

Mitigation and prevention plan for debris flows-induced disasters in El Melocotón and San Alfonso, upper Maipo River Basin, Chile

Plan de mitigación y prevención de desastres inducidos por flujos de detritos en El Melocotón y San Alfonso, cuenca alta del río Maipo, Chile

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ABSTRACT: At the end of January 2021, a climatological event triggered numerous flows in the villages of El Melocotón and San Alfonso (Chile), causing floods, and damaging houses and public facilities. Eight months later, AFRY was commissioned by the Government to develop a mitigation and prevention plan for debris flows-induced disasters. In this paper, the main results of the project are summarized. The hazardous processes were classified as debris and hyperconcentrated flows, and its sediment volume and water flow were estimated for a 100-yr scenario. Regarding structural mitigation, at El Melocotón was recognized designed adequations of bridges to prevent the overflow and to facilitate the water discharge in Maipo River, while for San Alfonso, were not recognized protection measures for the protection of the locality. With respect to non-structural measures, the Emergency Plan is under review, as a part of the future Disaster Risk Reduction Management Plan required by Law No. 21.364. For the moment, only El Melocotón has an evacuation plan generated by the January 2021 event. Under this evaluation, a plan of structural and non-structural mitigation measures was proposed to address the recognized deficiencies. The plan was delivered as a conceptual proposal, and it was remarked that its feasibility should be evaluated at later stages.

KEYWORDS: (1) debris flow, (2) hazard, (3) vulnerability, (4) mitigation.

1 INTRODUCTION

The recent urban expansion of cities and villages toward the foothills of mountain ranges has implied an alarming proximity of populated areas to watercourses and streams prone to flooding and debris flows paths, increasing the risk to cities and villages to be exposed to hydrometeorological hazards.

A flow is defined as a rapid to extremely rapid mass movement (Cruden & Varnes, 1996) that contains water and sediment of varying size, composition, and origin, which flows confined along a channel or streambed with steep slope. The volumetric concentration of solid material with respect to the total volume of the mixture typically exceed 20% (Costa, 1988) and may include rocks, anthropogenic material (cars, houses, garbage, etc.), tree trunks, among others. Compared to floods, flows are characterized by a higher sediment concentration and, according to Muñoz et al. (2021), by an unusually high maximum discharge on its front, which result in a greater damage potential.

At the end of January 2021, a climatological event triggered numerous flows in the villages of El Melocotón and San Alfonso, in the Maipo valley, central Chile (Figure 1 and Figure 2), causing inundations by flows, damaging homes and public facilities. Eight months later, AFRY was commissioned by the Government to develop a mitigation and prevention plan for debris flows-induced disasters, based primarily on the preparation of a baseline of existing mitigation measures, identification of hazardous processes, and vulnerability characterization. Additionally, a conceptual proposal for risk management was recommended.

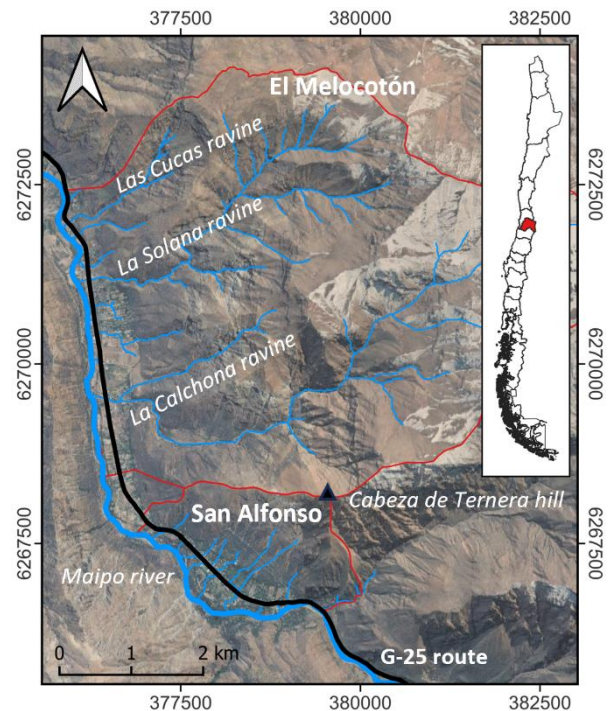


Figure 1. Location of El Melocotón and San Alfonso villages.



Figure 2. Deposits from the flow that occurred in the January 2021 event, San Alfonso. Photo facilitated by Andres Trincado, resident of El Melocotón.

2 BACKGROUND

The villages of El Melocotón and San Alfonso are located in the upper part of the Maipo River basin, situated within the Main Cordillera of the Central Andes, at the latitude of the city of Santiago (33.5 S). Administratively, both localities are part of the Municipality of San José de Maipo.

