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Distributed Hydrological Modeling of Suquía´s Basin, for Flood Warning System

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ABSTRACT

Heavy rains and urban floods are an important global issue under the context of climate change. Since the current effects of climate change, new strategies to mitigate the impact in vulnerable communities must be done. In this framework, the PREVENIR project is being implemented since 2022 for five years. The main goal of this project is to develop an impact-based early warning system for heavy rains and urban floods designed for two highly vulnerable urban basins in Argentina: one located in a plain region in Buenos Aires Province (Sarandí-Santo Domingo creek basin), and the other in the mountain region in Córdoba Province (Suquía River Basin). In this work, we tested the performance of the hydrologic RRI-tool for a semiarid region´s basin (Suquía´s basin) and tested the performance in the Dam upper and lower basins with different land uses area of the city of Córdoba, one of the largest urban areas in Argentina. Observed ground rain gauge and water level data were used for model calibration. Comparison of simulated and observed flow discharge and water level shows a good agreement both in the mountain area and in the urban area by considering detailed land use. Although some further enhancements must be done to improve flooding forecast for the Suquía river basin, this paper shows that RRI is a useful tool for flooding simulation in semi-arid region and it can also work in urban areas. These results provide useful information for using RRI tool in similar systems in other parts of the world.

Keywords: Hydrological distributed modelling, flood early warning system.

1. INTRODUCTION

Floods accounted for 54% of all water related disasters, causing high number of deaths and economic losses, both in developed and developing countries (Perera et al. 2019). There is growing experience that climate change and anthropogenic changes are increasing the frequency or the probability of extreme events, causing a decrease in water security (Szollosi-Nagy, 2021). Therefore, there is an increasing need for new strategies for reducing flood risk in vulnerable communities. Both structural and non-structural flood mitigation measures are needed to be implemented with the aim of minimizing flood disaster. Moreover, in developing countries, where resources are limited and structural measures sometimes are not possible due to the high cost, flood early warning systems can be critical to avoid casualties.

The PREVENIR project is an international cooperation project between Argentina and Japan since 2022 for five years, funded by the Japan International Cooperation Agency (JICA) and the Japan Science and Technology Agency (JST) under the Science and Technology Research Partnership for Sustainable Development (SATREPS) program. The main goal of PREVENIR is to develop an impact-based early warning system for heavy rains and urban floods for two highly vulnerable urban basins in Argentina: One located in a plain region in Buenos Aires Province (Sarandí – Santo Domingo Creek) and the other in the mountain region in Córdoba Province (Suquía river basin).

A key component of a Flood Early Warning System (FEWS) is the hydrological modelling of the basin. Thus, it is necessary to implement a numerical tool with the capacity of correctly represent the behavior of the target basin as well as being able to represent the hydraulic performance of the water courses inside the basin, to simulate water level and flood extent. There are many available hydrological tools for that purpose, but the need of a fast computation is extremely important for developing FEWS.

This paper´s target area is the Suquía river basin (Córdoba´s site of PREVENIR project), where some of the world´s deepest and largest convective storms developed according to Zipser et al (2006), which has motivated several intense research studies such as RELAMPAGO project (Nesbit et al 2021). This short and highly intense rainfall events produces challenging flash flood with fast flow response and short time to peak (Pal et al 2021).

Nowadays, a lumped hydrological model using HEC-HMS tool (USACE-HEC, 2016) is being used for dam operation and a Muskingum–kunge, transit model is being used to compute time of arrival of the flood peak to the city area. The actual scheme has some limitations when using them for FEWS, because experience in the study area has shown that the current lumped model cannot correctly represent regional heavy rainfall and flash flood processes due to the very fast runoff in the mountain (Pacher, M. et al 2022). On the other hand, the modelling scheme is not able to include middle and lower basin´s runoff into the flood transit model, moreover it cannot take in to account the effects of runoff in a large urban area like Córdoba´s city.

Previous studies have shown that physically based distributed hydrological modelling are more plausible to reproduce correctly flash flood than lumped models (Hapuarachchi et al 2011). For that reason, in this study a Rainfall-Runoff-Inundation (RRI) model was applied. RRI tool includes a physically based and distributed hydrological model which can represent rainfall-runoff process (Sayama et al. 2012). RRI software is a useful tool for hydrological modeling and specially for flood forecasting. RRI tool has been used widely in Asian monsoon area and few experiences in arid regions (Abdel-Fattah, m. et al 2018). Thus, some uncertainties about using RRI in Suquía´s river basin needs to be addressed such as whether the RRI model can reproduce accurately flash flood processes in both large basins and basins with high urban land use ratios.

