UNIVERSIDADE FEDERAL DO PARANÁ

MARIELE DE SOUZA PARRA AGOSTINHO

ASSESSMENT OF HYDRAULIC TRANSIENTS THROUGH INDICATORS IN AN INTEGRATED WATER SUPPLY NETWORK

CURITIBA

2018

MARIELE DE SOUZA PARRA AGOSTINHO

ASSESSMENT OF HYDRAULIC TRANSIENTS THROUGH INDICATORS IN AN INTEGRATED WATER SUPPLY NETWORK

Dissertação apresentada ao Programa de Pós-Graduação em Engenharia de Recursos Hídricos e Ambiental, Departamento de Hidráulica e Saneamento, Setor de Tecnologia, Universidade Federal do Paraná, como parte das exigências para a obtenção do título de Mestre em Engenharia de Recursos Hídricos e Ambiental.

Orientador: Prof. Dr. Cristóvão Vicente Scapulatempo
Coorientador: Dr. Bong Seog Jung

CURITIBA
2018

FICHA CATALOGRÁFICA ELABORADA PELO SISTEMA DE BIBLIOTECAS/UFPR
BIBLIOTECA DE CIÊNCIA E TECNOLOGIA

AG275a Agostinho, Mariele de Souza Parra

Assessment of hydraulic transients through indicators in an integrated water supply network / Mariele de Souza Parra Agostinho. – Curitiba, 2018.

94 p. : il. color. ; 30 cm.

Dissertação - Universidade Federal do Paraná, Setor de Tecnologia, Programa de Pós-Graduação em Engenharia de Recursos Hídricos e Ambiental, 2018.

Orientador: Cristóvão Vicente Scapulatempo.

Coorientador: Bong Seog Jung.

1. Transitório Hidráulico. 2. Rede de distribuição de água. 3. Saneamento. I. Universidade Federal do Paraná. II. Scapulatempo, Cristóvão Vicente. III. Jung, Bong Seog. IV. Título.

CDD: 627.86

Bibliotecária: Romilda Santos - CRB-9/1214

MINISTÉRIO DA EDUCAÇÃO
SETOR TECNOLOGIA
UNIVERSIDADE FEDERAL DO PARANÁ
PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO ENGENHARIA DE RECURSOS HÍDRICOS E AMBIENTAL

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em ENGENHARIA DE RECURSOS HÍDRICOS E AMBIENTAL da Universidade Federal do Paraná foram convocados para realizar a arguição da Dissertação de Mestrado de **MARIELE DE SOUZA PARRA AGOSTINHO**, intitulada: **ASSESSMENT OF HYDRAULIC TRANSIENTS THOROUGH INDICATORS IN AN INTEGRATED WATER SUPPLY NETWORK**, após terem inquirido a aluna e realizado a avaliação do trabalho, são de parecer pela sua aprovação no rito de defesa.

A outorga do título de Mestre está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

Curitiba, 19 de Dezembro de 2017.

CRISTOVÃO VICENTE SCAPULATEMPO FERNANDES(UFPR)
(Presidente da Banca Examinadora)

FABIO VERISSIMO GONÇALVES (UFMS) (skype)

BONG SEOG JUNG(UTORONTO) (skype)

ELOY KAVISKI(UFPR)

André Fabiani
André Luiz Tonso Fabiani (UFPR)

Centro Politécnico, Bloco V - Curitiba - Paraná - Brasil
CEP 81531-990 - Tel: (04) 1336-1321 - E-mail: pos.dhs@ufpr.br

ACKNOWLEDGEMENTS

My sincere gratitude to the individuals that have contributed to the completion of this work:

- Professor Cristóvão Vicente Scapulatempo Fernandes for supervision, opportunity, trust, time, technical guidance, and patience;
- Bong Seog Jung for trust, guidance, reviews and time;
- Professors Eloy Kaviski, Andre Luiz Tonso Fabiani and Fabio Verissimo Gonçalves for time and so kindly accept being part of this moment;
- My parents Maria Dolores and Claudecir, and my sister Mariane for your support and encouragement;
- Larissa Pereira for patience, encouragement, help, support and incentive;
- Master's collegues, especially Juliana Leithod and Gabriela Reichert, for making the journey easier and soft;
- Sanepar for the opportunities and make my schedule flexible making it possible;
- Sanepar's collegues for patient and advices. Especially: Juliana Pilotto for all the opportunities, teachings and incentive; Nicolas Lopardo for advices and help; Monica Tabor, Anderson Sabbag, Cezio, Anderson Preszunhuk, Katia Garcia and all my coworkers at USPE for the diary teachings and, contribution for my development.

RESUMO

O principal objetivo deste estudo é a análise de 14 indicadores de transitórios hidráulicos para sistemas distintos de distribuição de água, a fim de avaliar a potencial sensibilidade de eventos de surtos transitórios para representações de topologias reais distintas. Este estudo visou entender como os fenômenos de inércia e compressibilidade são potencialmente relevantes para determinar estratégias de proteção a fim de atenuar eventos transitórios e diminuir o risco de ruptura de tubulação por elevação e/ou excesso de pressão, contribuindo para a redução de perda e consequentemente demanda e captação de água. Um total de 208 cenários de três sistemas de distribuição de água, na Região Metropolitana de Curitiba, no Parana, Brasil: RVAM, GAAV e GEAV, foram considerados e depois comparados com os 14 indicadores de transitórios hidráulicos. O cálculo dos indicadores possibilitou a análise de sensibilidade da variação de: celeridade, fluxo, número de junção, diferentes dispositivos de proteção e zonas de pressão, e provou a forte necessidade deste estudo nos sistemas brasileiros. O estudo de diferentes zonas de pressão (RVAM, GAAV e GEAV) indicou que o risco não é um caso isolado no sistema de distribuição, mas comum e frequentemente. Os diferentes materiais provaram a forte influência da celeridade durante a simulação. Enquanto os materiais plásticos (PVC e HDPE) apresentaram resultados semelhantes, o ferro dúctil apresentou resultados bastante diferentes e complicados. A análise transitória de sistemas esqueletizados e completos provou a imprecisão e o perigo de esqueletização do modelo, pois pode sub ou superestimar os resultados.

Palavras-chave: Transitório Hidráulico. Rede de Distribuição de Àgua. Indicadores. Saneamento.

ABSTRACT

The main objective of this study is the analysis of 14 hydraulic transient indicators for distinct water distribution systems, in order to assess potential sensitiveness of surge events under real distinct topology representation. This study is to understand how inertia and compressibility phenomena are potentially relevant to determine protection strategies for attenuating transient events, and to decrease the risk of pipe breakage by uplift and/or excess pressure, contributing in the reduction of loss and consequently demand and uptake. Total 208 scenarios of three WDS in Metropolitan Region of Curitiba, Parana, Brazil: RVAM, GAAV and GEAV has been considered and then compared with the 14 hydraulic transient indicators. The calculation of the transient indicators made possible sensitivity analysis of the variation of: celerity, flow, junction number, different protection devices and pressure zones, and proved the strong need of this study in the Brazil's systems. The study of different pressure zones (RVAM, GAAV and GEAV) indicated that the risk isn't an isolate case in the WDS, but common and frequently. The different materials proved the strong influence of celerity during the simulation. While the plastic materials (PVC and HDPE) presented similar results, ductile iron presented quite different and complicate outputs.The hydraulic transient analysis of skeletonized and complete systems proved the inaccuracy and danger of model skeletonization, as it may under or over-estimating transient analysis.

Keywords: Hydraulic Transient. Water Distribution System (WDS). Indicators. Sanitation.

FIGURE LIST

TABLE LIST

SUMARY

1 INTRODUCTION

"The mind that opens to a new idea never returns to its original size" (Albert Einstein)

Water Distribution Systems (WDS) is a very specialized and totally integrated system to the main concepts of Sustainable development, and its main challenges are associated to: high energy costs, water scarcity, on-going leakage, customer frustration and threats associated with transient events, which contribute to high system costs and environmental impacts, as described worldwide and with significant concern in Brazil (Karney, 2014).

Hydraulic Transients is a phenomenon that occurs under unsteady flow conditions as a communication consequence which is transmitted as a pressure or water-hammer wave in the pipeline system (Chaudhry, 1979). It can be used beneficially, as in the case of some hydraulic pumps (hydraulic ram), that uses a large amount of flow from higher elevation, but more commonly, the destructive potential of water hammer is what attracts the attention of water engineers (Walski & Koelle, 2003).

Lansey & Boulos (2005), highlights that, it is the phenomenon generated in penstock characterized by the occurrence of pressure waves propagating along the pipe, 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. Transients during uncontrolled shutdown of the pump can lead to undesirable occurrence of water separation column, which could result in serious faults in the pipelines due to the increase of pressure after the collapse of vapor cavities, showing how dynamics systems can be transformed through inertia and compressibility effects.

According to Karney & McInnis (1990), the transient conditions can 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.

Usually people underestimate the occurrence and severity of transients in pipe networks because they believe that the system's network (looped or branched configurations) reduces the impact of water-hammer events and usually they create some "traditional laws" about the transient analysis, such as: a) maximum steady-state velocities produce maximum transient head change; and b) if one surge-protection device is efficient, then two are better. However, the literature demystifies this and suggests the opposite may be true sometimes (Karney & Mcinnis, 1990; Mcinnis & Karney, 1995).

The effects of pressure transients on distribution system of water quality degradation, as well, have been extensively reviewed (Wood et al., 2005; Boulos et al., 2004; Fernandes and Karney, 2002; Karim et al., 2003; Lechevallier et al., 2003; Kirmeyer et al., 2001; Funk et al., 1999) and are consequence of strong influence of inertia and compressibility effects, highliting the relevance of hydraulics inducing water quality degradation.

For the transient analysis to be successful and the designer be confident that transient conditions have been rationally and logically represented, the analysis must be carefully done. This implies that a wide range of flow conditions, operating scenarios and device combinations must be investigated. The potential benefits of such an approach include an improved model of system behavior, more economical system operation and, possibly, a lower capital lost (Karney & Mcinnis, 1990).

1.1 EVIDENCES OF INTEREST

As water is an essential element for the survival of human beings, distribution networks are an essential component of all water supply systems as well (Jung & Karney, 2006). Water is an economic asset, because it is finite, vulnerable and essential for the preservation of life and the environment and it is required to assure social and economic development, culture stability, and health balance in a country. Thus, it is relevant for water resources management strategies to consider WDS as part of all activities that interfere directly or indirectly in the Basin.

In this context, the study of hydraulic transient in WDS relies on understanding how inertia and compressibility phenomena are potentially relevant to determine protection strategies for attenuating transient events, in order to decrease the risk of pipe rupture by uplift and/or excess pressure, contributing in the reduction of loss and consequently demand and uptake. Another motivation for exploring transient issues that is important is water quality concerns.

Complementarily, the study of hydraulic transient relies on understanding how inertia and compressibility phenomena are potentially relevant to determine protection strategies for attenuating transient events, in order to decrease the risk of pipe rupture by uplift and/or excess pressure, contributing in the reduction of loss and consequently demand and uptake. Another motivation for exploring transient issues that is important is water quality concerns.

Thus, the study of the hydraulic transient and its application, in addition to its great importance to sanitation itself, being one of those responsibles to ensure efficiency and quality to the system, is part of the set of actions to be taken to manage water resources in a conscious and controlled order and to protect WDS in general.

1.2 BRAZIL SCENARIO

In Brazil, it is the responsibility of the municipality to provide, directly or through concession to private companies, basic sanitation services. So, the service quality is very variable depending of the municipality. Some Brazil's states have state companies – generally mixed private and state – have the concession for a lot of cities, as: SANEPAR, in Parana; SABESP, in Sao Paulo; CORSAN, in Rio Grande do Sul; COPASA, in Minas Gerais; CASAN, in Santa Catarina; CEDAE, in Rio de Janeiro; and others.

According to the National Information of Sanitation from Brazil (SNIS, 2017) the water losses varies from 20 to 70%. Despite the systems being composed by differents materials, the pipes are maily made in PVC. Also, just a few systems have automation and this happens basically in the big ones that control the main pumps and valves. The steady state pressure allowed by Brazilian standards is 10 to 40 mH2O.

Figure 1, as follows, represents the duration of interruptions and economies affected by interruptions from each Brazilian state and the Federal District. Roraima and the Federal District don't present any data. Each interruption affects in average 750 economies and takes on average about 7 hours to reestablish the system. The causes are many as: the pipe's steady state pressure above the allowed, hydraulic transients, breakups, natural disasters (as flood for example). However, this datas generally aren't separated by causes.

The water rates vary from free to around US$ 2,00 per cubic meter to the users. The places where the price is free, the costs are payed by the municipal government. The investments budgets come from taxes and federal government.

1.3 OBJECTIVES

The main goals can be presented as follows.

1.3.1 General Objective

Analysis of hydraulic transient indicators in a water distribution network.

1.3.2 Specific Objectives

The specific objectives are:

- Overall of hydraulic transients softwares;

- Modeling and simulation of hydraulic transient in three real water distribution networks: RVAM, GAAV and GEAV, all in Metropolitan Region of Curitiba, in Parana, Brazil;
- Calculate and evaluate indicators for network hydraulic transient;
- Compare the results for all pipes and skeletonized simulations;
- Guideline for analysis of hydraulic transient in water distribution system for sanitation companies.

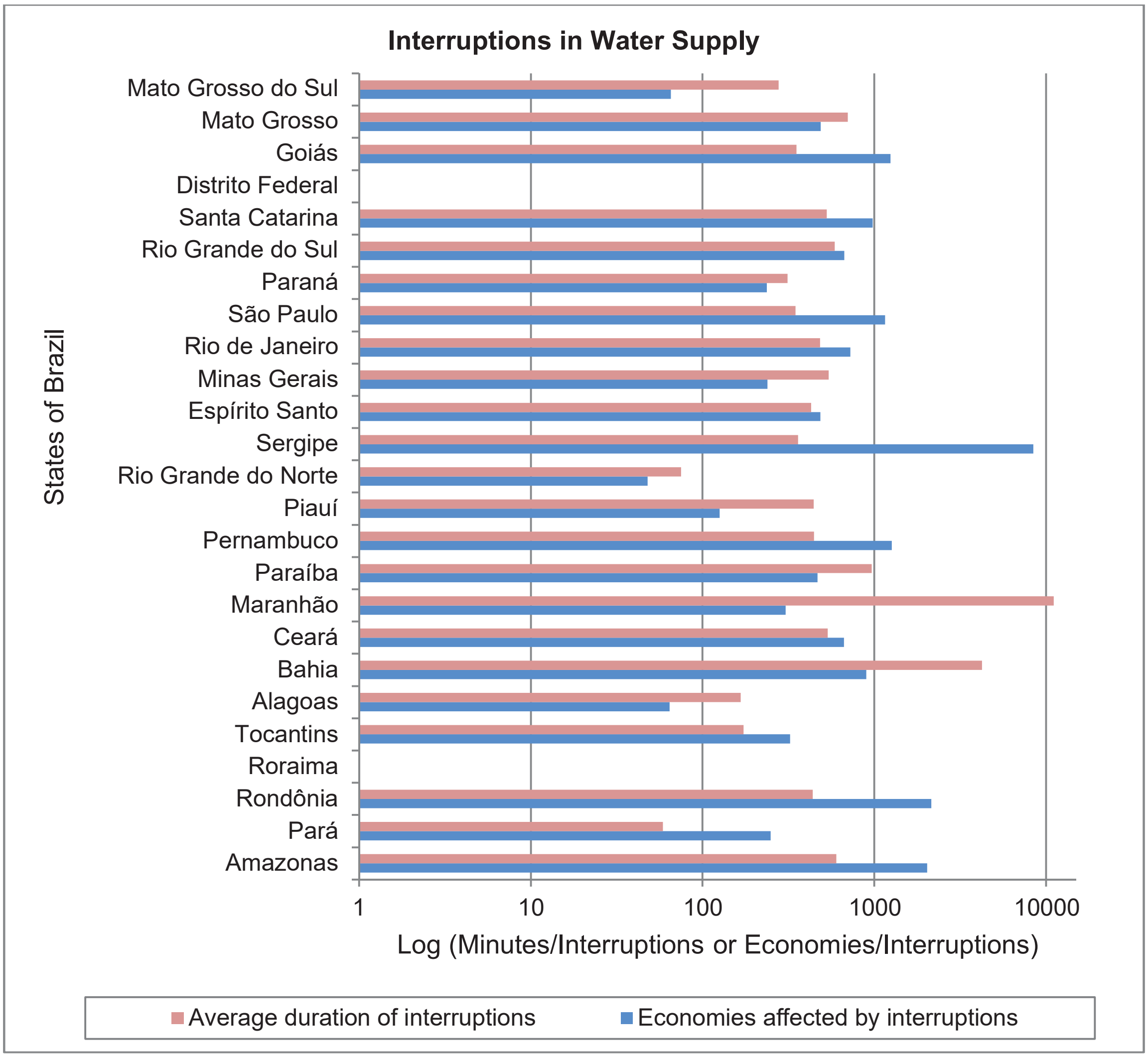


FIGURE 1: INTERRUPTIONS IN BRAZILIAN WATER SUPPLY SYSTENS

SOURCE: SNIS, 2017.

1.4 METHOD

The simulation of the hydraulic transient in the water distribution networks will be carried out through the software Hammer, Bentley, which uses as numerical method the Method of Characteristic (MOC). 200 scenarios were modeled to the three systems, being:

104 to RVAM and 48 to GEAV and GAAV. To analyse these was used 14 indicators, as following:

- C1 – Number of junctions with pressure < 0;
- C2 – Percentage of junctions with pressure < 0;
- C3 – Number of junctions with vacuum pressure;
- C4 – Total time cavitation;
- C5 – Severity of cavity index;
- C6 – Surge damage potential factor positive;
- C7 – Surge Damage Potential Factor Negative;
- C8 – Surge Damage Potential Factor;
- C9 – Pressure range;
- C10 – Minimum Pressure;
- C11 – Maximum Pressure;
- C12 – Negative Transient Risk Index;
- C13 – Positive Transient Risk Index;
- C14 – Damage Index.

1.5 DISSERTATION ORGANIZATION

Chapter 2 provides overviews about hydraulic transients. It also provides context on this topic, by considering causes, consequences, analysis, approaches, a brief Brazilian standard, design and protection devices.

Chapter 3 focuses on water distribution system, approaching water quality during hydraulic transients and skeletonization.

Chapter 4 develops the methodology used in this work. This chapter provides a brief analysis about six indicators shown in the literature, propose others eight indicators and shows the cases studies. Besides that, it presents the 200 scenarios that were calculated.

Chapter 5 summarizes the hydraulic transient indicators. Also, this chapter presents the analysis and comparison between all pipes and skeletonized simulations of the case studies.

Chapter 6 summarizes the conclusions from the thesis, and reaffirms the contributions of this work towards both research and sanitation companies.

2 THEORICAL BACKGROUND

“Only systematic and informed water hammer analysis can be expected to resolve complex transient characterizations and adequaly protect distribution system from vagaries and challenges of rapid transients” (Jung et al., 2007)

2.1 CAUSES AND CONSEQUENCES OF HYDRAULIC TRANSIENT

According to Wood (2005), 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 startup 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.

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 (Boulos et al., 2005):

- Maximum pressures in hydraulic systems. This is the most common consequence of hydraulic transients;
- Occurrence of local vacuum conditions at specific locations that may result in cavitation either within specific devices such as pumps or within a pipe;
- Hydraulic vibration of a pipe, its supports, or in specific devices;
- Occurrence of contaminant intrusion at joints and cross-connections.

According to Walski & Koelle (2003) if sub-atmospheric pressure conditions evolve, the risk of pipeline collapse increases for some pipeline materials, diameters, and wall thicknesses. 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. There are two distinct types of column separation:

- Gases cavitation involves dissolved gases such as carbon dioxide and oxygen coming out of the water. When it occurs, small gas pockets form in the pipe. Because these gas pockets tend to dissolve back into the liquid slowly, they can have the effect of dampening transients if they are sufficiently large.
- Vaporous cavitation in the vaporization of the water itself. With vaporous cavitation, a vapor pocket forms and then collapses when the pipeline pressure increases due to more flow entering the region and then leaving it. Collapse of the vapor pocket can cause a dramatic high-pressure transient if the water column rejoins very rapidly, which can cause the pipeline rupture. Vaporous cavitation can also result in pipe flexure that damages pipe linings. Cavitation can and should be avoided by installing appropriate protection equipment or devices in the system.

Martin (1983) measured transient cavitation in a simple reservoir-pipe-valve system. The water contained a minimal amount of dissolved gas. Limited cavitation (where the duration of the existence of the cavity at the valve is relatively short) was emphasized in contrast to previous studies (on severe cavitation) reported in the literature. The experimental results showed that the maximum pressure may exceed the Joukowsky pressure rise in the form of a short-duration pressure pulse.

Besides that excessive negative pressures groundwater can drawn into the system. Funk et al. (1999) assessed the intrusion risk by evaluating the possible volume of intruding groundwater given transient duration and severity (minimum water hammer pressure).

Chapter three will deal more fully with the potential for pathogen intrusion during pressure transients.

2.2 HYDRAULIC TRANSIENT EVOLUTION

Figure 2 depicts how the transient, in general, evolves in a system. It represents a view of the transient at a fixed point (x) just upstream of the valve that is being shut. In this graph, the pressure, P, is represented as a function of time, t, resulting from the operation of a control valve. In the figure, P_i is the initial pressure at the start of the transient, P_f is the final pressure at the end of the transient event, P_{min} is the minimum transient pressure, and P_{max} is the maximum transient pressure (Elbashir & Amoah, 2007).

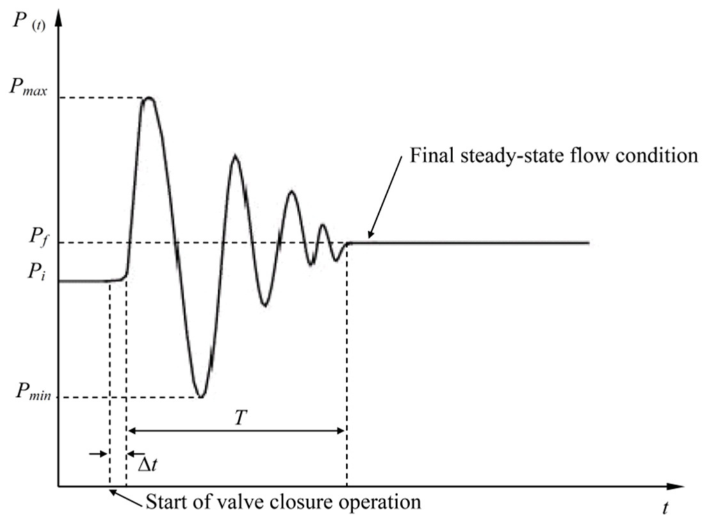


FIGURE 2: HYDRAULIC TRANSIENT AT POSITION X IN THE SYSTEM

SOURCE: Elbashir & Amoah (2007).

2.3 RIGID COLUMN AND ELASTIC COLUMN THEORIES

Transients in closed conduits are normally classified into two categories: slow motion mass oscillation of the fluid wich is referred to as surge, and rapid change in flow accompanied by elastic strain of fluid and conduit which is referred to as water hammer. For slow or small changes in flow or pressure the two theories yield similar results (Stephenson, 1984).

The rigid column theory usually involves mathematical or numerical solution of simple ordinary differential equations. The compressibility of the fluid and the elasticity of the conduit are ignored and the entire column of fluid is assumed to move as a rigid body (Tullis, 1989).

The elastic model assumes that changing the momentum of the liquid causes deformation in the pipeline and compression in the liquid. Because liquid is not completely incompressible, it can experience density changes. Based on these model assumptions, a wave propagation phenomenon will occur. The wave will have a finite velocity that depends on the elasticity of the pipeline and of the liquid (Walski & Koelle, 2003).

To generate equations describing the water hammer phenomenon, the unsteady momentum and mass conservation equations are applied to flow in a frictionless, horizontal and elastic pipeline. First, the momentum equation is applied to a control volume at the wave front following a disturbance caused by downstream valve action. The following equation was developed by Joukowsky in 1897/1989, which is applicable for wave propagation in the upstream direction:

$$\Delta p = -\rho a \Delta V \text{ or } \Delta H = -\frac{a}{g}\Delta V\,, \quad (1)$$

where:

$\Delta p =$ change in pressure (Pa);

$\rho =$ fluid density $\left({kg}/{m^3}\right)$;

$a =$ characteristic wave celerity of the fluid $({m}/{s})$;

$\Delta V =$ change in fluid velocity $({m}/{s})$;

$\Delta H =$ change in head(m).

The equations make intuitive sense in that a valve action causing a positive velocity change that will result in reduced pressure. Conversely, if the valve closes (producing a negative *V*), the pressure change will be positive.

By repeating this step for a disturbance at the upstream end of the pipeline, a similar set of equations may be developed for pulse propagation in the downstream direction:

$$\Delta p = \rho a \Delta V \text{ or } \Delta H = \frac{a}{g}\Delta V\,. \quad (2)$$

These equations are valid at a section in a pipeline in the absence of wave reflection. They relate a velocity pulse to a pressure pulse, both of which are propagating at the wave speed a. To be useful, a numerical value for the wave propagation velocity in the fluid in the pipeline is needed.

Assume that an instantaneous valve closure occurs at time *t*=0. During the period *L/a* (the time it takes for the wave to travel from the valve to the pipe entrance), steady flow continues to enter the pipeline at the upstream end. The mass of fluid that enters during this period is accommodated through the expansion of the pipeline due to its elasticity and through slight changes in fluid density due to its comprehensibility.

Equation 3 is generated by applying the conservation of mass equation to the entire pipeline for *L/a* seconds and combining it with the Equation (2) (Wylie & Streeter 1993):

$$a = \sqrt{\frac{\frac{E_V}{\rho}}{1+\frac{E_V \Delta A}{A \Delta p}}}\,, \quad (3)$$

where:

$a =$ characteristic wave celerity of the fluid $\left(\frac{m}{s}\right)$;

$E_V =$ bulk modulus of elasticity for the liquid(Pa);

$\rho = \text{fluid density} \left(\frac{\text{kg}}{\text{m}^3}\right)$;

$\Delta A = \text{change in cross} - \text{sectional area of pipe} \ (\ \text{m}^2)$.

For the completely rigid pipe, the sectional area of pipe doesn't change, i.e. *a* tends to infinity. For real, deformable pipelines, the wave speed is reduced, since a pipeline of area A will be deformed by a pressure change p.

The pressure wave generated by a flow control operation propagates with speed *a* and reaches the other end of the pipeline in a time interval equal to *L/a* seconds. The same time interval is necessary to reflect the wave to travel back to the origin, for a total of *2L/a* seconds. The quantity *2L/a* is termed the characteristic time for the pipeline. It is used to classify the relative speed of a maneuver that causes a hydraulic transient.

If a flow control operation produces a velocity change in a time interval (T_M) less than or equal to a pipeline's characteristic time, the operation is considered "rapid". Flow control operations that occur over an interval longer than the characteristic time are designated "gradual" or "slow". The classifications and associated nomenclature are summarized in the Table 1 below (Martin, 2000).

TABLE 1: TIME OPERATION

Operation Time	Operation Classification
$T_M = 0$	Instantaneous
$T_M \leq 2L/a$	Rapid
$T_M > 2L/a$	Gradual
$T_M >> 2L/a$	Slow

SOURCE: Martin (2000).

The characteristic time is significant in transient flow analysis because it dictates which method is applicable for evaluating a particular flow control operation in a given system. The rigid model provides accurate results only for surge transients generated by slow flow control operations that do not cause significant liquid compression or pipe deformation. Instantaneous, rapid, and gradual changes must be analyzed with the elastic model.

In 1848, Helmholtz demonstrated that wave celerity in a pipeline varies with the elasticity of the pipeline walls. Thirty years later, Korteweg developed an equation that allowed for determination of wave celerity as function of pipeline elasticity and liquid compressibility. When performing transient analyses today, an elastic model formulation with a correction to account for pipeline elasticity should be used (Walski & Koelle, 2003).

$$a = \sqrt{\frac{\frac{E_V}{\rho}}{1+\frac{DE_V}{eE}\Psi}}\,, \tag{4}$$

where:

$a =$ characteristic wave celerity of the fluid $\left(\frac{m}{s}\right)$;

$E_V =$ bulk modulus of elasticity for the liquid(Pa);

$\rho =$ fluid density $\left(\frac{kg}{m^3}\right)$;

$D =$ diameter (mm);

$e =$ wall thickness (mm);

$E =$ Young′s modulus for pipe material (Pa);

$\Psi =$ pipeline support factor .

Equation is valid for thin walled pipelines (D/e > 40). The factor Ψ depends on pipeline support characteristics and Poisson's ratio (μ), according to P-NB-591/1977 ABNT:

a) $\Psi = 1 - \mu^2$, if a pipe is anchored throughout against axial movement, $\Psi = 1 - \mu^2$, where μ is Poisson's ratio;
b) $\Psi = 1 - \mu/2$, if the pipe has functioning expansion joints throughout
c) $\Psi = 5/4 - \mu$, if the pipe is supported at only one end and allowed to undergo stress and strain both laterally and longitudinally.

For trick-walled pipelines, there are theoretical equations proposed to compute celerity; however, field investigations are needed to verify these equations.

