



The 2006 and 2009 Landslide and Flood Events in the Tartagal River Basin (Argentina)

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Abstract

The Tartagal River basin is placed in the Sub-Andean Hills in northwestern Argentina. In this area the town of Tartagal, in Salta Province, with 55,000 habitants, is located. At this site the contribution river basin is approximately 100 km². Between 2006 and 2009 the region was affected by extreme events of different characteristics, which created a risk to human lives, productive infrastructures and communications. In 2006, large rainfalls above average values generated landslides, with the appearance of large-scale gullies. In 2007, remedial works were carried out. In 2009, an avalanche of water and sediment with logs came down the Tartagal River reaching the city's main avenue bridge. After the 2009 event, structural and non-structural measures of short, medium and long term were implemented.

Keywords

Landslides • Woody debris • Tartagal • Argentina

Introduction

Between late 2005 and 2009, Tartagal River Basin, located in the Province of Salta in northwest Argentina (Fig. 1) was affected by precipitations with values above the historical average, and in some cases, above the maximum recorded values. This situation developed on a basin with characteristics that promote landslides and mud flow processes, led to the occurrence of extreme events in the basin, which resulted in major damage to productive and communication infrastructure, as well as loss of lives, with high socioeconomic and environmental impacts (Schuster and Highland 2001).

The events of 2006 and 2009 are particularly discussed in this work.

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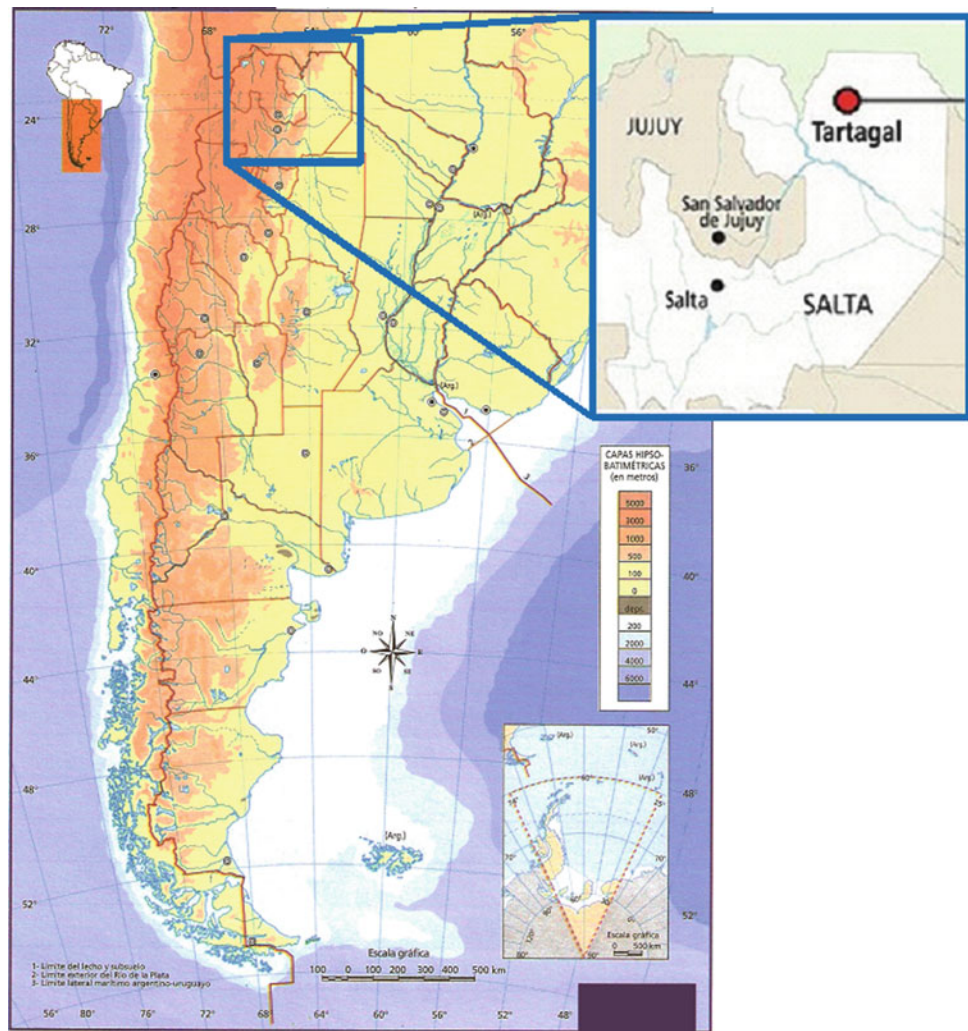
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Tartagal River Basin