El Melocotón exhibits a considerable range in altitude, spanning from approximately 1,030 m a.s.l. in the valley floor up to 2,815 m a.s.l. at an unnamed mountain peak. Conversely, in the neighboring village of San Alfonso, the highest peak is called Cabeza de Ternera (also called Fajas Blancas or Lonko Pichi Waka), standing at around 2,130 m a.s.l. Both peaks are ant summits of the primary massif in the area called Peladeros, reaching a height of 3,902 m a.s.l.

Noteworthy is in El Melocotón, the presence of three important NE-SW ravines, called La Solana, Las Cucas and La Calchona, which drains toward the Maipo River. In San Alfonso, the configuration is quite different, there are not such big catchment as in El Melocotón, but smaller gullies on the southwestern part of the Cabeza de Ternera hill, which drain debris and mudflows originated in the higher areas.

In general, the conditioning variables for flow occurrence identified in both locations are typical of an Andean mountainous environment, such as wide basins with predominantly concave-planar relief, slopes with soil presence and scant to no vegetation, tributary channels with steep gradients and abundant available material to be removed from their bed and walls, among others.

The geology consists mainly in volcanic rocks, such as gray andesites and andesitic tuffs with a fine-grained aphanitic texture, strongly folded. Generally, all volcanic rocks outcropping in both El Melocotón and San Alfonso are associated with the Abanico Formation. Geotechnically, these rocks exhibit moderate to intense fracturing, with a hard to very hard resistance and are unaltered to slightly weathered (Thiele, 1980; Baez, 2020). Above these rocks, it is possible to observe alluvial deposits, primarily confined to the lower sections of the ravines or forming fans at the outer edges of the ravines. Additionally, colluvial deposits can be found on the foothills of these mountain slopes.

Climate of San José de Maipo is rather temperate with an average temperature of 14°C, ranging from 1°C in winter to 28°C in summer (PRC, 2018; CIREN, 2022). Two types of climates can be identified in the area: Mediterranean Temperate Climate with a prolonged dry season, characterized by the presence of a prolonged dry season and a well-marked winter with extreme temperatures reaching zero degrees (CIREN, 2022); and High-Altitude Cold Climate, which is in the above 3,000 m a.s.l., characterized by low temperatures and solid precipitation (DGA, 2004; CIREN, 2022). Most of precipitation is accounted for a few storms that occur during winter months (Aceituno et al., 2021; Valenzuela et al., 2022). Precipitations occurring between May to September could be related to a shift of the semi-permanent anticyclone over the subtropical southeast Pacific, northward, allowing the arrival of frontal systems to the continent, many of them accompanied by Atmospheric Rivers, some of them responsible of warm and heavy rain during winter (Garreaud, 2013; Valenzuela and Garreaud, 2019; Valenzuela et al., 2022). During summer, the subtropical anticyclone moves southward, preventing arrival of frontal systems to Central Chile, so rain is nearly absent from December to February (Valenzuela et al., 2022). Summer rainfall primarily results from isolated, convective storms atop of the Andes often fed by moisture sourced over the interior of the continent and the Atlantic Ocean, which can trigger localized debris flows up in the Andes (Vergara et al., 2020; Valenzuela et al., 2022). In the hydrometeorological analysis proposed by Muñoz et al. (2021) for San Alfonso stream basin (next to San Alfonso village), and in accordance with what was indicated in Gajardo et al. (2013), Sepulveda and Jara (2016), and Marín et al. (2017), it is stated that the main triggering factor for flows ("debris flows") in El Melocotón and San Alfonso basins corresponds to an intense storm (frontal system and convective storms) occurring during an elevated 0°C isotherm, generally above 3,500 m a.s.l., with a minimum value of 2,800 m a.s.l. This 0°C isotherm condition favors mass movement, as it increases the surface area for liquid water capture. Liquid precipitation can reach up to 4,000 m a.s.l. in the mountains, above the typical snowline of 2,300 m a.s.l., altitude from which precipitation is in the form of snow in winter.

It is important to remark that there are several other phenomena that affects precipitation in Central Chile, such as El Niño Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO) and the Pacific Decadal Oscillation (PDO), among others.

3 METHODOLOGY SUMMARY

This study addresses the understanding of the following two dimensions of risk:

Hazard dimension: this involved the geological, geomorphological, and hydrological characterization of the contributing basins or watersheds. Geological surface maps were presented, along with an analysis of susceptibility to generate flows, rockfalls, and soil slides within them, at a 1:10,000 scale. The typology and behavior characterization of the occurring flows within the basins were also defined, along with an estimation of debris flow volumes (Gertsch, 2011) and the calculation of the maximum flow rate for a scenario with a 100-year return period.