The Continuity (5) and Momentum (6) Equations, governing flow of fluid in prismatic closed conduits under transient conditions (Lingireddy & Boulos 2005; Almeida & Koelle 1992; Wylie & Streeter 1993):

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0, \tag{5}$$

$$\frac{\partial H}{\partial x} = -\frac{1}{gA}\frac{\partial Q}{\partial t} + f(Q), \tag{6}$$

where:

$Q =$ flow rate ;

$H =$ pressure head;

$f(|Q|Q) =$ friction slope expressed as a funtion of flow rate;

$A =$ pipe flow area ;

$a =$ pipe celerity or wave speed,

$\text{g} = \text{gravitational acceleration},$

$\text{x and t} = \text{space} - \text{time coordinates}.$

The solution of these equations with appropriate boundary conditions will yield head and flow values in both spatial and temporal coordinates for any transient analysis problem. The above equations are first order hyperbolic partial differential equations in two independent variables, space and time (x and t) and two dependent variables, head ($H = H(x,t)$) and flow ($Q = Q(xt,t)$). The properties of the fluid and the conduit are included through celerity a. The full elastic water hammer equations cannot be solved analytically except by some approximate methods.

2.4 HYDRAULIC TRANSIENT MODELLING

Hydraulic transient studies began from the following investigations: propagation of sound waves in the air, wave propagation in shallow water and the blood flow in the arteries. Newton, in 1687, studied the sound wave propagation in air and water channels waves. Lagrange also contributed, together with Newton, to study the speed of sound in air. In 1759, Euler found a partial differential equation for the propagation of waves and developed a generic solution. Furthermore, in 1795, he tried to obtain the solution to the flow of blood in the arteries, with no success (Chaudhry, 1979).

The study of hydraulic transients is generally considered to have begun with the works of Joukowsky in 1898 and Allievi in 1902 with the Arithmetic Method, a method that neglects friction (Chaudry, 1979).

A number of pioneers made breakthrough contributions to the field, including R. Angus and John Parmakian in1963, who popularized and refined the graphical calculation method (Chaudry, 1979).

2.4.1 Eulerian and Lagrangian Approaches

Method of characteristic (MOC) and wave plan method (WPM) are two different methods to solve the continuity and momentum conditions. While MOC uses an Eulerian approach, WPM uses a lagrangian approach.

“The Eulerian approach reformulates the governing transient flow equations into total differential equations, which are then expressed in a finite difference form” (Wood et al., 2005). This approach is the most used and tested, with support for complex boundary conditions, friction and vaporous cavitation models (Jung et al., 2009).

MOC tracks disturbance in the time-space grid using a numerical method. The solution space comprises two equations called “characteristic equations” along with two compatibility equations for any point in a space-time grid. Compatibility equations are valid only when the characteristics equations are satisfied. MOC divides the entire pipeline into a predetermined number of segments, writes the characteristic and compatibility equations for every grid location and then solves these equations for head and flow at all grid locations. The line friction of the entire pipeline is distributed in each of these segments (Wylie & Streeter 1993, Streeter & Wylie 1967).

The Lagrangian approach to transient analysis is based on tracking the movement and transformation of pressure waves as they propagate with time throughout the WDS in an event-oriented environment. In this environment, the transient analysis problem is driven by distribution system pressure wave activities (Jung et al., 2009).

So, WPM tracks the disturbance based on wave propagation mechanics (Wood et al. 1966 and 2005). A pressure wave is also modified by the pipe friction. WPM consists essentially of two types of analyses called component analysis and junction analysis. Component analysis deals with the problem of transmission and reflection of pressure waves at a hydraulic device while junction analysis addresses the same problem at a pipe junction, a dead-end node, or a constant head reservoir. The entire line friction is modeled as an equivalent orifice situated at the midpoint of a pipeline or multiple orifices distributed uniformly throughout the pipeline (Wood et al. 2005).

According to Wood et al. (2005), both approaches:

- Assumes that a steady-state hydraulic equilibrium solution is available that gives initial flow and pressure distributions throughout the system;
- Obtain solutions at intervals of Δt at all junctions and components;
- Will virtually always produce the same results when the same data and model are used to the same accuracy.

These methods are used by many softwares around the world. Table 2 presents an overview about the most known of them.

2.5 STANDARDS AND HYDRAULIC TRANSIENTS

This section will address primarily the Brazilian Standards deal hydraulic transient issue and establish relations with international standards.

Currently the Brazilian standard that brings parameters for hydraulic transient analysis is the NBR 12215 - Water Main Design for public water supply.

According to NBR 12215, analysis of water hammer must be made for:

- New water main project;
- Existing installations which occur enlargements pressure changes or regime of flow in any section of the pipeline;
- Existing installations when changing operating conditions.

TABLE 2: SOFTWARES OF HYDRAULIC TRANSIENTS

Sotware	Created/ commercialized	Method	Price	Refence
Hammer	Bentley	MOC	~US$ 10,600	Bentley System, 2017
Surge	KYPIPE	WPM	~US$ 2,200	KYPIPE, 2017
Allievi	Universitat Politècnica de València	MOC	Free download in: http://www.allievi.net/allievi-es.php	Allievi, 2017
Wanda	Deltares (formerly: WL | Delft Hydraulics)	MOC	~ € 11,250	Deltares, 2017
AFT Impulse	Applied Flow Technology	MOC	~US$ 11,000	AFT, 2017
ITM	Univesity of Houston (Texas)	MOC	Free donwload in: http://www2.egr.uh.edu/~aleon3/ITM.htm	ITM, 2017
UFC6	Federal University of Ceara	MOC	Free	LAHC, 2017

The calculation of water hammer should be made in the normal operating conditions and the exceptional conditions. The **NORMAL** conditions are: a) proper functioning of protective devices and water hammer control provided; b) closing and opening maneuvers control valves and existing sectioning of the aqueducts; c) sudden interruption of pumping; d) start pumping; and e) simultaneous occurrence of sudden interruption of pumping condition in all lifts complex adduction system, for main booster. The **EXCEPTIONAL** conditions are: a) failure of any of the protective devices and control water hammer; b) inadequate maneuvers valves in accordance with the operating rules specified in the project; c) water main pipe breaks at maximum pressure section of steady state; and d) delayed closing of the check valve in the discharge of the pumps until the moment of maximum reverse speed, after stopping the pumping to pipeline booster.

The maximum pressures due to the water hammer supported by pipes, fittings, accessories and equipment, also called maximum allowable incidental pressures (MAIP), must be, according to NBR 15215, 1.5 times the maximum allowable pressure in static regime, i.e. the nominal pressure class, and the water hammer pressure of the system must be equal or below the MAIP. An overview of MAIP in international standards, expressed as a factor of the nominal pressure class is shown in Table 3.

Also, according to NBR 15215, in sizing blocks and pipes anchoring structures, fittings and equipments must adopt maximum pressure occurring in normal and exceptional conditions.

TABLE 3: OVERVIEW OF MAIP

CODE	MAIP
DVGW W303;1994 (German guideline)	1.00
ASME B 31.4 (1992), IS 328, BS 8010, ISSO CD 16708:2000	1.10
NEN 3650-1:2012	1.15
BS 806	1.20
Italian ministerial publication	1.25 – 1.50

SOURCE: Pothof & Karney (2012).

The minimum pressures due to water hammer that occur in any section of the pipeline should be larger than the allowable sub-atmospheric pressure. In normal operating conditions for any type of pipe and material used, the minimum permissible sub-atmospheric pressure is given by the absolute pressure of water vapor at room temperature minus the local atmospheric pressure. For thin-walled pipes, made of flexible material, the minimum permissible sub-atmospheric pressure is defined by the pressure of structural tube collapse if its value exceeds the permissible minimum pressure defined previously in any operating condition.

The **NBR 12215 standard** was actualized in November 2017 and now enables the designs to use other numerical methods besides the Method of Characteristics (MOC). Despite some sanitation companies already accept studies by the Wave Plan Method (WPM), the last standard version from 1991 just allowed the usage of the MOC.

2.6 PIPING SYSTEM DESIGN AND LAYOUT

When designing water distribution systems, the engineer needs to consider economic and technical factors. The pipeline system layouts should: (i) avoid high points that are prone to air accumulation or exposure to low pressures (or both); (ii) keep the minimum transient head grade line above the topographical profile of the piping system, because in this case the transient protection devices are most likely unnecessary; (iii) account for the occurrence of low transient pressures in low-head systems, to specify an adequate material; (iv) avoid vapor pressure conditions through surge protection measures; and (v) careful design when proposing piping above ground, because they are more susceptible to collapse than the buried pipelines, which the surrounding bedding material and soil provide additional resistance to pipeline deformations and help the pipeline resist structural collapse (Walski & Koelle, 2003).

To Jung et al. (2011) the WDS optimization should also consider, in addition to pipe size, the transient properties (e.g., operation speed), system characteristics (e.g., system topography, pipe material and thickness) and transient protection devices.

It is important highlight that though steel, PVC, HDPE, and thin-wall ductile iron pipes are susceptible to collapse due to vapor separation, any pipe that has been weakened by repeated exposure to these events may experience fatigue failure. A pipe weakened by corrosion may also fail (Walski & Koelle, 2003).

Pothof & Karney (2012) proposed a flow chart, Figure 3, about a systematic approach to pressure transient analysis integrating the design of anti-surge devices and distributed control systems. This approach applies in existing systems and each intervention Project.

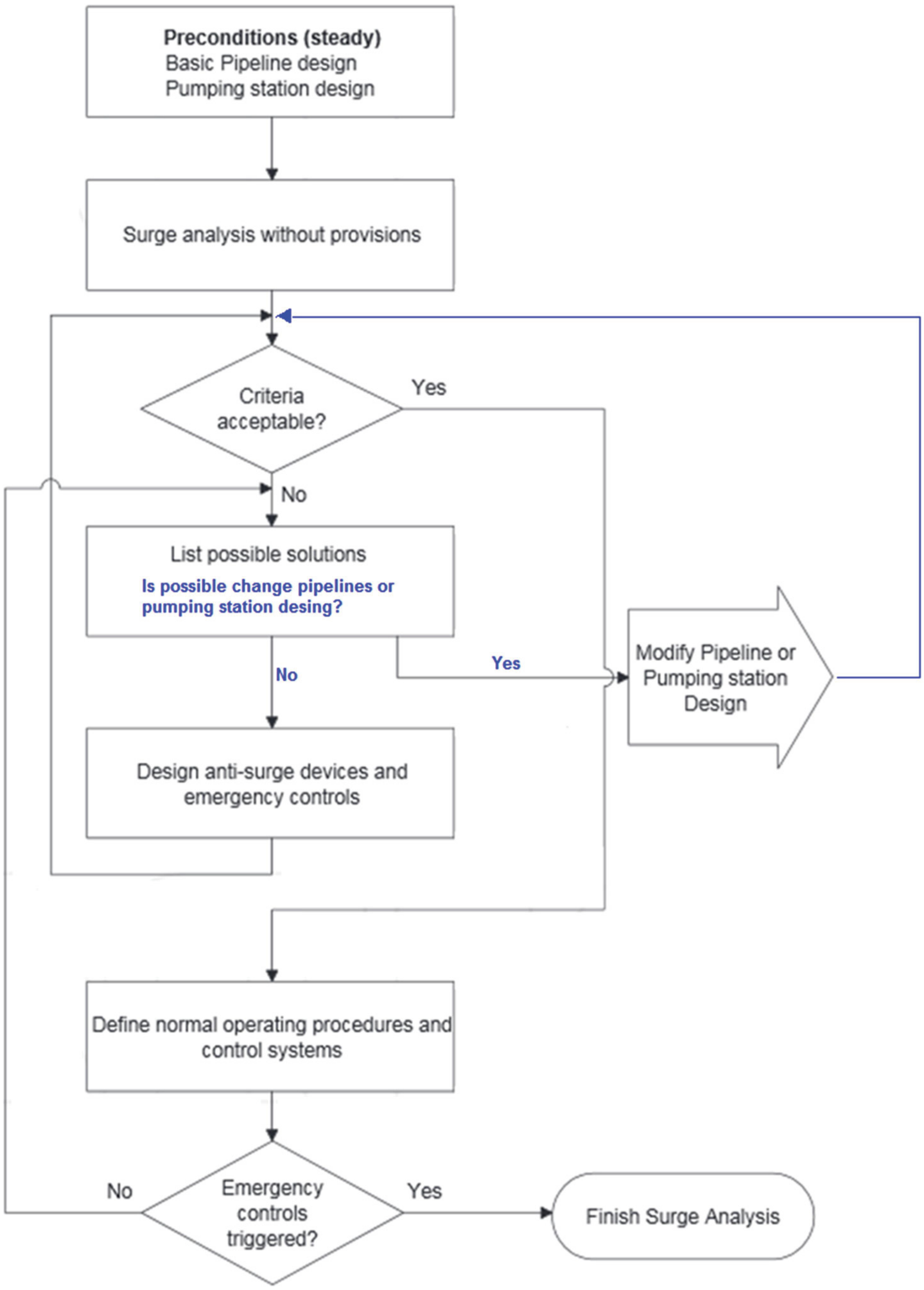


FIGURE 3: INTEGRATED DESIGN OF PRESSURE TRANSIENTS AND CONTROLS

SOURCE: Pothof & Karney (2012) adapted.

After considering these factors during the conceptual and preliminary designs of the system, the project should move into the final design phase. Any changes to the system during the final design should be analyzed with the transient model to verify that the previous analysis results and specifications are still appropriate (Walski & Koelle, 2003).

2.7 PRESSURE SURGE CONTROL DEVICES

Two possible strategies for controlling transient pressures exist. The first is to focus on minimizing the possibility of transient conditions during project design by specifying appropriate system flow control operations and avoiding the occurrence of emergency and unusual system operations. Some methods of transient prevention include: slow opening and closing of valves, proper hydrant operation, proper pump controls, through of ramping pump speeds up and down with soft starts or variable-speed drivers can minimize transients, lower pipeline velocity and others. The second is to install transient protection devices to control potential transients that may occur due to uncontrollable events such as power failures and other equipment failure (Walski & Koelle, 2003).

To control minimum pressures, the following can be adjusted or implemented:

- Pump inertia;
- Surge Tanks;
- Air-chambers;
- One-way tanks;
- Air inlet valves;
- Pump bypass valves.

To control the maximum pressures, the following can be implemented:

- Relief valves;
- Anticipator relief valves;
- Surge tanks;
- Air chambers;
- Pump bypass valves.

Because system components are tightly coupled, detailed economic analysis can be a complex undertaking. However, the net present value of anti-surge equipment may rise to 25% of the total costs of a particular system. Therefore, the systematic approach to the pressure transient analysis is preferably included in a life cycle cost optimization of the water system, because savings on investment costs may lead to operation and maintenance costs that exceed the net present value of the investment savings (Pothof & Karney, 2012).

2.7.1 Pump Inertia

Pump inertia is the resistance the pump has to acceleration or deceleration, and it's constant for a particular pump and motor combination. The higher a pump's inertia, the longer it will take the pump to stop spinning following pump shutoff. It they can help to control transients because it continues to move water through the pump for a longer time as they slowly decelerate. This behavior slows transient generation and can reduce the overall transient experience in a system with a short pipeline if the generation time is longer than the characteristic time (period) of the system. Pump inertia can be increased through the use of a flywhell. For long systems, the magnitude of pump inertia needed to effectively control transient pressures makes this control impractical due to the mechanical problems associated with starting high inertia pumps. Therefore, increasing pump inertia is not recommended as an effective option of controlling transient pressures for long piping systems (Walski & Koelle, 2003).

2.7.2 Air Valve

The suction is of great importance in reducing the amount of air present in the tubing. The trapped air, not properly removed, can cause serious damage to pipes and equipment. This is a very common problem that can cause ruptures in the pipeline, with major economic consequences (Chaiko et al., 2001).

Air-release/vacuum breaking valves are installed at high points in a pipeline to prevent low pressure (cavitation) by emitting air into the pipe when the line pressure drops below atmospheric conditions. The air is then expelled (ideally at a lower rate) when the line pressure exceeds atmospheric pressure (Boulos et al., 2005).

An air release valve used to control low-pressure transients should be designed to exhaust the air that was admitted to the system at a slow and controlled rate. If this air is allowed to discharge from the system at an uncontrolled rate, significant high-pressure transients can occur in the system at the air valve when the air is exhausted and the water column rejoins. Several cases of system failure due to inadequate air valve design have been documented. Additional air outflow control for low-pressure transient conditions can be obtained by utilizing a combination air valve that allows air to enter the system through a large orifice that closes during air outflow, forcing the air out of a small orifice air valve (Walski & Koelle, 2003).

According to Boulos et al. (2005) two-stage air valves release the air through a smaller orifice to prevent the “air slam” that occurs when all of the air is released and the water column rejoins, and a three stage air valve is designed to release the air through a second (smaller) orifice to further reduce the air slam.

According to the air valve manufacturer, BERMAD (see Figure 4a), the operation of the anti-surge air valve is as follows: a) During the filling process of a pipeline, high air flow is forced out through the kinetic orifice of the air valve; once water enters the valve’s chamber, the float buoyed upwards causes the kinetic orifice to close; the unique aerodynamic structure of the valve body and float ensures that the float cannot be closed before water reaches the valve; b) during pressurized operation of the pipeline, air accumulates in the upper part of the air valve chamber, causing the float to gravitate downwards, the automatic orifice opens in a two-step function, forming an air gap between the water level and the air release orifice and then releasing the accumulated air, while minimizing the spray effect, once the air is discharged, the water level and float rise, causing the automatic orifice to close; c) in the event of a pressure surge, the surge protection disc rises, partially closing the valve’s orifice, the approaching water column decelerates due to the resistance of the rising air pressure in the valve, this is typically used on pump stations and at specific pipeline locations to minimize pressure surges during pipe filling or power failure conditions at the pump station.

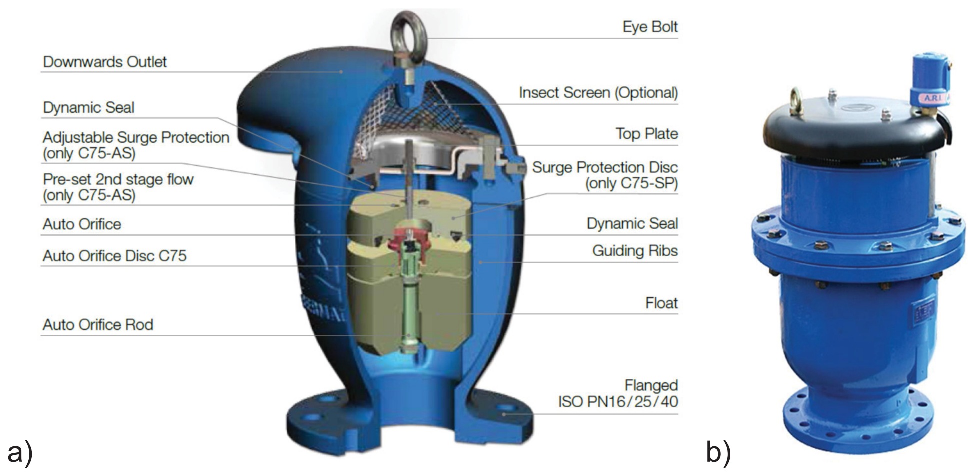


FIGURE 4: AIR VALVE
SOURCE: A) BERMAD (2017); ARI VALVES (2017).

According to the air valve manufacturer, ARI VALVES (see Figure 4b), the operation of the anti-surge air valve is as follows: a) when water, rapidly filling the pipe line, pushes the air out through the Air Valve, a differential air pressure is created across the valve orifice; b) when this differential pressure reaches a prefixed level (usually it will be prefixed at 0.02 - 0.03 bar) the orifice disc will close; c) air will continue to come out through the small orifice disc – until all the air will be exhausted and water will reach the kinetic float, it prevents the slam effect and therefore suppresses water hammer; when water reaches the kinetic float, it lifts it up, closing the kinetic orifice and completing the kinetic cycle; the vented Check Valve Orifice Disc will come back to its normal open position; when water is drained out of the pipe line, the resulting pressure drop lets the kinetic float fall down, opening the orifice fully for intake of high volume of air into the line.

Despite the effective role of air valves in air management, there are very little data about their frequency and efficiency of functioning, which is necessary information or better sizing and positioning and a more efficient application of air valves. Considering the operational and maintenance issues related to air valves, efficient application of such devices requires more broad-based research and development both in a theoretical context (e.g., understanding air valve physical behavior and modifying air valve numerical simulations) and in experimental or field studies (e.g., understanding air valve dynamic behavior and operational efficiency) (Ramezani et al., 2015).

2.7.3 Pressure-relief Valve

A pressure-relief valve ejects water out of a side orifice to prevent excessive high-pressure surges. The valve is activated when the line pressure at a specified location (not necessarily at the valve) reaches a preset value. Valve closure is initiated at a second prescribed head that is often about 20% lower than the activating head. The valve opens and closes at prescribed rates over which the designer often has some degree of control. The valves can eject water into the atmosphere, into a pressurized region, or into an open or closed surge tank (Boulos et al., 2005). One of the models of pressure-relief valve is represented in Figure 5.

According to Zhang et al. (2008), there are four design considerations for a PRV:

- The first defines the valve's location. In a high-pressure relief mode of operation, the PRV should be positioned so that high pressure and flow can be diverted around pressure-sensitive areas and excess flow can be discharged appropriately;
- An undersized PRV would be insufficient to protect a distribution system from extreme transient pressures. However, there is no point in oversizing a PRV because, beyond a certain point, there is little further improvement in its water hammer performance, even though its cost continues to increase;
- If the pressure set point is too extreme (i.e., too low for the low-pressure set point or too high for the high-pressure set point), the PRV will not adequately provide transient pressure control;

- If the PRV either opens too slowly or closes too quickly, it could cause dangerous occurrences of water hammer.

FIGURE 5: BERMAD PRESSURE RELIEF/SUSTAINING VALVE
SOURCE: BERMAD (2016).

2.7.4 Surge Anticipation Valve

A surge anticipation valve is much like a pressure-relief valve, but in addition it can be triggered to open on a downsurge in pressure (sensed at a specified location) in anticipation of an upsurge to follow. This valve, when activated, follows and completes a cycle of opening and closing based on valve opening and closing rates. For systems for which water column separation will not occur, the surge anticipation valve can solve the problem of upsurge at the pump caused by reverse flow or wave reflection. However, a surge anticipation valve must always be used with caution for it can make low-pressure conditions in a line worse than they would be without the valve (Boulos et al., 2005).

Care must be taken in setting the low-pressure activation point to avoid premature opening before the pump has spun down, which can cause a very steep negative transient wave (Walski & Koelle, 2003).

2.7.5 Open Surge Tank / Standpipes

Open surge tanks are protection devices that can relieve both excess and minimum transient pressures. The simplest form of open surge tank is a vertical standpipe connected to a pipeline. When pressure in the pipeline increases, the water level in the surge tank increases and when pressures in the pipeline decrease the surge tank provides a supply of water to reduce the minimum pressures. Transient pressures are dampened out by fluid friction as the water level in the tank fluctuates up and down. Because they are open, this type of surge tank must be designed sufficiently tall so that it will not overflow (Radulj, 2010).

So, these tanks can be installed only at locations in which normal static pressure heads are small (Boulos et al., 2005). Figure 6 shows a scheme of this tank and a real tank implanting in the water system of Curitiba, Parana, Brazil.

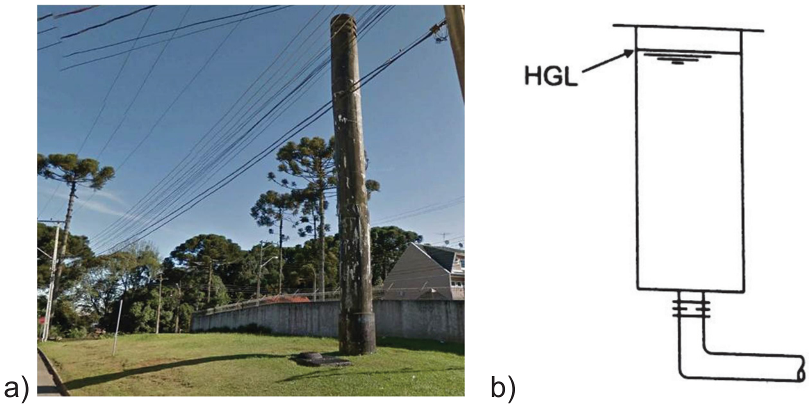


FIGURE 6: OPEN SURGE TANK

SOURCE: b) Walski & Koelle, 2003.

2.7.6 Feed Tank/One-way Tank

The purpose of a feed tank is to prevent initial low pressures and potential water column separation by admitting water into the pipe subsequent to a downsurge. Feed tanks can be either open or closed and can be installed anywhere on the line (Boulos et al., 2005). A scheme of feed tank in presented in Figure 7.

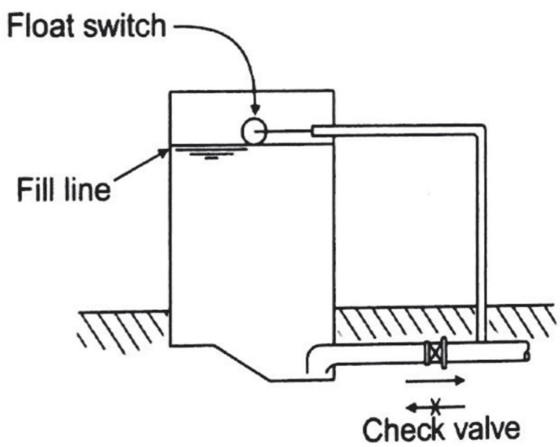


FIGURE 7: FEED TANK

SOURCE: Walski & Koelle, 2003.

A one-way tank is a storage vessel under atmospheric pressure that is connected to the system with a check valve that is normally closed and only allows flow from the tank into the system. When a low-pressure transient in the system reaches a one-way tank that has a greater head than the low-pressure transient, the tank check valve opens to feed water from the tank into the system. This action controls the magnitude of the low-pressure transient. After the tank discharges into the system, a float switch triggers the opening of a valve to refill the tank from the system through a separate connection. The significant advantage of using a one-way tank rather than a surge tank is that the check valve allows the one-way tank to have a much lower height (Walski & Koelle, 2003).

2.7.7 Surge Vessel, Air Chamber, Closed Surge Tank or Hybrid Tank

Air vessels, also known as closed surge tanks, are effective in protecting the distribution system against negative as well as positive pressures and are widely used in water distribution systems (Ramalingam, 2007). Several types of surge vessels are available:

A) Compressor (air) vessel

As known as Hydropneumatic tank, this vessel is equipped with a compressor to maintain the desired initial water level (and air volume) under normal operating conditions (Boulos et al., 2005). Figure 8 shows a scheme of this tank and a real tank implanting in the water system of Pinhais, Parana, Brazil.

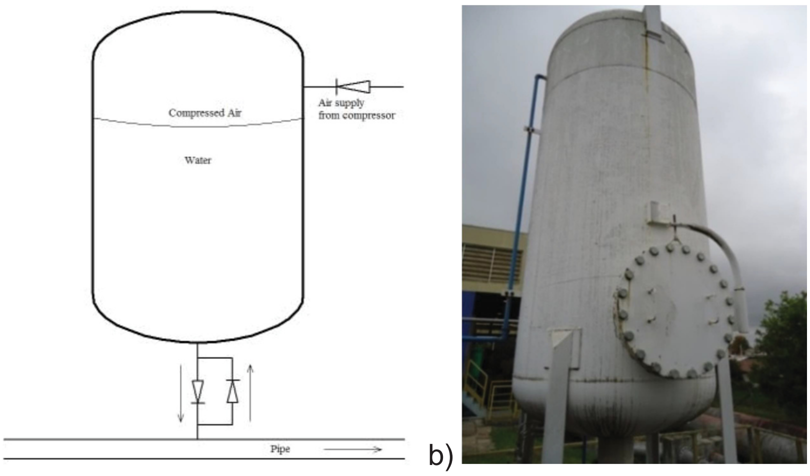
a)


FIGURE 8: COMPRESSOR VESSEL TANK

SOURCE: Ramalingam, 2007.

B) Bladder tank

This vessel has a bladder that is precharged to a predetermined pressure to maintain the desired air volume under normal operating conditions.

A pre-charge pressure is calculated to give the required elasticity to push the water into the system following a pump trip. As there is no contact between the compressed air and the water, there is no dissolution. Thus, there is no requirement for a permanent regulation system including compressors, etc. Once the vessel has been commissioned and the correct pre-charge has been introduced, the vessel will operate automatically, emptying when called upon and refilling with the return waves until naturally reaching its steady state balance (Charlatte, 2016).

The vessels can be installed either horizontally or vertically. Figure 9 presents an example of vertical vessel. There are several brands that market bladder tanks, such as: Bermad, Ari / Charlatte and Hydroballs.


a)

b)

FIGURE 9: BLADDER SURGES

SOURCE: a) CHARLATTE RESERVOIR, 2017; b) BERMAD, 2017.

The operation of Charlatte and Bermad tanks are similar (see Figure 10):

1. Initially, the pre-charge pressure must be adjusted to the value resulting from the hydraulic analysis (pre-charge can be either compressed air or nitrogen). At this stage, the bladder contains no volume;

2. When the gate valve is opened, the water will enter the vessel under static conditions and begin to compress the gas (static pressure is always higher than pre-charge pressure);

3. The water entering the vessel will further compress the pre-charged gas until a balance between the liquid and the compressed gas is reached. The bladder’s internal and external pressures are always equal; enabling inbound and outbound flows of water as needed;

4. Immediately after a pump trip, the pressure in the line will start to decrease and the elastic energy in the vessel will cause the discharge of water from the vessel into the line. This prevents dangerously low pressure along the pipe;

5. As the pressure may become very low, the flow will reverse. Water will then enter into the vessel via a reduced diameter (drilled non return valve or bypass) if hydraulically required. Several oscillations may occur before static state is reached;

6. When the pump restarts, the vessel will continue to fill until dynamic steady state is reached and it is then once again prepared for the next pump trip.

