ASSESSMENT OF GLACIER HAZARDS AND GLACIER RUNOFF FOR DIFFERENT CLIMATE SCENARIOS BASED ON REMOTE SENSING DATA: A CASE STUDY FOR A HYDROPOWER PLANT IN THE PERUVIAN ANDES

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ABSTRACT

Within an interdisciplinary feasibility study for a hydropower plant in the Peruvian Andes, an assessment of glacier-related hazards and a simulation of future glacier and runoff scenarios were performed. Due to the remoteness of the study area, a remote sensing-based approach has proven to be the only feasible way. For the hazard assessment, an algorithm for glacier lake detection based on ETM+ data was applied. A potentially hazardous glacier lake was thus discovered, and ASTER data was then used to compute a digital elevation model (DEM). A lake outburst flood model, based on the DEM and hydrological flow modeling, indicated areas of different hazard potential. Though no direct hazard for the hydropower plant was found, a lake outburst could temporally dam the main river and thus cause a sudden extremely high discharge. For the simulation of scenarios of the future glacier area and runoff, a parameterization scheme was applied using basic glacier parameters. Calibration of the parameterization scheme was achieved by glacier parameters derived from ETM+ data. The glacier inventory of Peru from 1962 served as the basic data set. The simulation showed that with a continuing atmospheric warming trend the glacier area and volume will decrease very significantly. Glacier runoff, of great importance for the hydropower operation during the dry season, is supposed to decrease almost completely in case of a temperature rise of 1.2°C. The study furthermore showed the large potential of ASTER data for deriving DEM's and subsequent modeling, particularly for remote areas.

INTRODUCTION

The present contribution is part of an interdisciplinary hazard assessment and feasibility study for a hydropower plant in the Peruvian Andes (1), (Fig. 1). The study focussed on glacier-related and geomorphodynamic hazards that might affect the hydropower plant. Particularly hazards from glacier lake outbursts have repeatedly been a serious problem in Peru and caused the loss of human lives and enormous damage to structures (2), (3), (4). Since the outburst catastrophe from Laguna Palcacocha in 1941 with over 6,000 victims in the city of Huaráz mitigation measures for glacier lakes have been initiated and intensified (2), (4). With increasing exploitation of the hydropower resources in Peru, such hazards have gained importance. A recent high-magnitude debris flow event in 1998 (25 to 50 mill. m^3 of sediment) which destroyed the hydropower plant of Machu Picchu (5) has enhanced the attention and risen concern in the hydropower business. As a consequence, an integrated hazard assessment study was initiated for the San Gabán hydropower plant.

For such hazard assessments an interdisciplinary approach is highly important (6), (7). In the present case, the co-operation of experts from the fields of geology, seismology, hydrology, glaciology, and geomorphology has proven to be successful. In this paper, the methods and results from glaciology and related geomorphodynamic processes only are presented. Results from hydrology and geomorphology have been presented in (8).

The paper consists of two main parts: The first part is concerned with the detection and evaluation of glacier-related hazards. Due to the remoteness of the study area, a remote sensing-based approach has proven to be the best feasible way. In the second part, a parameterization scheme is applied to the glaciers in the catchment of the hydropower plant, and scenarios under continued atmospheric warming are simulated enabling the expected future runoff decrease during the dry season to be estimated.

Figure 1: Location and study area in Peru (left) and view of the San Gabán hydropower plant (right)

Study Area

The catchment of the San Gabán hydropower plant (Central Hidroeléctrica San Gabán II, 2,200 m a.s.l.) can be divided into two morphologically different zones (Fig. 2). The larger part is represented by the Altiplano (4,000 – 4,500 m a.s.l.) with low precipitation, scarce vegetation, and glacierized peaks reaching elevations of 5,800 m a.s.l. Erosion processes are comparably weak, and moraines from the last glaciation (about 18,000 years ago) are still well preserved.

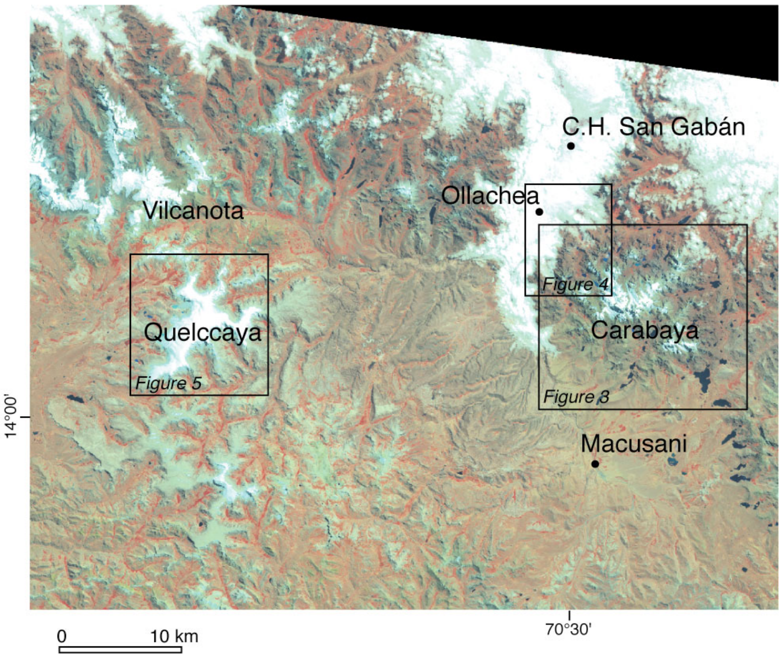


Figure 2: Overview of the study area (ETM+ image). The San Gabán hydropower plant is below clouds.