In this paper we tested the performance of RRI-tool in a semiarid region´s basin (the Suquía river basin) and tested the performance in the Dam upper and lower basins with different land uses area of the city of Córdoba, one of the largest urban areas in Argentina. The main objectives of the paper are implementing the RRI-tool in the target basin and calibrating it using observed data assessing the performance of the best simulated results with observations, seeking to answer the following questions:

- How is the performance of RRI model for large basins with flash flood processes, particularly in a semiarid region?
- How is the performance of RRI modelling tool for simulating hydrological processes in basins with high urban land use ratios?
- Can RRI-tool be used for FEWS in the Córdoba´s target basin for PREVENIR project?

First a detailed description of the study area is provided, presenting the most important information of the target basin. Then, the methodology used in work is described. Later, the main results are presented, where best simulation results obtained so far are compared with observed data. Finally, the main findings and conclusions are discussed.

2. STUDY AREA

2.1 Basin´s characteristics

The target area in Cordoba is shown in Figure 1. Figure 1.a shows an image of South America with the location of Argentina and Cordoba province (blue color). Figure 1.b shows the location of the Suquía river Basin and the Suquía river. The Suquía river basin has an area of approximated 2.500 km2. It includes a big portion of the Cordoba capital city, which is the second largest city of Argentina, and a densely populated area. The climate in the region is semiarid with a mean annual precipitation of about 800 mm (mostly concentrated between November and April), while the rest of the year, the weather is dry with low precipitation accumulated.

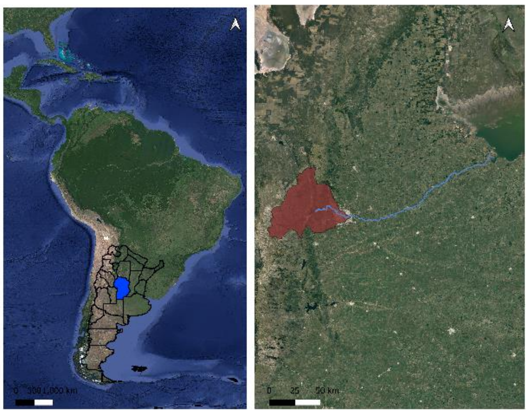

Figure 1. Location of the target area. a) An image of South America with the location of Argentina and Cordoba province (blue color). b) the location of the Suquía river Basin (red color) and the Suquía river

The San Roque dam is the main control of the system, and it has a capacity of 201 Hm^3. It is a multipurpose dam managed by the Cordoba province water resources agency (APRHi). The two main purpose of the dam are to prevent floodings of Cordoba City and the supply of water for consumption of half of the Cordoba city population. Upstream of the San Roque dam, the drainage network has a surface of 1580 km2. There are four main subbasins, Cosquin river subbasin, Mojarras creek subbasin, Chorrillos creek subbasin and San Antonio River subbasin. In the Lower basin, there are several subbasin of different sizes, Saldan´s creek Subbasin, Infiernillo creek Subbasin and Cañada creek Subbasin. Finally in the city area, there are a lot of urban catchments with high impermeability (Figure 2).

2.2 Available data

The target basin has over 50 meteorological stations which allows to have good amount of rainfall data in the basin for characterization of rainfall events (Figure 2). The basin also has 15 water level sensors installed in the most important rivers and creeks of the basin. The mentioned meteorological stations and water level sensors belong to two different monitoring networks, one depends on the National institute of Water of Argentina (national monitoring network) and the other network depends on the state of Córdoba, operated by the APRHi. The national network has about 15 years of data, while the state network has over 5 years of data, but it is increasing the number year by year. To estimate flow discharge using water level sensor, rating curves were developed for 5 water level sensors (Figure 2 shows the water level sensors and remark those with rating curve associated). Every rating curve has uncertainty due to the fitting of the observed data, error in the discharge measurement and error in the water level observed data, that was considered for the analysis of RRI-tools simulations.

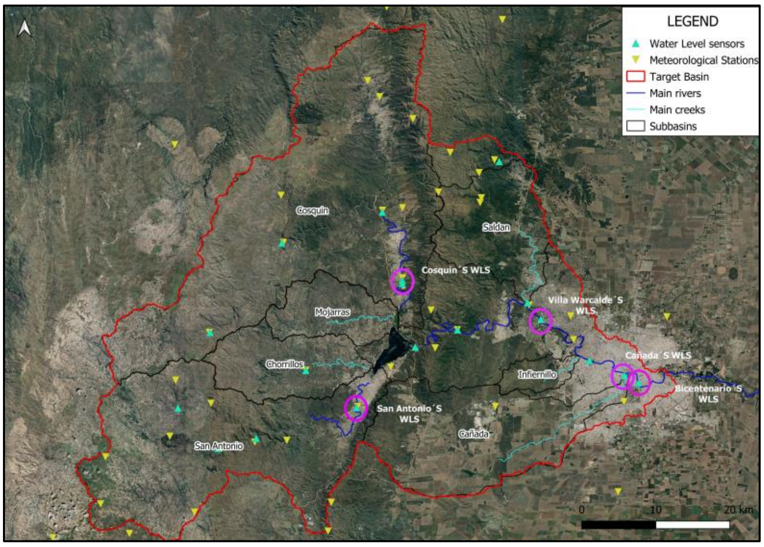

Figure 2. Hydrological system of the target basin. Circles shows the water level sensors with rating curve associated.

