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EVALUATION OF PHYSICAL AND WATER QUALITY INDICATORS IN ADUCTORS DURING HYDRAULIC TRANSIENT EVENTS

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Abstract

An indicator that correlates physical quantities with water quality has great relevance for the definition of projects and understanding of real hydraulic transient phenomena. The work proposing a method to estimate water quality in real system focusing on turbidity measurements during a transient, as surrogate to understand potential dynamics in real systems. In order to get an empirical formula to turbidity during hydraulic transients, was observed 5 years' data from a real system. This system is one of the mains important pipelines of the Water Supply System of Curitiba and Metropolitan Region, in South Brazil.

Keywords
Hydraulic Transient, Water quality, Real system, Turbidity.

1 INTRODUCTION

Hydraulic Transient is a phenomenon characterized by the occurrence of pressure waves propagating along the pipe, caused by interference or maneuver in the flow of the fluid, by varying operating pressures, which can generate or not a water hammer, depending upon how unstable fluid flows propagates through high-pressure forces and rapid acceleration of the fluid [1].

Typical events that require transient considerations include: pump start-up or shutdown; valve opening or closing; changes in boundary pressures; rapid changes in demand conditions; changes in transmission conditions; pipe filling or draining-air release from pipes; and, check valve or regulator valve action [2].

The consequence of strong influence of inertia and compressibility effects can: a) rupture a pipe directly through excessive pressure or they can exploit an existing weakness, like corrosion, earth pressures, construction faults, to damage the pipe indirectly [1], [3], [4]; b) cause water quality degradation [2], [5], [6], [7], [8], [9], [10].

As water utilities are under increasing pressure to improve the quality of service (less bursts and discoloration events) while reducing leakage, it is becoming essential to better understand and control the main factors affecting failures. Despite the importance, unfortunately, the occurrence of unsteady and quasi-unsteady state hydraulic conditions in operational networks remains poorly understood due to the limitations of existing telemetry systems and the capabilities of the data processing tools [11], especially in developing countries.

Furthermore, there is a lack of knowledge of the impact which the variety of transient events might have on specific assets and the complete system both in the short and long term [11].

1.1 Objectives

The main goal is to assess physical and water quality indicators in pipelines during hydraulic transient events. The specific objectives are: a) Proposing a method to estimate water quality in real system focusing on turbidity measurements during a transient, as a surrogate to understand potential dynamics in real systems; b) Modeling and simulation of hydraulic transient in water pipeline system, all in the Metropolitan Region of Curitiba, in Parana, Brazil; c) Measurement and evaluation of water quality parameters during transitory situations.

2 THEORICAL BACKGROUND

2.1 Hydraulic transient causes and consequences

In general, any disturbance in the water generated during a change in mean flow conditions will initiate a sequence of transient pressures in the WDS. Disturbances will normally originate from changes or actions that affect hydraulic devices or boundary conditions. Typical events that require transient considerations include: pump start-up or shutdown; valve opening or closing (variation in cross-sectional flow area); changes in boundary pressures (e.g., losing overhead storage tank, adjustments in the water level at reservoirs, pressure changes in tanks, etc.); rapid changes in demand conditions (e.g., hydrant flushing); changes in transmission conditions (e.g., main break or line freezing); pipe filling or draining-air release from pipes; and, check valve or regulator valve action [2].

Clearly, there is a direct relation between the consequences of transient effects and safety that impose equipment damage or operational difficulties. Some of the common consequences are [5]: a) maximum pressures in hydraulic systems. This is the most common consequence of hydraulic transients; b) occurrence of local vacuum conditions at specific locations that may result in cavitation either within specific devices such as pumps or within a pipe; c) hydraulic vibration of a pipe, its supports, or in specific devices; d) occurrence of contaminant intrusion at joints and cross-connections.

If sub-atmospheric pressure conditions evolve, the risk of pipeline collapse increases for some pipeline materials, diameters, and wall thicknesses [12]. Even if a pipeline does not collapse, column separation (sudden vaporous cavitation) caused by differential flow into and out of a section could occur if the pressure in the pipeline is reduced to the vapor pressure of the liquid. Besides that, excessive negative pressures groundwater can draw into the system. Studies assessed the intrusion risk by evaluating the possible volume of intruding groundwater given transient duration and severity (minimum water hammer pressure) [10].

2.2 Hydraulic transient affecting water quality

2.2.1 Potential for pathogen intrusion during pressure transients

Studies introduced three requirements to be met for stating risk conditions to human health due to contaminant intrusion: adverse pressure conditions (the driving force), a pathway (leakage points, badly fitted joints, air valves, cross-connections), and the contaminant source [13].

Drinking water distribution systems are vulnerable to external contaminant entry if there is a loss of physical integrity. The main driver for an intrusion event to occur is the failure to maintain an adequate pressure in the distribution system. Low and negative pressure events have the potential to result in intrusion of pollutants: negative pressures create a suction effect inside the pipe and the contaminant intrusion through pipe leaks [14].

Failures in the integrity of distribution pipes resulting in a system leak are therefore classed as high-risk routes of entry. Examples of typical leak types in water distribution system pipes are pin holes, cracks, corrosion clusters, and joint/ connection failures [15].

Transient negative pressure can draw leaked water back into the pipe at any point where water is leaking out of the system. Once these leaks or breaks occur, any microbial contamination in the vicinity of the break or leak can potentially enter the distribution system given the pressure changes that occur during breaks or leaks. A major fecal source is usually near sewer lines, which are notorious for leaking. Main breaks can also introduce high concentrations of injured coliform bacteria (undetectable by standard coliform techniques) into the distribution system [8].