In strong contrast to the Altiplano, there are deeply incised canyons draining towards the hydropower plant and to the Amazonian plain. This part is characterized by dense vegetation and abundant precipitation with high fluvial dynamics. The extremely steep lateral slopes show clear signs of slope instabilities, occasionally with large terrain displacements.

Two glacierized mountain ranges are part of the catchment (Fig. 2): Cordillera Carabaya in the southeast and Cordillera Vilcanota in the west. Both ranges drain to the Altiplano to a large extent and are relatively distant from the hydropower plant. In the Cordillera Vilcanota, only small glacierets form part of the catchment, except for the outlet glaciers of the Quelccaya ice cap. The climate is strongly dependent on the seasonal position of the Intertropical Convergence Zone (ITCZ) and on the topography. In the wet summer season, moisture-laden air masses from the Amazonian plain bring abundant precipitation, the amount of precipitation is decreasing with increasing altitude as it is typical of tropical mountain systems. Advection of wet air masses from the Atlantic stops during winter which is the dry season. Hence, glaciologically, the accumulation season is from December to April. Ablation is effective throughout the whole year but more marked in summer, though ablation can also reach relatively high values during winter with clear skies and high radiation (9), (10).

ASSESSMENT OF GLACIER HAZARDS

Data

Due to the remoteness of the study area, the survey of sufficiently reliable data was a crucial element of the study. The glacier inventory of Peru (11) represents a valuable basis of detailed information on each glacier, but does not represent the present situation since it is based on aerial photographs from 1962. Available topographic maps have a scale of 1:100'000 and are based on aerial photographs from 1962 and 1963. The remoteness of as well as the poor access to the mountain ranges made a complete field inspection impossible. Therefore, satellite images were used to compile current information over large areas. A Landsat-7 Enhanced Thematic Mapper (ETM+) scene (9 August 1999) and a Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scene (29 July 2001) were used.

Detection of glacier lakes

Glacier lakes and their possible outbursts are one of the main hazards which the hydropower plant may face from glacial environments. An algorithm enabling lake detection was applied on the ETM+ scene. The NDWI algorithm (Normalizd Difference Water Index) uses ETM+ spectral bands 1 and 4 for maximum and minimum spectral reflectance of water, respectively (12):

$$NDWI = (TM4 - TM1)/(TM4 + TM1)$$

Fig. 3 shows the resulting image for Cordillera Carabaya where lakes are denoted in black. The lakes thus detected in Cordilleras Vilcanota and Carabaya underwent a closer analysis considering the following factors:

- relation between glacier and lake (direct contact, possibility of ice break-offs and snow avalanches into the lake)
- topographic situation of the lake (surrounded by steep glaciers and/or rock walls, flat or steep terrain) and size of the lake (area, volume)
- dam characteristics (rock, moraine, ice)
- downvalley characteristics (topography, further lakes, erodible material, length of path to hydropower plant)
- occurrence of seismic events, climatic variability

More detailed information on the assessment of glacier lake hazard potentials is discussed in (12). For a closer analysis of the physical environment of the lakes detected, considering the factors mentioned above, the ETM+ pan channel was co-registered and fused (IHS-transformation) with the multispectral channels 4,3,2. Hence, a better visual interpretation of hazard-relevant structures and morphology was enabled. According to this analysis, most glacier lakes were found to be too far from the hydropower plant to present a hazard and/or drained into major lagunas that would act as full retention basins in case of outburst floods. One glacier lake, however, was detected and rated to be potentially hazardous. It is located at the foot of a glacier descending from Nevado Allin Cápac (5,824 m a.s.l.) and has formed behind a frontal moraine, yet did not exist on the maps from 1962.

