MOUNTAIN RESEARCH AND DEVELOPMENT, VOL. 17, NO. 3, 1997, PP. 229–238

WATER AVAILABILITY, PROTECTED AREAS, AND NATURAL RESOURCES IN THE ANDEAN DESERT ALTIPLANO

BRUNO MESSERLI, MARTIN GROSJEAN, AND MATHIAS VUILLE

Institute of Geography
University of Berne, Hallerstrasse 12
CH-3012 Berne, Switzerland

ABSTRACT The arid Andes between 18° and 30° South are located in the transition zone between the tropical and westerly circulation belts. Precipitation rates are lower than 150–200 mm/yr. Results from paleoclimatic and isotope hydrologic research suggest that modern recharge of the water resources in this area is very limited, or even below the level of detection. The groundwater resources of today were formed when precipitation rates were greater than at present by a factor of 2.5. Thus, water is a resource that is renewed extremely slowly, or is even non-renewable.

The distribution of mountain protected areas along the 7,500 km Andean Cordillera and the extent of the arid diagonal, the zone of extremely low precipitation that crosses from the western flank in southern Ecuador and Peru to the eastern flank in Argentina, are compared. This indicates the very low density of protected areas within the arid diagonal and the potential for endangerment of diversity in this highly sensitive, dynamic, and harsh environment.

Scientific knowledge about the age and origin of water resources and maps of water protection zones are the basic elements required for decision making. This type of information should help to resolve the growing conflict between the users of water, especially between the expanding mining industry, conservationists, and local communities concerned with the integrity of the fragile mountain ecosystems. Establishment of a series of new protected areas would be a modest but efficient measure for preserving the unique mountain environment and guaranteeing water resources for the benefit of both human development and nature conservation.

RÉSUMÉ *Disponibilité de l'eau, zones de protection et ressources naturelles dans l'Altiplano désertique des Andes.* Les Andes arides entre 18 et 30° Sud se situent dans la zone de transition entre les zones de circulation tropicale et extratropicale, avec une précipitation annuelle inférieure à 150-200 mm. Les résultats de recherches paléoclimatiques et hydrologiques isotopiques indiquent que le renouvellement des ressources hydriques y est très limité, même au-dessous du niveau de détection. Les réserves actuelles des nappes phréatiques se sont accumulées lorsque la précipitation était d'environ deux fois et demie la précipitation actuelle. L'eau est donc une ressource qui se renouvelle très lentement, si elle se renouvelle du tout.

La répartition des zones alpestres de protection le long des 7 500 km de la Cordillère des Andes et l'étendue de la diagonale aride, la zone de précipitation extrêmement faible qui s'étend du versant ouest dans l'Equateur sud et le Pérou jusqu'au versant est en Argentine, sont comparées. Cette comparaison indique une très faible densité des zones de protection dans la diagonale aride et une réduction possible de la biodiversité dans cet environnement ultra-sensible, dynamique et hostile à la vie.

De meilleures connaissances scientifiques concernant l'âge et l'origine des ressources hydriques, ainsi que des cartes des zones de protection des eaux, constituent les éléments de base de la prise de décision. Ce type d'informations devrait contribuer à la résolution sur conflit croissant entre les utilisateurs d'eau, en particulier l'industrie minière en expansion, les conservationnistes et les collectivités locales soucieuses de l'intégrité des écosystèmes alpestres fragiles. L'établissement de nouvelles zones de protection constiturait un moyen modeste, mais efficace, de préservation de cet environnement alpestre unique et de protection des ressources hydriques, au profit du développement humain et de la conservation du milieu naturel.

ZUSAMMENFASSUNG *Wasserverfügbarkeit, Schutzgebiete und natürliche Ressourcen in den trockenen Anden.* Die ariden Anden zwischen 18 und 30° S bilden den Trenn- und Übergangsbereich zwischen den tropischen und aussertropischen Zirkulationszonen mit jährlichen Niederschlägen von weniger als 150–200mm. Paläoklimatische und isotopenhydrologische Untersuchungen zeigen, daß die Erneuerung der Wasserressourcen unter heutigen Klimabedingungen sehr begrenzt ist. Die Grundwasserspeicher wurden in humideren Klimaphasen gebildet, grösstenteils im Spätglazial bis frühen Holozän (Taucaphase ca. 14000-8500 BP), als der Niederschlag um einen Faktor 2.5 grösser war als heute.

Die Schutzzonen entlang der 7500 km langen Kordillere lassen deutliche Lücken in den trockenen Anden erkennen. Der Grund mag in der reduzierten Biodiversität liegen. Die Quantität darf aber nicht das alleinige Kriterium sein, besonders nicht für die gefährdeten und seltenen Pflanzen und Tiere in einer höchst sensitiven, dynamischen und lebensfeindlichen Umwelt.

Bessere wissenschaftliche Kenntnisse über Alter und Herkunft des Wassers, sowie Gewässerschutzkarten sind grundlegende Elemente für Entscheidungsprozesse in einem wachsenden Konflikt verschiedener Interessengruppen, im besonderen zwischen der expandierenden Minenindustrie und den gefährdeten Gebirgsökosystemen. Eine Serie von neuen Schutzzonen wäre eine bescheidene, aber wirksame Maßnahme zur Entwicklung und Erhaltung dieses einzigartigen Gebirgsraumes.

RESUMEN *Disponibilidad del agua, areas protegidas y recursos naturales en el altiplano desertico andino.* Los Andes áridos, entre los 18° y 30° de latitud sur, se ubican en la zona de transición entre el cinturón de circulación tropical y los vientos constantes del oeste ('Westerlies'). En este sector la precipitación es inferior a los 150–200 mm/año. Las investigaciones paleoclimáticas con isótopos radioactivos que aquí se reportan constatan que la recarga de los acuíferos es muy limitada, desarrollándose posiblemente a un nivel mas bajo del que puede ser detectado. De esta manera, las aguas subterráneas de las que se dispone en la actualidad se han generado en momentos en que los niveles de precipitación en la zona eran 2.5 veces superiores al actual. Se observa que el agua disponible se renueva muy lentamente o, sencillamente, no se renueva.

En esta diagonal árida las áreas protegidas ocupan una superficie muy limitada. Esto es mas evidente cuando se la compara con la superficie que ocupan las áreas que se encuentran bajo protección a lo largo de los 7500 km de la Cordillera de los Andes. Es en este ambiente altamente sensitivo, dinámico y difícil—una zona de baja precipitación que se extiende desde las laderas occidentales de los Andes desde el sur del Ecuador y del Perú hasta las laderas orientales de los Andes en la Argentina—que la biodiversidad necesita ser protegida.

