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Landsat TM inventory and assessment of waterbird habitat in the southern *altiplano* of South America

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Abstract

The diverse set of wetlands in southern *altiplano* of South America supports a number of endemic and migratory waterbirds. These species include endangered endemic flamingos and shorebirds that nest in North America and winter in the *altiplano*. This research developed maps from nine Landsat Thematic Mapper (TM) images (254,300 km^2) to provide an inventory of aquatic waterbird habitats. Image processing software was used to produce a map with a classification of wetlands according to the habitat requirements of different types of waterbirds. A hierarchical procedure was used to, first, isolate the bodies of water within the TM image; second, execute an unsupervised classification on the subsetted image to produce 300 signatures of cover types, which were further subdivided as necessary. Third, each of the classifications was examined in the light of field data and personal experience for relevance to the determination of the various habitat types. Finally, the signatures were applied to the entire image and other adjacent images to yield a map depicting the location of the various waterbird habitats in the southern *altiplano*. The data sets referenced with a global positioning system receiver were used to test the classification system. Multivariate analysis of the bird communities censused at each lake by individual habitats indicated a salinity gradient, and then the depth of the water separated the birds. Multivariate analysis of the chemical and physical data from the lakes showed that the variation in lakes were significantly associated with difference in depth, transparency, latitude, elevation, and pH. The presence of gravel bottoms was also one of the qualities distinguishing a group of lakes. This information will be directly useful to the Flamingo Census Project and serve as an element for risk assessment for future development.

Introduction

The Andean *altiplano* of South America stretches from Peru southward to Bolivia, Chile, and Argentina. Cabrera and Willink (1980) divide the southern *altiplano* into two biotic provinces: the *altoandina* zone which consists of the high mountains above ~4500 m, and the *puna* encompassing the surrounding high tableland which ranges from 2000 to 4500 m. Geographically the *altiplano* is divided by the major cordilleras of the Andes and further separated by volcanism and local uplift into a system of endorheic basins called *salares* (Stoertz and Ericksen 1974). The northern portion of the *puna* has an annual rainy season from November through February; the region in the southern portion has its precipitation in the form of snowfall June–August (Vuille 1999; Vuille et al. 2000).

This combination of physical and climatological factors results in a variety of interiorly drained *salares* in the *puna* that contain often times highly saline, shallow lentic aquatic habitats locally called *lagos* or *lagunas*, located in the high dry shrub–grassland biogeographic zone called the *puna*. Very often these bodies of water have peripheral aquatic habitats called *vegas*, or locally known as *bofedales*, which form specialized wetlands supported by springs (Ruthsatz and Pia Movia 1975). Some of these wetlands are found even higher into the *altoandina* zone, at 5000 m and above (Ericksen 1993).

Aquatic ecosystems in the southern *altiplano* support an astonishingly rich diversity of avifauna, comprised of migratory waterfowl and 12 species of endemic birds, including three species of flamingos, two of which are unique to the *puna*, the Andean and James flamingos (*Phoenicoparrus andinus* and *Phoenicoparrus jamesi*). Both have recently been listed by the United Nations Environmental Program Convention on Migratory Species, by the Red Data Book (Collar et al. 1992), and by Partners in Flight as endangered species. One of these species, James flamingo, thought to be extinct between the early 1900s and the 1960s (Conway 1960, 1961), is found only in a limited area of the Andes where northern Argentina, southern Bolivia, and Chile come together. Breeding appears to be restricted to only a few *lagunas* in this region. New sites of importance to several species have been found indicating incomplete knowledge of their distribution. For example a group of James flamingos numbering more than 10,000 individuals was found in summer 1998 and 2000 by the census of the High Andes Conservation Group in Laguna Grande, Catamarca, Argentina (Caziani et al. 2001; High Andes Flamingo Conservation Group 2001). Nevertheless, the vast majority of these birds were found in a small number of *lagunas*. Breeding colonies are known from only a few areas (Valqui et al. 2000).

Accelerated development makes the present a critical time to develop inventories of the natural resources and their supporting habitats in the *altiplano.* In spite of the importance of this region in supporting hemispheric biological diversity, especially for both resident and migratory avifauna, its remoteness and difficulty of accessibility due to a lack of roads, topography, and elevation have prevented the acquisition of important data. Several electric power transmission lines and gas pipelines have recently crossed the Andes in the area covered in this study. Recent exploration in this area by mining interests and other development produce an array of threats to water resources and critical habitats for flamingos and other migratory waterbirds in this area. Surface and ground water withdrawal has already affected bird habitat associated with *lagunas* and *bofedales* or *vegas* in some areas of the *altiplano* (Messerli et al 1997; Carrasco 1999).

In order to identify, manage, and protect the natural resources critical to sustaining endemic and migratory waterbirds of the *altiplano*, the products from this research will provide critical elements in the risk analysis of these natural resources by providing an inventory, location, and evaluation of attributes of water bird habitat. The *lagunas* within the *altiplano* included in this study area several protected areas, including Argentine, Bolivian, and Chilean National Parks, UNESCO Biosphere Reserves, and six wetland areas designated under the International Ramsar Wetland Protection Treaty, as well as several areas under consideration for future designation as protected areas by the Argentine National Park Service, Ramsar Convention, and the World Heritage Convention (Blanco and Canevari 1998). Moreover, the lakes of the *puna* are also critical in supporting an array of avian species in that these aquatic ecosystems are important feeding areas for migratory shorebirds that breed in the Arctic and winter in southern South America.

