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Exacerbation of Hydrologic Events due to Anthropogenic Causes in Arid Zones

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Abstract

The effect of built structures on the outcome of extreme climatological events in an arid area is discussed. Devil´s Creek, located on the northern end of the Atacama Desert, had been inactive for approximately 93 years. In recent years, an increase in precipitation has caused casualties and extensive property damage in several towns of the region. Devil´s Creek encompasses 52.84 km^2, is 24.3 km long and its average slope is 5.1 %. Road crossings were built along Devil´s Creek. One of them, Camiara Pass, completely blocked the stream with a 13-meter-high embankment. When precipitation fell in the middle basin of Devil´s Creek the embankment dammed the flow, and it was eroded away by overtopping thus generating a dam break. The creek´s mouth and alluvial fan were partially settled without municipal authorization. Three people were dead, and 1945 homes, public buildings and city infrastructure were affected by the flood. This event was reconstructed using a hydrologic semi distributed simulation tool and a 2D hydraulic numerical model. The incoming peak flow for the February 21, 2020, event was estimated at 10.72 m^3/s. Simulations showed that for the no embankment condition damage to people and property may have been significantly less severe that for the event with embankment and dam break. It was concluded that the road crossing embankment exacerbated the effects of flooding downstream and that local and regional authorities should not allow the construction of embankments along the creek. In addition, human settlements near the creek´s mouth should be relocated.

Keywords: Urban flooding, 2D hydraulic models, arid zone, flashfloods

1. INTRODUCTION

This paper compares the outcome of a flood that caused the death of three people and caused extensive damage whose effects were amplified due to the existing of a 13-meter-high embankment used a road crossing with an event in which the embankment is not present. The event mentioned above took place in Tacna City, the capital of Tacna region, which is located on the northernmost end of the Atacama Desert, one of the most arid deserts in the world. Changes in precipitation patterns have been detected in recent years, such as increase in precipitation magnitude and intensity. Flooding had been reported in 2015, 2017 and 2019, when Mirave, a small town in a very narrow valley, was completely covered by debris flow (Kuroiwa, 2019). On February 21, 2020, precipitation higher than usual fell in the middle basin. Rainfall exceeding infiltration caused runoff. Flow crossed over an existing highway without eroding it away as it had been reinforced with rock masonry. An embankment used as a road crossing impounded runoff until it was overtopped and, subsequently, eroded away. The flood moved rapidly downstream towards Tacna City causing three deaths and extensive damage in some Human Settlements located at and near the mouth of Devil´s Creek. Changes in precipitation patterns have been detected in recent years (Pino-Vargas and Chávarri-Velarde, 2022a) and may affect towns and cities located in the path of a mostly dry watercourse. It is believed that a small increase in precipitation magnitudes and intensities was exacerbated due to the existence of an embankment built in a creek that had been essentially dry for more than eight decades. This article compares the outcome of the reconstructed hydrograph, obtained by interpolating data from rain gauge and from a national database developed by Peru´s National Hydrologic and Meteorologic Service, SENAMHI, and by using a semi distributed hydrological model. Hydraulic simulation was executed using a 2D shallow water model. Flooded areas depths and velocities were obtained for the two cases that were analyzed in graphical form and the outcome was superimposed over satellite images to show the impact of both scenarios. Results are summarized, and conclusions are presented at the end of this document.

2. MATERIALS AND METHODS

Devil´s Creek Basin is located near the Peru-Chile border in Southern Peru. The area where this watercourse is located constitutes the northern end of the Atacama Desert, on of the most arid regions in the world. Basin topography was collected from worldwide databases and local topography was obtained by means of aerial photography. Precipitation was obtained from regional weather stations and a national database. Data and procedures are briefly explained below.

2.1 Description of the Study Area

Devil´s Creek is located in Tacna, the southernmost region in Peru. This watercourse encompasses 52.84 km^2 and flows 24.3 km in the SW direction from the continental divide. Average slope of this watercourse is 5.1 %. Due to settlement in Tacna City, the creek´s mouth flows directly into the city´s outer neighborhoods. Figure 1 is oriented in the N-S direction and shows Devil´s Creek (area in blue light color), Highway PE-38 (as a red line), as well as the position of the old bridge, the road embankment and the area affected by floods. The road embankment is Camiara Pass, which is, in essence, an unauthorized embankment built by smugglers to avoid customs inspections near the Chile-Peru border.

