Rio de Janeiro's Flash Flood Warning System

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ABSTRACT: The present paper describes the path walked by the Environmental Agency of Rio de Janeiro (INEA) towards the implementation of a reliable weather forecast system in order to prevent impacts due to extreme events. In 2007 INEA started to acquire new equipment, extending its data collection net and aiming to create a flash flood warning system, through monitoring rain and river levels. It was a huge gain, but the system was only able to anticipate the events a few minutes before it happened, thus the agency decided to increment the forecast system with more robust equipment. In 2012 it started the proceedings to install weather radars. Nowadays, the net operated by INEA encompass 2 S-Band weather radars, installed at the cities of Rio de Janeiro and Macaé, capable of quantifying water in the atmosphere up to 250 km radius, which makes the State of Rio de Janeiro the first one in Brazil to have all its catchments covered by radar technology, including the neighbor States areas, besides 130 water levels and rain monitoring stations. This net provides data to the technical personnel, which interpret the collected information and contact the response teams in the municipal, state and federal levels, in case of need. Taking Quitandinha basin as an example, the mean lead time has significantly increased since the operation of the radar system. It was about 3 hours from 2011 to 2014 and increased to more than 6 hours during the last rainy season.

Keywords *Warning system, flash flood, weather radar*

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1. INTRODUCTION

The State of Rio de Janeiro since long time has equipment measuring the quality of the water in a few specific spots, as the Guanabara Bay (where the data goes back 30 years). Besides these measurement spots there were a few others which collected information with regards to water levels, intended to provide data to water collection systems.

Those hydrometeorological stations were of conventional reading at first, but after 2000 some stations, especially those installed at Rio de Janeiro lowland area, were automatized and gained telemetric data transmission.

Due to extreme weather events, the environmental agency decided to extend such data collection net in order to create a system that would anticipate heavy rains and its consequences. That system would allow the authorities to inform the potentially affected areas and prevent the loss of lives and properties.

1.1 The beginning of Rio de Janeiro's Flash Flood Warning System

In 2007 the agency started to acquire new equipment to lively monitor the rain and water levels of rivers which were relevant to its drainage basin. In order words, considering limited resources, the agency chose to install the measurement stations in the most important water bodies.

Rio de Janeiro lowland area received the first warning system of the state in 2008, when INEA started using a few telemetric stations that were installed before. During the same year new telemetric stations were installed in Nova Friburgo, a municipality in the mountain area, which gave rise to the second warning system in the state. Later, in 2011, the monitoring spread to the north area of the state, where flood events are not so frequent, but affect large areas for many days.

Unfortunately, during that same year Brazil faced its greatest natural disaster, when large accumulated precipitation reached the mountainous region of Rio de Janeiro for several consecutive days, causing associated events of landslides and floods, taking hundreds of lives. After that, INEA inherited a weather station network from a research centre located in Petropolis, one of the most affected municipalities.

1.2 Rio de Janeiro's Weather Radars

The hydrometeorological stations were only able to anticipate an extreme event a few minutes before it happened. This means that, only after the water levels were significantly above the regular standards, it was possible for the Civil Defences to make the decision about an evacuation or other protection measures.

In this sense, the agency decided to increment the forecast system with more robust equipment. In 2012 it started the proceeding to install weather radars. The challenges to such idea were enormous and the doubts were vast: (i) What equipment to acquire? (ii) Should an environmental agency be responsible for weather forecast? (iii) Where would such expensive and complex equipment be installed? (iv) Which allocation could provide maximum coverage with minimum risks; (v) How would the agency operate and maintain such radars? Among several others.

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The acquisition of the radars were only initiate after answering the aforementioned questions and the entire process took more than one year, considering the public tender proceedings, equipment and building erection, personnel training and actual operation of the facilities. All of this was funded by the World Bank.