Studies collected and tested soil and water samples in the immediate vicinity of water mains at eight locations in six US states and found that often these soils contain potentially harmful bacteria and pathogens such as coliforms (detected in 58% and 70%, of water and soil samples, respectively) and fecal coliform bacteria (detected in 43% of the water and 50% of the soil sample) [7].

Experimental procedure was conducted that analyzed the risk of contamination in two cases: intermittent water and transient. It wasshown that both can allow a large number of contaminants inside the pipes. In the intermittent system, the contaminants get into the pipe by means of infiltration when the pipe is partially empty and the service gets discontinued. The pressurization of pipes ejected part of them from the pipe but a large amount remained, and it was supplied to the users. To transient involving negative pressure the physical process was similar, but the temporal scale of the process was much smaller and the number of contaminants flowing into the pipe was smaller. In this case it was strictly related with the extension and the magnitude of the negative pressure transient but the contamination was still present and it could produce risks for the users [16].

Weston et al. improved the understanding of intrusion volumes and supported previous research, providing physical evidence that contaminant intrusion can occur due to dynamic pressure transient events within water distribution systems. The work shows how intrusion volumes change as a function of the hydraulic conditions within in a full-scale laboratory pipeline that replicates operational environments. Expected underlying trends are clearly evidenced: as the change in velocity increases (increasing initial pressure surge), the volumes of intrusion increase, and as the change in pressure increases (increasing the initial pressure offset), the volumes of intrusion decrease [17].

Studies investigated the volume of contamination intruded into the pipeline using mathematical and numerical modeling of the phenomenon. The study estimated the intrusion amount for 72 different scenarios including: two lengths of pipeline (i.e. short and long), three different leak locations, three different fluid velocities in the pipe, two leak diameters and two pipeline materials (elastic and viscoelastic). The results showed that the: a) amount of intrusion in viscoelastic pipes was clearly less than that in elastic pipes, especially in long pipelines; b) It may seem that higher Joukowsky pressure or leak size produces more intrusion volume, but this is not always true and the numerical results demonstrate several counter-examples. Large leak sizes are prone to significant leak induced wave reflections, thus making the leak position zone of high intrusions quite unpredictable (case dependent); c) The critical zone of high intrusion risk is identified close to the downstream valve for small leak sizes, nevertheless, it is difficult to estimate this zone in the case of large leaks due to significant interactions between nodal components (valve, leak, reservoir) [18].

The numbers of pathogens introduced from a sewage contaminated groundwater during a transient intrusion can theoretically result in unacceptably large numbers of microorganisms being transported to consumers, even when adequate chlorine residuals are present [19]. Despite studies have provided a comprehensive description of the mathematical solution of hydraulic transients with intrusion and advection [6], very few results from real system performance under water quality and transient conditions have been reported.

2.2.2 Relation between discoloration and hydraulic transient

Discoloration is mainly attributed to the re-suspension of accumulated particles and not true change of color [20]. Discoloration pathways can be classified as follows: a) Gravitational sedimentation: re-suspension of particles settled in the bottom of pipes; b) Non-gravitational accumulation: detachment of particles accumulated over the entire circumference of pipes; c) Corrosion-related: release of iron particles either directly from corrosion, or accumulation of iron produced during corrosion in the form of scales on the pipe wall which is then released by dissolution or shear stress; and, d) Biofilm-related: entrapment of particles in biofilms and subsequent release due to biofilm sloughing.

Biofilms play a major part in the microbial characterization of drinking water quality in distribution. These films or slimes, as presented in Figure 1, become established in sediments, corrosion tubercles, static areas of slow water flow, dead-ends, standpipes, and storage tanks [20].

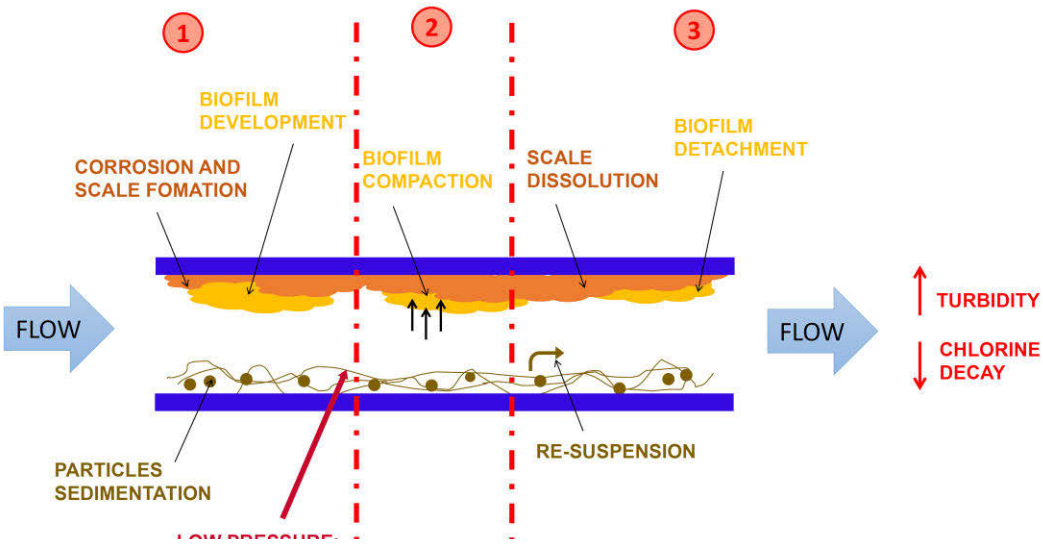

Figure 1 – Main Interactions Affecting Water Quality Decay Inside Distribution Systems

FONTE: The author, adapted from: Mays [20]

Weston et al. proposes that there are three key components of hydraulic transients that could theoretically lead to mobilization of biofilms growing or other material accumulated on the pipe wall, releasing such material into the bulk water and possibly causing water quality/health concerns, as presented in Figure 2. These mechanisms are consequence of induced shear stress due to velocity changes, induced stress due to a pressure differential across the wave front and structural changes from cavitation expansion and collapse. Once mobilized, biofilms and previously entrapped material have the potential to cause discoloration and water quality failures [21].