Vulnerability dimension: this included the estimation of the population, an inventory of threatened houses and relevant infrastructure, and the identification of current mitigation works for protection against debris flows.

In general terms, the study scope involved the revision of relevant background information, considering data provided by public authorities as well as internally gathered data. It also included a short field campaign for both locations, during which a team of specialists consisting of geologists, geographers, and hydraulic engineers complemented the information gathered in the background review.

Considering the develop of the hazard and vulnerability dimensions, a preliminary diagnosis and a disaster prevention and mitigation plan was carried out, based primarily on the preparation of a baseline of existing mitigation measures, the identification of hazardous processes, and a vulnerability characterization. As a part of the conclusion of the study, a conceptual proposal for risk management was recommended.

4 BASELINE OF EXISTING MITIGATION MEASURES

4.1 Structural Mitigation Measures

4.1.1 El Melocotón

In El Melocotón, structural measures were found at the intersection between the three major ravines with the G-25 route.

a) La Solana Bridge: It's located at the homonymous ravine. It presents a concrete box-type culvert with an upstream and downstream channel composed by a concrete bottom and a mix of concrete and mortar-grouted riprap walls.

b) El Melocotón Bridge (Figure 3): It's located at Las Cucas ravine. It is a bridge with concrete abutments, steel beams, and a concrete central pier. Riprap bank protection upstream and downstream of the bridge was recognized.

c) La Calchona Bridge: It's located at the homonymous ravine. The bridge has a steel corrugated pipe culvert with a horseshoe shape. Upstream channel banks are protected with riprap.

No mitigation works were identified further upstream of the ravines.



Figure 3. Downstream view of El Melocotón Bridge.

4.1.2 San Alfonso

In San Alfonso, seven erosion and alluvial control works were recognized on the ravines of the Cabeza de Ternera hill, to prevent erosion of the channel bed which is over the GasAndes's buried gas pipeline. Each structural measure consists of two rigid-permeable barriers to retain the sediments, and gabion walls along the ravine edge to protect the channel banks (Figure 4). San Alfonso does not have bridges for flow passage under the G-25

route. There are only small culverts incapable of allowing the passage of a flow through them.

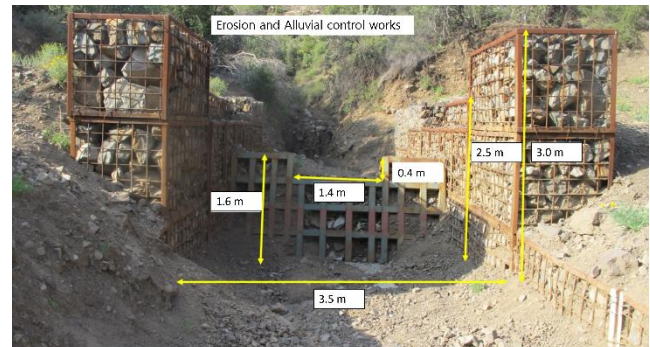


Figure 4. Erosion and alluvial control work at the Cabeza de Ternera hill, San Alfonso.

4.2 Non-structural Mitigation Measures

As of the study date, both localities do not have a municipal territorial planning instrument regulating land uses and defining risk areas within the urban limit. Only a regional territorial planning instrument (PRMS – Plan Regulador Metropolitano de Santiago) is available as an instrument containing specifically restricted or excluded areas for urban development, associated with mass movement processes; however, it operates outside the urban limit.

Regarding emergency management, the Municipality of San José de Maipo indicated that the Emergency Plan is under review, as well as the Disaster Risk Reduction Management Plan required by Law No. 21.364. At moment, the Civil Protection and Emergencies Office, under the Civil Protection, Emergencies, and Operations Directorate of the Municipality of San José de Maipo works hand in hand with the Early Warning Center (CAT – Centro de Alerta Temprana) of National Emergency Office (ONEMI – Oficina Nacional de Emergencias, currently named as SENAPRED – Servicio Nacional de Prevención y Respuesta ante Desastres) to inform forecasts and events likely to cause harm to the population, by a constant and real-time monitoring of events. Evacuation plans resulting from the January 2021 event were developed by ONEMI for the La Calchona, La Solana, and Las Cucas ravines in El Melocotón locality. Furthermore, evacuation drills have been conducted jointly by ONEMI, National Geology and Mining Service (SERNAGEOMIN – Servicio Nacional de Geología y Minería), and the Municipality of San José de Maipo. On the contrary, San Alfonso locality does not have evacuation plans, and given that flows descend through the main streets, it is noted that it is complex to develop one, and even more, there are just a few available areas that could be used as safe zones.