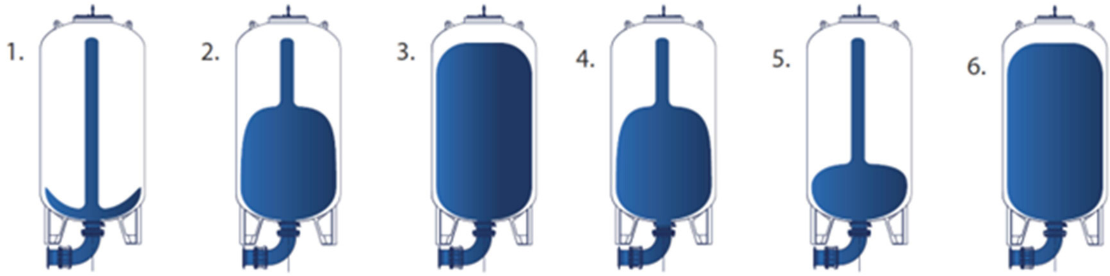


FIGURE 10: ILLUSTRATION OF AN OPERATION BLADDER SURGE
SOURCE: CHARLATTE RESERVOIRS, 2017.

The HYDROBALLS ® tank operates with many inflated spheres or balls, made of special polymer, that are inserted into the tank. The number of spheres and its inflating pressure are determined by the characteristics of each discharge line. Figure 11 shows a scheme of this tank and a real tank implanting in the water system of Maringa, Parana, Brazil.

The dynamic of the response to the water-hammer by HYDROBALLS ® uses the same physical concept as the other types of hydropneumatic tanks or water-hammer arrestors. When the pipe is filled with water, the air inside the balls is compressed a bit. When the water-hammer occurs caused by a pump shut off, the pressure drops in the beginning of the line and therefore inside the hydropneumatic tank. This provokes the balls to expand, injecting water to the pipe and reducing the fall-off in the pressure. Then, when the over-pressure follows, the water enters the tank compressing the spheres (Hydroballs, 2016).

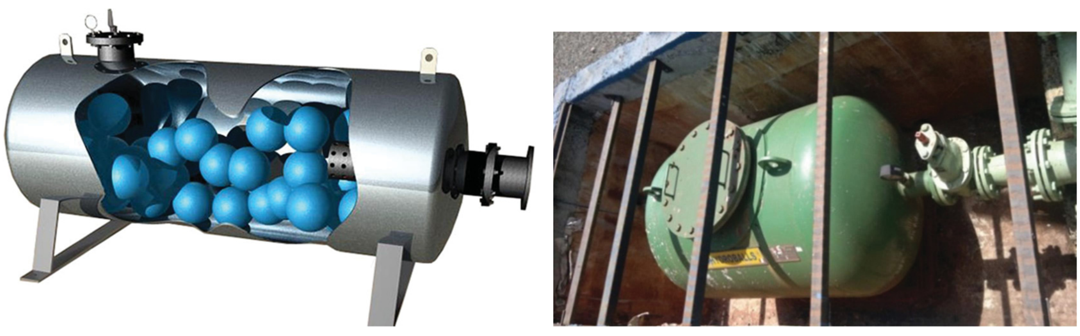


FIGURE 11: HYDROBALL BLADDER SURGE
SOURCE: A) HYDROBALL, 2017.

C) COMBINED DEVICES

If an air clamber has an air inlet valve installed on top of it, it can double as a one-way tank. This combined device admits air into the clamber during an extreme low-pressure transient and acts as an air cushion during a high pressure transient to control maximum pressure. In some cases this combination protection device allows the size of the air chamber to be optimized. The combined protection device can allow the use of a smaller air chamber sized for "normal" low-pressure transients, but it can still protect the system against "extreme" low-pressure transients when the volume of air in the chamber is insufficient (Walski & Koelle, 2003).

2.7.8 Booster Pump By Pass

In low-head pumping systems that have a positive suction head, a bypass line around the pumps can be installed to allow water to be drawn into the discharge line following a power failure and a downsurge. Bypass lines are usually short pipe segments equipped with a check valve preventing backflow (from the pump discharge to the suction side) and installed parallel to the pump in the normal flow direction. They are activated when the pump suction head exceeds the discharge head and are useful for two reasons: to prevent high-pressure buildup on the pump-suction side, and to prevent cavitation on the pump-discharge side (Boulos et al., 2005)

The bypass can open to transfer water from the upstream pipeline to the downstream pipeline, which helped to attenuate or control the maximum and minimum pressure transients on the upstream and downstream sides of the station. If the low-pressure surge generated on the discharge side of the pump is still greater than the high-pressure surge generated on the suction side of the pump, the bypass will not open (Walski & Koelle, 2003).

3 REFLECTIONS ON RELEVANCE OF HYDRAULIC TRANSIENTS

"An adequate water supply (in terms of availability and quality) is vital to performing many daily tasks, and disruptions to a water supply through planned maintenance or leakage repairs can cause significant problems" (White, 2013).

This chapter focus is given for assessing the main philosophical aspects associated with hydraulic transient.

3.1 HYDRAULIC TRANSIENTS IN WDS

According to Karney & Mc Innis (1992) it has been recognized for many years that long pipelines of large diameter may experience severe transient loading. Despite this, there is a feeling among practitioners that networks are somehow intrinsically more robust than series pipe systems. For them, this assumption is troublesome, and the dynamic character of these critical systems should not be rationalized away on potential faulty notions of conservatism.

Starczewska et al. (2014), in a hydraulic transient study in Yorkshire Water Ltd, analyzed the high-resolution pressure data obtained from different points in a complex water distribution network and found that pressure transients can propagate throughout WDS (and remain clearly distinguishable from background features), highlighting that opposite belief that the complexity of the systems damps and dissipates the transients. It was assessed that in some cases network configuration may lead to transient amplification.

Figure 12 summarizes the overall strategy used by modelers and water managers to evaluate the system response considering complete and skeletonized sizing. While the complete system uses literally all pipes that constitute it, skeletonizaton is the process of representing a water network by only selected pipes.

Skeletonization techniques, derived from hydraulic equivalency theory (Jung et al., 2007), have been used to reduce the size and complexity of theses systems and generate smaller skeletonized models an normally are adequate for master planning and energy studies. However, because of branches and loops, distribution system responds differently than transmission lines, and excessive pressures surges can be present in distribution piping. The rules of skeletonization ignore the inherent problem of interaction of the surge waves in different components and the pipe properties of a water distribution system. At pipe junctions and dead-end branches, wave reflections and transmissions occur, which often magnify or attenuate the impinging surge waves. Furthermore, wave speed is a function of pipe material, diameter, and thickness (Jung et al., 2007).

Besides Jung et al. (2007), these pitfalls of traditional steady-state based skeletonization and decomposition for transient models have been investigated and analyzed by many researchers in the literature (e.g., Walski et al. 2004; Ebacher et al. 2011). These researches demonstrated that the accuracy of transient simulation results can be affected by inappropriate system skeletonization and decomposition, such that detailed representative models remain essential to accurately determine transient pressure extremes.

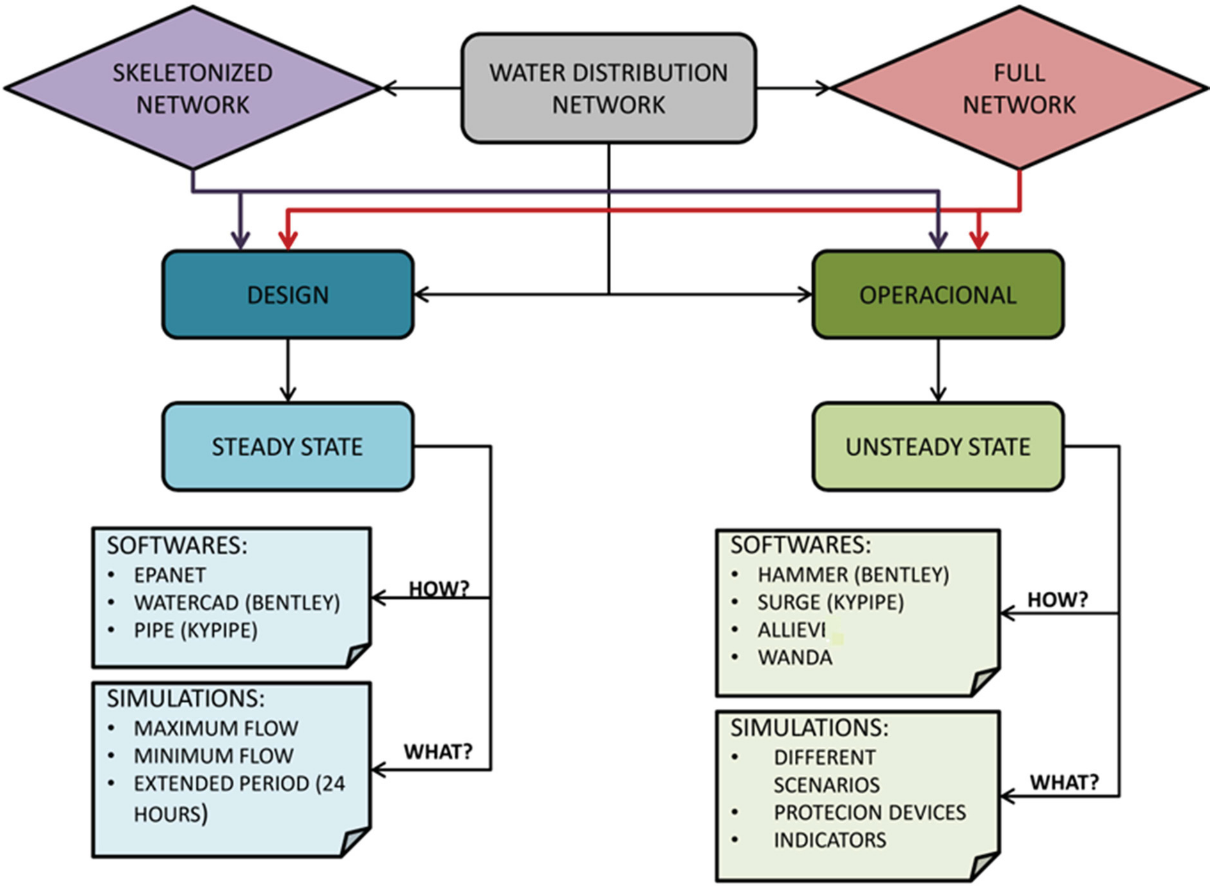


FIGURE 12: FLOWCHART WATER DISTRIBUTION NETWORK

The choice of appropriate modeling strategy is a challenging task, especially because sizing is composed by design and operational characteristic that have strong influence. The adequate design sizing provides conditions to supply water, under steady state conditions during 24 hours of the day in quantity and quality needed. The common softwares are: EPANET (EPA, 2017), WATERCAD (Bentley, 2017), PIPE (KYPipe, 2017) and others.

On the other hand, under unsteady flow conditions, for simulating operational sizing the following softwares have been used (Table 2) as presented in Chapter 2.

Additionally, the connection between hydraulic transient and leakage detection has been deeply studied. According to Colombo et al. (2009) it is possible to identify the leak comparing the pressure signal registered by monitoring devices relative to the signal that would be observed if the system did not contain the leak or singularity. As a high-pressure wave passes, the leak causes some attenuation in the primary transient signal by permitting escape of some pressurized fluid. Despite all have bestowed upon the technique some measure of approval, up to now, little field testing has been reported in the literature. An important issue is that leaks do in fact provide a degree of transient protection and fixing them removes some of this benefit, then a well-thought program to fix leaks should explicitly address transient phenomena.

3.2 POTENTIAL FOR PATHOGEN INTRUSION DURING PRESSURE TRANSIENTS

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 (Collins & Boxall, 2013).

Lindley & Buchberger (2002) 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 contaminant source.

Intrusion may result from water pressure fluctuations in pipes. 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 (LeChevallier, 1999).

Karim et al. (2003) 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).

Fontanazza et al. (2015) conduced an experimental procedure that analysed the risk of contamination in two cases: intermittent water and transient. It was showed that both can allow a large amount 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 pressurisation 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 amount 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.

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 (McInnis, 2004).

Fernandes & Karney (2004) provided a comprehensive description of the mathematical solution of hydraulic transients with intrusion and advection.

4 HYDRAULIC TRANSIENT INDEXES

“With modern computer techniques it is possible to analyze distribution systems under a wide range of flow conditions and with relatively few restrictions”. (Karney & McInnis, 1990)

4.1 MODELING AND SIMULATION

According to the Walski & Koelle (2003), the use of computational models to carry out the transient analysis of a hydraulic system requires the following:

- Obtain accurate information about equipment and system operations;
- Determination of the operational characteristics of the system flow control equipment and transient protection devices;
- Verification of the operational limitations of flow control equipment and transient protection devices.

Hydraulic transient analysis was made by Method of Characteristics (MOC) with the support of the Hammer software by Bentley. Hammer is one of the most known and validated software in the world and the author had acess to it through the Sanitation Company of Parana.

Hammer provides a wide range of rotating equipment (pumps and turbines) and protection devices (as surge tank, hydropneumatic tank, pressure relief valve, surge anticipation valve, air vales) and perform an unlimited number of operating scenarios to develop the most appropriate strategy for surge mitigation (Bentley Systems, 2017).

With HAMMER, users can employ this product as a stand-alone application or work from within ArcGIS, MicroStation, or AutoCAD. Besides that, users can import your network data from EPANet and the included LoadBuilder and TRex modules help engineers allocate water demands and node elevations based on geospatial (Bentley Systems, 2017).

For information on equipment and system operations, information recorded in Sanepar systems will be used and field surveys will be carried out. The Sanepar operational control center has information on the constants of the inlet and outlet of each reservoir, reservoir levels and operating time and frequency of pumps, and pressure at the outlet of elevations.

During the simulation of hydraulic transient was used the flowchart for surge control in water distribution systems proposed by Boulos (2005) and represented in Figure 13. It represents the steps to be followed to make the system protected from surges, starting with the specification of system and fluid characteristics and analyzing if the transient can be modified, if the system can be modified and if the surge control devices can be used.

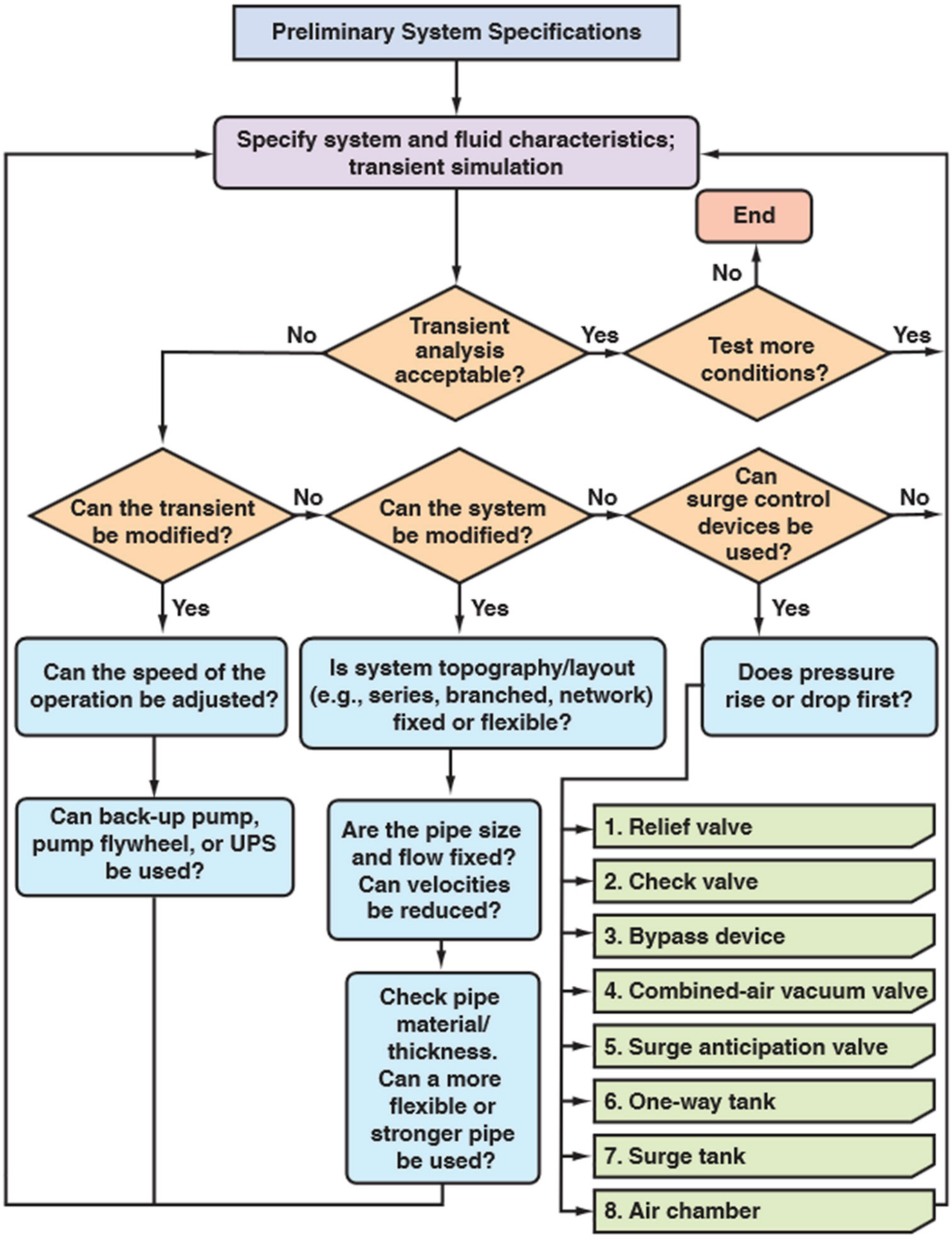


FIGURE 13: FLOWCHART FOR SURGE CONTROL IN WDS

SOURCE: Boulos et al. (2005).

4.2 INDEXES

To decide which system characteristics or protection devices are better in a water distribution system, it can use metrics to analyze the transient pressures quantitatively.

Table 4 summarizes some of the metrics used to quantify the severity of transient events. All these metrics are associated with maximum and minimum transient pressures occurring in the system.

TABLE 4: METRICS - SEVERITY OF TRANSIENT PRESSURES

Author	Index	Definitions of variables	Comments
Friedman el al. (2004)	Intrusion potential	Total number of nodes experiencing negative pressures and total time when those nodes experience negative pressures.	To determine severity of surge and intrusion potential during transient events.
Jund and Karney (2006)	H_{max} - H_{min}	H_{max} and H_{min} = maximum and minimum pressures, respectively	To minimize difference between maximum head and minimum head during transient events
Jung and Karney (2011)	$SPDF = \int_{ieN_{node}} H_i dt$	H_i= pressure at each node either > H_{max} (maximum allowable pressure) or < H_{min} (minimum allowable pressure)	Surge damage potential factor (SPDF) to determine likelihood of damaging transient event
Martin (1983)	$S = \frac{T_{SC} a}{2L}$	S= severity of cavity index; T_{SC}=duration when cavity occurs	To determine severity of cavitation during transient events
Radulj (2009)	$TRI^{+} = \int_{0}^{T^{+}} P_{maz} dt$ $TRI^{-} = \int_{0}^{T^{-}} P_{min}\, dt$	TRI^{+} and TRI^{-}= positive and negative transient risk index, respectively; $T^{+}$and T^{-}= maximum return period from data set-associated maximum and minimum pressures, respectively (days).	To quantify risk assessment associated with hydraulic transient.
Shinozuka and Dong (2005)	$D = \frac{H_2 - H_1}{t_2 - t_1}$	D=damage index; H_2 and H_1=pressure heads at a node at time t_1 and t_2, respectively	To locate damaged pipe or malfunctioning equipment when water system exhibits acute transient behavior.

SORCE: Ghorbanian et al. (2016)

Jung and Karney (2006) propose a method to optimize the preliminary selection, sizing and placement of hydraulic devices in a pipeline system in order to control its transient response, which the global optimal solution is sought using both genetic algorithm (GA) and particle swarm optimization (PSO) approaches involving an unknown combination of hydraulic devices to cope effectively with water hammer conditions. In this study, three simple objective functions were considered: (1) to minimize the maximum head; (2) to maximize the minimum head; and (3) to minimize the difference between the maximum head and minimum head in the system. Several case studies are tested numerically using different protection strategies. Significantly, in this case, any of these choices effectively targets the transient envelope of the response and thus produces similar outcomes and decisions in the test system. The study shows that the integration of a GA or PSO with a transient analysis technique can improve the search for hydraulic protection devices in a pipe network and that the selection of an optimum protection strategy is an integrated problem, involving consideration of loading conditions, device and system characteristics, and protection strategy.

Shinozuka & Dong (2005) studied transient system behaviors resulting from pipe damage and equipment malfunction due to natural and manmade hazards including terrorist attack, using the method of rapidly detecting and locating the damage/malfunction in a water delivery system taking advantage of sharply transient change in hydraulic parameters such as water head and flow rate under disaster events. For this purpose, was used code HAMMER in an ARC/GIS platform so that the inventory, operational, and management features can be integrated into the transient analysis all at the outset. They demonstrated by numerical simulation that the local water head gradient, for example, can serve as key signature in finding the source of damage/malfunction. The proposed technology will serve as a next generation of the SCADA (Supervisory Control and Data Acquisition) system. Current generation of SCADA system that the utility industry deploys primarily for the purpose of system operation, not for rapid response to acute transients resulting from severe damage sustained by pipes, sudden stoppage of pump operation, and the like. In this study the $t_2 - t_1 = 0.2$ second.

Radulj (2009) proposed a preliminary transient risk assessment methodology, the Transient Risk Index (TRI). The goal of a TRI is to assess the cumulative risk of all transient events for a pressure monitoring period and to then ideally extend this to the complete lifespan of a system. The basic notion here is that small magnitude transient events (both positive and negative) occur frequently but with lower consequence, and that large magnitude transient events (both positive and negative) occur infrequently but with high consequence. Unlike in the case of a traditional risk analysis, it is not only the rare and high consequence event that presents a risk to the system, but actually it is the combined effect of all events. While the TRI is likely not the only viable metric or approach, system indices such as these are very simple to understand, benchmark, and compare, and are therefore quite useful for understanding the transient performance (and therefore the risk) of a system. The proposed TRI methodology is intended to provide a simple and easy method for determining the degree of the overall transient pressure risk, quantitative in nature, for water and wastewater systems. More importantly, it is intended to provide a simple link and understanding between continuous transient pressure monitoring and a risk assessment. Having said that, the concept, methodology and definitions for the TRI are still in their preliminary stage, and the TRI may end up simply being used as a stepping stone for more comprehensive (yet still quantitative in nature) hydraulic transient risk assessments. The Figure 14 presents a generic graphical representation of a possible TRI.

.

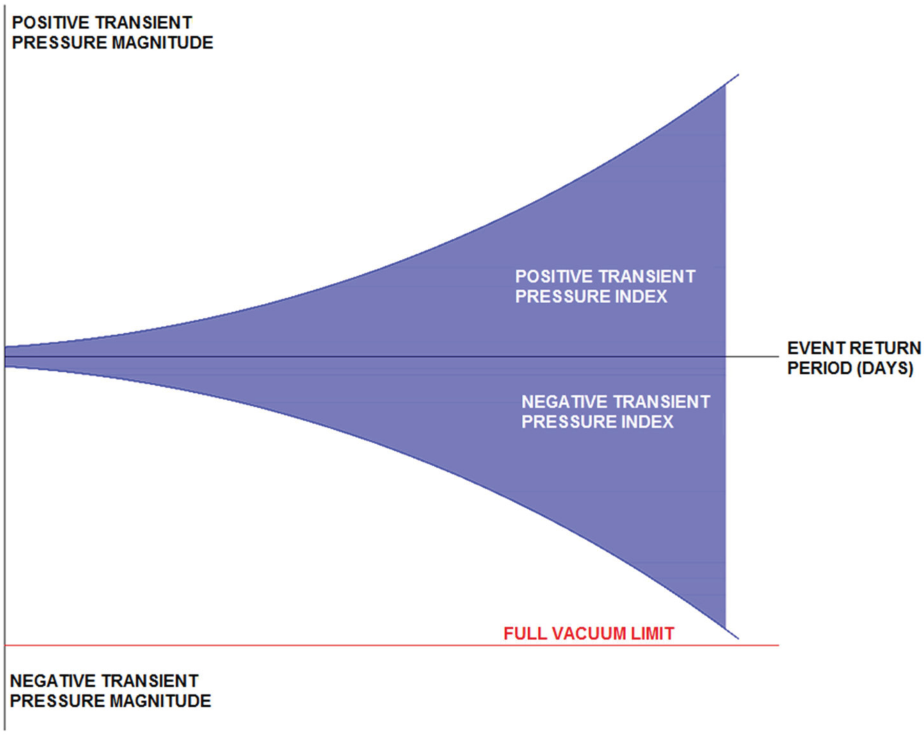


FIGURE 14: EVENT RETURN PERIOD

SOURCE: Radulj, 2009.

Jung & Karney (2011) in order to determine an optimal WDS design and minimizing the effects of a transient event proposed an index called Surge Damage Potential Factor (SDPF). The SDPF is the integration of the transient pressures that are lower than the minimum level or higher than the maximum level. These levels are determined by the user as a percentage of over and under pressure regarding the initial steady state pressure.

Martin (1983) introduced the cavitation severity index $S = T_{cs}a/(2L)$, inferring the cavitation duration, T_{cs}.

Friedman et al (2004) confirmed that negative pressure transients can occur in the distribution system and that the intruded water can travel downstream from the site of entry. Locations with the highest potential for intrusion were sites experiencing leaks and breaks, areas of high water table, and flooded air-vacuum valve vaults.

In this study the metrics shown was applied in simulations of pressure zones of a real water distribution system with some modifications and/or adaptations, like shows the Table 5.

To calculate some indicators, it was created a program in RSTUDIO that is a free and an open-source integrated development environment for R, a programming language for statistical computing and graphics. This program imports output files from the transient hydraulic simulation program, Hammer, calculates the indicators C1, C2, C6 to C9 and C12, and creates a text file with the results. The graphs and other indicators were made in Excel.

TABLE 5: METRICS TO QUANTIFY THE SEVERITY OF TRANSIENT PRESSURES

Risk	Index	Author	Code	Definitions of variables	Adaptations
Risk assessment associated with negative pressure	Intrusion potential	Friedman et al. 2004	C1	Number of junctions with pressure < 0 mH_2O	No changes
		Friedman et al. (2004) adapted	C 2	% of junctions with pressure < 0 mH_2O	This index was created to represent the % of junctions with pressure below zero.
	Cavitation		C 3	Number of junctions with vacuum pressure	This index was created to represent the number of junctions with vacuum pressure.
			C 4	Total time cavitation	This index was created to represent the sum of duration when cavity occurs in each junction.
	Severity of cavity index	Martin (1983)	C 5	$S = \frac{T_{SC} a}{2L}$ S=severity of cavity index; a=celerity; TSC=duration when cavity occurs; L=length	The index was applied in each junction with vacuum pressure, and it was summed to get the system severity of cavity index.
	Surge Damage potential factor (SPDF)	Jung and Karney (2011) adapted	C 6	$SPDF^- = \frac{\int_{ieN_{node}} H_i dt}{junctions}$ Hi = pressure at each node either <Hmin (min allowable pressure)	The adaptation was to separate the positive and the negative part of the function and divide by the number of junction to make the number easier to compare.
Risk assessment associated with positive pressure			C 7	$SPDF^+ = \frac{\int_{ieN_{node}} H_i dt}{junctions}$ Hi = pressure at each node either > Hmax (allowable pressure)	
Risk assessment associated with negative and positive pressure			C 8	$SPDF = \frac{\int_{ieN_{node}} H_i dt}{junctions}$ Hi > Hmax or <Hmin	
	Pressure range	Jung and Karney (2006)	C 9	ΔP = Hmax - Hmin maximum and minimum pressures	No changes
	Hmax		C10	Minimum Pressure	Created to evaluated the maximum and the minimum pressure
	Hmin		C11	Maximum Pressure	
	Positive and negative transient risk index	Radulj (2009) adapted	C12	$TRI^- = \frac{\int_0^{T^-} P_{min} dt}{junctions}$	The adaptation was to divide by the number of junction to make the number easier to compare.
			C13	$TRI^+ = \frac{\int_0^{T^+} P_{maz} dt}{junctions}$	
Risk assessment associated with rapid change of pressure	Damage index	Shinozuka and Dong (2005)	C14	$D = \frac{H_2 - H_1}{t_2 - t_1}$ D = damage index H2 and H1 = pressure heads at a node at time t1 and t2, respectively	The adaptation was to apply the index in the results of the simulation and not in an actual system pressure measurement.

5 CADE SUDIES

“Knowing is not enough; we must apply. Wishing is not enough; we must do.” (Johann Wolfgang Von Goethe)

5.1 THE COMPANY

The Water Distribution Network that is being studied belongs to Sanitation Company of Parana (Sanepar), headquartered in Curitiba (see Figure 15), and it was created on January 23, 1963. The company provides services for supplying the population with treated water, collection services and treatment of sanitary sewage, and also of selective collection and disposal of solid waste.