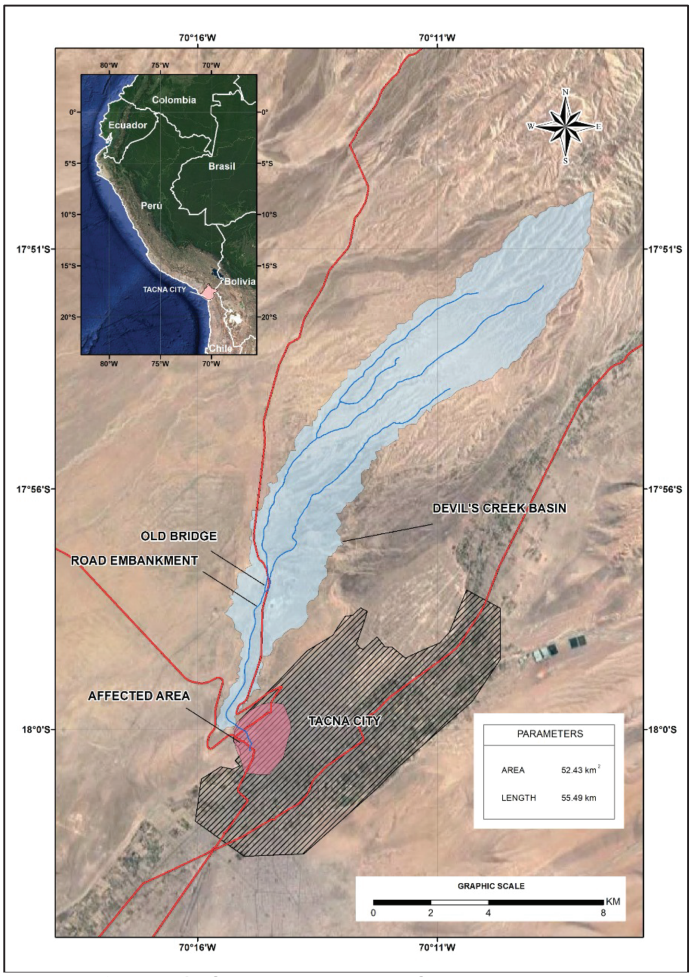

Figure 1. Devil´s Creek Basin, Tacna City and main crossings.

2.2 Precipitation data

Daily Precipitation data from five weather stations were collected and analyzed for the 1966 – 2020 period (Pino-Vargas et al., 2022b). Missing data was completed using the Climatology software, which is based on the approach proposed by Paulhus and Kohler (1952). Jorge Basadre station is owned and operated by Universidad Nacional Jorge Basadre Grohmann (UNJBG) located in Tacna and has been gathering precipitation data since 1993. Precipitation data from Jorge Basadre station best adjusted to a Gumbel distribution. Most climatological data in Peru is gathered by the National Service of Meteorology and Hydrology of Peru (SENAMHI). Precipitation was compared with data obtained from the Peruvian Interpolated data of SENAMHI's Climatological and hydrological Observations (PISCO) database (Aybar et al., 2017). Data from PISCO database was adjusted using the quantile mapping technique and validated for Devil´s Creek using local rain gauges. Daily precipitation at Jorge Basadre Station was compared to the generated by PISCO and the Nash-Sutcliffe efficiency index was 0.85 which shows a good correlation of precipitation estimated by PISCO with actual data from the station. Jorge Basadre precipitation was found to be 1.31 times precipitation estimated by PISCO. PISCO precipitation for the upper and middle basin was 1.06 times the precipitation obtained at Jorge Basadre station. Therefore, PISCO precipitation was 1.38 times precipitation recorded at the automatic station located near Jorge Basadre Station. Three main events were identified in the period December 7, 2019, to May 7, 2021. One of them was the February 21, 2020, event. In addition, virtual rain gauges were generated using IMERG and CHIRPS products. Further details can be found in Pino-Vargas et al. (2022b).

2.3 Hydrologic simulations

Hydrologic simulations were conducted using the MINERVE RS software package. The Soil Contribution model (SOCONT) was used considering that equivalent precipitation is equal to precipitation as the basin has no glaciers contributing to surface runoff. Devil´s Creek basin was divided in five sub basins and precipitation was assigned by using the virtual stations mentioned in the previous sub section. Soil was characterized using sol samples gathered across Devil´s Creek Basin. Clayey silt, sandy silt with gravel and clay and sandy silt with gravels was found.

Froelich approach was used to calculate breach generated by overtopping of the 13-meter-high Camiara Pass embankment (Froelich, 2008). Volume-height curve was determined based on topographic surveys and the volume was estimated at 23 911.5 m^3 when the embankment was being overtopped. Therefore, the calculated breach width was 9.8 m.

