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Analysis of the effects of the stream confluence on the Alagoas Aqueduct

Análise dos efeitos da confluência do Riacho Seco no Canal Adutor do Sertão Alagoano

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ABSTRACT

The project of the Canal do Sertão (Alagoas Aqueduct) is an important step toward social and economic development in the semiarid region of Alagoas State in Brazil. Therefore, a hydrodynamic assessment in the canal is necessary due to a complex drainage system under parameters that were not considered during the project design and execution, mainly along the reach km 67, where it is located a convergent confluence and an overchute structure. The analysis conducted in this study addressed three main aspects: i) verify possible risks to the water quality of the canal, pumped from São Francisco River; ii) evaluate scenarios with risks to the canal structure due a convergent confluence between Riacho Seco and the stream of the tributary basins, which flows over a drainage structure crossing the canal at km 67.28; and iii) analyze the water level elevation into the overchute structure, submerged during flood events, and the water level elevation in the upstream reach of the confluence of the Riacho Seco, with a length of 620 m parallel to the canal and separate by a distance of 80 m from each other, where the level may rise reaching the left levee of the canal. Thus, were assessed the potential effect of the Riacho Seco confluence with the flow discharge of the tributary basins on the overchute structure at km 67.28 of the Canal do Sertão. The analysis of the water elevation and its possible risks to the water quality and the canal structure for different flood scenarios were performed by using the hydrodynamics models HEC-HAS. It was noticed that there is an elevation of the water surface of the tributary streams in the upstream reaches of the convergent confluence and that the drainage structure over the canal do Sertão fails for flow discharge with a return period of 50 years or more, overflowing the water from the drainage system into the channel.

Keywords: Canal do Sertão; Confluences; Convergent junction; Flood; Hydrodynamic model.

RESUMO

O Canal do Sertão alagoano tem grande importância social e econômica para o Estado de Alagoas, sendo, portanto, importante a realização de investigações hidrodinâmicas em um trecho de complexidade relevante do sistema de drenagem das águas pluviais, sob parâmetros não analisados nos projetos básico e executivo, em uma região abrangida por um trecho do canal, nas proximidades do km 67. As análises conduzidas nesse trabalho tratam de três aspectos: i) verificar os riscos à qualidade da água escoada através do canal do sertão, aduzida a partir do rio São Francisco; ii) os riscos a estrutura do canal, junto a uma junção convergente entre o Riacho Seco e o afluente das bacias tributárias que escoam sobre uma estrutura de drenagem que atravessa o canal no km 67,280; e, iii) analisar a elevação do nível de água no interior da estrutura do over-chute 3 que será submergido por ocasião das cheias, e do trecho à montante da confluência ao longo do Riacho Seco, que se desenvolve por 620 m ladeando o canal, a uma distância média de 80 m em relação ao seu eixo, podendo elevar-se sobre o espaldar externo do dique esquerdo do canal. Assim, são analisados os possíveis efeitos causados pela confluência do Riacho Seco com a descarga das bacias tributárias através do over-chute 3, nas imediações do km 67,280 do canal adutor do sertão alagoano. A análise das elevações e seus possíveis riscos à qualidade da água e à estrutura do canal adutor, para diferentes cenários de cheias, foi realizada com a utilização do programa de modelagem hidrodinâmica HEC-RAS. Observou-se que há elevação da lâmina d'água nos riachos, nos trechos a montante da junção convergente e que para vazões com tempo de recorrência de 50 anos ou mais, a estrutura de drenagem sobre o canal adutor do sertão falha, havendo galgamento da água da drenagem para o interior do canal.

Palavras-chave: Canal do Sertão Alagoano; Confluências; Junção convergente; Modelo hidrodinâmico.

INTRODUCTION

The Alagoas Aqueduct project (hereafter called Canal do Sertão, as it is known in Portuguese) was designed with a capacity of 32 $m^3 s^{-1}$. The water pumping structure is located on the shore of Lake Apolônio Sales in the city of Delmiro Gouveia, Alagoas State. After its implementation, the Canal do Sertão will provide water supply for a population of about 1,1 million inhabitants (estimation to 2050), in the cities and villages, besides irrigation, industry usage, livestock feed, among others. Along its watercourse, the Canal do Sertão will cross several watersheds, of different sizes, until reaching its final section in the city of Craíbas, microregion of Arapiraca municipality, with approximately 250 km of extension (ALAGOAS, 2003).

The Canal do Sertão is located between a semiarid climate region and a transition climate region of Alagoas, and the study area of this work is situated among the cities of Água Branca, Inhapi and Olho d'Água do Casado. The Figure 1 presents the watercourse of the Canal do Sertão and a highlight of the study area.

Along of the first 92 km of the watercourse, the Canal do Sertão present some streams cross sections where the channel bottom of the sections is lower than the bottom of the streams, depending on the local topography (see a typical section at Figure 2). This has normally occurred along the channel profile when the canal is crossing terrain elevation due land cut areas (up to 15 m below the natural terrain surface) and/or close to inlets/outlets of the water tunnels, as it occurs in the canal reach that comprehends the km 69.02 to km 71.70. In these cases, whenever necessary, special structures of drainage (overchute section over the Canal do Sertão) were designed in order to keep the Canal free of contaminants, as saline water, which is very common in the streams of this region (AGUIAR NETTO et al., 2007). Moreover, the overchute structures also help to protect the structure of the Canal from possible physical damages that may be caused by flood events.

For the canal reach considered in this study, the Canal do Sertão has a left levee structure parallel to Riacho Seco (RS) along 3,200 m, between km 65.4 and km 68.6 of the Canal (Figure 2), being crossed by the overchute 3 at km 67.28.

The purpose of this work was to evaluate the effects of the convergent confluence (water level elevations - W.L.) between the local streams and the overchute 3, as well as the left levee structure, analyzing risks of possible structural failure, and overflow into the Canal do Sertão.

Water level elevation in convergent confluences

Convergent confluences are a very common hydraulic structure in river junctions and have been commonly applied in artificial channels for different purposes: irrigation, sanitary sewage system, pluvial drainage structure (COELHO; SOUZA;

Figure 1. Watercourse of the Canal do Sertão (dark grey thick line) with a highlight of the study area (round window, left side). (Source: Adapted from SEPLANDE, 2009).

BAPTISTA, 2003; COELHO et al. 2001; ZHANG; XU; WU, 2008). Analyzing the flow conditions under confluence points is important to evaluate the occurrence of occasional overflows or generalized floods caused by the conflict flow waves and by the elevation of flow levels in the upstream canals, respectively (VICENTINI; COELHO, 2003).