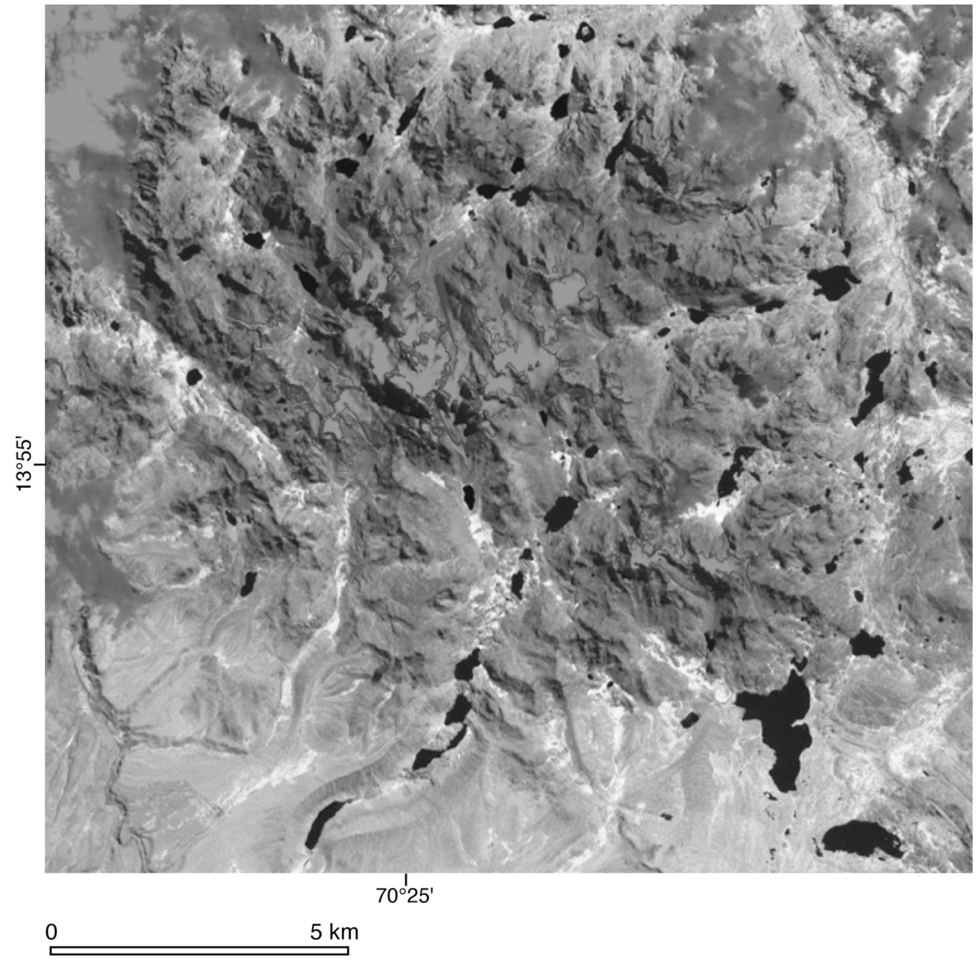


Figure 3: NDWI image of Cordillera Carabaya. Lakes are shown in black.

Hazard Assessment

Other glacier hazards such as ice avalanches from other glaciers in Cordilleras Vilcanota and Carabaya could be excluded, because the ice masses were too remote from the hydropower plant to represent either direct or indirect hazards (e.g. lake outbursts due to ice avalanches). Therefore, the following hazard assessment concentrates on the above-mentioned glacier lake (called 'Laguna Nueva') detected to be potentially dangerous.

The glacier calving into Laguna Nueva reaches an inclination of more than 40° and thus is assumed to be potentially unstable (7), (13) and able to produce ice break-offs. The maximum ice break-off volumes were estimated as 800'000 m^3. Further rock and ice avalanche hazards were considered from the lateral hanging glaciers and rock walls. The frontal moraine damming the lake is from the Little Ice Age (LIA) and consists of typical unconsolidated morainic material. The Laguna Nueva thus clearly showed an outburst potential which had to be assessed quantitatively.

The lake area was measured on the 1999 ETM+ scene as 170,000 m^2. For a volume estimate, three different average depths (5, 10, and 15 m) were assumed and, as such, entered the calculation. Based on empirical data, the maximum discharge of an outburst can be expressed as (12):

$$Q_{max} = 0.00077\ V^{1.017}$$

Maximum discharge values of lake outbursts were related to the reach of damage and travel distance of corresponding outburst floods (amount of water > 50%) and debris flows (amount of water < 50%), respectively, by (14). Thereby, a critical average slope (calculated as the elevation difference divided by the distance between the starting and the end point of an outburst flood) is defined for a given maximum discharge. The following values were thus found for an outburst of Laguna Nueva, where the critical average slope is derived from the relation in (14):

Lake volume		Critical average slope	Critical average slope
		Water amount < 50 %	Water amount > 50 %
		Debris flow	Flood
V_5 = 845'000 m^3	Q_{max} = 821 m^3/s	11° /19.4%	2°/3.5%
V_{10} = 1'690'000 m^3	Q_{max} = 1661 m^3/s	10.5°/18.5 %	1.8°/ 3.1%
V_{15} = 2'350'000 m^3	Q_{max} = 2322 m^3/s	10.4°/18.4%	1.7°/3.0%

The amount of available unconsolidated material downvalley from the Laguna makes the formation of a debris flow the most probable scenario in case of an outburst.

