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Economic Impacts of Rapid Glacier Retreat in the Andes

PAGES 261, 264

In the Andes, runoff from glacierized basins is an important element of water budgets, assuring year-round flows for agriculture, potable water, power generation, and ecosystem integrity. Thus, changes induced by tropical glacier retreat constitute an early case of the need for adaptation and the type and size of associated economic and social impacts caused by climate change.

Field observations and historical records have been used to document the current pace of glacier retreat in the Andes [*Francou et al.*, 2005]. This retreat is consistent with upward shifts in the freezing point isotherm and coincides with an overall warming of the Andean troposphere [*Kaser,* 2001; *Francou et al*., 2003]. Modeling work and projections indicate that many of the lower-altitude glaciers in the cordillera could completely disappear during the next 10–20 years [*Bradley et al*., 2006; *Ramírez et al.,* 2001].

Tropical glaciers (located between Bolivia and Venezuela) covered an area of over 2940 square kilometers in 1970 but declined to 2493 square kilometers by 2002 [*Kaser and Osmaston*, 2002]. Many of the smaller glaciers (less than 1 square kilometer in area) have already declined in surface area, and most are likely to disappear within a generation. For example, Bolivia's Chacaltaya glacier has lost most (82%) of its surface area since 1982 and may completely melt by 2013 [*Francou et al*., 2003]. This rapid retreat has resulted in a temporary but unsustainable net increase in hydrological runoffs [*Pouyaud et al.*, 2005].

Indeed, several glaciers, such as Ecuador's Cotacachi, have already disappeared, providing an early glimpse of upcoming consequences. The area around Cotacachi is experiencing declines in agriculture and tourism and a loss of biodiversity [*Rhoades et al*., 2006]. Waterless streams and a decrease in water levels already have led to more water conflicts; these are expected to worsen, and more are expected over time [*Rhoades and Zapata*, 2004].

Water Supply and Glacier Retreat

While Perú accounts for about 4% of the world's annual renewable water resource [*World Bank,* 2006], most (over 98%) of its available water is located east of the Andes, where population density is low and agricultural activity is marginal [*Ministry of Agriculture,* 2006]. The majority of the population and economic activity are located along the Pacific coastal plains and western slopes of the Andes, where the land is typically dry and dependent on runoff from the cordilleras [*Ministry of Agriculture,* 2006]. As glaciers cease to act as runoff regulators, seasonal water and power supplies will be affected unless alternative measures are quickly implemented.

For urban centers such as La Paz and El Alto in Bolivia (population 2.3 million), where glaciers of the Cordillera Real supply 30–40% of potable water, or Quito in Ecuador (population 2 million), where the Antizana and Cotopaxi glaciers supply a significant fraction of drinking water [*Bartolone,* 2006], the changing hydrological conditions can affect water costs and ultimately may impair the ability of these cities to maintain vibrant local economies.

Specifically, the long-term sustainability of existing water supplies to Quito is at risk [*Francou et al*., 2000]. Estimates indicate that glacier melt represents up to 50% of the surface runoff measured in Antizana's and Cotopaxi's river basins. The latest addition to Quito's water supply is the La Mica system, which collects water from the Antizana. The minimum cost expansion alternative for the city's water supply is the Rios Orientales project, which also captures waters from Antizana and Cotopaxi (see Figure 1 in the online supplement to this *Eos* edition).

As part of a comprehensive hydrologic analysis of the Antizana glacier basin, the hydrologic behavior of the watersheds draining at Crespo and Humboldt stations, both located downstream from the glacier, and the area between the two stations were examined. The overall water balance shows 527 millimeters per year of runoff, of which 239 millimeters per year are glacier-contributed. Moving downstream, as the proportion of glaciered area of the watershed decreases, it is expected that the percentage of glacier contribution will be reduced. For the Mica project, at the foothills of the Antizana glacier, the glacier contribution is conservatively assessed at 35% of the total runoff.

For example, on the basis of historical records and standard hydrologic analysis, there is a 95% probability that the La Mica system could yield discharges ranging from 1.7 to 2.2 cubic meters per second (m^3/s). However, when the analysis excludes glacier contributions, the potential yields are severely reduced, down to 1.1–1.4 cubic meters per second (Table 1). Thus, as glaciers retreat, the city will experience a shortfall in water supply. To compensate, more water sources must be diverted and additional reservoir capacity of about 30–43 million cubic meters will be required, at an estimated cost of US$13 million.