From the physiographic point of view, the Tartagal river basin is developed in the hill of the same name, forming part of the Sub-Andean Sierras system. Geology in the upper and middle basin is represented by laminated and folded sequence of sedimentary rocks, while in the foothills, there are terraced fluvial deposits. The tropical humid climate conditions in the mountains have generated intense weathering, which led to deep soils with medium to fine texture.

The study area has a tropical highland climate, due to the presence of a series of mountain ridges oriented in the direction of the meridians, which intercept the passage of the moist winds from the Atlantic and establish a heavy condensation and rains at summer time.

As it was said, precipitation is closely related to winds and topography. Its tropical character is revealed in the simple form of a peak in summer and a minimum in winter. The highest percentage of precipitation is concentrated in the months from November to April, occurring in the form of local showers with big drops that shed a considerable

Fig. 1 Location of the study area

amount of water in a short time preceded by thunderstorms, or in the form of torrential rains that are diffuse across the country. The annual average rainfall recorded between 1934 and 1990 at Tartagal is 911 mm with a maximum of 1,914 mm in 1984. In summer months between five and ten storms by month can happen, while in winter they are extremely rare. Wood in tropical streams has the potential to be more mobile than wood in otherwise similar temperate streams (Cadol and Wohl 2010).

With respect to natural morphoevolutive processes, those linked to surface runoff actions are manifested in the form of water erosion in all its forms, to an extent dependent on the alteration of natural vegetation cover, which acts as a regulator. The landslide processes governed by factors such as terrain nature and slope, and have the weather as the main trigger, are evident in the basin, in the past and present, by the frequent presence of scars on the hillsides. These scars have varying degrees of evolution, manifested in the growth state of natural vegetation, which may be dragged when processes are reactivated.

Tartagal City is located in the foothills, growing on both banks of the Tartagal River. The basin upstream the city has an area of 96.68 km² and a perimeter of 75.67 km, with minimum and maximum altitude of 405 and 1,032 m a.s.l., respectively (Fig. 2).

The 2006 Event

Tartagal River was channelled around 1980 in the segment that crosses the city, with concrete slabs from Packham Avenue to the National Route 34 forming a trapezoidal section (Fig. 3).

Product of intense rainfall occurred in the basin and in Tartagal City since late December 2005 to April 2006, significant discharges with high sediment transport in the Tartagal River were generated. Destruction of much of channel revetment, the collapse of the slopes of its margins and a retrograde erosion process at the main channel, resulted due to floods (Fig. 4).



Fig. 2 Tartagal River basin and Tartagal City



Fig. 3 Tartagal City detail

The building infrastructure of the city, as shown in Fig. 5, was severely affected by the fall of margin slopes due to retrograde erosion process at the channel.

The solution of the problem was a new river channel, with a segment of high slope, and reconstruction of the margins. The design flow rates were determined from the events recorded between December 2005 and March 2006, at pluviographs installed in the region, in the basin and surrounding areas, with few years of record (Table 1).