Some works have presented experiments that consider the relationship between the inflows on the main channel and the outflows of the confluence, associated with the relationship between the upstream and downstream water surface elevation at the confluence point (HSU; WU; LEE, 1998); the downstream flow regime (BAGHLANI; TALEBBEYDOKHTI, 2013); the relationship between inflow and outflow at the confluence point in the main channel with the elevation of the upstream and downstream water surface of the junction (HSU; LEE; CHANG, 1998); changes in the flow conditions, such as increase in the hydraulic depths and wave propagation (VICENTINI; COELHO, 2003); flow variations, the junction angles and the widths of the channels with variations of the separation zone length in function of the flow rates (COELHO et al., 2001; GOUDARZIZADEH; MOUSAVI JOHROMI; HEDAYANT, 2010); the relationship between flow, different inflow angles and water surface level (HSU; LEE; CHANG, 1998; RAMAMURTHY; TRAN; CARBALLADA, 1994); study of the components that cause the elevation of the water level through experimental analyses (COELHO; SOUZA; BAPTISTA, 2003); confluences under conditions of downstream subcritical flow regime (COELHO, 2003); relationship between the inflow and separation zone of the water surface along the adjacent wall on the confluence in the main Canal (ZHANG; XU; WU, 2008).

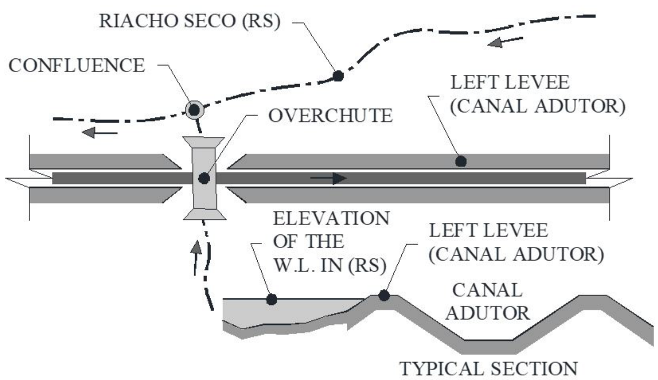

Figure 2. Design of the situation (canal layout above, and canal profile below).

Analyzing the relationship between the level of water surface upstream of the junction (h_{AM}) and the level of the water surface downstream of the junction (h_{AJ}) as a function of the relation between the inflow on the junction (Q_A) with the outflow on the junction (Q_S), the Equations 1 and 2 may be used to define the N_q and N_y ratios, thus measuring the difference in the water surface occurred between a section immediately upstream and another section immediately downstream of the confluence. The Nq and Ny ratios are presented below.

$$N_q = \frac{Q_A}{Q_S} \quad (1)$$

$$N_y = \frac{h_{AM}}{h_{AJ}} \quad (2)$$

where: Nq is the ratio between the inflow and the outflow on the junction and Ny is the ratio between the level of the water surface upstream and downstream of the junction.

Hsu, Wu and Lee (1998), in their experimental study, obtained the N_q and N_y values shown in Table 1. The column "Q_A" shows the inflows that reach the junction through the streams; the "Q_E" column shows the flows in the main channel; the "Q_S" column indicates the outflows of the confluence point; the column "h_{AM}", the hydraulic depth in a section upstream of the junction; in the "h_{AJ}" column are shown the hydraulic depth in a section downstream of the junction.

The results of the experimental work of Hsu, Wu and Lee (1998) show that when the ratio N_q is equal to 0.40, the ratio N_y is equal to 1.23 for rectangular channels with confluence angle (θ) = 90 °. It is noticed, in Table 1, that there is a slight decrease in the N_y ratio when there is a reduction in the N_q. For confluence angles with θ = 30 °, θ = 45 ° and θ = 60 °, the experiments of Hsu, Lee and Chang (1998) present N_y with values slightly smaller than those found in Hsu, Wu and Lee (1998). In this case, the studies show that when N_q is approximately 0.40, Ny is approximately equal to 1.17 for the junction with θ = 60 ° (Table 1).

METHODOLOGY

This work was developed considering the following steps:

- Characterization of the study area;

Table 1. Experimental parameters to the junctions.

a – junction with θ = 90° (HSU; WU; LEE, 1998)							b – junction with θ = 60° (HSU; LEE; CHANG, 1998)						
Flow (L s⁻¹)			Hydraulic Depth (cm)		Ratio		Flow (L s⁻¹)			Hydraulic Depth (cm)		Ratio	
Q_A	Q_E	Q_S	h_{AM}	h_{AJ}	N_q	N_y	Q_A	Q_E	Q_S	h_{AM}	h_{AJ}	N_q	N_y
3.443	3.451	6.894	10.22	8.30	0.50	1.23	3.990	2.450	6.440	10.050	8.540	0.62	1.18
2.451	3.677	6.128	9.28	7.56	0.40	1.23	3.430	3.280	6.710	10.250	8.730	0.51	1.17
2.524	3.785	6.309	9.51	7.80	0.40	1.22	2.990	4.040	7.030	10.520	9.000	0.43	1.17
1.665	3.884	5.549	8.73	7.50	0.30	1.16	2.170	4.600	6.770	10.160	8.780	0.32	1.16
1.611	3.760	5.371	8.45	7.04	0.30	1.20	1.400	5.190	6.590	9.694	8.638	0.21	1.12
1.011	3.540	4.551	7.45	6.39	0.22	1.17	0.610	5.650	6.260	9.115	8.510	0.10	1.07

Adapted from Hsu, Wu and Lee (1998) and Hsu, Lee and Chang (1998).

- Acquisition of inflow hydrographs data in the confluence sections;
- Determine the ratios level in the upstream sections of the confluence;
- Definition of simulation scenarios and analysis of backwater curves in the reaches upstream of the confluence;
- Failure risks assessment for the simulated scenarios.

Characterization of the study area

The coordinate point of the confluence studied here is located on, E = 633,255.905 m; N = 8,968,853.245 m, UTM Zone 24; Datum: SAD 69, bordering with Água Branca and Olho d'Água do Casado municipalities in the State of Alagoas, Brazil. The study area is the Riacho Seco watershed, located in the mesoregion of the Alagoas Semiarid. The Riacho Seco basin comprehends part of the Água Branca and Inhapi municipalities, whereas its tributary basins are situated in the Olho D'água do Casado municipality.

The cartographic bases used here to collect geospatial information to the model, is composed by geographic charter with nomenclature index SC-24-X-C-III - scale (ES) 1: 100,000, produced by the Geographic Service Bureau of the Army (DSG); Image from Google Earth; Digital survey mapping with ES = 1: 5,000 (agreement with the National Department of Irrigation of the Integration Ministry of Brazil- SENIR and with the Land Institute of Alagoas - ITERAL), with equidistant levels curves at each 2 m; topographic survey with ES = 1: 1,000, and level curves at each meter.

For the development of this work, was also conducted a specific topographic survey on the confluence region, including stream reaches upstream and downstream of the confluence, with the purpose of a better cross section spacing of the Canal, and a high resolution representation of the terrain surface, with level curves at each 0.5 m. The delimitation of the basins and the stream reaches studied, were produced using as support the available database already described above, especially the charters with ES = 1: 5,000.

