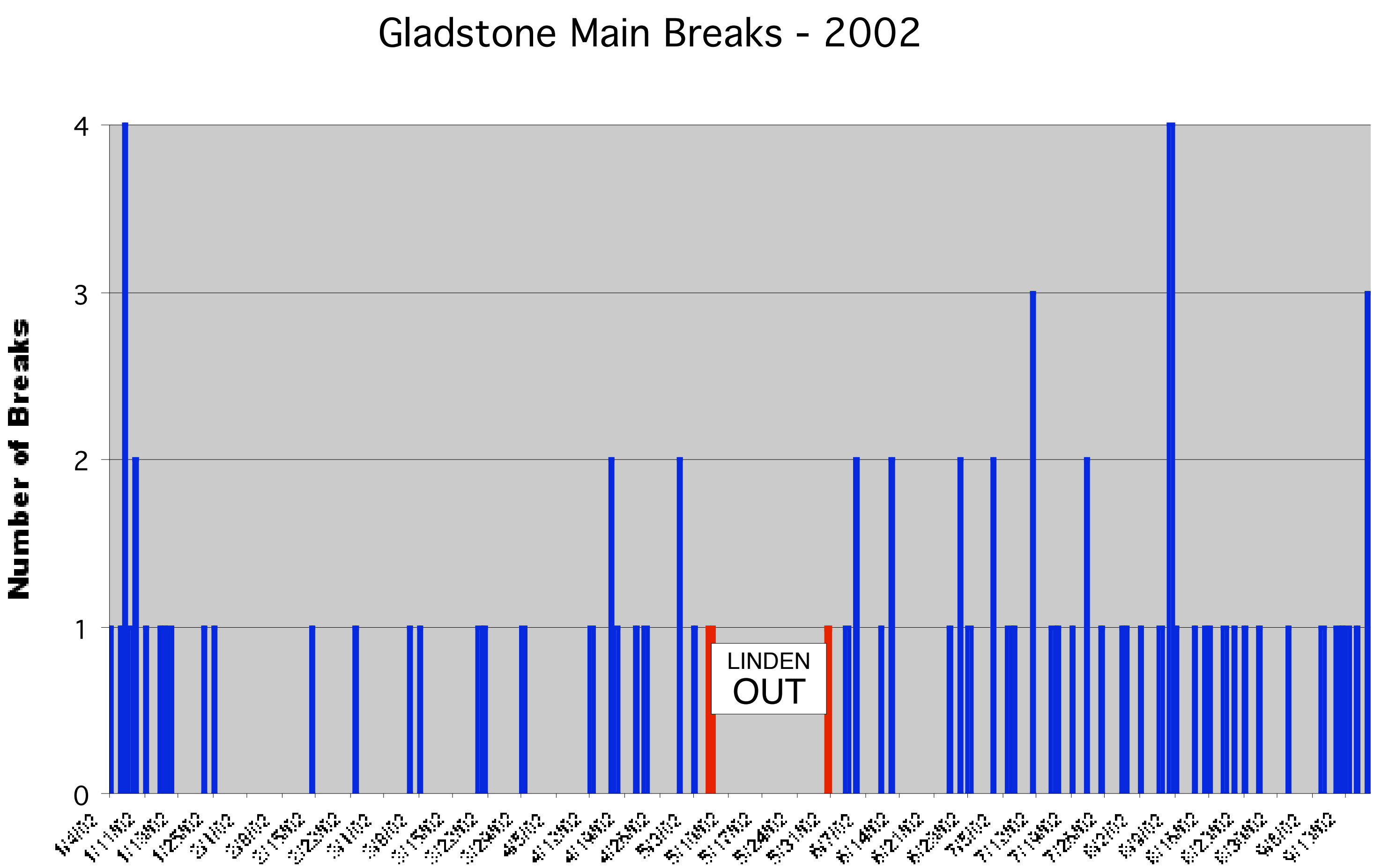
Main Breaks

National Research Council of Canada, 1995

Pipe Material	Length (km)	# Breaks /100 km / year
Cast Iron	8,770	35.9
Ductile Iron	*4,238*	*9.6*
Asbestos Cement	2,105	5.8
PVC	1,818	0.7
Prestressed Concrete	623	0.7

Gladstone

Pipe Material	Length (km)	# Breaks /100 km / year
Cast and Ductile Iron	*209*	*62.2*



The number of main breaks, by day, is shown in the plot, above, for the year 2002. The number of breaks ranges from 0 to 4 breaks per day.