Topographic data was collected from a national data base. The geographical national institute (IGN) has developed a Digital elevation model for the whole country with a spatial resolution of 30 meters and a vertical resolution of 2 meters (IGN, 2019). For Land use data, the province of Cordoba has an agency in charge of the GIS products with useful information (https://www.mapascordoba.gob.ar/#/mapas). One of the products is Land cover data, with is updated every year. In the Figure 3 the land cover data of the target area is shown, there are around 22 types of land cover, with a resolution of 100 m x 100 m. This map is the latest available and it was published in 2021.

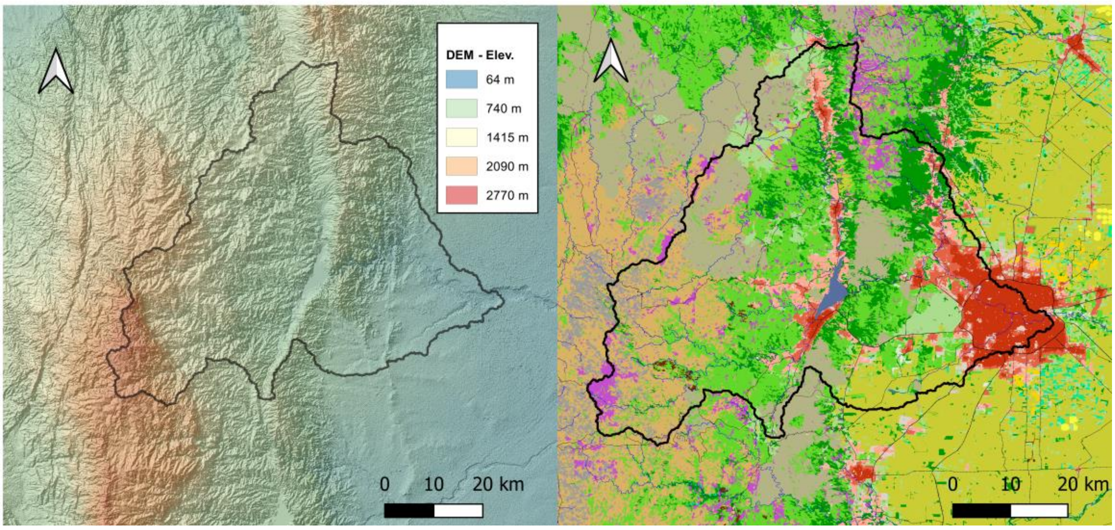

Figure 3. a) Topographic data (left) and b) Land Use data (right) for the target basin.

2.3 Current situation

Nowadays, there is an operative scheme for the operation of San Roque dam, which consist of meteorological forecast, hydrological modelling of the San Roque dam´s basin, simulation of the operational decision and a routing model for estimates flow discharge and water level in the city of Córdoba. The scheme is working nowadays and is operated by the Water resources agency (APRHI). Based on the Meteorological forecast, a hydrological model with HEC-HMS modelling tool (USACE-HEC, 2016) is used for computing hydrographs of the inflow in the San Roque Lake. With the Inflow hydrograph estimated from the hydrological model, operative's decisions are made for the dam outflow systems.
San Roque dam´s management is a challenging task. The mistaken land planning of cities located near the lake and in Cordoba city (downstream of the dam) has reduced dam storage and dam outflow capacity. The San Roque Lake has two outflow valves of 40 cubic meters per second each and a morning glory spillway. Management decisions must be taken with caution given the fact that not leaving enough storage capacity in the Lake could cause a flood on the cities near the lake. On the other hand, if the outflow of San Roque´s dam is excessive, it could flood areas located downstream of the dam (Calera city and Córdoba city). The most challenging issue is that Cordoba city water supply depend on the San Roque dam storage at the end of the rainy season (April). Thus, the dam´s management office tries to end up April with the water level of the lake as close as possible to the spillway level. This situation makes the system very vulnerable if a large rainfall event occurs on the last month of the rainy season.
Lumped model used nowadays is limited to represent flash flood response of the basin, being the peak flow discharge value reasonably well represented while time to the peak of the flow discharge and the volume of the hydrograph are not well simulated when they are compared with observed data (Pacher et al. 2022). On the other hand, the existing rooting model for downstream basin, correctly represents the routing of San Roque´s dam outflow. However, it is not able to accurately represent the flow discharge generated by the runoff of the urban area of Cordoba city. It is a weakness of the dam operation scheme available nowadays since dam operations decision are done without considering the runoff process in the urban area.