Figure 3 shows the local topography after the improvement of the data obtained with the field survey. It is worth mentioning: i) the streams reach, including the surface of the overchute 3; ii) the location of the control sections along at each stream reach (reaches 1 and 2 of the RS with 11 cross sections, being 5 cross sections distributed along reach 2 and 7 cross sections along reach 1, respectively, and the reach 1 of the tributary stream, with 11 cross sections too); iii) level curves of the terrain with vertical equidistance of 0.5 m; iv) the limits of the study region; v) the axes of the thalwegs; vi) the angle formed between the upstream reach of the convergent junction, considering the main stream (RS) and the tributary stream (θ = 85.26 ° - adopted 85 °); vii) the banks of the streams, defining the main channel (ridge crests) of the RS and the tributary; viii) the Canal do Sertão reach along the study region; ix) the flow direction of the terrain in the RS, tributary stream and also in the watercourse of the Canal do Sertão and; x) the flood polygon for the discharge flows defined in scenario 2.

The hydrographic basin in this region of the Canal do Sertão is composed by six (6) basins, being five (5) tributary basins located on the right bank of the Canal (hydrographic region of the tributary basins), and a part of the Riacho Seco watershed, located on the left bank. The data of basin areas (A_B), length of the streams (L_T), geometric differences (Δ_H) and the CN values (Curve Number), adopted as input data on the hydrological model are presented in the Table 2

The basins were denominated and characterized as follows:

- Tributary basin 1 (BT1), is the smallest of the basins, highly anthropized, marked by having no vegetation cover during the dry season of the region;
- Tributary basin 2 (B_{T2}), has the same morphological features of B_{T1};
- Tributary basin 3 (B_{T3}), is the largest of the basins located on the right bank of the Canal do Sertão, partially covered by Caatinga vegetation (typical vegetation of semiarid regions of Brazil), and slope less accentuated than B_{T1} and B_{T2};

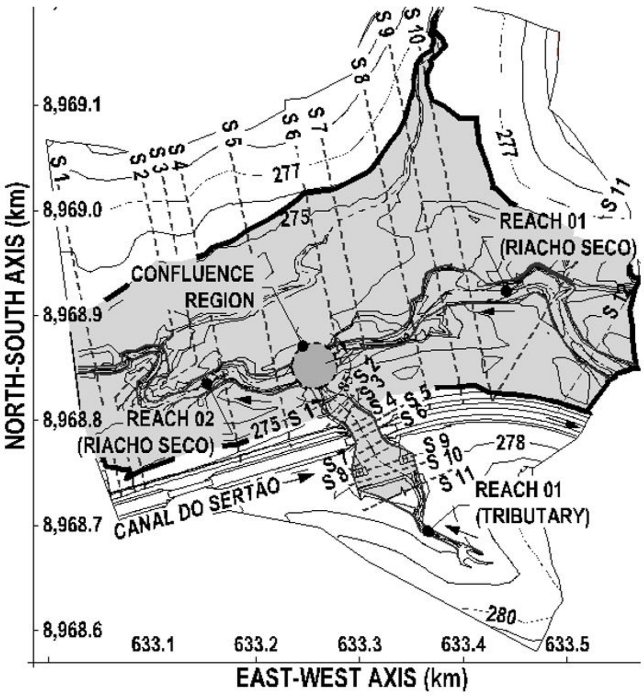

Figure 3. Topographic information, control sections, and flood polygon, in the confluence region.

Table 2. Characterization of the basins.

Basin	Parameters			
	A_B (km²)	L_T (km)	ΔH (m)	CN
B_{T1}	0.13	0.44	14.0	90
B_{T2}	2.09	2.36	30.0	90
B_{T3}	3.33	3.91	36.5	85
B_{T4}	0.18	0.54	13.5	90
B_{T5}	0.21	1.72	17.0	92
B_{RS}	9.64	7.38	65.5	90

- Tributary basin 4 (B_{T4}), is a small basin with the same features as B_{T1};
- Tributary basin 5 (B_{T5}), is totally anthropized by the construction sites of the Canal do Sertão - part of the area is impermeable due the roads and side slopes;
- Riacho Seco basin (B_{RS}), is the largest drainage area of the study region, highly anthropized, also marked by having no vegetation cover during the dry season of the region, and accentuated slope.

The geology of the hydrographic area is determined by crystalline rocks with low infiltration capacity. Figure 4 shows a schematic representation of the hydrographic area. In the basins B_{T1} and B_{T2} there are two small lakes that are part of the drainage system of the Canal do Sertão, lake 1 (on B_{T1}) and lake 2 (on B_{T2}). The discharge flows from the B_{RS} and the tributary basins (B_{T1} to B_{T5}), flow to the confluence.

In the diagram of Figure 5, are indicated the relative position of the control points where the flow rates were determined as input on the hydrodynamic model. The control point 1 was placed at the spillway of lake 1; control point 2 was placed at the spillway of the lake 2 and receives flows contribution from B_{T1} and B_{T2} basins; control point 3 is located at the junction of the connecting channel 2 with the B_{T3} outlet, receiving the flows contribution of the upper parts of the B_{T1}, B_{T2} and B_{T3} basins; control point 4 is located on the energy sink element of the overchute 3, and receives the flows of the entire hydrographic area of the tributary basins and; control point 5 is located at the confluence, target of this study, this point receives the flows from its upstream drainage area, B_{RS} basin and all tributary basins (B_{T1} to B_{T5}).

Inflow hydrographs of the confluence sections

During the decade of 1980-1990 (there is no exact information of the year), a historical flood occurred in the region of the confluence, whit an event estimated for a return period (rp) of 100 years, where the flooded areas in the RS reached more than 1m above the ground level in some houses, located less than 1,500 m from the point of confluence (Poço Salgado village). In the event that occurred on 17/12/2013, while the canal was being constructed, an intense rainfall precipitated in the region, mainly concentrated over the B_{T1} and B_{T2} basins, causing an overflow of the lakes 1 and 2 into the auxiliary channel (Figure 4), and consequently damages on the plant construction of the Canal do Sertão.

However, there is no systematic flow discharge record in the rivers of the region, which difficult the calibration of models and/or a statistical analysis of the data series. Therefore, many parameters used in the model simulations were obtained in a secondary way, based on the physical characteristics of the region and average values of the literature. The basin areas are small with a large numbers of watercourses, with shallow soil and crystalline rocks, causing a very rapid response to hydrological events. Short-duration intense rainfall with a concentrated spatial distribution is frequent, emphasizing the spatial effect of the precipitation (GARCEZ; ALVAREZ, 1988; TUCCI, 2007).