For a number of days (the period shown between the red bars), there were no recorded breaks in the Gladstone distribution system. During this period, the Linden water tower was out of service. As a result, system pressures would have been somewhat lower and the cycling of pumps, on and off, to fill the tower would have diminished. This empirical evidence suggests that lowered pressures, or even the removal of the Linden water tower from service, might markedly reduce breakage.

The AWWARF report, (Distribution System Performance Evaluation, 1995), sets the following goals for main breaks and leakage in an effort to limit service interruptions. If higher rates of main breakage and leakage are observed, the authors conclude that structural deficiencies are indicated.

- Main breaks: < 25 to 30 breaks/100 miles/year Gladstone: 100 breaks/100 miles/year
  Water leakage: < 4,000 to 6,000 gallons/day/mile Gladstone: 4700 gallons/day/mile

Street Map - Locations of Main Breaks

The fold-out map included depicts all of the main breaks from the period January 1999 through February 2002. While breaks are generally dispersed throughout the city, they have a slight tendency to occur more frequently in the southeast, where elevations are as much as 231 feet lower and, as a result, system pressures are 100 psi higher. Also, certain locations exhibit clusters of breaks — as many as eight in the same small area. Again, these "hot spots" tend to be located in the southeast portion of the city. These locations would be good candidates for the evaluation of surge suppressors or for the initiation of the main replacement program. More specifically, mains should be replaced where breaks occur in older pipe (>40 years), and surge suppressors should be evaluated where breaks occur in newer pipe.

Street Map - Location of Proposed Main Replacements

A modified version of the main break location map illustrates those areas which might first be included in a main replacement program. These areas have been selected based on the number of breaks they have experienced. With repeated breakages, these mains have been progressively weakened.

Corrosion

External corrosion was clearly visible on sections of ductile cast iron pipe that had been removed from service due to failure. Rather than occurring uniformly across the pipe surface, corrosion was localized. In the illustration below, whereas the pipe appears to be in generally good condition, a longitudinal break has occurred along a line passing through two large and deep external pits.

Soil characteristics that support and accelerate external corrosion of iron pipe include:

- high soil moisture content, particularly where dissolved minerals increase electrical conductivity,

- spatial differences in oxygen concentrations along the pipe length that lead to the creation of 'oxygen concentration cells'. These concentration cells can result in the initiation of pits at anodic (low oxygen) regions. The extensive cathodic regions remain smooth and intact while pitting corrosion occurs at the localized anodes creating weak spots in the ductile iron pipe,

- high organic content soils that can support microbial action that results in anaerobic sulfide production and the formation of organic acids,

- highly acidic or alkaline soils, landfills, swamps, marshes, cinder beds,...

Longitudinal Break through Two Distinct Corrosion Points

DIPRA Report

Representatives of the Ductile Iron Pipe Research Association (DIPRA) performed an analysis on seven soil samples from Gladstone. Their report is appended. Citing the low resistivity of the soil (440 to 1,400 ohm-cm), their conclusion was that “the water main corrosion has occurred as a result of corrosive soil conditions.”

ANSI / AWWA

soil classification	*resistivity (ohm-cm)*
Very corrosive	< 500
Corrosive	**500 -1,000**
Moderately corrosive	1,000 - 2,000
Mildly corrosive	2,000 - 10,000
Progressively less corrosive	> 10,000

Other factors, such as soil pH (6.8 to 7.2) and oxidation/reduction (redox) potential (+190 to +342 mV), did not suggest a corrosive soil. Additionally, the pipe sections removed from service due to failure did not exhibit uniform corrosion along the surface, but rather discrete points of corrosion.