FIGURE 15: CURITIBA LOCATION

Currently with 345 municipalities in Paraná State and 1 in Santa Catarina State, the Company benefits 10.8 million people with water and 7.1 million with sewage services. Sanepar has 164 water treatment plants, 239 sewage treatment plants, around 84.600 kilometers of water and sewage pipes and more than 7,000 employees. The company is a reference in the sanitation sector in the country due to its operational efficiency, its economic results and its solid socio-environmental policy (SANEPAR, 2016).

5.2 THE SYSTEM

The area under study belongs to the Water Supply System of Curitiba and Metropolitan Region, named SAIC.

In addition to the state capital, SAIC comprises part of the municipalities of the Metropolitan Region of Curitiba, which are Almirante Tamandaré, Araucária, Campina Grande do Sul, Colombo, Fazenda Rio Grande, Pinhais, Piraquara, Quatro Barras and São José dos Pinhais.

The Metropolitan Region of Curitiba was created in 1974, initially composed of 14 municipalities. It currently has 29 municipalities, as shown in Figure 16, and the area covered by the SAIC is delimited by a dashed line. The following is an expanded view of the municipalities served by the SAIC.

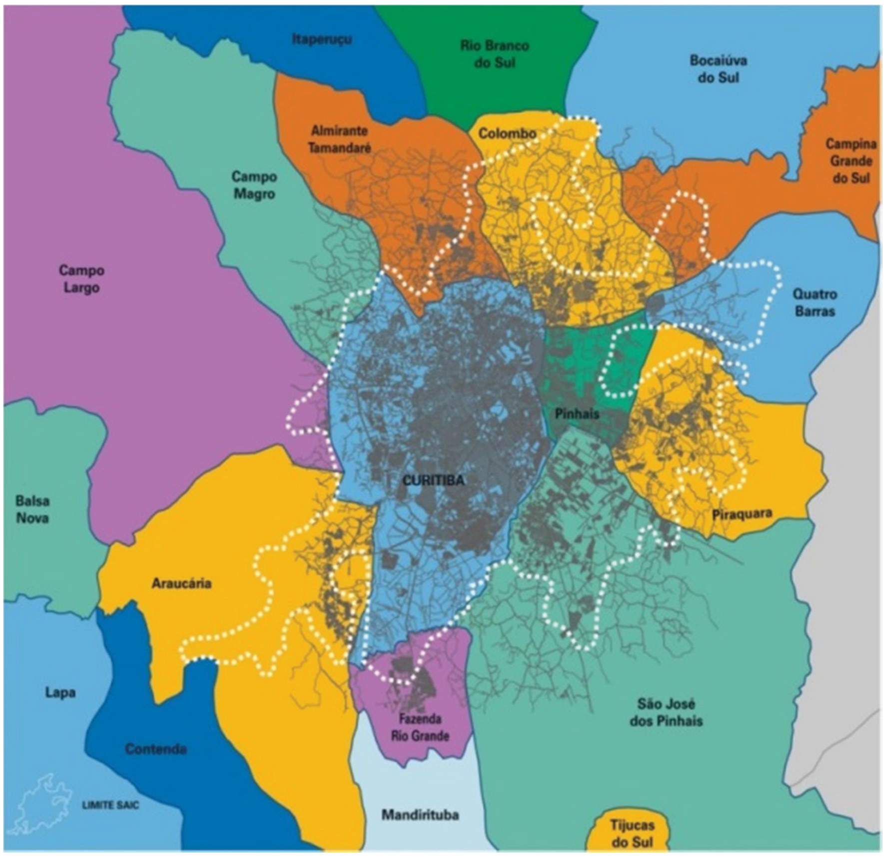


FIGURE 16: WATER SUPPLY OF CURITIBA AND METROPOLITAN REGION
SOURCE: SANEPAR (2013)

The current production and treatment system is around 9.9 m³/s. After the treatment, the water is sent to around 50 existing reservation centers, being in all 377.650 m3 reserved. There are currently 160 pressure zones serving 3.5 million people.

5.3 THE NETWORK WATER

The water distribution network to be studied is the network supplied by the Reservoirs supported Vila Amelia and Alphaville and the Reservoir Elevated Alphaville, which are located in the city of Pinhais, and as mentioned belong to the Integrated Water Supply System of Curitiba and Metropolitan Region.

These reservoirs receive water from the Irai Water Treatment Plant (Figure 17). From the Iraí System water is pumped to the Piraquara, Guarituba Redondo, Cajuru, Jacob Macanha and Vila Amélia reservoirs (Pinhais).

FIGURE 17: IRAI WATER TREATMENT PLANT
SOURCE: SANEPAR (2016).

The transportation of water to the Vila Amélia reservoir is done with on-the-go distribution through ductile ducts DN 400 and DN 300. From this reservoir, the Reservoir Supported: Alphaville is supplied by a DN 200, which supplies the Elevated Reservoir Alphaville.

Figure 18 below shows the networks that will be part of the study, and the identification of the pressure zones of the study. Being:

- RVAM: network supplied by the Vila Amelia Reservoir by pumping;
- GAAV: network supplied by Reservoir Supported Alphaville by gravity;
- GEAV: network supplied by the Elevated Reservoir Alphaville by gravity.

The Figure 19 shows the network`s topology in the software, with junctions and pipes.

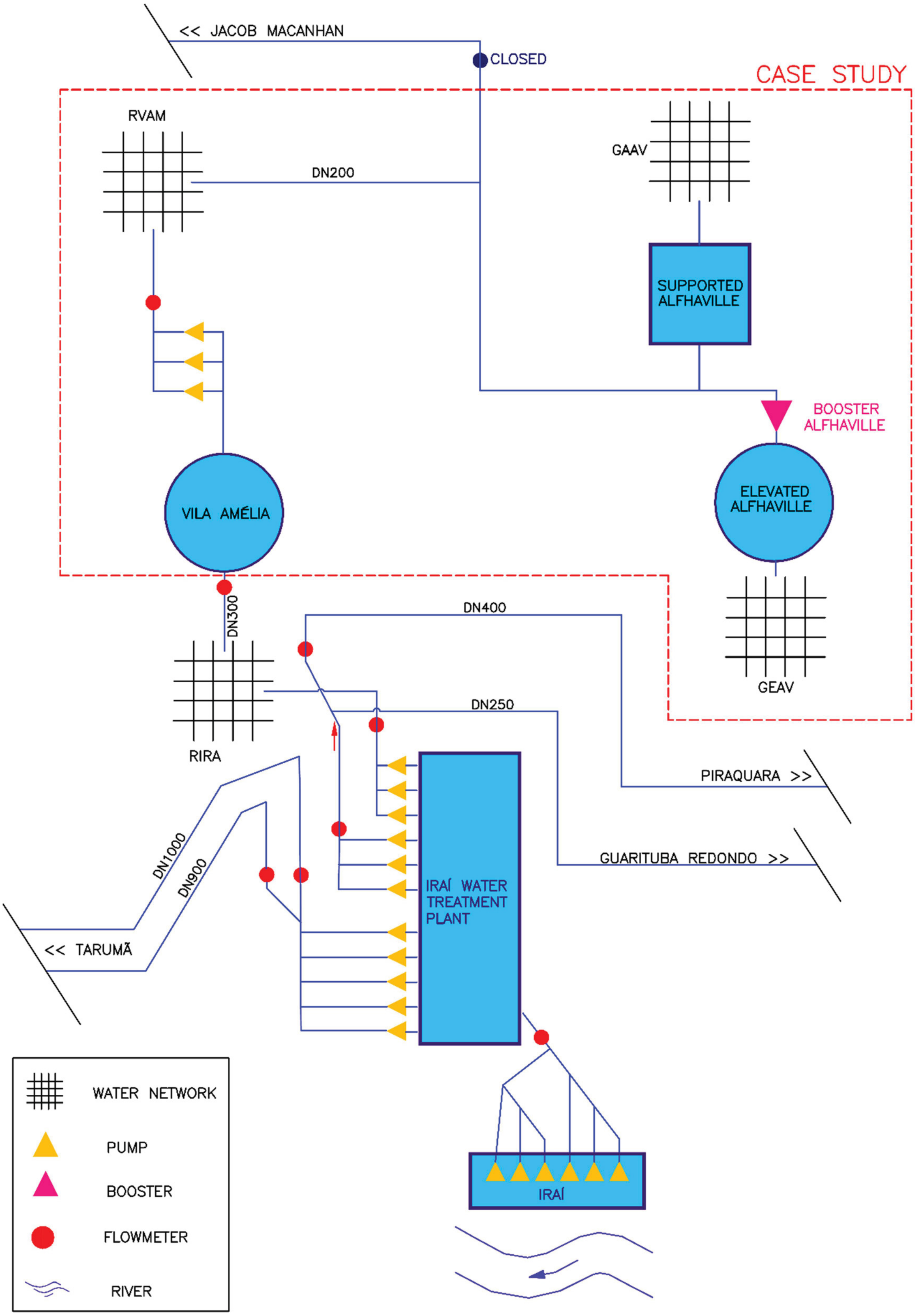


FIGURE 18: STUDY LOCATION FLOWCHART

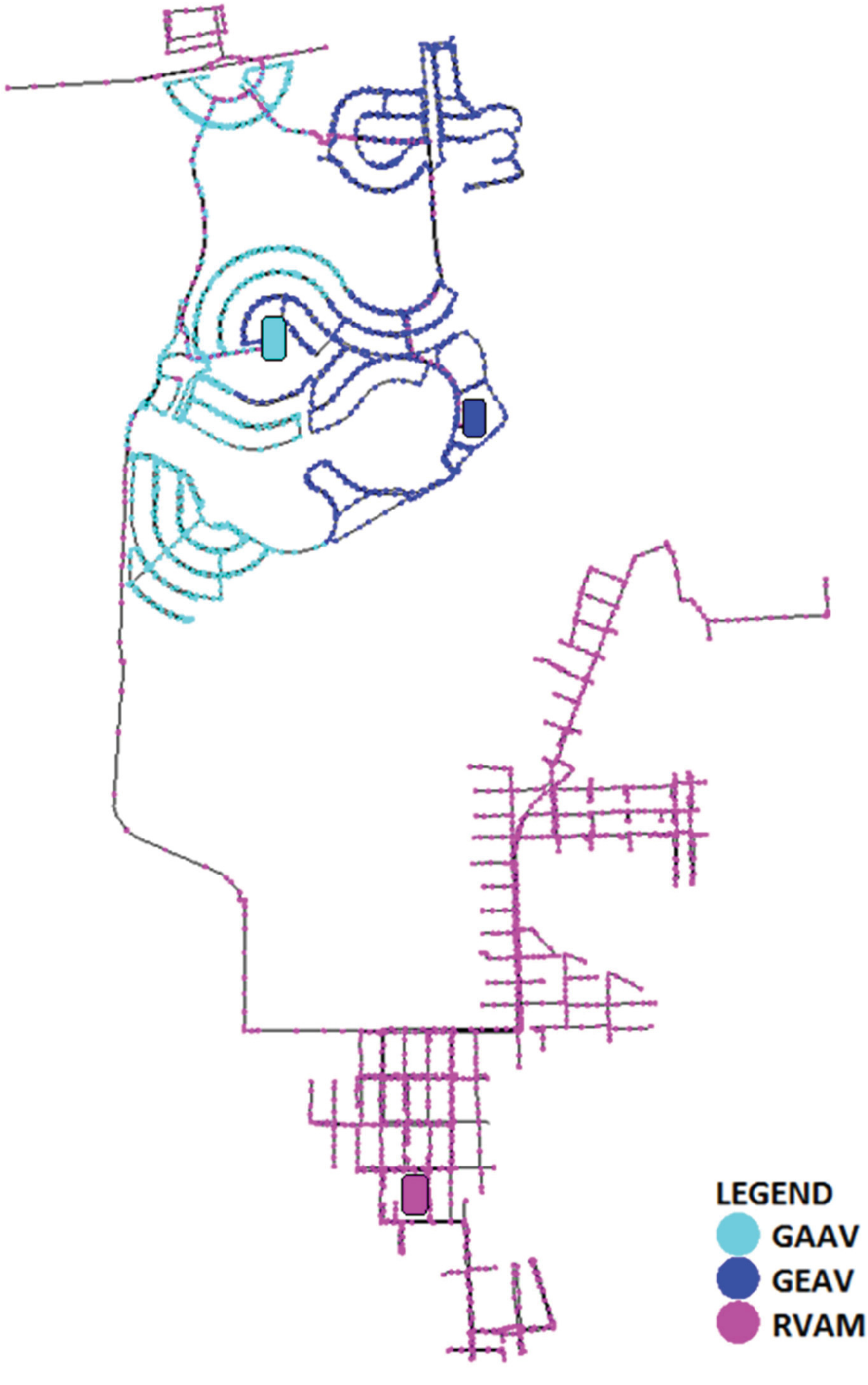


FIGURE 19: NETWORK'S TOPOLOGY

5.3.1.1 RVAM

Currently, the Vila Amélia pump station attends the Alphaville CR with control by a pressure relief valve at the entrance of its reservoir and also attends the Alphaville booster that serves the REL Alphaville, distributing in march to the pressure zone denominated RVAM. This pump station is composed of three sets of motor pumps with the characteristics presented in Table 6.

TABLE 6: RVAM PUMPS

Brand	EBARA	HAUPT
Model	BHS 813	P84
Number of stages	3	2
Manometric height	53 mH2O	53 mH2O
Flow	32 l/s	32 l/s
Power	35 HP	35 HP
Rotation	3500 rpm	3500 rpm
Quantity	2	1

SOURCE: SANEPAR, 2016.

The Vila Amélia Reservoir distribution network has about 3,350 economies. The average consumption of this sector is 12.26 L/s. The Table 7 shows the consumption of RVAM network during the year of 2016.

TABLE 7: RVAM CONSUMPTION

	Month	Number of economies	Monthly volume (m³)	Monthly average consumption (l/s)	Average consumption (l/s)
2016	January	3192	35944	13.42	12.26
	February	3303	33026	13.18	
	March	3307	31601	11.80	
	April	3307	33105	12.77	
	May	3457	32295	12.06	
	June	3337	29383	11.34	
	July	3341	31346	11.70	
	August	3344	32553	12.15	
	September	3348	31947	12.33	
	October	3359	33108	12.36	
	November	3370	31948	12.33	
	December	3378	30345	11.71	

SOURCE: SANEPAR, 2016

This consumption added to the actual and apparent losses generates a demand. Figure 20 shows the average curve, which was plotted by averaging all the flows in each time of year 2016 measured by a flow meter installed in the outlet pipe of the reservoir supplying this zone of pressure. This flow meter includes the RVAM demand plus the transportation to reservoirs: supported and elevated Alphaville.

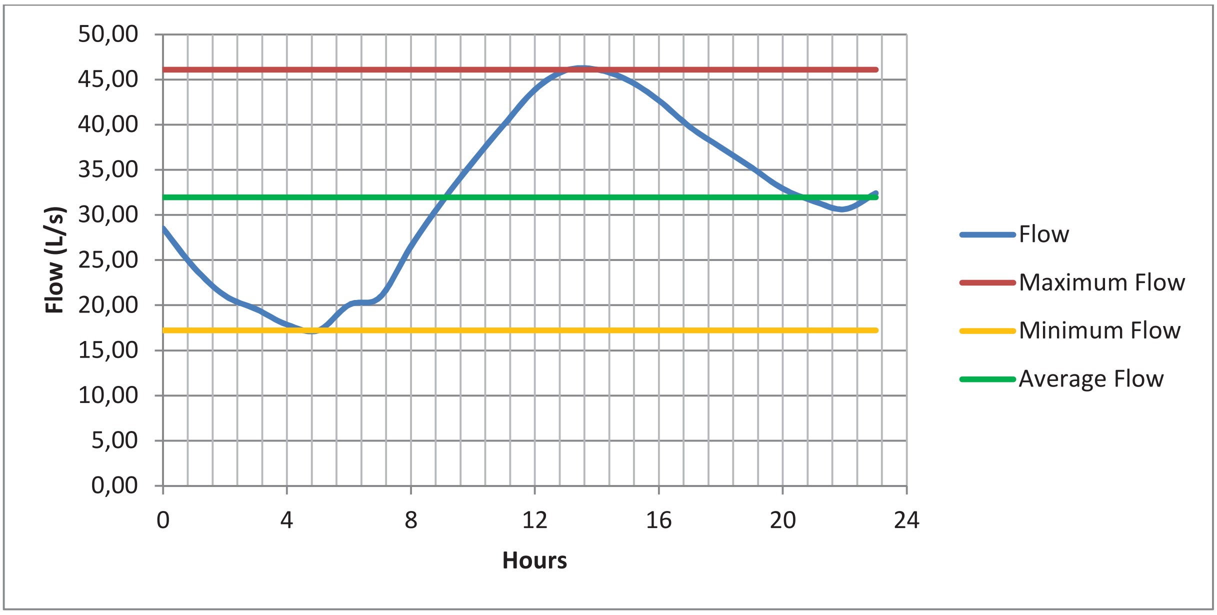


FIGURE 20: RVAM FLOWS

SOURCE: SANEPAR, 2016

This network is composed of pipes with diameters ranging from 40 to 300 mm, as presented in Table 8.

TABLE 8: RVAM PIPES

MATERIAL	DIAMETER	METER
PVC	40	259.33
PVC	50	20511.94
PVC	75	5299.62
PVC	100	1136.39
PVC	150	2191,37
PVC	200	2137.42
PVC	250	378.79
PVC	300	1068.22
TOTAL		32986.41

SOURCE: SANEPAR, 2016

5.3.1.2 GAAV and GEAV

The Alphaville Supported Reservoir's (Figure 21) distribution network has about 350 economies. The average consumption of this sector is 3.54 L/s in 2016, like shown in Table 9.

TABLE 9: GAAV CONSUMPTION

	Month	Number of economies	Monthly volume (m³)	Monthly average consumption (l/s)	Average consumption (l/s)
2016	January	335	7823	2.92	3.54
	February	335	8248	3.29	
	March	337	9103	3.40	
	April	337	8967	3.46	
	May	336	9234	3.45	
	June	342	9226	3.56	
	July	343	9163	3.42	
	August	348	10417	3.89	
	September	349	9564	3.69	
	October	349	9952	3.72	
	November	350	10.208	3.94	
	December	350	9.714	3.75	

SOURCE: SANEPAR, 2016.

This network is composed of pipes with diameters ranging from 50 to 200 mm, as presented in Table 10.

TABLE 10: GAAV PIPES

MATERIAL	DIAMETER	METER
PVC	50	14290.23
PVC	75	1474.33
PVC	100	812.35
PVC	150	2866.11
PVC	200	1777.83
TOTAL		21400.44

SOURCE: SANEPAR, 2016

FIGURE 21: ALPHAVILLE SUPPORTED RESERVOIR

This consumption added to the actual and apparent losses generates a demand. Figure 22 shows the average hourly demand curve, which was plotted by averaging all the flows in each time of year 2016 measured by a flow meter installed in the outlet pipe of the reservoir supplying this zone of pressure.

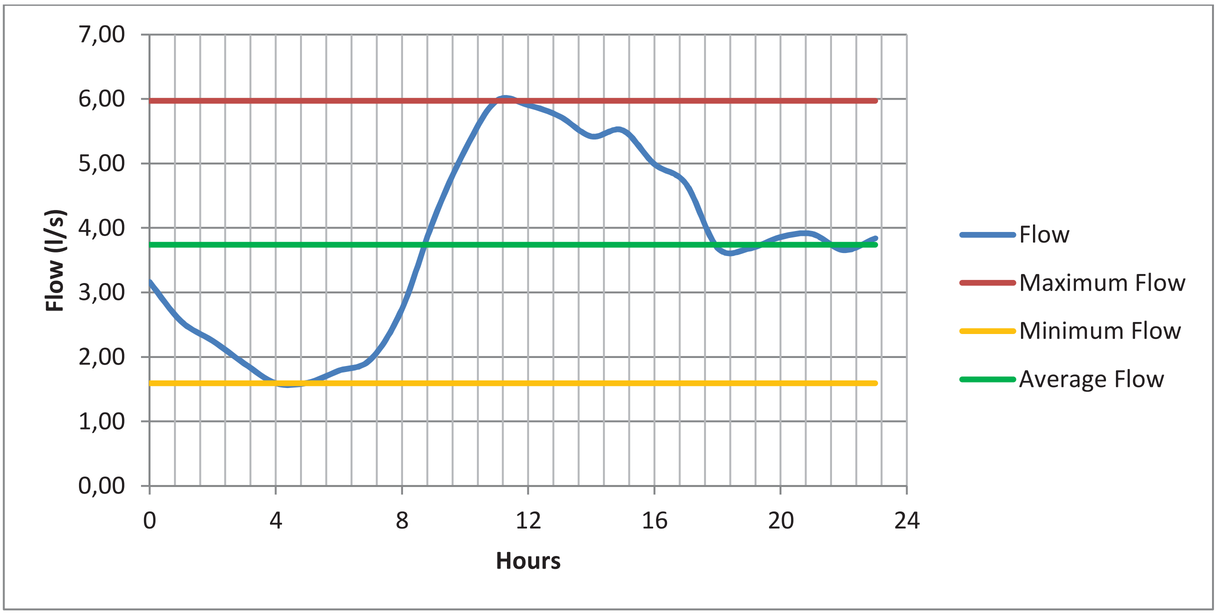


FIGURE 22: GAAV FLOWS

SOURCE: SANEPAR, 2016.

The Elevated Reservoir Alphaville (Figure 23) has 200 m³ of volume and is supplied by Vila Amelia Reservoir through of the booster Alphaville (Figure 24).

FIGURE 23: ALPHAVILLE ELEVATED RESERVOIR

The booster Alphaville is composed of 2 motor pumps with the characteristics of Table 11.

TABLE 11: BOOSTER PUMPS

Brand	KSB
Model	MEGABLOC 32-160
Rotor	176 mm
Manometric height	44 mH2O
Flow	8,6 l/s
Power	10 HP
Rotation	3500 rpm

SOURCE: SANEPAR, 2016

FIGURE 24: ALPHAVILLE BOOSTER

The distribution network of the Elevated Reservoir Alphaville, has 520 active connections, with 538 economies. The average consumption of this sector is 4.25 L/s in 2016, like shown in Table 10.

TABLE 12: GEAV CONSUMPTION

	Month	Number of economies	Monthly volume (m³)	Monthly average consumption (l/s)	Average consumption (l/s)
2016	January	518	10281	3.84	4.25
	February	518	9166	3.66	
	March	519	10271	3.83	
	April	519	10908	4.21	
	May	517	11115	4.15	
	June	517	11115	4.29	
	July	517	10553	3.94	
	August	518	10971	4.10	
	September	518	12823	4.95	
	October	517	12093	4.52	
	November	518	12408	4.79	
	December	520	12217	4.71	

SOURCE: SANEPAR, 2016.

This consumption added to the actual and apparent losses generates a demand. Figure 25 shows the average hourly demand curve, which was plotted by averaging all the flows in each time of year 2016 measured by a flow meter installed in the outlet pipe of the reservoir supplying this zone of pressure.

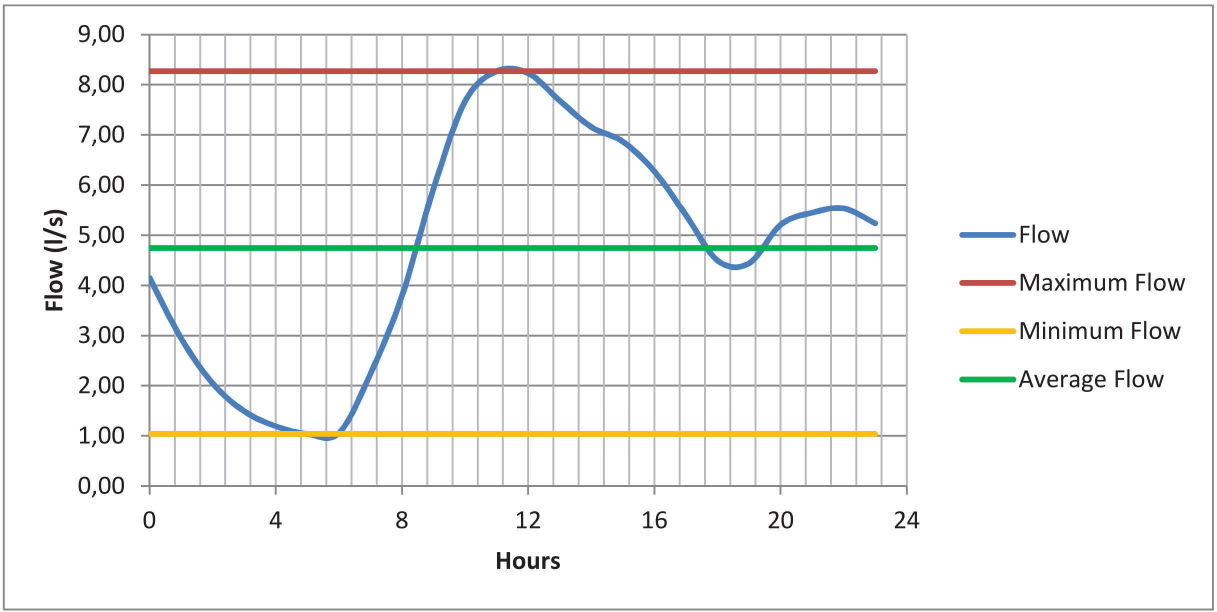


FIGURE 25: GEAV FLOWS
SOURCE: SANEPAR, 2016

This network is composed of pipes with diameters ranging from 50 to 200 mm, as shown in Table 13.

TABLE 13: GEAV PIPES

MATERIAL	DIAMETER	METER
PVC	50	17686.69
PVC	75	1787.57
PVC	100	123.89
PVC	150	3801,84
PVC	200	181.91
TOTAL		23581.89

SOURCE: SANEPAR, 2016

5.4 SCENARIOS

A total of 200 scenarios were simulated, with 104 in the RVAM water distribution network, 48 in the GAAV water distribution network and 48 in the GEAV water distribution network.

5.4.1 RVAM

To simulate the hydraulic transient RVAM pressure zone, it was defined some scenarios like shown on Table 14.

TABLE 14: RVAM – MACRO SCENARIOS

Macro Scenario	Material	Protection
NP – PVC	PVC 0,6 MPa	No
P1a - PVC		Air valves
P1b - PVC	PVC 1 MPa	Air valves
P2 – PVC	PVC 0,6 MPa	Surge Tanks
P3 – PVC		Hydropneumatic Tank
NP – DI	DUCTILE IRON	No
P1 – DI		Air valves
P2 – DI		Surge Tanks
P3 – DI		Hydropneumatic Tank
NP - HDPE	HDPE 1 MPa	No
P1 - HDPE		Air valves
P1 - HDPE		Surge Tanks
P3 - HDPE		Hydropneumatic Tank

To each one of these scenarios, it was made eight simulations, like shown on Table 15:

TABLE 15: RVAM – MICRO SCENARIOS

Micro Scenario	Pipes that was simulated	Number of junction	Transient cause	Flow
A 1 Max	All pipes of network	1218	Shut off in the RVAM pumps and booster	Maximum (two pumps)
A 1 Min				Minimum (one pump)
S 1 Max	Skeletonized network	554		Maximum (two pumps)
S 1 Min				Minimum (one pump)
A 2 Max	All pipes of network	1218	Shut off just in the RVAM pumps	Maximum (two pumps)
A 2 Min				Minimum (one pump)
S 2 Max	Skeletonized network	554		Maximum (two pumps)
S 2 Min				Minimum (one pump)

5.4.2 GEAV E GAAV

To simulate the hydraulic transient of GAAV e GEAV pressure zones was define some scenarios like shown on the Table 16.

TABLE 16: GAAV E GEAV – MACRO SCENARIOS

Macro Scenario	Material	Protection
NP - PVC	PVC 0,6 MPa	No
P1 - PVC		No – avoid transient – slowly valve close
P2 - PVC		Air valves
P3 - PVC		Hydropneumatic Tank
NP - DI	DUCTIL IRON	No
P1 - DI		No – avoid transient – slowly valve close
P2 - DI		Air valves
P3 - DI		Hydropneumatic Tank
NP - HDPE	HDPE 1 MPa	No
P1 - HDPE		No – avoid transient – slowly valve close
P1 - HDPE		Air valves
P3 - HDPE		Hydropneumatic Tank

To each one of these scenarios was made four simulations, like shown on Table 17.

TABLE 17: GAAV E GEAV – MICRO SCENARIOS

Micro Scenario	Pipes that was simulated	Number of junction		Transient cause	Flow
		GAAV	GEAV		
A Max	All pipes of network	566	670	Quick close valve downstream of the reservoir	Maximum
A Min					Minimum
S Max	Skeletonized network	120	104		Maximum
S Min					Minimum

6 RESULTS

“Transient flow simulation has become an essential requirement for ensuring safety and the safe operation of drinking water distribution system” (Boulos et al., 2005).

This chapter provides the results of three water distribution systems: RVAM, GAAV and GEAV, presenting the indicators results of each one, a general analysis of the results and the indicators.

6.1 SIMULATIONS AND INDICATORS

Despite the systems being independent, the simulation performed considering a complete system. The RVAM network was represented by 1.218 junctions, while GAAV and GEAV networks were represented by 566 and 670, respectively. It produced a file with 2.454 junctions that was simulated by 240 seconds with 0.3 seconds of hydraulic time step, i.e. 800 steps simulated in each scenario, and the cause of hydraulic transient was configured to happen 2 seconds after the effective action (pump failure or valve closure).