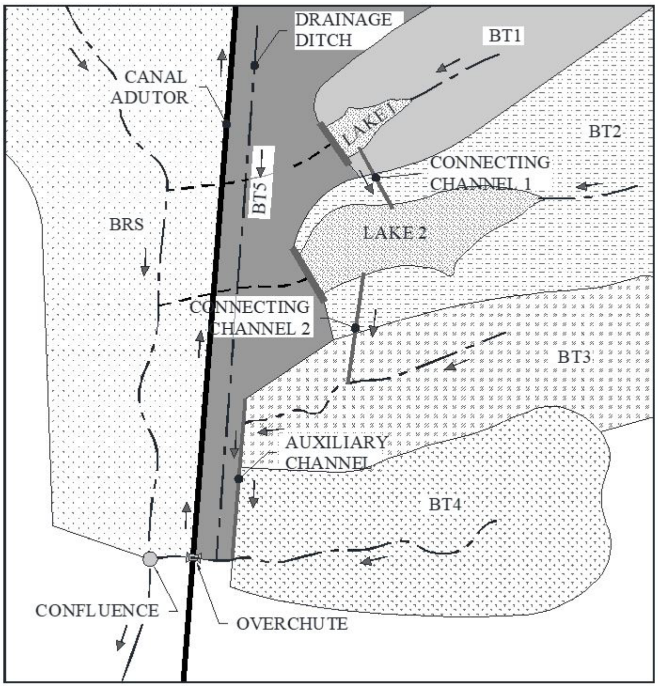

Figure 4. Schematic representation of the hydrographic area.

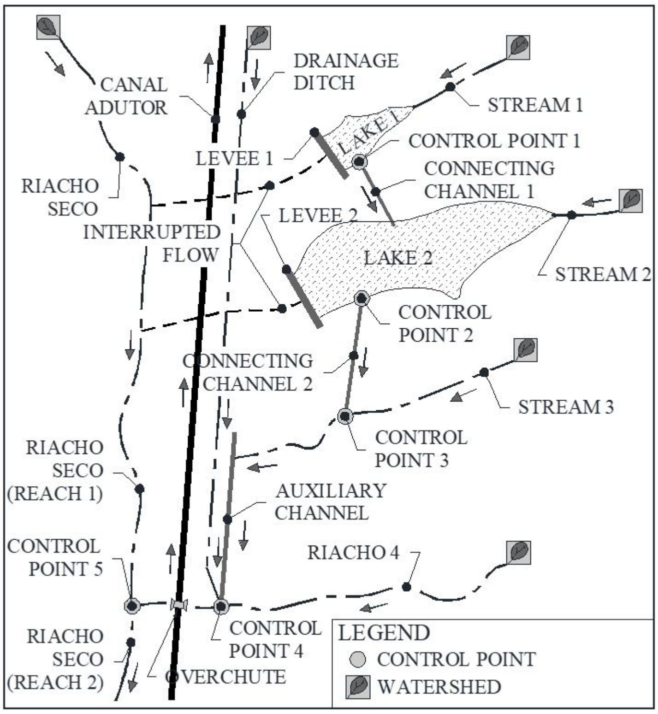

Figure 5. Diagram of the control points of the basins.

For the analysis of extreme rainfall events, was used the data series from the rainfall gauge station (00937013), located in the city of Delmiro Gouveia / AL, about 25 km far from the studied confluence. For comparative purposes, was also used the rainfall gauge station (00638034 - São Gonçalo / PB), due its data series had been used on the drainage project of the Canal do Sertão. This gauge station is often used for hydraulic projects in Alagoas semiarid region, probably because it is the only one available in the region that has an IDF curve established in the technical literature.

Thus, a simulation was performed using discharge flows from the rainfall data series of the gauge station (00638034), considering the simulation of discharge flows for an event with RP of 50 years. The rest of the discharge flows data (obtained by rainfall-runoff simulation) were calculated using the rainfall data series from the Delmiro Gouveia rainfall gauge station (00937013).

The analysis of heavy rainfall was performed using maximum daily precipitation, with rainfall disaggregation by duration coefficients, according to Tucci (2007), and Gumbel distribution for adjustment of different durations.

Table 3 presents the results of the analysis of heavy rainfall for the gauge station 00937013 (Delmiro Gouveia, AL), the last column (RP 50-SG), presents data from gauge station 00638034 (São Gonçalo, PB). It is noticed that the SG gauge station, although located in a region that has climate similarities to those of Delmiro Gouveia (PARAHYBRA; LEITE; OLIVEIRA NETO, 2006; SILVA NETO, 2013), its estimations of events with 50-years rainfall is higher than those for 100-years rainfall in Delmiro Gouveia gauge station. It is worth emphasizes again, that its use in this work is a reference for comparative analysis, as this gauge station was applied on the hydraulic project of the Canal do Sertão.

The transformation of rainfall to runoff was performed using the hydrological model IPHS1 (TASSI et al., 2005) for different scenarios, which will be presented in the results section.

It was used the SCS-CN model and the CN parameter values for the hydrographic basins were determined based on their physiographic and morphological characteristics, such as land use and occupation of the region, the slope of the basins, level of anthropization, lithology, soil physical properties. It was used satellite images, visual analysis during field trips, the topography of the region and data of the literature, as no local studies which relate the CN parameter were found (ARAUJO NETO et al., 2012; TUCCI, 2007; LOBATO et al., 2009). The CN values for each basin have already been presented in Table 2.

Water level relationship in the upstream cross sections of the confluence

The HEC-RAS hydraulic model (USACE, 2010), has been used in solving problems of reach junctions, presenting good results (COELHO; SOUZA; BAPTISTA, 2003; COELHO, 2003; PAIVA; COLLISCHONN; BRAVO, 2011; COELHO et al., 2001).

The study case, as presented in Figure 6, analyze a convergent confluence defined from three cross sections: the cross sections of reach 1 of the RS and of reach 1 of the tributary (AF) located immediately upstream of the confluence, and the cross section of reach 2 of RS located downstream of the confluence (PAIVA; COLLISCHONN; BRAVO, 2011).

The water bodies located in the Northeastern semiarid region of Brazil are susceptible to sedimentation over the time, due to the physical characteristics of the soil of the region. The Lakes 1 and 2 are small, constructed without a bottom outlet and situated in a deforested area that constitutes, therefore, a land surface without preservation (erosion containment) and with a superficial layer of soil that is easily erodible (ARAÚJO, 2003). Over the years, the lakes 1 and 2 will tend to reduce their storage capacity (a consequence of the sedimentation), reducing their capacity of damping maximum hygrograms of the B_{T1} and B_{T2} basins, increasing the flow rates that drain through the cross section of the control point 4.

Thereby, was considered two initial conditions for the lakes on the model: (i) empty lakes, representing an ordinary

Table 3. Design rainfall used in the generation of the hydrographs of different scenarios of return period.

