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Impact of Erosion, Mass Wasting, and Sedimentation on Human Activities in the Río Grande Basin, Jujuy Province, Argentina

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Abstract

Nearly all dry mountainous regions are affected by severe erosion, floods, and debris flows during times of intense precipitation. The lithology, geologic structure, and climate in Jujuy Province, Argentina combine to place at serious risk the people who live along the Río Grande, the major river that drains the east side of the Cordillera Oriental and the west side of the Sierras Subandinas. Nearly all precipitation falls during summer (January–March) with little during the remainder of the year; most of the basin is semi-arid to arid, although the southern end has a humid subtropical climate. Relief is great, as much as 4,000 m in 15 to 20 km, and the streams that drain the mountains have high gradients. Rapid runoff during the wet season changes the Río Grande, nearly dry most of the year, into a torrent that erodes bridge abutments and floods the valley floor. Precambrian-age low grade metaclastics shatter in the frost climate of the higher mountains and become source material for debris flows that damage or bury roads, railroads, and houses. Poorly consolidated deposits of late Tertiary rocks and Quaternary deposits along the sides of the valley erode readily and yield large volumes of sediment in addition to that coming from higher parts of the basin.

These processes are common to all rivers that drain mountainous regions, but lack of understanding of the geomorphic regime of the rivers has led to unexpected hazardous conditions that are expensive to correct. Most communities are along transportation routes that follow the river. Many bridges and levees are inadequately designed for the high runoff rates and sediment load, thus are frequently damaged or destroyed. Dam construction causes aggradation upstream and scouring downstream. Housing in the city has expanded onto the floodplain; flood walls to protect the residents of these “barrios de emergencia” constrict the channel. Application of adequate geomorphic and geologic information provided prior to new construction may reduce the costs of future repair.

Introduction

Debris flows and floods take place every summer, the time of the year of greatest precipitation, in the Río Grande basin of Jujuy Province, Argentina, which lies between 23°38' and 25°30' South Latitude and 65°00' to 65°45' West Longitude (Figure 1). The Río Grande is a major stream that drains the east side of the Cordillera Oriental and the west side of part of the Sierras Subandinas (Figure 2). In this region, not only do the processes of erosion and sedimentation have a major influence on human activities, but some of the changes made by man exert a significant effect on erosion and sedimentation. More than 225,000 people live in the region, at least 10,000 of whom are at serious risk of being flooded by high water or being buried by mud and debris flows during the wet season. This stream behavior is typical of the region along the eastern margin of the Puna, the high plateau that is the southward extension of the Altiplano of Bolivia and Peru (Figure 1), but both geologic factors and human activities cause local variations in these processes.

The Cordillera Oriental is a segment of the Andean Chain that extends southward from Peru through Bolivia to near the city of Tucuman in Argentina. In northwestern Argentina, it stands on the east flank of the Puna. It consists of a series of large *en echelon* folds, with Precambrian-age rocks of low metamorphic grade cropping out in the cores of the anticlines beneath folded sedimentary strata of Cambrian, Ordovician, and Cretaceous age. North of the provincial capitol, San Salvador de Jujuy, steep slopes and streams that are deeply entrenched in the folded and fractured rocks are typical of the Cordillera Oriental. Southward from the capitol city, however, the terrain is smoother. The two mountain ranges bifurcate, and the eastern range is part of the Sierras Subandinas.

Figure 1. Map of Jujuy Province, Argentina, showing boundaries of the morphostructural regions of the province and the locations of the Río Grande drainage basin.

A line of high angle reverse faults separates the Cordillera Oriental from the Sierras Subandinas (Turner and Mon, 1979). The Sierras Subandinas are part of a mountainous belt more than 1,500 km long and almost 100 km wide that extends northward from Tucumán through Bolivia and into southern Peru. It is a zone of complex folding that became active during the Pliocene (Mingramm et al., 1979) and continues to rise.

The purpose of this report, which is based on observations of the authors from 1980 to 1994, is to present an examination of hydraulic processes in the parts of the Cordillera Oriental and Sierras Subandinas that make up the basin of the Río Grande and that frequently have disastrous effects on the human environment. Not only do the natural geomorphic processes of mass wasting, erosion, sediment transport and deposition, and flooding cause damage, injuries, and deaths to inhabitants of the basin, but human activities undertaken without adequate understanding of the geology have also altered geomorphic conditions and processes, often resulting in even greater damage. These natural phenomena are repeated every summer, the period of the year with greatest precipitation.

