Kurdish Studies
April 2024
Volume: 12, No: 3, pp 170-185
ISSN: 2051-4883 (Print) | ISSN 2051-4891 (Online)
www.KurdishStudies.net

DOI: 10.53555/ks.v12i3.3011

Hydraulic Analysis and Water CAD simulation of the Water Distribution Network applied to marine Recirculating Aquaculture Systems

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Abstract
Water supply is crucial for all human activities, especially when large volumes and high quality are required. Therefore, greater efficiency is sought in water storage, distribution, use and reuse systems. The present design and simulation work was carried out simultaneously with the physical installation of a Recirculating Aquaculture System (RAS) for the breeding of the marine fish Chita in Callao - Peru. The sizing of the RAS components and hydraulic characterization was carried out by applying mass balance theory, using an Excel spreadsheet and hydraulic simulation of the distribution network with WaterCAD software. The objective was to apply these software tools and compare the simulation results with parameters conventionally used in the design of RAS installations, and to investigate head losses, hydraulic pressure and diameter assignment in the pipe network. Demonstrating the adaptability of WaterCAD in the verification of pressures, flow rates and flow velocities in the distribution of water in a RAS, and finding that the diameters conventionally used, based solely on empirical criteria, were 7.76% larger than those of the simulation. Consequently, it is deduced that the hydraulic parameters present significant differences that must be considered to conceptualize an adequate water distribution network. The introduction of WaterCAD simulation in the design and operation of the RAS system is recommended to obtain safer pipe networks, that guarantee the stable state condition of the RAS system. Opening the possibility of more stable water flows, with lower energy costs associated to the operation of pumps.

Keywords: Aquaculture, Marine RAS, Water CAD simulation, Water distribution network, Fish culture.

1. Introduction

Recirculating aquaculture systems (RAS) are considered a high-tech alternative aimed at the pro duction of aquatic animals through water reuse (Bregnballe, 2022). RAS engineering has developed methodologies to size its main components as a whole (Wheaton, 2008; Timmons and Ebeling, 2007; Pillay and Kutty, 2005; Lekang, 2007; Takeuchi, 2017). Other researchers have also worked on the design of: solid separators (Blanco Salazar, 2004; Rincón and Herrera, 2014; Vesga-Rodríguez et al., 2019; Yao, 1970), and biological filters (Godoy-Olmos et al., 2016; Babadjanova, 2017; Uzukwu et al., 2010; Shrivastava et al., 2015; Kamstra et al., 1998; Tanveer, 2017). These components work in conjunction with complementary equipment to achieve more refined levels of water quality, such as skimmers, degassers, UV lamps, etc., operating together and interconnected. These RAS elements require a network of pipes for water transport, the design and operation of which has received little attention to date.
Water distribution mainly refers to the supply of drinking water, widely studied (Izinyon and Anyata, 2011; Kusnayat et al., 2019; Kadhim et al., 2021), however, water transportation through pipelines is also topic of recirculation systems for the breeding of aquatic animals. Distribution systems consist of main, secondary, branch and lateral pipes; which are generally placed taking advantage of the available geometric hydraulic head (Garg, 2017). The definition of the optimal configuration and parameters of the distribution network that can satisfy the required water flow and pressure results from hydraulic analyzes and cost-benefit indicators (Dasic and Djordjevic, 2004; Kadhim et al., 2021). Regarding the reliability of the sizing, in water resources systems, the probability of failure results from examining the possibility of satisfying the demand under predefined scenarios of minimum demand. In practice, this results in an oversizing of some elements of the system (Dasic and Djordjevic, 2004).

WaterCAD helps design and optimize water distribution systems (Bentley Systems, 2023; Eryürük, 2021; Kadhim et al., 2021; Septiawati et al., 2019). An insufficient water flow associated with hydraulic pressures lower than those necessary in a RAS system causes a decrease in process performance in each of the system components. WaterCAD is capable of performing simulations under steady-state conditions and long-period scenarios, with the option to test assumed scenarios (Bentley Systems, 2023). To guarantee an adequate environment for fish production, recirculation systems (RAS) must maintain permanent water flows, avoiding alterations in the hydraulic regimes in their components, being aware of possible flow reductions due to the adhesion of organic matter inside of the pipes (Kals, 2004). The objectives of the present study were (i) Apply the commands, tools and processes of the WaterCAD software for the hydraulic simulation of the water supply pipe network of a recirculating system for marine aquaculture, and (ii) Evaluate the resulting data on head losses, hydraulic pressure, water velocity and pipe diameter, compared to the operating parameters of the physical model of the RAS system.

Steady state systems concept

Before defining 'Steady State System' which a very transcendent concept in recirculating aquaculture systems design, it should be explain how Mass Balance Theory fits in this part of Aquaculture Engineering. Based on the concepts developed for the general theory of Mass Balance, the cases applied to RAS systems correspond mainly to the so-called "Simple Mass Balances" (Rojas González, 2012), those in which there is no chemical transformation, or in which that no equilibrium equation is needed for its solution. Being the operating regime, permanent; that is, it operates in a stable state with continuous flow. According to Deiana et al. (2018), Ashrafizadeh and Tan (2018), and Londoño García (2015), systems can be categorized as open or closed. In the open system there is mass transfer across its boundaries, while in a closed system no mass enters or leaves its limits. At the same time, the open system can operate in a stable or transient state. The open system is stationary when there is no accumulation of mass in it, while the transient open system presents mass accumulation.

Transferring these concepts to the components of a RAS system, each of its elements, whether called a fish tank, solids separator, biofilter, etc., represent open systems in a steady state, because ideally– during their operation– accumulation should not occur. And this concept is what allows us to properly conceive a balanced system in a RAS installation, and from there develop the formulas and calculations. Ashrafizadeh and Tan (2018) conclude by pointing out that when a system is in a steady state, all its properties and variables do not change with time, and the total mass of the system is constant. Furthermore, the calculations in the design of the RAS are carried out considering that a mass balance problem is constituted by a volumetric balance equation plus a mass balance equation (Eq. 1 and 2), as explained by Olivares (2012), for each of the species or compounds considered:

$$\frac{dV}{dt} = \sum_{i=1}^{N} Q_{ent,i} - \sum_{j=1}^{M} Q_{sal,j} \qquad \text{……… Eq. 1,}$$

$$\frac{d}{dt}\left(V.C_{sis}\right) = \sum_{i=1}^{N} Q_{ent,i}.C_{ent,i} - \sum_{j=1}^{M} Q_{sal,j}.C_{sal,j} + \sum_{k=1}^{L} V.r \qquad \text{…… Eq. 2.}$$

where, V is system volume, Q is the flow rate, C is the concentration of a substance or compound, and r is the renewal rate. According to Ashrafizadeh and Tan (2018), for any material in the system, under chemical reactions, it is appropriate to consider for equilibrium, quantities of production or consumption within the system, in addition to the inputs and outputs of the material across its boundaries.

