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Daniel Vallejo

Juan Guillermo Saldarriaga

Diego Alejandro Páez

Santiago Serrano

A NEW METHODOLOGY FOR THE DESIGN OF RESIDENTIAL WATER DISTRIBUTION NETWORKS AND ITS POPULATION RANGE OF APPLICATION

DANIEL VALLEJO (1), JUAN SALDARRIAGA (2), DIEGO PÁEZ (3), SANTIAGO SERRANO (4)
(1) *Researcher, Centro de Investigaciones en Acueductos y Alcantarillados from Universidad de los Andes (CIACUA), Carrera 1 No. 18ª-10, Bogotá, Colombia. Email: d.vallejo49@uniandes.edu.co, Telephone: 3394949 Ext: 2810.*
(2) *Titular Professor, Email: jsaldarr@uniandes.edu.co.*
(3) *Instructing Professor Email:da.paez27@uniandes.edu.co.*
(4) *Researcher, Email: s.serrano1657@uniandes.edu.co.*

INTRODUCTION

Different assumptions have to be made regarding water distribution system (WDS) and residential water network (RWN) design, because the design methodologies applied for each are different. Although these methodologies have been modified, it still isn't clear for what city size or population size they can be applied to.

A new RWN design methodology will be presented in this paper, as well as the calculation of the limit population that determines which of both methodologies should be used.

In order to determine the limit population some networks where designed under WDS design methodology using the software REDES (software developed by the Water Distribution and Sewerage Research Center from the Universidad de los Andes - CIACUA) for different occupancies (populations) which implies different demand flows. Once a near optimal design was obtained, an equation relating the number of occupants in the network with the network's cost was calculated. Followed this, the same networks were designed using the new RWN design methodology. This process was conducted using the software DisRed (software developed by CIACUA). Using these ideal designs and its cost, a limit population was calculated by equating the costs found in both methodologies, this limit is known as the equilibrium population.

THEORETICAL FRAMEWORK

The same physical principles govern the design process for WDS and RWN, yet the methodologies differ specially when determining the joint's minimum pressure and design flows.

MINIMUM PRESSURE IN WDS Every country has its own normativity for the WDS's minimum pressure. In Colombia it is established in the RAS (Reglamento Técnico del Sector de Agua Potable y Saneamiento Básico). The minimum pressures vary between 10 and 15 meter depending on the size of the network.

Finding the demands in a WDS

RAS presents 3 methodologies for the estimation of the design demand in the network: Areas method, Unitary Load method and the Average Distribution Method. The demands used during this investigation were calculated using the Unitary Load method. The method is based on determining the demanded amount of water per person or Maximum Hourly Flow (MHF) in the network; RAS establishes the values for net provision d_{net} which are multiplied by the population (*Pop)* of the network. The values for the constants k_1 and k_2 are also presented in RAS.

$$MHF = \frac{Pop * d_{net}}{86400} * k_1 * k_2 \quad (1)$$

Pressures and flow demands in RWN

RWN design depends on knowing the behavior of each consumption's junction. This implies one must know about what type of appliance is connected and what its behavior is. Appliance refers to sinks, showers, toiles and all other kind of utensils that are connected to the water network.

Several methodologies have been used for the design of this kind of networks such as British Method, Square Root German Method, Rational Method and Hunter's Method, all based on empirical data summarized in tables in order to obtain the pressures and flows at the junctions.

Later the processes known as modern methods appeared. The main characteristic of these methods is they don't assume water demand as homogeneous along the day and start working with water demand's pulses.

On 2011 a RWN design software called RIDAPS (Ciacua, 2011) was developed based on pulses concept. Although this software was capable of designing the network it had some computational and methodological deficiencies (Vallejo, 2012), hence a new methodology and software were needed.

This paper presents a new methodology for designing RWN alongside with new software that implements this methodology and thereby obtains better results and computation times than previous software.

Flow-pressure relation

Residential Water Networks have appliances in every demand junction. This means demanded flow depend on the pressure at the node. Due to this, it was necessary to find the relationship between the pressures and flows for every kind of appliance (Acero, 2009). The following figure shows this relationship for a shower as an example of the graphs calculated for different kind of appliance.

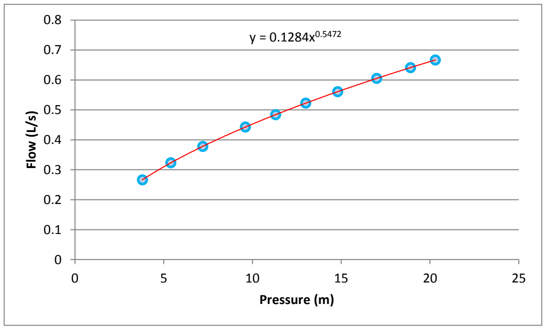

Figure 1. Relationship Flow vs Pressure for a shower.

