Steps towards an early warning model for flood forecasting in Durazno city in Uruguay

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Abstract

A hydrologic–hydrodynamic model of the Yi River basins in Uruguay has been developed as a support tool to the Emergency Coordination Centre of Durazno city. The purpose was to improve the existing decision support system and the emergency planning by providing information on gauge height and its permanence in time, and the risk of flooded areas. Four past flood events of high return period were used for calibration and validation with accurate results. The input data to the operational model in real time are hourly observed rainfall and gauge height, as well as rainfall forecasts by several international sources. The use of predictions from numerical weather forecasts allows for the generation of pre-alert scenarios with larger lead time. These scenarios can warn the emergency coordinators, and thus are of great value to premanage a probable emergency. Operation of a meteorological weather alert issued by the National Meteorological Board is discussed.

Introduction

The occurrence of extreme natural phenomena with significant negative consequences for the inhabitants of Uruguay is mainly due to flooding. The country is affected by floods, with an average frequency of about 2 years. According to the authorities responsible for the management of national emergencies, Durazno is the second largest city frequently affected by floods that cause considerable socio-economic damage.

In recent years, a severe flooding occurred on the night of 8 May 2007. The Yi River reached 12.95 m gauge height in Durazno city, which corresponds to a return period of 500 years according to the distribution function for extreme water levels adjusted by Cascos Blancos (2002). It should be noted that the range of yellow alert, with a number of minor evacuees, varies between 7.5 and 8.5 m. As a result, more than 6 000 inhabitants were evacuated, which means about 20% of the population. The flooding was caused by a storm of 4-day duration, with an accumulated average rainfall of 229 mm, of which 90% occurred within 2 days. This figure must be compared with the average monthly rainfall ranging between 58 and 111 mm.

The main social-economic consequences were (1) interruption of activities in schools and colleges; (2) health problems related to outbreaks of diarrhoea, requiring a vaccination campaign against influenza and A-hepatitis; (3) infrastructure damage, such as water supply being suspended for 72 h, overflowing of wastewater treatment plant, cemetery and roads being damaged, and at least 70 houses destroyed. The response to the emergency was very difficult, owing that the peak occurred at night and the maximum water level that occurred in the past was exceeded at about 1.8 m, which means that not prior experience existed regarding the behaviour of the river and the flooded incremental areas.

This paper describes the development of a framework for decision support systems (DSS) for flood event management applied to the Yi River basin in Uruguay. The tools comprise weather forecasts and real-time hydrologic–hydrodynamic modelling in order to forecast flooded areas and its permanence in time.

During the initial stage of the project, another severe flooding with similar consequences occurred in the first week of February 2010. The Yi River reached 12.20 m gauge height in Durazno city, which corresponds to a return period of about 250 years. The flooding was caused by a storm of 8-day duration, with an average rainfall of 334 mm.

Summarising, two extraordinary floods corresponding to a return period of 500 and 250 years, respectively, occurred in less than 3 years.

Figure 1 Location of Durazno city and the study area.

Methodology

The methodological approach comprises a description of the study area, a brief discussion about the objectives of the DSS and its requirements, background to the developed DSS for Durazno city, an explanation of the conceptual model for DSS management, and the development of the hydrologic–hydrodynamic model of the Yi River basin and the procedures for its calibration and validation.

Study area

Durazno is a city in central Uruguay, at 33°22’53” South Latitude and 56°31’12” West Longitude, and a main altitude of 91 m a.m.s.l. The city is located on the left bank of the Yi River, a tributary of the Negro River, as shown in Figure 1. Its population is about 30 700 inhabitants. The population living in high-risk flood areas is approximately 5 000 inhabitants, which occupy an urban area of about 500 ha.

The Yi River basin has an area of 8 900 km^2 upstream of the Durazno city. The time of concentration computed according to Kirpich (1940) is 52 h. The main physical characteristics of the basin are summarised in Table 1.

Table 1 Main physical characteristics of the basin

Surface area (km^2)	8,900
Length of main channel (km)	192
Main channel slope (%)	0.12

The Yi River has an alluvial meandering stream with a significant flood plain regarding the main channel. Its flood plain between Sarandi del Yi, a town located upstream, and the Durazno city, is about 500–1 000 m wide. Indeed, for the floods that occurred in 2007 and 2010, the main channel flow area represents only 11.5% and 12.6%, respectively, of the total flow area. Figure 2 illustrates the maximum water level achieved for the 2010 flood. The cross-section in Figure 2 is located in Durazno city, 400 m downstream with regard to the bridge of the national road Nr. 5.

DSS

The purpose to develop a flood event management DSS is to assist the Emergency Coordination Centre of Durazno city (CECOED in Spanish) in improving emergency planning by providing information on the flood hazard. This support should be given during the preparation phase of flood event management and/or during the actual flood response as suggested by Lumbroso *et al.*, 2009. The support should lead to risk-based decision making, that is the risk of flooded areas and its permanence in time resulting from different weather forecast is compared and assessed. The flooded areas are determined by integrating the modelled gauge heights at cross-sections of the river on their way through the city with a digital elevation model.