Head losses in pipes formulas

Walker et al. (2014), Larock et al. (2000) and USDA (2023), explain the two most used equations for calculating head losses in pipe sizing: the Darcy-Weisbach equation and the Hazen-Williams equation. The Darcy-Weisbach equation (Abdulameer et al., 2022; Larock et al., 2000; Dawe, 2000) has the form of:

$$h_f = f\frac{L.V^2}{D.2.g} = f\frac{L}{D}\frac{L.Q^2}{2.g.A^2} \qquad \text{… Eq. 3,}$$

where h_f = friction head loss (m); f = unitless friction constant; L = pipe length (m); D = hydraulic diameter of the pipe (m), D = 4A/P being A and P cross-sectional area and wetted perimeter, respectively (for a completely filled cylindrical pipe, the hydraulic diameter is equal to the inner diameter); V = Q/A, fluid flow velocity (m/s), Q = discharge (m^3/s), A = cross-sectional area of the pipe (m^2); and g = acceleration due to gravity (9.81 m/s^2), according Larock et al. (2000), is the most sound and versatile equation for frictional head loss, although implies difficulties of determining the friction factor "f ". Because Darcy-Weisbach equation has non-empirical origin is considered as the most accurate method for modeling (Abdulameer et al., 2022). Also named in Mawengkang et al. (2023), as pressure drop equation due to friction (ΔP pressure drop across the pipe = h_f), and has the form:

$$\Delta P = f.\frac{L}{D}.\frac{1}{2}.\rho.V^2 \qquad \text{… Eq. 4,}$$

being, ΔP is the pressure drop, f the Darcy friction factor, which depends on the roughness of the pipe surface and the Reynolds number, L the length of the pipe, D the diameter of the pipe, ϱ the density of the fluid and V the velocity of the water.

The Hazen-Williams equation is a formula derived empirically from pipe water flow data (USDA 2023), mainly used in pressure analysis (Abdulameer et al. 2022) and the calculation of head losses in pipes (h_f), has the following form, depending on the flow:

$$h_f = \frac{K.L}{D^{4.87}}(\frac{Q}{C})^{1.85} \qquad \text{… Eq. 5,}$$

where *hf* is head loss (m); k is a unitless constant (0.85 for SI units); L is pipe length (m); Q is the flow rate (m^3/s); C is Hazen-William's coefficient, ranges from 80 to about 150; D is pipe diameter (m), possibly the Hazen-Williams equation is the most widely used (Larock et al., 2000). The relationship between the flow rate and the pipe diameter is highly non-linear, which in practice leads to increasing the diameters to reduce energy costs in transporting the liquid. In Dawe (2000), the Hazen-William's equation is also shown in the following form:

$$h_f = \frac{6.79}{D^{1.16}}(\frac{v}{C})^{1.85} \qquad \text{… Eq. 6,}$$

where, "v" represents the average velocity (m/s), "C" the relative roughness factor. Or in the form presented by USDA (2023), solving for h_f as function of "Q" the flow rate:

$$h_f = 10.704(\frac{Q}{C_{HW}})^{1.85}\frac{L}{D^{4.87}} \qquad \text{… Eq. 7,}$$

For International System (SI), corresponding units are: *hf* (m), L (m), Q (m^3), and C_{HW} the Hazen-Williams relative roughness factor (unitless).

2. Methodology

The research work was carried out in La Punta district, Callao province, Perú. The desert climate predominates in the area, with 168 mm of precipitation and an average ambient temperature of 18°C. The lowest water temperatures in September are 15.70 °C and the highest averages reach about 21 °C in the month of February. These are the general climatic parameters according to statistics from CLIMATE-DATA.ORG. La Punta is a district located on the beaches of the Pacific Ocean, on the central coast of Peru at less than 10 meters above sea level (Figure 1).

Figure 1: Location of the research laboratory in La Punta, Callao.

The physical model of the recirculating aquaculture system for this research was oriented to the breeding of marine fish "Chita" (*Anisotremus scapularis*) in circular tanks, within the framework of a project executed by the National Agrarian University La Molina, with financing from the National Program of Innovation in Fisheries and Aquaculture (PNIPA).

2.1. Fish characteristics and water quality monitoring

The recirculation system was designed to achieve operating parameters similar to those of a scalable commercial pilot production, during a period called "Initial Growth" on land, in the process of breeding *A. scapularis*, which consists of bringing the fingerlings until they reach a size that ensures the resistance of the fish, still young, to the oceanographic conditions of the floating cages in the sea, where the fattening process is completed until reaching commercial adult size. The fish used for the experimental trial were captured in Arica beach, district of Lurín - Lima (12°18'20.85"S and 76°50'57.06"W), 2500 juveniles with lengths in the range of 9.7 and 11.3 cm, and weights between 14.32 and 27.20 g. To evaluate the water quality, an OAKTON brand pH meter, model pHTestr 30, a YSI DO 200A-4 model oximeter was used to measure the dissolved oxygen (DO, g/m^3) and saturation level (%), a ATS refractometer – salinometer, and a model YSI 9500 photometer to measure total ammoniacal-N, nitrite-N, nitrate-N and alkalinity.

The collection of water samples was carried out with the purpose of seeing the variations of the physicochemical parameters during the time that the observation period lasted, with sampling every 15 days and; also evaluate the hourly stability of water quality, with sampling every 2 hours for 24 hours a day. These two approaches to assessing water quality provided a reliable reflection of the degree of stability of the system, which is what is sought as the operating principle of the RAS system, a stable system.

2.2. Hydraulic analysis and simulation procedure using Water CAD

Configuration of the RAS System: water distribution network

The design of the aquaculture recirculation system for this research has gone through three stages: the first consisted of defining the maximum biomass, fish in culture tanks, that the system must handle. The second stage consisted of defining the components of the RAS and calculating its capabilities. The third stage consisted of defining the Water Distribution Network (WDN), according to the location of the RAS components and considering pipe accessories such as valves, reductions, bends, unions, etc. including return branches to regulate water pressures and flows. In the second and third stages, it was considered to place all the RAS elements in the available space, having resulted in a very compact RAS plant, with a fair circulation path and also anticipating traffic during equipment replacement, repair or maintenance activities. In the present study, the fish tanks, settler, sand filter, trickling filter, cooling tank and UV lamp were appropriately located in the work area according to the layout plan previously drawn using AutoCAD software (Figure 2).

The adopted design was inspired by the Dutch model, whose characteristic is the use of a parallel plate settler and trickling biofilter (Remmerswaal, 1993). These filters are easy to build, simple to operate and robust enough that, in addition to nitrification, they cause the release of CO_2 and the incorporation of oxygen (Losordo and DeLong, 2015). This set of advantages has been evident after calculations, the design process and installation, during start-up and RAS operation, which is reflected in water quality parameters and fish behavior.

The sizing of the RAS system components was carried out applying the mass balance principles described by Timmons et al. (2009); Geankoplis et al. (1998); Olivares (2012); Lekang (2007). The RAS system was composed of three fish tanks 2.40 m in diameter and 1.00 m high, with a water depth of 0.80 m. The tanks had two water inlets: a main one from the electric pump (P2) with a 2" diameter PVC pipe and a secondary one from the Chiller cooling tank (CH) with a 1 ½" PVC pipe. Likewise, the tanks had a drain made up of a central 3" diameter PVC pipe.