NEW METHODOLOGY

In 2011 a new RWN design methodology was proposed at Universidad de los Andes, Colombia (Páez, 2011). This methodology calculates the design flow by determining the number of apppliances being used at a given time, followed by adding their individual flow using the Standard Curve for every appliance which is a concept explained below.

Design State

The proposed methodology defines State as the number of appliances, downstream of any pipe, which are being used simultaneously at a given time. For example a pipe that has 4 appliances downstream would have the possibility of having 4, 3, 2, 1 or none appliances active and thus it would have 5 possible states. It should be noted that in this case there are 2^4 = 16 different scenarios corresponding to all the possible combinations of appliances turned on and off. Therefore, a probability of occurrence for each possible state with x turned on appliances, can be calculated using Equation 3 (Poisson Binomial Distribution).

$$\#C_x = nCr(NN, x) \quad (2) \qquad P_{NN}(X = x) = \sum_{\#C}\left(\prod_{i}^{x} p_i * \prod_{j}^{NN-x}(1 - p_j)\right) \quad (3)$$

where $\#C_x$ is amount of scenarios in an state x, NN is the number of appliances downstream the pipe, and p_i is the probability that the appliance i is being used. This allows the estimation of the number of appliances turned on to be considered for design purposes at the analyzed pipe.

However, if this process was made for a pipe in which the number of appliances downstream was 16, 65.536 probability evaluations would be necessary; implying large computation times. In order to improve the efficiency of the evaluations an approximation for the Poisson Binomial Distribution proposed by Paez (2013) was used (Equation 4).

$$P_{NN} = (X = x) = nCr(NN, x) * p^x * (1 - p)^{NN-x} \quad (4)$$

$$p = \left(\prod_{i=1}^{NN} p_i\right)^{\frac{1}{NN}} + \left(1 - \left(\left(\prod_{i=1}^{NN} p_i\right)^{\frac{1}{NN}} + \left(\prod_{i=1}^{NN}(1 - p_i)\right)^{\frac{1}{NN}}\right)\right) * \frac{\left(\prod_{i=1}^{NN}(1 - p_i)\right)^{\frac{1}{NN}}}{\left(\prod_{i=1}^{NN} p_i\right)^{\frac{1}{NN}} + \left(\prod_{i=1}^{NN}(1 - p_i)\right)^{\frac{1}{NN}}} \quad (5)$$

This procedure allows to determine the design flow by calculating a design state x_D with a cumulated probability higher than $\left(1-p_{failure}\right)$and then adding the flow of the x_D appliances with the biggest demanded flow.

In order to use the new methodology, new software called DisRed (Vallejo, 2012) was developed.

Appliance Standard Curves

As explained before the new methodology requieres the use of some curves realting flow and preassure which are necesarry to determine the flow for every applaiance. These curves are one of the paramaters of DisRes, and it is necessary to introduce an specific curve for every kind of appliance (Acero, 2009).

Althoug using the curves encrease the reliability of the results, the flow used by an appliance does not only depend on the network's pressure but on valve's aperture, implying that for each appliance there are a series of different curves as shown in figure 2.

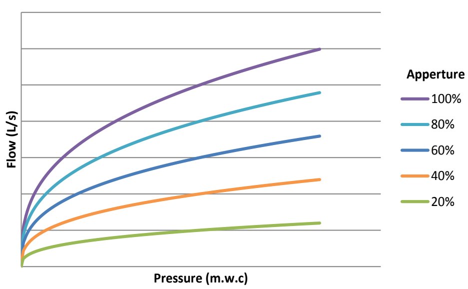

Figure 2. Pressure vs Flow for different apertures.

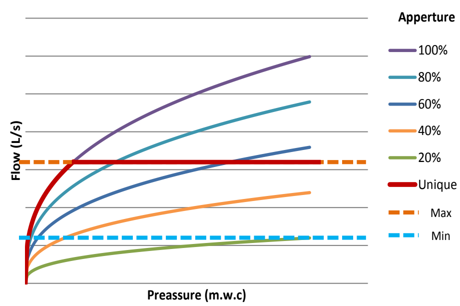

Figure 3. Standard Curve

Even though the flow depends on the apperture there are some limits for the flow. There's always going to be a minimum flow for which the appliance will fullfill its original purpose. There will also be a maximum, that when overpassed, the flow will become excessive making the appliance unusefull. Based on this, the Standard Curve is defined.

Finding the design flow

- Probability of usage

In order to determine the design flow, it is necessary to calculate the probability that a given appliance is being use at a given time(p_i). Once the probabilities have been calculated we proceed to determine the probability of occurrence for every possible state at the analyzed pipe, including the state $x = 0$; and the sum of these probabilities must add to 1.
Then, it is necessary to recalculate the conditional probabilities assuming the system is being used. This can be done by distributing the probability assigned to $x = 0$ among the other states.
Finally it is determined the state for which the cumulated probabilities overpasses the failure probability. This state defines the number of appliances downstream the given pipe that would be assumed to be under usage. This process is presented in the following table. In the presented case the failure probability was of 95% which is overpassed by the state number 5.