3. MATERIAL AND METHODS

3.1. Modelling strategy

RRI model is a distributed hydrological model, 2D grid cell-based which can simulate both rainfall-runoff and flood inundation simultaneously. Diffusive 2D equations are used, and the model allows also simulate vertical infiltration based on the Green-Ampt model and saturated subsurface flow in mountainous areas. To solve

differential equations, RRI model employs the fifth order Runge-Kutta method with adaptative time (Sayama et al. 2012).
Simulating the whole basin as one model, has several problems. First, the basin has a large area, that requires a high computational time, which is not convenient for calibration and operation processes. But the most important issue is the presence of the San Roque dam, since this dam is a key component of the system, and it has not a defined operation rule to incorporate to the modelling. For that reason, we decided that the best way to simulate the system is divide into two different models that will be connected by the dam´s outflow discharge. Thus, two different models were implemented; first an upper one (upstream San Roque´s dam) and a lower one (Downstream the dam) with a boundary condition that depends on the dam´s operation. The spatial resolutions used in the modelling was 100 meters both in upper and lower basins.
The Upper Basin´s model uses a distributed rainfall by Thiessen polygons as an input made with the precipitation data available. For parameter calibration, two water level sensors were used, one for the Cosquin river and the other for the San Antonio River. Both mentioned sites have a rating curve to estimate flow discharge from the measurements of water level. For the Lower basin, the precipitation input was used in the same way as for the upper basin, but a boundary condition downstream of the San Roque´s dam was included upstream the Suquía river: The dam operation office has shared the time series of the outflow the dam. Finally, for calibration purposes three water level sensors were used in the Suquía River downstream of the dam: Villa Warcalde sensor upstream the urban area, Cañada creek and Bicentenario in the urban area (see Figure 2).
For a first modelling approach of the hydrological system, a simplification model of land use (Figure 4 shows only five different land uses) was done while the source data had over 20 different types of land use. Land use classification was done with 5 categories: (i) Mountain, (ii) Grassland, (iii) Urban, (iv) Farmland and (v) Water bodies. The upper basin classification is presented in the Figure 4. About 47% of the land use is grassland, while 36% is Mountain area, being the two most important land uses in the upper basin. For the lower basin, the proportions are 47% Grassland, 28% Urban, 20% Farmland and less than 5% of mountain area. Due to land use ratios, flash flood processes simulation with RRI-tool was assess by analyzing the performance of the upper basin model, since mountain land use proportion is significant. While urban´s performance of RRI was evaluated with the performance of the lower basin´s model, due to the high ratio of urban area.

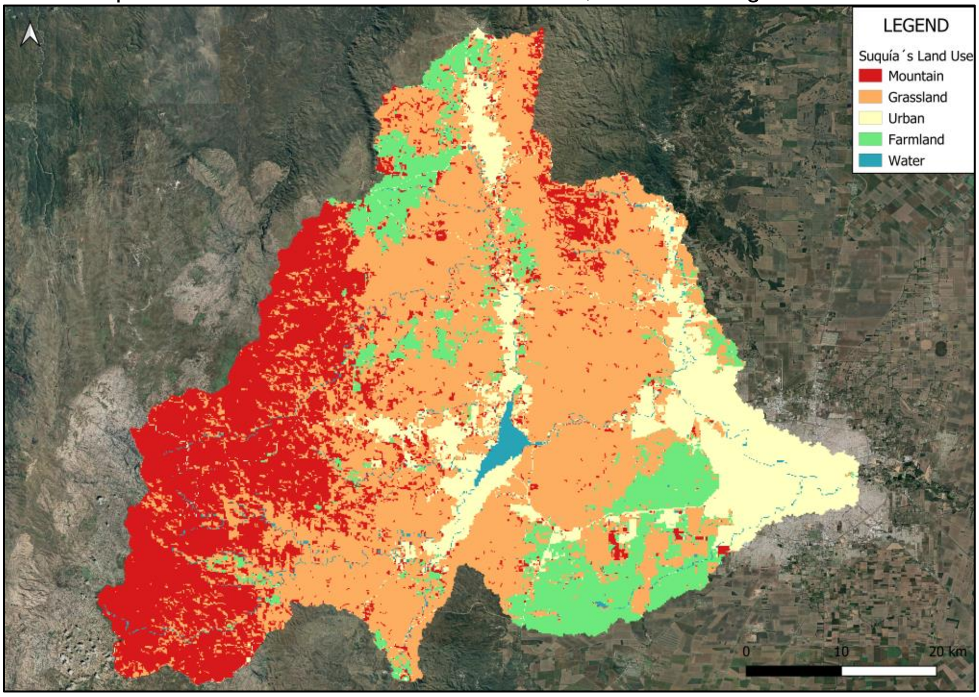

Figure 4. Simplified Land use categories used in the simulation.