The water collection network for the tanks was designed with three (03) sections of pipes: the first included the collection of effluent water from the three fish tanks (T1, T2 and T3) with a 3" PVC pipe, that goes to the parallel plate settler (ST). The second section, strictly suction, included the suction flows of the two electric pumps P1 and P2, in a pressurized network, where the pump P1 sucks a portion of the output flow of the plate settler (SP) and the pump. P2 sucks the remaining portion together with the output flow of the trickling biofilter (TRICK-F), the third section consists of pressurized flows towards the different water treatment components starting from the two electric pumps, the pump P1 distributes its flow into two fractions, towards sink 1, as water return, and the second flow enters the sand filter (SF). The effluent water from the sand filter was separated into two, one part was redirected to sump tank 1 generating a second return and the other part of the flow entered the biofilter mixing with the pump flow (P2). Pump P2 discharges the flow in three parts, the first consists of a return to sump 2 (S2), the second flow feeds the trickling biofilter (TRICK-F) mixing with the sand filter flow (SF) and the third flow - that passes the UV lamp (UV) – feeds the cooling tank 'chiller' (CH) and towards the fish tanks, this flow being the main one. The flow leaving the cooling tank is delivered to the fish tanks as a secondary flow (see Figure 2). The calculations at this point end with flow data for each RAS component, specifically.

The network of water distribution pipes in the marine recirculation system has been designed considering the expected performances for each of the components of the system, which were previously calculated using the formulas and parameters specific to the function that each of them fulfills. For these calculations, an Excel spreadsheet was used, similar to that shown by Losordo and Hobbs (2000), applying the theory of mass balance.

Simulation methodology

The hydraulic analysis and simulation of the water distribution network in the RAS system was preceded by the calculations of fish biomass and water volumes in breeding tanks, the definition of characteristics of the components (settler, mechanical and biological filters, cooling tank, and others), and the positioning of RAS elements within available area for definitive installation of the RAS.

Having defined position of each RAS components, next steps corresponded to WDN design and simulation in WaterCAD software, similar to what was presented in (Patel and Mehta, 2022): (i) the RAS design is drawn in a WaterCAD file, (ii) data was entered into the software: diameters, demands, elevations, coordinates, material, etc. (iii) the water demand pattern is imported, here a continuous water supply was assumed, and (iv) Once the data is entered: the model is executed. WaterCAD is a Windows-based, stand-alone system software developed by Haestad Methods Inc. of Cincinnati, Ohio, USA. It is an easy-to-use hydraulic and water quality modeling application for water distribution systems, (Bentley Systems, 2023; Izinyon and Anyata, 2011; Sarker, 2021).

Simulation using WaterCAD software begins to identify water distribution pipes to and from each RAS component. Moving further into the simulation, pipe segments and nodes were placed at their coordinates and elevations above the floor. In addition, the properties of the pipes, entirely made of Polyvinyl Chloride (PVC), were entered: diameters and corresponding roughness coefficient. The number and length of the pipes were 30 and 36.04 m, respectively. The water flow rate assigned to each RAS component as a result of its sizing calculations was entered into the nodes and the hydraulic simulation was run. The hydraulic calculations were carried out considering the Hazen- William equation (Eq. 7), taking the friction coefficients. The relative location of the components of the RAS system, presented in plan and elevation views, with flow rates and pipe diameters for practical use, was seen in Figure 2 (a). Nodes are points where the hydraulic conditions of the flow change and can represent water. fountains, storage tanks, discharge points, bypass pipeline sites, etc. (Mawengkang et al., 2023). This information was input to a WaterCAD file going through the following two activities:

a. Transfer the schematic of the RAS system (components + pipe network) to a scaled
b. The images in the AutoCAD software, recorded in DXF format, were imported into the WaterCAD program using the Model Builder command, as seen in the modeling images.

Hydraulic analysis of water distribution systems includes the calculation of pressure loss in the WDN. Today, WaterCAD is used to calculate energy losses in water distribution systems for the most varied uses, because this software is easy to use, versatile enough (Kusnayat et al., 2019), and is the most advanced and powerful software (Kadhim et al., 2021). In this work, the WaterCAD program was used according to the design and the necessary pressures to adequately provide the water flows to the fish tanks and the biofilter, as the main demand points. The flow rates were defined through the hydraulic calculation carried out, to transport the necessary oxygen and eliminate the contaminating compounds resulting from the metabolism of the fish. This was done through PVC pipes of different diameters, class 10 smooth PVC pipes were used, taking into consideration criteria of corrosion resistance, pressure resistance, installation characteristics and availability on the market.

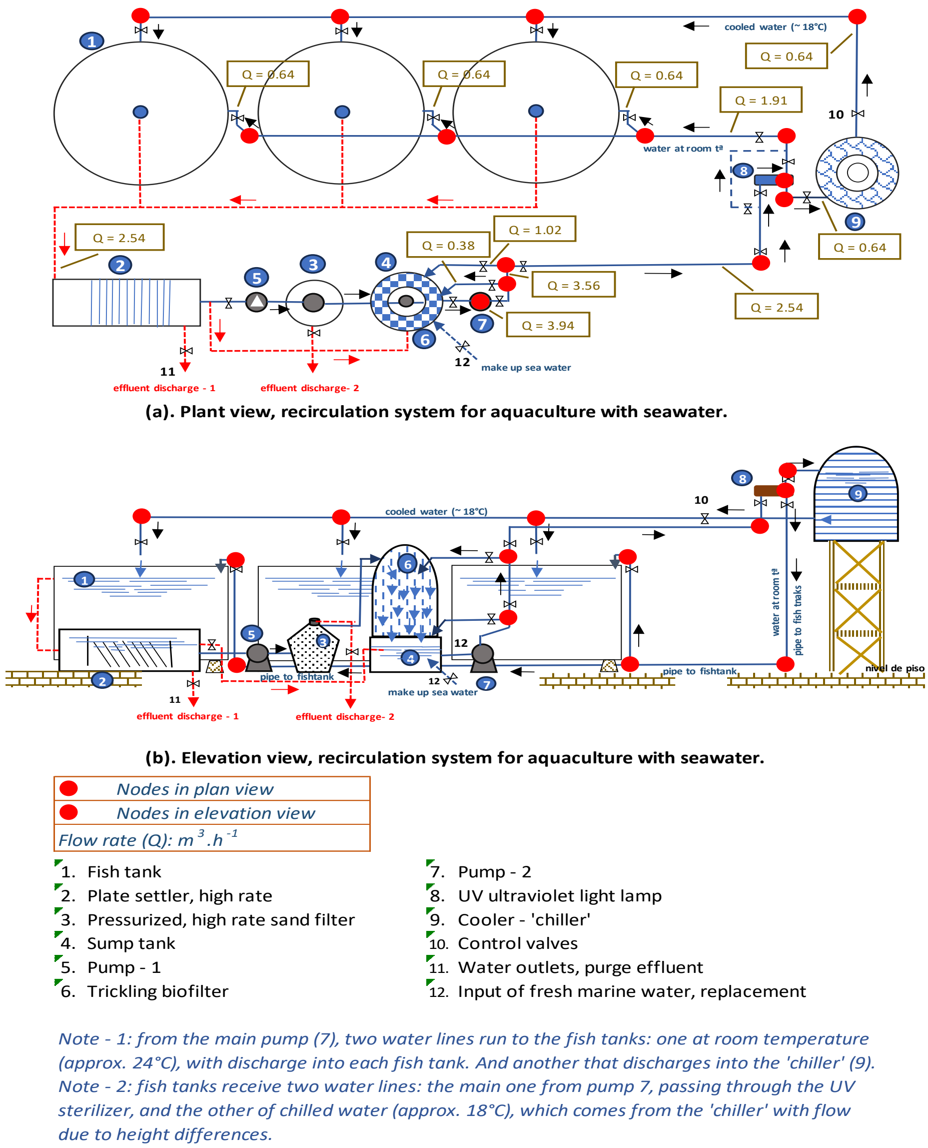

Figure 2: Water flow diagram and views of the general layout of the RAS system, with nodes location.