Table 1. Cumulative Probability to determine the design state. Example.

State (x)	$P_{NN=6}(X=x)$	$P_{NN=6}(X=x \mid x \neq 0)$	$P_{NN=6}(X \leq x \mid x \neq 0)$

6	0,01	0,01	1,00
5	0,03	0,04	**0,99**
4	0,10	0,14	0,94
3	0,16	0,23	0,80
2	0,19	0,27	0,57
1	0,21	0,30	0,30
0	0,30		
Total	**1,00**	**1,00**	

- Finding the Flow

Once the design state x_D has been calculated the design flow can be established. The first step is to find the x_D appliances, with greater flow, downstream the analyzed pipe. These flows are established through the Standard Curve for every appliance.

- Diameter calculation

Once the design flows are established for each pipe the OPUS design methodology (Takahashi et al, 2011) is implemented. As this methodology is based on the I Pai Wu criterion (1975), of optimal energy use, the objective heads in each node is assigned and then a continuous diameter is calculated for each pipe using the design flows and the difference of upstream and downstream heads. Then a round-off process is required to adjust the pipe sizes to available diameters. This step is performed as recommended by Takahashi, with a Potential Rounding.

DETERMINING THE LIMIT POPULATION

Small cities or temporary camps may reach populations beyond 5000 people. Therefore a good design for their WDS is essential. For the Colombian case, there is no explicitness whether these systems must be modeled and designed through RWN's considerations or by WDS's considerations.

Even though, the hydraulics characteristics for both methodologies are quite similar, the parameters used, such as pressures and flows, greatly differ. Due to these differences, it is necessary to establish a limit population that defines which is the recommended methodology for the design process of the network.

In order to find this limit 6 small cities' water networks where chosen. Each of these networks was designed by WDS and RWN methodologies and the results were compared.

WDS

As was previously mentioned, the 6 networks were design by WDS's methodologies, this process was achieved using the OPUS methodology implemented in software REDES (CIACUA, 2011). These designs were done using the Unitary Load method, decision based on (Torrado, 2012) .

To calculate demanded flow in every node is necessary to establish some parameters established in Colombia's regulation. In this case they were a net provision of 100 L/day, 27% of leakage, and values of 1.3 and 1.6 for k_1 and k_2 respectively; as recommended by RAS. The population on these networks was considered to be uniformly distributed and so the demand.

For the design, the used flow was the Maximum Hourly. Every network was designed for different total populations and for every case the cost of the network was calculated. Equation 8 established the network's cost where *L* and *D* represent the length and diameter of the pipe *i* respectively, and k and *r* are parameter obtained from the cost curve shown in Figure 4.

$$C = \sum k * l_i * {D_i}^r$$

(6)

For the study cases the estimated values were *k=1.0139* and *x=0.6728 (Figure 4)*

Once the cost for every network was and every population was calculated, it was necessary to determine an equation that could describe them. After some analysis it was found that potential regressions where the ones that best fitted the values.

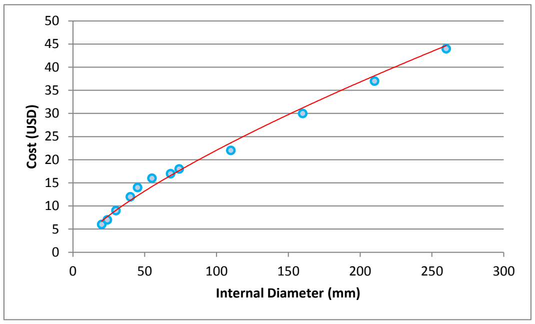

Figure 4. Cost Curve

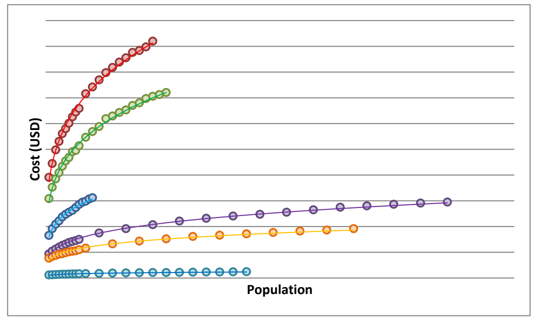

Figure 5. Population vs cost for every population and network

The Figure 5 describes the relationship between population and cost for every study case. It can be clearly seen that potential regressions have high fitness for every case, always reaching a R^2 coefficient above *0.987*.

RWN

RWN designs were made using the software DisRed; with the probabilities of usage based on Blocker (2010) data and the standard curves based on Acero (2009) results.