Once the demand for water approaches existing supply capacity, the city will need to divert additional water streams. The Rios Orientales project would divert waters via a 20-kilometer tunnel connected to the distribution grid. Table 2 summarizes the expected water yield for hydrologic conditions with and without glacier retreat. Without the glacier contribution, the city will have to build its water infrastructure at an accelerated pace. The incremental net present value of the accelerated investments for the next 20 years is US$100 million (about a 30%

Table 1. La Mica Water Yields Under Present and Future Conditions

Project: La Mica–Quito Sur	Yield With Melting, m^3/s	Yield Without Melting, m^3/s
Alternative 1: Three creeks	1.722	1.119
Alternative 2: Five creeks	1.868	1.214
Alternative 3: Eight creeks	2.175	1.414

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increase over the infrastructure required under the scenario without climate change). Thus, supplying water to the city will be more expensive and require diversions from a wider area (Table 3). Water supply shortages and other effects of climate change will affect the surrounding ecosystem. Additionally, reduced water regulation (retention of water during wet periods and release during dry periods) would affect soil cover and dependent fauna [*Mulholland et al.,* 1998; *Melack et al.,* 1998].

Table 2. Water Yields in Rios Orientales Project, With and Without the Impact of Glacier Retreat[a]

Rios Orientales Main creek system	Yield With Melting, m^3/s	Yield Without Melting, m^3/s
1. Papallacta-Tumiguina	1.975	1.167
2. Chalpi	1.885	1.225
3. Blanco Grande	0.410	0.267
4. Quiljos	0.324	0.211
5. Azufrado-Pucalpa	1.760	1.144
6. Cosanga	0.891	0.579
7. Antizana-Tambo	1.256	0.816
8. Reservoirs and minor creeks	2.479	1.611

[a] Data provided by Quito's Metropolitan Utility for Sewer Systems and Potable Water [*Institut de Recherche pour le Développement,* 1997]. The runoff estimates without melting from glaciers follow the same approach used for the Mica Project in Table 1.

Table 3. Investment Needs: Rios Orientales With and Without Climate Change[a]

Year	Existing Conditions: Creek systems diverted	Investment, US$ million	Expected Conditions: Creek Systems Diverted	Investment, US$ million
2010	Papallacta, Chalpi, Blanco Grande, Quiljos, Azufrado	110	All creek systems are required	143
2011		110		143
2012		113		144
2021	Cosanga	10	Reservoirs and minor creeks	39
2022		11		40
2026	Antizana-Cosanga	22		
2027		22		
	Total NPV value	298		391

[a] Detailed scheduling of the water supply expansion needed for Quito for two scenarios (data from *Caceres et al.* [2004]). The existing expansion path is shown in second and third columns under the hypothesis of a stable climate (past records are good estimates of future hydrologic behavior). Fourth and fifth columns correspond to the infrastructure expansion path required to supply Quito with its water needs under the scenario of no glacier contribution to runoff.

Power Generation and Glacier Retreat

The Andean region has become highly dependent on hydropower (comprising over 50% of total energy in Ecuador and about 80% in Perú), but this contribution will be diminished in areas where basins are glacier-dependent. For example, an analysis of hydrology data for 12 watersheds in Perú's Rio Santa basin, with glacial coverage ranging from 2% to nearly 40% of the total watersheds, indicates that current runoff includes a substantial glacier contribution. Nearly 220 millimeters per year (±35.6 millimeters per year) of water-equivalent, as measured at the La Balsa station, the second lowest altitude gauge in the watershed, is contributed by glaciers (after accounting for discharges, precipitation, and estimated evapotranspiration; see Table 4), representing 60% of total ex-glacier runoff [*Mark et al.,* 2005]. The interannual average discharge, over the length of a 48-year historical record (592 ± 3.4 millimeters per year) [*Pouyaud et al.,* 2003] at La Balsa, would be reduced to 482 millimeters per year (±52.6 millimeters per year) with a 50% decrease of glacier runoff, and to 371 millimeters per year once the glaciers cease to contribute water. Clearly, the disappearance of glaciers will have serious consequences for power supply.

Using data from Perú's power system [*Ministry of Energy and Mines,* 2005], we estimate that the average yearly energy output for the Cañon del Pato hydropower plant on the Rio Santa would drop from 1540 gigawatt-hours to 1250 gigawatt-hours (±10.9%) with a 50% reduction in effective glacier runoff, and would be reduced further to 970 gigawatt-hours (±14.2%) once the glacier contribution disappears.