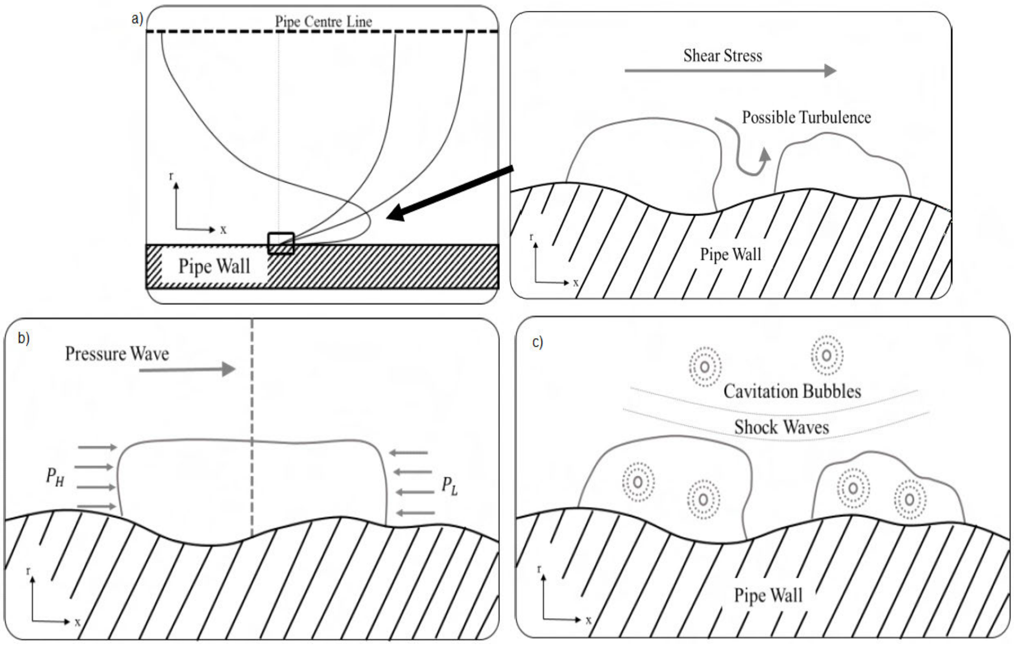

Figure 2 - Mobilization of biofilms growing or other material accumulated on the pipe wall [22]

Experimental findings conclusively prove mobilization of pipe-wall adhered material due to hydraulic transients, which was only suggested from indirect observations in other works. Both valve closing and valve opening transients can mobilize this material where steady-state hydraulic conditions cannot. This study presents a schematic of possible transient and steady state mobilization force relationships, as illustrated in Figure 3 as very in-depth explanation for potential physical changes in pipes, under dynamics conditions. Linear relationships are drawn as the simplest association possible, which may or may not pass through the origin. The area above each relationship indicates that the magnetic forces are too high for mobilization to occur due to the hydraulic force. The area below each relationship indicates the magnetic forces are too low, thus mobilization would occur due to the hydraulic force. If transient relationships sat above the steady state relationship an area would exist where the transients can cause mobilization, but steady state cannot (green highlight). A direct implication of this research is that by reducing transient events a water utility provider could reduce the risk of discoloration contacts, the major cause of water quality related customer dissatisfaction [22].

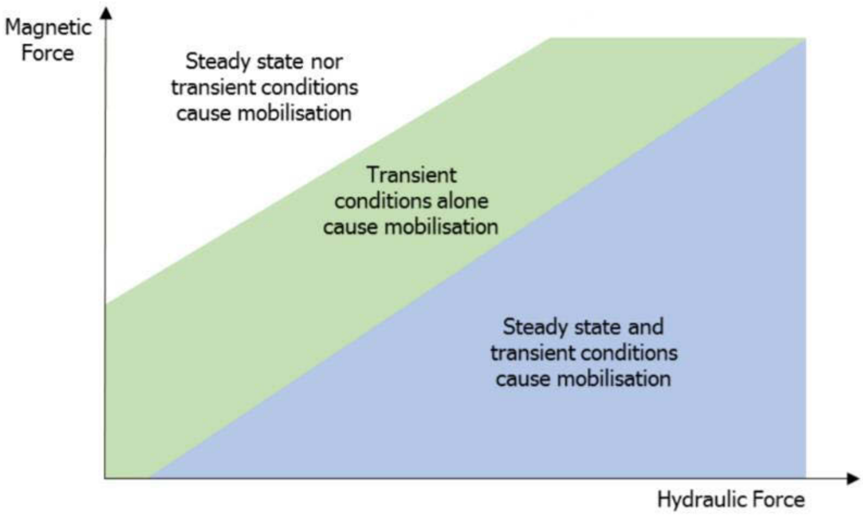

Figure 3 – Schematic of possible transient and steady state mobilization force relationships [22]

As highlighted by Speight "Understanding the processes and interactions occurring within complex, ageing drinking water distribution systems is vital to ensuring the supply of safe drinking water. While many water quality samples are taken for regulatory compliance, the resulting data are often simply archived rather than being interrogated for deeper understanding due to their sparse nature across time and space and the difficulties of integrating with other data sources" [23].