3.2. Events Selection

In the upper basin, the main challenge is simulating the flashflood. In the water level time series, flash floods can be seen as a big rise of the water level in a few couple of minutes. In semi-arid region, as it was mentioned before, the rainfall period occurs mostly during the summertime, so the runoff generation should change whether rainfall occurs at the beginning of the rainy season (with the basin in a dry condition) and at the end of the rainy season (with a wet basin). For that reason, we have decided to simulate two flood events, one in the beginning and one at the end of the rainy season. The simulation period starts, for each case, 1

month before the selected event and finish 1 month after this event. The first event occurred on November 12th of 2018 with significant rainfall in the upper basin, with no impact on the lower basin because the dam retained much of the runoff. On the other hand, the second event selected for the calibration occurred on the March 16th of 2021, at the very end of the rainy season, with the dam´s water level close to the spillway elevation.
An important issued is considered for the lower basin model when calibrating parameters. The basin´s area is big, and then different rainfall distribution in the lower basin could produce different response of the system. In addition, the most important topic to be analyzed in this modelling is if it is possible to represent the system performance when there is San Roque´s dam outflow and when there is no Outflow (or just environmental flow release). For that purpose, two events were selected as calibration events. Firstly, one without San Roque´s dam outflow (only environmental flow), to calibrate runoff with no river effect, and then one event with a high discharge released from the San Roque dam to account for the effect of that operation and to evaluate routing performance, which is extremely important for flood alert (Figure 5). The first event occurred on the January 30th of 2021, The rainfall presented high accumulated values in the area close to the San Roque´s dam, and close to Córdoba city and there was just a small discharge released by the San Roque´s dam for environmental purpose. The second event took place on March 16th of 2021 (same as for upper basin), the rainfall presented high accumulated values in the area close to the San Roque´s dam, and in the Saldan´s creek basin and dam´s outflow was important due to the rainfall event in the upper basin and the correspondent dam operation.

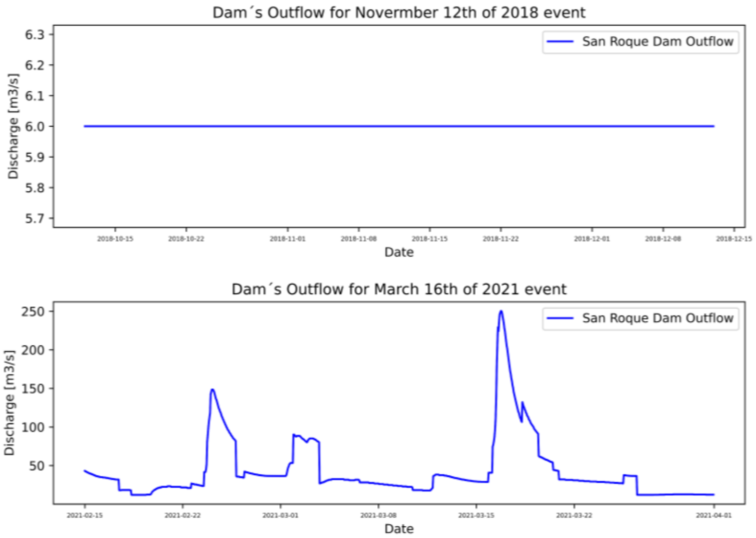

Figure 5. San Roque´s dam outflow discharge used for upper boundary condition in the lower basin model. Top: Discharge time series for the November 12th of 2018 event; Bottom: Discharge time series for the March 16th of 2021 event.

No initial conditions of discharge or soil moisture were included, except for the dam´s operation in the Lower basin model as it was explained. Calibration process was done manually until achieving a significantly good agreement between the simulated discharge values and the observed ones. Parameters are adjusted for one event and then used for the second selected event. And Nash Sutcliffe Efficiency (NSE) is used to measure the goodness of fit, where values higher that 0.7 indicates very good accuracy (Nash, J. E. & Sutcliffe, J. V., 1970).

4. RESULTS

4.1. Upper Basin´s results

The best results for the upper basin model were obtained with the set of parameters presented on Table 1. The calibration results for the November 12th of 2018 event in the upper basin are presented in Figure 6 for two sites in the upper basin, one in the Cosquin river and the other one in the San Antonio River). Both sites show a good agreement for the simulated period, but for the selected event, there are some differences with the observed data, in both cases the time to the peak is simulated faster than the observed, flow discharge peak value are close but, in both cases, lower than the observed. Nevertheless, NSE values show a good agreement between simulated and observed data.