The simulation run requires around 10 minutes to the complete representation and 3 minutes to the skeletonized. To each simulation, it was generated a file that has 532 Mb and 168 Mb, respectively. This file was uploaded in the R software to calculate the indicators C1, C2, C6 to C9 and C12. Appendix A presents the pipes celerity.

6.1.1 RVAM

As previously mentioned, RVAM is a system that has been stressed through scenarios of pump failure and 3 distinct protection strategies: air valves (P1), surge tank (P2) and hydropneumatic tank (P3). Figures 26, 27, 28 and 29, as follows, and Appendix B presents the fourteen indicators for the RVAM water distribution network, for complete and skeletonized representation to three diferents materials: PVC, ductile iron and HDPE.

Remembering the codes adopted as shown in Tables 14 and 15, in Chapter 4:

- Protections: NP – No protection; P1 – Protection with air valves; P2 – Protection with surge tanks; P3 – Protection with hydropneumatics;
- System: A – All pipes; S – Skeletonized;
- Flow: Max – Maximum; Min – Minimum Flow.

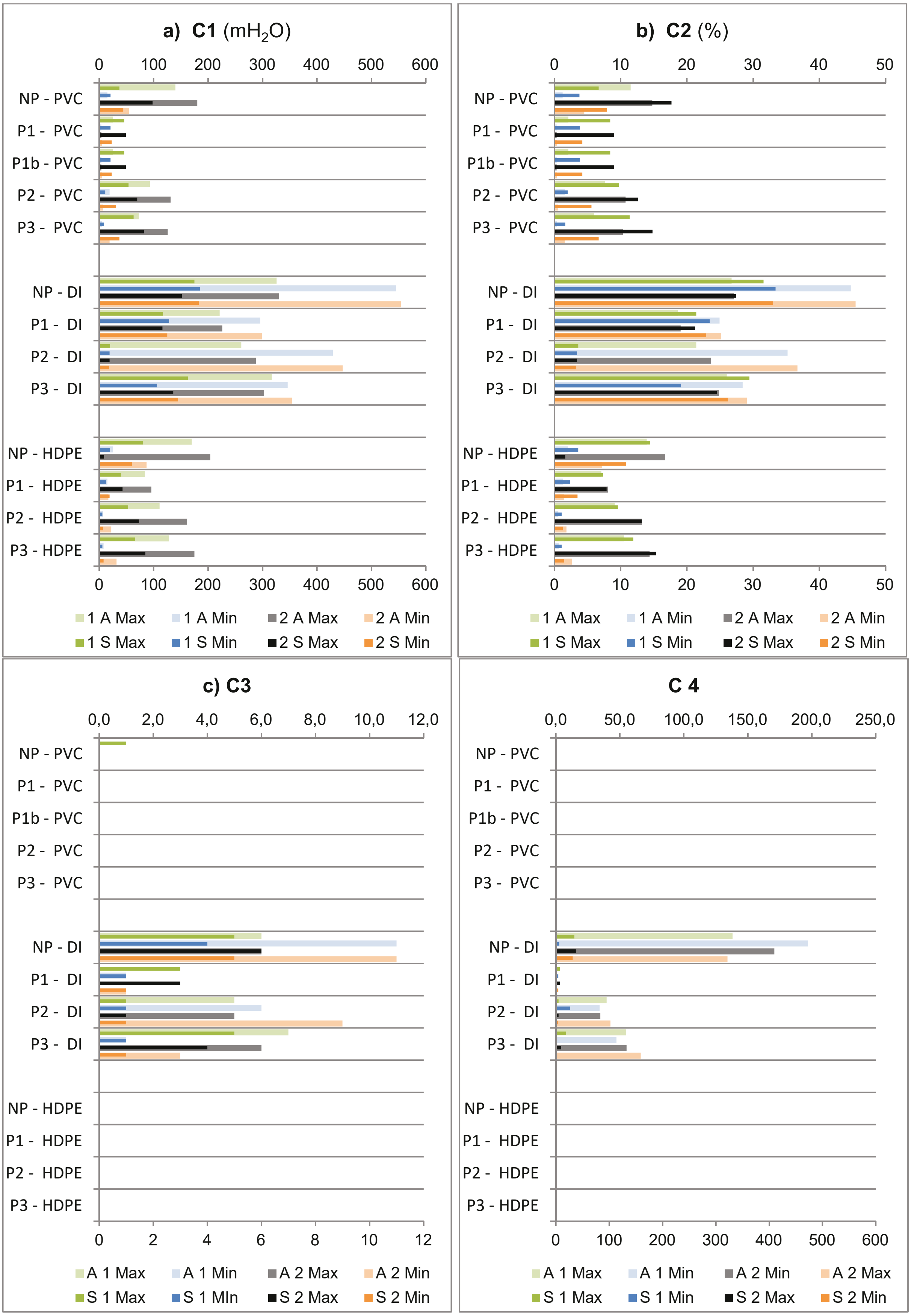


FIGURE 26: RVAM – a) C1 – Number of junctions with pressure < 0; b) C2 – Percentage of junctions with pressure < 0; c) C3 – Number of junctions with vacuum pressure; d) C4 – Total time cavitation.

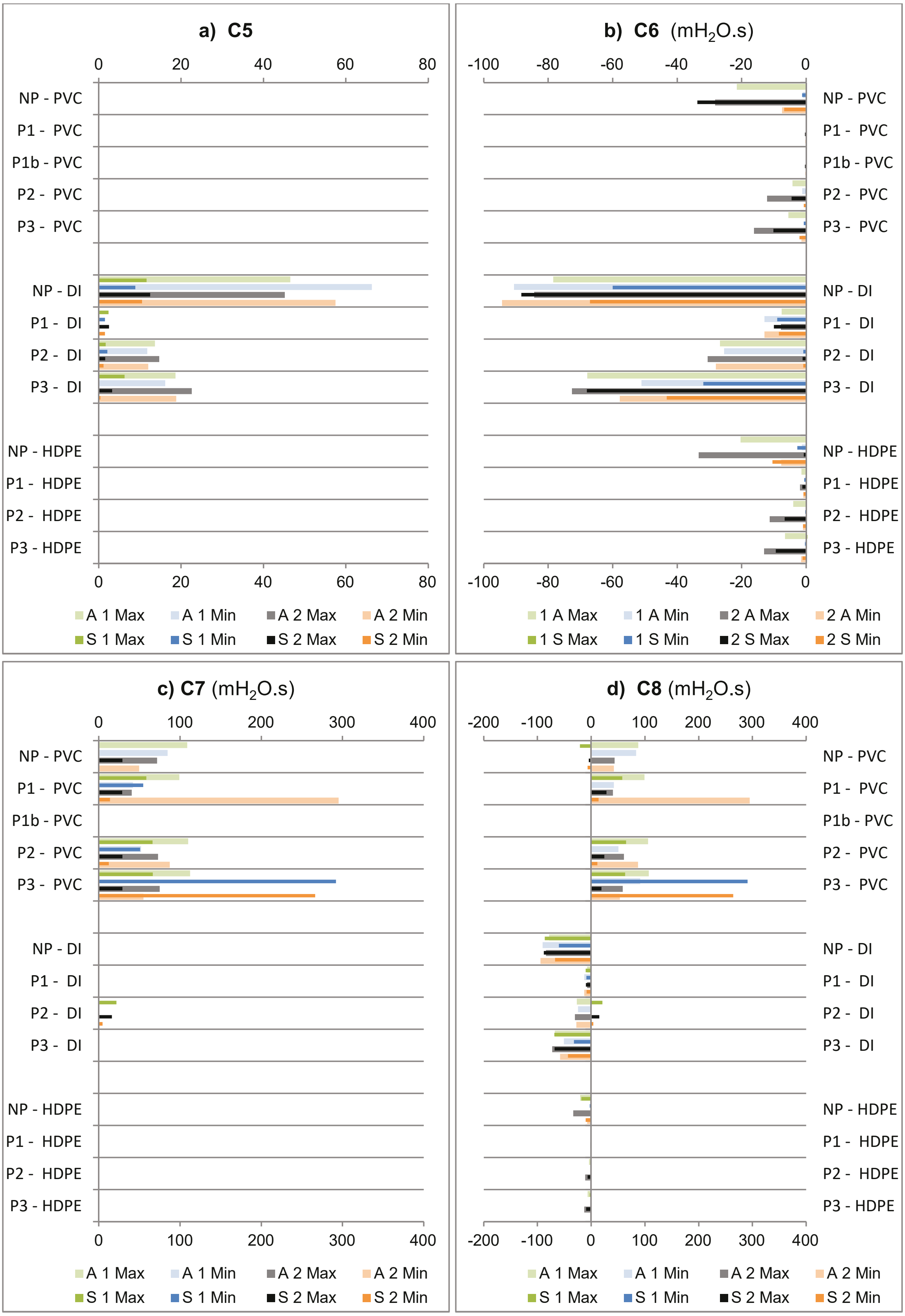


FIGURE 27: RVAM – a) C5 – Severity of Cavity Index; b) C6 – Surge Damage Potential Factor Negative; c) C7 – Surge Damage Potential Factor Positive; d) C8 – Surge Damage Potential Factor.

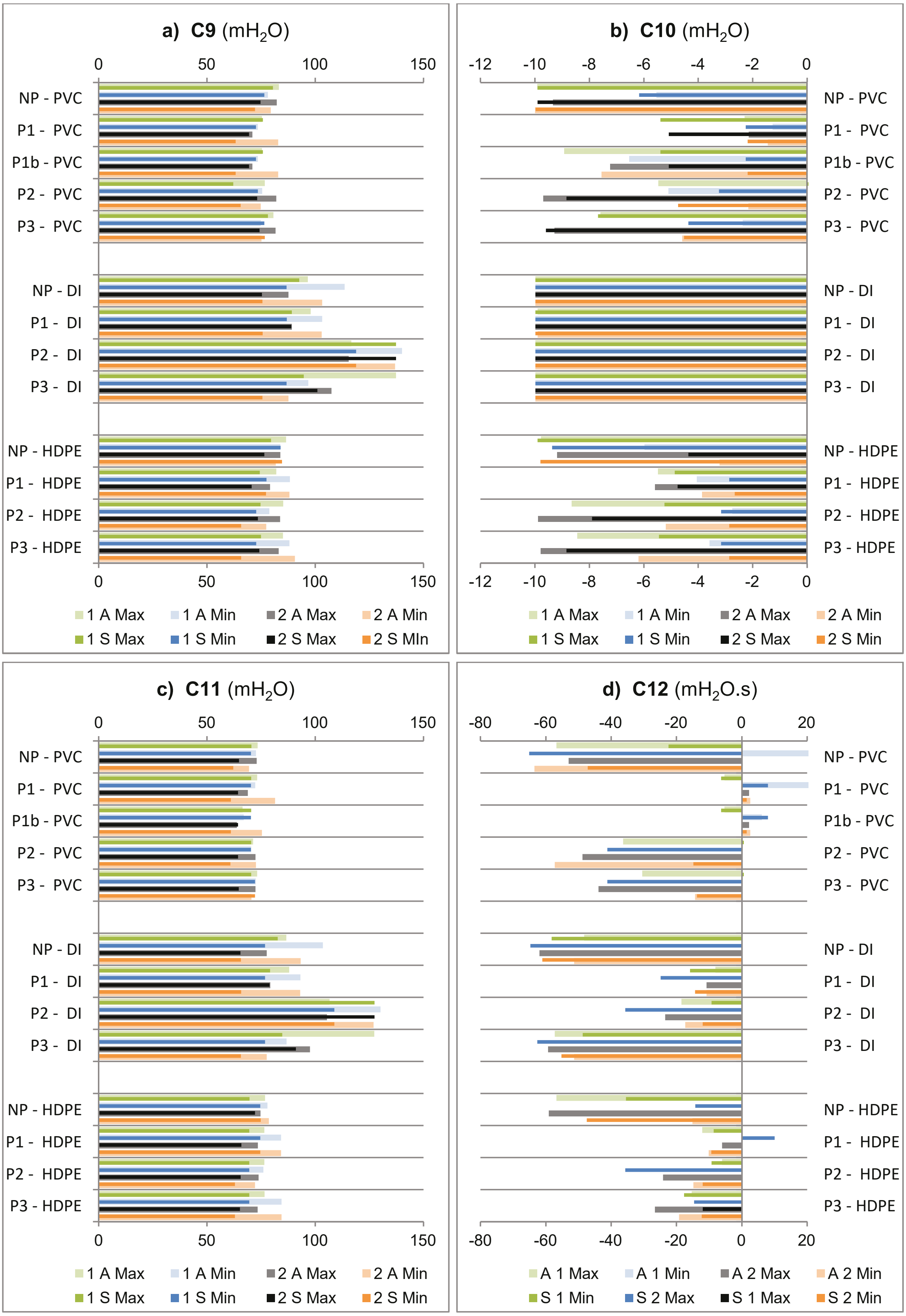


FIGURE 28: RVAM – a) C9 – Pressure range; b) C10 – Minimum Pressure; c) C11 – Maximum Pressure; d) C12 – Negative Transient Risk Index.

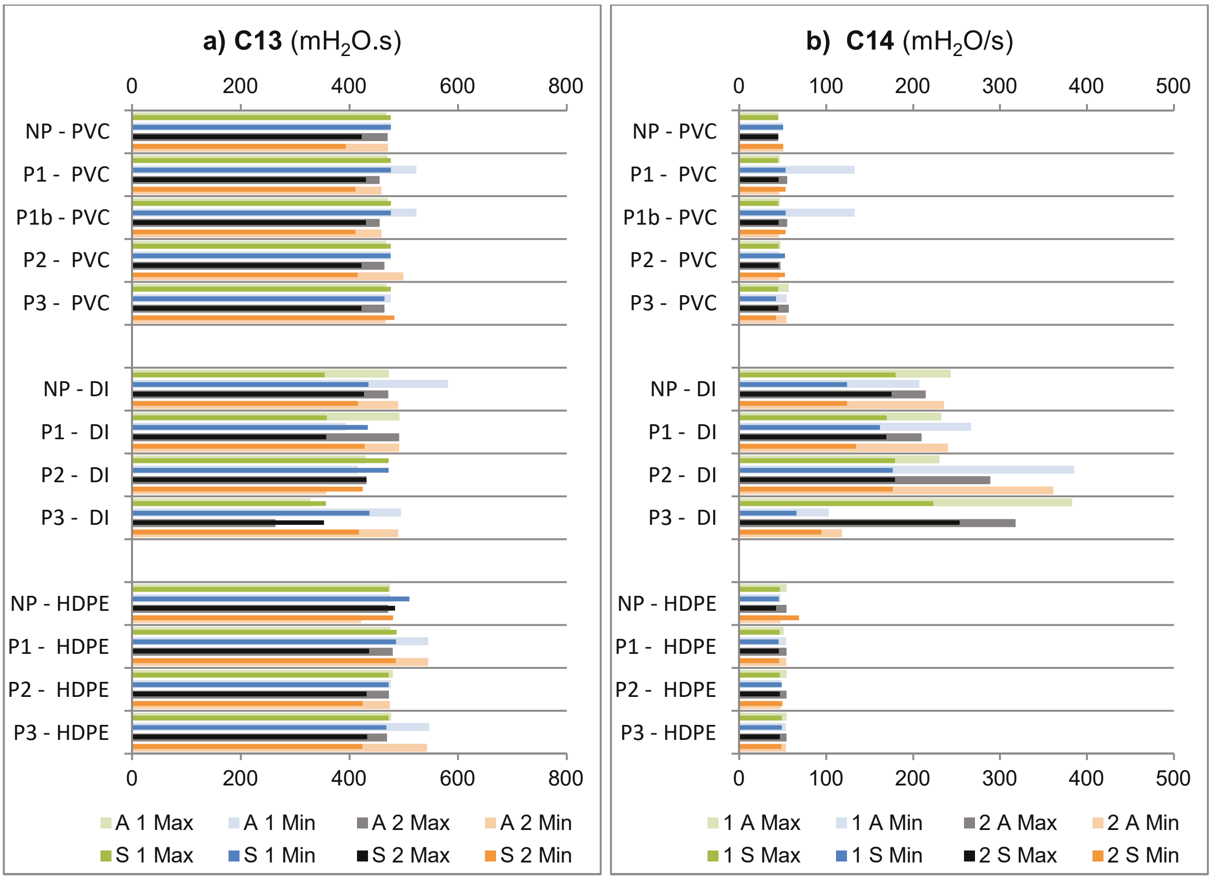


FIGURE 29: RVAM - A) C13 – Positive Transient Risk Index; B) C14 – Damage Index

The overall analysis of the fourteen indicators reveals the difference between complete and skeletonized systems representation as potentially significant, as for C2 - Percentage of junctions with pressure minor than zero, that skeletonization overestimated the percentage, for example, in the scenarios of minimum flow with ductile iron and underestimated, for example, in the PVC's scenarios. In the C1 - Number of junctions with pressure minor than zero all skeletonized representation underestimated the value, what is understood because the number of junctions is 1218 in complete representation and the skeletonized is only 554. In the C6 – Surge Damage Potential Factor Positive, C7 – Surge Damage Potential Factor Negative, C8 – Surge Damage Potential Factor, C9 – Difference between maximum and minimum pressure and C14 – Damage Index the skeletonized representation tends to underestimate the values, however it's no uniform like the maximum flow (1 S Max) in surge protection (P2) with ductile iron in the C9 index and some scenarios (2 S Max and 2 S Min) of surge protection (P2) with HDPE.

Considering the transient damage potential indicators, we found that the risks are associated with negative and positive pressure, as shown in Figures 27b and 27c (C6 – Surge Damage Potential Factor Positive and C7 – Surge Damage Potential Factor Negative). The maximum pressure found to the no protection scenario (NP) was 89.6 mH2O to PVC, 128.6 mH2O to ductile iron and 83.4 mH2O to HPDE, as shown in Figure 28b (C10 – Maximum Pressure) and the minimum pressure found was the vacuum to ductile iron and next to the vacuum to PVC and HDPE, as shown in Figure 28c (C11 – Minimum Pressure). The risk associated with positive pressure occurs only to the scenarios of PVC and it occurs because the maximum pressure was considered the maximum supported by the pipe in the steady state. Figure 30 presents the pressure in the junction with maximum pressure and the junction with minimum pressure in no protection scenario of ductile iron running the complete system in the maximum flow.

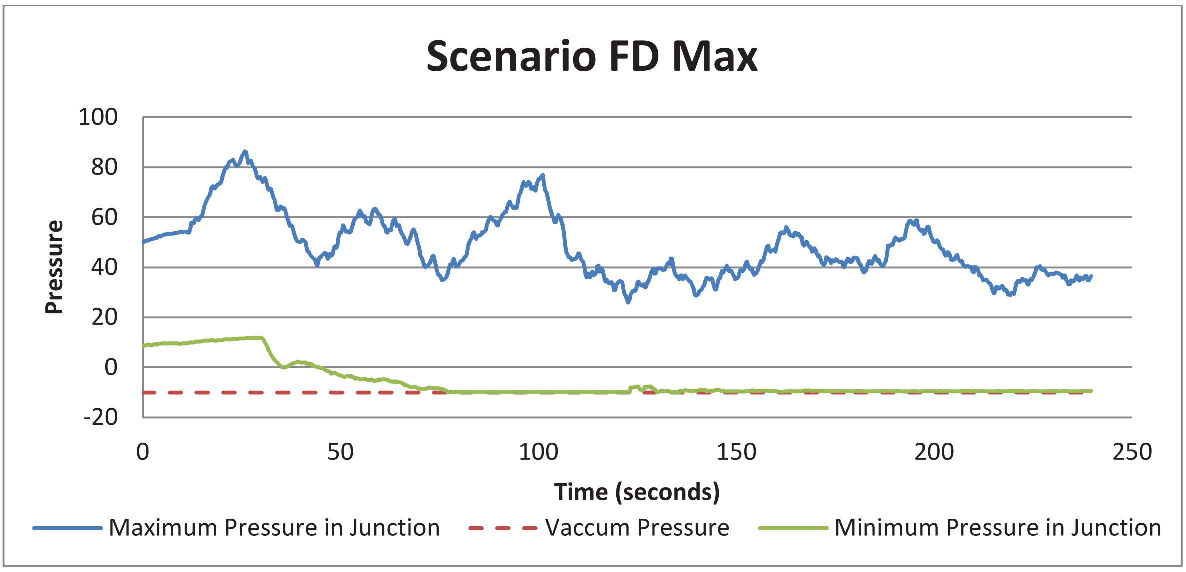


FIGURE 30: RVAM – Pressure Maximum and Mininum in the NP - DI Scenario 1 A Max

The maximum pressure supported by each pipe material is 60 mH2O for PVC pipe CL 12 and 100 mH2O for PVC CL 20 (scenario P1b PVC) in the steady state and in the transient condition (Tigre, 2017), 100 m H_2O for ductile iron in the steady state and varies from 120 to 770 m H2O in the transient condition (PAM Saint Gobaim, 2017) and 100 m H_2O for the HDPE in the steady state and 150 m H_2O in the transient condition (ABPE, 2017).

The risks associated with negative pressure occur with the three types of materials. For minimum pressure was considered the pressure of 0 m H_2O, i.e. pressure equal to atmospheric pressure.

Comparing the air valves, scenarios P1, with the surge tank, scenarios P2, and hydropneumatic tank, scenarios P3, protection devices, the air valves are the most effective to this network, like shown in the Graphs C1 to C11. To the damage index (C14), the results were similar to these devices.

6.1.2 GAAV

As previously mentioned, GAAV is a system that has been stressed thorough a scenario of closing valve downstream the reservoir with three distinct protection strategies: slow closing valve (P1), air valves (P2) and hydropneumatic tank (P3). Figures 31, 32, 33 and 34, as follows, and Appendix C represents the results obtained in the fourteen indicators for the GAAV water distribution network, for complete and skeletonized representation.

Remembering the codes adoptedes as shown in Tables 16 and 17, in Chapter 4.

- Protections: NP – No protection; P1 – Protection avoiding the transient, slowly valve closure; P2 – Protection with air valves; P3 – Protection with hydropneumatics;
- System: A – All pipes; S – Skeletonized;
- Flow: Max – Maximum; Min – Minimum Flow.

The GAAV analyses highlights of fourteen indicators that reveal the difference between complete and skeletonized systems representation as potentially significant. While C3 – Number of Junctions with Vacuum Pressure, C4 – Total Time Cavitation, C5 – Severity of cavity index, C9 – Difference between maximum and minimum pressure, C10 – Maximum Flow, C11 – Minimum Flow and the maximum flow of C14 – Damage Index, skeletonized representation tends to underestimate the values, C6 – Surge Damage Potential Factor Positive, C7 – Surge Damage Potential Factor Negative, C8 – Surge Damage Potential Factor and minimum flow of C14 tends to overestimating them. However, trends are not uniform. C2 - Percentage of junctions with pressure minor than zero don't present a reasonable tendency. The underestimating of skeletonized system in C1 - Number of junctions with pressure minor than zero, like in RVAM, is understood by the difference of junctions, 566 and 120, in complete and skeletonized, respectively.

In relation to cavitation, the scenarios with PVC and HDPE materials did not show any junction with vacuum pressure, even for the scenarios without any transient protection. For ductile iron, vacuum was detected in some scenarios.

By analyzing the transient damage potential graphs, we see that for this network the risks are only associated with negative pressure, since all positive pressures have been below the maximum allowed by the material, as shown in C7 – Surge damage potential factor negative (Figure 32c). The maximum pressure found to the no protection scenario (NP) was 46.6 to PVC, 62.6 to ductile iron and 46.1 to HPDE, as shown the Figure 33b (C10 – Maximum Pressure) and the minimum pressure found was -9.5 to PVC, vacuum to ductile iron and -9.8 to HPDE, as shown in Figure 33c (C11 – Minimum Pressure).

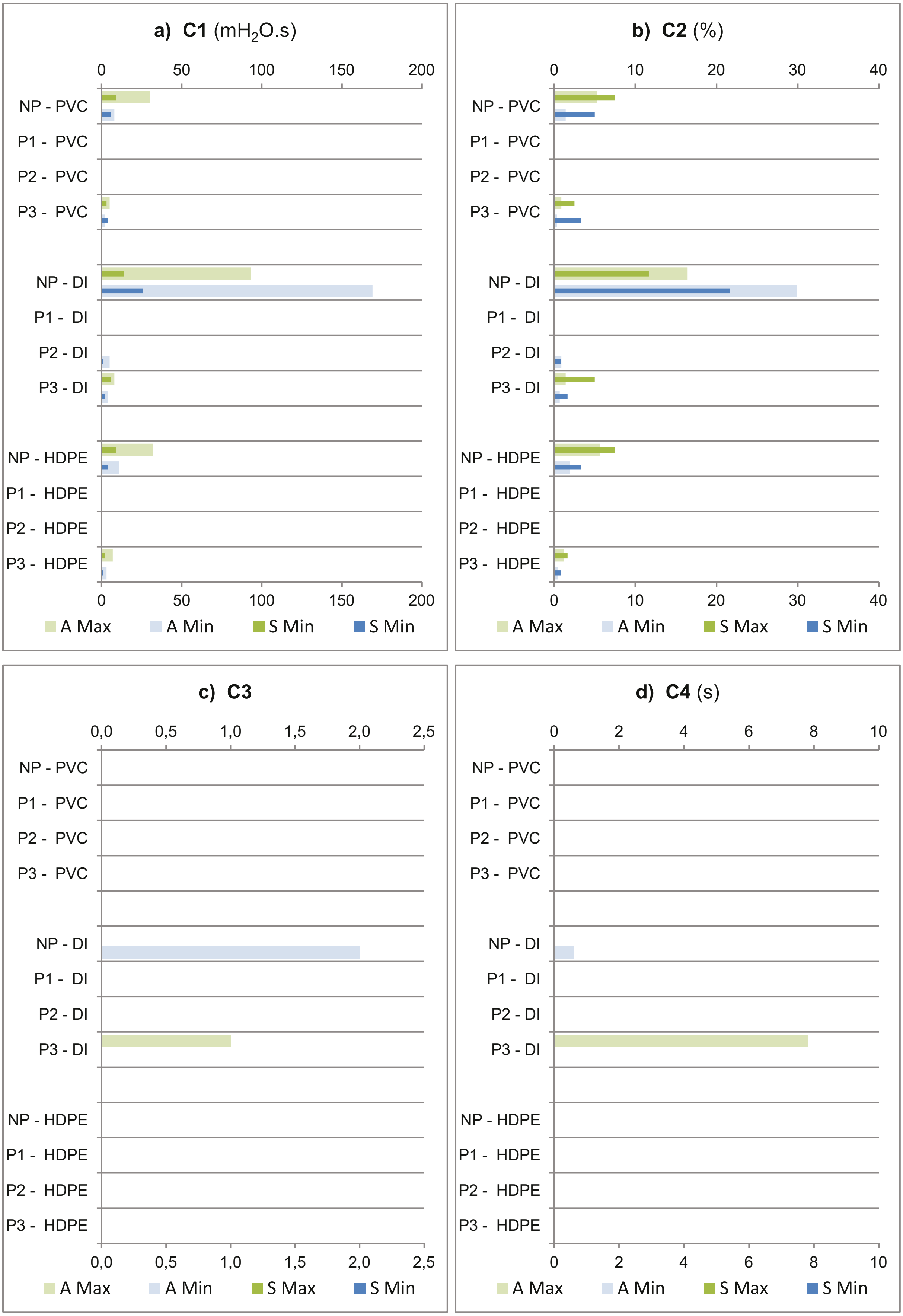


Figure 31: GAAV – A) C1 – Number of Junctions With Pressure < 0; B) C2 – Percentage of Junctions With Pressure < 0; C) C3 – Number of Junctions With Vacuum Pressure; D) C4 – Total Time Cavitation.