El conocimiento científico sobre la edad y el origen de los recursos hidrológicos, y el acceso a mapas de áreas de protección de los acuíferos constituyen elementos básicos que requiere todo proceso de toma de decisiones. Este tipo de información facilitará la resolución del creciente conflicto entre los usuarios del recurso, particularmente entre la actividad minera en expansión, grupos conservacionistas y las comunidades locales que dependen directamente del recurso. El establecimiento de una serie de áreas protegidas en esta diagonal árida será una medida modesta aunque eficáz para preservar el medio ambiente de montaña, y de esa manera garantizar recursos hídricos que lleven al desarrollo sostenible de las actividades humanas promuevan la conservación.

INTRODUCTION

Discussion of conservation programs and protected areas in the Andes is usually focused on natural forests and the great variety of forest ecosystems, ranging from the tropical to the subantarctic zone (Lauer and Erlenbach, 1987; IUCN, 1994), that makes South American forests the most diverse in the world. However, the Andean mountain system, which extends from the Caribbean Sea (about 11–12° N) to Tierra del Fuego (55° S), a distance of approximately 7,500 km, has a vast central area with semi-arid to extreme arid conditions. This dry zone stretches from the Pacific coastal ranges in Ecuador to the eastern slopes of the cordillera in Patagonia and is referred to as 'the arid diagonal' (Figure 1). Thus, between about 5 and 33° S there is a mountainous area with many types of arid ecosystems, depending on local and regional climatic conditions, on altitude and exposure, and on relief and geology. This arid diagonal of South America represents the border or transition zone between tropical and extra-tropical circulation and precipitation patterns. It is characterized not only by extreme variability, but also by extreme climate changes in the past. It is not within the purpose of this study to discuss the effects of these changes on the vegetation, and especially on the migration of elements of the flora (Kalin Arroyo *et al.*, 1988). It is evident, however, that the key element for support of life in this zone is water availability. Therefore, any discussion about protected areas must acknowledge that the water resources are not only vital to flora and fauna, but have also been the basis of all human activities in the past and present; as development of resources, especially mining, proceeds, water availability will become progressively more critical in the future. If the highest priority is not given to the protection of water resources, especially in the most arid mountain ecosystems between about 18 and 30° S, very soon natural habitats will be destroyed and the agricultural, tourist, and economic (mining) developments will be endangered.

In recent years several field research studies have been undertaken in Northern Chile to increase understanding of past climate change, from the last cold maximum at about 18,000 BP, through the Holocene, to the present; there was a special focus on the more humid periods in the past and their significance for today's water supply. The rapidly growing conflicts between natural resource management and economic development were indicated; of special significance is the use of non-renewable water reserves, which has increased the demand for water. In this light, the following questions are serious and urgent: (1) will an overuse of water, especially of fossil water, destroy natural habitats and endanger economic development? (2) can researchers and decision makers on all levels be encouraged to understand each other and to openly share all available information? (3) can a coordinated program for protected areas be a long-term solution to reconcile different interests and development objectives?

WATER RESOURCES AND CLIMATE CHANGE

In the context of the above-mentioned conflicts between economic development, cultural heritage, and natural habitats, water resources are widely seen as the most critical element for the sustainable development of this area; availability of water is the most likely limiting factor for future activities. Despite this, there is little knowledge about groundwater storage, modern water recharge, and about the age and the origin of water resources. Thus, in order to assess the potential effects of large-scale water extraction for whatever reason, the following uncertainty must be clarified: does groundwater recharge occur under the existing hyper-arid climatic conditions or are the groundwater resources of the Atacama Desert mainly fossil, non-renewable resources formed during significantly more humid, pluvial climatic phases in the past?

Clarification of this uncertainty was one of the major

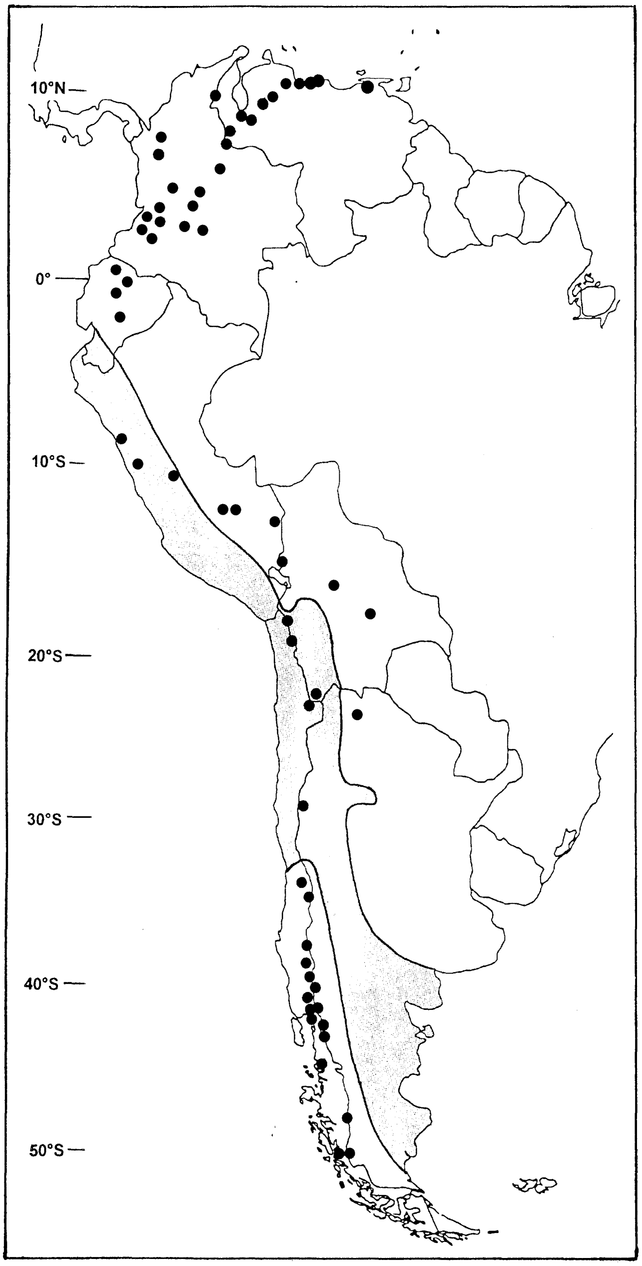

FIGURE 1: Mountain protected areas in the Andes (dots) and the Andean dry diagonal (shaded areas represent regions with less than 500 mm annual precipitation). Source: World Conservation Monitoring Centre.

goals of the project, 'Climate Change in the Arid Andes.' Modern precipitation patterns were assessed (Ammann, 1996; Vuille, 1996), past climatic conditions and precipitation rates were reconstructed from a large set of proxy data (e.g., Messerli *et al.*, 1993; Grosjean, 1994), and modern components (i.e., < 40 years) were evaluated. The origin and age of water in lakes, rivers, and groundwater bodies on the Altiplano (Grosjean *et al.*, 1995) were also investigated.