Downvalley from the Laguna Nueva, three more lagunas (lakes) were found (Suirococha, Cañocota, Huañunacocha). An outburst flood of Laguna Nueva would have to pass through them. Smaller outbursts can be absorbed by these lagunas, as they act as retention basins. The terrain is furthermore not very steep in between these lagunas. It can, however, not definitely be excluded that an outburst of maximum size (full breach of the lake) would pass all over through the lagunas and a debris flow would form below the lowermost laguna reaching the main valley of San Gabán. Therefore, considerations are made about an outburst reaching the lowermost laguna Huañunacocha and a subsequent debris flow from laguna Huañunacocha to the main valley. Three different lake depths and volumes of laguna Huañunacocha are considered:

Lake volume		Critical average slope	Critical average slope
		Water amount < 50 %	Water amount > 50 %
		Debris flow	Flood
V_5 = 560'000 m^3	Qmax.= 540 m^3/s	11.7°/20.7%	2.3°/4.0%
V_{10} =1'120'000 m^3	Qmax =1093 m^3/s	10.9°/19.3%	1.9°/3.3%
V_{15} =1'680'000 m^3	Qmax =1651 m^3/s	10.5°/18.5%	1.8°/3.1%

The average slope from laguna Huañunacocha down to the main valley of Río San Gabán is 12.8°/22.7%. A debris flow from laguna Huañunacocha would thus reach the main valley. A rough estimate of the amount of material transported and deposited at the confluence with Río San Gabán is 100,000 m^3. This could cause a blockage of the main river and, in case of a rupture of the blockage, a sudden peak discharge of up to 1,000 m^3/s. Such an extreme discharge could seriously damage structures of the hydropower plant as well as dwellings and people at the riverside around the location of Ollachea. It seems that a similar event of river blockage has happened somewhere along Río San Gabán in 1995 when a peak discharge of up to 500 m^3/s was observed. In the Cordillera Vilcanota, no glacier-related hazards which would pose a threat to the hydropower plant could be found using the described approach.

Outburst Flood Modeling

The case of an outburst of Laguna Nueva was investigated in more detail on the basis of the July 2001 ASTER scene. As for the ETM+ scene, collection of ground control points had to be made on the basis of 1:100'000 topographic maps, since no better information was available. With roughly 20 ground control points distributed evenly over the whole scene a root mean square error of about 3 pixels was achieved. In view of the scarcity of data in such a remote area, this was considered to be sufficient to compute a digital elevation model (DEM) for outburst flood modeling. The potential of ASTER data for deriving DEMs is owing to stereo viewing of a separate sensor. For DEM calculation, an epipolar image pair with the co-registered nadir-looking (3N) and back-looking channel (3B) is computed. A DEM of the whole scene with coarser ground resolution (60 m) for orthorectification of the multispectral channels 3N,2,1 and a DEM of a subset with higher resolution (30 m) for outburst flood modeling was then calculated (15), (16).

Input data to the outburst flood model is basically the DEM derived from ASTER data and the area of Laguna Nueva extracted from the NDWI image. The pixels of the lake represent the starting point of the outburst model. The modeling is performed within a GIS-environment and is based on hydrological flow modeling. The direction of the downhill flow is according to the next steepest neighbour in a 3x3 window (D8 method), (17). In addition to the flow along the steepest path, a factor is introduced which allows the flow to divert horizontally up to 45° on both sides. A linear function defines that the more the flow diverts from the steepest downslope direction the greater is the resistance. Following the specific terrain downvalley from the outburst source, a certain area is covered by the outburst flood. The probability that a pixel at the very side of this area be affected is lower than for a corresponding pixel along the steepest downslope direction. Fig. 4 shows the outburst flood model starting from Laguna Nueva. The colors relate to the probability that a certain pixel be covered by the outburst flood. The outburst flood can be simulated with satisfactory level of detail. Downvalley from laguna Huañunacocha, the model fails due to errors in the DEM caused by cloud cover. The main part of the distance is marked by a medium-probability hazard.

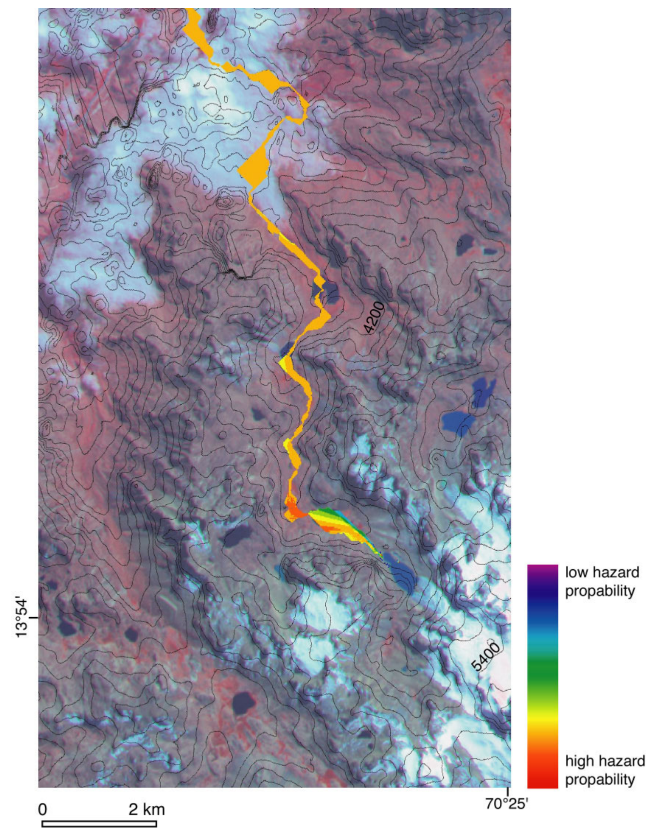


Figure 4: Outburst flood model from Laguna Nueva. The DEM and hence the model is not valid under clouds.