5 HAZARD CHARACTERIZATION

5.1 El Melocotón

5.1.1 La Solana ravine

The flows from this catchment are strongly confined to an oblique-walled alluvial channel of approximately 3 to 4 m wide and high, which are developed by erosion through the old alluvial deposits.

Additionally, the presence of boulders over the channel edge evidence a possible lateral overflow prior to the January 2021 event (Figure 5). The confined advance of the flows through the channel is lost near the La Solana Bridge, where an abrupt slope change promotes debris deposition over the route and downstream.

The recognized deposits within the ravine mainly exhibit sedimentary and morphological characteristics of debris flow and, to a lesser extent, hyperconcentrated flow. Generally, they are described as randomly subrounded to subangular rocky fragments ranging from gravel to boulder size embedded in a sandy-silty matrix. The deposit is clast-supported and consolidated to semi-consolidated. The presence of boulders with maximum size of up to approximately 2 m in their major axis is noteworthy.

In terms of sediment volume, 800 m³ has been estimated for a 100-year return period. Regarding its water discharge, for a 100-year return period, a maximum water flow rate of 16 m³/s was obtained considering a 0°C isotherm at 2,200 m a.s.l.

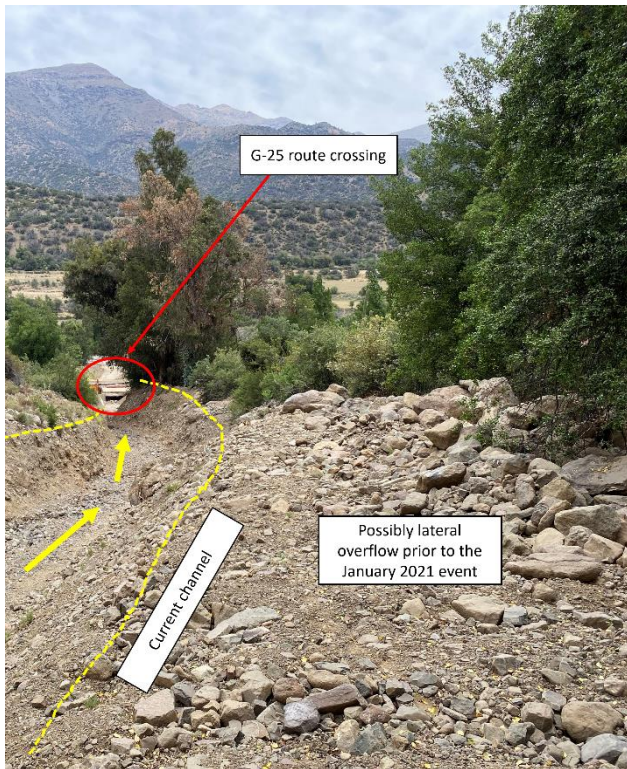


Figure 5. La Solana ravine. Downstream view of the ravine showing the current channel. A lateral overflow deposit is shown as well.

5.1.2 Las Cucas ravine

The headwater of the ravine presents hillslopes steeper than 40°, with a larger soil coverage compared to La Solana ravine. In addition, there is presence of old colluvial deposits on hillslopes with less than 30° located in the middle portion of the eastern slope of the ravine.

The ravine exhibits alluvial morphologies such as alluvial floodplains and bars, evidencing a meandering development of the stream. The ravine can reach up to 40 m in width at its meandering curves. Generally, the channel is bounded by rocky slopes, except for its middle portion, where the undercutting of the

base of ancient colluvial deposits was identified. Downstream from this undercutting, rock walls reappear on both sides of the slope accompanied by a sudden change in slope where the rock bed becomes vertical forming a waterfall. In the waterfall area the confinement is increased, which promotes local overflows. Downstream from the waterfall, the flow continues channeling with minor lateral overflows on the channel, identified by the presence of branches and sediments on the channel bank. Towards the intersection with the G-25 route, the channel bank is rocky, and there is a decrease in slope, leading to the deposition of the flow towards the Maipo River.

The deposits exhibit sedimentary and morphological characteristics of debris and hyperconcentrated flows. Generally, their deposits consist of randomly or moderately stratified rocky fragments, subrounded to subangular, gravel to boulder-sized, embedded within a sandy-silty matrix, clast-supported, with moderate consolidation. The presence of maximum block sizes of about 0.8 m in their major axis is noteworthy, as are anomalies of up to about 5 m in their major axis.

A sediment volume of 10,000 m³ has been estimated for a 100-year return period. Regarding its discharge, for a 100-year return period, a maximum water flow rate of 44 m³/s was obtained considering a 0°C isotherm at 2,200 m a.s.l.