Modern precipitation on the Altiplano is highly variable in space and time. Annual precipitation rates rarely exceed 150–200 mm/yr in the center of the arid diagonal. Field measurements and sequential digital NOAA/AVHRR data show that winter snowfall was heavily underestimated as a potential source of water (Vuille and Baumgartner, 1993; Vuille, 1996). However, observations during the ablation phase of the winter snow cover, and isotope data ($\partial^{18}O$, D) on modern precipitation and groundwater, suggest that this water source does not contribute to groundwater formation. Up to 70 percent of the snow is lost to the atmosphere due to sublimation, and infiltration of meltwater is limited due to frozen ground during winter time. Tritium ^3H is an ideal isotope for tracing modern water components and thus for evaluating recharge in groundwater bodies with atmospheric water within the last 40 years. Tritium data strongly support the finding that modern recharge of the groundwater bodies and springs is very limited in small, high-elevation catchments, and even below the detection level in larger, (sub)regional discharge systems. Determining the age of groundwater with ^{14}C data on total dissolved inorganic carbon compounds (TDIC) is an approach with inherent methodological difficulties (Fritz *et al.*, 1979; Grosjean *et al.*, 1995). However, the $^{14}C_{TDIC}$ data from a large number of catchments on the Altiplano suggest that a high proportion of the existing water resources can be assigned to the Late-Glacial/early Holocene humid Tauca phase and/or, to some extent, related to individual, heavy storms with short-term flooding during the Holocene. These findings are in agreement with an increasing number of results from isotope hydrologic studies in adjacent areas, including the Atacama lowlands, in particular in the protected area of the Pampa de Tamarugal (Fritz *et al.*, 1979; Magaritz *et al.*, 1990; Aravena, 1995). Furthermore, Pourrut (1995) concluded that the discharge in the Rio Salado (22°15′ S) is fully decoupled from modern precipitation; unrealistically high runoff-coefficients of 0.52 on average (observation period 1975–1990) would be required to account for the measured river discharge. In summary, it is concluded that modern hyper-arid climatic conditions have little or no effect on the recharge of water resources in the Atacama area. Modern recharge, although at very limited rates, is restricted to the high-elevation belt of the Altiplano. This shows the crucial importance of the Altiplano with regard to regional water supply. The current climate is so arid that there are no glaciers, even in the continuous permafrost belt above 5,600 m.

What kind of climate prevailed at the time of groundwater formation? Lake sediments and carbonate deposits on fossil shorelines from large paleo-lakes (Figure 2), glacial deposits, and archaeological sites provide detailed information about significant changes in climate in the past. Environmental conditions during the last global cold maximum (18,000 ^{14}C yr BP) were even drier than those of today. Such harsh conditions were followed by the humid Tauca phase during Late-Glacial and early Holocene times (14,000 to 8,500 ^{14}C yr BP). Precipitation rates increased to more than 500 mm/yr (compared to < 200 mm/yr today), and lake surfaces expanded by a factor of 6 to > 10. Some of these freshwater lakes were up

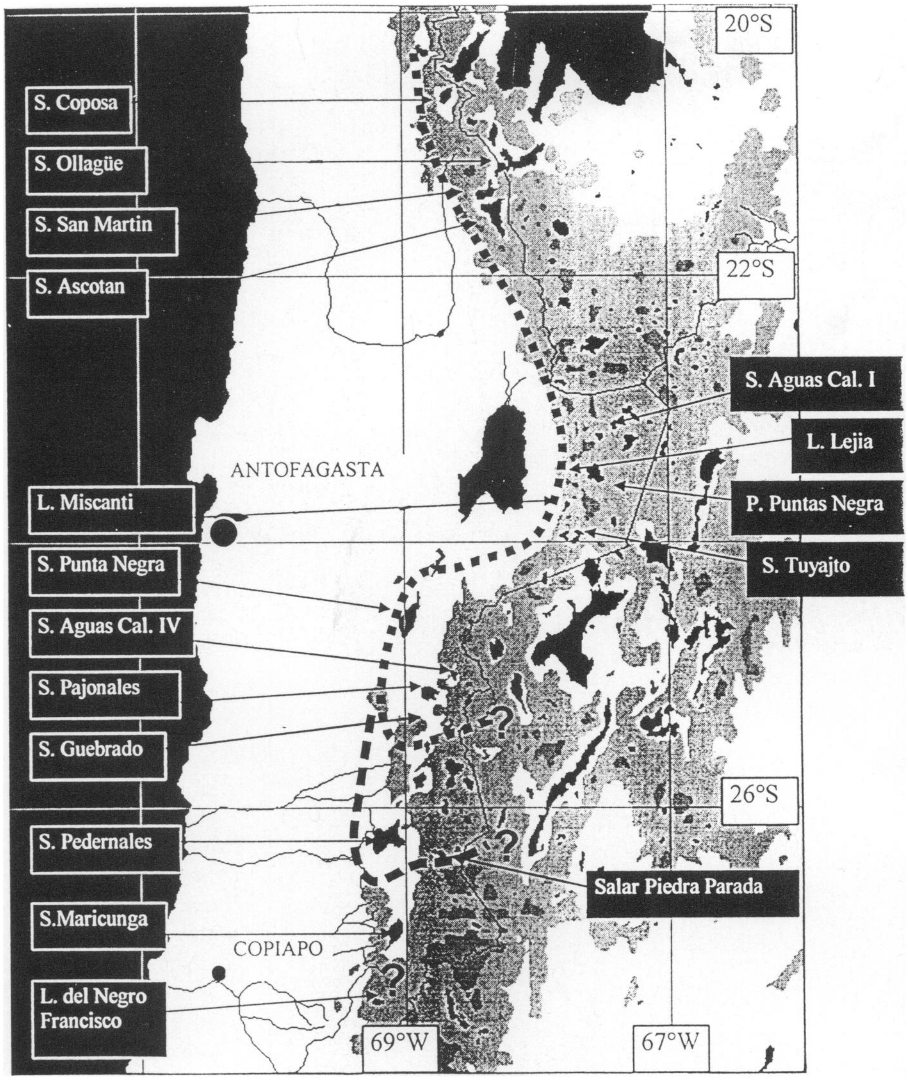

FIGURE 2: Paleo-lake basins in the research area; the dotted line represents the western and southern border of the area with Tauca phase paleo-lakes (14,000–8,500 yr BP). The shaded area represents the Altiplano above 4,000 m.