1.3 Network new challenges

When a network becomes big, new challenges are faced. The first one is that it requires people enough to analyse the data, 24 hours a day, 7 days a week. In 2008 INEA entered into a contract in order to operate the System, however this contract only provided 3 meteorologists and 4 meteorology technicians, which allowed only 1 person each shift to monitor the entire state. When that contract was over, in 2015, a new one was signed and had 1 meteorologist coordinator, 3 meteorologists in shifts, 5 meteorology technicians in shifts, and 1 more meteorology technician working on business hours to maintain contact with 5 field maintenance technicians. That number of professionals allows 2 people each shift to analyse the data, operate the radars, send alerts and make reports.

It is now much better than before, but is still a challenge since the team has to evaluate each type of data separately (weather and hydrological stations, weather radars, lightning, satellite images). Thus, the team is evaluating softwares capable of integrate several types of data and make new products through them. There are some shelf solutions at the market and the one to be chosen shall be able to integrate other environmental data such as air quality and water quality and forest fire risk.

It is notable that the System's efficiency has increased, but we need a way to quantify such evolution, as part of INEA's compromise to the World Bank.

2. MATERIALS AND METHODS

2.1 Flash flood alert system network

Currently there are 108 water levels monitoring stations (most of them with rain sensor too) and 42 rain monitoring stations (figure 1). This net provides data to the technical personnel, that interprets the collected information and contact the response teams in the municipal, state and federal levels, in case of need.

In addition to that, the net operated by the Environmental Agency of the State of Rio de Janeiro encompasses 2 S-Band weather radars, installed at the cities of Rio de Janeiro and Macaé, capable of quantifying water in the atmosphere up to 250 km radius, which makes the State of Rio de Janeiro the first in Brazil to have all its catchments covered by radar technology, including the neighbour States' areas.

Both the radars operations and data forwarding system work remotely, using a dedicated internet link between the radar sites and INEA. After receiving these data, INEA sends pre-determined products to some clients, as Rio de Janeiro City Alert System (that sends heavy rain and landslides alerts), the North of Rio de Janeiro State University (research in meteorology), among other partners. All of it is possible because the data provided by the radars allow multiple kinds of use, therefore Rio de Janeiro's government encourages data sharing, especially for the prevention of natural disasters.

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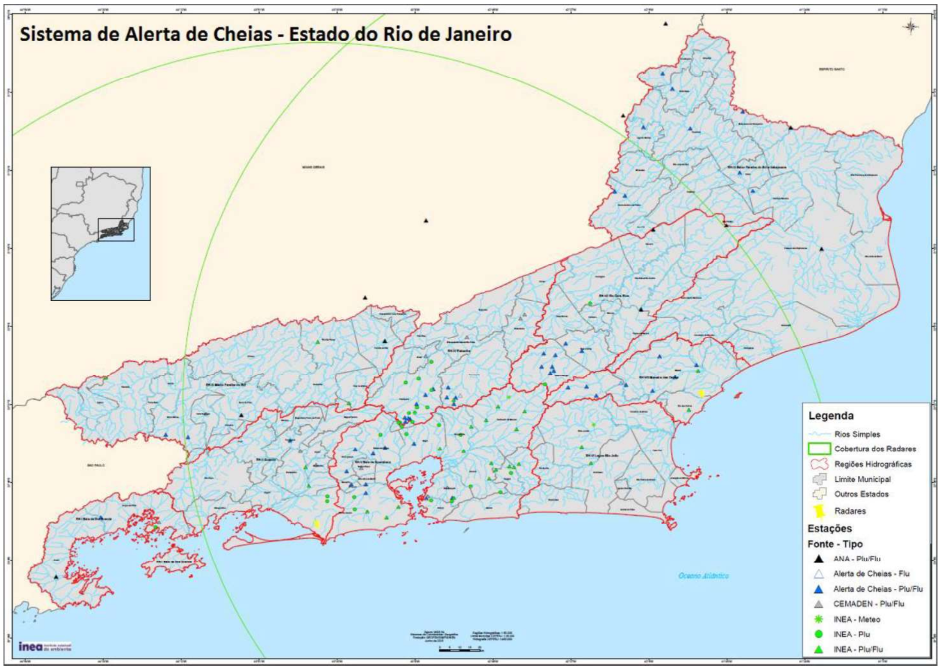

Figure 1. Flash flood alert system network. Source: INEA, 2016

2.2 Flash flood alert system protocol

The flash flood watch system works following three steps. The protocol is descripted in figure 2.