Table 1. Upper basin parameter settings after calibration. (N: Manning roughness; DA: soil depth times effective porosity K: Vertical saturated hydraulic conductivity)

	N	DA[CM]	K[M/S]
RIVER	0.055	-	-
MOUNTAIN	0.15	4	0
GRASSLAND	0.35	20	1e-4
URBAN	0.15	20	3.56e-6
FARMLAND	0.35	20	1e-4

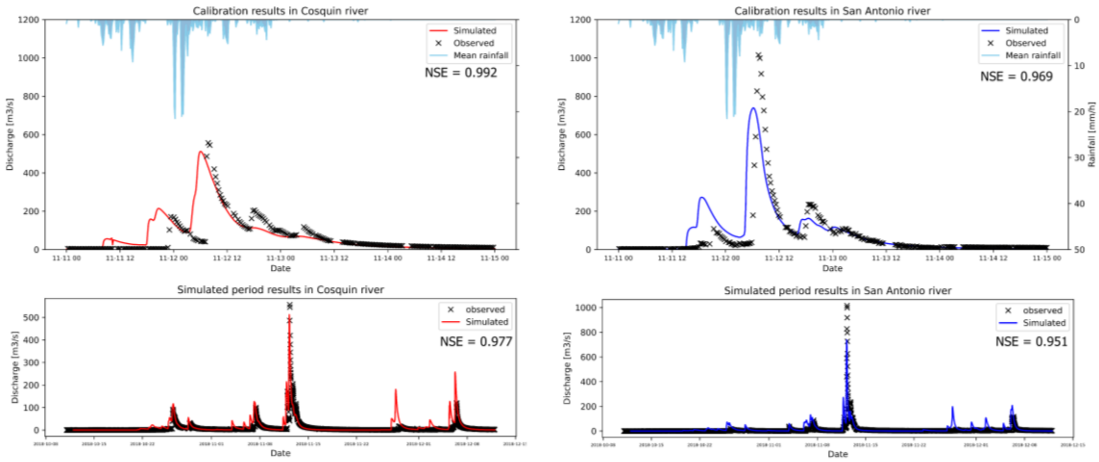

Figure 6. November 12th of 2018 event´s calibration results for the upper basin model. (Upper left: Cosquin´s river results for the event; upper right: San Antonio´s river results for the event; lower left: Cosquin´s river results for the simulated period; lower right: San Antonio´s river results for the simulated period)

The Figure 7 shows the verified results for the second event in the upper basin, this event occurred at the end of the rainy season. Both sites show a good agreement when comparing simulated an observed values for the simulated period. The Cosquin´s river results, shows a significant good match between simulated and observed for the event, in time to peak, peak value and volume, with a high value of NSE (Nash Sutcliffe estimation) indicating a good performance of simulation. In the case of San Antonio´s, flow discharge peak value is well represented, as well as time to the peak, but volume is over estimated, NSE values were negative, indicating that simulation is not able to represent correctly observed data. It is important to point out that during calibration process some problems with the monitoring network at San Antonio´s subbasin were detected and communicated to the office in charge of it. It has caused problems in the simulation since the main input had differences with real precipitation and NSE value is a good indicator to show the monitoring network´s office that there is a problem with rainfall data.

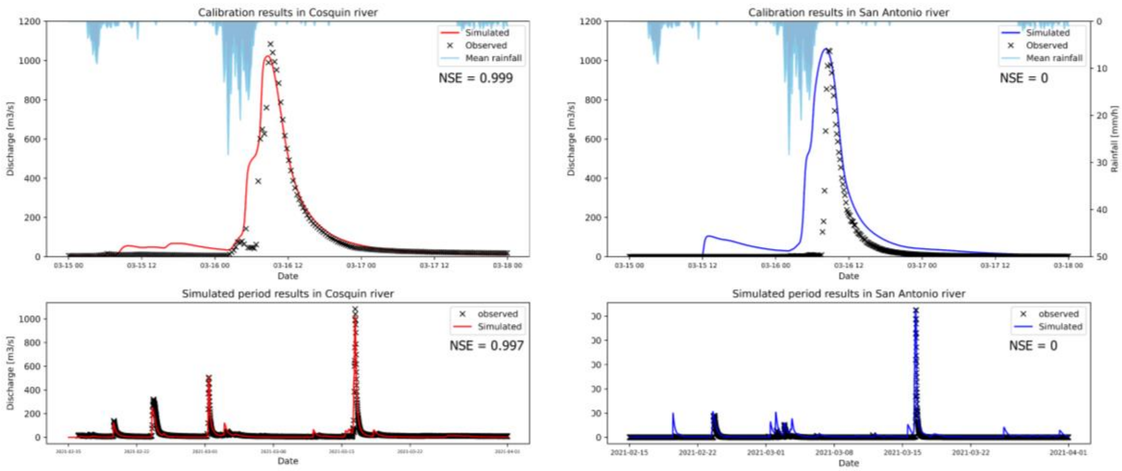

Figure 7. March 16th of 2021 event´s calibration results for the upper basin model. (Upper left: Cosquin´s river results for the event; upper right: San Antonio´s river results for the event; lower left: Cosquin´s river results for the simulated period; lower right: San Antonio´s river results for the simulated period).