5.1.3 La Calchona ravine

As Las Cucas ravine, its headwater presents hillslopes steeper than 40°, a larger soil coverage than La Solana ravine with both old and recent colluvial deposits on both hillslopes, and a ravine with alluvial morphologies. It corresponds to the contributing basin of the greatest extension, as well as the ravine with the greatest development of alluvial morphologies within the study.

The path of the flows from this headwater is contained by the ravine, which presents widths of approximately 10 – 20 m with maximums of 70 m at its meandering curves. Generally, the ravine maintains these dimensions until near to the end of the foothill (376,954 mE, 6,269,489 mS, Datum WGS84), where channel confinement increases and the bed of the channel becomes vertical, forming a waterfall. Sediment contribution is limited near this sector due to the presence of rocky walls. After the waterfall, the bed channel opens again to approximately 10 – 20 m, up to a natural dam formed by boulders of 1 – 4 m in size left by previous flow events. Downstream from this natural dam, the flows are channeled between banks of 4 to 5 m high. The wide of the bed channel range between 3 and 4 m. Generally, sediment contribution occurs along the flow path due to bank and bed scouring and from some recognized soil slides in the basin head.

The deposits exhibit sedimentary and morphological characteristics of debris and hyperconcentrated flows (Figure 6). Generally, their deposits consist of randomly or moderately stratified rocky fragments, subrounded to subangular, gravel to boulder-sized, embedded within a sandy-silty matrix, clast to matrix-supported, with inverse or normal gradation, and moderate consolidation. The presence of maximum block sizes of about 0.4 – 0.6 m in their major axis is noteworthy, as are anomalies of about 3 – 5 m in their major axis.

A sediment volume of 12,000 m³ has been estimated for a 100-year return period. Regarding its discharge, for a 100-year return period, a maximum water flow rate of 52 m³/s was obtained considering a 0°C isotherm at 2,200 m a.s.l.

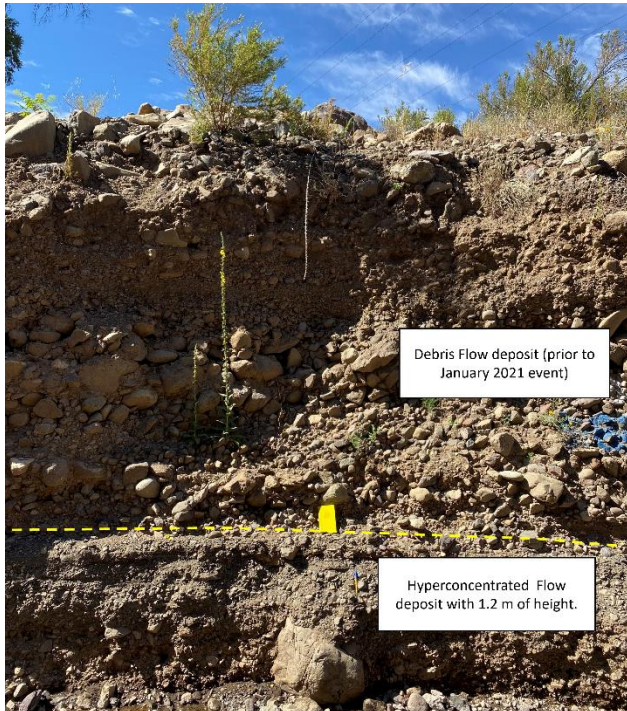


Figure 6. La Calchona ravine. Profile of sediments on an alluvial channel where pulses or events of debris and hyperconcentrated flows were recognized.

5.2 San Alfonso

A minimum of seven gullies originating from the southern slope of Cerro Cabeza de Ternera towards the town of San Alfonso were identified, that present two geomorphological dynamics.

In the western and eastern extremes (Figure 7-A), areas of soil erosion and incipient gullies were identified over the slopes, which are understood as the major sediment contributors for the flows. Generally, these slopes are steeper than 30°. The flows from these slopes descend through the gullies towards the Casa Chocolate sector (western extreme) or Viña Los Nietos (easter extreme), where the transition to a slope of less than 30° and the loss of channel confinement promote the flow deposition.

Conversely, the middle portion of Cerro Cabeza de Ternera presents gullies with greater development than those located at its western and eastern extremes (Figure 7-B). These gullies originate on rocky slopes with variable soil development and slopes steeper than 30°. From these, the flows are conveyed through channels between 3 to 6 m wide and 3 to 8 m high, which develop on hillslopes with a slope between 20 and 30°. Generally, it was identified that the banks of this channeling are oblique to subvertical and are prone to be undercut by flow events. Around 1200 m a.s.l, there is a loss of channel confinement due to the decrease in slope of the hill (less than 30°), promoting deposition of the flows.