2.4 Hydraulic simulations

Two hydrographs obtained from the MINERVE RS model were incorporated into the numerical model HEC-RAS V 6.0 2D model to simulate runoff on Devil´s Creek downstream of Camiara Pass and in the urban sectors that were affected by the February 21, 2020, flood. HEC-RAS 2D use and capabilities are thoroughly described in Brunner (2021a) and Brunner (2021b). The first hydrograph corresponds to the condition without the Camiara Pass embankment and the second one is the output of the simulation of dam break generated by overtopping of the embankment of Camiara Pass. This hydrograph also corresponds to the upstream hydrograph of the dam break simulation, which is described below.

Table 1. Hydrograph of the Febraury 21, 2020 without the embankment of Camiara Pass.

Date	Time	Q (m^3/s)
21/02/2020	16:00	0.000
21/02/2020	17:00	0.093
21/02/2020	18:00	0.659
21/02/2020	19:00	1.623
21/02/2020	20:00	6.870
21/02/2020	21:00	10.629
21/02/2020	22:00	10.719
21/02/2020	23:00	9.079
22/02/2020	00:00	7.573
22/02/2020	01:00	6.399
22/02/2020	02:00	5.490
22/02/2020	03:00	4.779
22/02/2020	04:00	4.215
22/02/2020	05:00	3.763
22/02/2020	06:00	3.398

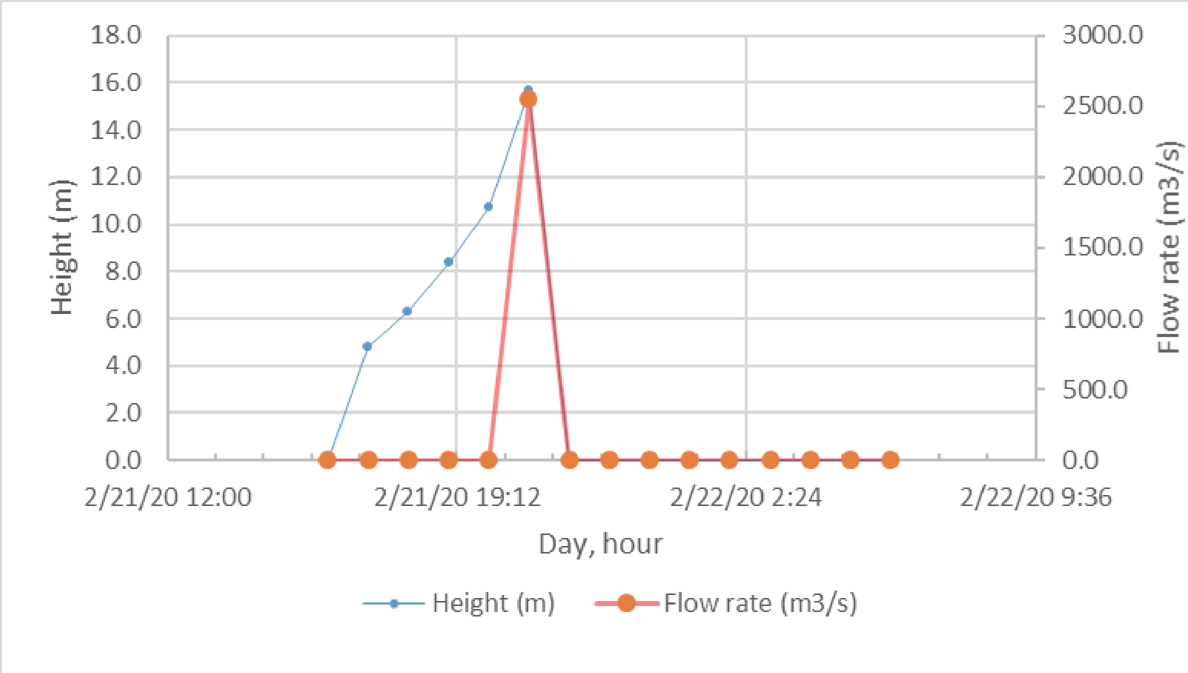

Figure 2. Hydrograph generated for the condition with embankment and dam break.

When the hydrograph shown in Table 1 is the upstream condition of the dam break simulation, the water impounded behind the embankment induces breaching of the embankment when the height reaches 15.7 m, thus generating a peak discharge of 2500.8 m^3/s.