3. Results

3.1. Hydraulic analysis of the RAS water distribution network

Since this work is the first on water distribution networks (WDN), applied to marine RAS systems, the variable “pipe diameter” has been taken to evaluate the degree of proximity between the diameters of the installed network and the diameters of resulting simulation. In the present study, installed pipes have been found with a diameter 7.76% larger than that determined in the simulation, see Table 1.

Table 1. Comparison of the results of pipe diameters, from the simulation hydraulic analysis with the data collected from the RAS facilities in operation

Label	Initial node	Final node	Pipe diameter installed (mm)	Pipe diameter simulated (mm)	Difference (%)
T-1	J-2	J-1	57.00	43.40	31.34%
T-2	J-4	J-3	57.00	43.40	31.34%
T-3	J-6	J-5	57.00	43.40	31.34%
T-4	J-8	TRICK-F	57.00	43.40	31.34%
T-6	J-9	J-10	57.00	57.00	0.00%
T-7	J-10	J-20	57.00	57.00	0.00%
T-8	J-10	J-14	57.00	43.40	31.34%
T-9	J-11	J-6	57.00	43.40	31.34%
T-10	J-12	J-2	57.00	43.40	31.34%
T-11	J-12	J-11	57.00	57 .00	0.00%

T-12	J-13	J-4	57.00	43.40	31.34%
T-13	J-13	J-12	57.00	57.00	0.00%
T-14	J-14	CHILLER	57.00	43.40	31.34%
T-15	J-16	J-17	57.00	67.80	-15.93%
T-16	J-16	J-19	57.00	43.40	31.34%
T-5	J-17	J-8	57.00	43.40	31.34%
T-18	J-17	J-29	57.00	57.00	0.00%
T-19	J-19	RETURN	57.00	43.40	31.34%
T-20	J-20	J-21	57.00	57.00	0.00%
T-21	J-21	J-13	57.00	57.00	0.00%
T-22	J-22	TK-03	43.40	43.40	0.00%
T-23	J-24	TK-02	43.40	43.40	0.00%
T-24	J-24	J-22	43.40	57.00	-23.86%
T-25	J-26	TK-01	43.40	43.40	0.00%
T-26	J-26	J-24	43.40	57.00	-23.86%
T-27	J-28	J-26	43.40	57.00	-23.86%
T-28	J-29	J-9	43.40	57.00	-23.86%
T-29	T-6	PUMP	57.00	67.80	-15.93%
T-17	PUMP	J-16	57.00	67.80	-15.93%
CHILER	CHILER	J-28	57.00	57.00	0.00%

Table precedent shows 'pipe diameter installed' which correspond to PVC pipe dimeter as function of flow rates required for projected capabilities in each RAS components, those indicated in labels in Figure 3.

Of a total of 25 pipe sections resulting from the RAS pipe networks, in 12 of them the pipe diameter is oversized, in 7 sections smaller diameters than the simulation results were installed. And in 11 sections the diameters obtained from the simulation are equal to those installed. Having found differences in the diameters of the pipes, it is therefore possible to expect proportional differences in the series of hydraulic parameters of the RAS water distribution network.

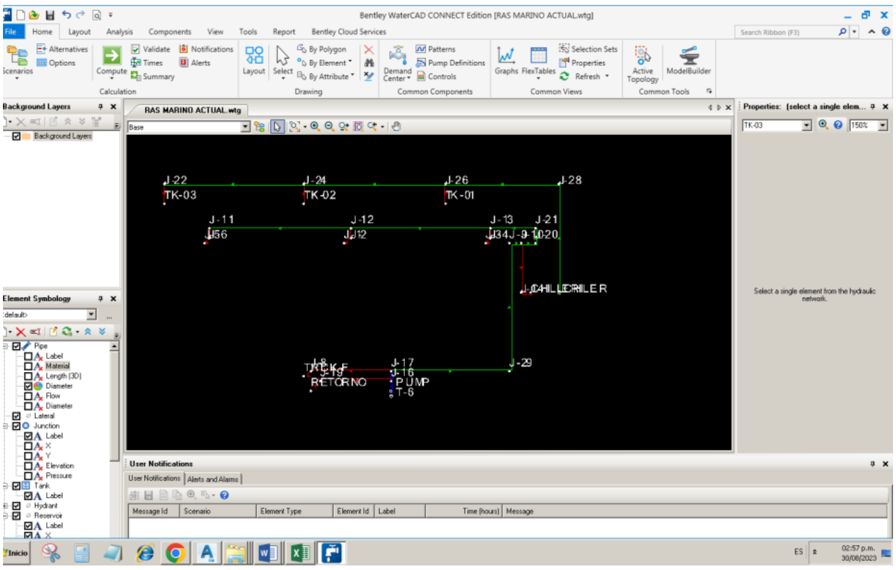

Figure 3: Screenshot from WaterCAD software: Plan view of the water distribution network showing the gravity-fed branch and the pressurized branch

3.2. Modeling the distribution network in WaterCAD

Modeling using WaterCAD software served to verify that the design of the hydraulic network ensured the delivery of water from a suction point (S2) to the highest and most distant points of the marine RAS. Condition that is verified in the data generated by the simulation and during the operation of the facilities in the experimental research.

As a result of the geometry of the RAS, and also the flow and volume requirements of water, two water branches were clearly configured in the WDN: the main one coming from the electric pump (P2) with 2" diameter PVC pipe (series J -16, J-17, J-29, J-20, J-21, J-13, J-12 and J-11) and a secondary one from the Chiller cooling tank (CH) with PVC of 1 ½" (J-27, J-28, J-26, J-24 and J-22 series), in Figure 3. The latter constitutes what is called "gravity-fed system", according to Action Contre la Faim, (2008), because it works by gravity. The water stored in the cooling tank descends under its own weight, flowing through the pipes to the fish tanks. In this system the pipes and faucets are at a lower level than the water level in the chiller tank.

Hydraulic gradient and pressures in the distribution network of the RAS system

The location of the nodes, as shown in Figure 2 and Table 2, was defined by UTM coordinates in the plan view, and the vertical position had a reference level with zero elevation, corresponding to the floor level. From these references, the simulation allowed the calculation of the hydraulic gradient and pressure, which ranged between 2.37 and 8.89 m for the gradient values and 0.37 to 8.76 m for the hydraulic pressure.