An experimental study demonstrates that pre-transient conditions of both flow and pressure combine in a complex manner and play key roles in the mobilization effects of both accelerating and decelerating flow transients. Further analysis shows that in transients with decelerating flow conditions, post-transient flow rate is also important for mobilization. All accelerating flow transients caused mobilization, those starting at zero flow and those starting with non-zero flow rates. Conversely only decelerating flow transients that ended at zero flow conditions caused mobilization, independent of the magnitude of the change in flow. The timing of mobilization was shown to be slower than the propagation of pressure wave front, suggesting the pressure wave front is not responsible for the mobilization. Conversely, links are made to the boundary shear stress of dynamic changes in velocity profiles observed in other research [24].

2.2.3 Water Quality Monitoring

Samples can be collected and analyzed in two ways: grab samples and continuous samples. Grab samples are collected manually in the field and analyzed in the field or in the laboratory. Continuous monitoring is conducted by means of sensors and remote recording stations. Grab samples are more labor intensive and provide data only at the time of collection. Continuous monitoring requires a capital expense for the monitoring equipment and for equipment maintenance time, but it provides a continuous time-series profile of changes in water quality. A comprehensive monitoring plan can make use of both grab and continuous methods [20].

A routine monitoring program should be established to meet regulatory requirements and to collet additional water- quality information that is useful in the operation of a water system. Table 1 lists parameters that are frequently measured in a routine monitoring.

Table 1 – Water Quality Parameters for Finished Water Storage Facilities [9]

PARAMETER	PURPOSE	SAMPLING PROCEDURE USED
Alkalinity	Indicates the potential buffering capacity	On-line ion-selective electrode or grab sample and laboratory analysis
Aluminum	Indicates the potential coagulant overfeeding	
Ammonia, total or free	Indicates potential for nitrification	
Chorine residual, total or free	Indicates protection from bacterial growth and provides early warning sign of water-quality deterioration: control re-chlorination when practiced	
Conductivity, specific	Can quickly indicate relative changes in total dissolved solids, e.g. alkalinity	
Iron	Indicates potential corrosion reactions	
Nitrate	Indicates possibility of nitrification	
pH	Indicates changes from the water source. Indication of corrosion of concrete or an unlined new facility.	
Coliform, total and/or fecal	Indicates presence of indicator bacteria	Grab sample and laboratory analysis
Disinfection by products	Represents potential for ongoing chemical reactions and DBP formation	
Heterotrophic bacteria	Indicates conformance to MCL; provides early warning sign of water-quality deterioration	
Taste and odor	Evidence of water-quality problem in progress	
Temperature	Differences within storage facility indicate possible stratification and stagnant zones. Early warning sign of potential	On-line sensor
Turbidity	Provides early warning sign of water-quality deterioration	On-line turbidimeter sensor and analyzers

2.3 State of Art

The last six years of literature review was selected and the main papers about water quality in distribution system was summed up in Table 2. The first highlight is the incipient number of researches that associate water quality with the hydraulic transient state in real networks. Research involving the subject is essentially in networks installed in laboratory with small pipe diameter and flow, with high control of parameters through sensors. Another finding is that the vast majority of cases involving high frequency sensors are in laboratory networks.

Table 2 – Art State Overview linking water quality and water distribution system

	Theme	Real or Lab	Hydraulic state	Observed or simulated?	Pipeline or network?	High-resolution sensor	Math model	Data statistical generation	Index?	Reference
1	Discoloration	Lab.	Intermittent	Observed	Pipeline	No	No	No	Yes	[25]
2	Discoloration	Lab.	Transient	Observed	Pipeline	Yes	NO	No	Yes	[24]
3	Discoloration	Lab.	Steady state	Observed	Network	No	No	No	No	[26]
4	Discoloration	Lab.	Transient	Observed	Pipeline	Yes	No	No	No	[27]
5	Discoloration	Real	Steady state	Observed	Network	No	No	Machine learning	No	[23]
6	Discoloration	Lab.	Steady state	Observed	Pipeline	No	No	No	No	[28]
7	Chlorine decay	Real	Steady state	Both	Network	No	No	No	No	[29]
9	Discoloration	Review	-	-	-	No	no	no	No	[30]
10	Discoloration	Real	Steady state	Observed	Network	no	no	no	no	[31]
11	Discoloration	Real	Steady state	Observed	Network	No	No	No	Yes	[32]
12	Discoloration	Real	Steady state	Observed	Network	No	No	No	Yes	[33]
13	Discoloration	Real	Steady state	Observed	Pipeline	No	yes	no	Yes	[34]
14	Discoloration	Real	Steady state	Observed	Network	No	No	No	No	[35]
15	Discoloration	None	Transient	Review	None	No	No	No	No	[21]
16	Discoloration	Real	-	Observed	Pipelines	No	Yes	No	Yes	[36]
17	Discoloration	Lab.	Transient	Observed	Pipeline	Yes	No	No	No	[37]
18	Discoloration	Lab.	Transient	Simulated	Pipeline	no	yes	no	No	[38]
19	Intrusion	-	Transient	Simulated	pipeline	No	Yes	No	No	[18]
20	Intrusion	Lab.	Transient	Observed	Pipeline	Yes, video	No	No	No	[17]
21	Chlorine decay	Lab.	Transient	Observed	Pipeline	Yes, pressure - 100 Hz Chlorine - 1 Hz	Yes	No	No	[39]
22	Chlorine decay	Lab.	Steady state	Observed	Pipeline	No	No	No	No	[40]
23	Chorine decay	-	Steady state	Observed					No	[41]
24	Chorine decay	Lab.	Steady state	Observed		No	No	No		[42]
25	Turbidity	Lab.	Steady state	Observed	Network	No	No	No	No	[12]
26	Disinfection byproducts (DBP)	Lab.	Steady state	Observed	-	No	No	No	No	[43]
27	Disinfection byproducts (DBP)	Lab.	Steady state	Observed	Pipeline	No	No	No	no	[44]
28	Corrosion	Lab.	Steady state	Observed	Pipeline	No	No	No	No	[45]
29	Bacterial regrowth	Review	-	-	-	No	No	No	No	[46]
30	Bacterial regrowth	Review	-	-	-	No	No	No	No	[47]
31	Bacterial regrowth	Review	-	-	-	No	No	No	No	[48]
32	Bacterial regrowth	Lab.	Steady state	Observed	Pipeline	No	No	No	No	[49]
33	Bacterial regrowth	Real	Steady state	Observed	-	No	No	No	No	[50]