to 70 m deep (Figure 3) and lasted for more than 1,000 years at these levels. Evidence of the Tauca lakes was found in the Titicaca area, in the Uyuni basin, and in more than 12 endorheic basins on the Chilean Altiplano between 21 and 25° S. In contrast to the modern situation, Andean glaciation was widespread at that time (Clapperton, 1993; Jenny and Kammer, 1996), and coexisted with the high paleo-lake stands. It is interesting to note that the first phase of human occupation in this area (10,800–8,000 yr BP) was related to such favorable environmental conditions, characterized by abundant water, animal, and vegetation resources (Nuñez, 1994; Grosjean and Nuñez, 1994). The available proxy data for this time indicate a fundamental change in the ecosystem: the landscape at 24° S might have looked similar to the Altiplano at 18°, with impressive glaciers, lakes, and high biodiversity, as found today in the Lauca National Park and the Sajama area (UNESCO, 1994; Liberman, 1995).

A significant, abrupt shift towards hyper-arid conditions took place after 8,500 ^{14}C yr BP. Detailed seismic profiles across lake basins, and high-resolution records of lake sediment cores suggest significantly lower lake levels than those of today. Such hostile environmental conditions culminated in a regional hiatus in human occupation, the 'Silencio Arqueológico', between 8,000 and 4,800 ^{14}C yr BP. Such extremely arid conditions were interrupted by low-frequency, heavy storms. These are evidenced by individual debris flows in canyons, and flood deposits on the plains (e.g., in the Salar de Atacama). Radiocarbon dating showed return periods of about 200 years for such events. Subsequently, modern climatic conditions were established between 3,600 and 3,000 yr BP. Preliminary results from lake sediments suggest drier conditions than those of today during the Little Ice Age (Valero-Garces *et al.*, forthcoming).

The late Quaternary climatic history of this area leads to the conclusion that, potentially, two distinct climatic phases have favored groundwater recharge: the extended humid Tauca phase, with precipitation rates higher than 500 mm/yr and, to a lesser degree, a heavy mid-Holocene storm period, with short-term floods. The current state of knowledge suggests that both paleoclimatic episodes have been spatially restricted to the Altiplano.

FIGURE 3: Impressive fossil shorelines in the basin of Salar San Martin. The Tauca phase paleo-lake was 70 m deep.

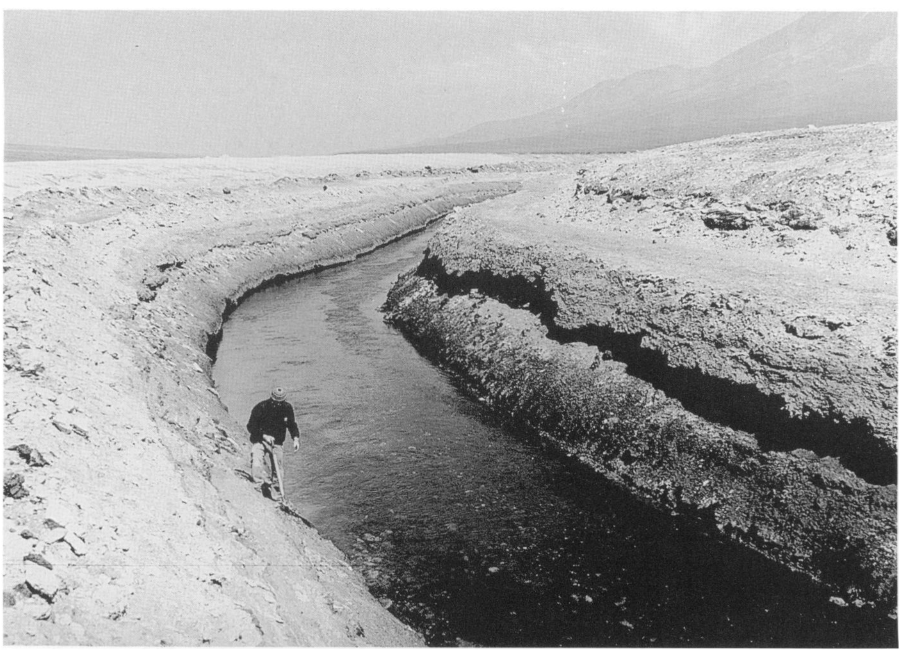

FIGURE 4: An artificial channel for water extraction in the Ojos de San Pedro area. What was once an extended wetland, floral, and faunal habitat at 37,110 ^{14}C yr BP, (the date for the basal peat strata at 380 cm depth) is now a desiccated, anthropogenically induced desert.

What are the consequences of past and present climatic conditions for the topic under discussion?

- Modern recharge of water resources is extremely limited in the Atacama Desert. Traces of a modern component in the groundwater are found exclusively in small, high-elevation catchments. ^{14}C and ^{3}H data on groundwater suggest that the humid Late-Glacial/ early Holocene Tauca phase accounted for much of the formation of present-day water resources in the area. Thus, modern economic development (mines, tourism, urban growth), the cultural heritage, and natural habitats in lower regions depend largely on fossil water reserves which are barely renewable or even non-renewable. It is emphasized that the high-elevation sites on the Altiplano, are of outstanding importance because they are the present and past recharge areas for the regional water supply at lower elevations (e.g., Salar de Atacama, Pampa de Tamarugal).

- Past and present conditions show the high sensitivity of Altiplano ecosystems to the smallest changes in hydrologic conditions. This implies that anthropogenically-induced changes (e.g., water extraction for agriculture or mining) must be carefully assessed in order to prevent damage (Figure 4). A watershed approach is therefore mandatory when boundaries for protected areas with aquatic systems (lakes, salars, 'bofedales,' or peat bogs) are defined. Under the prevailing hydrogeological conditions on the Altiplano, it is not appropriate to focus exclusively on areas with high biodiversity, e.g., around lakes. The entire catchment, including the groundwater basins and the source area of the open water, must be evaluated and included in protected area designation.

VEGETATION COVER AND PLANT DIVERSITY IN AN EXTREMELY ARID MOUNTAIN ENVIRONMENT

Although this area of the Andes is extremely arid, it is by no means a total desert with no plant cover. These harsh environmental conditions (extreme aridity and low temperature) restrict diversity but, nevertheless, the limiting climatic factors, precipitation and temperature, produce a unique and distinctive vegetation pattern depending primarily on elevation and latitude. This is indicated by a study carried out by Kalin Arroyo *et al.* (1988), which analyzed the present-day vegetation cover and species spectra in this part of the Andes.