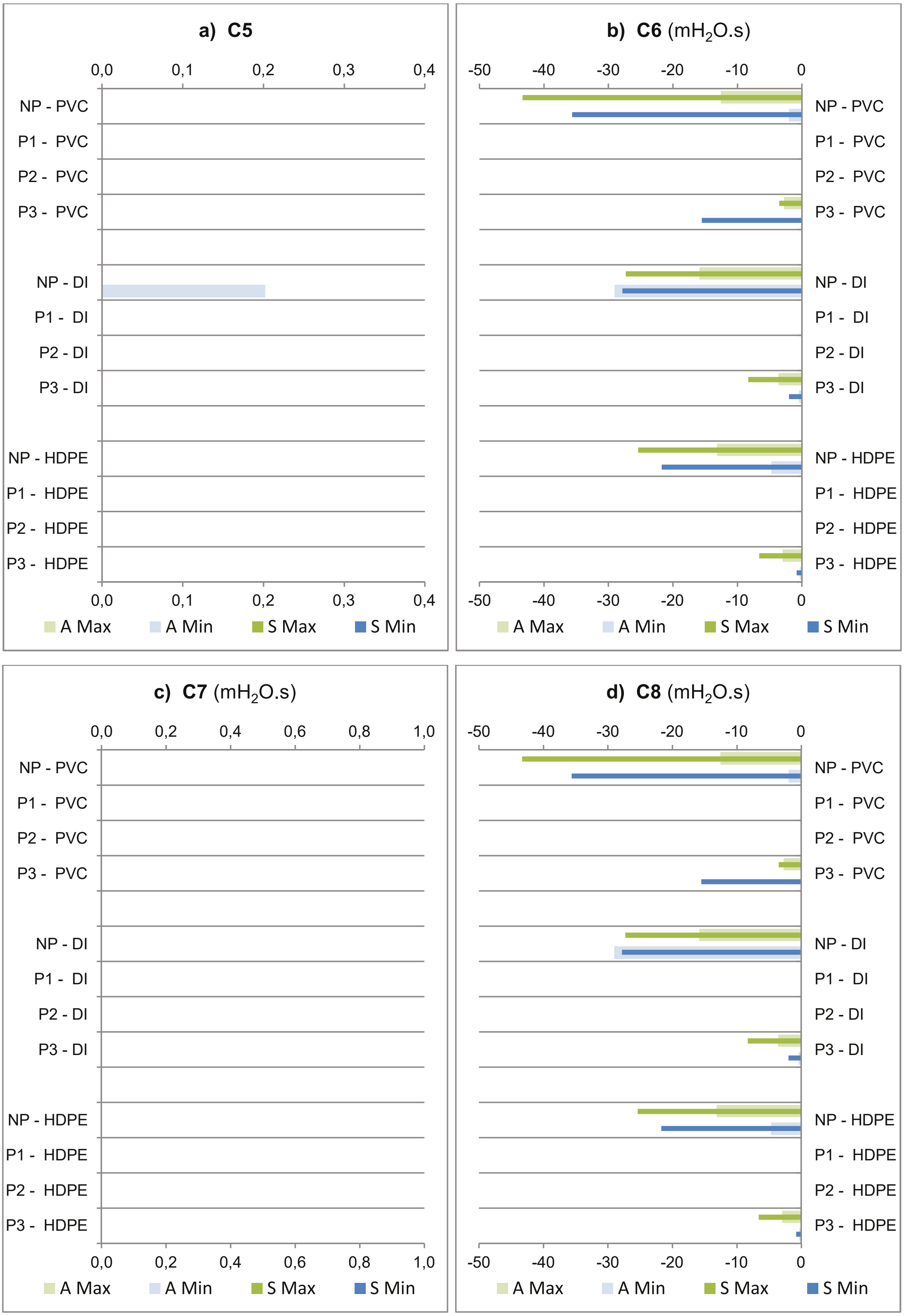


FIGURE 32: GAAV – a) C5 – Severity of Cavity Index; b) C6 – Surge Damage Potential Factor Negative; c) C7 – Surge Damage Potential Factor Positive; d) C8 – Surge Damage Potential Factor.

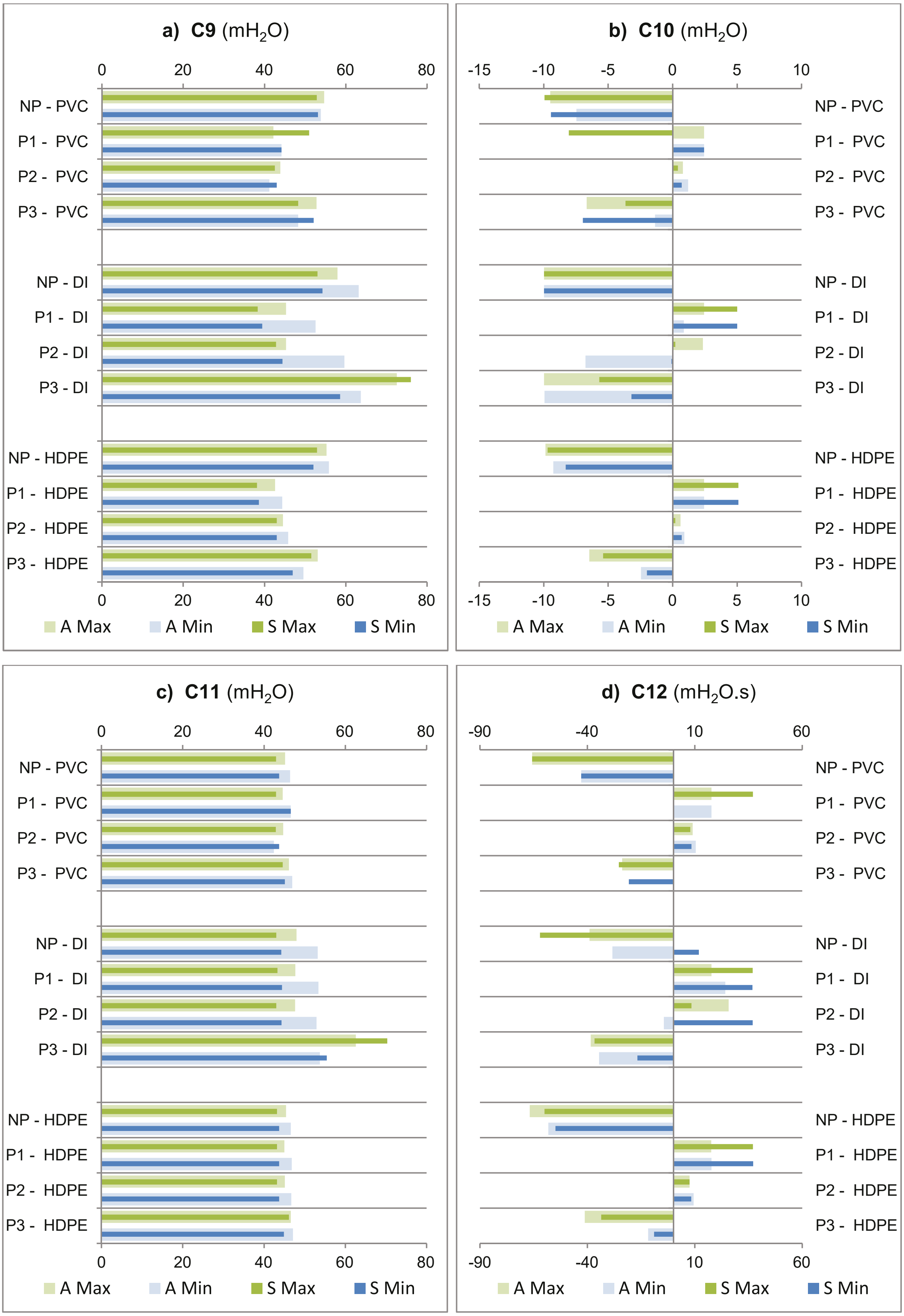


Figure 33: Gaav – A) C9 – Pressure range; B) C10 – Minimum Pressure; C) C11 - Maximum Pressure; D) C12 - Negative Transient Risk Index.

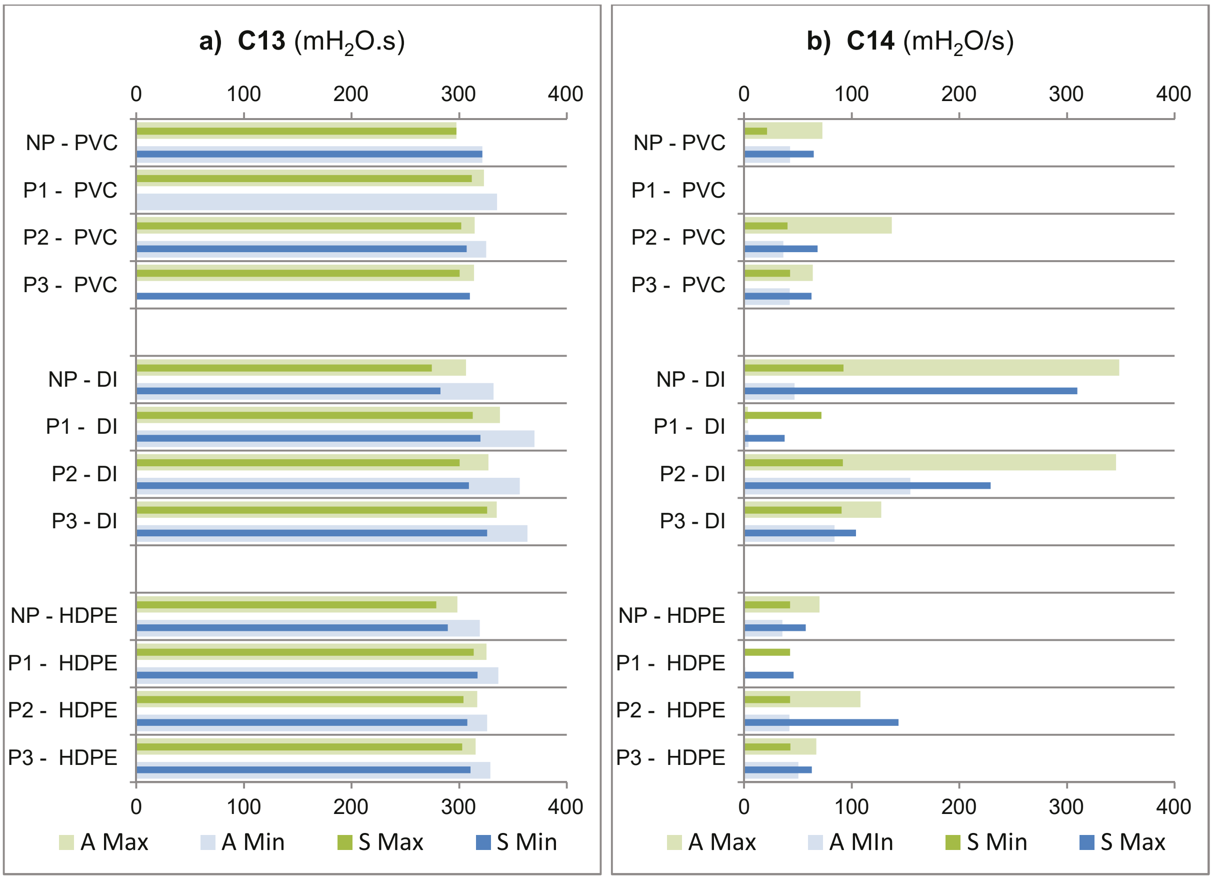


FIGURE 34: GAAV – a) C13 – Positive Transient Risk Index; b) C14 – Damage Index.

Figure 35 presents the pressure in the junction with maximum pressure and the junction with minimum pressure in no protection scenario of ductile iron.

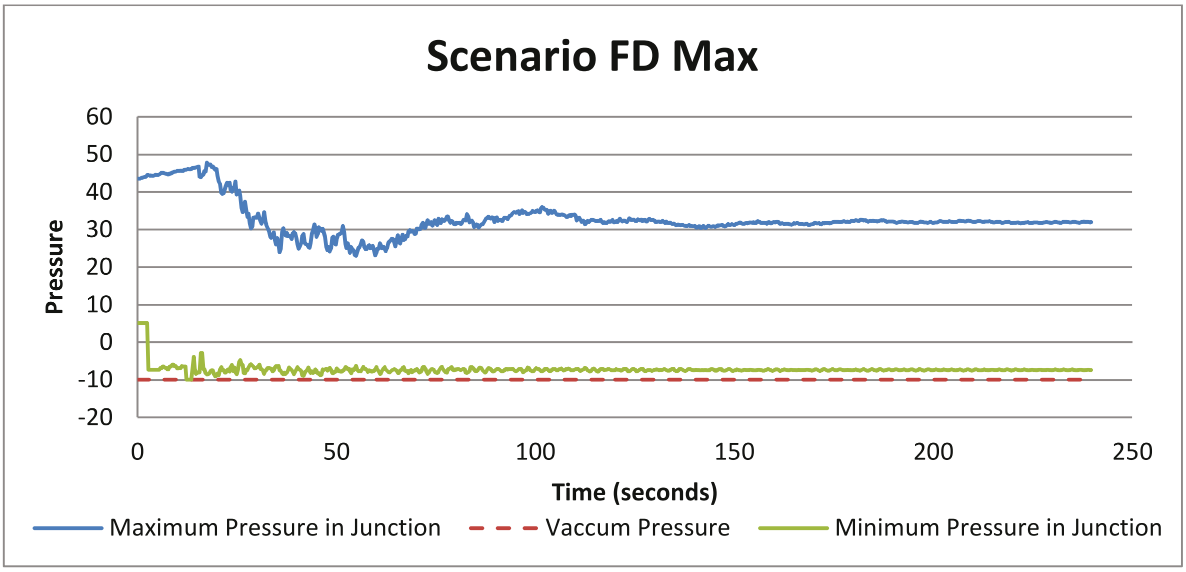


FIGURE 35: GAAV – Pressure Maximum and Mininum in the NP - DI Scenario

By avoiding the rapid hydraulic transient through a slow valve closure (P1), in 120 seconds, the indicators C1 to C8 are zero, i.e. all pressures are within the allowed limits. For the indicators C9 to C14 are the scenarios with better values, that is, less potential of damage to the pipeline. This scenario is the ideal operating condition, which avoids rapid hydraulic transient and. It is possible through an electric valve with a generator, manual operation following guidelines company, and others. In case of valve control failure, the valve is operated again according to the unprotected scenarios and transient protection devices are necessary.

Comparing the air valves (P2) and hydropneumatic tank (P3) protection devices, the air valves were more effective, eliminating all negative pressure junctions for PVC and HDPE and greatly reducing the number for ductile iron.

6.1.3 GEAV

As previously mentioned, GEAV, like GAAV, is a system that has been stressed thorough a scenario of closing valve downstream the reservoir with 3 distinct protection strategies: slow closing valve (P1), air valves (P2) and hydropneumatic tank (P3). Figures 36, 37, 38 and 39, as follows, and Appendix D represents the results obtained in the fourteen indicators for the GEAV WDS, for complete and skeletonized representation.
Remembering the codes adoptedes as shown in Tables 16 and 17, in Chapter 4.

- Protections: NP – No protection; P1 – Protection avoiding the transient, slowly valve closure; P2 – Protection with air valves; P3 – Protection with hydropneumatics;
- System: A – All pipes; S – Skeletonized;
- Flow: Max – Maximum; Min – Minimum Flow.

The GEAV analysis has indicated interesting results. While C3 – Number Of Junctions With Vacuum Pressure, C9 – Difference between maximum and minimum pressure, C10 – Maximum Flow, C11 – Minimum Flow and C13 - Positive transient risk index, skeletonized representation tends to underestimating the values, C2 - Percentage of junctions with pressure minor than zero, C4 – Total Time Cavitation, C6 – Surge Damage Potential Factor Positive, C8 – Surge Damage Potential Factor, C10 – Minimum Pressure and C12 – Negative Transient risk index tends to overestimating them. However, these tendencies aren’t uniform. C5 – Severity of cavity index, C7 – Surge Damage Potential Factor Negative and C14 – Damage index don't present a reasonable tendency. The underestimating of skeletonized system in C1 - Number of junctions with pressure minor than zero, like in GAAV and RVAM, is understood by the difference of junctions in complete and skeletonized systems, 566 and 120, respectively.

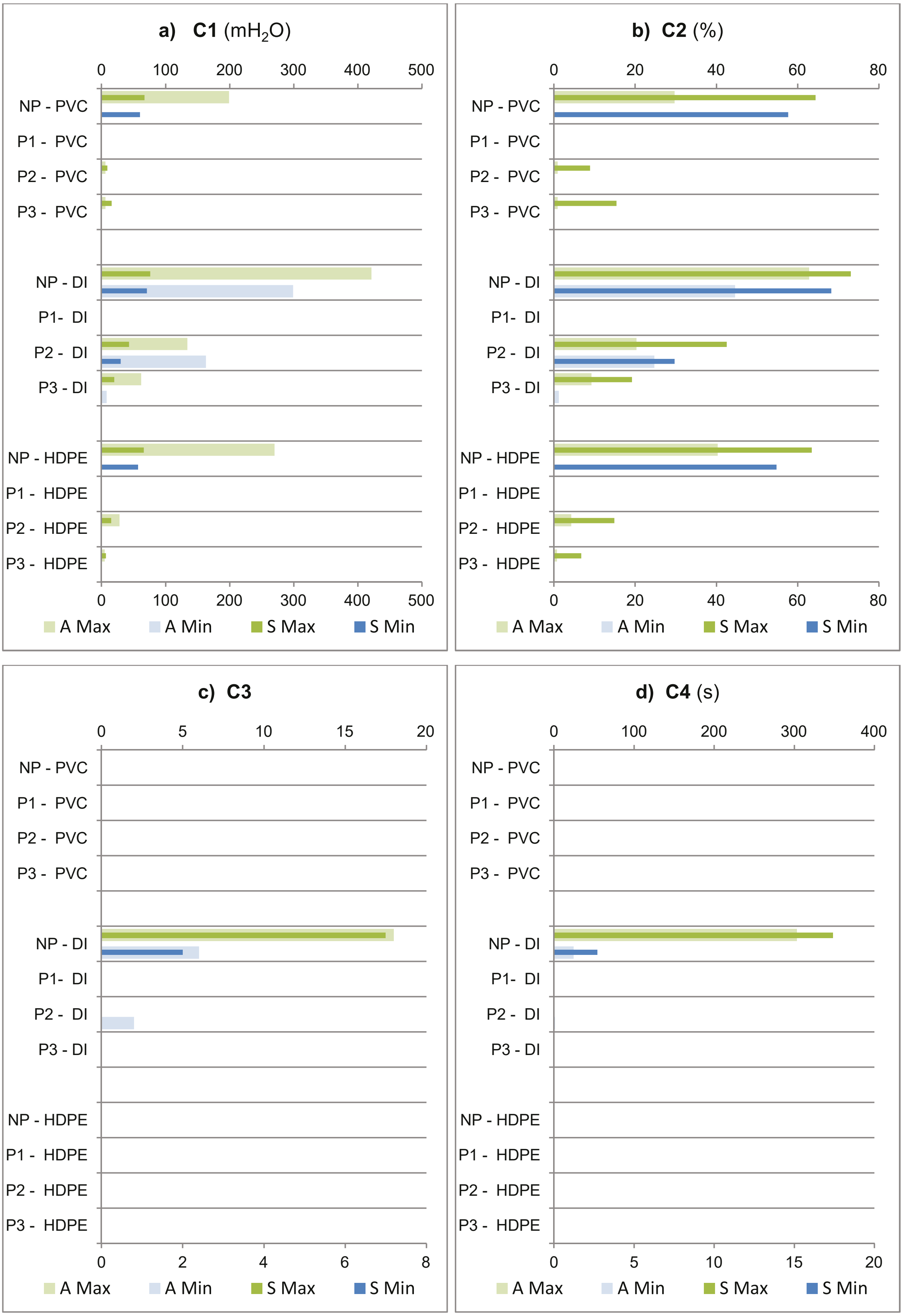


FIGURE 36: GEAV – a) C1 – Number of junctions with pressure < 0; b) C2 – Percentage of junctions with pressure < 0; c) C3 – Number of junctions with vacuum pressure; d) C4 – Total time cavitation.

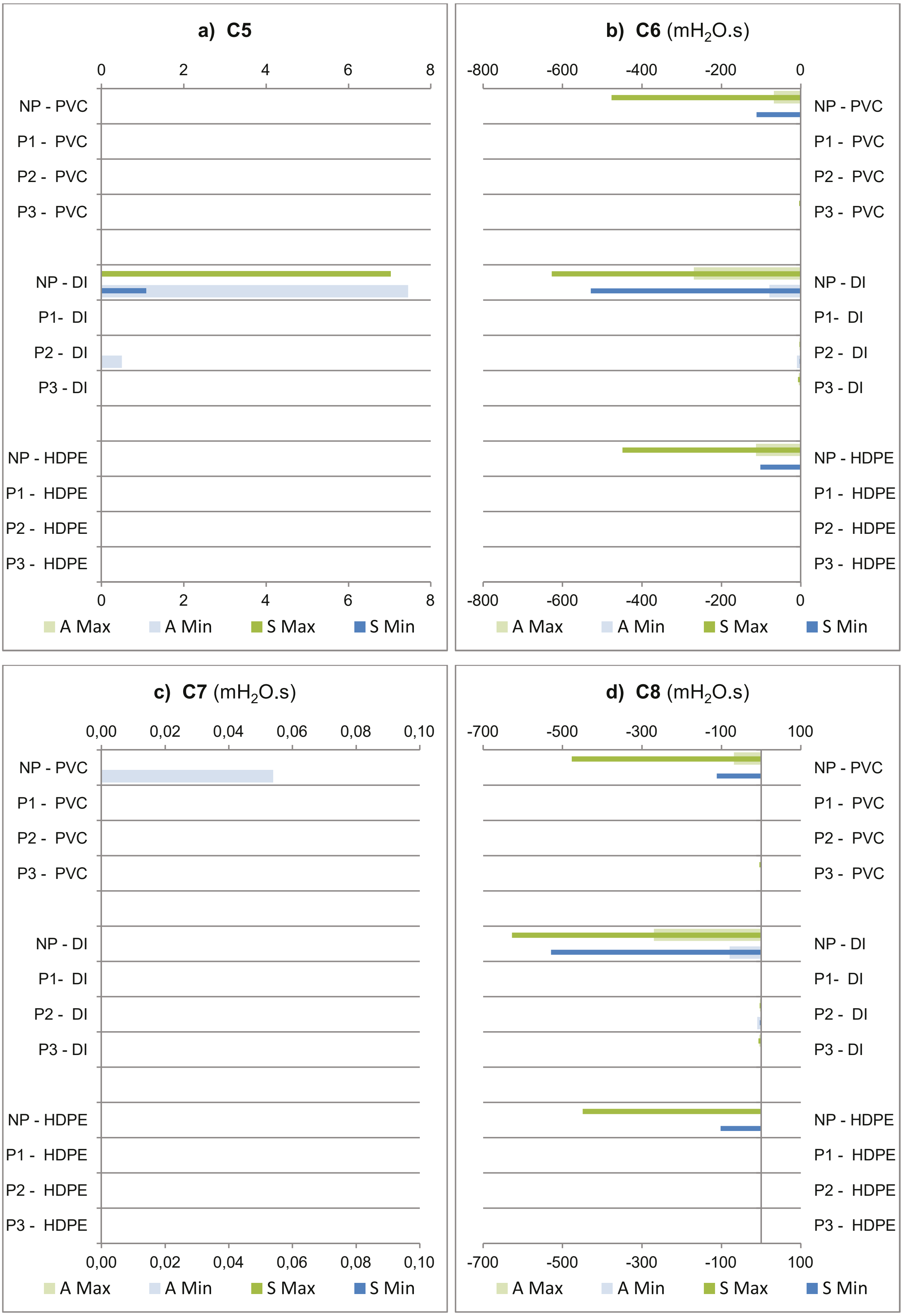


FIGURE 37: GEAV – a) C5 – Severity of Cavity Index; b) C6 – Surge Damage Potential Factor Negative; c) C7 – Surge Damage Potential Factor Positive; d) C8 – Surge Damage Potential Factor.

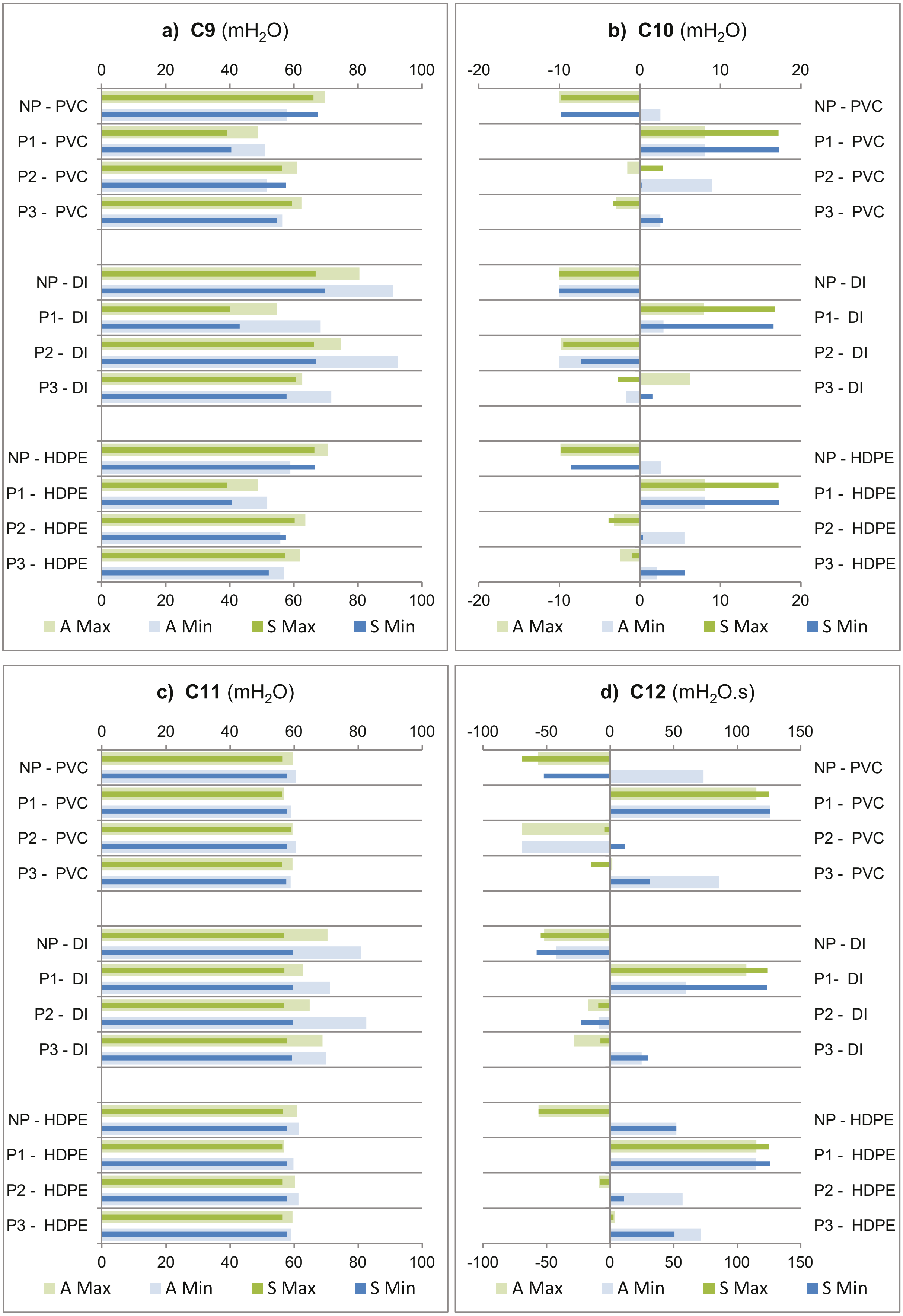


Figure 38: GEAV – a) C9 – Pressure range; b) C10 – Minimum Pressure; c) C11 – Maximum Pressure; d) C12 – Negative Transient Risk Index.

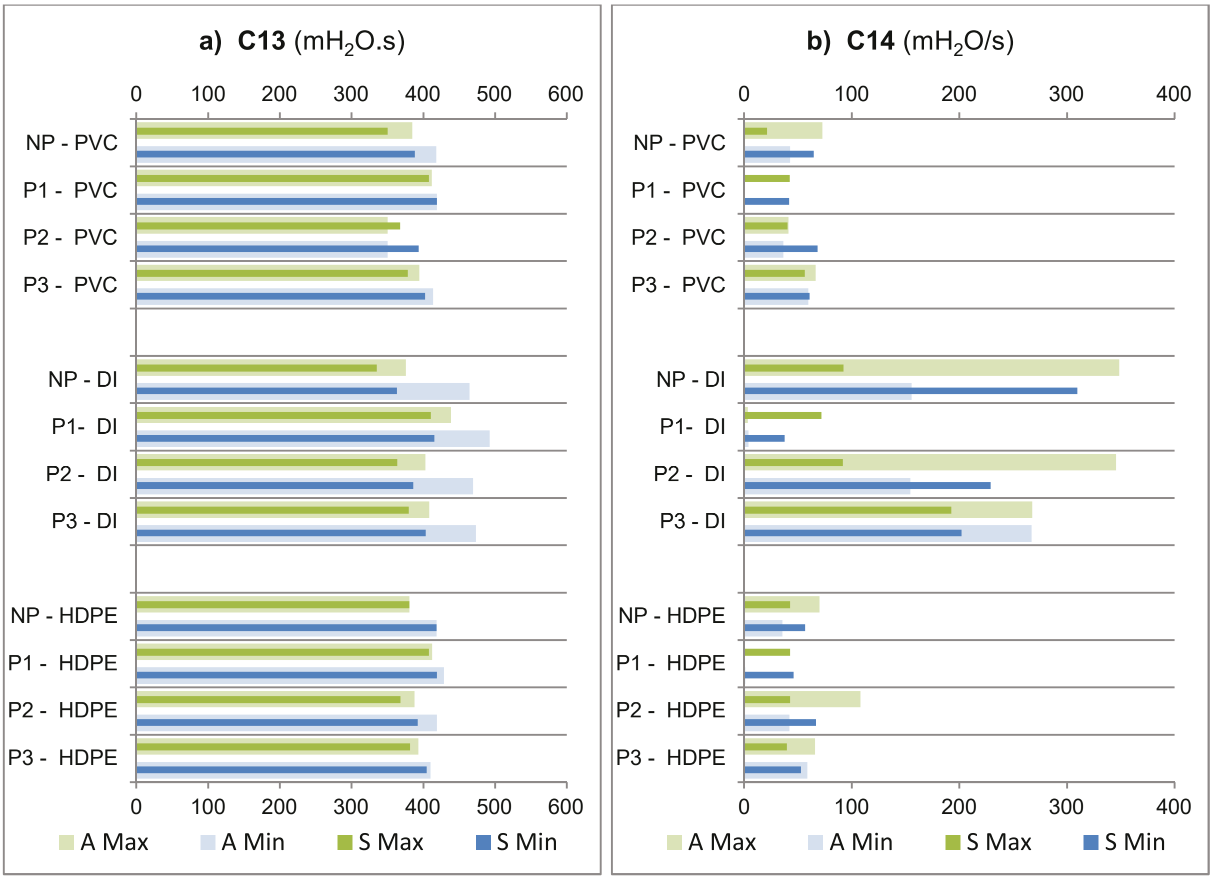


FIGURE 39: GEAV – a) C11 – Positive Transient Risk Index; b) C12 – Damage Index.