3 MATERIAL E METHODS

3.1 The system

The area under study belongs to the Water Supply System of Curitiba and Metropolitan Region, named SAIC. The current production and treatment system is around 9.9 m^3/s. After the treatment, the water is sent to around 50 existing reservation centers, being in all 377650 m3 reserved. There are currently 160 pressure zones serving 3.5 million people. In this study was selected one of the mains important pipelines of the SAIC system, that are responsible for treated water transportation by Iguacu Treatment Plant to Corte Branco Tank, as represented in Figure 4, and composed by: three pipelines being two of 800 mm ductile iron and one of 1,100 mm iron and six pumps, being five used and one back up. The average flow is 2,600 L/s.

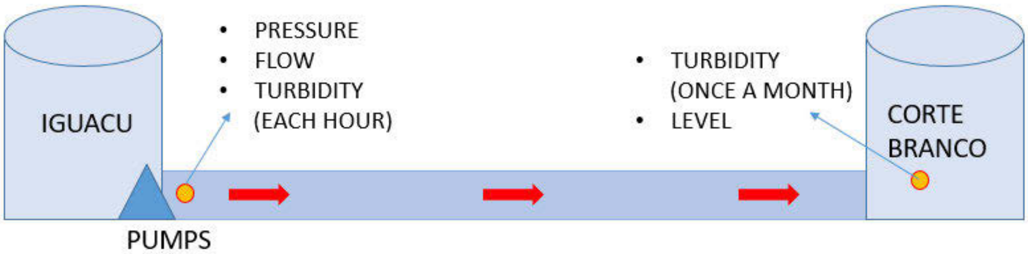

Figure 4 – Schematic Sketch of Pipeline

The Figure 5 presents the real data of Flow, Pressure after pumps and Level' Corte Branco, collect in 2020.

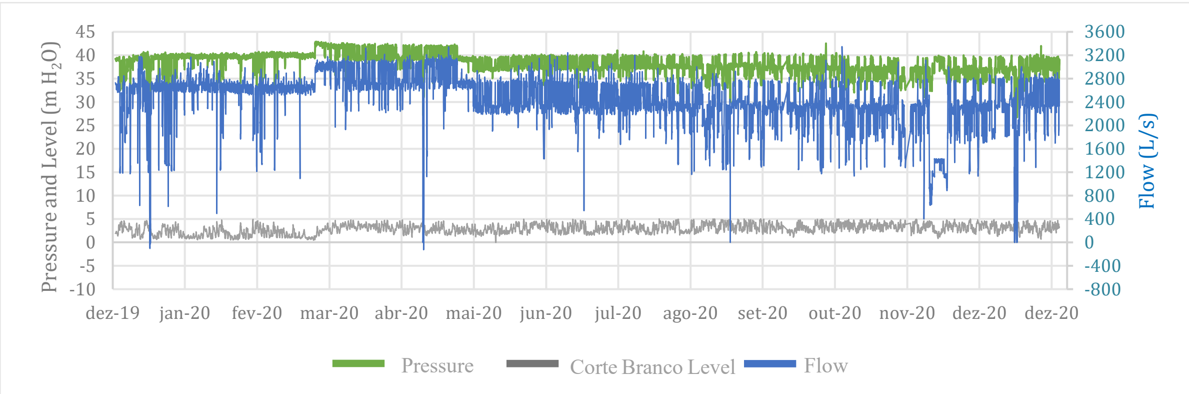

Figure 5 – Real Pipeline Data

3.2 Fundamental Database

In order to get an empirical formula to turbidity during hydraulic transients, was observed 5 years' data from the real system. The data used, as present in Figure 6, are the ones required by Brazilian regulation.

From that data was create simple correlations between the Corte Branco turbidity and: a) Flow; b) Pressure after pumps; and c) Level; and d) between the difference of turbidity (Corte Branco and Iguaçu) and Pressure pumps. These correlations are presents in Figure 7.