The study analyzed six vegetational transects across the Andes, located at 18, 19, 21, 24, 26, and 28° South (Figure 5). In all transects the lower vegetation limit was determined by lack of precipitation, while the upper limit was controlled by low temperatures which inhibited any further plant growth. In the northern transects (at 18, 19,

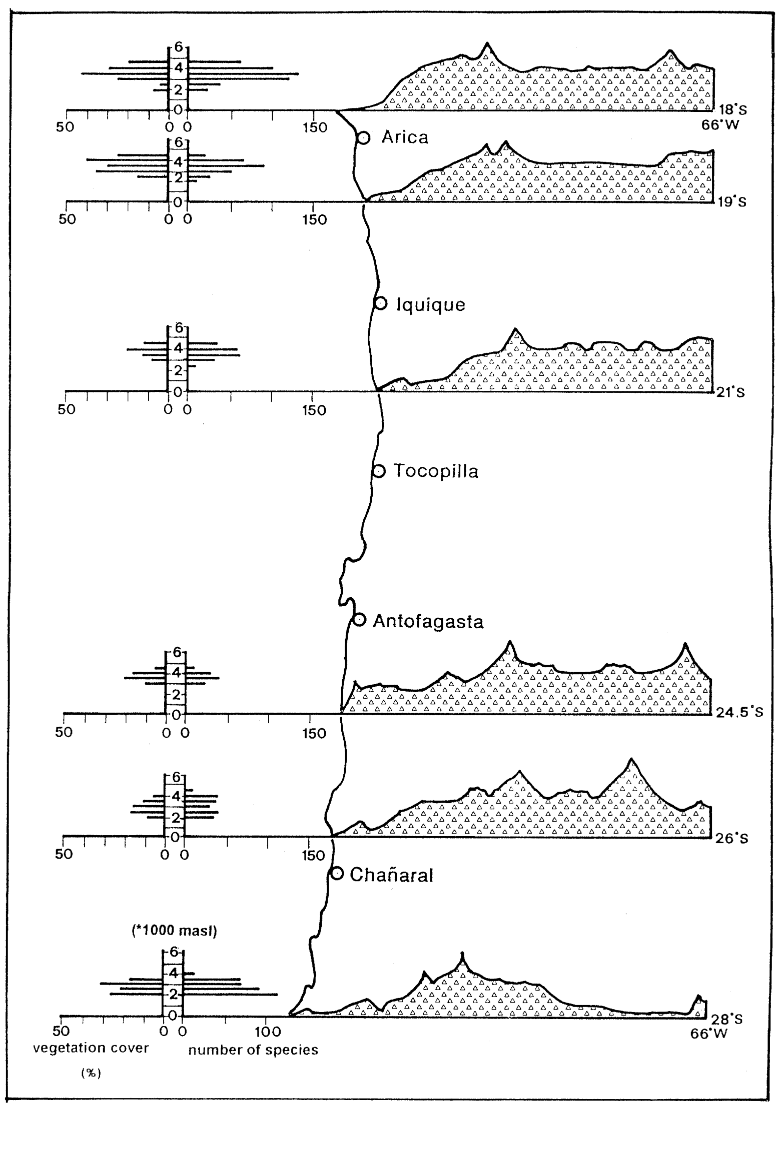

FIGURE 5: Vegetation cover and number of species as a function of elevation and latitude.
Data source: Kalin Arroyo *et al.*, 1988; Messerli *et al.*, 1992.

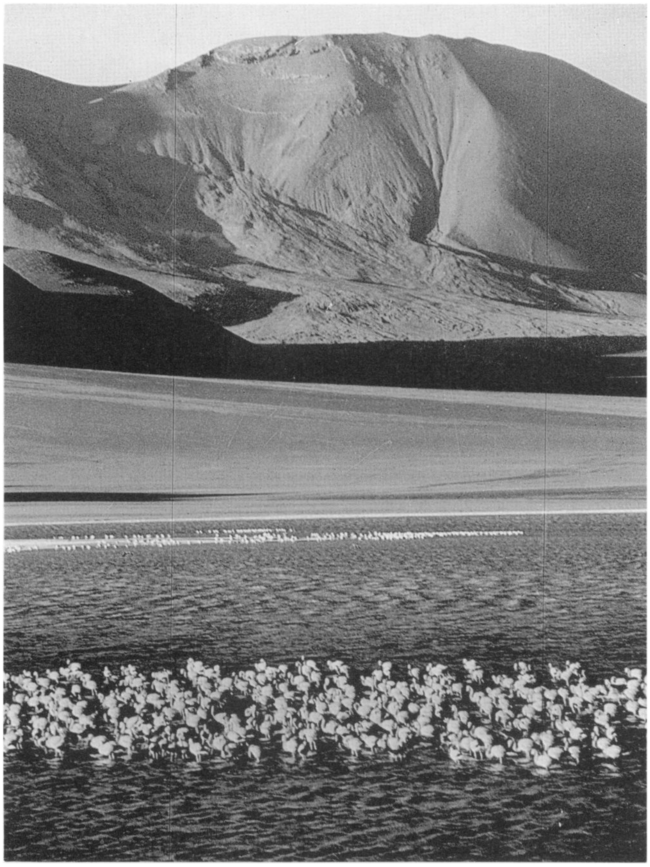

FIGURE 6: Altiplano lakes are important feeding grounds for flamingo populations. Laguna Lejía is host to the largest number of flamingos but is not part of the 'Los Flamingos' protected area.

21, and 24° South), still within the tropical summer rainfall zone, species abundance peaks at middle elevations between 3,500 and 4,500 m. This elevation belt represents optimum growth conditions (enough precipitation and still moderate temperatures). Polylepis trees can be found ranging from relatively dense stands at Sajama National Park at 18° South (Liberman, 1995) to the last dwarf-trees north of Ollagüe at 21° South. At lower elevations, precipitation decreases rapidly, resulting in very sparse vegetation cover. All of these northern transects receive most of their precipitation between November and April, due to an intensification and southward displacement of the tropical circulation zone.

In the winter precipitation zone (transects at 26 and 28° South), species abundance is highest at lower altitudes, between 2,000–3,000 m, and decreases with increasing elevation, due to the lower temperatures. Below 2,000 m lack of precipitation prevents growth of vegetation. In the area of these two transects, precipitation is most abundant from May through September, originating in the planetary west-wind zone.