In relation to cavitation, the scenarios with PVC and HDPE materials did not show any junction with vacuum pressure, even for the scenarios without any transient protection. For ductile iron, vacuum was detected in some scenarios.

By analyzing the transient damage potential index, we see that for this network the risks are associated with positive pressure only to PVC material and with negative pressure to PVC, ductile iron and HPDE, as shown in C6 – Surge damage potential factor positive (Figure 37b) C7 – Surge damage potential factor negative (Figure 37c). The maximum pressure found to the no protection scenario (NP) was 46.6 to PVC, 62.6 to ductile iron and 46.1 to HPDE, as shown the Figure 38b (C10 – Maximum Pressure) and the minimum pressure found was -9.5 to PVC, vacuum to ductile iron and -9.8 to HPDE, as shown in Figure 38c (C11 – Minimum Pressure). Figure 40 presents the pressure in the junction with maximum pressure and the junction with minimum pressure in no protection scenario of ductile iron running the complete system in the maximum flow.

By avoiding the rapid hydraulic transient through a slow valve closure (P1), in 160 seconds, the indicators C1 to C8 are zero, i.e. all pressures are within the allowed limits. For the indicators C9 to C14 are the scenarios with better values, i.e. less potential of damage to the pipeline. This scenario is the ideal operating condition, which avoids rapid hydraulic transient and, it is only possible through an electric valve with a generator. In case of valve control failure, the valve is operated again according to the unprotected scenarios and transient protection devices are necessary.

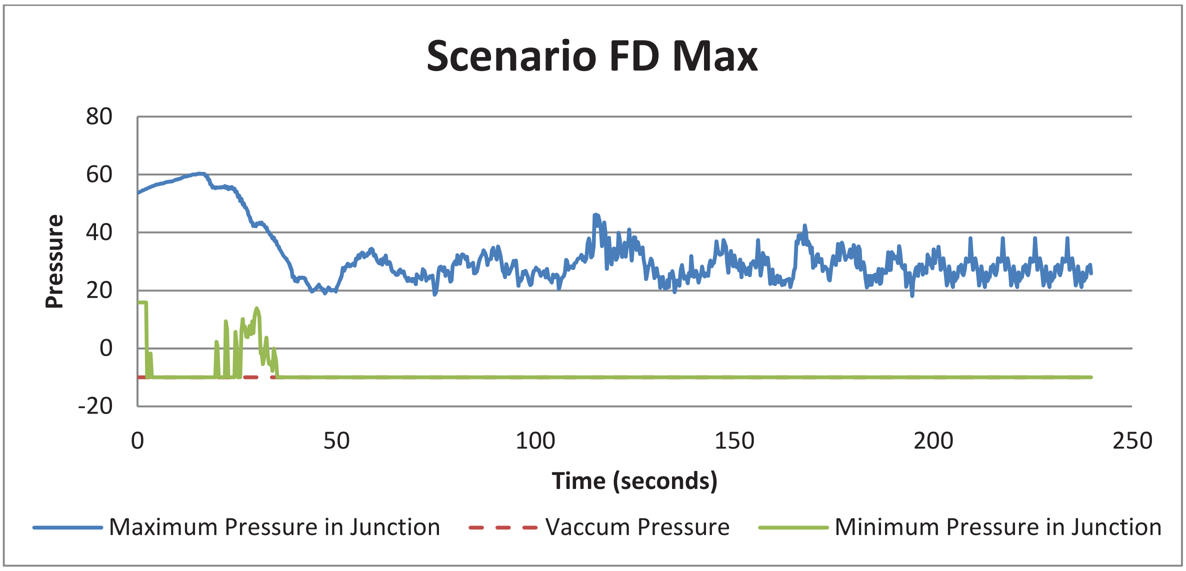


FIGURE 40: GEAV – Pressure Maximum and Mininum in the NP – DI Scenario

Comparing the air valves (P2) and hydropneumatic tank (P3) protection devices, the air valves were more effective, eliminating all negative pressure junctions for PVC and HDPE and greatly reducing the number for ductile iron.

6.1.4 NETWORK ANALYSIS

Analyzing the results of these three networks and comparing the unprotected scenarios that represent all the pipes of the three materials: PVC, ductile iron and HDPE, it is possible to observe that the highest indicators, or greater risks due to transients, are ductile iron, followed by HDPE and lastly PVC. This is due to the celerity of the materials, the ductile iron being about two-three times greater than the plastic materials. It is worth mentioning that although the ductile iron has represented the results in relation to these indicators, as current joints guarantee the tightness to the exterior, even in case of partial vacuum in the pipe.

Comparing also the scenarios with all pipes and scenarios with skeletonized pipes, which is the case the number of junctions are significantly reduced, the skeletonized scenarios tend to underestimate the extreme surge pressures, not correctly representing the real value of the risks and should not be used for analysis of water distribution systems

Other fact observed in these three networks is that the scenarios with plastic materials (PVC and HDPE) the maximum flow scenarios tend to be the ones with worst results, i.e. the critical scenario, and with ductile iron the minimum flow scenarios tend to be the ones with worst results. However, this is just a tendency and isn't constant to all indicators, and it is advisable to simulate both flows for any material.

6.2 INDICATOR ANALYSIS

Table 19, 20 and 21 summarize the analysis of the three distribution networks based on Table 18, which adopted limits to characterize network risk.

TABLE 18: ADOPTED LIMITS TO CHARACTERIZE NETWORK RISK

		IDEAL	ALLOWED	NOT ALLOWED
C1	Number of junctions with pressure minor than zero	0	0 < J ≤ 25	> 25
C 2	Percentage of junctions with pressure minor than zero	0	0 < J ≤ 5	> 5
C 3	Number of junctions with vacuum pressure	0		> 0
C 4	Total time cavitation	0		> 0
C 5	Severity of cavity index	0		> 0
C 6	Surge damage potential factor positive	0	-10 < C6 ≤ 0	< -10
C 7	Surge damage potential factor negative	0	0 < C7 ≤ 10	> 10
C 8	Surge damage potential factor	0	-10 < C8 ≤ 10	< -10 or > 10
C 9	Pressure range	≤ 60	60 < C9 ≤ 100	> 100
C10	Minimum pressure	> 0	-10 ≤ C10 ≤ 0	< -10
C11	Maximum pressure	≤ 60	60 < C11 ≤ 100	> 100
C12	Negative transient risk index	> 0	-25 < C12 ≤ 0	< -25
C13	Positive transient risk index	≤ 300	300 < C13 ≤ 400	> 400
C14	Damage index	≤ 50	50 < C14 ≤ 100	> 100

The adoption of limits was based on:

- Vacuum pressure was treated as unacceptable, so *C3, C4* and C5 have just the ideal situation that is no presence of vacuum and the not allowed situation that has the presence of vacuum.
- Index related with maximum pressure used as ideal situation the system pressure below of the PVC pipe supported pressure, that is 60 mH_2O, and to not allowed, system pressure above the HDPE and ductil iron supported pressure in steady state, that is 100 mH_2O. As allowed situation was used the system pressure between ideal and not allowed. This parameter was used in the *C9* and *C11* indexes.

TABLE 19: RVAM

SYSTEM			COMPLETE														SKELETONIZED													
C			1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PVC	NP	1M	🔴	🟡	🟢	🟢	🟢	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🔴	🔴	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🔴	🟡	🟡	🟡	🟡	🔴	🟡
		2M	🔴	🟡	🟢	🟢	🟢	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🔴	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🟢
		2m	🔴	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🟡
	P1	1M	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡
		2M	🟡	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🟡	🟡	🟡	🟢	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🔴	🟢
		2m	🟡	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🟡	🟡	🟡	🟢	🔴	🟢	🟡	🟡	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🔴	🟡
	P1B	1M	🔴	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟢	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡
		2M	🔴	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟢	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟢	🔴	🟢
		2m	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟢	🔴	🟢	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟢	🔴	🟡
	P2	1M	🔴	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟢	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟢	🔴	🟡
		2M	🔴	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟢
		2m	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟡
	P3	1M	🔴	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟢	🔴	🟢
		2M	🔴	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🟢
		2m	🟡	🟡	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🔴	🟢
DI	NP	1M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🟢	🟡	🔴
		1m	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴
		2M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴
		2m	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴
	P1	1M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🟡	🔴
		1m	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟡	🔴	🟡	🟡	🔴	🔴
		2M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🟡	🟡	🔴
		2m	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟡	🔴	🟡	🟡	🔴	🔴
	P2	1M	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🟡	🟡	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴
		1m	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🟡	🟡	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🔴	🟡	🔴	🟡
		2M	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🟡	🟡	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
		2m	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴	🔴	🟡	🔴	🟡
	P3	1M	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🟡	🟢
		1m	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🟢
		2M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🟡	🔴	🟡	🟢
		2m	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🟡
HDPE	NP	1M	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟡	🔴	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟡	🔴	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🔴	🔴	🟢
		2M	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟡	🔴	🔴	🟢	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
		2m	🔴	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟡	🔴	🔴	🟡
	P1	1M	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟢	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
		2M	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟢	🔴	🟢
		2m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
	P2	1M	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
		2M	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🔴	🔴	🟢
		2m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
	P3	1M	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
		1m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
		2M	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟡	🔴	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢
		2m	🔴	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🟢

- Index related with minimum pressure, as *C10*, was classified in ideal when pressure system was above the atmospheric pressure and as not allowed below tha vaccum pressure. As allowed situation between vaccuem and atmospheric pressure.
- The others indexes, as: *C1, C2*, surge damage potential (*C6, C7* and *C8*), transient risk index (*C12* and *C13*) and damage index (*C14*) was arbitrated parameters based on results of the scenarios. However, much more networks need to be run and indexes calculate to have better classification.

The objective of the classification is become more visual the obtained results, however the accepction of differents results depends of the materials they are exposed, so it can change depending the network.

To represent the maximum flow was used M, and the minimum flow m.

TABLE 20: GAAM

SYSTEM			ALL PIPIES														SKELETONIZED													
C			1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PVC	NP	M	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🔴	🟢	🟡	🟡	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🔴	🟢	🟡
		m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🔴	🟡	🟢	🟡	🟡	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🔴	🟡	🟢
	P1	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟡	🟢
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
	P2	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢
	P3	M	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🔴	🟡	🟡
		m	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟡	🟢	🟡	🟡	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🟡	🟡	🟢
DI	NP	M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟢	🟡	🟢	🔴	🟡	🔴	🟡	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🔴	🟢	🔴
		m	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🟡	🟢	🔴	🟡	🟡	🟡	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🟢	🟢	🟡
	P1	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡
	P2	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴
		m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🔴	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟡	🟡
	P3	M	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🔴	🟡	🔴
		m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟢	🔴	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟡	🟡
HDPE	NP	M	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟢	🟢	🔴	🟢	🟡	🟡	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🔴	🟢	🟡
		m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟢	🟢	🔴	🟡	🟢	🟡	🟡	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🟡	🟢	🔴	🟢	🟢
	P1	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢
	P2	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢
	P3	M	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟢	🟢	🔴	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🔴	🟡	🟡
		m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟡	🟢

Tables 19, 20 and 21 makes possible compare the three water distribution system. It's interesting to compare, for example, which of the no protection scenario shows the most critical risks and could be a metodology to sanitation companies stablish a priority the investments in hydraulic transient protection. Besides that, it's easier to choose the most effective protection device.

TABLE 21: GEAV

			ALL PIPES														SKELETONIZED													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12		
PVC	NP	M	🟡	🟡	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟢	🔴	🟡	🟡	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟢	🔴	🟡	🟡
		m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🟢	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟢	🔴	🟡	🟢
	P1	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
	P2	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🔴	🟡	🟢	🟡	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟢	🟢	🟡	🟡	🟡
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢
	P3	M	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟢	🟢	🟡	🟡	🟡	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟡	🟡
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
DI	NP	M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟢	🔴	🟡	🟡
		m	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🟡	🔴	🟢	🔴	🟡	🟢
	P1	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
	P2	M	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟢	🟡	🟢	🟢
		m	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🔴	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟢	🟡	🟢	🟢
	P3	M	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟡	🟢	🟡	🟢	🟢
		m	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🟡	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
HDPE	NP	M	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟢	🔴	🟡	🟡
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🔴	🟡	🔴	🔴	🟢	🟢	🟢	🔴	🟢	🔴	🟡	🟡	🟢	🟢	🔴	🟢
	P1	M	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
	P2	M	🔴	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🟡	🟡	🟡
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢
	P3	M	🟡	🟡	🟢	🟢	🟢	🟡	🟢	🟡	🔴	🟡	🟢	🟢	🟡	🟡	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🟢
		m	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🔴	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢

7 FINAL CONSIDERATIONS

“Science never solves a problem without creating ten more” (George Bernard).

Operation of existing water distribution systems considering lower power consumption, smaller physical loss and less spent on corrective maintenance is one of the major challenges faced by sanitation companies. In Brazil this need is increasingly being known and required by the population, compare to water and energy crisis and the lack of investment by the government.

With this in mind, this project provides a complete analysis of water distribution systems focusing on hydraulic transient, does proving the strong need of this study in Brazilian systems.

The calculation of the fourteen indicators to three diferents networks made possible sensitivity analyse of the variation of: celerity, flow, junction number, differents protection devices and pressure zones.

The differents materials proved one more time the influence of celerity during the simulation. While the plastic materials (PVC and HDPE) presented similar results, ductile iron presented well more caotics scenarios.

Depending of the scenario, the critic scenario was variable between the maximum and the minimum flow, proving the need of run both scenarios to evaluate the most efficient hydraulic protection.

The analysis of skeletonized and complete systems proved the non effiency of the skeletonized to calculate WDS hydraulic transient. The results indicates that the designers can potentially add devices that won't be useful in the network protection, by under or superestimating transient analysis.

On the other hand, the detailed analysis was possible only because of the use of software that simulates more than 2.000 juntions in 800-time steps in just ten minutes for each scenario.

Despite in this study had been choose some devices protection to analyse, that were surge: tank, hydropneumatic tank and air valves, as presented in chapter two, the number of protection is huge so many others possibilitys can be make as: pressure-relief valve, surge antecipation valve, feed tank, differents closed tanks and change the pump inertia. Furthermore, the garantee of system safety can be made by the combination of more than one protection device.

The study of differents pressure zones indicated that the risk isn't an isolate case in the WDS, but common and frequently. Moreover, the indicators enabled evaluate the pressures zones more exposed to the risks.

The real systems nowadays are operating in the unprotected scenario of PVC and all of them have been shown to be susceptible to hydraulic transient conditions. Therefore, they are exposed to negative and positive pressures during transients, below and above, respectively, of the pipe's allowed pressure. This can break pipes and junctions causing water physical loss and repair costs. Besides that, when the outside pressure is higher than inside, can imply in contamination of the water.

In view of the results, this study encourages the Brazilian sanitation companies to demand the hydraulic transient calculation in the water distribution networks designs.

However, this kind of study is yet a challenge to be surpassed. Nowadays the studies required by Brazilian sanitation companies are limited to water and sewage transfers pipes and most of them is presented with low technical level and with basic conceptions mistakes.

The time spent to run a WDS hydraulic transient is several times greater than to run just a line because of the complex network. Additionaly, the possible combination of protection devices is also greater.

Other thing to be surpassed is that a lot of designers still think that the WDS don't sufer the effects of hydraulic transients because of topology and greater number of pipes.

In order to make this applicable, investments in courses and the development of a guideline to the Brazilian conditions is required. To design new water networks, the hydraulic transient should be calculated in the conception to help in the decision of what material will be used and the topology of pipe distribution.

With the material chosen at least the following scenarios should be simulated:

- No protection;
- Turning the fast transient in slow: should explain how make it possible;
- Evaluation of maximum and minimum flow;
- Protection devices: at least three scenarios, with protections combinations

By calculating the 14 indicators proposed in this dissertation is possible to choose what protection could be used. In case of similar protection with different devices, it should be calculated the Operating Expenses – OPEX and chosen the smallest one.

7.1 FUTURE WORKS

As possible future works can be pointed:

- Compare the simulations results with real datas of pressure that can be mesured by high frequency datalloggers (like 25 or 100 datas by second);
- Mensure the water distribution networks quality in the points that the study indicated low pressure during the hydraulic transient;
- Compare the costs between to implant protection devices and repair costs in pipes and junctions summed up to the water losses costs. The difficulty in this study is the little information on pipe rupture records that not relate exactly the cause of them.

8 REFERENCE

AFT. Applied Flow Technology. Available from: <http://www.aft.com/products/impulse/>. Acess in 1st November 2017.

ALLIEVI. Available from: <http://www.allievi.net/allievi-es.php>. Acess in 1st November 2017.

ARI VALVES. Available from: <https://www.arivalves.com/index.php/products/water-supply>. Acess in 24th August 2017.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 12215 - Projeto de adutora de água para abastecimento público (Water Main Design for public water supply). 1991

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 12215 - Projeto de adutora de água para abastecimento público (Water Main Design for public water supply). 2017.

BERMAD. Available from: <http://www.bermad.com/products/waterworks/>. Acess in 3rd February 2017.

BENTLEY SYSTEMS. Available from: <https://www.bentley.com/en/products/product-line/hydraulics-and-hydrology-software/hammer>. Acess in 9th September 2017.

BOULOS, P.; KARNEY, B; WOOD, D; LINGIREDDY, S. (May, 2005). Hydraulic Transient Guidelines for Protecting Water Distribution Systems. Journal AWWA, pp. 111-124.

CHAIKO, M. A. et al. (March, 2002). Models for analysis of water hammer in piping with entrapped air. Journal of Fluids Engineering, v. 124, n. pp. 194–204, 2001. ISSN 00982202.

CHAUDHRY M. H. (1979). Applied Hydraulic Transients. Van Nostrand Reinhold Company. New York.

CHARLATTER. Available from: <http://www.charlattereservoirs.fayat.com/fr/gamme-eaux-claires>. Acess in 5th October 2017.

COLOMBO, A; LEE, P; KARNEY, B. (2009). A selective literature review of transient-based leak detection methods". Journal of Hydro-environment Research 2, pp. 212-227

COLLINS, R.; BOXALL, J. (2013). Influence of Ground Conditions on Intrusion Flows through Apertures in Distribution Pipes, J. Hydraul. Eng.-ASCE 139, pp. 1052-1061.

DELTARES. Available from: <https://www.deltares.nl/en/software/wanda/>.Acess in 1st November 2017.

EBACHER, G.; BESNER, M. C.; LAVOIE, J.; JUNG, B. S.; KARNEY, B. W.; PRÉVOST, M. (2011). Transient modeling of a full-scale distribution system: comparison with field data. J Water Resour Plan Manag 137(2):173–182

ELBASHIR, M.; AMOAH, S. (2007). Master Thesis. Hydraulic Transient in a Pipeline Using Computer Model to Calculate and Simulate Transient. Lund University, Sweden.

EPA (2017). United States Environmental Protection Agency. Available in: <https://www.epa.gov/water-research/epanet>. Acess in 10th October 2017.

FERNANDES, C.; KARNEY, B. (2004). Modelling the advection equation under water hammer conditions. Urban Water Journal. 1:2, 97-112, DOI: 10.1080/15730620412331290038

FILION, Y.; AND KARNEY, B. W. (2002). A Numerial Exploration of Transient Decay Mechanismis in Water Distribution Systems. Proceedings of the ASCE Environmental Water Resources Institute Conference. America Society of Civil Engineers, Roanoke, Virginia.

FONTANAZZA, C. M. (2015). 13th Computer Control for Water Industry Conference. Contaminant intrusion through leaks in water distribution system: experimental analysis.

FRIEDMAN, M. L.; RADDER, S.; HARRISON, D.; HOWIE, M.; BRITTON, G.; BOYD, H.; WANG, R.; GULLICK, M.; LECHEVALLIER, D.; WOOD, D; FUNK, J. (2004). Verification and Control of Low Pressure Transients in Distribution Systems. AWWA Research Foundation. Denver, CO.

FUNK, J. E.; WOOD, D. J.; VANVUUREN, S. J.; LCCHEVALLIER, M. (1999). Pathogen intrusion into water distribution systems due to transients. Proc., 3rd\ASME/JSME Joint Fluids Engineering Conference, July 18e23, San Francisco.

GHORBANIAN, V.; KARNEY, B.; GUO, Y. (2016). Pressure Standards in Water Distribution Systems: Reflection on Current Practice with Consideration of Some Unresolved Issues. J. Water Resour. Plann. Manage. 04016023. DOI: 10.1061/(ASCE)WR.1943-5452.0000665.

HYDROBALLS. Available from: <http://www.hydroballs.com/en/>. Acess in 22nd May 2017.

ITM – Illinois Transient Model. University of Houston. Available from: <http://www2.egr.uh.edu/~aleon3/ITM.htm>. Acess in 3rd November 2017.

JUNG, B.; KARNEY, B. (2003). Optimum Selection of Hydraulic Devices for Water Hammer Control in Pipeline Systems Using Genetic Algorithm. Joint Fluids Engineering Conference Honolulu, Hawaii, USA, July 6-10, 2003.

JUNG, B.; KARNEY, B. (2006). Hydraulic Optimization of Transient Protection Devices Using GA and PSO Approaches. Journal of Water Resources Planning and Management. January/february ASCE 44-52.

Jung, B. S.; Karney, B. W. (2011). Application of fluid transients on pipeline optimization: Worst-case scenario search and systematic protection. Proc. Conf. on Probabilistic Methodologies in Water and Wastewater Engineering, Toronto.

JUNG, B. S.; BOULOS, P. F.; WOOD, D. J. (2007). Pitfalls of water distribution model skeletonization for surge analysis. Journal AWWA 99(12):87–98

JUNG, B.; BOULOS, P.; WOOD, D.; BROS, C. (2009). A Lagrangian wave characteristic method for simulating transient water column separation. Journal AWWA, 64-73.

JUNG, B.; BOULOS, P.; ALTMAN, T. (2011). Optimal transient network design: A multi-objective Approach. Journal AWWA, 103:4, 118-127

KALAISELVAN, A. S. V.; SUBRAMANIAM, U.; SHANMUGAM, P.; HANIGOVSKI, N. (2016). A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system. Applied Energy, 181, 495-513.

KARIM, M.R.; ABBASZADEGAN, M.; LECHEVALLIER, M. (2003). Potential for pathogen intrusion during pressure transients. Journal of AWWA 95 (5), 134-146.

KARNEY, B.; MCINNIS, D. (1990). Transient analysis of water distribution systems. Journal of AWWA, R2 (7), 62-70.

KARNEY, B.; MCINNIS, D. (1992). Efficient Calculation of Transient Flow in Simple Pipe Networks. J. Hydraul. Eng. 118: 1014-1030.

KARNEY, B.; SIMPSON, A. (2007). In-line check valves for water hammer control. Journal of Hydraulic Research, Vol. 45, No. 4 (2007), pp. 547-554

KARNEY, B., (2014). Water Infraestructure: Long Term Supply, Demand Management and Planning. Journal of AWWA, R2 (7), 62-70.

KIRMEYER, G. J. et al. (2001). Pathogen intrusion into the distribution system. AWWA Research foundation, AWWA, Denver.

KYPIPE (2017). Available from: <http://kypipe.com/surge/>. Acess in 14th September 2017.

LAHC. Laboratorio de Hidraulica Computacional. Available from: <http://www.lahc.ufc.br/>. Acess in 26th October 2017.

LANSEY, K.; BOULOS, P. (2005). Cmprehensive Handbook on Water Quality Analysis for Distribution Systems. 448 pages.

LECHEVALLIER, M.W. (1999). The Case for Maintaining a Disinfectant Residual. Journal of AWWA. 91: 86-94.

LINDLEY, T. R.; BUCHBERGER, S. G. (2002). Assessing intrusion susceptibility in distribution systems, J. Am. Water Works Assoc. 94, pp. 66-79.

MARTIN, C. S. (1983). Experimental investigation of column separation with rapid closure of downstream valve. Proc., 4th Int. Conf. on Pressure Surges, British Hydromechanics Research Association (BHRA), Bath, U.K.

MARTIN, C. S. (2000). Hydraulic transient design for pipeline systems. In: Water Distribution Systems Handbook.

MCINNIS, D.; KARNEY, B. (1990). Transient in Distribuition Networks: Field Tests and Demand Models. Canadian Water Network, 1-5.

MCINNIS, D. (2004). A relative-risk framework for evaluating transient pathogen intrusion in distribution systems. Urban Water Journal, 1:2, 113-127, DOI: 10.1080/15730620412331290010

PARMAKIAN, J. (1963). Waterhammer Analysis. Dover Publications, Inc., New York, New York.

PEROBA JUNIOR, F. (2007). Dissertação, Modelagem computacional de ventosas de duplo efeito como mecanismo de alívio do golpe de aríete. Fortaleza - Ce: [s.n.], p.152.

POTHOF, I.; KARNEY, B (2012). Guidelines for Transient Analysis in Water Transmission and Distribution Systems, Water Supply System Analysis - Selected Topics, Dr. Avi Ostfeld (Ed.), ISBN: 978-953-51-0889-4, InTech, DOI: 10.5772/53944. Available from: <http://www.intechopen.com/books/water-supply-system-analysis-selected-topics/guidelines-for-transient-analysis-in-water-transmission-and-distribution-systems>

RAMALINGAM, D. 2007. Design Aids for Air Vessels for Transient Protection of Large Pipe Networks - A Framework Based on Parameterization of Knowledge-Base Derived From Optimized Network Models. Lexington, Kentucky

RAMEZANI, L.; KARNEY, B.; MALEKPOUR, A (2015). The Challenge of Air Valves: A Selective Critical Literature Review. J. Water Resour. Plann. Manage.

RADULJ, D. (2009). Assessing the hydraulic transient performance of water and wastewater systems using field and numerical modeling data. Master's thesis, Univ. of Toronto, Toronto.

RADULJ, D. (2010). Assessing the Hydraulic Transient Performance of Water and Wastewater Systems Using Field and Numerical Modeling Data. Master of Applied Science Graduate Department of Civil Engineering. University of Toronto.

SNIS. Sistema Nacional de Informação do Saneamento. Available from: <http://www.snis.gov.br/>. Acess in 27th October 2017.

STARCZEWSKA, D.; COLLINS, R.; BOXALL, J. (2014). Transient behavior in complex distribution network: a case study. 12th International Conference on Computing and Control for the Water Industry, CCWI 2013

STEPHENSON, D. J. (1984). Pipeflow Analysis, Volume 19. 1st Edition. eBook ISBN: 9780080870106. Imprint: Elsevier Science. Published Date: 1st February 1984

SHINOZUKA, M.; DONG, X. (2005). Monitoring and management of water supply systems. 4th Korea Infrastructure Safety and Technology Corporation (KISTEC) Int. Seminar on Safety of Infrastructures, KISTEC, Jakarta, Indonesia.

STREETER, V. L.; WYLIE, E. B. (1967). Hydraulic transients, New York, ch. 3

Tullis, J. P. Hydraulic of pipelines: pumps, valves, cavitation, transients, one Ed., John Wiley & Sons, Inc., New York, 1989.

WALSKI, T. M.; KOELLE, E. Transients in Hydraulic Systems. In: WALSKI, T. M.; CHASE, D. V.; SAVIC, D. A.; GRAYMAN, W.; BECKWITH, S.; and KOELLE, E. "Advanced Water Distribution Modeling and Management". 1. ed. Waterbury, CT, 2003. cap.13, p. 573-623.
Walski TM, Daviau J, Coran S (2004) Effect of skeletonization on transient analysis results. Proc. ASCE EWRI Conf., Salt Lake City.

WYLIE, E. B.; STREETER, V. L. (1993). Fluid Transients in Systems. Prentice-Hall, Englewood Cliffs, New Jersey.

WOOD, D.; LINGIREDDY, S; BOULOS, P.; KARNEY, B; MCPHERSON, D. (2005). Numerical methods for modeling transient flow in distribution systems. Journal AWWA, 97:7

WOOD, D. (2005). Waterhammer Analysis – Essential and Easy (and Efficient). Journal of Environmental Engineering. Vol. 131, No. 8, August 1, 2005. ASCE, ISSN 0733-9372/2005/8-1123–1131. Pg.1123 – 1131.

ZHANG, K.; KARNEY, B.; MCPHERSON, D. (2008). Pressure-relief valve selection and transient pressure control. Journal of AWWA, 100:8, pp. 62-69.

APPENDIX A – CELERITY OF PIPES

The speed of the pipes was calculated by Equation (5), as shown in follow Table. Clean water 20°C.