Glacier and Runoff Scenarios

A decrease in glacier area and runoff in the catchment of Rio San Gabán will have a major impact on the hydropower plant operation. The method to quantitatively evaluate the possible decrease is described in the following.

A parameterization scheme developed within a former UNEP (United Nations Environment Programme) project (18) was applied on the glaciers of Cordillera Vilcanota and Carabaya. The scheme uses simple algorithms for non-measured glaciers, i.e. where only basic parameters are known. The model then enables additional parameters to be derived which are necessary for the simulation of the future change in glacier area, volume, and runoff.

As a complete database on all glaciers in the mountain ranges under question, the glacier inventory of Peru (11) was used. The inventory, however, is based on aerial photographs from 1962 and, thus, is not appropriate for direct estimates of present glacier extents. Therefore, the 1999 ETM+ scene was used to derive basic parameters of a set of test glaciers (19). These glaciers were selected according to the requirement of a representative set of different glacier types and of mapping the extent of the last maximum of the LIA (around 1880) according to LIA-moraines visible on the satellite image (Fig. 5).

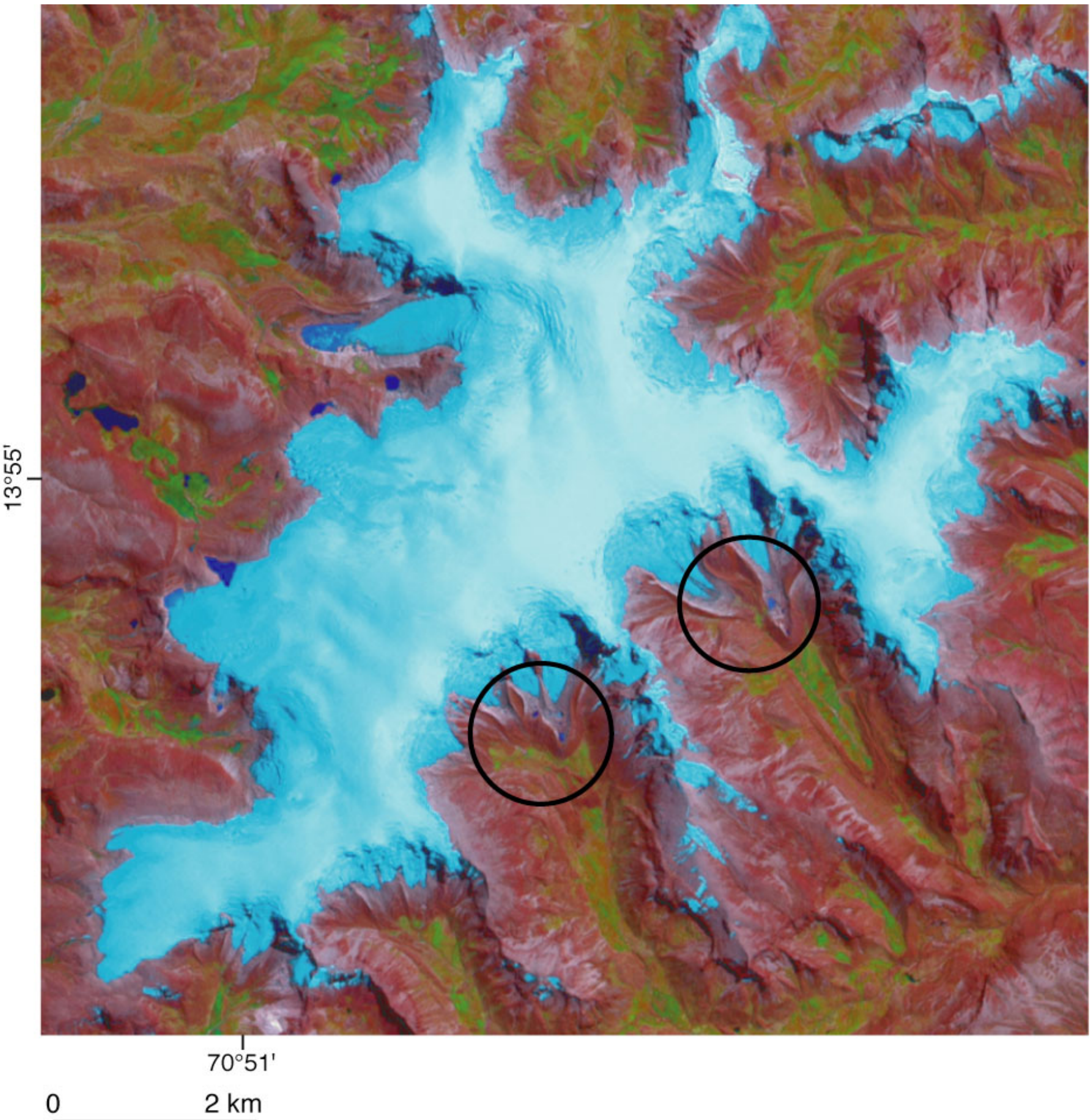


Figure 5: Quelccaya ice cap and outlet glaciers. Moraines of the last LIA-maximum are clearly visible and indicated (ETM+ image merged from pan and multispectral channels).