Table 2. Data resulting from the simulation: hydraulic gradient and pressures in the distribution network of the RAS system

Flex Table: Junction Table

Label	East (X) (m)	North (Y) (m)	Elevation (m)	Hydraulic Gradient (m)	Pressure (m H_2O)	Head Pressure (m)
CHILLER	261,293.96	8,667,345.87	2.35	8.79	6.43	6.44
J-1	261,290.55	8,667,346.78	1.41	8.77	7.35	7.36
J-2	261,290.67	8,667,346.90	1.53	8.77	7.23	7.24
J-3	261,293.10	8,667,346.78	1.41	8.77	7.35	7.36
J-4	261,293.22	8,667,346.90	1.53	8.77	7.23	7.24
J-5	261,288.00	8,667,346.78	1.41	8.77	7.34	7.36
J-6	261,288.11	8,667,346.90	1.53	8.77	7.23	7.24
J-8	261,289.95	8,667,344.51	1.90	8.87	6.96	6.97
J-9	261,293.58	8,667,346.81	2.35	8.80	6.44	6.45
J-10	261,293.76	8,667,346.81	2.35	8.80	6.43	6.45
J-11	261,288.11	8,667,347.10	0.07	8.77	8.68	8.70
J-12	261,290.67	8,667,347.10	0.01	8.77	8.75	8.76
J-13	261,293.22	8,667,347.10	0.07	8.78	8.69	8.71
J-14	261,293.76	8,667,345.87	2.50	8.79	6.28	6.29
J-16	261,291.40	8,667,344.31	0.95	8.89	7.92	7.94
J-17	261,291.40	8,667,344.51	1.90	8.88	6.96	6.98
J-19	261,290.09	8,667,344.31	0.95	8.89	7.92	7.94
J-20	261,294.03	8,667,346.81	2.35	8.80	6.43	6.45
J-21	261,294.03	8,667,347.10	0.07	8.78	8.69	8.71
J-22	261,287.26	8,667,347.87	1.99	2.37	0.38	0.38
J-24	261,289.82	8,667,347.87	1.99	2.37	0.38	0.38
J-26	261,292.37	8,667,347.87	1.99	2.37	0.38	0.38
J-28	261,294.46	8,667,347.87	1.99	2.37	0.38	0.38
J-29	261,293.58	8,667,344.51	1.90	8.84	6.93	6.94
RETURN	261,289.94	8,667,344.16	0.83	8.89	8.04	8.06
TK-01	261,292.37	8,667,347.58	1.40	2.37	0.96	0.97
TK-02	261,289.82	8,667,347.58	1.40	2.37	0.96	0.97
TK-03	261,287.26	8,667,347.58	1.40	2.37	0.96	0.97
TRICK-F	261,289.84	8,667,344.40	1.78	8.87	7.08	7.09

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The highest values of hydraulic pressure in the RAS system correspond to the line of pipes coming from the centrifugal pump (P2). While the lowest values correspond to the "gravity-fed system" branch, that is, the one coming from the cooling tank, as well as the branches controlled by valves, such as those returning to tank S2. These pressures, according to the specifications of the class 10 PVC pipe used in the installation of the RAS, do not exceed its resistance, so there would be no cases of explosion due to excessive hydraulic pressures.

Associated with the hydraulic gradient and hydraulic pressures, the head losses and the speed of the water flow were determined by simulation, resulting, with class 10 PVC pipes, in the values contained in Table 3. The water flows are those expected for ensure the correct functioning of RAS components. However, it is worth paying attention to the speed of the water flow, which varies from 0.06 m/s to 0.98 m/s. All these values seem insufficient to avoid the accumulation of solids in the pipes.

Table 3. Data resulting from the simulation: head losses and flow velocity in the distribution network of the RAS system

Flex Table: Pipe Table

Label	Initial Node	Final Node	Length (3D) (m)	Diameter (mm)	Flow rate (L/s)	Hazen-Williams C	Head Loss Gradient (m/km)	Loss Pressure (m H2O)	Head Loss (m)	Velocity (m/s)
T-1	J-2	J-1	0.21	43.40	0.30	150.0	1.29	0.00	0.00	0.20
T-2	J-4	J-3	0.21	43.40	0.30	150.0	1.29	0.00	0.00	0.20
T-3	J-6	J-5	0.21	43.40	0.30	150.0	1.29	0.00	0.00	0.20
T-4	J-8	TRICK-F	0.21	43.40	0.56	150.0	4.10	0.00	0.00	0.38
T-6	J-9	J-10	0.18	57.00	2.49	150.0	17.21	0.00	0.00	0.98
T-7	J-10	J-20	0.27	57.00	1.44	150.0	6.24	0.00	0.00	0.56
T-8	J-10	J-14	0.95	43.40	0.45	150.0	2.73	0.00	0.00	0.30
T-9	J-11	J-6	1.47	43.40	0.30	150.0	1.29	0.00	0.00	0.20
T-10	J-12	J-2	1.53	43.40	0.30	150.0	1.29	0.00	0.00	0.20
T-11	J-12	J-11	2.55	57.00	0.30	150.0	0.34	0.00	0.00	0.12
T-12	J-13	J-4	1.47	43.40	0.30	150.0	1.29	0.00	0.00	0.20
T-13	J-13	J-12	2.55	57.00	0.60	150.0	1.23	0.00	0.00	0.24
T-14	J-14	CHILLER	0.25	43.40	0.45	150.0	2.73	0.00	0.00	0.30
T-15	J-16	J-17	0.97	67.80	3.05	150.0	10.76	0.01	0.01	0.84
T-16	J-16	J-19	1.31	43.40	0.38	150.0	2.00	0.00	0.00	0.26
T-5	J-17	J-8	1.45	43.40	0.56	150.0	4.10	0.01	0.01	0.38
T-18	J-17	J-29	2.18	57.00	2.49	150.0	17.21	0.04	0.04	0.98
T-19	J-19	RETURN	0.24	43.40	0.38	150.0	2.00	0.00	0.00	0.26
T-20	J-20	J-21	2.30	57.00	1.44	150.0	6.24	0.01	0.01	0.56
T-21	J-21	J-13	0.81	57.00	1.44	150.0	6.24	0.01	0.01	0.56
T-22	J-22	TK-03	0.66	43.40	0.15	150.0	0.36	0.00	0.00	0.10
T-23	J-24	TK-02	0.66	43.40	0.15	150.0	0.36	0.00	0.00	0.10
T-24	J-24	J-22	2.55	57.00	0.15	150.0	0.09	0.00	0.00	0.06
T-25	J-26	TK-01	0.66	43.40	0.15	150.0	0.36	0.00	0.00	0.10
T-26	J-26	J-24	2.55	57.00	0.30	150.0	0.34	0.00	0.00	0.12
T-27	J-28	J-26	2.09	57.00	0.45	150.0	0.72	0.00	0.00	0.18
T-28	J-29	J-9	2.34	57.00	2.49	150.0	17.21	0.04	0.04	0.98
T-29	T-6	PUMP	0.22	67.80	3.43	150.0	13.38	0.00	0.00	0.95
T-17	PUMP	J-16	0.96	67.80	3.43	150.0	13.38	0.01	0.01	0.95
CHILL ER	CHILL ER	J-28	2.03	57.00	0.45	150.0	0.72	0.00	0.00	0.18

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Pressure diagram of WDN – marine RAS

Figures 4 and 5 present the location in plan and elevation view of each node with the hydraulic parameters considered in the simulation, resulting in an interesting tool to make adjustments to the pipeline layout. The plan view, combined with the elevation view, better shows the location of pipes and control valves, not only to regulate flow rates, but also pressures. The maximum pressure in the J-16 node at 0.95 m from the pump (P2) can be observed at 7.92 mH_2O, and the minimum 0.38 mH_2O in the line coming from the cooling tank, which belongs to the gravity-fed system.