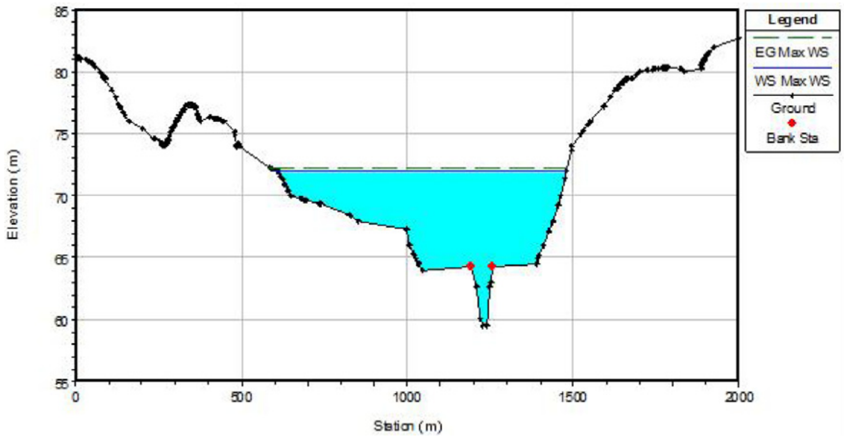


Figure 2 Main channel and flood plain Yi River cross-section for the 2010 simulated flood.

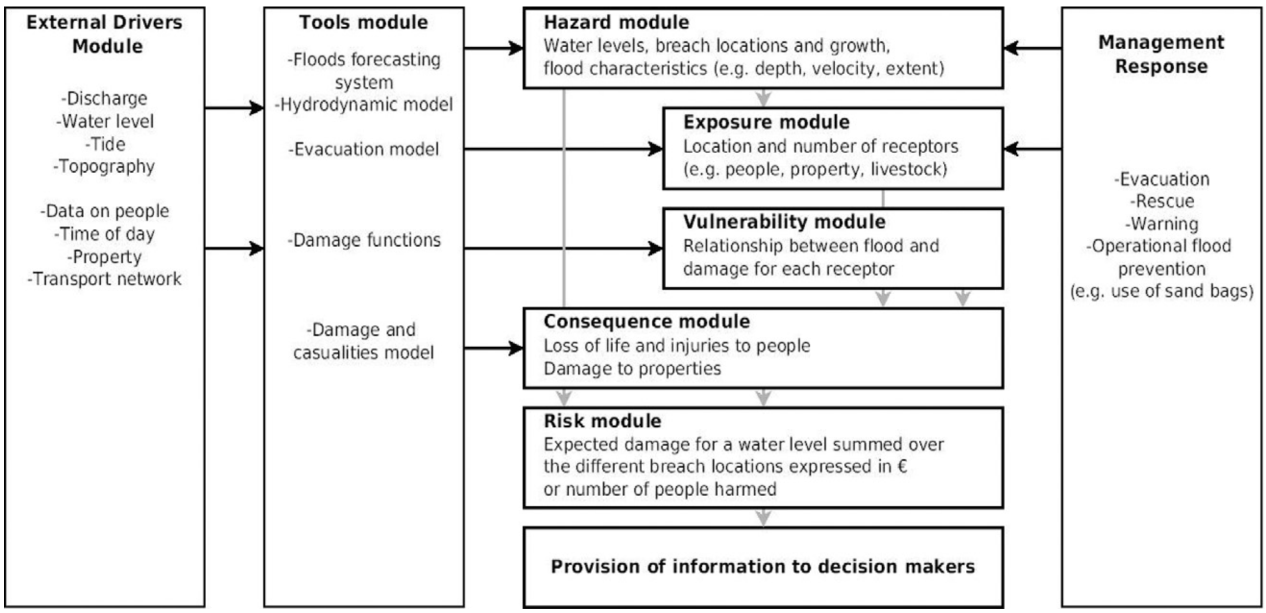


Figure 3 Methodological framework for flood event management. *Source*: Lumbroso *et al*., 2009.

The work described in this paper follows a methodological framework developed for the flood event management DSS by Van der Vat *et al*. (2007) and Mens *et al*. (2008), which consists of eight modules that are generally relevant to flood event management, as shown in Figure 3. This paper focuses on the tools, hazard and the exposure modules.

Emergency Coordination Centre requirement for a DSS

For any DSS to be successful, it is essential that the end-users (e.g. the emergency coordination centre) are integrated into the development of the framework (Lumbroso *et al*., 2009). According to Logtmeijer (2006) and Lumbroso *et al*. (2009), the most important user's requirements are as follows: (1) prerun results for various flood scenarios; (2) the flood hazard at vulnerable locations; and (3) user-friendly in terms of presentation of results. Other requirements, such as (1) details of receptors at risk; (2) safe havens and exit routes; and (3) coordination of all event response personnel, are not included in this work because the Emergency Coordination Centre of Durazno city (CECOED in Spanish) has extensive experience in making key decisions relating flood event management and evacuation rescue strategies, which is documented in the Emergency Operations Departmental Plan (Comité Departamental de Emergencia de Durazno, 2011).