Time (min)	Design Rainfall (mm)			
	RP 50	RP 100	RP 200	Rp 50-SG
10	25.3	28.1	30.8	29.1
20	37.9	42.1	46.2	48.7
30	46.8	52.0	57.1	62.2
40	55.7	61.8	67.9	72.2
50	61.2	67.9	74.6	81.4
60	63.3	70.2	77.2	90.3
70	72.1	80.0	87.9	94.4
80	80.4	89.2	98.0	100.0
90	88.1	97.8	107.5	104.2
100	95.4	105.9	116.3	108.1
110	102.2	113.4	124.6	111.8
120	108.5	120.4	132.3	115.2

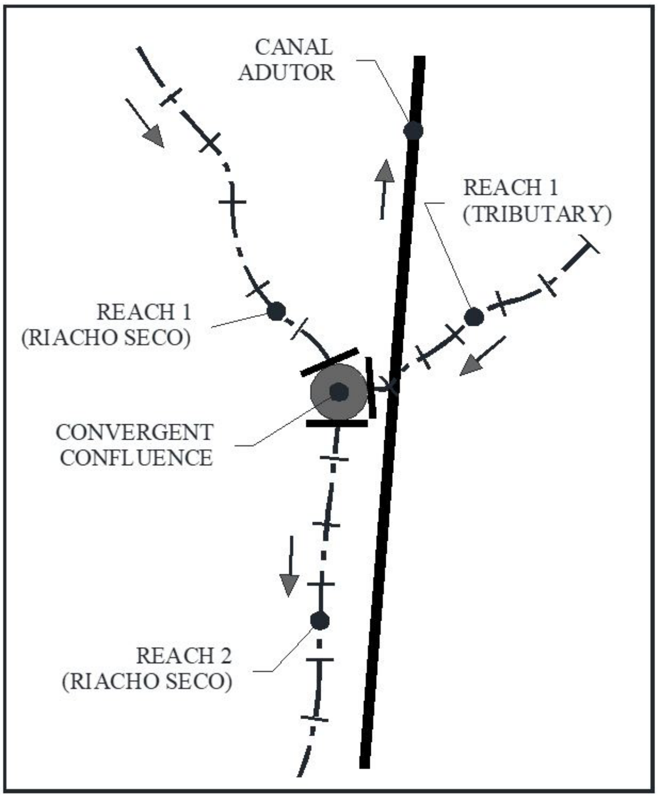

Figure 6. Diagram of a three reaches system of rivers and a confluence (Adapted from PAIVA, COLLISCHONN; BRAVO, 2011).

condition of the semiarid region, with intermittent rivers and low water storage and (ii) filled up lakes, because of successive rainfalls events or completely sedimented. Thus, flow discharges on junctions 4 and 5 were obtained considering the two possible conditions of initial levels for the lakes 1 and 2. These criteria (see Table 4) are represented in the simulated scenarios and will be discussed further.

The cross sections location was defined in Riacho Seco and in the tributaries in ascending order, from downstream to upstream. The location of the cross sections at each reach, the number of cross sections and the distance between them may be seen in Figure 3 and is also indicated in Table 5. The reach 1 of the tributary, it is where the overchute is located (Figure 7).

Scenarios and criteria adopted

The precipitations occurred in the region are, in general, classified as convective rainfall, with concentated spatial distribution and rapid displacement, characterized with high intensity and short duration (TUCCI, 2007; GARCEZ; ALVAREZ, 1988). These characteristics, associated with recorded events, contributed to the definition of the analyzed scenarios. The basin areas are small, ranging from 0.13 km^2 to 9.64 km^2.

Seven scenarios were defined, being five scenarios considering the rainfall data from the gauge station 00937013 and two scenarios calculated with rainfall data from the gauge station 00638034. Data from the gauge station 00638034 was also used for flow discharges calculations for a 50-year flood as a comparison scenario, due to the overchute 3 structures has been dimensioned using such information, despite the distance from the study area. The scenarios were chosen (Table 4) in order to simulate critical conditions for the confluence (junction 5) and eventual backwater conditions with the elevation of the upstream water surface level.

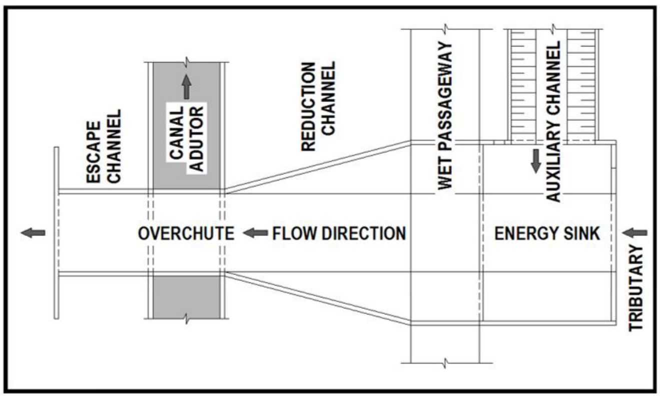

Figure 7. Drainage structure of the overchute 3 over the Canal do Sertão.

Flow discharges for each scenario, used as input data in HEC-RAS (USACE, 2010), are presented in Table 4. For each scenario, was considered the criteria related to the water levels in the lakes, and it was assumed that the maximum flow discharge comes at the same time in the convergent confluence (junction 5), it means that the junction 5 will receive at the same instant the design runoff of the RS and the overchute 3. The flow regime considered was in the steady flow.

The angle θ between the axis of the tributary and the axis of the RS was measured in the plant from the additional topographic survey, and its value is 85° (Figure 3).

In the hydraulic simulation, variations of the Manning coefficient were considered in the reaches based on its physical characterization. In the natural reaches a minimum coefficient of 0.045 was adopted in the riverbed because they are stony meandering, and a maximum of 0.07, for some floodplain areas, because they have caatinga vegetation with trees and bushes with heights that may reach 3 m or more. Depending on the weather conditions (after the first rains in the region), a large amount of shrubby vegetation start to grow up, with a lower height than the caatinga, creating conditions that make it difficult to flow (FRENCH, 1986). In the artificial Canal of the overchute 3, prismatic canal finished with good a concrete, a Manning coefficient of 0.014 was adopted in the whole Canal length (FOX; MCDONALD, 1998; FRENCH, 1986; BAPTISTA; COELHO, 2010; ÇENGEL; CIMBALA, 2015). These criteria were used for all scenarios.

RESULTS

The results of the hydrodynamic model for the water surface elevation (freeboard of the structures at each cross section) are presented in Table 5. The cross section S7 of the tributary (AF) and the cross sections S11 and S12 of reach 1 of the RS were the sections where the water surface reached the highest

Table 4. Analysed scenarios.

Scenarios to analyses with the hydrodynamic model							
Scenario	RP (year)	Flow on junctions 4 and 5			Station	Volume in the lakes (%)	
		B_{T1-T5} (JUNCTION 4)	B_{RS} (JUNCTION 5)	$B_{RS}+B_{T1-T5}$ (JUNCTION 5)			
		Q_E (m^3 s^{-1})	Q_E (m^3 s^{-1})	Q_S (m^3 s^{-1})		Lake 1	Lake 2
1	50	60.95	120.00	180.95	00937013	0	0
2	50	78.16	120.00	198.16	00937013	100	100
3	50	70.78	133.72	204.50	00638034	0	0
4	50	89.25	133.72	222.97	00638034	100	100
5	100	72.75	136.82	209.57	00937013	0	0
6	100	90.42	136.82	227.24	00937013	100	100
7	200	102.64	153.76	256.40	00937013	100	100

Table 5. Differences between the water surface elevation and the structures top level (ΔH) of the Canal do Sertão.