The transport of water volumes in RAS systems must be carried out with a high degree of reliability, constantly and guaranteeing regular water quality and, therefore, a stable environment. Therefore, it was necessary to use computer tools to predict flows, pressures, pipe diameters, among other hydraulic parameters. WaterCAD data was imported for drawing in AutoCAD to work on the flowchart and overall design views of the RAS system, to present them with values for the different hydraulic parameters.

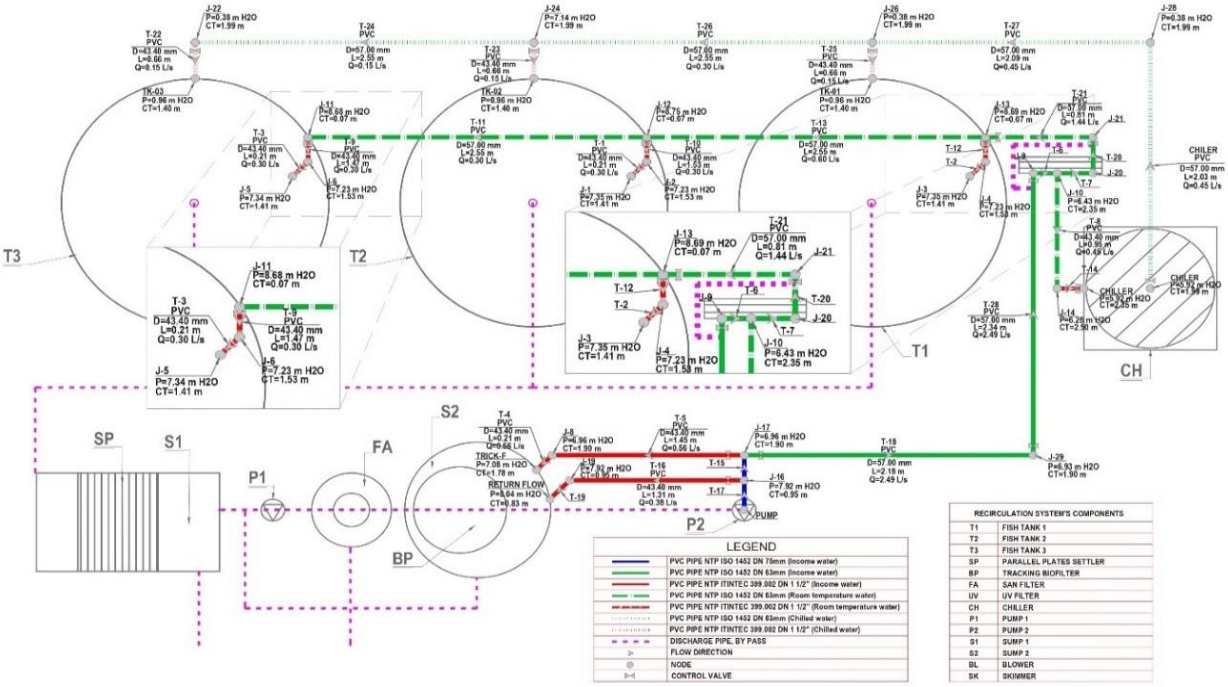

Figure 4: Plan view of the water distribution network and hydraulic simulation parameters, in WaterCAD file, for presentation purposes.

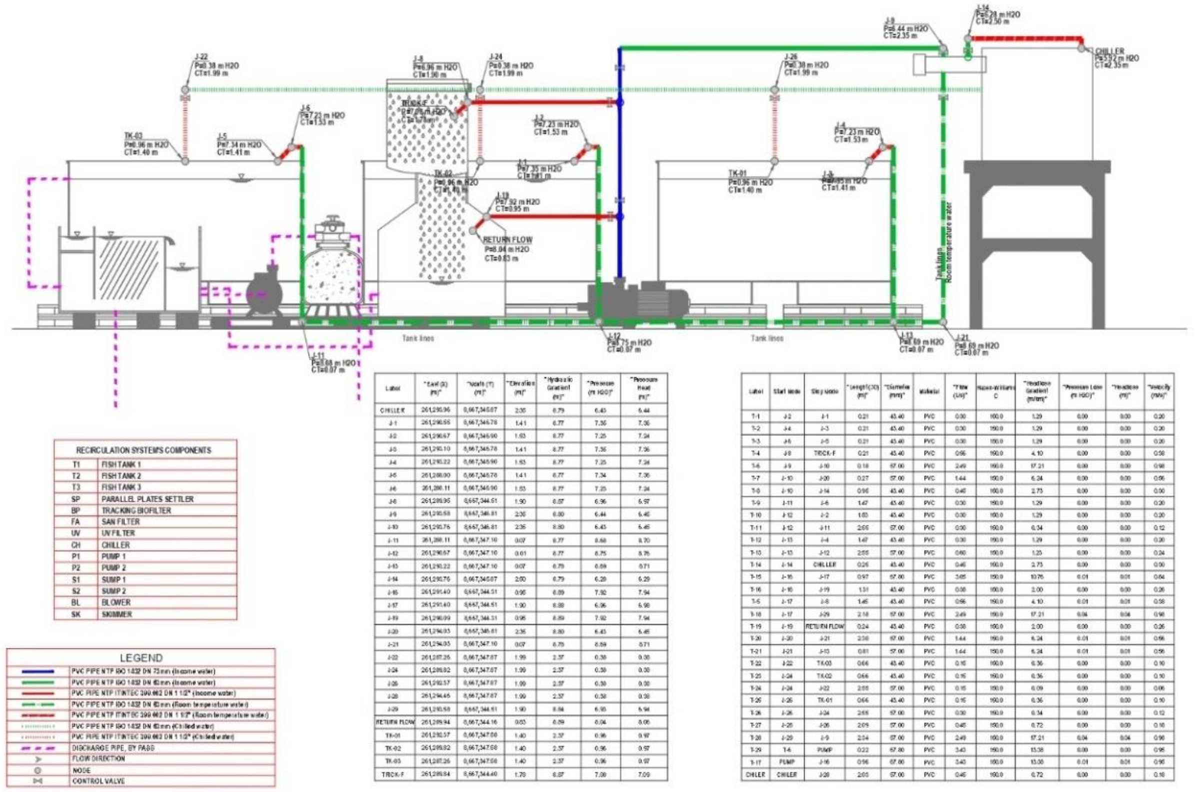

Figure 5: Elevation view of the water distribution network and hydraulic simulation parameters, in WaterCAD file, for presentation purposes.

The return flows in the RAS system have played a great role by having served to regulate the discharges and pressures in the pipes towards the key elements of the RAS system, such as the two centrifugal electric pumps (P1 and P2), the sand filter (SF), biofilter (TRICK-F), ultraviolet light lamp (UV); that operate in continuous flow and in a closed circuit. As can be seen, the returns branches worked under relative high pressure: 8.04 mH_2O for return to sump 2 tank, see Fig. 5.