1) The flash flood alert system has a network of telemetric stations and weather radars that send data in real time, regarding rain and river level.
2) In the situation room, meteorologists and meteorology technicians monitor the weather and river levels 24 hours a day, every day.
3) When there is heavy rain or overflow forecast, INEA sends alerts via SMS to civil defence agents and registered population.

Stage	Situation
Vigilance	No significant rain forecast that could cause rivers level elevation.
Attention	River level elevation is possible because of rain occurrence.
Alert	Elevation above normal level of a monitored river, with elevation forecast.
Maximum alert	Imminent overflow of a monitored river, with elevation forecast.
Overflow	Overflow of a monitored river registered.

Figure 2. Flash flood alert system protocol. Source: INEA, 2016

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Every alert emitted is registered at a spread sheet, which contains the time when it happened, the watershed, municipality, station, river and the warning level sent, like the example of figure 3.

	A	B	C	D	E	F	G	H	I	J
1	PROCESS	WATERSHED	MUNICIPALITY	STATION	RIVER	ATTENTION	ALERT	MAXIMUM ALERT	OVERFLOW	VIGILANCE
2	201603030315	Piabanha	Petrópolis			201603030315				201603041055
3	201603041935	Baía da Ilha Grande	Angra dos Reis			201603041935				201603050140
4	201603061912	Médio Paraíba do Sul	Barra Mansa	Fazenda Escola UBM	Barra Mansa	201603061912	201603062229	201603070025		-
5		Médio Paraíba do Sul	Barra Mansa	Fazenda Escola UBM	Barra Mansa	-	201603070930			201603072120
6	201603071350	Piabanha	Petrópolis			201603071350				201603080145
7	201603071445	Rio Dois Rios	Nova Friburgo			201603071445				201603080145
8	201603081912	Piabanha	Teresópolis	Comari	Paquequer	201603081912	201603081930			201603090535
9	201603102115	Baía de Guanabara	São João de Meriti			201603102115				201603110921
10		Baía de Guanabara	Duque de Caxias	Santa Cruz da Serra	Saracuruna	201603102115	201603102145			201603110921
11	201603111045	Piabanha	Petrópolis			201603111045				201603112330
12	201603111155	Piabanha	Teresópolis			201603111255				261603112330
13	201603121350	Baía de Guanabara	Nova Iguaçu			201603121350				201603130610
14		Baía de Guanabara	São João de Meriti	Cet Meriti	Pavuna	201603121350	201603122010			201603130610
15		Baía de Guanabara	Duque de Caxias	Santa Cruz da Serra	Saracuruna	201603121350	201603121640			201603130610
16		Baía de Guanabara	Magé			201603121350				201603130610
17		Guandu	Paracambi			201603121350				201603130610
18		Médio Paraíba do Sul	Barra Mansa	Barra Mansa	Barra Mansa	201603121730	201603122030			201603130610
19	201603121740	Macaé e Das Ostras	Macaé	Barra do Sana	Sana	201603121740	201603122015			201603130610
20		Macaé e Das Ostras	Macaé	São Pedro	São Pedro	201603121740	201603122025			201603130610
21	201603121750	Piabanha	Petrópolis			201603121750				201603130610
22	201603131615	Baía de Guanabara	Duque de Caxias			201603131615				201603132053
23	201603151405	Piabanha	Petrópolis	Cel Veiga	Quitandinha	201603151405	201603151725	201603151730	201603151745	201603160145
24	201603151635	Piabanha	Teresópolis			201603151635				201603160145
25	201603151835	Baía de Guanabara	Duque de Caxias	Santa Cruz da Serra	Saracuruna	201603151835	201603151850			201603160550

Figure 3. Warning process for March, 2016. Source: INEA, 2016

2.3 Contingency table method

One of the big issues we wanted to minimize is the false alarm rate, therefore we have used the contingency table method (table 1) in order to quantify some statistic indexes and assess the system accuracy (Murphy, 1993). The numbers of alerts sent in the past 4 years are show in table 2.