The change in vegetation cover and species abundance from north to south reflects a change in the temperature regime as well as a change from a convective summer precipitation regime in the north to an advective winter regime in the south. However, the influence of both precipitation regimes diminishes towards the center of the study area. This fact is reflected by the much less dense vegetation cover and decreasing species abundance in the central transects at 21, 24, and 26° South. This part of the Andes is regarded as the most arid region, where the diagonal of aridity crosses from west to east. The steep tropical rainfall gradient, leading to a 80 percent decrease in species abundance and a 50 percent decrease in the vegetation cover, is very evident between 18 and 24° South.

In conclusion, the study undertaken by Kalin Arroyo *et al.* (1988) indicates the great dependence of plant species on the availability of water. Only minor climatic changes or changes in the water budget of an area can induce a dramatic gain or decrease in vegetation cover and plant diversity. Furthermore, many species in this arid environment are limited to bog habitats, which are very important grazing resources for the Altiplano pastoral economy. These bog habitats show less dependence on precipitation. Their presence depends more on the availability of local freshwater or groundwater (Ruthsatz, 1995). It is self-evident that these bog habitats are extremely sensitive to any artificial water transfers with the danger of immediate and irreversible habitat destruction. This aspect has to be considered when discussing the future water demands of the growing Chilean economy.

Moreover, many animal species live in this arid zone. Vicuñas and guanacos are most prominent amongst the mammals. Where there are open water bodies in the arid Andes there is very rich avifauna (Figure 6). In the Lauca National Park (18° South) about 150 species occur, including all three Andean species of flamingos (Veloso and Bustos, 1982; UNESCO, 1994).

It must be emphasized that the arid Andes are by no means a region without fauna and flora, where human impacts have no consequences. However, because of the extreme sensitivity and vulnerable adaptation of the vegetation to this harsh environment, even minor human interventions can lead to destruction or irreversible change. Therefore, the costs of human impact can be very high, and must be carefully considered before intervention in such a fragile mountain area.

PROTECTED AREAS AND WATER RESOURCES

The subtropical arid zones always constitute barriers and borders between tropical climate and vegetation on one side and a Mediterranean-temperate type of climate and vegetation on the other side. This situation is reinforced in South America by the north–south Andean cordillera. Reduced precipitation, or lack of precipitation, in this arid belt has led to reduction or lack of plant diversity and tree cover. For this reason it was not considered necessary to create national parks and protected areas at the same rate as in the neighboring climatic zones, especially in the inaccessible higher parts of the Andes. The lack of protected areas between about 20 and 32° South is clearly indicated on Figure 1.

However, the protection of biodiversity cannot be only a question of quantification. It should be emphasized that the arid belt is a most interesting transition zone where the climatic conditions have changed dramatically several times in the last 20,000 years. Here, the vegetation has adapted through extensive altitudinal and latitudinal differentiation to the harsh and highly dynamic environment. Some species and associates could form a certain reservoir for migration in the event of future climatic change. Reduced diversity under these highly sensitive conditions can also represent richness. But most important is that people, plants, and animals depend on the universal life-limiting factor: water!

Infrastructure for water capture and water drilling can be seen throughout the Altiplano (Figure 4). Water pipelines extend for hundreds of kilometers from the higher Andes to the mining industrial complexes and the large towns on the Pacific coast. Soil and water contamination around the mines is inevitable. Moreover, a high percentage of this water could be non-renewable or fossil, and the processes of development may be irreversible on a time scale of generations. This could lead to devastation of most sensitive ecosystems, and also provide a threat to the region's growing population and economy.

Figure 7 shows the interaction between the resources of the Andes and the intended and unintended processes that are taking place. Investments for mining in this area are among the highest in the world, with more than US $10 billion foreseen for the near future (Romero and Rivera, 1996). The costs of the unintended and unpredictable processes, however, are still unknown. Assessment and allocation of potential costs cannot be determined. Moreover, in zones where surface or ground water is available, export-oriented agriculture (for example, table grapes in the valley of Copiapo), with high water demand, is being practiced. But tourism is also growing (e.g., in the area of San Pedro de Atacama) and depends on exploitation of new water sources.

In view of the growing potential for conflicts, new initiatives for protected areas in the arid Andes have been taken in Argentina, Chile, and Bolivia. The Aconquija and Ojos del Salado national parks planned in Argentina (Halloy *et al.*, 1991; 1994), covering parts of the provinces of Tucuman, Catamarca, and Salta, hold great promise for the future. The protected areas in Bolivia have been indicated on a vegetation map (Ribera *et al.*, 1994), and in Chile several new protected areas are being planned, such as those in the regions of San Pedro de Atacama, Salar Maricunga, and Ojos del Salado. Of special interest is the Chilean National Biodiversity Action Plan (WRI *et al.*, 1995). Of all the Andean countries, Chile has the highest number (21) and the largest extent (8.5 million ha) of mountain protected areas (Thorsell and Paine, 1995) and more than 18 percent of the country is included in legally designated protected areas (Pardo *et al.*, 1994). It is interesting to note that the last World Congress on National Parks and Protected Areas designated national needs as follows: in Chile the Atacama Desert belongs to the under-represented ecosystems; in Argentina the Andean Patagonia is insufficiently covered; in Bolivia special areas of the Puna and the Andean highlands with inter-Andean dry valleys have no protected areas; and in Peru, the mountain ecosystems are severely degraded and under-represented in the current network (Pardo *et al.*, 1994: 355, 357). The establishment of new protected areas in the arid Andes becomes crucial because very little is known about the water resources and the recharge of the groundwater under present climatic conditions. Completely dry basins with no vegetation nor animals prove that unknown water resources have been overused and that there is no information on how much of a certain groundwater basin is renewable and how much is non-renewable. Research and management are needed to reach the overriding goal of mountain protected areas, which should include water conservation and the maintenance of landscapes, because landscape protection provides the greatest hydrologic safety for the future in this fragile environment (Poore, 1992: 20-23; Harmon, 1994).

CONCLUSIONS

There are many publications that include guidelines for protected areas (IUCN and World Conservation Monitoring Centre, 1994) and especially for mountain protected areas (Poore, 1992), management planning guidelines (Alexander, 1995), guidelines for the coordination of research and management (Harmon, 1994), the current state of knowledge (UNESCO, 1994, Thorsell, 1995; Thorsell and Paine, 1995; Hamilton, 1995), the integrated program for the Andes (Oliveira Costa, 1993), and future needs (Pardo *et al.*, 1994).