Physical Processes That Influence Mass Movements, Erosion and Sedimentation

The more significant geologic factors that contribute to the processes of the mobilization of sediments and the resulting earthflows, mudflows, debris flows, floods, and stream erosion are a) physiography, b) hydrography, c) geologic structure, d) lithology, e) magmatism, and f) tectonism. In addition, human activities that impact the natural system include a) development of transportation routes, b) engineering works to increase availability of water resources, c) urbanization, and d) agricultural activity.

Physiography

The basin of the Río Grande consists of two distinct areas based on climatic characteristics, vegetation, geology, and relief. The part of the basin that lies north of Barcena (24° South Latitude) is characterized by low precipitation, with isohyets of 200-250 mm, sparse vegetation, and a high temperature range. It has a semi-desert climate, but some valleys experience a milder

Figure 2. Drainage basin of the Río Grande of Jujuy Province. Locations of Perchel narrows (P) and Yacoraite narrows (Y) shown by encircled letters (compiled from maps, scale 1,250,000, Instituto Geografico Militar de Argentina, 1990).

microclimate. Southward from Barcena, the region is characterized by abundant precipitation, which can reach an average annual value as great as 1,550 mm, and lush subtropical vegetation.

Two mountain belts oriented approximately north-south bound the region. The eastern mountain ranges are the Serrania de Zapla, Sierra de Zenta, and the southernmost end of the Sierra de Santa Victoria. The western side consists of the Sierra de Aguilar and the Sierra de Chafii (Figure 2). Of these, all except the Serrania de Zapla are part of the Cordillera Oriental; the Serrania de Zapla is one of the Sierras Subandinas.

Altitudes generally increase from east to west and from south to north. The maximum altitude, however, is 5,896 m along the divide at Nevado del Chafii, located in the southwest part of the region; the minimum elevation is the mouth of the Río Grande at San Juancito, 447 m above sea level. The relief of the area is great, as much as 4,000 m in a distance of 15- 20 km.

Drainage

The basin of the Río Grande is drained by more than 60 water courses that empty water and sediment into the principal channel. The shape of the basin is roughly rectangular with a north-south orientation; in the southern end the river flows toward the southeast (Figure 2). The regional position and orientation of the tectonic blocks (Figure 3) have controlled the shape of the basin (Chayle and Aguero, 1987). The profile across the basin is asymmetrical; streams entering Río Grande from the east are shorter than those that enter from the west (Figure 4). Streams entering from the west range in length from 20 to 90 km. Most of the tributaries from the east are less than 20 km long. A few, however, are longer; one (Río Calete) is as long as 60 km.

The surface area of the basin is about 7,250 km², and total length of the streams is approximately 1,900 km. The principal stream, Río Grande, heads at the extreme north end of the basin, empties to the southeast, and is 250 km long. From Tres Cruces, at an altitude of 3,707 m, the channel descends 3,260 m in elevation to San Juancito for an average gradient of 0.013 *mlm*. The valley floor is wide except in some of the "narrows," where it is little wider than the channel. The valley width depends on the type of rock that the river has cut through. The Perchel "narrows," for example, is quartzite; at the Yacoraite "narrows" the rock is graywacke (Figures 2 and 3). Less resistant rocks are present where the valley widens.

Mean discharge of the Río Grande, measured at the downstream end of the basin, is 7.800 m³/sec. Maximum discharge is 121 m³/sec and minimum discharge is 0.700 m³/sec.

The valley drained by the Río Grande is youthful. Called the Quebrada de Humahuaca, it was a series of separate tectonic basins during the Late Tertiary and Early Quaternary, into which streams draining the mountains that rise to the west deposited thick sequences of alluvial fan and lacustrine sediments (Figure 5). The Río Grande eroded through the barriers that separated the individual basins and now form the "narrows" in the valley to become a single integrated stream only in mid to late Quaternary time. Holocene erosion of these poorly consolidated sediments on the sides of the valley has resulted in deeply entrenched streams and in many places, badland topography.

Geology

Structure

Elongate tectonic blocks with longitudinal to sub-longitudinal orientation, bounded along their margins by faults of similar alignment (Figure 3), characterize the region (Turner and Mon, 1979; Chayle and Aguero, 1987). In addition, the beds are folded with longitudinal to sublongitudinal axes. Faulting dominates over folding, and jointing is important because it forms blocks of rock that can be weathered more readily. The region exhibits these structural characteristics because it underwent repeated diastrophic phases throughout its geologic history (Mon et al., 1993). These structures become less evident southward, where a cover of Cenozoic sediments masks a large part of them.