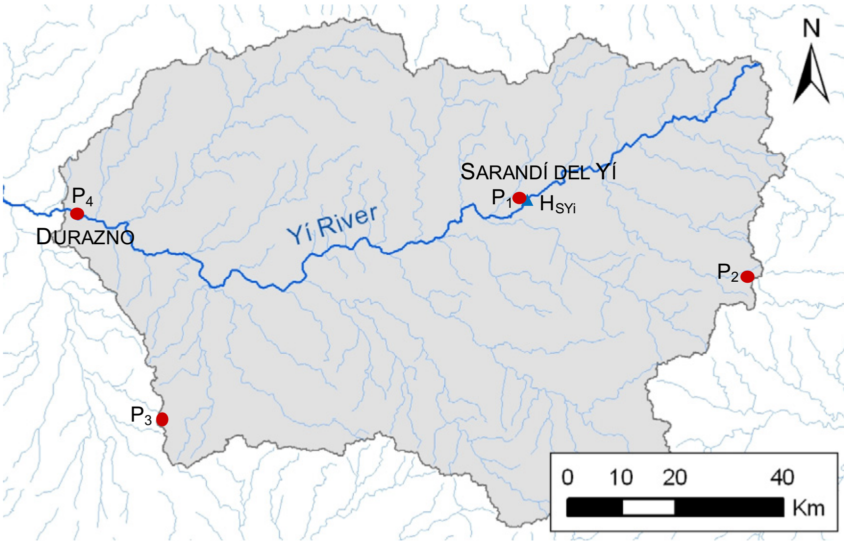


Figure 4 Network used by the White Helmets project to forecast the maximum gauge height in Durazno city. *Notes*: $H_D = \alpha_1 \times H_{SYi}^{\beta 1} + \alpha_2 \times P_1^{\beta 2} + \alpha_3 \times P_2^{\beta 3} + \alpha_4 \times P_3^{\beta 4} + \alpha_5 \times P_4^{\beta 5}$, where H_D is the water surface elevation in Durazno; H_{SYi} is the water surface elevation in Sarandi del Yi; P_1 is the rainfall from rain gauge 2215; P_2 is the rainfall from rain gauge 2266; P_3 is the rainfall from rain gauge 2395; and P4 is the rainfall from rain gauge 2206.

Schröter *et al.* (2009) pointed out that for evaluation of early warning systems (EWS) effectiveness and efficiency, two important aspects have to be addressed: the reliability of the warning and the damage prevented by the warning.

For Durazno city EWS, the reliability of the warning evaluation is performed by comparing the real-time events forecasted hydrograph with the observed limnigraph in Durazno city. The forecasted limnigraph results from the tools module in Figure 3 (hydrologic–hydrodynamic model). In this paper, an example of real-time operation and its evaluation is included.

Background to the developed DSS for Durazno city

The development of a methodological process for the preparation of emergency plans and warning systems for floods was initiated with the implementation of the project called ‘Emergency Plan for Flood Control of the City of Durazno’ (Cascos Blancos, 2002). This project was supported by the Organization of American States, Inter-American Development Bank and Volunteers for Humanitarian Assistance in Latin America (White Helmets Commission of Argentina), as well as the Ministry of Transport and Public Works, through its National Water Board and the Municipality of Durazno. The result was a statistical relationship based on the maximum gauge height measured in Sarandi del Yi and daily rainfall from four rain gauges to forecast the maximum gauge height in Durazno city as shown in Figure 4. This tool represented a significant improvement for managing emergencies.

Nevertheless, faced with a weather alert, which can cause a flood emergency, the focal coordination centre of Durazno city needs to be able to estimate the timing, extent and depth of flooding. There is also a need to assess the risk that people and properties may be exposed to under different weather forecast scenarios, and to assess evacuation times. Knowledge is also invaluable for the emergency management because it allows calculating in advance the number of people to be evacuated, and their need for food and shelter. Flood event management discussed in this paper focuses on the short-term actions just before and during a flood incident occurs, where people may be evacuated from the area in advance of a flood. The existing maps of flooded areas were calculated for return periods between 2 and 500 years on the basis of Gumbel distribution fitted for maximum gauge heights in Durazno city (Cascos Blancos, 2002).

The conceptual model for DSS management

The purpose of any flood warning is to diminish damages by taking preventive measures. Hence, an effective warning system provides reliable forecasts sufficiently in advance to realise the according actions (e.g. by improving the warning lead time).