Table 1. Contingency table

		Event Observed		
		Yes	No	Total
Event Forecasted	Yes	A	B	A + B
	No	C	D	C + D
	Total	A + C	B + D	A + B + C + D = N

Where: A = Hits; B = False alarms; C = Misses; D = Correct negatives

Table 2. Total number of alerts sent

2012				2013			
LowlandArea				LowlandArea			
Attention	Alert	MaximumAlert	Overflow	Attention	Alert	MaximumAlert	Overflow
63	7	2	2	59	8	7	4
MountainArea				MountainArea			

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Attention	Alert	MaximumAlert	Overflow	Attention	Alert	MaximumAlert	Overflow
114	5	3	2	133	8	8	7
North Area				North Area			
Attention	Alert	MaximumAlert	Overflow	Attention	Alert	MaximumAlert	Overflow
47	2	2	1	61	5	4	4
2014				2015			
LowlandArea				LowlandArea			
Attention	Alert	MaximumAlert	Overflow	Attention	Alert	MaximumAlert	Overflow
49	4	3	1	38	5	4	2
MountainArea				MountainArea			
Attention	Alert	MaximumAlert	Overflow	Attention	Alert	MaximumAlert	Overflow
106	10	5	4	85	5	4	1
North Area				North Area			
Attention	Alert	MaximumAlert	Overflow	Attention	Alert	MaximumAlert	Overflow
30	0	2	1	14	0	0	0

2.4 Lead Time

Another point likely to improve with the use of radars is the lead time on sending alerts. Cel. Veiga station, located in Quitandinha river basin, was selected considering it is the one for which the greatest number of alerts is emitted.

We could not expect a great lead time for this station considering the small size of its contribution area (13 Km^2), in a downhill area. In this sense a hydrograph analysis was used to quantify some parameters, such as its response time, using LENCASTRE & FRANCO's (1984) proposal described in figure 4.

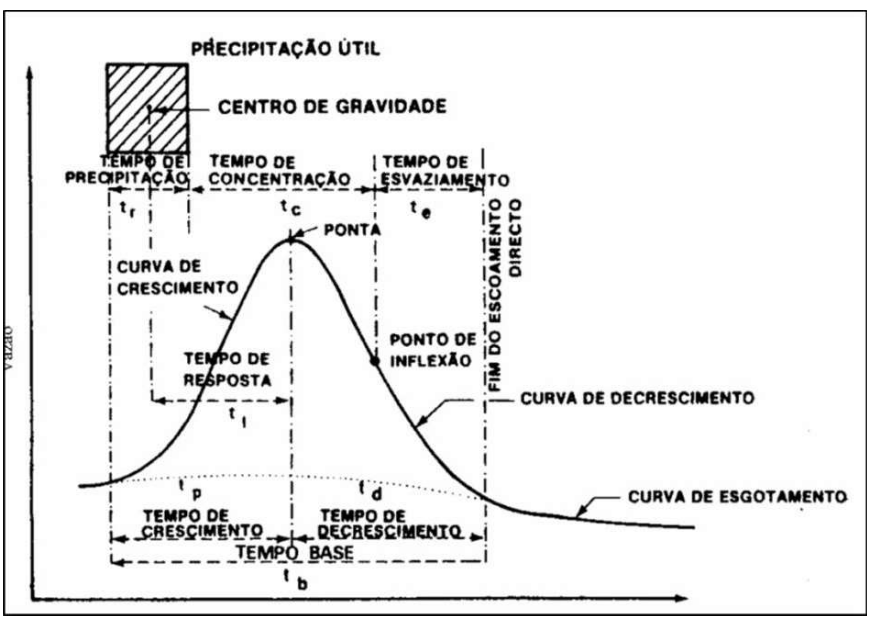

Figure 4.Hydrograph analysis model. Source: LENCASTRE & FRANCO, 1984

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After that, all of the alert protocol to Cel. Veiga's station were listed and separated, taking into account two periods: (i) between the date of its installation to 2015's dry season; and (ii) 2015-2016's rain season. All the processes are listed in table 3.