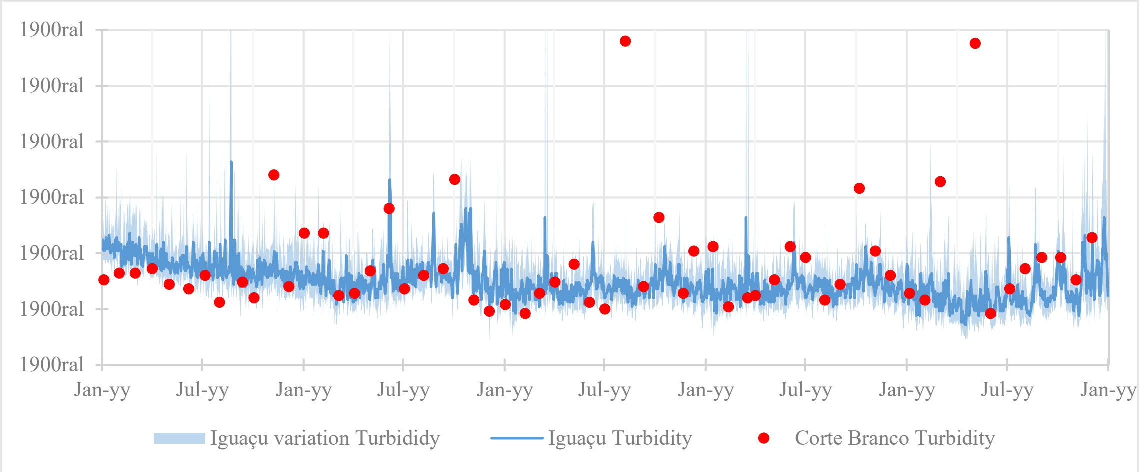

Figure 6 – Turbidity Data

Figure 7 – Water Quality x Physical Correlations [51]

The boxplot chart was used to assess the empirical distribution of the data. The boxplot consists of the first and third quartiles and the median. The lower and upper stems extend, respectively, from the lower quartile to the lowest value not lower than the lower limit and from the upper quartile to the highest value not higher than the upper limit, as present in Figure 8. Applying the obtained equations in the 2020' data, as illustrated in Figure 9, the results propose that the maximum turbidity was around 1.2 uT.

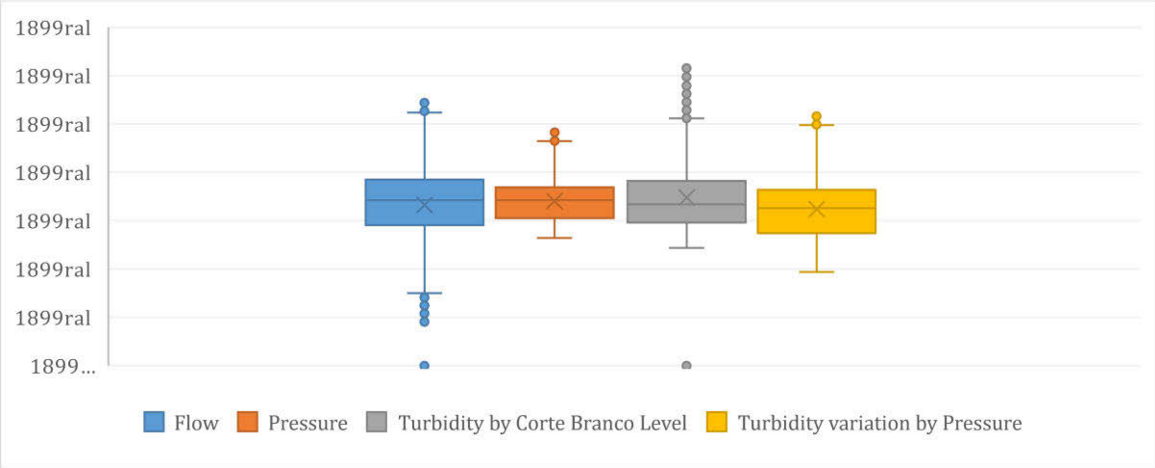

Figure 8 – Correlation's Comparison

Analyzing the data, the graph that presented the most confidential equation with an of 22% was based in Corte Branco's Level. This make sense because the sample is taken directly of the Tank, but cannot be extrapolated to transients, considering that tank does not vary in time during a transient. The second graph that presented more confidential the correlation is the variation of turbidity between the Corte Branco's Level and the Iguaçu, and the pressure.

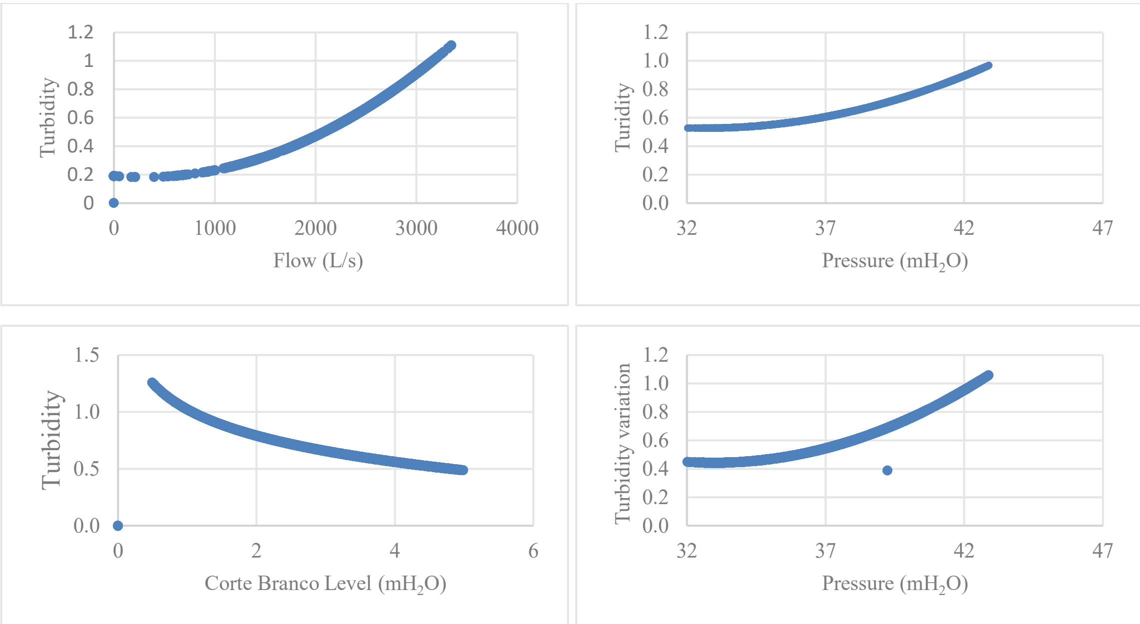

Figure 9 – Turbidity Applying the Generated Correlations

3.3 Field Campaigns

Two water quality measurement campaigns were realized during hydraulic transient events in order to obtain the relationship between the physicals and quality results. The samples were used to measure the turbidity and chlorine.