Generally, for San Alfonso, the deposition facies of the flows have the most interaction with the community, promoting the deposition of sediments, rock fragments, debris, vegetal matter, and the passage of surface water runoff during flood events (Figure 7-C and Figure 7-D).

The deposits exhibit sedimentary and morphological characteristics of hyperconcentrated flows and debris flows. These deposits consist of randomly or moderately stratified rocky fragments, subrounded to subangular, gravel to boulder-sized, embedded within a sandy-silty matrix, clast to matrix-supported, and with moderate consolidation. The presence of maximum block sizes of about 1 - 1.5 m in their major axis is noteworthy.

Only in small watersheds the sediment volume could reach between 300 to 900 m³ for a 100-year return period. For the most prominent watershed of San Alfonso, the sediment volume could reach 2,800 and 4,100 m³, which is consistent with the larger deposits of the January 2021 event. In San Alfonso, maximum water flows with a 100-year return period ranged from 0.7 to 8.6 m³/s with an average of 2.3 m³/s, considering a 0°C isotherm at 2,200 m a.s.l.

6 VULNERABILITY CHARACTERIZATION

El Melocotón and San Alfonso are neighboring localities connected only by the G-25 route also called Camino al Volcán Avenue. The route has a two-lane bidirectional roadway. Both localities correspond to semi-urban areas that mixes agricultural lands, some of which are pleasure plots, with smaller single-family homes (PRC, 2018).

Regarding population, the Municipality of San José de Maipo has 18,179 inhabitants (Census, 2017). At a local level, San Alfonso and El Melocotón have populations of 768 and 580 inhabitants, respectively (Census, 2017). Comparing the population at a municipal level, San José de Maipo recorded a demographic increase of 4,813 inhabitants (36%) compared to the 2002 Census, well above the regional and national growth rates, showing that in just 15 years, the municipality became a population attraction center (PRC, 2018).

Respect to housing, the population of the San José de Maipo municipality inhabits a total of 6,926 homes (Census, 2017). At a local level, San Alfonso and El Melocotón have 295 and 270 homes, respectively (PRC, 2018). Due to the essentially rural condition of the municipality, it is common to find mostly low-rise construction. Regarding occupancy levels, it was estimated that up to 20.7% of homes could be seasonal residences. Houses have basic available services such as electricity and cell phone connectivity. Drinking water is resolved thanks to the Rural Potable Water (APR) and both localities lack a sewage evacuation and treatment system (PRC, 2018).

Concerning services, the educational establishments are El Melocotón Elementary School (G-638) and San Alfonso Elementary School (G-636), which are administratively dependent on the municipality. In terms of health, the municipality has three rural health posts located in the villages of Las Vertientes, San Gabriel and El Volcán. Regarding security equipment, Melocotón has the 2nd Fire Company that serves the entire municipality and is trained to respond to urban-rural interface fires.