Reach	Stream	Section	L_T (m)	Summary of freeboard - ΔH (m) –, to the 1 to 7 scenarios						
				Scenario						
				1	2	3	4	5	6	7
1	RS	S12	644.21	0.69	0.69	0.63	0.62	0.62	0.60	0.52
	RS	S11	574.96	0.88	0.86	0.81	0.79	0.80	0.77	0.68
	RS	S10	485.78	1.09	1.04	1.00	0.94	0.98	0.92	0.81
	RS	S9	457.17	1.10	1.05	1.01	0.95	0.99	0.93	0.82
	RS	S8	418.10	1.15	1.09	1.06	0.99	1.04	0.97	0.86
	RS	S7	365.04	1.20	1.13	1.11	1.03	1.09	1.01	0.90
	RS	S6	338.41	1.23	1.16	1.14	1.06	1.12	1.04	0.93
2	RS	S5	273.75	1.58	1.51	1.49	1.42	1.47	1.41	1.30
	RS	S4	216.63	1.72	1.65	1.63	1.56	1.61	1.54	1.44
	RS	S3	127.46	1.85	1.78	1.75	1.68	1.73	1.66	1.56
	RS	S2	71.99	1.93	1.86	1.83	1.76	1.81	1.74	1.64
	RS	S1	4.41	2.17	2.10	2.08	2.01	2.06	2.00	1.90
1	AF	S11	155.72	0.33	0.22	0.26	0.15	0.25	0.15	0.08
	AF	S10	131.46	0.73	0.51	0.60	0.37	0.58	0.36	0.22
	AF	S9	118.51	0.79	0.56	0.66	0.42	0.63	0.41	0.27
	AF	S8	104.98	0.42	0.20	0.29	0.06	0.26	0.05	-0.09
	AF	S7	95.97	0.23	0.02	0.10	-0.11	0.08	-0.13	-0.25
	AF	S6	83.97	0.40	0.25	0.32	0.09	0.30	0.07	-0.05
	AF	S5	76.29	0.40	0.28	0.33	-0.10	0.31	-0.11	-0.23
	AF	S4	69.42	0.48	0.34	0.40	0.13	0.38	0.12	0.02
	AF	S3	57.32	-0.01	-0.09	-0.02	-0.02	-0.03	-0.01	-0.10
	AF	S2	49.83	0.55	0.39	0.45	0.33	0.44	0.32	0.23
	AF	S1	37.00	0.31	0.18	0.23	0.11	0.22	0.10	0.03

elevation, presenting the smallest differences (ΔH) between the level of the water surface (HA) and the level of the structures (H) of the Canal do Sertão (ΔH = H – HA). For the scenario 1, the highest water surface level reached on the top of the wall of the overchute 3 at S7 cross section is ΔH = 0.23 m (Figure 8). It is observed that the elevation of the water surface at cross section S11, in reach 1 of the RS, upstream reach of the confluence, reached ΔH = 0.88 m from the top of the Canal's levee (Figure 9). In Table 5 the L_T column indicates the distance from the origin of the reach to each control point.

The sections S1 to S5 of the AF will not be discussed because they appear inside of the floodplain of the RS, not representing a risk of failure to the Canal drainage system.

In the hydraulic profile of Figure 10, the RS shows changes in the water surface level in the region of the convergent confluence (reach between cross section S5 and cross section S6), showing the effect of elevation of the water surface level in this region. Probably this change is due to the energy losses caused by the junction of two reaches (conflict of the waves).

The profile that presents the reach 1 of the AF (Figure 11) shows that there is supercritical regime between cross section S2 and the convergent confluence and between cross sections S5 and S4 (Table 6). It is noticed in this profile that there is a slightly accentuated geometric gradient (slope i ≈ - 0.025m / m) in the last 45 m towards the junction.

The freeboard on the rest of the cross sections for scenario 1 may be seen in Table 5.

The cross sections of reach 2 of the RS have shown high freeboard (above 1 m) for all scenarios, and with subcritical flow

Table 6. Flow regime in each stream reach - AF (scenario 1).

Scenario 1: Flow regime				
Stream	Reach	Section	L_T (m)	n_F
AF	T1	S5	76.29	1.14
AF	T1	S4	69.42	1.19
AF	T1	S3	57.32	0.90
AF	T1	S2	49.83	1.54
AF	T1	S1	37.00	1.58

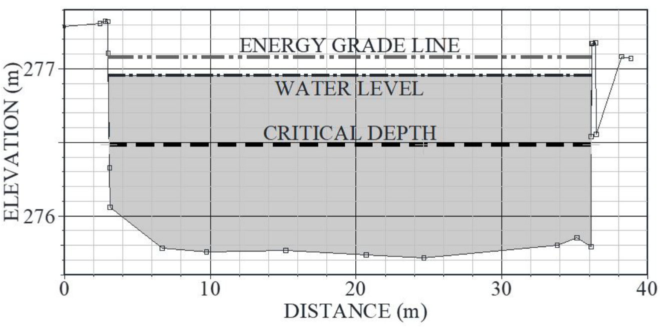

Figure 8. Water surface elevation at cross section 7 on tributary reach 1 (scenario 1).

regime along the two reaches of RS (Froude number (nF) <1) for all scenarios.

In Table 5 the difference between the water surface level of the section S6 and the section S5 on the RS (reach defining the convergent confluence) is 0.35m (scenario 1), indicating the effect of energy losses at the confluence. The difference between the water

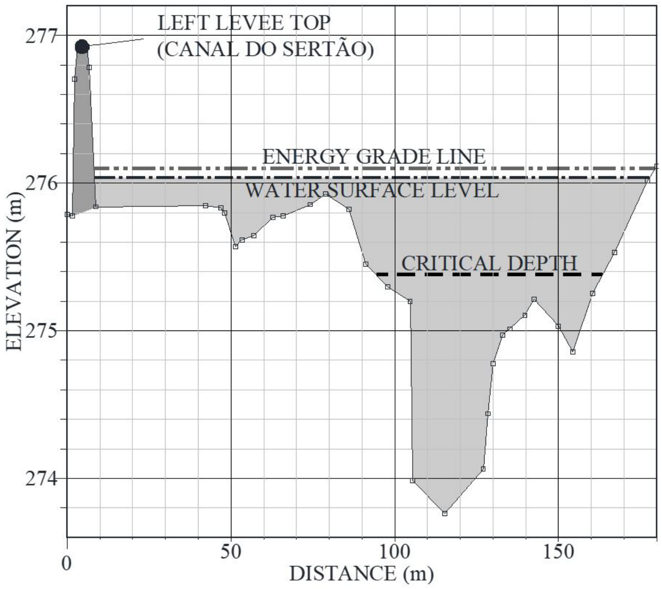

Figure 9. Water surface elevation at section 11 of Riacho Seco reach 1 (scenario 1).