It was also necessary to include in the networks' models the part of the system directly connected to the appliances in order to apply the proposed RWN's design methodology. The following figures represent the same network. *Figure 6(a)* represents the model used for WDS design while *Figure 6(b)* is the model used for RWN design.

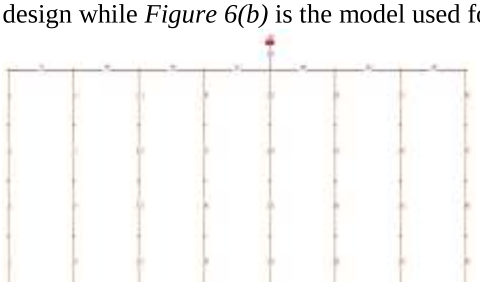

Figure 6(a). Scheme for WDS design, R-28 network.

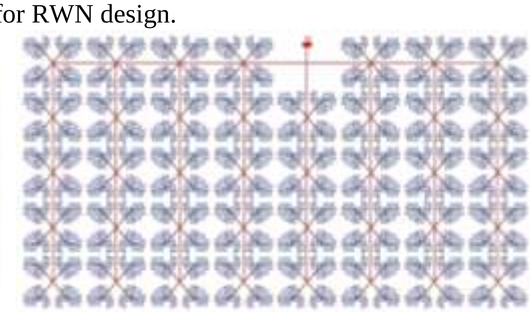

Figure 6(b). Scheme for RWN design disaggregated R-28 network. Scheme for WDS design, R-28 network.

Once the RWN model was made, minimum pressure, appliance curve, frequency, users and duration values for every appliance were assigned. Once the design was obtained, the cost of every network was calculated using the same cost curve (Equation 6)

FINDING THE EQUILIBRIUM POPULATION

Before the limit population is calculated it is necessary to determine the equilibrium population. This popultion refers to the number of persons for which the cost for a RWN equals WDS's one. To find this value it is necessary to equal the potential equation obtained for the WDS with the cost of the RWN. For instance, for the Campamento 1 study case, the RWN design reached a cost of $13.694,6 and as the potential relation between WDS design cost and system's population is given by $C = 2.079,8 \cdot Pop^{0.2451}$, the equilibrium population is:

$$C = 2.079,8Pop^{0,2451} \rightarrow 13.694,60 = 2.079,8Pop^{0,2451} \rightarrow Pop = \left(\frac{13.694,60}{2.097,8}\right)^{\frac{1}{0,2451}}$$

$Pop = 2.186\ persons.$

The same process was done for the other 6 networks. The results are shown on the following table.

Table 2. Equilibrium Population

Red	Equilibrium Population (N° of Habitants)
Campamento 1	2,186
Campamento 2	4,425
R-28	4,487
Oasis IV	11,372
Red Elevada	6,154
San Vicente	5,896

COMPARISON

As observed on Table 2, not all equilibrium populations are the same. However it was found there is a clear relationship between the WDS's design flow (Maximum Hourly) and the equilibrium population, this relationship is presented in the following figure.

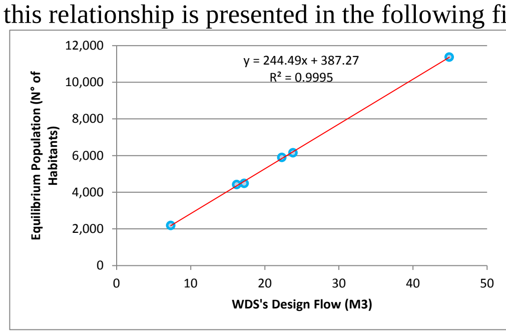

Figure 7. Relationship between WDS's design flow (Maximum Hourly) and equilibrium population.

The found relationship was described by the following equation:

$$EP = 244.49Q + 387.27 \quad (7)$$

CONCLUSIONS

A new RWN design methodology was presented. It is based on the Poisson Binomial Distribution as a stochastic characterization of the systems usage and on the Standard Curve as a hydraulic characterization of appliances behavior.

DisRed software implementing the presented methodology gives the possibility to apply the methodology to big sized systems and compare the results with other design procedures.

During this investigation it was also found that as the population of the network grows its cost incensement decreases. In other words the bigger the population and network, the lower the cost per habitant of the network.

We can conclude the equilibrium population of a network varies lineal with respect to the WDS's design flow. Due to the accuracy of this regression (R^2=0.9995) it can be said that this relationship could be applied or extrapolated for other networks.

Finally, we found that there can't be a single population limit that defines which methodology should be used for the design process of the network. Yet by using Equation 7 it is possible to define which methodology should be used. For a given WDS's design flow if the network's population overpasses that established by Equation 7, the network should be designed using RWN's process, otherwise WDS's process should be used.

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