USDA Natural Resources Conservation Service

The most common classes of soil pH are:

Extremely acid	3.5 – 4.4
Very strongly acid	4.5 – 5.0
Strongly acid	5.1 – 5.5
Moderately acid	5.6 – 6.0
Slightly acid	6.1 – 6.5
Neutral	6.6 – 7.3
Slightly alkaline	7.4 – 7.8
Moderately alkaline	7.9 – 8.4
Strongly alkaline	8.5 – 9.0

Inhibiting External Corrosion

Since external corrosion of cast iron pipe has been widely experienced, a number of techniques for its control have evolved. For example, to extend their service life, extra wall thicknesses may be proscribed for new or replacement pipe. A less costly approach is to have a bitumastic or coal-tar coating applied to the outside of the pipe. Today, ductile cast iron pipe is generally furnished with a 1 mil thick asphaltic coating to minimize atmospheric oxidation during transport and storage.

Cathodic protection requires the attachment of a sacrificial (zinc or magnesium metal) anode to the iron pipe using an insulated wire. Ideally, this results in the solution of the more readily oxidized zinc or magnesium rather then the iron.

The Ductile Iron Pipe Research Association (DIPRA) recommends that external corrosion be inhibited by the use of low density polyethylene (LDPE) plastic wrap applied at the time the pipe is installed. LDPE pipe wrap is available in thickness' of 8 to 14 mil at a cost of less than 35¢/foot.

Unfortunately, techniques to inhibit corrosion in existing pipe (sacrificial anodes, excavating and wrapping), are not cost-effective.

Pipe Bedding Conditions

Excessive external loads are cited as the greatest single cause of water main breaks. Breaks caused by external loading are usually *circumferential* because they result from ‘beam loading’ on the pipe. Susceptibility to excessive external loads are attributed to:

- Poor installation practice (faulty bedding or backfill; inadequate thrust blocking; poor joint assembly)
- Changes in surface load or bedding conditions (settlement; small leaks that undermine pipes; frost)
- Contact during excavation
- Pipe tapping (taps create weak spots similar to corrosion pits)

Internal Pressures

Breaks related to internal pressure are usually *longitudinal* and are attributable to defective pipe, damage during installation or external corrosion. Most pressure-related breaks occur when water hammer surges result from pump startup or shutdown; valve opening or closing. Power outages which result in the precipitous shutdown of pumps may also be a significant factor in creating pressure surges.

Alternatives for Reducing the Rate of Main Breakage

- Reduced Pressure in Distribution System (Reset of Pressure Reducing Valves and/or Removal of Linden Tower from System)

- Surge Protection: Variable Speed or Magnetic Drive for Pumps

- Rehabilitation: Replacement of Undersized, Encrusted, Externally Corroded Mains and Valves

- Maintenance: Unidirectional Flushing; Valve Exercising; Undersized Valve Replacement; Pigging

- Pipe Wrapping: Encasement of New Mains/Broken Pipe in Loose Polyethylene

Pipeline Rehabilitation and Replacement

While the recommendations in this report are intended to help minimize the number of main breaks, many pipes in the distribution system are over fifty years old, and eventual pipe replacement is inevitable. Due to age and encrustation and the resultant increase in breakage and decrease in flow, many pipes in the distribution system will need to be replaced in the foreseeable future. At that time, a pipe replacement plan should be developed, and alternate materials should be considered (PVC, HDPE).

Pipe which is structurally sound may be rehabilitated by cleaning, installing internal joints if applicable, and lining. Pipeline rehabilitation will generally leave the existing pipe in place while appurtenant structures such as line valves, air/vacuum valves, and blow-off valves will be replaced.

If a portion of the distribution system suffers from structural problems, as indicated by main breakage, or if it has insufficient hydraulic capacity due to corrosion or deposition, the pipeline should be replaced. Replacement pipe is new pipe installed by the conventional ‘cut and cover’ method or by trenchless methods where the existing pipe is burst or removed. Sliplining, or pipe bursting, which is considered to be pipe replacement, involves pulling polyethylene pipe through the existing main.

Inhibiting Surge

The effects of surging *(mass oscillation* referred to as *rigid column* or *inelastic effect)* can be moderated by incorporating strategically placed reservoirs of more compressible air into the distribution system piping. Stainless steel canisters of various volumes are available from Heil2O who make the following recommendations for the placement of their units.