In the first campaign the pipelines were with no flow for about 3 hours. The test consisted in turn on the pumps following the operational routine, turning on one by one. Then, a time was wait and after that, all of them were turned off together. In the second one the pipelines were operating. The test consisted in turn off all pumps. Then turn on one by one and them turn off all of them.

The samples were collected in the end of the pipeline each five minutes in the first test and two minutes in the second one.

1.2 Hydraulic Transient Calculation

The simulation of the hydraulic transient in the pipelines was carried out through the software Hammer, Bentley, which uses as numerical method the Method of Characteristic (MOC).

4 PRELIMINARY RESULTS

Simulating the hydraulic transient caused by the shutdown of the pumps during 600 seconds, the results expressed in Figure 10 were obtained.

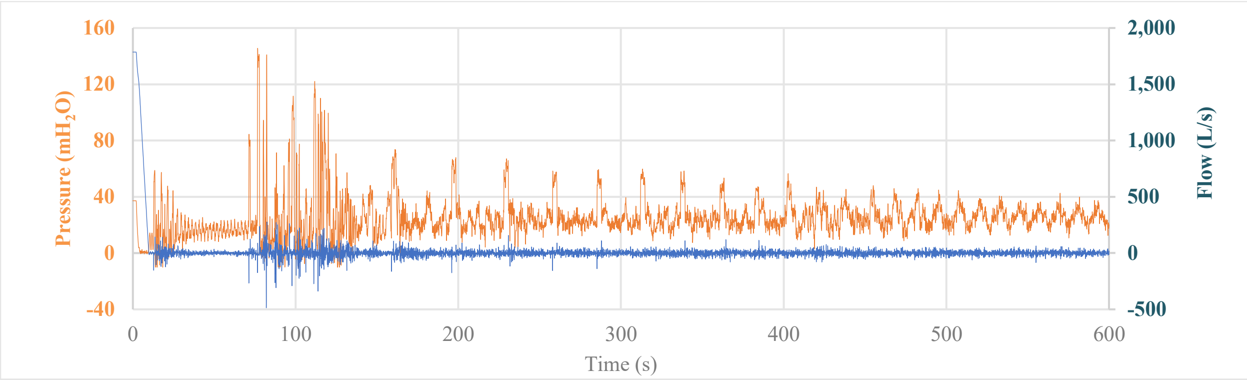

Figure 10 – Pressure and Flow during a Hydraulic Transient Event

Applying the generated equations of quality in the physical results of hydraulic transients, the Figure 11 is obtained.

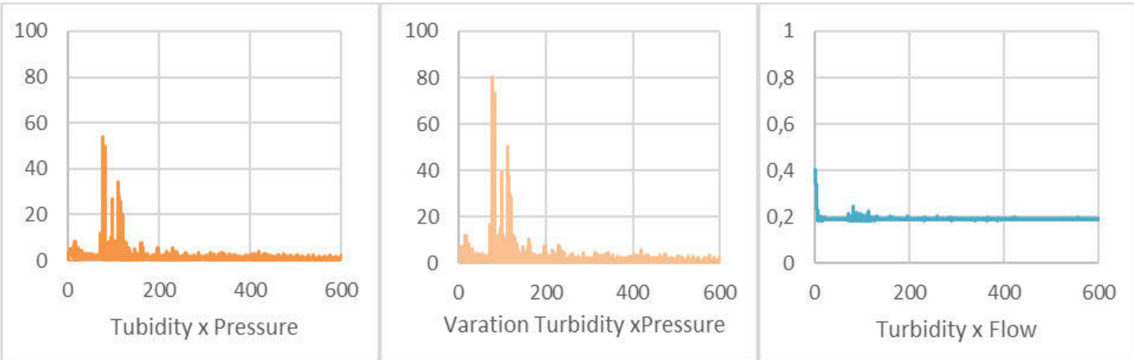

Figure 11 – Theoretical Turbidity During Hydraulic Transient

The result of the first water quality measurement campaign is presented in Figure 12 and the second one in Figure 13.

Analyzing the graphs is clear that the water quality change during the hydraulic transient. In the first test is observed that chlorine was zero in the begging of the test because the flow was zero for two hours before the test, and it take a time to increase, probably influenced by wall's pipeline effect. When the pumps were turned off the turbidity increase about 0,6uT.

In the second test is observed the turbidity increasement was about 0.7uT and 1.3 in one episode. The chlorine index had slight variation when the flow was different of zero, with a tendency to fall when the flow decreases to zero, probably influenced by wall's pipeline effect.

These preliminary results show in a real water system the relationship between hydraulic transients and the turbidity increase.