The basis of the parameterization scheme consists of input data on the total length (L_0), maximum and minimum altitude (H_{max}, H_{min}) and total surface area (F) of the investigated glaciers. Corresponding information was collected for the time steps of 1999 (satellite image), 1962 (inventory data), and 1880 (derived from satellite image).

The set of test glaciers for the period of 1962 to 1999 was used to calibrate the model and to derive the change in mass balance which is needed to calculate the glacier changes of all glaciers. The concept of glacier-length changes is based on given disturbances of mass balance with respect to the characteristic dynamic response time (20) in the sense of step functions between steady-state conditions. A given disturbance in mass balance δb is derived from $\delta b = \delta L b_t / L_0$, where δL is the glacier-length change and b_t the annual ablation at the glacier tongue which is computed as $b_t = db/dH (H_m - H_{min})$. H_m is the mean altitude ($H_m = [H_{max} - H_{min}]/2$) and db/dH the mass-balance gradient (18), (21). The mass-balance gradient is a key parameter of the model and had to be evaluated in several test runs, since no corresponding information was available for Cordillera Carabaya and Vilcanota. It was then set as db/dH = 1.7 m w.e. per 100 m in accordance with studies in the Cordillera Blanca by (9).

In order to calculate the change of the equilibrium-line altitude (δELA) and of the air temperature (δT) between 1962 and 1999, δELA can be expressed as $\delta ELA = \delta b/(db/dH)$. For the period between 1962 and 1999, δELA is thus calculated as δELA = 52 m with a corresponding temperature rise of δT = 0.34°C with a temperature gradient of 0.65°C per 100 m and assuming that the mass-balance change is only caused by a change in air temperature. A temperature rise of 0.34°C is actually a very realistic value for the period between 1962 and 1999. The data on the glacier extents of 1880 and its modeled comparison with 1999 was needed to further calibrate the model and estimate the behaviour of the glaciers in Cordillera Vilcanota and Carabaya. This was essential for a largely unknown and remote region where no corresponding measurements have been done to date. For the period between 1880 and 1999, δELA was computed as δELA = 125 m with a temperature rise of δT = 0.8°C.

Once δb and b_t were obtained for the period between 1962 and 1999, the glacier-length changes of all glaciers of Cordillera Vilcanota and Carabaya could be calculated following the relation $\delta L = L_0 \delta b / b_t$. Glacier area and volume were computed applying an empirical relation between glacier length and area and glacier area and volume derived from the inventory data and the volumes calculated for the test glaciers (21).

For the future operation of the San Gabán hydropower plant, the runoff from glaciers will be essential, in particular in the dry season. Therefore, different climate scenarios were defined to calculate the expected change in glacier area and volume as well as glacier runoff. According to present global climate models (22) three different scenarios for approximately the next 50 years were defined.

Scenario +0.15°C (2007 – 2015):

Starting from 1999, this scenario assumes a temperature rise of 0.15°C until a period between 2007 and 2015 depending on the climate model applied. It suggests a continuation of the rate of temperature rise as observed since 1962. The rise in ELA is 23 m and δb, hence, -0.39 ma^{-1}.

Scenario +0.3°C (2015 – 2025):

A temperature rise of 0.3°C for 2015 to 2030 is accompanied by a rise in ELA of 48 m and a δb of -0.82 ma^{-1}.

Scenario +1.2°C (2040 - 2060):

This scenario is on a more long-term basis but equally important for the hydropower plant, since its operation-time horizon is in the range of 50 years. δELA is then 178 m and δb -3.0 ma^{-1}.

Simulation Results

In view of gaining significant results for the San Gabán hydropower plant, only those glaciers of Cordillera Vilcanota and Carabaya that are part of the catchment of Río San Gabán were selected. For a more detailed analysis, in particular concerning the runoff, a further differentiation was made for glaciers part of

1. the total catchment of Río San Gabán

2a. Cordillera Vilcanota as part of the San Gabán catchment

2b. Cordillera Carabaya as part of the San Gabán catchment

3a. Cordillera Vilcanota draining directly towards San Gabán without passing through lagunas with water damping effects