Lithology

Rocks that crop out most extensively in the basin, in order of abundance, are Paleozoic, Cenozoic, Proterozoic, and Mesozoic, in age. Clastic rocks dominate and chemical rocks are proportionally less important. Relative to these, magmatic rocks are insignificant. The Precambrian-age rocks consist of graywacke, slate, quartzite, and schist, which are cut by veins of milky quartz. Limestone is present in the Precambrian sequence along the Río Grande toward the south. Cambrian-age rocks are sandstone and shale. Post-Cambrianage Paleozoic rocks are represented by beds of silicified sandstone, shale, graywacke, conglomerate and some limestone. Rocks of Mesozoic age include well cemented sandstone, some of it calcareous, and limestone with intercalated beds of sandstone. The Cenozoic rocks consist of weakly consolidated clayey sandstone, some beds of sandy limestone, and deposits of conglomerate and mudstone. The Precambrian, Paleozoic, and Mesozoic (Cretaceous) rocks crop out in bands elongated from north to south, whereas the Cenozoic sediments are restricted to topographically low sections, generally along the principal drainage line of the basin.

Figure 3. Generalized geologic map of the basin of the Río Grande (adapted from Chayle and Agüero, 1987); P = Perchel narrows; Y = Yacoraite narrows.

Figure 4. Topographic-structural profile across the Río Grande basin through Maimará..

Magmatism

Outcrops of igneous rocks are insignificant. Intrusive rocks are represented by granite (Halpern and Latorre, 1973; Amengual and Zannetini, 1974; and Mendez, 1974). Dikes and lava flows are among the volcanic rocks of the Upper Precambrian-Lower Cambrian Pampean Cycle of tectonism and sedimentation (Acefiolaza and Toselli, 1984; Turner and Salfity, 1977; Chayle and

Coira, 1987; and Manca and Coira, 1987). Beds of volcanic ash are also present in the Tertiary sediments. The contact zone adjacent to magmatic rocks was altered when they were emplaced, and the alteration facilitates weathering. In some places, hydrothermal processes have been significantly involved in the present condition of the sediments.

Figure 5. Cliffs of Pleistocene sediments deposited by concentrated stream flow and debris flow that form part of the alluvial fan of the Río Purmamarca on the west side of the Río Grande.

Tectonism

Between the close of Precambrian time and the end of the Ordovician, the marine rocks of the region were subjected to tectonic processes. The region then remained above sea level until late Mesozoic time. The late Mesozoic submergence was not a true marine invasion. It was basically continental, continuing to the late Tertiary, when reactivation of the Andes resulted in deposition of additional sediments. Periglacial climatic conditions and increased effective precipitation during the Pleistocene glaciations generated significant accumulations of sediments, principally as debris flows. Thick beds of Pleistocene debris-flow sediments and coarse gravel deposited by concentrated streamflow accumulated as alluvial fans and now stand . above the west side of the Río Grande valley near Purmamarca (Figure 5). Erosion of these sediments provides some of the heavy debris load of the Río Grande and its tributaries today. Neotectonic activity in the region has regulated the conditions of erosion, sedimentation, and modification in the drainage net of the basin (Chayle and Chalabe, 1990) and will continue to do so in the future. Sierra de Zapla is an example of this activity. Its rise results from E-W compressive forces (Mon et al., 1993), the consequences of which are clearly evident in the Quebrada de Tumbaya Grande, where one can see highly folded sediments of Plio-Pleistocene age, truncated alluvial cones, and faults produced by the compressive forces pushing toward the west (Chayle et al., 1990).

Geologic and Geomorphic Processes

The tectonic setting, lithologic character of the rocks, and climatic conditions combine in the Río Grande basin to make large amounts of sediment available to be transported following the intense rainfall that takes place early each summer. Weakly consolidated Upper Cenozoic sediments yield the greatest volume of material eroded and carried to the Río Grande. The phyllites and slates of Precambrian age, and the shales, sandstones and limestones of Paleozoic and Mesozoic age are better consolidated than the sandstones and shales of Cenozoic age, but their present integrity depends on the extent to which they have been altered tectonically by faulting, folding, and jointing. The Santa Victoria Group (Ordovician) includes thick beds of shale that break down to yield materials that are readily mass-wasted on steep slopes and road cuts. The Puncoviscana Formation (Precambrian), which consists largely of low grade metamorphic slates and phyllites, forms the crests of the ranges in the Cordillera Oriental. These rocks are subjected to severe frost weathering in the periglacial region, which breaks them down into angular rock fragments in a silt and sand matrix that covers many of the upper slopes and ~accumulates in hollows in the heads