Research needs for decision making:

No important water distribution system should be initiated without improved knowledge of available resources, their origin, and age. This research is expensive and requires the best methods and techniques currently available; it can be undertaken only with the support of governments, the mining industry, and urban and village authorities. Maps of water protection zones should be prepared at different scales; they are an important tool for decision making. They should indicate the depth of groundwater and the quantity of surface stream flow, estimate reservoir size, and provide information on the recharge situation, absolute age determination, and proposed protection measures. To avoid overuse of resources and collapse of the economy, it will be necessary to set priorities among the demands of the mining industry, urban centers and villages, agriculture, and tourism, and to regulate local

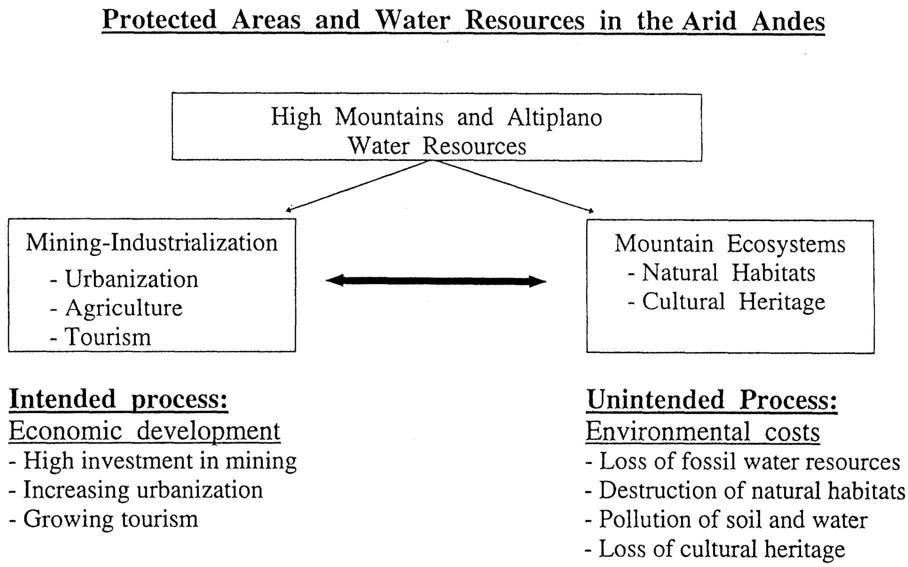

FIGURE 7: Highland-lowland interactions: processes and conflicts.

and regional distribution of available water. Without scientific knowledge and without cooperation among different users, destruction of unique mountain ecosystems appears inevitable. This would lead to crises in the economic development of certain regions.

Long-term economic and ecological planning by all partners:
It is no longer acceptable that concessions for ore exploitation in a certain area are granted with no restrictions or limitations. At present mining companies, for example, have the right to keep their estimations of water resources secret. Why are they not willing to allow water analysis by a neutral and competent scientific institution? Why are the results of their drilling activities not known to the government and administrators? Many legal and political problems remain unsolved; lack of attention to them is evidence of short-term economic thinking which could have severe economic, financial, environmental, and even political consequences in the long term. Without governmental and public control of water and of natural resources, and without the goodwill of the economic community, especially foreign investment companies from North America, Europe, and Japan, there will be no chance to continue the present development process in the long term. The mistakes of today must be paid for tomorrow.

Protected areas and sustainable development:
The creation of protected areas in the most sensitive zones of the High Andes can be a small, modest, but important measure to preserve the environment and the all-important water resources. It is the task of governments and their administrative units to institutionalize the necessary legal base and to take the responsibility for efficient management. In the case of the arid Andes, this includes measures for protection of plant diversity, habitats of rare and endangered plant and animal species, landscapes for traditional pastoral farming and tourism, and archaeological, historical, and cultural heritage, sites. But it is the water resources that are the critical element for all future economic development. In the final analysis, the High Andes, source of precipitation and water reservoirs, will determine the 'limits to growth' for the whole region.

Lawrence S. Hamilton has written:

> Montane areas are often the last bastions of wild nature in a sea of transformed landscape, so the task of maintaining the natural heritage of a region or a nation often falls mostly on the mountains. In the case of the continent-long Andean Cordillera, a corridor of linked protected areas of various kinds would offer needed opportunities for migration and gene-flow of the wonderful biodiversity of the Andean uplands.
> Hamilton, 1996

Transboundary parks or protected areas would reinforce the concept of a habitat corridor and solve many political conflicts, in some cases even those related to water resources. The vision of a corridor of protected areas along the Andes from the Caribbean Sea to Tierra del Fuego must include the arid central region as a connecting area between the humid northern and southern Cordillera.

ACKNOWLEDGEMENTS

This study was made possible by a grant from the Swiss NSF (20-36382-92). We thank W. Egli, Marcela Espinoza (DIFROL), and CONAF for supporting the fieldwork and the "Chilean" team for discussion and comments.

REFERENCES

Alexander, M., 1995: Management planning in relation to protected areas. IUCN Gland, Switzerland. *Parks,* 5 (1): 2–11.

Ammann, C., 1996: Climate Change in den trockenen Anden. Aktuele Niederschlagsmuster. *Geographica Bernensia,* G46. Institute of Geography, Berne.

Aravena, R., 1995: Isotope hydrology and geochemistry of Northern Chile groundwaters. *Proceedings, Aguas, Glaciares y Cambios Climaticos en los Andes Tropicales.* ORSTOM/UMSA/SENAMHI/CONAPHI, La Paz, pp. 109–117.

Clapperton, C., 1993: *Quaternary Geology and Geomorphology of South America.* Elsevier, Amsterdam, London, New York. 779 pp.

Fritz, P., Silva, C. H., Suzuki, O., and Salati, E., 1979: *Isotope Hydrology in Northern Chile.* IAEA-SM-228/26, pp. 525–543.

Grosjean, M., 1994: Paleohydrology of the Laguna Lejía (north Chilean Altiplano) and climatic implications for late-glacial times. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 109: 89–100.

Grosjean, M., Geyh, M. A., Messerli, B., and Schotterer, U., 1995: Late-glacial and early Holocene lake sediments, groundwater formation and climate in the Atacama Altiplano 22–24° S. *Journal of Paleolimnology,* 14/3: 241–252.

Grosjean, M., Messerli, B., Ammann, C., Geyh, M. A., Graf, K., Jenny, B., Kammer, K., Nunez. L., Schotterer, U., Schreier, H., Schwalb, A., Valero, B., and Vuille, M., 1995: Holocene environmental changes in the Atacama Altiplano and paleoclimatic implications. *Bull. Inst. Français Etudes Andines,* 24(3): 585–594.

Grosjean, M. and Nuñez. L. A., 1994: Lateglacial, Early and Middle Holocene environments, human occupation, and resource use in the Atacama (Northern Chile). *Geoarchaeology: An International Journal,* 9 (4): 271–286.