The warning lead time for flood management based on upstream monitoring of water surface level only capitalises the travel time in the water course, and thus most often is inadequate (Schröter *et al.*, 2009). Consequently, the use of rainfall run-off models is necessary in order to enlarge the lead time, which then starts from the instant rainfall is observed. However, the lead time only increases in the order of the time of concentration. A further gain of the forecast lead time can only be achieved by including quantitative precipitation forecasts from numerical weather prediction systems. Examples of these systems are NOAA Global Forecast System (Fanglin *et al.*, 2006), CPTEC/COLA (Bonatti, 1996) or CPTEC/ETA (Gonçalvez de Moura *et al.*, 2010). The use of quantitative predictions of any atmospheric variable requires a process of assessment of the uncertainty of the predictions and correction of their systematic errors. This can be achieved through the use of data from retrospective forecasts of the variables of interest and the correspondent field measurements, and is an object of a forthcoming work. Nevertheless, it was found that a preliminary use of numerical weather predictions can yield scenarios that are useful to the management of emergencies, by giving pre-alert information with valuable lead time, yet with less accuracy as lead time extends (Yates *et al.*, 2000; Aldana *et al.*, 2003; Collier, 2007). However, any increase in warning lead time could provide a highly useful decrease in human and economic exposure to flood risk, especially for severe cases.

Consequently, a hydrologic–hydrodynamic model based on observed and predicted rainfall has been selected to provide quantitative information about the future evolution of water surface levels. Thus, hydrographs are simulated using observed rainfall until the time t_i and the rainfall forecast available at the same time t_i. In this regard, flood forecasts support the DSS on flood alerts and emergencies management. However, it should be noted that the forecast of future events is always uncertain due to the variability in space and time intrinsic to natural processes. Moreover, the knowledge about the future development of weather conditions is still limited. In general, the uncertainty concerning the forecasted flood event covers the magnitude and the timing of the expected flood peak and the permanence above critical water surface evacuation levels (Schröter *et al.*, 2009). Then, the corresponding sample of errors (i.e. the difference between observed and forecasted water surface levels) reflects the predictive performance of the forecasting model throughout the analysed period.

The decision to develop a hydrologic–hydrodynamic model is also supported by the existing systematic monitoring from the beginning of the twentieth century. The intensively monitoring of rainfall and water surface levels in this basin is due to the fact that the Yi River basin is a sub-basin of the Negro River basin, which has an installed hydropower capacity of about 600 MW.

The hydrologic–hydrodynamic model of the Yi River basin

The Yi River basin, defined by the telemetric station Barra de Porongos located at its outlet, was divided into 16 sub-basins as shown in Figure 5. These sub-basins, which were selected according to available hydrometeorological data, contribute with flow hydrographs to the Yi riverside.

A hydrologic model computes for each sub-basin the input flow hydrograph to Yi River. The hydrologic model is a lumped conceptual model that represents the main hydrological process, such as infiltration and the basin run-off response function. The infiltration process was modelled according to curve number (CN) methodology developed by the Natural Resources Conservation Service (NRCS, 1997). This method assumes a variable infiltration rate decreasing over time, as the soil becomes saturated owing to the input rainfall. The average input daily rainfall was computed according to the Thiessen polygons, weighted by the area associated to each rain gauge. The infiltration curve depends on soil type, land use and antecedent soil moisture conditions, with the CN as the main parameter (Chow, 1994). The CN was computed using the Soil Survey Chart of Uruguay (Doti *et al.*, 1979), the classification of soil into hydrological groups according to the NRCS method, and the land use was estimated by observing the Google Earth satellite image.

The basin run-off response function was modelled using the triangular unit hydrograph proposed by the NRCS (1997). The main parameters are the effective rainfall and the time of concentration of each sub-basin. The initial value of the time of concentration was computed according to the Kirpich method (1940).

The hydrodynamic model of the Yi River covers the section between Sarandi del Yi (upstream) and Barra de Porongos (downstream), totalling a length of approximately 174 km. The public domain model HEC-RAS 4.0, developed by the Hydrologic Engineering Center (HEC) Corps of Engineers U.S. Army (USACE), was selected (http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html). The input data consisted of cross-sections of the Yi River and its flood plain. A total of 34 cross-sections between Paso San Borja and Paso del Bote were surveyed by the earlier White Helmets project, while the 20 cross-sections between Sarandi del Yi and Paso San Borja were surveyed by the PROHIMET project. Thus, a total of 54 cross-sections were used by the hydrodynamic model, as shown in Figure 6. Daily water level data were available in Durazno city hydrometric station consisting of a manual reading scale observed three times a day.

The boundary conditions downstream were (1) the water surface levels recorded at the Barra de Porongos hydrometric gauge, located 30 km downstream Durazno city, and (2) the input hydrographs from each sub-basin, while the initial condition was a base flow to mitigate instabilities at the beginning of the simulations. The calibration parameter of the hydrodynamic model is the Manning roughness coefficient of the channel and the associated flood plain.