of first order streams. Intense storms during the summer, when these accumulations become saturated, turns them into a dense fluid that becomes a destructive debris flow where it reaches a populated region. Annually, debris flows derived from the Puncoviscana slates and phyllites in the mountains to the west bury the highway and rail line that was built across the distal edge of the alluvial fan of Ao. del Medio (Figure 2; González Díaz and Fauque, 1987). In 1983, a destructive debris flow buried the community at Purmamarca station. No deaths resulted, but occupants of some houses were forced to cut holes in their roofs to escape (Figure 6).

The gradient of the Río Grande is high; where it enters a constriction, however, its velocity slows and some of the sediment load of the river is dropped above the constriction, reducing the gradient in that reach. Where it leaves the constriction, though, the increased velocity of the water scours the bed, thus steepening the gradient of the bed of the stream. The constriction, thus, serves as a "leaky dam," slowing the water that approaches it so that much of the load is deposited on the upstream side of the "narrows." The discharge passes rapidly through the constriction with a higher gradient, then, having dropped much of its load on the upstream side, scours the bed and picks up a new load within a short distance downstream from the constriction.

Just upstream from the Perchel narrows (Figure 2), the gradient of the river bed is 0.0105; below this narrows it steepens to 0.163 m/m (Chayle and Agüero, 1987). The channel narrows abruptly again at the Arroyo del Medio fan (Figure 2), where debris flow sediments from this stream block the Río Grande nearly every summer. This constriction serves as a local base level, and the gradient of the river on the upstream side of the constriction is 0.008. After the temporary blockage has been removed by erosion, base level falls and gullies cut rapidly into the sediments that accumulated. Where the channel emerges from this blockage, its gradient increases to 0.047. The greater velocity of the water provides the energy needed for the river to transport huge quantities of coarse sediment during times of high discharge (early summer). A similar situation exists wherever a man-made barrier constricts or blocks the flow of the river.

Impacts on and by Human Activity

Human activity exerts a notable influence on the behavior of fluvial action and, as a consequence, affects the processes of erosion, mass movement, and sedimentation in the Río Grande basin. The appearance of unplanned housing on land unsuited for intensive use is one of the characteristics of many developing countries, including Argentina. Unstable slopes and the floodplains of rivers frequently are utilized in this way,

Figure 6. House along National Route 9 at Purmamarca station that was buried during the March 1983 debris flow. Occupants escaped through hole they cut in roof.

particularly by people of little means. San Salvador de Jujuy is no exception, and such “barrios de emergencia” have spread across some of the land immediately adjacent to the Río Grande, which passes through the city. Upstream, modification of the stream’s regime by construction activities (bridges, road beds, and dams) has created hazardous conditions for communities that were originally secure from flooding.

Transportation Routes

The most important access to the Puna, the northern part of the Province of Jujuy, and Bolivia are National Route 9 and the railway line, both of which follow an historic trade route, the Quebrada de Humahuaca. These are important for commercial activity and contact with the population centers, as well as for transport of mineral and agricultural products. Unfortunately, both the highway and the railroad were built throughout the length of the valley on terraces, across alluvial fans, and, in some places, on the floodplain itself. Because both transportation routes were placed along the side of the river, many engineering works were needed, but most of them were constructed without consideration or understanding of the magnitude of sediment movement in rivers like the Río Grande. Bridges, culverts, and flood protection structures generally were inadequately

built for the volume of sediments carried by tributary streams; thus structures were destroyed or buried (Figure 7). The large volume of sediments flushed each year onto the alluvial fan of Arroyo del Medio, which forces the channel of the Río Grande against the east wall of the valley, regularly blocks or buries both the highway and the railroad beneath debris that is carried from the upper part of the basin (González Díaz and Fauque, 1987). For the purpose of protecting the routes from erosion or sedimentation along the Río Grande itself, flood protection barriers and debris-flow diversion structures of rock or concrete were installed, but the force of the debris-laden river damaged them as well as the routes and buildings these structures were built to protect. At the same time and with the intent of improving roads, several ramps extend across a large part of the river plain, thus making a shorter bridge possible but also constricting the channel of the river (Figure 8). During periods of high flow, currents sometimes erode the ramps leading to bridges, halting traffic until they can be repaired.