Heil2O’s Recommendations for the Placement of Surge Tanks:

- Approximately every 1000 feet
- At the exit of pumping stations
- At the latest break location
- At the end of the piping system
- At the high and low points of the piping system
- Before major directional changes
- Before and after control and check valves
- At line reducers

Modulus of Elasticity

The elasticity or *compliance* of various pipe materials are represented by the values of their respective Young’s modulus. For ductile cast iron, this value is 172 whereas it is about 3 for the more elastic polyethylene and 0.8 for very flexible PVC pipe. Therefore, these plastic materials can withstand repeated flexure more readily without undergoing fatigue.

Alternative Pipe Material

A comparison of iron and plastic pipe material is included here because plastic pipe (PVC, HDPE) is finding increased use in potable water distribution systems throughout the United States. Many systems have both materials in service in their systems.

The piping material that reportedly causes the most serious water quality problems in the distribution system is unlined cast-iron pipe. Water quality problems include ‘red’ water, chlorine depletion, and bacterial regrowth.

Ductile Cast Iron	Sizes: 4-54 inches	Maximum Pressure 200-350 psi
	Standard Length: 18 feet	Joints: Rubber, mechanical, flanged

Internal Lining: Cement mortar, fusion-bonded epoxy, coal-tar enamel

Advantages: Durable, strong, high flexural strength, good corrosion resistance, smooth (C=140), easily tapped.

Disadvantages: Corrosion in adverse environments.

Polyvinyl Chloride Sizes: 4-36 inches Maximum Pressure 100, 150, 200 psi

Advantages: Lightweight, low cost, easy to cut and install, very flexible, smooth interior (C ≥150), excellent corrosion resistance (chemically inert), high tensile and impact strength, absorbs short-term pressures, especially suitable where water hammer may occur, resists freeze damage, abrasion resistant, does not require lining.

Disadvantages: Difficult to locate, susceptible to damage (gouging) during handling and bedding, buckling under vacuum, permeable to hydrocarbons (e.g., gasoline), requires protection from UV exposure, undergoes considerable expansion and contraction.

High-Density Polyethylene Pipe

Approved (AWWA Standard C906, 1992) as distribution system piping material.
Sizes: 4-63 inches Maximum Pressure 100, 150, 200 psi
Joints: *Thermal butt-fusion*, flange, mechanical (not by solvents or adhesives)

Advantages: Lightweight, low cost, easy to cut and install, very flexible, smooth interior (C ≥150), excellent corrosion resistance (chemically inert), high tensile and impact strength, absorbs short-term pressures, especially suitable where water hammer may occur, resists freeze damage, abrasion resistant, does not require lining, resistant to cracking and damage due to seismic events,.joints do not require thrust restraints, gaskets not required where thermal butt-fusion used.

Disadvantages: Difficult to locate, susceptible to damage (gouging) during handling and bedding, buckling under vacuum, permeable to hydrocarbons (e.g., gasoline), requires protection from UV exposure, undergoes considerable expansion and contraction.

V Hydraulic Model

EPANET, the hydraulic modeling software from USEPA, was used for the creation of Gladstone's distribution system model. The computer model simulates the hydraulic behavior of physical facilities and water use patterns within the system. The model simulates flows and head loss through pipes and valves, energy input at pumps, contributions from or replenishment of reservoirs, and water leaving the system due to customer use. Head loss through pipes is a function of flow rate, pipe diameter, and internal roughness; minor losses due to valves, reducers, and other appurtenances are not accounted for in the model.

Distribution system models simulate complex water system performance. The model can be programmed to simulate proposed operating practices, such as operation of pumps based on water levels in storage facilities or system pressures. The model performs extended period simulations (EPS), simulating the distribution system over a period of time while varying water demands (representative of typical daily demand fluctuations) and operating conditions.

Results from model analyses include the following:

- Pressures throughout the system
- Flows, directions, and head loss in pipes
- Water elevations in storage facilities

The hydraulic model can be used to

- experiment with different operational protocols
- evaluate concepts for multiple pressure zones
- identify areas with low-demand or excessive detention time
- examine different siting options for future facilities
- study water age, pressures, and flow characteristics
- train new personnel on system operation

Model Development and Assumptions

Hydraulic model construction included input of distribution system data representing physical facilities and water system demands. Additional information required to construct water system models included pump curves, storage facility capacity and operating levels, and operating controls.