A design discharge of $800 \text{ m}^3/\text{s}$ was adopted from available information, being necessary to carry out a verification for a flow of $1,000 \text{ m}^3/\text{s}$. With this information, the control work was planned, which was also studied in a physical model developed for this purpose in the laboratories of the National Water Institute of Argentina (Fig. 6).

Due to the emergency situation, the project and its execution began immediately after the flood period. The reconstruction of the channel was completed in June 2007. Figure 7 shows the new works during the construction phase and Fig. 8 illustrates a view of the completed channel.



Fig. 4 Processes observed in Tartagal River at Tartagal City, 2006

The 2009 Event

After the 2006 event, the following years were quiet until 2009. On Monday, February 9, 2009 in the morning, an avalanche of water, logs and sediment came down from the Tartagal River reaching the Packham Avenue Bridge. The contraction generated by the bridge caused the damming of the waters and the consequent accumulation of logs and branches carried by the flow of water and sediment, upstream of the road bridge.

Situation worsened when the action of mudflow and transported vegetation made the railway bridge located upstream to collapse, pivoting on the left abutment, and hitting the Packham Avenue urban road bridge (Fig. 9).

The events described led to the obstruction of the drainage section, causing a damming of logs and sediments, which impeded the free drainage of water, causing the overflow to both margins, going over the bridge embankment. This flow diverted to the sides of the river went into the houses adjacent to it, killing two people, and causing heavy damage and material loss (Fig. 10).



Fig. 5 View of the Tartagal River after the event in 2006 and the affectation of the building infrastructure

Table 1 Accumulated precipitation during December 2005 and January 2006 [mm/month]

Station	December 2005	January 2006	Total
Galarza	580.5	535	1115.5
Piquirenda	403	466	869
Chorrillo	377.5	308	685.5
Piquirenda plant	474	433	907
INMAC Tartagal	n/d	456	
Historical average	150	200	350
Historical maximum	300	460	



Fig. 6 Physical model at the National Water Institute – Argentina. Scale 1:40



Fig. 7 Construction phase



Fig. 8 Upstream view of Tartagal River channel in 2007. In the background the Packham Avenue bridge and the railway bridge can be seen



Fig. 9 Packham Avenue bridge during the flood



Fig. 10 The red polygon indicates the area most affected in the city, the light yellow area indicates how far the water and the solid material during flood went



Fig. 11 Log deposits upstream Packham Avenue bridge, after the 2009 flood

An important difference between the 2006 and the 2009 events, was the presence of large amounts of woody and debris material, absent in 2006. This is evident in the deposits remaining after the flood, recorded in Fig. 11.

Based on available data and relevant information it was found that the process was triggered due to locally heavy rains that had an impact on the middle river basin. An important proof came from the lagoons and marshes on the upper basin, where no signs of flooding, or flood, were found, on the contrary identifying areas of marshlands partially dry or with clean water.

The event was reconstructed thanks to photographic and film evidence, coupled with eyewitnesses' testimony, who indicated that the event duration was short, beginning at approximately 8 pm on February 9, and declining at 10 pm, hence lasting only 2 h.

People living near the roadway bridge also mentioned the occurrence of two peaks, a first one with water and little plant material, and a second one with plenty of vegetation

and sediment. This scheme has not been confirmed, but partly coincides with the available film information.

However, this situation would be endorsing the hypothesis of breaking natural stick dams in the basin. Flights over the watershed allowed finding visible evidence of the presence of natural stick and log levees, especially in tributaries to the river (Fig. 12).

The formation mechanism of these dams is, once a landslide is produced with fall trees and sediments, that it can block all or part of the section of a stream or river (Braudrick and Grant 2001). The strong contribution of logs into the system, makes the sticks accumulate, creating small reservoirs which also accumulate water (Gomi et al. 2001). When water pressure exceeds the strength of natural levee, it is broken, causing a flood peak, able to transport the removed material downstream, reinforced by the high slope of the channels in the basin.