4.2. Lower Basin´s results

For the lower basin, the best results were obtained with the set of parameters presented in the Table 2. For the event of January 30th of 2021, Figure 8 shows a good agreement in every site for the simulated period. This event did not consider an outflow discharge of the San Roque´s dam. For this event, Villa Warcalde site shows a good agreement with observed data, both in time and value, as well as volume, NSE indicates a very good agreement with observed data. For the Cañada creek case, the time to the peak and volume have a good agreement with the observed, but the peak discharge value is underestimated, this might be because the Cañada creek is a concrete channel and is computed as a river, but still NSE values shows a good performance. Finally, Suquía's river at Bicentenario site, being it the most challenging site because it is hardly affected by the urban area, still the results show a good match in peak value, volume but some differences in the time to the peak, arriving the wave later than the observed. One reason for the difference in time to peak might be that the DEM resolution in urban area is not enough to represent the correct shape and location of the river. For that reason, the location of Bicentenario site is closer to the junction of Cañada creek and Suquía's river, therefore transit wave time is shorter than it should be, this explains the low NSE values for this site.

Table 2. Lower basin parameter settings after calibration.

	N	DA[CM]	K[M/S]
RIVER	0.045	-	-
MOUNTAIN	0.15	5	0
GRASSLAND	0.35	30	1e-4
URBAN	0.015	20	3.56e-6
FARMLAND	0.35	20	1e-4

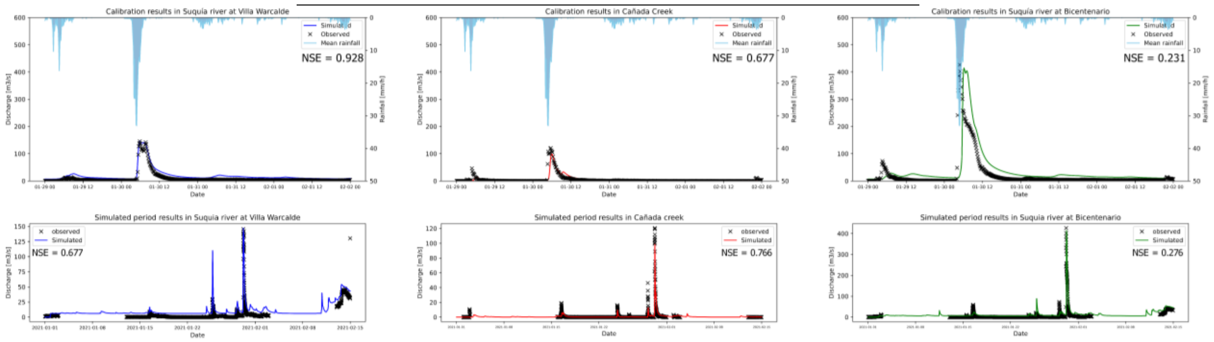

Figure 8. January 30th of 2021 event´s calibration results for the lower basin model. (Upper left: Suquia´s river at Villa Warlcade results for the event; upper middle: Cañada creek results for the event; upper right: San Antonio´s river results for the event; lower left: Cosquin´s river results for the simulated period; lower middle: Cañada´s creek results for the simulated period; lower right: San Antonio´s river results for the simulated period).

The second event simulated in the lower basin, included the discharge of San Roque´s dam according to dam´s management office. The results show again a good agreement in every site for the complete simulated period. For this event, Villa Warcalde site shows a good agreement with the observed data, with high values of NSE that indicates a good match with observed data (Figure 9). The Cañada creek has the same behavior as in the previous event. Finally, the Bicentenario site, shows an interesting agreement with observed data, being able to represent the first peak due to urban runoff and later the arrival of San Roque´s dam outflow, being time to peak, peak discharge value and volume reasonably well represented, with high values of NSE that suggest a good performance besides DEM´s resolution in urban area.