3b. Cordillera Carabaya draining directly towards San Gabán

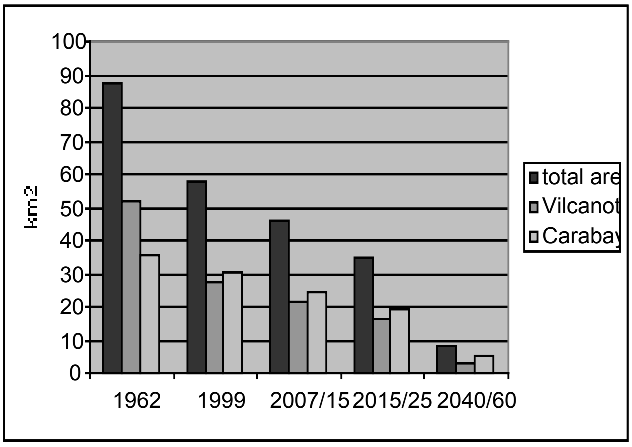
The glacierized area of the total San Gabán catchment was reduced by a third between 1962 and 1999 (Fig. 6, Tab. 1). This is an impressive rate for the past four decades. The annual mass balance decrease during the same period was about 0.20 ma-1 on average. While Cordillera Vilcanota showed a considerably larger glacierized area than Cordillera Carabaya in 1962, the latter has become slightly larger in 1999. In fact, the glacierized area of Cordillera Vilcanota is decreasing and will decrease in the future at a higher rate than Cordillera Carabaya. This is related to the characteristics of each Cordillera, especially with respect to the altitudinal extension of the glaciers. In general, the glaciers of Cordillera Carabaya extend over a larger range of altitude than those of Cordillera Vilcanota.

According to the simulations, the glaciers would lose another fifth of their area from 1999 to the '2007-2015' scenario and about two fifths until '2015-2025' with the assumed climatic scenario. For the long-term scenario ('2040-2060'), only a marginal part of the current glacier area will persist. The volume will decrease accordingly such that a very significant part of the water reserves will be lost.

Table 1: Change of glacier area and volume and related runoff according to the scenarios defined.

Total runoff	1962	1999	scenario 2007/15	scenario 2015/25	scenario 2040/60
Total area (km^2)	87.42	57.60	46.12	35.13	7.89
Total volume (km^3)	1.69	1.12	0.89	0.68	0.15
Max. runoff (m^3/s)	7.59	5.00	4.00	3.05	0.68
Min. runoff (m^3/s)	2.53	1.67	1.33	1.02	0.23
Average runoff (m^3/s)	5.06	3.33	2.67	2.03	0.46

Direct runoff	1962	1999	scenario 2007/15	scenario 2015/25	scenario 2040/60
Total area (km^2)	52.87	28.25	22.68	16.59	2.63
Max. runoff (m^3/s)	4.59	2.45	1.97	1.44	0.23
Min. runoff (m^3/s)	1.53	0.82	0.66	0.48	0.08
Average runoff (m^3/s)	3.06	1.64	1.31	0.96	0.15



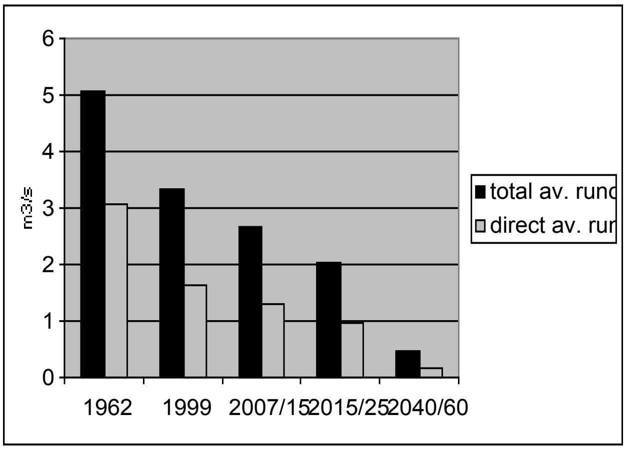


Figure 6: Glacier (left) and runoff (average values, right) changes for the scenarios defined.

The runoff from the glaciers of the San Gabán catchment was derived from the results of the above scenarios. Since there is abundant water supply in the wet season (summer), the glacier runoff was calculated only for the dry season (winter), when the hydropower plant heavily relies on runoff from glaciers. 200 days of ablation were considered for the dry season with an average ablation of between 2 m and 3 m. The ablation area was taken as varying between 25% and 50% of the total area of each glacier. Therefore, a minimum and a maximum runoff value resulted for each scenario (Tab. 1). The runoff values are divided into direct and indirect runoff following the same scheme as for glacier area (cf. above). This was done in order to evaluate the amount of water directly draining towards the hydropower plant. Water draining through major lagunas does not exhibit a significant influence on daily runoff variations, since the lagunas have an important damping effect.

The results show a sharp decrease in runoff between 1962 and 1999, and this trend will continue with the scenario ‘2015-2025’ (Fig. 7). For a temperature rise of 1.2°C (scenario ‘2040-2060’), the direct runoff from glaciers in the dry season decreases almost to zero. Taking into account that such a climate scenario is well placed within probable scenarios (22), serious concern about the operation of the hydropower plant in the dry season may arise.