3.3. Water quality, an indicator of steady-state condition

It is observed, Figure 6 and 7, that the water quality occurred in the system have reflected having a habitat in stable conditions during the experimental period. The water quality indicators, in general, have shown a linear trend without a slope but rather a horizontal one, with the temperature having varied between 24.70 °C and 26.90 °C with an average of 26.04±2.46 °C (summer season). These values exceeded the temperatures reported by Dionicio-Acedo et al. (2018) and Castro-Fuentes et al. (2022). However, the extreme values in the present work have not been outside the permissible range for the species; León-Palomino et al. (2017), reported a maximum upper thermal limit of 32.6°C for juveniles of the species.

The salinity of the water was maintained at stable levels, 35.20 ±0.16 ppt, with fresh water having been added to compensate for losses due to evaporation. The pH presented an average of 7.79±0.05, being above 7.0 as also reported by Dionicio-Acedo et al. (2018) and Castro-Fuentes et al. (2022). The oxygen level in the fish tanks was maintained in sufficient quantities for the species, registering a minimum of 5.71 mgO_2/L, a maximum of 6.48 mgO_2/L, with an average of 6.12±0.05 mgO_2/L, equivalent to 90.77±1.02% saturation.

The average concentration of total ammonium-N was 0.24±0.08 mgN/L, similar values obtained by other authors (Dionicio-Acedo et al., 2018; Castro-Fuentes et al., 2022). While the N-nitrite values in the present study were above those reported by the aforementioned authors: an average of 1.39±0.328 mgN/L. Both parameters varied within the recommended ranges for the species, demonstrating that the nitrification process that occurred in the system was stabilized and maintained adequate levels for the species. N-nitrate levels were found within acceptable ranges, although higher than those reported by Castro-Fuentes et al. (2022). The RAS system in this study operated with a water replacement level of less than 5%, a fairly low percentage compared to that reported for other RAS systems, the average being in general and by definition 10% or less, as indicated by Ebeling and Timmons (2012). Alkalinity varied between 300 and 550 mg $CaCO_3/L$ with an average of 387.50 ± 20.68 mg $CaCO_3/L$, a typical level of saline waters.

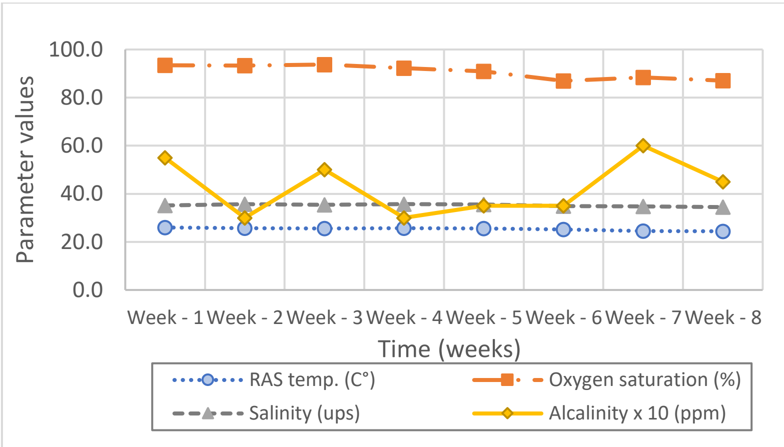

Figure 6: Values of water quality parameters, during the experiment time: temperature, salinity, dissolved oxygen saturation and alkalinity.

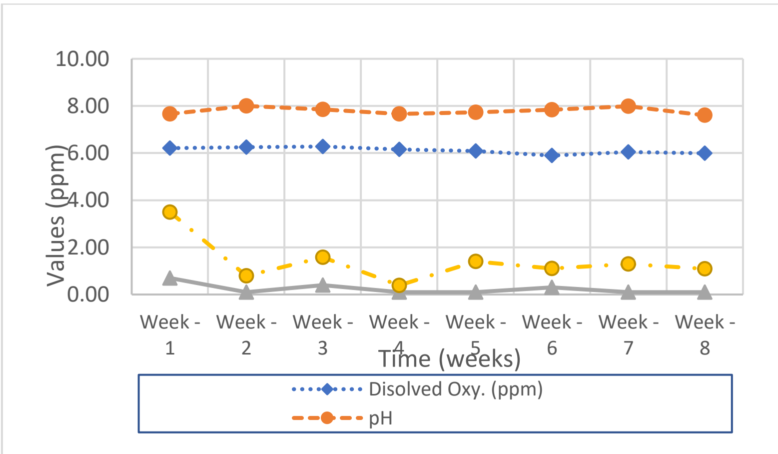

Figure 7: Values of the water quality parameters, during the experimentation time: pH, oxygen, ammoniacal nitrogen and nitrite.

In general, the water analysis results demonstrate the proper functioning of the RAS system, implicitly with adequate sizing of its components, and the appropriate configuration of the pipe network for water distribution. Water quality values remained within the recommended ranges, with low variability and a horizontal orientation, maintaining this trend over time. However, there are no elements to qualify this RAS system as the most efficient from the point of view of energy consumption, since empirical criteria were applied in its installation.

4. Discussion

Hydraulic analysis: parameters observed in operation versus simulated

Once the simulation was carried out, significant differences were observed between the results of the analysis using the WaterCAD software and the hydraulic operating parameters of the RAS, highlighting the following: RAS systems are installed following common sense criteria, oversizing the diameter of the pipes, to ensure sufficient driving capacity throughout the WDN. However, since they are estimates, they do not always result in an adequate diameter of the pipes. In the present hydraulic analysis, first in water recirculation for aquaculture, the pressure losses and hydraulic load were taken into account because these parameters are directly related to the energy consumption for the operation of the RAS systems.

For installations of medium or small RAS systems, it has not been observed that hydraulic calculations are carried out for the water distribution pipe network. The application of WaterCAD in the simulation of pressure losses in pipe networks, although it is a frequent practice for drinking water installations, in installations of water recirculation systems for aquaculture, would be a new practice, which will undoubtedly contribute to an improvement in the installation and operation of these systems.

It has also been observed that the hydraulic pressure in the pipes, during the operation of the RAS system, exceeded the values estimated by simulation with the WaterCAD software. A 1.0 HP electric pump was installed, which far exceeded the required power according to hydraulic calculations. At this point, practical criteria that are not supported by hydraulic calculations lack reliability and lead to excessive energy expenditure and, consequently, unjustifiably high operating costs.

Excessive pressures generate risks for pipes, accessories and some equipment that works with the same internal pressure of the network, such as the case of the UV ultraviolet light lamp (see Fig. 4 and 5). On the other hand, the technical specifications of the equipment do not necessarily contain the maximum recommended working pressure, which generates a potential danger that the water supply in the network may be interrupted due to lack of water flow or loss of efficiency in some specific processes. So much so that in the present study the explosion of a UV lamp was experimented.

The returns fulfill the purpose of facilitating the regulation of flows and pressures in pipes of the majority of elements of the RAS system, which function as a continuous output in a closed circuit, with regulation valves. In this way, closed flow circuits are configured within the general recirculation of the RAS system, such as the returns of pump 1 (P1) and pump 2 (P2), which return part of the pumped flow to the sump tanks, S1 and S2, respectively.