Aerial photography was obtained using a fixed-wing drone with absolute X, Y, Z accuracy of 15 mm. GSD was 50 mm/pixel. Size of the Digital Terrain Model (DEM) elements is 0.2 m x 0.2 m. Based on the field visit and available satellite images, it has been verified that they adequately represent terrain features of Devil´s Creek and surrounding areas. The model allows to identify the streets and houses of El Mirador Human Settlement, as well as the La Florida Housing Association and a fill that was eroded by the action of the flood in February 2020. Satellites images from 2018, before the event occurred, show that the fill is in good condition, that is, the current topography reflects the erosive action of the flows that passed through the area.

To execute modeling with adequate outputs, successive adjustments were made to have outputs that represent what can happen in a series of scenarios. As part of the adjustment, larger mesh sizes (lower resolution) were tested, and the mesh size was reduced until adequate results were obtained. In the final simulations, a 1 m x 1 m mesh has been used to model the terrain in such a way that it allows representing both the natural characteristics of the terrain of the creek and the outlet, as well as the characteristics of housing associations and urban areas. affected by the flows coming from the Quebrada del Diablo. The affected areas are, mainly, the Florida Housing Association, La Rotonda (Roundabout), Grau Market and the Busl Terminal. Discharges from the ravine flowed along the Vía Circunvalación (Panamericana Sur), surrounding the Roundabout, heading south. The adjusted time interval was 0.1 seconds.

Manning´s coefficient

Estimates of the Manning´s roughness coefficients (n) for the Quebrada del Diablo were made based on field observations and recommendations of the United States Geological Survey (USGS). Manning´s coefficient was estimated at 0.035 in the river channel. The main channel is irregular, although the width does not vary significantly. The bottom has deposits of sand and gravel along its path, as well as material deposited because of the collapse of slopes. In addition to tables, the former SCS method has been used to corroborate the value of Manning's coefficient estimate.

3. RESULTS OF HYDRAULIC SIMULATIONS

The main purpose of this article is to compare the possible effects of a large flood produced by a relative intense precipitation in a creek that is dry most of the time with the actual event that was generated by damming of the same watercourse produced by an embankment which was part of an unauthorized local road. The first sub section deals with the no embankment scenario and the second subsection approaches the flood that occurred on February 21, 2020.

4.1 Event without Camiara Pass Embankment

Results of the hydraulic modeling indicate that the simulated event in the "without blockage" condition of the channel (that is, without the Camiara pass) does not generate greater flooding of the streets, as seen in Figure 3. The maximum depth within the ravine (canyon reach, upstream from the urban area) is approximately 0.20 – 0.50 m, except in a few spots where it may reach 1 m.

Figure 4 shows in greater detail the maximum depths of flooding. Depth of inundation in the flooded streets reaches approximately 0.2 m in most cases, because, although there is an acceleration of the flow immediately upstream of the entrance to the urban area, the flow is dispersed through the streets whose roadway is approximately 6 m and whose sidewalks are between 1 – 1.20 m wide. There is an area on the right bank of the creek near the exit where the sanitary landfill is located where there is an excavation where waste from the city of Tacna was being deposited. In this area there was a flooding of approximately 0.50 m. Immediately downstream of the roundabout there is a depressed area in which the accumulation of water would reach 1.8 m in the deepest section. Figure 5 shows flow velocities and they seldom exceed 2.5 m/s. It can be inferred from the hydrograph presented in Table 1 that inhabitants of the affected zone could have been warned of flooding at the beginning of the event as it took five hours to reach the peak flow, 10.9 m^3/s.

Figure 3. Output of flow depth superimposed with satellite image of the affected area for the no embankment condition.

Figure 4. Flow depths for the "No embankment" scenario.

Figure 5. Flow velocities for the "No embankment" scenario.

4.2 Event with Camiara embankment

When the upstream hydrograph of the dam break is routed through Devil´s Creek and into Tacna City, a large area is inundated at very high speeds. Figure 6 shows in more detail depths of flow and Figure 7 shows flow velocities. Near the creek mouth, where a human settlement interrupts the course of the creek, flow depths between 2.8 and 4.9 m are reached in the hydraulic simulation. This depth is sufficient to cover one or two floors. In addition, simulated flow velocities near the creek´s mouth are from 5 to 15 m/s and may even reach 35 m/s in one of the streets (shown in yellow color). These velocities that are to be further examined, can cause destruction of houses as it happened in the buildings that were closest to the creek´s mouth. Figure 8 shows destruction of a brick and concrete house where a few concrete columns remained standing. An event such the one described in section 4.1 may not have caused such destruction as the depths and velocities were not high enough.

Figure 6. Maximum flow depths of the recreation of the February 21, 2020, event.