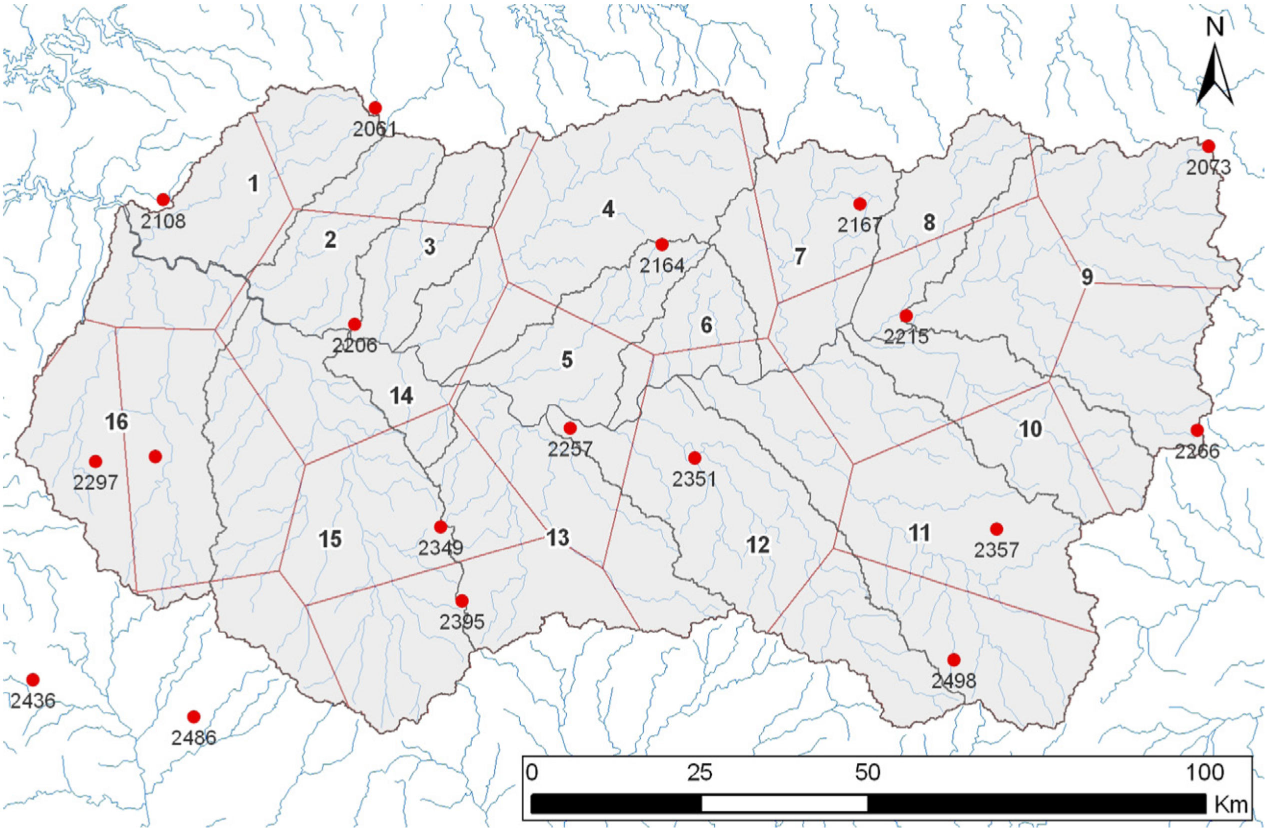


Figure 5 The Yi River basin divided into 16 sub-basins.