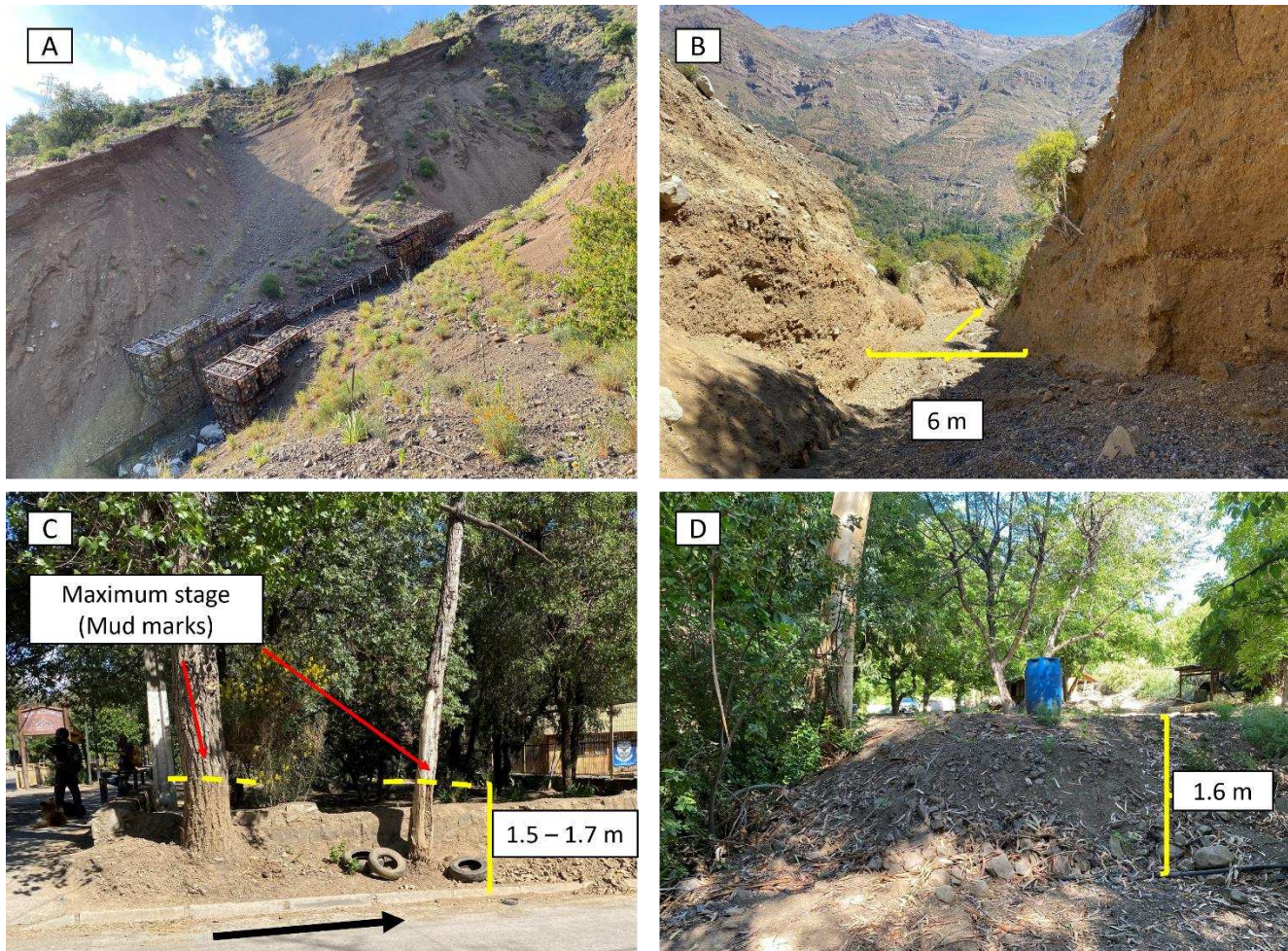


Figure 7. View of different evidence recognized for flow events in San Alfonso. A) Zone of erosion soil identified in the ester extreme of locality B) Channel in the middle portion of Cabeza de Ternera hill. The wall has a maximum height of ca. 7 m and is affected by scour processes C) Mud marks recognized in San Alfonso downtown which evidence a flow height up to 1.7 m. D) Flow deposit left in the vicinity of Viña Los Nietos.

Concerning exposure and vulnerability during the January 2021 event, we can say that the damage was focused on the G-25 route and bridges crossings. Particularly, La Solana ravine corresponds to the most critical zone, here, El Arenal sector, a place with precarious housing with lightweight material, was affected by the runoff flow of the January 2021 event (Figure 8-A and Figure 8-B). Around Las Cucas ravine, there are exposed highly vulnerable installations, such as the elderly home foundation Las Rosas situated outside the urban limit northward, on the ravine edge (Figure 8-C). It is also noteworthy that various tourist businesses were identified around La Calchona ravine increasing the exposure. In general terms, strategic infrastructure such as the bridges and G-25 route was exposed to the flows of the ravines in study.

For San Alfonso, evidence of at least three flows were recognized, where the paths followed the course of streets and avenues such as Carmen Grossi and Bernardo O'Higgins streets (Figure 8-D and Figure 8-E), covering a large part of the populated area, affecting housing, equipment, and infrastructure. Sports and

social equipment, such as San Alfonso Development Corporation, were also exposed to this event. The soccer field was affected, as well as part of San Alfonso square. Parallel to the G-25 route, there are also sewer pipes that do not have sufficient capacity to allow optimal flow and water passage, causing obstructions. Damage was widespread throughout the locality (Figure 8-F).

7 DIAGNOSIS AND MITIGATION RECOMMENDATION

Based on the inventory of infrastructure, housing, and its association with historical flow events, it can be identified that, in general, infrastructure is exposed to threat conditions from flows. Additionally, there is important equipment due to its role as a facilitator or supporter during emergencies, known as essential facilities (e.g. healthcare, education equipment), which is also exposed to these types of threats; this is mainly observed in San



Figure 8. A) Mud marks on house in El Arenal sector. B) On the side of La Solana ravine, there are precarious houses of light material in an informal settlement. C) Elderly home foundation Las Rosas situated outside the urban limit to the North, next to Las Cucas ravine. D) Mud marks and deposits inside a house, upstream Bernardo O'Higgins avenue. Deposits exceeding 1.5 m in height. E) Damage observed on house due debris/hyperconcentrated flow impact. F) Reconstruction of houses devastated by flows of January 2021.