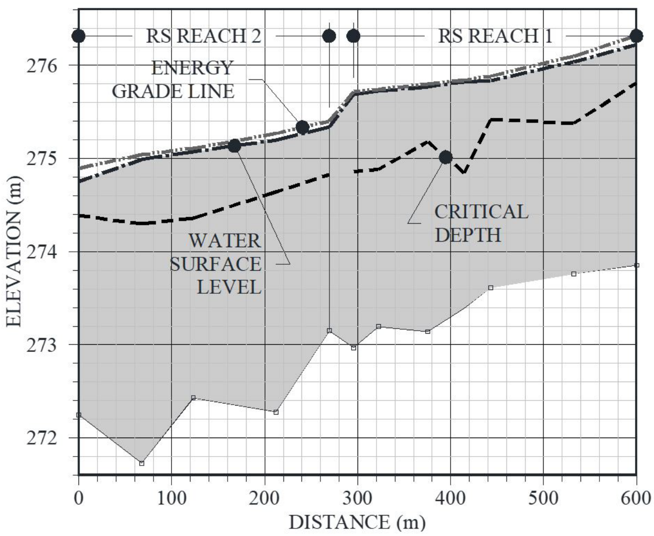

Figure 10. Water surface elevation in the Riacho Seco profile (scenario 1).

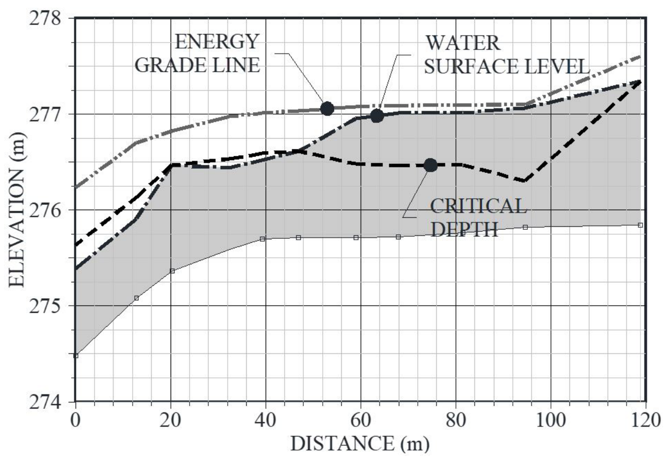

Figure 11. Water surface elevation on tributary profile (scenario 1).

surface level at section S7 of reach 1 of the AF and the height of the top of the structure wall indicates that the overchute 3 is on its limit of flow capacity for scenario 2 (ΔH = 0.02m). The elevation of the water surface at section S7 of reach 1 of the AF is not due to backwater effects on the junction, since the flow regime is supercritical (Table 7) from cross section S5 to the confluence point, indicating a slightly difference on the water surface level of the hydraulic profile (i ≈ - 0.025 m/m). The elevation of the water surface reaching the top of the wall is due to the increase of the flow rate over the overchute 3 in comparison to scenario 1 (Q = 60.95m^3 s^{-1} in scenario 1 and Q = 78.16m^3 s^{-1} in scenario 2 (Table 4).

The water surface level at cross section 11 in reach 1 of the RS, upstream of the confluence region, in scenario 2, reaches 0.86m of the Canal do Sertão levee's top (Figure 9).

Analyzing the cross section S7 of the AF for scenario 4, water surface level rises 0.11m above the top of the structure wall of the overchute 3, indicating a drainage system failure. The failure, however, is not due to the influence of energy losses at the junction, because there is a considerable level difference between the junction point and the section S5 of the AF, creating a supercritical regime between the cross sections S3 to S1 (Table 8).

The overbank on the Riacho Seco, causes the elevation of the water surface in the left levee of the Canal, mainly in the upstream of the confluence (reach 1 of the RS). Figure 3 shows the flooding polygon, and it was produced from the water surface width data in the control sections, presented in the "C_T" column of Table 9 for scenario 2.

The flooding polygon shows the water surface progress toward the left levee of the Canal do Sertão. It may be noticed in the sections of the RS that the highest level curves are reached by the water surface level in the reach between cross sections S6 to S12, due to the effect of energy losses at the confluence region, indicating that the water surface level rises more in the upstream of the convergence junction (see cross section S5 and section S6 in column C_T of the Table 9, Figure 3 and Figure 10). From the cross section S6 the water surface always rises above HA = 275.7m. There is a noticeable slope at the top of the water surface level between

Table 7. Flow regime for each stream reach (scenario 2).

Scenario 2: Flow regime				
Stream	**Reach**	**Section**	**L_T (m)**	**n_F**
AF	T1	S5	76.29	1.18
AF	T1	S4	69.42	1.19
AF	T1	S3	57.32	1.02
AF	T1	S2	49.83	1.44
AF	T1	S1	37.00	1.59

Table 8. Flow regime for each stream reach - AF (scenario 4).

Scenario 4: Flow regime				
Stream	**Reach**	**Section**	**L_T (m)**	**n_F**
AF	T1	S6	83.97	0.90
AF	T1	S5	76.29	0.76
AF	T1	S4	69.42	1.00
AF	T1	S3	57.32	1.30
AF	T1	S2	49.83	1.47
AF	T1	S1	37.00	1.61

Table 9. Reached width of the water surface along each cross section to the scenarios (1 to 7).

Stream - Reach	Section	Scenario						
		1	2	3	4	5	6	7
		C_T (m)	C_T (m)	C_T (m)	C_T (m)	C_T (m)	C_T (m)	C_T (m)
RS-T1	S12	140.29	140.39	141.04	141.19	141.21	141.35	142.29
	S11	169.43	170.04	171.54	172.39	172.02	172.84	175.57
	S10	273.80	284.69	292.21	309.84	297.56	314.21	328.98
	S9	261.25	262.89	264.15	266.52	264.87	267.14	272.56
	S8	190.07	198.46	203.77	220.02	208.17	224.19	237.27
	S7	179.55	205.64	215.89	222.01	220.72	222.39	224.96
	S6	181.45	183.81	184.48	187.21	185.19	187.74	191.34
RS-T2	S5	194.92	199.46	201.24	206.29	202.65	207.42	214.18
	S4	183.24	186.60	187.80	191.17	188.74	191.93	196.89
	S3	237.06	242.09	243.87	248.97	245.28	250.11	256.64
	S2	227.83	230.52	231.47	236.59	232.88	237.73	245.28
	S1	134.33	137.38	138.42	143.82	139.24	145.55	157.04
AF	S11	60.93	67.32	64.55	71.80	65.14	72.03	76.95
	S10	60.12	60.14	60.13	60.14	60.13	60.14	60.15
	S9	47.96	51.10	49.79	53.01	50.13	53.21	55.12
	S8	44.88	44.94	11.92	44.98	44.93	44.98	48.81
	S7	33.14	33.19	33.17	36.55	33.17	37.97	39.85
	S6	25.08	25.09	25.09	25.10	25.09	25.11	28.50

Note: the RS-T1 upstream reach of the confluence; the RS-T2 downstream reach of the confluence and AF reach of the tributary.

the cross section S6 and cross section S5, which may also be seen in Figure 3. The upstream section of the convergent confluence, reach 1 of RS, shows that the water surface level for scenario 2 rise in the left levee of the Canal, particularly from cross section S10 to the last cross section, S12. Between the cross sections S6 and S10, there is an overflow of the RS, where the water surface level reaches the base of the Canal's levee. The cross section S11 on reach 1 of RS indicates that the water surface rises 0.79 m from the top of the left levee of the Canal do Sertão, however, there was no risk of overflowing into the canal, for this scenario (scenario 4).