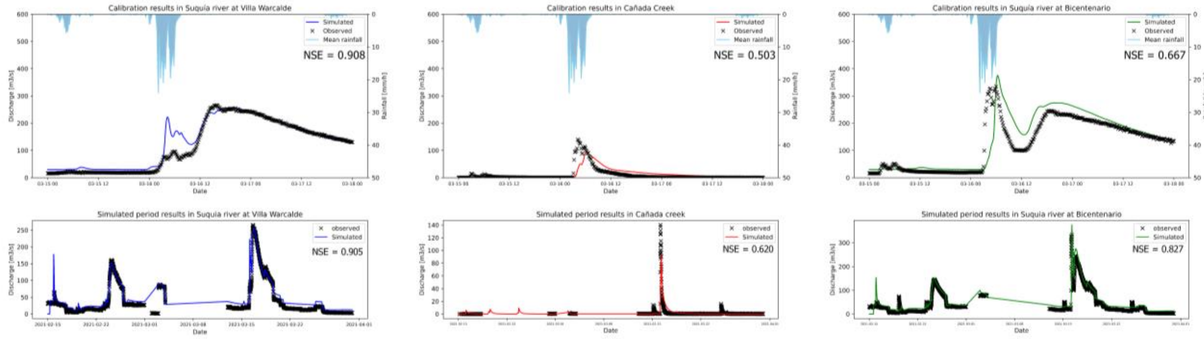

Figure 9. March 16th of 2021 event´s calibration results for the lower basin model. (Upper left: Suquia´s river at Villa Walrcade results for the event; upper middle: Cañada creek results for the event; upper right: San Antonio´s river results for the event; lower left: Cosquin´s river results for the simulated period; lower middle: Cañada´s creek results for the simulated period; lower right: San Antonio´s river results for the simulated period).

5. DISCUSSION

The RRI modelling tool has been implemented in the target basin, pursuing the goal proposed for the PREVENIR project, being the first time RRI is used in Argentina.
Regarding the first question we proposed in the previous section, addressing the performance of RRI tool for semiarid region with flash floods, the Upper basin model was used to answer it since there was not much influence of rapid urban runoff processes. The calibration process for the upper basin model, especially for the second event in the Cosquin river shows a good agreement between the simulated and observed discharge values, which indicates the capability of RRI tool for representing correctly the hydrological system in this type of basins, where semiarid and flashflood conditions doesn´t seem to affect the performance of RRI. The others result of the upper basin suggest that further work needs to be done, by improving the monitoring network, rating curves, and model parameters. Until now the existing tools could never represent the hydrograph shape as like the observed as the RRI tool, for that reason it seems that achieving good results in the San Antonio River is a matter of time.
To answer the second question, it is necessary to make an analysis of the lower basin results. The best calibration results, suggest that further improvement is necessary for operative propose, but the results show a good agreement with the observed data. The hydrograph rooting is significantly well represented and very similar to the observed hydrographs in the Suquía river. The rapid runoff process in the large urban area was the most challenging topic since the RRI tool cannot include sewage system. In addition, the results show a significant good match with the observed data. Figure 10 upper right shows how well the first hydrograph peak was simulated and after the arrival of the transit wave. This suggest that with more detailed information such as land use and topographic data, RRI tool will be useful for simulating the lower basin behavior. It is important to remark that now, there is no tool available to simulate the lower basin, being this a big improvement for water management purposes.
Finally, the third question was about the capability of RRI tool for being used as the hydrological modelling tool in the FEWS. Even though more improvements must be done for being ready to be used in the FEWS, the results suggest that RRI is a great improvement in comparison with the existent tools used in the target area. Computational time of RRI is relatively low considering it is a distributed model. For example, 2 month of simulation period took less than 2 hours for the upper basin and about 1 hour for the lower basin, in a personal computer. We believe that RRI tool will be very useful for flood early warning system purposes in the target basin, and in many similar basins in other parts of the world.
Although results shows that RRI in the Suquía river basin are encouraging, future improvements must be done. In the upper basin, problems with rain gauges monitoring network were detected. This is an important result since the monitoring network is used for dam management, therefore it is necessary to improve the rainfall monitoring network and considering other rainfall products such as radar and satellite rainfall estimation. The group leading this work are working on this regard. Also, in the upper basin, one set of parameters have been used so far, since San Antonio´s and Cosquin´s subbasin might have different land uses, it may be necessary to determine the parameters for each, including geological information.
In the case of the lower basin model, it was shown that DEM resolution affected the performance of the modelling in the urban area. For that reason, Detailed elevation surveys are being done to improve DEM resolution and solve this problem. Additionally, only one set of parameters were considered for urban land use, but it may be necessary to change the parameters for the central area and the suburban area, since urban density is different.

6. CONCLUSIONS

In the context of climate change heavy rainfall will occur more often and flooding preventions systems are necessary to prevent casualties and reduce damage. In this study, we tested the performance of the RRI-simulation tool for a semi-arid region´s basin (Suquía´s basin) near Córdoba city, one of the largest urban areas in Argentina. Observed ground rain gauge and water level data were used for model calibration. Comparison of simulated and observed discharge and water level shows a good agreement both in the mountain area and in the urban area by considering detailed land use. Even though some further improvements must be done to improve flooding forecast for the Suquía river basin, this paper shows that RRI modelling tool is a useful tool for flooding simulation in semi-arid region and it can work in urban areas with some limitations. These results provide useful information for using RRI modelling tool in similar systems in other parts of the world.

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8. REFERENCES

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