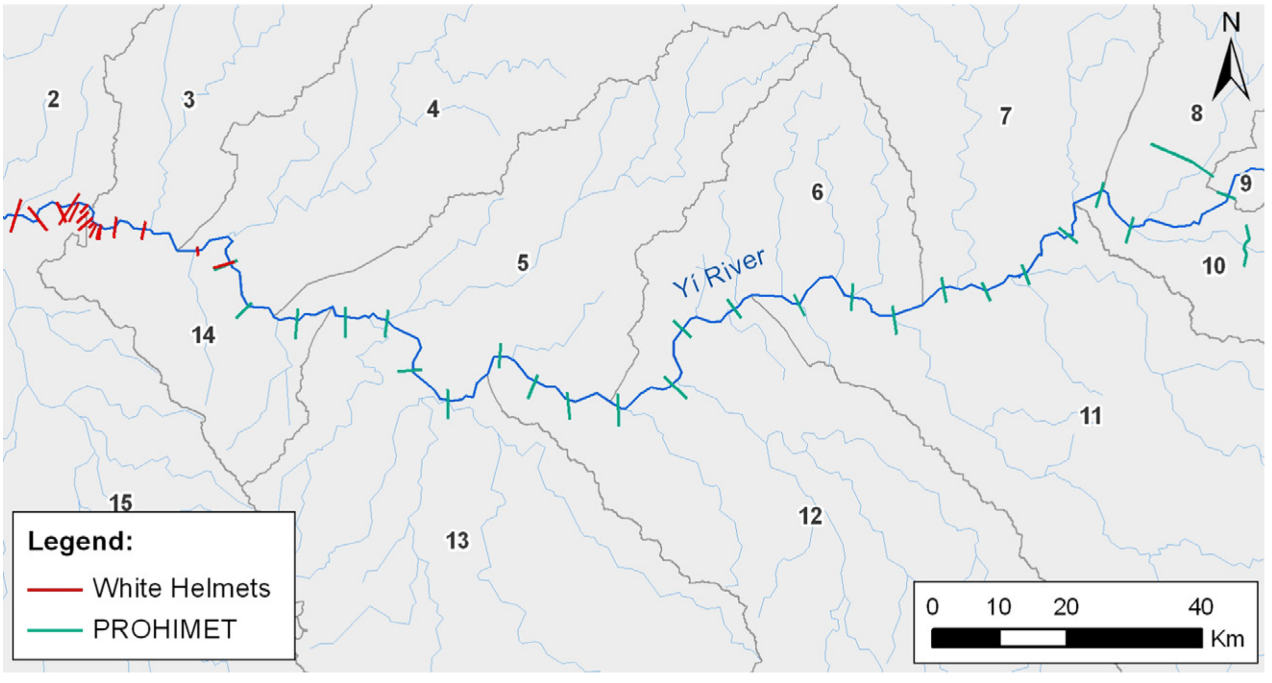


Figure 6 Cross-sections of the Yi River surveyed by the White Helmets and PROHIMET projects.

Calibration and validation of the hydrologic–hydrodynamic model

The parameters of the hydrologic–hydrodynamic model (i.e. CN, time of concentration and Manning roughness coefficient) were calibrated by adjusting the recorded and simulated water surface levels in Durazno city on the basis of available observations for a selection of past flood events of high return period. For the validation of calibrated parameters, a subset consisting of one available extreme event has been used. The characteristic of these events is summarised in Table 2.

Thereafter, the model was run in 'real time' to forecast the water level in Durazno city for an event classified as orange alert by the Uruguayan Meteorological Service.

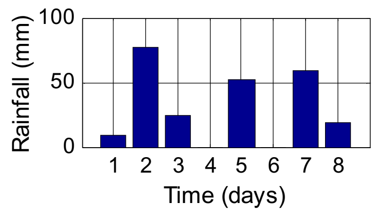
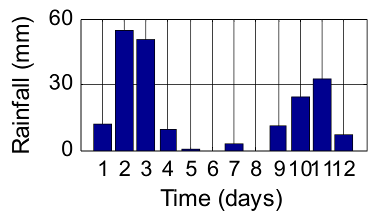
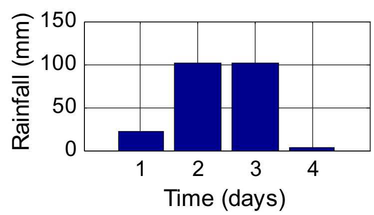
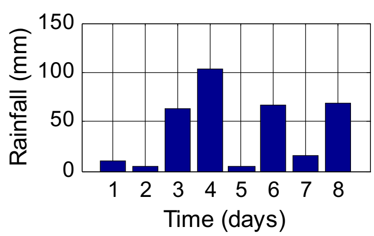
Results

The calibration process began by using the theoretical values of hydrologic parameters described in the methodology, and finding the optimal values of the Manning roughness coefficient. Figure 7 shows the result for the three events used for calibration, where an underestimation of run-off volume and maximum water level can be observed.

In order to improve the results, the time of concentration (Tc) and the CN were increased. An increase of these parameters enlarges, respectively, the peak time and the run-off volume. To increase the Tc, the NRCS formulation, which takes into account the channel slope and the CN, was applied instead of the Kirpich (NRCS 1997; Tucci, 2000; Trimble and Ward, 2004). The CN was increased by 20% compared with the theoretical values for all watersheds, maintaining the same spatial variability. Then, the input hydrographs were recalculated for the new values of Tc and CN, and the Manning roughness coefficient was calibrated. Figure 8 shows the improved result obtained during this second calibration step for the three events represented before. Nevertheless, a less underestimation of run-off volume and maximum water level is still observed.

The next step to improve the calibration was to correct the incident rainfall by the wind speed (Musy and Laglaine, 1992) according to

Table 2 Characteristics of the past flood events used for calibration and validation of the hydrologic–hydrodynamic model

Event 1 (Calibration) Date: 16–23 May 2003 Total rainfall: 241 mm Maximum daily rainfall: 120 mm	
Event 2 (Calibration) Date: 3–14 June 2005 Total rainfall: 204 mm Maximum daily rainfall: 138 mm	
Event 3 (Calibration) Date: 4–7 May 2007 Total rainfall: 229 mm Maximum daily rainfall: 161 mm	
Event 4 (Validation) Date: 1–8 February 2010 Total rainfall: 334 mm Maximum daily rainfall: 166 mm	