Table 3. Alert processes for Cel. Veiga station

2013 - 2015	**Day**	**ATTENTION**	**ALERT**	**MAXIMUM ALERT**	**OVERFLOW**	**VIGILANCE**
1	20/01/2013	201301201225	201301201554	201301201612	201301201600	201301210755
2	05/03/2013	201303051505	201303052015	201303052025	201303052045	201303070800
3	09/03/2013	201303091700	201303091750	201303091800	201303091845	201303102308
4	17/03/2013	201303171405	201303171600	201303171700	201303172015	201303191540
5	22/03/2013	201303221405	--	201303221520	201303221515	201303222140
6	23/03/2013	201303231215	201303231455	201303231508	201303231500	201303240850
7	02/04/2013	201304021320	--	201304021925	201304021915	201304030755
8	17/05/2013	201305170650	201305171010	201305171025	201305171045	201305180950
9	22/10/2013	201310220254	--	201310220400	201310220345	201310220725
10	17/11/2013	201311171410	201311171525	201311171535	201311171545	201311180800
11	05/12/2013	201312051610	201312051800	201312052251	201312052300	201312060720
12	08/03/2014	201403081455	201403081828	201403081838	201403081830	201403091000
13	28/03/2014	201403281330	201403281605	201403281605	201403281600	201403281940
14	23/04/2014	201404231445	--	201404231520	201404231530	201404241050
15	24/04/2014	201404241230	--	201404241615	201404241600	201404250945
16	30/12/2014	201412301720	201412301850	--	201412301900	201412310635
17	08/02/2015	201502081625	201502081705	--	201502081715	201502090400
2015 - 2016	**Day**	**ATTENTION**	**ALERT**	**MAXIMUM ALERT**	**OVERFLOW**	**VIGILANCE**
18	29/11/2015	201511291410	2010511291455	--	201511291545	201511300526
19	15/01/2016	201601151435	201601151515	201601160028	201601160035	201601161246
20	27/01/2016	201601271450	--	201601271500	201601271515	201601271950
21	11/02/2016	201602110945	--	201602111905	201602111910	201602120710
22	16/02/2016	201602161700	201602161735	201602161815	201602161830	201602170540
23	20/02/2016	201602201641	201602201849	201602201901	201602201908	201602210605
24	28/02/2016	201602281435	201602281635	201602281645	201602281700	201602290500
25	29/02/2016	201602291230	201602291610	201602291635	201602291645	--

3. RESULTS AND DISCUSSION

3.1 False Alarm Rate

In accordance with the methodology adopted herein, a false alarm happens when, after issuing a maximum alert, an overflow event does not occur. A false alarm situation can happen for multiple factors, including the decrease of the rain, inaccuracy of the data and lack of information with regards to the basin contribution area and runoff characteristics.

As can be seen by the figure 5, the false alarm rate was calculated for the last 4 years considering the progress between all the steps and the values such as displayed below.