WaterCAD software offers the advantage of exercising full control to configure a WDN in aquaculture water recycling systems, developing, evaluating and comparing an unlimited number of hypothetical scenarios for the same case. Facilitating decision making, analyzing design alternatives for multiple variants in production planning. And providing support for the selection, sizing and operation of pumps and elements such as connectors for disassembly or control of water flows.

With the flow rates calculated for the operation of the different components, pump power (P2) and pipe diameters assigned during the installation of the marine RAS, it was found by application of the Water CAD tools, that the water pressure in the network distribution was sufficient for the water to reach all its components. It has been taken into account that the maximum pressure is that which does not cause excessive discharges and does not cause damage to the components of the RAS and in addition to maintaining a pressure as stable as possible, as stated by Tian et al. (2023). An important aspect for pressurized pipe networks is their hydraulic capacity, which allows them to meet the design flow and another important aspect is flow control Mawengkang et al. (2023), which allows flow adjustments to be made. Therefore, in recirculation systems, as in any WDN, a broader analysis is necessary to ensure the correct functioning of the facilities. According Izinyon and Anyata (2011), solving the distribution of water flow and head loss for particular elements of the system, given the total flow or total head loss, is the central hydraulic problem of WDN.

Hydraulic gradient and pressures

The pressure in the distribution of water for domestic consumption, depends on the height of the buildings (Izinyon and Anyata, 2011). In RAS systems, the pressures will depend on the location heights of their components. Al-Mousawey and Abed (2023) reported 12.23 mH_2O as the lowest pressure value, and considered acceptable values of 15.29 to 21.41 mH_2O in a domestic water supply system, much higher than the values found in this work.

This shows that the pipes of water networks in aquaculture correspond to low pressure systems, which privilege the flow of water volumes. In this way, in pump selection, the water flow pump is chosen instead of the pressure pump.

Regarding head losses, Table 2 shows that in general these have insignificant values, due to the length of the pipes and the material used to manufacture them, so they could not be considered in the sizing of the pump, the loss loading as additional work. It is also observed in the same table that the water velocities resulting from the WaterCAD simulation range from 0.06 to 0.98 m/s, resulting lower than those reported by Al-Mousawey and Abed (2023), 0.15 to 3.85 m/s for 160 mm PVC- HDPE pipes. Conventionally, 0.4 m/s is considered as the lower limit for a self-cleaning drinking water distribution system; Izinyon and Anyata (2011) adopted 1.5 m/s as a maximum value and 0.2 m/s as a minimum. Low velocities would represent a problem for RAS systems, as long as the flow rates are met, however the low velocity values are associated with a possible accumulation of solids. This is an important factor to consider, since the recirculating water contains living cells (microalgae) and small organisms (copepods, worms, etc.) that are a natural fauna accompanying the recirculating aquaculture waters. It is worth paying attention not to neglect the pressure losses, even if they are very small, since this is a system operated by a pump 24 hours a day, the energy cost must be the minimum necessary, due to its contribution to operating costs of water recirculation systems in aquaculture.

Pressure diagram of the marine RAS

Recirculation aquaculture systems ultimately end up being complex hydraulic systems in which the experience and ingenuity of the operator will allow obtaining the much-appreciated dynamic balance between each of the components of the RAS system, operating at their maximum capacity, according to design calculations. Simultaneously, the operation of the RAS system water network must be configured in optimal flow and pressure scenarios that avoid physical water losses, and report the reduction of energy consumption in pumping, allowing the network to operate with lower pressures, avoiding over pressurization (Marques et al., 2023). Ranjan et al. (2022) points out that in most intensive recirculation systems, the total lifting height is about 2 to 3 meters, which favors the use of low-pressure pumps to be more efficient.

In addition to optimizing pipe layout, WaterCAD simulation allows you to better visualize the placement of accessories for easier and more timely attention to any occurrence of hydraulic failures that may occur during the operation of the RAS system, the inadequate attention of which would endanger an important population of fish, of high economic value. Likewise, simulation with WaterCAD allows generating n-conditions or scenarios to finally choose the one with the lowest energy cost during its operation, since energy cost is an important aspect in the design of WDN as pointed out by Kurian et al. (2018), considering that finally the general economic balance of aquaculture based on RAS facilities lies in the energy costs.

The pressure diagram resulting from this research gives a clear idea of how both piping systems work: the “gravity-fed network” and the “pressurized network”, fed with gravity energy and pumping energy respectively. It seems that the gravity fed system is more reliable and favors the care of the pump because it works at a constant hydraulic head.

Since water became the main and critical factor in aquaculture production, knowledge in hydraulics and the latest advances in simulation developed for drinking water network systems were very useful to adapt it to the design and operation of recirculation systems in aquaculture. Therefore, the design of a water distribution system has at least two main challenges: (i) the correct discharge rate and (ii) the required water pressure. The distribution of hydraulic pressure in the networks and discharge points, as well as the water flow proportional to the demands, are part of the task of the dynamic hydraulic model that is finally developed to achieve adequate water distribution. And minimize the volumes of water loss but also guarantee the efficiency in the work of the RAS components and the infrastructure as a whole (Abu-Mahfouz et al., 2019). Based on previous work on RAS installation and observations made in the present study, distribution systems often have many technical problems that can be predicted with simulation tools, which represents an important contribution to good design practices. of RAS systems.

5. Conclusions

Based on the results of the hydraulic analysis of RAS system network and the observations made in the present study, the following can be concluded:

- The water supply of the RAS system was found within the optimal operating scheme since the water quality remained stable and within recommended ranges for the life and growth of the fish confined in the marine RAS system.
- The water flow pressures found by simulation of the pipe network do not exceed the maximum value established for the class 10 PVC pipe used. However, when equipment is incorporated that operates under the same network pressure, it does not necessarily support the pressures recorded during the operation of the RAS.

- Two branches' pipes have been installed in the WDN corresponding to the water supply lines to the fish tanks, the one that worked with energy transmitted directly by the pump (P2), and the "gravity-fed" line that worked with gravity energy. This second case would be more stable, however susceptible to obstruction problems due to the low speeds reported by the simulation.
- In light of the results of the application of simulation using WaterCAD in the design of the RAS system, this practice would allow deciding on a better distribution of the pipes, the best circuit design, the more appropriate location of the control valves, and better schemes of return pipes. Favoring a major control of the operation of water distribution networks in RAS systems and lower energy costs in pumping.

The recommendations that have emerged as a result of this work, it is noted:
- To obtain comparable numerical field data, it is recommended to place pressure gauges in the pipe sections between the nodes to know the working pressures. The installation of flowmeters is also recommended to detect variations in flow rates in the operation of the RAS system.
- It is recommended also to correlate the field data with the results of the hydraulic analysis using WaterCAD simulation, during the development of the designs in order to avoid overpressures and achieve lower energy costs, considering that the pumping equipment in the RAS systems works tirelessly.

Acknowledgments
The authors thank to National Innovation Program in Fisheries and Aquaculture (PNIPA-ACU-SIADE-PP-000070). Ministry of Production. Government of Peru.

Conflict of Interests
The authors of this research declare not have any conflicts of interest with all the organizations that could influence the content to this manuscript.

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