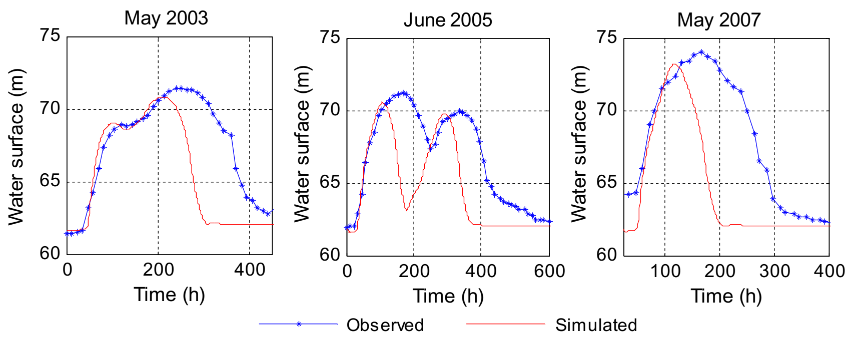


Figure 7 Observed and modelled water surface levels for Durazno city. Calibration step 1 (theoretical values of time of concentration and curve number).

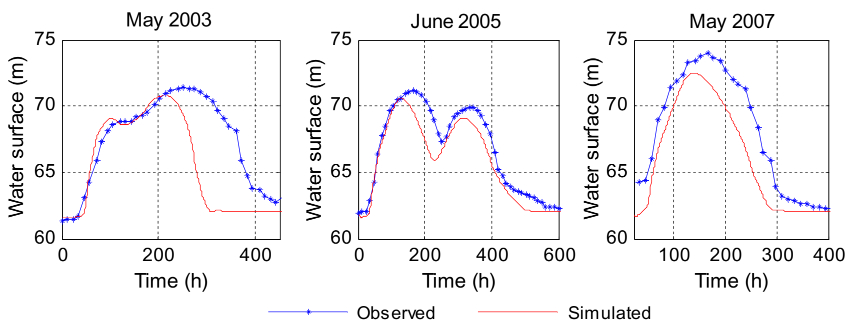


Figure 8 Observed and modelled water level for Durazno city. Calibration step 2 (increased time of concentration and curve number).

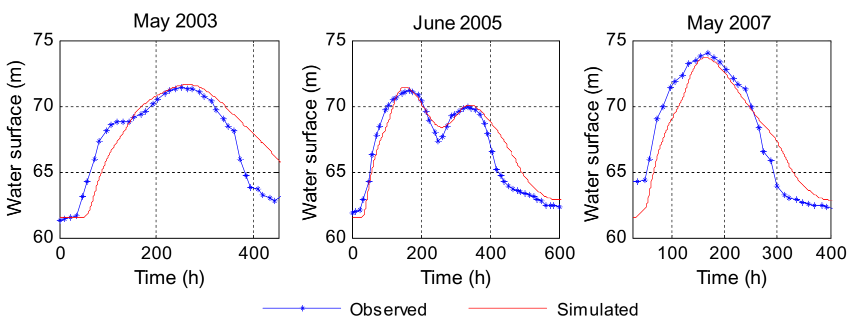


Figure 9 Observed and modelled water level for Durazno city. Calibration step 3 (input rainfall corrected by the wind speed).

$$Pw = P\left(1 + \frac{(-0.076441\,v^2 + 2.828121\,v + 0.031469)}{100}\right)$$

where:

Pw is daily rainfall (mm) corrected by the wind speed;

P is the average daily rainfall (mm) computed from the available data at the network of rain gauges; and

v is the wind speed (m/s) recorded at the meteorological station of Durazno city.

Figure 9 shows the improved result obtained during this third calibration step. It shows that the differences between the recorded and modelled peak water levels were between 0.19 and 0.33 m.

Table 3 shows the hydrologic parameters values achieved in each calibration step, explained above. CN and concentration time (T_C) are mean values for the whole river basin, and Manning roughness is set for channel and flood plain (nc and np) for the whole modelling reach.

Then, the calibrated model parameters were validated by using the extreme event that occurred between 1 and 8 February 2010. This extreme event was similar to the event in May 2007 in terms of the flooded area and number of evacuees, but different in terms of the accumulated total rainfall and its distribution in time, as shown in Table 2. Figure 10 shows that the difference between the maximum observed and simulated water level was 0.91 m. Taking

Table 3 Hydrologic model parameters for each calibration step

Calibration step	Curve number	Concentration time (hs)	Channel Manning (s/m$^{(1/3)}$)	Flood plain Manning (s/m$^{(1/3)}$)
Step 1	74	18	0.030	0.10
Step 2	88	60	0.030	0.10
Step 3	88	60	0.080	0.15