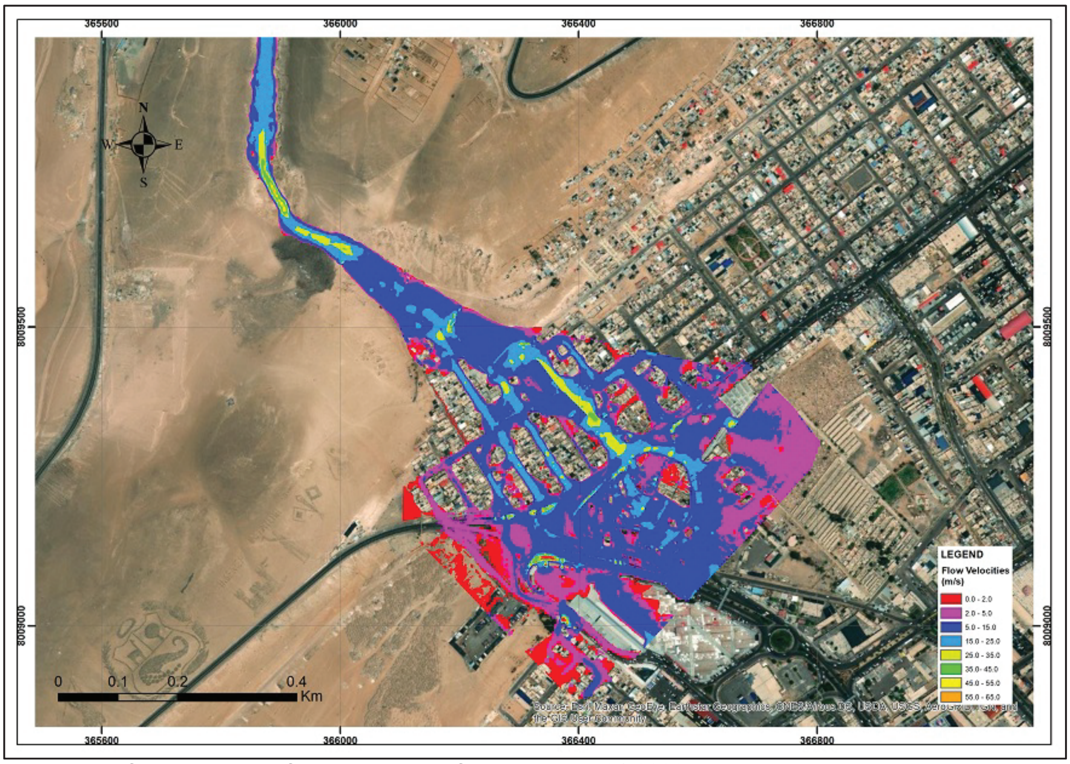

Figure 7. Maximum flow velocities of the recreation of the February 21,2020, event.

Figure 8. Houses destroyed by the February 21, 2020, flood.

The computer simulation performed using HEC-RAS 2D shows that the road embankment greatly amplified the effects of runoff in Devil´s Creek. Without the embankment a maximum flow depth in the order of 0.5 m and velocities nearing 2 m/s may have occurred along the streets near Devil´s Creek mouth. On one hand it became evident that no embankment that blocks the flow in Devil´s Creek should be built, and, on the other hand, the human settlement located near the creek´s mouth should be relocated.

4. CONCLUSIONS AND RECOMMENDATIONS

A comparison between the effects of a hypothetical flood that may have occurred without the presence of an earth embankment that eventually collapsed and with the embankment that collapsed was made. The latter was the event that left three people dead, houses, public building and infrastructure affected. The first scenario was simulated by assuming that the incoming hydrograph was routed through the creek and into the Tacna city. The second scenario was the recreation of the event that occurred on February 21, 2020. A field trip was conducted to verify site conditions and hydrologic and hydraulic simulations were performed leading to the following conclusions and recommendations:

In the scenario in which the Camiara embankment was not taken into consideration, flooding in Tacna City did not produce large inundation areas or was significantly deep. Velocities were low and the inhabitants could have been warned as runoff was first detected and it took six hours to reach the peak discharge.

The former embankment placed on Devil´s Creek played a major role in the inundation of Tacna City. Simulation of the dam break event produced results that somehow reproduce the events of February 21, 2020. High velocities and depths can cause the destruction that was observed in the area.

This investigation concludes that a small increase in precipitation led to a major disaster not because of the magnitude or intensity of the precipitation but because of the existence of an embankment that dammed incoming flows until it was overtopped leading to faster and deeper flows downstream. Therefore, no new embankment should be built along Devil´s Creek as it may constitute a hazard for the inhabitants of Tacna City.

Human settlements situated near Devil´s Creek mouth should be relocated to a safe area.

5. ACKNOWLEDGEMENTS

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