The economic consequences of this reduction were assessed using three indicators: (1) the price of energy paid to the producer (US$20 per megawatt-hour), measuring the impact on owners of the hydropower plant, the investors; (2) the long-run average price for electricity (US$35 per megawatt-hour), measuring the opportunity cost to society; and (3) the cost of rationing energy (US$250 per megawatt-hour) [*Perú's Ministry of Energy and Mines*, 2006], measuring the consequences of forced rationing due to insufficient power capacity (see Table 5). The Cañon del Pato Power Plant's hydrologic input is characterized by the station La Balsa, described in Table 4. As indicated in Table 4, glaciers are calculated to contribute 221 millimeters per year of measured runoff. The economic assessment was made under hypotheses of a 50% reduction in melting rate and of no melting. Economic data were obtained from *Ministry of Energy and Mines* [2005]. National estimates in Table 5 are an extrapolation of the results described for Cañon del Pato to other glaciered basins feeding hydropower plants.

The rationing costs would be triggered if the rapid reduction in runoff continues, and if adaptation measures are not implemented in anticipation of these changes. In addition to higher capital requirements, the replacement of lost hydropower capacity by thermal-based alternatives would mean higher operation and maintenance costs and a large increase in the carbon footprint of the power sector.

Beyond economic costs, glacier retreat will also have social and cultural costs for the Quechua and Aymara cultures, which have long revered the glaciated Apus (highest peaks) as religious icons.

Economic Consequences

Rapid glacier retreat in the Andes will disrupt the water cycle in glacier-dependent basins, affecting water regulation and availability. For the city of Quito, we estimate an associated increase in the current investment costs for future water supply of about US$100 million. Annual incremental costs to Perú's power sector are estimated at US$1.5 billion (should rationing conditions be allowed to occur), or US$212 million (if a gradual adaptation scenario is implemented). In any case, Perú will likely have to invest in additional power capacity, most likely thermal-based, at a cost of about US$1 billion per gigawatt installed, resulting in higher costs to end users.

These consequences are akin to a climate tax imposed by energy-intensive societies on populations that have contributed little to the climate change problem. Advanced planning and measures, including the gradual displacement of hydropower capacity by alternative energy sources and additional reservoir capacity, will avoid much higher costs to these economies.

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Table 4. Water Balance in Glacierized Basins in the Cordillera Blanca in Perú[a]

Watershed	Area km^2	Area Glaciers 1970	Area Glaciers 1991	Rainfall P, mm/yr	Outflow Q, mm/yr	Q – P, mm/yr	ΔS [Q-P+EV], mm/yr	ΔV [Area x ΔS], Mm^3/yr
Recreta	290	6.0	5.1	613	300	-313	38	10.88
Pachacoto	210	24.3	20.3	929	640	-289	61	12.75
Querococha	66	4.0	2.1	1000	829	-171	179	11.83
Quitaracsa	390	36.0	30.0	1048	877	-171	179	69.81
La Balsa	4840	580	(472.3)	721	592	-129	221	1070.61
Olleros	176	28.5	(24.5)	986	862	-124	226	39.79
Los Cedros	116	26.0	24	911	932	22	372	43.09
Colcas	236	51.0	39.0	874	772	-102	248	58.58
Chancos	271	90.5	65.3	888	1016	128	478	129.59
Quillcay	250	92.5	45.9	908	909	1	351	87.80
Llanganuco	87	35.0	33.7	995	1080	85	435	37.84
Paron	48.8	25.0	23.2	1019	1210	191	541	26.40
Artesoncocha[b]	8.4		6.6	1015	1915	900	1250	10.50

[a] The evapotransporation term (EV) was estimated at 350 mm/yr; 1953 to 2001 rainfall (P) discharge records (Q) were used. Numbers in parentheses are estimates. The term ΔS represents the total change in the volume of water stored in the watershed in tanks, reservoirs, groundwater formations, and glaciers. ΔV is the estimated average volume of water losses from glaciers per year.

[b] Data for Artesoncocha were not included in the calculations as it lacks adequate rainfall and discharge records.

Table 5. The Cost of Glacier Retreat for Energy Sector, Perú (US$ million/year)

	Cañon del Pato Power Plant		National Estimates	
	Reduced Glacier Runoff	No Glacier Runoff	Reduced Glacier Runoff	No Glacier Runoff
Wholesale price	5.7	11.5	60.0	120.0
Opportunity cost	10.1	20.3	106.0	212.0
Rationing cost	71.5	144.0	748.0	1,503.0

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