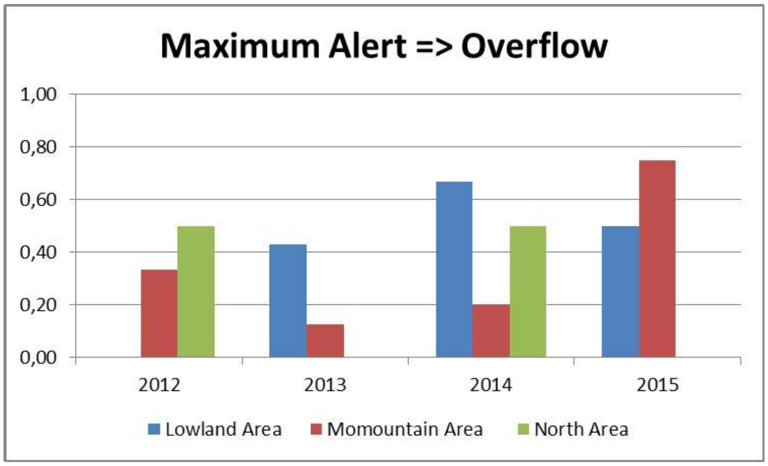

Figure 5. False alarm rate between Maximum Alert and Overflow. Source: INEA, 2016

The figure above shows that there is still room for improvement in the State's forecast system, despite the recent expansion of the net. In this sense, it is important to note that the acquisition of new and more modern equipment were steps needed to be taken in the past.

Nowadays, however, it is important to provide new products from the data collected by the radars and monitoring stations. In others words, although the equipment may be able to provide a significant amount of raw data, the agency should be able to extract more information by means of more sophisticated interpretation proceedings.

In this sense, information such as contribution area and runoff coefficients, for example, can help to improve the forecast interpretation methodology as well as the system's accuracy. The knowledge of whole characteristics of the watershed is the main factor to decrease the number of false alarms.

In addition to that, we also need to be able to interpret and cross exam different types of data, such as weather conditions, water levels and basin characteristics, for example.

3.2 Lead Time to Quitandinha

In order to estimate some hydrological parameters using the hydrograph method, we have analysed the most important overflow cases for Cel. Veiga station during the last rain season. Table 4 give us all hydrological parameters estimated for this station and Figure 6 shows an example of the analysis.

Table 4. Hydrological parameters estimated Lead time for Cel. Veiga station during 2015-2016 rain season. Source: INEA, 2016

Date	Rainfall duration (Tr) [h]	Basin Lag (Tp) [h]	Response time (Ti) [h]	Time of concentration (Tc) [h]	Emptying time (Te) [h]	Decreasing Time (Td) [h]	Useful rainfall (p) [mm]
02/01/2016	02:15	02:45	01:15	03:15	04:15	07:30	24,75
27/01/2016	00:30	00:45	00:45	01:15	02:45	04:00	15,50
28/02/2016	00:15	00:30	00:30	01:15	01:15	02:30	42,70
29/02/2016	03:15	03:30	01:30	03:45	06:00	09:45	33,50

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Average	01:33	01:52	01:00	02:22	03:33	05:56	29,11