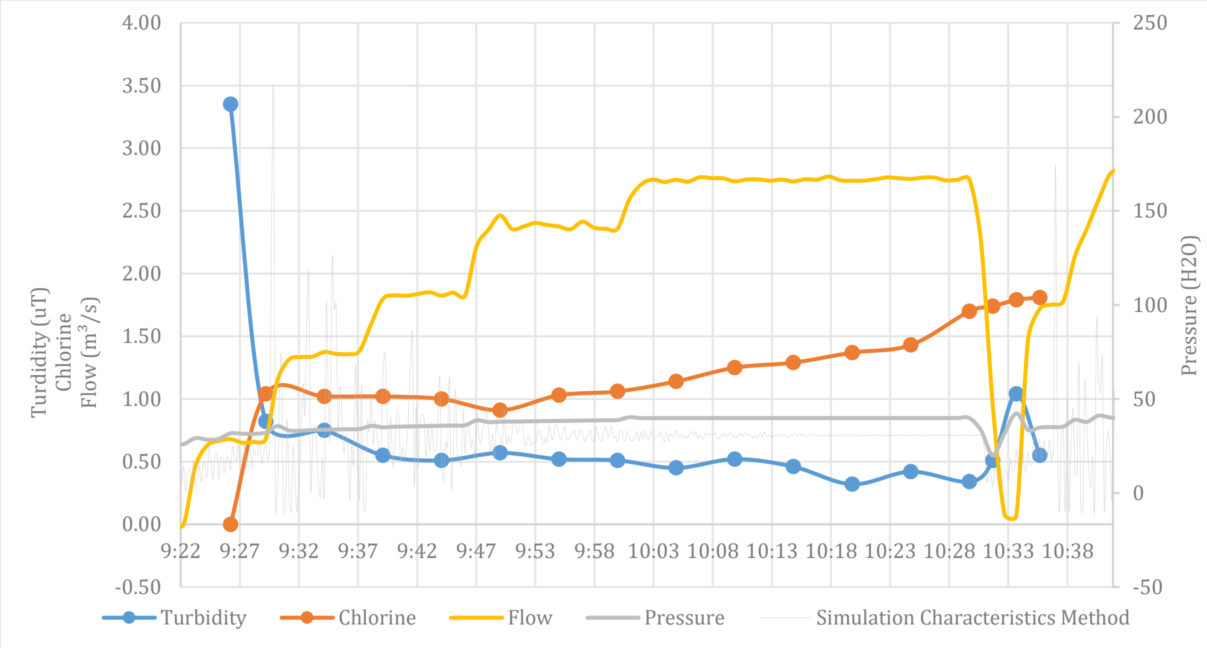

Figure 12 – First Campaign

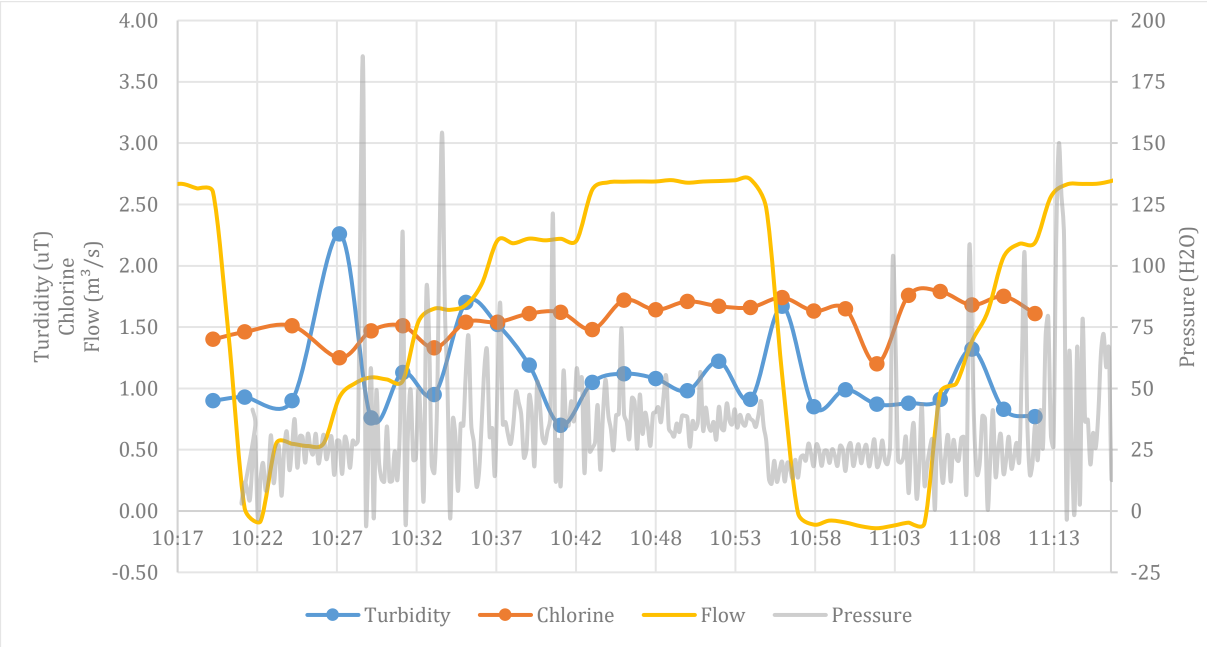

Figure 13 – Second Campaign

5 CONCLUSION

In addition, it is worth mentioning that monitoring and investigation of transients in operational systems is only occasionally done to investigate perceived problematic areas over a short period of time, and generally with physical focus. That happens because of the usually inability to manage the vast volumes of data generated from sampling with significantly higher temporal resolution than the state of art fifteen minutes [11].

The results prove in a real system the relationship between hydraulic transients and the turbidity increase. In this scenario, an indicator that correlates physical quantities with water quality has great relevance for the definition of projects and understanding of real hydraulic transient phenomena. It can be used to: compare different protect solutions; change material; get better flushing procedures or redefine any other condition. The studies are still in development and next steps is evaluate the preliminary results.

6 ACKNOWLEDGEMENTS

Part of the results already have been published in a Brazilian Nacional Seminary [51].

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