The inability of the trunks to bend in the curves of the river, make the concave areas favourable starting sectors to



Fig. 12 Log levees in the middle river basin observed during a flight 24 h after the event



Fig. 13 Landslide scars in the Tartagal middle river basin observed during a flight 24 h after the event

develop these dams, because the logs are locking each other as they arrive, and then the water accumulates to failure (Nakamura and Swanson 1993; Abbe and Montgomery 1996; Zielonka et al. 2009).

The analysis of rainfall records indicates that the total dropped water from 04 to 12 am was in the order of 95 mm in Railway Station (Tartagal) and San Pedrito (nearby mountains). Some reports indicate that most of this amount of rain was concentrated in a span of 45–60 min. According to hydrological studies background for Tartagal River Basin, intensity values of the order of 100 mm/h have recurrence of about 25 years.

In villages near Tartagal as General Mosconi and Campamento Vespucio, the daily average rainfall for the same date yielded less than 30 mm. This would confirm the presence of a typical convective high intensity cell but with a small areal coverage.

What was previously said, supports the hypothesis that the phenomenon occurred was generated by a short duration rainfall, locally very intense, on the Tartagal middle basin, which caused large landslides in areas with a well developed vegetation cover (Fig. 13).

To identify the landslides occurring during heavy rains, considered the sources of woody debris and avalanche solid material, a comparison of an area inside the Tartagal middle river basin in 2006 and 2009 after the critical event is shown in Fig. 14. The large amount of mass removal in vegetated surfaces without clearing is evident.

Another aspect to be considered for its possible relationship with the phenomenon is that a rainfall occurred in the region during the 3 days before the landslides, which might have created a state of soil saturation in the basin, weakening the erosion resistance for subsequent events.



Fig. 14 Comparison between 2006 and 2009 after landslides. The area is inside Tartagal middle river basin (Aguay Plant zone)



Fig. 15 New Packham Avenue bridge

Actions Taken

Emergency, short and medium term measures were established during and after the 2009 event.

During the emergency and the following days, the broken railway bridge was removed, the board of the Packham Avenue bridge was also taken away, to increase discharge capacity at that control point, the traffic was restored with a Bailey bridge and the affected areas downstream from the bridge were repaired.

Short term measures were taken in the first weeks to raise public awareness. During the first 2 months the possibility of a new damming was also discussed, the design of the new Packham Avenue bridge was revised increasing its length and height, partially damaged slabs were repaired and the relocation of the accumulated wood was defined.

In the medium term (first year), the Packham Avenue Bridge was rebuilt (Fig. 15), the plan and development of an early warning system began and a hydro-geological risk study and a planning and zoning project were scheduled. Protection concepts cannot be based on structural measures alone but should contain forest-technical measures.

Discussion and Conclusions

There was no evidence of human action in the basin related to cutting of trees, open pathways, clearing of forests, or for activities related to road or oil infrastructures, or water management that may have influenced the development of landslides and avalanches, as, during and even after the event, many individuals and NGOs stated.

It is estimated that the 2009 event was generated by a storm, on a sector of the middle basin. Flood characteristics due entirely to hydrological, geological and geomorphological processes, occurred in the watershed.

The intensity of landslide scars clearly indicates the occurrence of localized weather event. There are clear evidences that the event happened is a recurrent phenomenon in the recent geological past. Considering the not extraordinary magnitude of the occurred rainfall, at least on a monthly basis, and the great availability of upstream forest mass, the possible occurrence of similar phenomena in the near future can be considered as true. The presence of a significant amount of material available on slopes has been observed, thus indicating a high degree of potential instability which could occur after a new similar weather event. This is compounded with the presence of large amounts of wood and debris on the streams that affect channel morphology (Jackson and Sturm 2002).

As a result, also following the medium term measures adopted after the 2009 episode, studies to assess the feasibility of works in the basin and in the river, to control the processes due to new climatic events, are considered indispensable.

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