Even though these engineering works temporarily solved some problems, in the longer view, the changes they made turned out to be damaging. The engineering works not planned correctly have brought about a disequilibrium in fluvial processes in the tributaries and main channel, with disastrous consequences in the rates of erosion and sedimentation.

Figure 7. Bridge on National Route 9 over Ao. Incahuasi. Debris-flow sediments bury the bridge and the railroad at this location almost annually; both must be reopened by excavation.

Water Resource Developments

The most important engineering work along the Río Grande is the Los Molinos Dam (Figure 9), an earth fill structure with concrete spillway that was constructed immediately downstream from the mouth of the tributary Río Reyes in 1978–1979 to divert water for irrigation. Construction of the dam and impoundment of water changed base level so as to cause an increase in sedimentation upstream, not only along the Río Grande but also along its tributaries. Because of this, the bed of the Río Reyes began to aggrade at the rate of 40 cm per year (Aguero, 1986). As a result of the aggradation after construction of the dam, the channel of the Río Reyes has risen so significantly that the community of Villa Jardín de Reyes now lies below the level of the bed of the tributary, and floodwater and debris submerged the railroad bridge regularly (Figure 10A) until recently, when the bridge was raised more than 2 m (Figure 10B). Release of unloaded discharge below the dam is causing serious erosion downstream along the Río Grande, and installation of energy dissipating structures was necessary recently at the base of the dam to prevent its collapse (Figure 9). This demonstrates that engineering works undertaken without adequate planning, and an understanding of the surficial geologic processes that are involved, in addition to loss of efficiency of the

structures, can require expensive maintenance work to preserve them.

Urbanization

Urban development along the Río Grande includes at least 12 population centers; the largest of them is the capitol of the province of Jujuy. As a result of the increase in human population, many new houses have been constructed in locations that are subject to floods. This has resulted in the need to erect protective barriers. Those installed are concrete barriers and earthen walls that have confined the river to a more narrow channel through some reaches. The sediment-laden water in the main channel spreads, dumping much of its load where it leaves the confined zones. This unexpected diversion of floodwater and sediment has caused destruction of houses that are located at the same level or below the bed of the river.

At the mouth of Arroyo Volcán, which drains the north side of the spectacular alluvial cone of Arroyo del Medio described by Harrington (1946), Monteverde and Kittl (1969), and by González Díaz and Fauque (1987), debris-flow sediments plugged and blocked temporarily the channel of the Río Grande (Figures 2 and 11). This natural dam resulted in the inundation of the village of Volcán, which is located on a low terrace

Figure 8. One of bridges over the Río Grande near León, where the embankment extends across much of the floodplain and constricts the channel greatly during periods of high discharge.

Figure 9. Los Molinos dam on the Río Grande. The row of barriers was installed at the toe of the dam to reduce the velocity and erosive power of the unloaded water discharged from the outlet works.

Figure 10. Railroad bridge over the Río Reyes. Before construction of Los Molinos dam, this bridge stood more than 3 m above the channel. A) January 1986: the channel has aggraded to the level of the railroad grade, and floodwater covers the track. B) March 1994: The railway bridge was raised more than 2 m so that it clears floodwater and sediment.

just upstream from the junction of the two streams. In order to reduce or avoid future flooding, the natural opening cut by the river through the sediment plug was enlarged and deepened, which lowered base level and caused the river to erode rapidly. As a result, increased headward and lateral erosion into terrace sediments

upstream along the Río Grande places part of the village of Volcán at risk of being destroyed, because rapid headward erosion is now taking place in the lacustrine and alluvial sediments within a few meters of the village. Emplacement of rip rap or other protective barriers such as gabions will be needed to prevent future

Figure 11. Río Grande downstream from the Arroyo del Medio fan (visible in background). Debris-flow and hyperconcentrated floodwater sediment destroyed this 4-km long segment of highway and railway in January 1986.

A) January 1986: Road, railroad, and protective barriers destroyed; a one-lane emergency route cut into slope above the floodplain carries traffic around damaged segment.

B) January 1987: Road, railway, and protective levees repaired; new route cut into slope being improved. Road cuts above new route are in steeply dipping shale (Santa Victoria Formation) which erodes readily to form debris cones on the road.