Freeboard heights may be seen in Table 5 for the other scenarios.

The table 9 summarizes the widths (C_T) reached at each cross section on the top of the water surface level. It is noticed that with the increase of the flow rates coming through the AF, and considering the same flow in the RS (comparing scenario 1 with scenario 2, for example), there is an increase in the section width due to the elevation of the water surface level generated by the hydraulic effect of the confluence, although the enlargement of the water surface is not only relative to the elevation of the water surface level, but also of the topography conditions at each cross section. In this case, it is noticed that there is an increase of the water surface width in the cross sections, when the inflow is also increased, unlike the constant width in a rectangular canal, where there are only vertical variations of the water surface. This result confirms the influence of changes in the hydraulic conditions in the junction and its effect on the elevations and enlargement of water surface, for this study case.

In the Table 9, results for cross sections S1 to S5 of the AF were not showed, since they were inside of the Riacho Seco floodplain area.

Table 10. Relationship between the inflow rate variation and the upstream water surface elevation of the junction, at section S6.

Variation in water surface at section S6		
Scenario	S6	Δh (m)
	H_A (m)	
1	275.69	0.07
2	275.76	
3	275.78	0.08
4	275.86	
5	275.80	0.08
6	275.88	

Analyzing the scenarios 1 to 6, in pairs - scenarios 1 and 2 have the same flow discharge in the RS and different flow discharge in the AF, the same also occurs in scenarios 3 and 4, and 5 and 6 (Table 4). It is observed that the elevations vary according to the rate of the inflow. Considering the cross section S6 as reference section, immediately upstream of the junction in Riacho Seco, a rise in the water surface elevation is noticed when there is an increase of the inflow rates. Table 10 presents the effects of the water surface elevation according to the scenarios, it was observed that there was 7 cm water surface elevation between scenario 1 and scenario 2.

Table 11 shows the results of Nq and Ny relationship on the considered convergent confluence.

Both results of the water surface elevations shown in Table 5 and in Table 10, as well as the results of increasing of widths in the water surface of Table 9, show that there is a relationship between inflow rates and elevation of the water surface upstream of the convergent confluence (scenarios 1 and 2, 3 and 4 and 5 and 6), characterizing the energy losses at the confluence due to changes in the flow conditions.

Table 11. Relationship between flow discharge and hydraulic depth in the confluence regions between section S5 and section S6 to the RS.

Scenario	Flow ($m^3 s^{-1}$)			Hydraulic Depth (m)		N_q	N_y
	Q_A	Q_E	Q_S	h_{AM}	h_{AJ}		
1	60.95	120.00	180.95	2.53	2.19	0.34	1.16
2	78.16	120.00	198.16	2.60	2.26	0.39	1.15
3	70.78	133.72	204.50	2.62	2.28	0.35	1.15
4	89.25	133.72	222.97	2.70	2.35	0.40	1.15
5	72.75	136.82	209.57	2.64	2.30	0.35	1.15
6	90.42	136.82	227.24	2.72	2.36	0.40	1.15
7	102.64	153.76	256.40	2.83	2.47	0.40	1.15

The study presented here shown that, when the Nq ratio is close to 0.4, the Ny ratio is close to 1.15, for a confluence angle (θ) of 85° (Table 11).

The results found in the analysis of the confluence, show that Ny reached similar values compared to literature. The values of the Ny ratio in Table 11 reached 94.3% of the ones found in the experiments of Hsu, Wu and Lee (1998), with Nq value close to 0.4 with $\theta = 90°$ (comparing the results of Table 11 with those of Table 1a). Such difference (reduction in the Ny ratio of this work in comparison with the experimental data of Hsu, Wu and Lee (1998) may be explained due to the fact that the angle of the inflow stream presented here ($\theta = 85°$) is lower than the value of angle ($\theta = 90°$) of the experiment performed by Hsu, Wu and Lee (1998), which was simulated in a rectangular streams and, mainly, considering that the flow conditions of these studies are different. This work studied flow conditions in a stream with irregular channel (irregular sections with high lateral expansion), producing results that show differences when compared with the experiment, performed at laboratory for regular rectangular sections. This may be noticed in Table 9 and Figure 3, where it is possible to see that the left and right bank of the RS was flooded, preventing a higher elevation of the water surface in the upstream region and, consequently, generating a lower Ny ratio.

Differently from a rectangular channel, where there is no lateral expansion of the water surface due to the confinement caused by the section, but rather a vertical elevation (increasing the Ny ratio in the case of junctions), in natural irregular streams the water surface tends to spread out over the area, reducing the Ny ratio.

In the experimental data from the Hsu, Wu and Lee (1998), shown in Table 1a, the "Nq" column may be compared with the results of the relationship between the upstream and downstream water surface level of the convergent confluence of this study, presented in Table 11, indicating that the ratio Ny of this work presents reasonable values in comparison to those ones of the experiment of Hsu, Wu and Lee (1998).

The Table 1b, elaborated by Hsu, Lee and Chang (1998), for different flow rates in the upstream reach of the convergent confluence is presented here with the purpose of compares the results. In the experiment of Hsu, Lee and Chang (1998), when the Nq ratio approaches 0.40 the Ny ratio is close to 1.17. The Nq and Ny ratios of this study present a good values approximation with the results of the experiment developed by Hsu, Lee and Chang (1998) for $\theta = 60°$ (Ny of this work reaches approximately 98.28% of the experiment for Nq ≈ 40).

CONCLUSIONS

We could see that the hydraulic effects of the elevations of the water surface level observed in the control sections for natural drainage streams (irregular streams), indicates that there is an influence of the confluence region in the upstream reaches due to changes in the flow conditions, generating energy losses at the junction and, as a consequence, the rise in the water level over the channel.

This work presented results that may help in the definition of engineering intervention close to the junctions in natural streams, since analyzed together considering the possible range of the parameters used.

Regarding the failures detected, considering the flow rates of scenarios 4, 6 and 7, this work presents guidelines for the decision making, indicating that the overchute 3 structure walls should be raised between sections S8 and S6 of the reach 1 of the tributary stream. The risk that the overflow of the wall may cause, however, is qualitative (quality of the water that flows into the Canal do Sertão), without risk of rupture of the concrete structure.

Concerning the elevation of the water surface level over the left levee (structure in compacted soil) of the Canal do Sertão along the upstream reach of the convergent confluence (section 2 of RS), the external energy sink element of the side slope must be protected to avoid erosion.

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Authors contributions

Jerônimo Leoni Leandro Lima: contributed in field survey, data analysis and processing, hydraulic and hydrologic modelling, generation and assessment of results.

Vladimir Caramori Borges de Souza: Contributed on drafting and supervision of the research, discussion of results, writing of the article and final paper review.