Water demands assigned to the model are as important as physical facilities data. Historical water use data and operator experience were used to determine overall demand and daily variations in water use. Demand Pattern 1 represents a high demand day (5.0 MG), and Pattern 2 represents a more average day (3.5 MG).

The clearwell at the water treatment plant was modeled as a constant reservoir at an elevation of

910’ msl.

The ground storage tank is a 146’ diameter tank at elevation 1000’ msl. The minimum water level is 1000’, and the maximum level is 1037’. Mixing model is LIFO.

The Antioch Tower sits at an elevation of 990’ msl. The operating range for water level elevation is 1104’ to 1144’ msl (114’ to 154’), which translates to a pressure at the tower’s bottom of 49 to 67 psi.

The Linden Tower sits at an elevation of 1010’ msl. The operating range for water level elevation is 1127’ to 1160’ msl (117’ to 150’), which translates to a pressure at the tower’s bottom of 51 to 65 psi.

The following table shows the names, descriptions, and control logic of the pumps:

name	**gpm**	**head (in ft)**	**control logic**
PlantHSP1	1300	225	
PlantHSP2	2800	290	ON when Linden level < 125'; OFF when Linden level > 148'
PlantHSP3	2800	290	ON when Linden level < 130'; OFF when Linden level > 145'
PlantHSP4	1300	225	
PlantHSP5	2800	290	
GSTpump1	1800	145	ON when Linden level < 135'; OFF when Linden level > 140'
GSTpump2	3500	180	ON when Linden level < 132'; OFF when Linden level > 138'
GSTpump3	3500	180	

All pipes were assigned a C factor of 100.

Once the construction of the model was completed, the values in the following table were calculated. This provides an estimate of the length of different diameter pipe installed in the system as well as the amount of water (over 2 million gallons) contained in the pipes.

	diameter	total length	water stored
	inches	*feet*	*gallons*
	1	6,679	272
	2	13,408	2,188
	4	37,000	24,050
	6	163,571	250,450
	8	379,163	993,407
	10	9,664	39,524
	12	41,869	246,608
	16	8,661	90,416
	18	126,009	166,687
	20	5,250	85,681
	24	9,455	222,202
TOTAL		**687,329**	**2,111,484**
		(130 miles)	

VI Summary of Recommendations

Recommendations for Treatment Plant Operations and Modifications

- Replace media in all four filters.
- Correlate effluent quality (turbidity, iron) with flow rate and time between backwashes.
- Maintain filtered water goals of turbidity in the range of 0.1 to 0.4 ntu and 90% iron removal.
- Incrementally decrease filter flow rates towards a target of 2 gpm/sf.
- Incrementally reduce filter cycles towards a target of 48 hours between backwashes.
- Increase recarbonation rates to reduce finished water pH to 8.5.
- Expand plant filtration capacity.

Recommendations for Reducing the Rate of Main Breakage

- Reduce high pressures in distribution system by establishing a second pressure zone.
- Remove Linden Tower from service on a trial basis.
- Surge Protection: Install and evaluate three Heil2O surge suppressors at locations with a history of breakage where the pipes are not particularly old (e.g., Brooktree, Carriage Hills, Kendallwood). Possibilities include:
    - NE 68th Street
    - NE 61st Street
    - NE Kendallwood Parkway and NE 60th Street

  Other candidate locations for surge suppression are the pumping stations.

Priorities and Recommendations for Main Replacement

- Replace older mains (>40 years) in areas experiencing breaks. Possibilities include:

area	*approx. length and main size*
• N. Garfield / N. Euclid area	1900'; 6"
• Michigan Place	1000'; 6"
• NE 57th Terrace	575'; 2"
• NE 58th Street	575', 2"

- Use C-900 Class 200 PVC pipe on a trial basis.
- During routine main flushing, conduct flow tests to look for low flows, which can be indicative of encrusted mains.
- Conduct leak detection surveys to identify leaking mains that should be repaired or replaced.
- Wrap any new or repaired ductile iron mains in polyethylene.