PIPE CELERITY

Material	Nominal Diameter (mm)	Celerity (m/s)
PVC	50	191.55
	75	229.36
	100	258.83
	150	300.20
	200	341.28
	250	377.05
	300	408.95
Steel	50	1,419.87
Ductile iron	80	1,380.26
	100	1,354.29
	150	1,273.49
	200	1,232.49
	250	1,164.56
	300	1,291.99
HDPE	50	292.76
	75	291.92
	100	289.79
	150	290.44
	200	290.74
	250	290.74
	300	290.42

RVAM		PVC																			
		NO PROTECTION				AIR VALVES				AIRVALV/PVC CL20				SURGE TANK				RHO			
		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump	
		Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min
ALL PIPES	C1	140	15	180	55	25	4	4	5	25	4	4	5	93	19	131	7	73	5	126	19
	C2	11.49	1.23	14.78	4.52	2.11	0.34	0.34	0.42	2.11	0.34	0.34	0.42	7.64	1.56	10.76	0.57	5.99	0.41	10.34	1.56
	C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	-21.54	-1.08	-28.27	-7.49	-0.18	-0.03	-0.04	-0.04	-0.18	-0.03	-0.04	-0.04	-4.22	-1.26	-12.16	-0.18	-5.48	-0.21	-16.20	-1.50
	C7	108.95	84.80	71.81	49.66	99.31	42.23	40.65	295.14	0.00	0.00	0.00	0.00	110.07	52.00	72.93	87.53	112.55	91.29	75.07	55.00
	C8	87.41	83.71	43.54	42.17	99.13	42.20	40.61	295.09	-0.18	-0.03	-0.04	-0.04	105.85	50.75	60.77	87.35	107.07	91.07	58.87	53.50
	C9	83.27	78.16	82.24	79.46	75.41	73.54	71.02	82.90	75.41	73.54	71.02	82.90	76.75	75.54	82.05	74.78	80.71	74.88	81.65	75.15
	C10	-9.91	-5.54	-9.34	-9.99	-2.29	-1.26	-2.15	-1.44	-8.92	-6.54	-7.23	-7.56	-5.46	-5.09	-9.69	-2.16	-7.59	-2.36	-9.29	-4.59
	C11	73.36	72.62	72.90	69.47	73.12	72.28	68.87	81.46	66.49	67.00	63.79	75.34	71.29	70.45	72.36	72.62	73.12	72.52	72.36	70.56
	C12	-56.71	-26.96	-53.01	-63.44	-5.28	-5.36	2.23	2.61	-5.28	-5.36	2.23	2.61	-36.35	-2.03	-48.78	-57.24	-30.47	-0.37	-43.84	-14.34
	C13	468.16	476.34	470.54	471.11	470.20	523.26	455.80	459.13	470.20	523.26	455.80	459.13	467.99	475.94	464.22	498.85	467.90	475.96	464.21	466.11
	C14	45.00	50.67	45.00	50.67	46.67	133.00	55.33	46.00	46.67	133.00	55.33	46.00	47.33	46.00	47.33	46.00	57.00	54.33	57.00	54.33
SKELETONIZED	C1	37	21	98	44	46	21	49	23	46	21	49	23	54	11	70	31	63	9	82	37
	C2	6,68	3,79	17,69	7,94	8,42	3,85	8,97	4,21	8,42	3,85	8,97	4,21	9,75	1,99	12,64	5,60	11,37	1,62	14,80	6,68
	C3	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	C4	1,80	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	C5	0,21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	C6	-21,06	-1,25	-33,76	-6,82	-0,79	-0,13	-0,40	-0,20	-0,79	-0,13	-0,40	-0,20	-1,35	-0,25	-4,52	-0,74	-3,29	-0,74	-10,13	-2,07
	C7	0,00	0,00	29,19	0,00	58,73	54,66	29,02	13,86	0,00	0,00	0,00	0,00	66,19	50,90	29,08	12,32	66,47	291,88	29,19	266,42
	C8	-21,06	-1,25	-4,57	-6,82	57,94	54,53	28,62	13,67	-0,79	-0,13	-0,40	-0,20	64,84	50,65	24,56	11,58	63,18	291,14	19,06	264,35
	C9	80,43	76,49	74,67	72,15	75,81	72,58	69,45	63,27	75,81	72,58	69,45	63,27	62,14	73,56	73,21	65,58	78,10	76,51	74,28	76,67
	C10	-9,90	-6,17	-9,90	-9,97	-5,39	-2,26	-5,08	-2,19	-5,39	-2,26	-5,08	-2,19	8,28	-3,24	-8,84	-4,74	-7,68	-4,36	-9,60	-4,52
	C11	70,53	70,32	64,77	62,18	70,42	70,32	64,37	61,08	70,42	70,32	64,37	61,08	70,42	70,32	64,37	60,84	70,42	72,15	64,68	72,15
	C12	-59,70	-22,41	-65,08	-47,18	8,86	-6,34	7,98	1,47	8,86	-6,34	7,98	1,47	-2,07	0,60	-41,17	-14,81	-0,69	0,60	-41,17	-13,75
	C13	476,29	475,99	422,50	393,11	476,34	475,92	430,14	410,61	476,34	475,92	430,14	410,61	476,23	475,85	422,07	415,05	476,29	464,63	422,07	482,91
	C14	45,00	50,33	45,00	50,33	45,00	53,33	45,33	53,33	45,00	53,33	45,33	53,33	45,33	52,67	45,33	52,67	45,00	42,33	45,00	42,33

RVAM		DUCTILE IRON															
		NO PROTECTION				AIR VALVES				SURGE TANK				RHO			
		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump	
		Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min
ALL PIPES	C1	326	545	330	554	221	296	226	299	261	429	288	447	317	346	303	354
	C2	26.77	44.75	27.09	45.48	18.62	24.94	19.04	25.19	21.43	35.22	23.65	36.70	26.03	28.41	24.88	29.06
	C3	6.00	11.00	6.00	11.00	0.00	1.00	0.00	1.00	5.00	6.00	5.00	9.00	7.00	1.00	6.00	3.00
	C4	138.00	196.80	134.10	170.70	0.00	0.30	0.00	0.30	39.60	34.20	42.60	34.80	54.60	47.40	66.30	55.20
	C5	46.49	66.29	45.17	57.50	0.00	0.10	0.00	0.10	13.67	11.80	14.70	12.01	18.62	16.16	22.61	18.82
	C6	-78.48	-90.55	-84.33	-94.35	-7.57	-12.91	-7.81	-12.96	-26.79	-25.43	-30.56	-27.97	-67.85	-51.01	-72.62	-57.80
	C7	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.95	0.03	0.50	0.08	0.00	0.00	0.00
	C8	-78.48	-90.35	-84.33	-94.35	-7.57	-12.91	-7.81	-12.96	-26.76	-24.48	-30.54	-27.48	-67.77	-51.01	-72.62	-57.80
	C9	96.57	113.51	87.61	103.20	97.87	103.14	89.20	102.94	116.60	140.04	115.40	136.84	137.26	96.77	107.50	87.61
	C10	-9.98	-9.98	-9.98	-9.98	-9.90	-9.98	-9.98	-9.90	-9.98	-9.98	-9.98	-9.98	-9.98	-9.98	-9.98	-9.98
	C11	86.59	103.53	77.63	93.22	87.97	93.16	79.22	93.04	106.62	130.06	105.42	126.86	127.28	86.79	97.52	77.63
	C12	-48.23	-43.11	-61.97	-51.35	-8.11	-15.28	-10.82	-10.82	-18.47	-13.18	-23.45	-17.31	-57.27	-47.60	-59.29	-51.35
	C13	472.83	581.78	471.53	489.72	491.87	392.98	491.74	491.74	429.82	415.35	431.63	356.69	327.84	495.10	263.91	489.72
	C14	243.00	207.00	214.67	235.33	232.33	266.67	209.67	240.33	230.33	385.00	288.67	361.33	383.00	103.00	318.00	118.00
SKELETONIZED	C1	175	185	152	183	117	128	116	125	20	19	19	18	163	106	136	145
	C2	31,59	33,39	27,44	33,03	21,43	23,44	21,25	22,89	3,61	3,43	3,43	3,25	29,42	19,13	24,55	26,17
	C3	5,00	4,00	6,00	5,00	3,00	1,00	3,00	1,00	1,00	1,00	1,00	1,00	5,00	1,00	4,00	1,00
	C4	34,80	26,70	37,50	31,50	7,20	4,50	7,50	4,50	5,10	6,30	4,80	3,60	19,20	0,60	9,90	1,20
	C5	11,62	8,91	12,52	10,51	2,41	1,51	2,51	1,51	1,69	2,09	1,59	1,19	6,28	0,20	3,24	0,39
	C6	-86,30	-59,98	-88,30	-67,08	-10,41	-9,00	-10,02	-8,47	-1,13	-0,89	-1,13	-0,89	-68,81	-31,89	-68,02	-43,27
	C7	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	21,87	0,68	16,29	4,66	0,00	0,00	0,00	0,00
	C8	-86,30	-59,98	-88,30	-67,08	-10,41	-9,00	-10,02	-8,47	20,74	-0,21	15,16	3,78	-68,81	-31,89	-68,02	-43,27
	C9	92,60	86,75	75,43	75,65	89,13	86,85	88,93	75,75	137,31	118,81	137,31	118,81	94,70	86,75	101,00	75,65
	C10	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98	-9,98
	C11	82,62	76,77	65,45	65,67	79,15	76,87	78,95	65,77	127,33	108,83	127,33	108,83	84,72	76,77	91,02	65,67
	C12	22,17	-58,18	-64,75	-61,08	-25,80	-15,87	-24,85	-14,29	-22,77	-9,26	-35,69	-11,96	-63,16	-48,67	-62,57	-55,20
	C13	354,44	435,02	426,51	415,40	358,61	434,07	357,58	428,16	472,30	472,16	431,72	424,16	356,73	436,80	353,03	417,23
	C14	180,00	124,00	175,00	124,00	169,67	162,00	169,33	134,33	179,33	176,67	179,33	176,67	223,33	66,00	253,33	94,67

RVAM		HDPE															
		NO PROTECTION				AIR VALVES				SURGE TANK				RHO			
		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump		Shut down rvam pump and booster		Shut down just rvam pump	
		Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min
ALL PIPES	C1	170	25	204	87	84	15	96	17	111	7	161	22	128	8	175	32
	C2	13.96	2.05	16.75	7.14	7.08	1.26	8.09	1.43	9.11	0.57	13.22	1.81	10.51	0.66	14.37	2.63
	C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	-20.43	-1.34	-33.40	-7.67	-1.50	-0.36	-1.89	-0.78	-3.98	-0.19	-11.25	-1.01	-6.63	-0.45	-13.07	-1.53
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	-20.43	-1.34	-33.40	-7.67	-1.50	-0.36	-1.89	-0.78	-3.98	-0.19	-11.25	-1.01	-6.63	-0.45	-13.07	-1.53
	C9	86.57	83.87	83.91	81.81	82.01	88.32	79.15	88.12	85.17	78.78	83.75	77.35	85.07	88.05	83.15	90.65
	C10	-9.78	-5.98	-9.19	-3.22	-5.49	-4.06	-5.59	-3.86	-8.65	-2.76	-9.89	-5.19	-8.45	-3.59	-9.79	-6.19
	C11	76.79	77.89	74.72	78.59	76.52	84.26	73.56	84.26	76.52	76.02	73.86	72.16	76.62	84.46	73.36	84.46
	C12	474.77	475.83	471.22	421.55	475.07	545.07	479.81	545.07	479.81	476.38	472.42	474.28	476.84	546.60	469.00	542.60
	C13	-56.77	-56.77	-59.06	-15.15	-12.10	-10.11	-6.06	-10.11	-6.06	-15.58	-24.15	-14.81	-15.36	-7.40	-26.61	-19.24
	C14	54.33	47.67	54.33	47.67	51.33	54.00	54.67	54.00	54.33	48.00	54.33	48.00	54.33	53.66	54.33	53.67
SKELETONIZED	C1	80	20	9	60	40	13	43	19	53	6	73	7	66	6	85	8
	C2	14,44	3,61	1.62	10.83	7.33	2.38	7.88	3.48	9.57	1.08	13.18	1.26	11.91	1.08	15.34	1.44
	C3	0,00	0,00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0,00	0,00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0,00	0,00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	-18,45	-2,75	-0.74	-10.49	-1.09	-0.61	-1.18	-0.83	-1.83	-0.33	-6.64	-0.97	-2.78	-0.40	-9.38	-1.15
	C7	0,00	0,00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	-18,45	-2,75	-0.74	-10.49	-1.09	-0.61	-1.18	-0.83	-1.83	-0.33	-6.64	-0.97	-2.78	-0.40	-9.38	-1.15
	C9	79,53	84,02	76.51	84.66	74.38	77.51	70.63	77.31	74.76	72.68	73.47	65.74	74.96	72.68	74.12	65.74
	C10	-9,90	-9,37	-4.36	-9.80	-4.86	-2.86	-4.76	-2.66	-5.24	-3.16	-7.90	-2.86	-5.44	-3.16	-8.84	-2.86
	C11	69,63	74,65	72.15	74.86	69.52	74.65	65.87	74.65	69.52	69.52	65.57	62.88	69.52	69.52	65.28	62.88
	C12	-58,49	-35,46	-14.27	-47.48	10.37	-8.62	10.02	-9.36	-22.77	-9.26	-35.69	-11.96	-18.64	-17.70	-14.60	-12.29
	C13	472,31	510,54	483.77	480.43	486.58	485.48	436.43	485.15	472.30	472.16	431.72	424.16	472.28	468.10	432.90	423.54
	C14	46,67	45,67	42.33	69.00	46.33	45.33	45.67	46.00	46.67	49.00	46.80	49.70	49.00	49.00	46.67	48.67

APPENDIX C – GAAV INDICATORS

GAAV		PVC								DUCTILE IRON								HDPE							
		VALVE CLOSING								VALVE CLOSING								VALVE CLOSING							
		NO PROTECION		MORE TIME		AIR VALVE		RHO		NO PROTECION		MORE TIME		AIR VALVE		RHO		NO PROTECION		MORE TIME		AIR VALVE		RHO	
		Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min	Q máx	Q min
ALL PIPES	C1	30	8	0	0	0	0	5	2	93	169	0	0	0	5	8	4	32	11	0	0	0	0	7	3
	C2	5.30	1.41	0.00	0.00	0.00	0.00	0.88	0.35	16.43	29.86	0.00	0.00	0.00	0.89	1.41	0.71	5.65	1.94	0.00	0.00	0.00	0.00	1.24	0.53
	C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	0.00	7.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	2.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	-12.58	-2.00	0.00	0.00	0.00	0.00	-2.76	-0.05	-15.85	-29.04	0.00	0.00	0.00	-0.07	-3.58	-0.46	-13.13	-4.73	0.00	0.00	0.00	0.00	-3.01	-0.29
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	-12.58	-2.00	0.00	0.00	0.00	0.00	-2.76	-0.05	-15.85	-29.04	0.00	0.00	0.00	-0.07	-3.58	-0.46	-13.13	-4.73	0.00	0.00	0.00	0.00	-3.01	-0.29
	C9	54.68	53.88	42.19	44.19	43.92	41.22	52.79	48.29	57.96	63.17	45.29	52.55	45.28	59.68	72.59	63.69	55.28	55.88	42.59	44.39	44.52	45.82	53.08	49.58
	C10	45.18	46.42	44.62	46.62	44.72	42.42	46.12	46.92	47.99	53.19	47.72	53.42	47.62	52.92	62.61	53.74	45.42	46.62	45.02	46.82	45.12	46.72	46.62	47.12
	C11	-9.50	-7.46	2.43	2.43	0.80	1.20	-6.67	-1.37	-9.97	-9.98	2.43	0.87	2.34	-6.76	-9.98	-9.95	-9.86	-9.26	2.43	2.43	0.60	0.90	-6.46	-2.46
	C12	-65.76	-42.91	17.66	17.71	9.00	10.40	-23.89	-22.73	-39.05	-28.44	17.69	24.18	25.69	-4.46	-38.50	-34.62	-66.88	-58.20	17.66	17.72	7.55	9.46	-41.23	-11.79
	C13	297.30	321.50	322.97	335.21	314.39	325.04	313.76	318.99	306.28	331.89	337.79	369.82	327.18	356.22	334.73	363.25	298.25	318.95	325.25	336.20	316.79	326.02	315.35	328.88
	C14	72.67	42.67	0.67	0.67	137.33	36.33	63.67	42.33	348.67	46.70	3.33	4.00	345.67	154.33	127.33	84.00	70.00	35.66	0.67	1.00	108.00	42.00	67.00	50.33
SKELETONIZED	C1	9	6	0	0	0	0	3	4	14	26	0	0	0	1	6	2	9	4	0	0	0	0	2	1
	C2	7.50	5.00	0.00	0.00	0.00	0.00	2.50	3.33	11.67	21.67	0.00	0.00	0.00	0.85	5.00	1.67	7.50	3.33	0.00	0.00	0.00	0.00	1.67	0.83
	C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	-43.31	-35.63	0.00	0.00	0.00	0.00	-3.54	-15.52	-27.33	-27.83	0.00	0.00	0.00	0.00	-8.31	-2.00	-25.39	-21.75	0.00	0.00	0.00	0.00	-6.61	-0.84
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	-43.31	-35.63	0.00	0.00	0.00	0.00	-3.54	-15.52	-27.33	-27.83	0.00	0.00	0.00	0.00	-8.31	-2.00	-25.39	-21.75	0.00	0.00	0.00	0.00	-6.61	-0.84
	C9	52.88	53.18	51.00	44.19	42.52	43.02	48.28	52.09	53.02	54.25	38.32	39.42	42.82	44.42	76.03	58.62	52.92	52.02	38.12	38.62	43.02	43.02	51.52	46.92
	C10	42.93	43.73	42.94	46.62	42.92	43.72	44.62	45.12	43.04	44.27	43.32	44.42	43.02	44.32	70.33	55.42	43.22	43.72	43.22	43.72	43.22	43.72	46.12	44.92
	C11	-9.95	-9.45	-8.06	2.43	0.40	0.70	-3.66	-6.97	-9.98	-9.98	5.00	5.00	0.20	-0.10	-5.70	-3.20	-9.70	-8.30	5.10	5.10	0.20	0.70	-5.40	-2.00
	C12	-65.76	-42.91	37.04	38.04	7.89	8.44	-25.44	-20.72	-62.09	11.83	36.90	36.79	8.37	36.90	-36.72	-16.80	-59.96	-54.91	37.04	37.08	7.55	8.30	-33.56	-9.03
	C13	297.30	321.50	311.61	305.42	301.76	307.02	300.39	309.87	274.44	282.48	312.65	319.70	300.25	308.91	325.91	325.96	278.65	289.24	313.38	316.99	303.91	307.46	302.72	310.38
	C14	64.67	21.33	0.67	0.67	68.33	40.33	62.67	42.67	309.67	92.33	37.67	71.67	229.00	91.67	104.00	90.67	57.33	42.67	46.00	42.67	143.40	42.67	63.00	43.00

APPENDIX D – GEAV INDICATORS

<table>
<tr><th colspan="2" rowspan="3">GEAV</th><th colspan="8">PVC</th><th colspan="8">DUCTILE IRON</th><th colspan="8">HDPE</th></tr>
<tr><th colspan="8">VALVE CLOSING</th><th colspan="8">VALVE CLOSING</th><th colspan="8">VALVE CLOSING</th></tr>
<tr><th colspan="2">NO PROTECION</th><th colspan="2">MORE TIME</th><th colspan="2">AIR VALVE</th><th colspan="2">RHO</th><th colspan="2">NO PROTECION</th><th colspan="2">MORE TIME</th><th colspan="2">AIR VALVE</th><th colspan="2">RHO</th><th colspan="2">NO PROTECION</th><th colspan="2">MORE TIME</th><th colspan="2">AIR VALVE</th><th colspan="2">RHO</th></tr>
<tr><th></th><th></th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th><th>Q máx</th><th>Q min</th></tr>
<tr><td rowspan="14">ALL PIPES</td><td>C1</td><td>199</td><td>0</td><td>0</td><td>0</td><td>6</td><td>1</td><td>6</td><td>0</td><td>421</td><td>299</td><td>0</td><td>0</td><td>134</td><td>163</td><td>62</td><td>8</td><td>270</td><td>0</td><td>0</td><td>0</td><td>28</td><td>0</td><td>5</td><td>0</td></tr>
<tr><td>C2</td><td>29.70</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.91</td><td>0.15</td><td>0.90</td><td>0.00</td><td>62.84</td><td>44.63</td><td>0.00</td><td>0.00</td><td>20.33</td><td>24.73</td><td>9.25</td><td>1.19</td><td>40.30</td><td>0.00</td><td>0.00</td><td>0.00</td><td>4.25</td><td>0.00</td><td>0.75</td><td>0.00</td></tr>
<tr><td>C3</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>18.00</td><td>6.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>2.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C4</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>303.00</td><td>24.60</td><td>0.00</td><td>0.00</td><td>0.00</td><td>1.50</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C5</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>91.73</td><td>7.45</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.50</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C6</td><td>-68.49</td><td>0.00</td><td>0.00</td><td>0.00</td><td>-0.05</td><td>0.05</td><td>-0.21</td><td>0.00</td><td>-270.26</td><td>-79.51</td><td>0.00</td><td>0.00</td><td>-3.60</td><td>-10.19</td><td>-4.83</td><td>-0.74</td><td>-113.40</td><td>0.00</td><td>0.00</td><td>0.00</td><td>-0.27</td><td>0.00</td><td>-0.13</td><td>0.00</td></tr>
<tr><td>C7</td><td>0.00</td><td>0.05</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C8</td><td>-68.49</td><td>0.05</td><td>0.00</td><td>0.00</td><td>-0.05</td><td>0.05</td><td>-0.21</td><td>0.00</td><td>-270.26</td><td>-79.51</td><td>0.00</td><td>0.00</td><td>-3.60</td><td>-10.19</td><td>-4.83</td><td>-0.74</td><td>-113.40</td><td>0.00</td><td>0.00</td><td>0.00</td><td>-0.27</td><td>0.00</td><td>-0.13</td><td>0.00</td></tr>
<tr><td>C9</td><td>69.64</td><td>57.86</td><td>48.86</td><td>51.00</td><td>61.08</td><td>51.48</td><td>62.46</td><td>56.36</td><td>80.41</td><td>90.87</td><td>54.70</td><td>68.33</td><td>74.65</td><td>92.47</td><td>62.58</td><td>71.64</td><td>70.66</td><td>58.86</td><td>48.86</td><td>51.70</td><td>63.54</td><td>55.78</td><td>61.96</td><td>56.86</td></tr>
<tr><td>C10</td><td>-9.98</td><td>2.56</td><td>8.06</td><td>8.06</td><td>-1.56</td><td>8.94</td><td>-2.94</td><td>2.56</td><td>-9.98</td><td>-9.98</td><td>7.96</td><td>2.93</td><td>-9.82</td><td>-9.98</td><td>6.24</td><td>-1.75</td><td>-9.86</td><td>2.66</td><td>8.06</td><td>8.06</td><td>-3.22</td><td>5.54</td><td>-2.44</td><td>2.16</td></tr>
<tr><td>C11</td><td>59.66</td><td>60.42</td><td>56.92</td><td>59.06</td><td>59.52</td><td>60.42</td><td>59.52</td><td>58.92</td><td>70.43</td><td>80.89</td><td>62.66</td><td>71.26</td><td>64.83</td><td>82.49</td><td>68.82</td><td>69.89</td><td>60.80</td><td>61.52</td><td>56.92</td><td>59.76</td><td>60.32</td><td>61.32</td><td>59.52</td><td>59.02</td></tr>
<tr><td>C12</td><td>-56.76</td><td>73.47</td><td>115.05</td><td>126.07</td><td>-69.20</td><td>-69.20</td><td>1.71</td><td>85.72</td><td>-51.78</td><td>-42.42</td><td>107.17</td><td>59.62</td><td>-17.09</td><td>-9.20</td><td>-28.56</td><td>24.86</td><td>-56.36</td><td>52.16</td><td>115.03</td><td>114.94</td><td>-8.49</td><td>57.05</td><td>3.55</td><td>71.69</td></tr>
<tr><td>C13</td><td>384.61</td><td>417.92</td><td>411.98</td><td>418.73</td><td>350.17</td><td>350.17</td><td>394.38</td><td>413.57</td><td>375.48</td><td>464.58</td><td>438.68</td><td>492.34</td><td>402.88</td><td>469.26</td><td>408.10</td><td>473.37</td><td>380.61</td><td>418.44</td><td>412.31</td><td>428.85</td><td>387.89</td><td>418.80</td><td>392.83</td><td>409.95</td></tr>
<tr><td>C14</td><td>72.67</td><td>42.67</td><td>0.67</td><td>0.67</td><td>41.20</td><td>36.33</td><td>66.33</td><td>59.67</td><td>348.67</td><td>155.67</td><td>3.33</td><td>4.00</td><td>345.67</td><td>154.33</td><td>267.67</td><td>267.00</td><td>70.00</td><td>35.67</td><td>0.67</td><td>1.00</td><td>108.00</td><td>42.00</td><td>66.00</td><td>58.67</td></tr>
<tr><td rowspan="14">SKELETONIZED</td><td>C1</td><td>67</td><td>60</td><td>0</td><td>0</td><td>9</td><td>0</td><td>16</td><td>0</td><td>76</td><td>71</td><td>0</td><td>0</td><td>43</td><td>30</td><td>20</td><td>0</td><td>66</td><td>57</td><td>0</td><td>0</td><td>15</td><td>0</td><td>7</td><td>0</td></tr>
<tr><td>C2</td><td>64.42</td><td>57.69</td><td>0.00</td><td>0.00</td><td>8.91</td><td>0.00</td><td>15.38</td><td>0.00</td><td>73.08</td><td>68.27</td><td>0.00</td><td>0.00</td><td>42.57</td><td>29.70</td><td>19.23</td><td>0.00</td><td>63.46</td><td>54.81</td><td>0.00</td><td>0.00</td><td>14.85</td><td>0.00</td><td>6.73</td><td>0.00</td></tr>
<tr><td>C3</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>7.00</td><td>2.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C4</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>17.40</td><td>2.70</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C5</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>7.02</td><td>1.09</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C6</td><td>-476.59</td><td>-111.62</td><td>0.00</td><td>0.00</td><td>-0.29</td><td>0.00</td><td>-4.65</td><td>0.00</td><td>-627.44</td><td>-529.11</td><td>0.00</td><td>0.00</td><td>-3.68</td><td>-3.27</td><td>-7.19</td><td>0.00</td><td>-449.20</td><td>-102.09</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>-0.35</td><td>0.00</td></tr>
<tr><td>C7</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>C8</td><td>-476.59</td><td>-111.62</td><td>0.00</td><td>0.00</td><td>-0.29</td><td>0.00</td><td>-4.65</td><td>0.00</td><td>-627.44</td><td>-529.11</td><td>0.00</td><td>0.00</td><td>-3.68</td><td>-3.27</td><td>-7.19</td><td>0.00</td><td>-449.20</td><td>-102.09</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>-0.35</td><td>0.00</td></tr>
<tr><td>C9</td><td>66.13</td><td>67.56</td><td>39.03</td><td>40.46</td><td>56.23</td><td>57.56</td><td>59.43</td><td>54.66</td><td>66.78</td><td>69.70</td><td>40.13</td><td>43.05</td><td>66.25</td><td>66.96</td><td>60.57</td><td>57.74</td><td>66.37</td><td>66.46</td><td>39.13</td><td>40.56</td><td>60.23</td><td>57.46</td><td>57.33</td><td>52.16</td></tr>
<tr><td>C10</td><td>-9.80</td><td>-9.80</td><td>17.20</td><td>17.30</td><td>2.80</td><td>0.20</td><td>-3.30</td><td>2.90</td><td>-9.98</td><td>-9.98</td><td>16.80</td><td>16.60</td><td>-9.52</td><td>-7.31</td><td>-2.74</td><td>1.61</td><td>-9.85</td><td>-8.60</td><td>17.20</td><td>17.30</td><td>-3.90</td><td>0.40</td><td>-1.00</td><td>5.60</td></tr>
<tr><td>C11</td><td>56.33</td><td>57.76</td><td>56.23</td><td>57.76</td><td>59.03</td><td>57.76</td><td>56.13</td><td>57.56</td><td>56.80</td><td>59.72</td><td>56.93</td><td>59.65</td><td>56.73</td><td>59.65</td><td>57.83</td><td>59.35</td><td>56.52</td><td>57.86</td><td>56.33</td><td>57.86</td><td>56.33</td><td>57.86</td><td>56.33</td><td>57.76</td></tr>
<tr><td>C12</td><td>-69.20</td><td>-52.24</td><td>125.19</td><td>126.09</td><td>-4.28</td><td>11.90</td><td>-14.64</td><td>31.34</td><td>-54.60</td><td>-57.84</td><td>123.73</td><td>123.58</td><td>-9.32</td><td>-22.80</td><td>-7.68</td><td>29.65</td><td>-56.36</td><td>52.16</td><td>125.19</td><td>126.07</td><td>-8.20</td><td>10.91</td><td>2.75</td><td>50.56</td></tr>
<tr><td>C13</td><td>350.17</td><td>388.20</td><td>407.87</td><td>418.68</td><td>367.80</td><td>393.70</td><td>378.32</td><td>402.37</td><td>335.26</td><td>363.29</td><td>410.56</td><td>415.48</td><td>363.53</td><td>386.13</td><td>379.68</td><td>403.41</td><td>380.61</td><td>418.44</td><td>407.87</td><td>418.73</td><td>368.18</td><td>392.26</td><td>381.49</td><td>404.72</td></tr>
<tr><td>C14</td><td>64.67</td><td>21.33</td><td>41.67</td><td>42.33</td><td>68.33</td><td>40.33</td><td>60.73</td><td>56.27</td><td>309.67</td><td>92.33</td><td>37.67</td><td>71.67</td><td>229.00</td><td>91.67</td><td>201.90</td><td>192.47</td><td>56.77</td><td>42.67</td><td>46.00</td><td>42.67</td><td>66.67</td><td>42.67</td><td>52.67</td><td>39.67</td></tr>
</table>