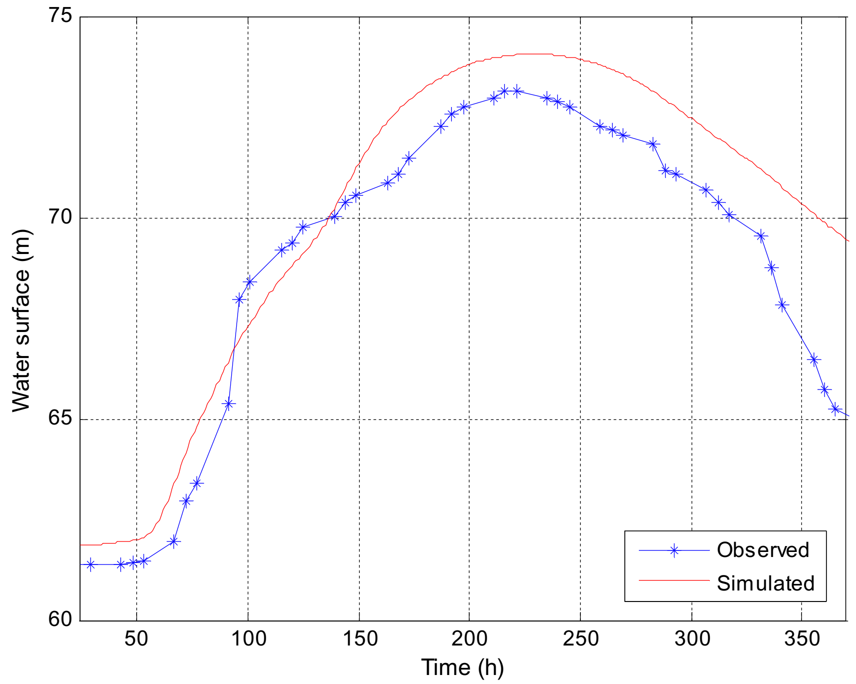


Figure 10 Observed and modelled water level for Durazno city. Validation step.

into account the elevation representation uncertainties (±0.3 m) and the reduced number and differences of the events used for calibration and validation steps, it was concluded that the hydrologic and hydrodynamic model represents an acceptable first approximation of the observed levels in Durazno city. In order to improve the results, a recalibration process was implemented as new flood events are recorded.

Examples of real-time operation

Three events occurred between May and July 2011. These events may be qualified as minor events, different from those used in the calibration and validation steps. Only the events occurred in July resulted in 40 inhabitants evacuated. Moreover, it should be noted that the model calibration was performed using input rainfall data recorded in a network consisting of 18 rain gauges, while the real-time operation was performed using input data recorded hourly in the existing telemetry network consisting of three stations located along the Yi River (Sarandi del Yi, Polanco del Yi and Durazno city). The hydrologic–hydrodynamic model was run 24 h before the events on the basis of meteorological forecast. Thereafter, the gauge height forecast was adjusted every 6 h on the basis of recorded rainfall. The maximum gauge height was predicted about 5 days in advance. Table 4 shows the simulated and observed maximum gauge height in Durazno city, as well as the predicted and observed occurrence date and time. The simulated and observed results are also compared with the results of the statistical relationship developed by the White Helmets project to predict the maximum gauge height in Durazno city. Table 4 shows that the hydrologic–hydrodynamic model successfully represents the events that occurred between May and July 2011, despite the lower representation of the spatial distribution of rainfall.

The model is running every day for the real-time operation, on the basis of recorded data and rainfall forecasts. For each precipitation forecast, the gauge height in Durazno city is simulated, taking into account the soil moisture antecedent condition determined by the rainfall events that occurred in the previous 3 days. The output shows the

Table 4 Real–time operation of the hydrologic–hydrodynamic model between May and July 2011 by using limited input data from the existing telemetry network consisting of three stations located along the Yi River (Sarandi del Yi, Polanco del Yi and Durazno city)

	Maximum gauge height in Durazno city (m) and occurrence time (day and h)					
Event	White Helmets		Hydrologic–hydrodynamic model		Observed	
24–25 May 2011	7.58	–	6.64	28 May 5:00	6.20	27 May 13:00
16–19 June 2011	8.46	–	6.42	21 June 18:00	6.74	21 June 18:00
15–16 July 2011	7.26	–	8.30	20 July 10:00	8.62	20 July 10:00

forecasted gauge height in Durazno city for the different sources of precipitation forecast overlapped with the recorded gauge height.

Conclusions

A hydrologic–hydrodynamic model has been developed for the Yi River basin as a support tool for DSS.

The use of quantitative rainfall forecasts based on numerical weather prediction systems brings considerable uncertainties. This requires the measurement and correction of the systematic error of the predictions, and the assessment of confidence intervals for the random errors that result after the correction is done. This is part of our current work and will be reported in a forthcoming paper. Nevertheless, the rainfall predictions from numerical weather systems are being used in a preliminary way in order to produce scenarios that can give an early pre-alert to the emergency coordinators. These scenarios may be useful in cases of severe storms.

The forecasted gauge height for three alerts operated in real time between May and July 2011 showed enough accuracy to improve the CECOED's emergency planning, particularly regarding planning of evacuation time and human and material resources needed for each event.

Further steps to be considered in the future are as follows:

- to follow up new events in real time in order to assess the validity of calibration parameters for a wide range than that used for calibration and validation, particularly the Manning coefficient; and
- to explore the potential value added to flood forecasting by the use of numerical weather predictions products and satellite-based precipitations estimates.

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