Alfonso locality. What is relevant to consider is that this locality does not have evacuation plans and there are very few available areas that could be used as safe zones. In addition to the above, El

Melocotón only has mitigation measures where the G-25 route crossings with La Solana, Las Cucas, and La Calchona ravines. These crossings consist of concrete abutments or steel corrugated

pipe culverts and concrete and/or riprap walls upstream and/or downstream of the bridges. The objective of these current mitigation works is to prevent erosion and increase the capacity of discharge of the channels near to the bridges. No structural mitigation works were found in the upper parts of the ravines. On the other hand, in San Alfonso, the G-25 route does not have bridges, culverts, or channels that allow the discharge of flows to the Maipo River. However, it has seven erosion and alluvial control works at the intersection of the GasAndes's buried gas pipeline with some ravines. These current mitigation works were designed to protect the buried gas pipeline from undercutting that could occur in the ravines during intense precipitation events. Although these works retain sediments, they do not have the necessary capacity to contain flows like those of the January 2021 event.

Given this understanding of the current situation, a plan of structural and non-structural mitigation measures was proposed to address the recognized deficiencies.

Respect structural mitigation measures, in El Melocotón the strategy aims to ensure that flows pass safely under the bridges without causing overflow. For this purpose, we proposed mainly bridge design adjustments and, in some cases, a riprap installation upstream of the bridges, on the ravine's edge to prevent erosion. In San Alfonso, the structural mitigation strategy was more complex, there is a limitation on the available space on which to build mitigation works without causing harm to the community. The focus of structural mitigation works in San Alfonso should be a mix of active and passive structural mitigation, aimed to reduce the possibility of flow generation, or once these occur, to reduce the volume flow and/or redirecting them safely through the locality to discharge into the Maipo River. For this purpose, slope reinforcement to prevent sediment contributions, diverting and containing walls that allow flow discharge to established sectors are proposed. The option of retention systems like flexible barriers or sediment traps was included only at an idea level, as preliminary estimates indicate a low performance compared to the cost these measures entail. The volumes of water and sediment delivered in this study can help to size the first sketches of these protection systems.

Respect to non-structural measures, it was recommended to close as soon as possible the development of a municipal territorial planning instrument that allows the identification and the regulation of the risk zones. In this sense, it is urgent to develop a tool that allows the recognition of the regional risk zones of the PRMS and to detail them at a local level, the use of planning criteria, the postponement of building permits, and the protection of vital lines and essential buildings. It was also emphasized that both structural and non-structural measures must be accompanied by an educational and awareness campaign that allows the understanding the risk to which society is exposed, as well as acting preventively (e.g., an emergency evacuation plan) and being prepared for an emergency (e.g., coordination between the community and institutions).

8 CONCLUSIONS

The villages of El Melocotón and San Alfonso are in an Andean mountainous environment where natural conditions for flow occurrence exist. As a general characterization, flows exhibit sedimentary and morphological characteristics of debris flow and hyperconcentrated flow.

For El Melocotón, flows are mainly channelized, and the risk is focused on the G-25 route and bridge crossings. Although it process is localized, the flows could affect exposed and highly vulnerable sectors such as El Arenal (precarious housing) or the elderly home foundation Las Rosas. For San Alfonso, is expected that the damage will be widespread throughout the locality, where the flow-paths follow the course of streets and avenues such as Carmen Grossi or Bernardo O'Higgins streets.

Regarding structural mitigation, El Melocotón presents adequations on its bridges to prevent the overflow and facilitate the water discharge into Maipo River, and in San Alfonso, permeable barriers were recognized on the hillslope of the Cabeza de Ternera hill to prevent erosion of the channel bed, which is over the GasAndes's buried gas pipeline. Mitigation measures currently built for the protection of San Alfonso were not recognized.

Although the Emergency Plan as well as the Disaster Risk Reduction Management Plan required by Law No. 21,364 is under develop, is noteworthy the existence of the emergency plan generated as a consequence of the January 2021 event thanks to the joint effort between ONEMI, SERNAGEOMIN, and the Municipality of San José de Maipo.

Under this evaluation, AFRY proposed a plan of structural and non-structural mitigation measures to address the recognized deficiencies. The plan was delivered under an idea-level concept, and it was remarked that its feasibility should be evaluated at later stages.

9 ACKNOWLEDGEMENTS

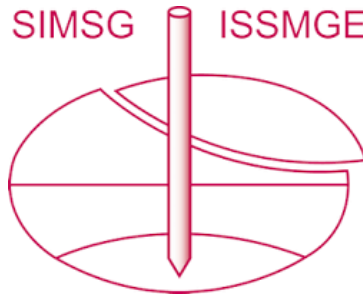
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