Halloy, S., González, J. A., and Lavilla, E. U., 1991: Propuesta de una Reserva de Flora y Fauna autóctonas en el área del Ojos del Salado (Catamarca–Argentina). Límites, Zonificación y Maneja. Serie Conservación de la Naturaleza 5, Fundación Miguel Lillo, Tucuman, Argentina. 15 pp.

Halloy, S., González, J. A., and Grau, A., 1994: Proyecto de Creación del Parque Nacional Aconquija (Tucuman). *Serie Conservación de la Naturaleza* 9. Fundación Miguel Lillo, Tucuman, Argentina. 55 pp.

Hamilton, L. S., 1995: Sustainable mountain development and key control areas for mountain conservation. Paper presented at the Second International Symposium on Sustainable Mountain Development. Huarina–La Paz (Unpublished).

______, 1996: The role of protected areas in sustainable mountain development. *Parks,* 6(1): 2–123.

Harmon, D. (ed.), 1994: *Coordinating Research and Management to Enhance Protected Areas.* IUCN with G. Wright Soc, SMPAA, Comm. of the Europ. Union. 116 pp.

IUCN, 1994: Forest Conservation Programme. *Newsletter,* 18. 16 pp.

IUCN and World Conservation Monitoring Center, 1994: *Guidelines for Protected Area Management Categories.* Gland, Switzerland. 261 pp.

Jenny, B. and Kammer, K., 1996: Climate Change in den trockenen Anden. Jungquartäre Vergletscherungen. *Geographica Bernensia,* G46. Institute of Geography, Berne, Switzerland.

Kalin Arroyo, M. T., Squeo, F. A., Armesto, J. J., and Villagran, C., 1988: Effects of aridity on plant diversity in the northern Chilean Andes: Results of a natural experiment. *Ann. Missouri Botanical Gardens,* 75: 55–78.

Lauer, W. and Erlenbach, W., 1987: Die tropischen Anden. *Geographische Rundschau,* 39, H.2: 86–95.

Liberman, M., 1995: Los Bosques de Polylepis Tarapacana en el Parque Nacional del Nevado Sajama. II Internat. Symposium on Sustainable Mountain Dev., Field guide, Bolivia, pp. 61–69.

Magaritz, M., Aravena, R., Peña, H., Suzuki, O., and Grilli, A., 1990: Source of ground water in the deserts of northern Chile: Evidence of deep circulation of ground water from the Andes. *Ground Water,* 28/4: 513–517.

Messerli, B., Grosjean, M., Graf, K., Schotterer, U., Schreier, H., and Vuille, M., 1992: Die Veränderungen von Klima und Umwelt in der Region Atacama (Nordchile) seit der letzten Kaltzeit. *Erdkunde,* 46: 257–272.

Messerli, B., Grosjean, M., Bonani, G., Bürgi, A., Geyh, M. A., Graf, K., Ramseyer, K., Romero, H., Schotterer, U., Schreier, H., and Vuille, M., 1993: Climate change and dynamics of natural resources in the altiplano of northern Chile during Late Glacial and Holocene time. First Synthesis. *Mountain Research and Development,* 13(2): 117–127.

Nuñez, L. A., 1994: The western part of South America: southern Peru, Bolivia, north-west Argentina and Chile during the Stone Age. *In* De Laet, S. J. *et al.* (eds.), *History of Humanity, Vol. I: Prehistory and the Beginning of Civilization.* Unesco, Paris, pp. 348–362.

Oliveira Costa, J.P., 1993: *Programa Integrado de Conservación Ambiental y Desarollo Sustenable de la Cordillera de los Andes.* Anexo 2. IUCN, La Paz, Bolivia, pp. 44–48.

Pardo, C., Torres, H., and Ormazábal, C., 1994: *South America. Protecting Nature. Regional Reviews of Protected Areas.* IV World Congress on Nat. Parks and Prot. Areas, Caracas, Venezuela. IUCN, Gland, Switzerland, pp. 347–372.

Poore, D., 1992: Guidelines for Mountain Protected Areas. IUCN, Gland, Switzerland, *Protected Area Programme,* Series No.2. 47 pp.

Pourrut, P., 1995: *Existencia de Agua en la IIa Región de Chile: Interrogantes e hipótesis. Proc. Aguas, Glaciares y Cambios Climáticos en los Andes Tropicales,* ORSTOM/UMSA/SENAMHI/CONAPHI, La Paz, pp. 119–129.

Ribera, M. O., Liberman, M., Beck, S., and Morales, M., 1994: Mapa de la Vegetación y Areas protegidas de Bolivia 1:500,000. Inst. de Ecología, La Paz.

Romero, H. and Rivera A., 1996: Global Changes and Unsustainable Development in the Andes of Northern Chile. *JB Geogr. Gesellschaft,* Bd.58. Berne, Switzerland (in press).

Ruthsatz, B., 1995: Vegetation und Ökologie tropischer Hochgebirgsmoore in den Anden Nord-Chiles. *Phytocoenologia,* 25(2): 185–234.

Thorsell, J., 1995: Parques y reservas de la cordillera de los Andes. *Flora, Fauna y Areas Sylvestres* (FAO), 9(22): 23–26.

Thorsell, J. and Paine, J., 1995: Mountain Parks and Reserves in the Andes. Paper presented at the Second International Symposium on Sustainable Mountain Development. Huarina–La Paz (Unpublished).

UNESCO, 1994: *Biosphere Reserve Directory.* Chile. Unesco, Paris.

Valero-Garces, B., Grosjean, M. Schwalb, A., Geyh, M. A., Messerli, B., and Kelts, K., (forthcoming). Late Holocene environmental change in the Atacama Altiplano: Limnogeology of Laguna Miscanti, Chile. *Journal of Paleolimnology* (spec. Issue AMQUA Vol II)

Veloso, A. M. and Bustos, E. O., 1982: *La vegetación y los vertebrados ectotérmicos del transecto Arica–Lago Chungara.* UNESCO MAB 6. ROSTLAC, Montevideo. 327 pp.

Vuille, M., 1996: Zur raumzeitichen Dynamik von Schneefall und Ausaperung im Bereich des südlichen Altiplano, Südamerika. *Geographica Bernensia,* G 45. Institute of Geography, Berne, Switzerland. 117 pp.

Vuille, M. and Baumgartner, M. F., 1993: Hydrologic Investigations in the North Chilean Altiplano Using Landsat–MSS and–TM Data. *Geocarto International,* 8,(3): 35–45.

WRI, UNEP, and IUCN, 1995: *National Biodiversity Planning. Guidelines Based on Early Experiences Around the World.* Washington, Nairobi, Gland. 161 pp.