C) January 1994: Original roadbed now abandoned; route cut into slope above river has been widened to a 2-lane road to carry year-round heavy traffic. Rail line still in use.

damage to buildings from erosion of the unconsolidated sediments.

In addition, sediment is accumulating downstream from the enlarged opening near Volcán, where debris-laden floodwater damaged seriously both the highway and the railroad. Both the railroad and the highway have been rebuilt, but in order to maintain traffic flow on this important route, a high water emergency road was carved into the valley wall after a debris flow ruptured the floodwall and destroyed both the railroad and the highway in January 1986 (Figure 11A). During the ensuing years, the emergency road has been improved to carry two lanes of traffic, thus allowing the old road to be abandoned (Figure 11B and C). The new road is well above the floodplain, thus free of danger of flood damage, although accumulation of debris where the road cuts through shale must be cleared occasionally.

Agriculture

From the north end of the basin to León (Figure 2), the introduction of trees and the installation of floodwall structures to protect cultivated land have also contributed to disequilibrium of the profile of the Río Grande or its tributaries. In many cases, reliance on these safeguards resulted in loss of everything, because the structures turned out to be inadequate for the magnitude of the torrents. Geologic characteristics of the valley are different south of León, where cultivated areas are much more extensive and mechanized agriculture is very important. First, removal of trees in wide areas leaves the soil unprotected from erosion; secondly, the mechanization compacts the subsoil, which slows normal infiltration of both rainfall and streamflow. This reduction of permeability slows infiltration of water, thus increasing the possibility of flooding, and increases surface runoff, resulting in sheet erosion of soil, with the sediments being deposited in the channels.

From León northward, cultivated fields lie along both sides of the Río Grande; southward, however, nearly all the cultivated land lies between the tributaries along the west side of the river. Construction of the highway, National Route 9, has placed a physical barrier on the floodplain surface, and compaction of sub grades in the building of the road has reduced the permeability of the thin layer of alluvial sediments beneath the roadbed. The presence of the road thus impedes the flow of water from higher levels, so, some land along the route thus becomes flooded that formerly had been cultivated. Installation of additional drainage culverts beneath the highway route in places where such flooding is most common probably would alleviate some of it.

Conclusions

Whenever natural geologic and geomorphic processes, such as those that have taken place along the Río Grande, damage a populated area, the social and economic costs are high. Even though no deaths may result from a particular flood or debris flow on the river, the repeated expenses of repairing damage to structures and living quarters and providing help to those displaced by the event become a serious drain on both public and private resources (Jovel, 1989). We cannot predict when such events will take place, and to move large segments of the population away from the areas of risk may be impossible. We can, however, by acting on an understanding of the geomorphic processes involved, reduce the numbers of people who build houses in potentially hazardous sites. We can also do a better job of helping engineers in the planning stages of projects, so that they neither under-design nor over-design structures. Had adequate geomorphic knowledge and geologic data been available to the engineers who planned some of the structures that have been damaged along the Río Grande, it may have been possible to reduce significantly the extent of damage.

A careful airphoto analysis of the slopes and the drainage basin above a project generally will allow a geomorphologist to determine the area where large volumes of weathered debris have accumulated that are likely to become mobilized during a severe storm. After the identification of susceptible areas, construction of preventive or diversion devices often can stop or slow a debris flow before it gains destructive momentum and size. Where it is impossible to avoid or prevent construction on sites likely to be damaged by debris flows, installation of drains in colluvium-filled swales above populated fans often will prevent instability (Montgomery et al., 1991), and debris fences or dams high in ravines below debris-filled hollows may catch or deflect the moving sediment so that damage is reduced or prevented. Deflection walls can be installed to protect individual structures from small debris flows (Hollingsworth and Kovacs, 1981). Because some of the more intense and destructive debris flows (i.e., Purmamarca, 1983) have coincided with the El Niño! Southern Oscillation event, costs of repair may be minimized if protective measures in the most susceptible basins can be in place in advance of the return of this phenomenon.

Where geologic and geomorphic maps exist, they can be used to prepare derivative maps that define areas or zones where processes take place like the ones that have regularly caused damages in the Río Grande basin. Although the cost of the preparation of such maps may seem high, that expense is repaid manyfold in regions

where good maps are available and used by those responsible for the design and placement of engineering works and by those who plan urban developments. Because the costs of remediation to protect structures and communities already in existence are high, avoidance of areas likely to be damaged by these natural geomorphic processes is the most desirable and least expensive way to reduce damage to future structures.

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