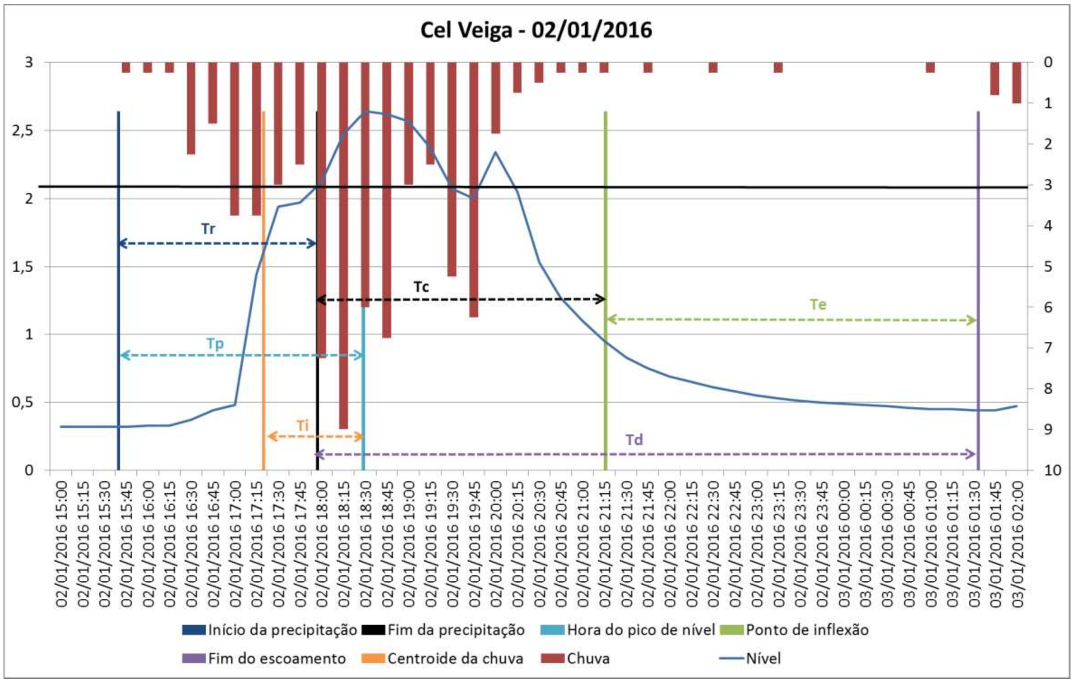

Figure 6. Hydrograph analysis to Cel. Veiga station in January, 2016. Source: INEA, 2016

After assessing the results from table 4, it is clear that Quitandinha basin has a small response time (1h) and is vulnerable to overflows during events with moderate rain amounts (~20mm/h). The growth line is very steep (figure 6) and it takes just 1 hour to change between a normal to an overflow level. It happens because of the small size of the basin and the slope geography of the area.

Taking this into account, we have compared the time between Petrópolis city receiving an attention warning and the overflow of Quitandinha's river. The results are shown in tables 5 and 6 and are separated in accordance with the periods before and after the radar system implementation.

Table 5. Lead time for Cel. Veiga station after the radar system. Source: INEA, 2016

2013 - 2015	PROCESS	Lead Time before Radar System	2013 - 2015	PROCESS	Lead Time before Radar System
1	201301201225	03:35	10	201311171410	01:35
2	201303051505	05:40	11	201312051610	06:50
3	201303091700	01:45	12	201403081455	03:35
4	201303171405	06:10	13	201403281330	02:30
5	201303221405	01:10	14	201404231445	00:45
6	201303231215	02:45	15	201404241230	03:30
7	201304021320	05:55	16	201412301720	01:40
8	201305170650	03:55	17	201502081625	00:50
9	201310220254	00:51	Median Lead Time		03:07

Table 6. Lead time for Cel. Veiga station after the radar system. Source: INEA, 2016

2015 - 2016	PROCESS	Lead Time after Radar System	2015 - 2016	PROCESS	Lead Time after Radar System
18	201511291410	01:35	23	201602201641	02:27
19	201601151435	09:00	24	201602281435	02:25
20	201601271450	00:25	25	201602291230	04:15
21	201602110945	09:25	Median Lead Time		06:52
22	201602161700	01:30			

Comparing the average lead time before and after the radar system operation, it has grown from ~3h to ~7h**.** It probably happened because of the radars' capability of monitoring the rain over the entire basin, which shows the importance of the acquired equipment and its proper operation.

4. CONCLUSION

As seen by the results presented above, despite the improvement of the monitoring net operated by the State Agency, there is still room for improvement. The scenarios assessed in this study show that the acquisition of more data does not necessary generate more accuracy to the system, which can be caused by the need of more sophisticate interpretation methodology.

On the other hand, the equipment made possible to increase the lead time more than twice, anticipating extreme events and the issuance of alerts to vulnerable neighborhoods. Such increased lead time provided more safety for the potentially affected population and the decrease of risks for human life and properties.

The next steps to be taken by the Agency should encompass data integration (radar, lightning, river levels and rain gauge) and hydrologic modeling of the watersheds using radar data and nowcast (Demerit et al., 2013). Both measures would help to reduce the false alarm rate and increase the lead time.

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