CONCLUSIONS

The present study has shown that remote sensing imagery is a very valuable – and in fact the only – tool to close information gaps in remote high mountain regions. In particular the advent of the ASTER sensor opens a new way to obtain digital elevation data of such areas. This is a premise for digital modeling of processes for hazard assessments but also for use in other fields of geoscience. With respect to the hydropower plant of San Gabán, no direct glacier-related hazard was found, because the hazard sources were too distant from the plant. The hazard analysis, however, recognized that an outburst of a specific glacier lake in the Cordillera Carabaya could indirectly represent a hazard, mainly by blocking the main river with a subsequent peak flood in the main river. Field works confirmed the hazard potential of the lake, and mitigation measures were recommended. Analysis of the present state of glaciers in the San Gabán catchment and simulation of scenarios of future glacier shrinkage revealed that a process of rapid glacier shrinkage has taken place in the past four decades and that this trend will continue under current climate change predictions. For the San Gabán hydropower plant in particular, and for the water resource exploitation in Peru and comparable regions in general, the rapid glacier shrinkage, and thus the runoff decrease during the dry season, give reason for serious concern in the near and distant future.

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REFERENCES

1. Fichtner Agua y Energía. 2000. Estudio de vulnerabilidad en la central hidroelélectrica San Gabán II por fenómenos externos. (Lima).
2. Lliboutry, L., Morales Arnao, B. and Schneider, B. 1977. Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru, I. historical failures of morainic dams, their causes and prevention. J. Glaciol.18(79): 239–254.
3. Ames, A. 1998. A documentation of glacier tongue variations and lake development in the Cordillera Blanca, Peru. Z. Gletscherkd. Glazialgeol. 34: 1-36.
4. Reynolds, J.M., Dolecki, A. and Portocarrero, C. 1998. Construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru. Geohazards in Engineering Geology, edited by Maund, J.G. and Eddleston, M. (Geological Society, London, Engineering Geology Special Publications 15), 41-48.
5. Carlotto, V. et al. 2000. Los aluviones de Aobamba (Machupicchu) y Sacsara (Santa Teresa): geología, geodinámica y analisis de daños. Proccedings of X Congreso Peruano de Geología, Lima, 2000: 126. Lima, Sociedad Geológica del Perú.
6. Kääb A. et al. 2000. Glacier- and permafrost-related hazards in high mountains: Integrative assessment in the Swiss Alps based on remote sensing and geo-information systems. Proceedings of X Congresso Peruano de Geologia. Lima. 2000. Volumen de Presentaciones. CD-ROM. Sociedad Geológica del Perú.
7. Huggel, C. et al. (submitted). Glacier-related hazards in the Swiss Alps: first-order assessments in relation to real events. J. Glaciol.
8. Huggel, C., E. Ayros, A. Bardossy, W. Haeberli and C. Portocarrero. 2001. Interdisciplinary assessment of risks related to flood and geomorphodynamic events for an existing hydropower plant in Peru. Proceedings EGS 26th General Assembly, Nice, 2001. (Geophysical Research Abstracts, Vol. 3).
9. Kaser, G., Ames, A. and Zamora, M. 1990. Glacier fluctuations and cliamte in the Cordillera Blanca, Peru Ann. Glaciol. 14: 136-140.
10. Hastenrath, S. and Ames, A. 1995. Diagnosing the imbalance of Yanamarey glacier in the Cordillera Blanca of Peru. J. Geophys. Res. 100(D3), 5105-5112.
11. Hidrandina S.A. 1988. Glacier inventory of Peru. (Huaráz, Peru).
12. Huggel, C. et al. 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Canad. Geotech. J. 39(2).
13. Alean, J. 1985a. Ice avalanches: some empirical information about their formation and reach. J. Glaciol. 31(109): 324-333.
14. Haeberli, W. 1983. Frequency and characteristics of glacier floods in the Swiss Alps. Ann. Glaciol. 4, 85–90.
15. Kääb, A. 2002. Monitoring high-mountain terrain deformation from digital aerial imagery and ASTER data. ISPRS-J Photogramm Remote Sens. (In press).
16. Kääb, A. (this issue). Glacier monitoring from ASTER imagery: accuracy and applications. Proceedings of the EARSeL Workshop Remote Sensing of Land Ice and Snow 2002.
17. Jenson S. K. and Domingue. J.O. 1988. Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. Photogramm. Eng. Remote Sens. 54(11): 1593-1600.

18. Haeberli, W. and Hoelzle, M. 1995. Application of inventory data for estimating characteristics of and regional climate change effects on mountain glaciers - a pilot study with the European Alps. Ann. Glaciol. 21: 206-212.

19. Paul, F. (this issue). Comparison of TM-derived glacier areas with higher resolution data sets. Proceedings of the EARSeL Workshop Remote Sensing of Land Ice and Snow 2002.

20. Jóhanesson, T., Raymond, C. and Waddington, E. 1989. Time-scale for adjustment of glaciers to changes in mass balance. J. Glaciol. 35(121): 355-369.

21. Hoelzle, M. and Haeberli, W. 1995. Simulating the effects of mean annual air temperature changes on permafrost distribution and glacier size. An example from the Upper Engadin, Swiss Alps. Ann. Glaciol. 21: 400-405.

22. IPCC. 2001. Climate change 2001 – the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press).