This project had three principal objectives:

1. To produce habitat maps of wetlands and aquatic ecosystems for the southern portion of the *altiplano* in Argentina, Bolivia, and Chile using Landsat Thematic Mapper (TM) imagery and geographic information systems (GIS);
2. To relate habitats delineated in the Landsat analysis to use by waterbird guilds, including flamingos and shorebirds from representative lakes where data were collected; and
3. To identify critical environmental variables to be used in a classification system for lakes, accompanying wetlands, and their aquatic

habitats in the *altiplano* as a resource base for aquatic avifauna.

Methods

Field data collection

Collection of data sets in the field took place in February 1999 and 2000. We selected representative lakes for fieldwork within selected TM images. The first year's effort was concentrated in four TM images in northern Argentina, southern Bolivia, and adjacent Chile (Figure 1). The second year's effort was conducted in the area covered by five TM images to the south, primarily in Argentina and adjacent areas of Chile. The purpose of the field data was to identify the habitat use by the waterbird species, and to gather geo-referenced data to test the classification of various habitats within the images. This time period (February) represents the terminus of the rainy season as well as the time interval when migratory birds utilize the southern altiplano. It is also the period of nesting and egg laying for the flamingos.

Water was analyzed in the field for pH, temperature, dissolved oxygen concentration, conductivity, transparency (Secchi disc depth), and turbidity. The nature of the bottom was also classified in shallow water lakes as limnoclay, sand, gravel, or bedrock. Water samples were taken from each lake and analyzed for a suite of anions and cations at the Soil and Water Testing Laboratory, Colorado State University. During the field work, based on previous experience from the High Andean census (Caziani and Derlindati 2000; Caziani et al. 2001), we identified six habitats that were present in each lake as: salt flats, mud shores, mud with a film of water, shallow water (<1 m depth), deep water (>1 m depth), and *vegas*. Habitat analysis within the images was keyed to and facilitated by type photographs taken in the field. Then we estimated waterbird abundance via censuses by habitat within each *laguna* sampled from one to several points on the shoreline, depending on the size and shape of the lake, using binoculars or spotting scopes and manual counters. Number and position of the census points were chosen to improve visibility and to ensure a total census. For groups <4000, we counted individuals of each species, and for groups >4000 we counted estimated blocks (10, 100, etc.) (Bibby et al. 1992).

Figure 1. Location of the nine Landsat TM scenes taken in the *altiplano* of Argentina, Bolivia, and Chile (February 1999 and 2000).

Multivariate data analysis

We used detrend correspondence analysis (DCA) to establish the patterns and relationships among bird communities and habitat use; canonical correspondence analysis (CCA) to determine the relationship between physical and chemical variables of the *lagunas* and variations in structure of the bird communities among the various *lagunas*; and redundancy analysis (RDA) to explore the relationship between the various bird species and specific chemical variables measured in the laboratory (Gauch 1982; Ter Braak and Verdonschot 1995).

Remote sensing and GIS analysis

Four Landsat 5 TM and five Landsat 7 enhanced TM (ETM) scenes were used to classify flamingo and shorebird habitat in the *altiplano*. One TM scene (path 233/row 76) was acquired by the satellite on February 1, 1999. Two TM scenes (path 232/rows 76 and 77) were acquired on February 10, 1999, and TM scene path 233/row77 was acquired on February 17, 1999. Two ETM scenes were acquired on February 5, 2000 (path

232/rows 78 and 79), and three ETM scenes were acquired on February 12, 2000 (path 233/rows 78, 79, and 80).

All processing was completed using the ERDAS Imagine software on Sun Unix, NT, and Windows 2000 systems. The nine scenes were rectified using coordinates taken from the series of 1 : 250,000-scale maps produced by the Instituto Geográfico Militar of Argentina. Nearest neighbor was the method used to resample the pixel data. Six classes were identified for each scene: (1) deep water (>1.0 m); (2) shallow water (<1.0 m); (3) wet mud or salt; (4) salt flat; (5) mud with water, and (6) *vegas*. Selected *lagunas* were subset from the images and processed separately. The classified imagery for these lakes was patched back into the nine-scene mosaic for the final classified product.

Signatures for TM scene path 232/row 76 were developed using three techniques. First, the iterative self-organizing data analysis technique (ISODATA) was used to create 300 signatures. Each signature was examined using image alarm, mean signature plots, and histograms. Second, mixed signatures from ISODATA were further analyzed by making a subset of the image alarm pixels and running ISODATA on the subset. The original mixed signatures were discarded and the subset signatures were used. Third, signatures were developed using the supervised technique based on field knowledge. This signature set was used to produce a maximum likelihood classification for scene path 232/row 76 and for scene path 232/row 77 after modifying signatures for the salt class.

Signatures for scenes path 233/rows 76, 77, 79, and 80 and path 232/row 78 were developed using ISODATA to create 300 signatures per scene. The developed signature set was then used to make a maximum likelihood classification. Each signature created by ISODATA was examined using image alarm, mean signature plots, and histograms. Mixed signatures from ISODATA were subset using as a mask the same class in the maximum likelihood output. The signatures in the subset were added to the original set of signatures after removing the signature used to create the subset. Image alarms, mean signature plots, and seven-band digital numbers from inquire cursor were used to determine the cover class type. The signature set developed for scene path 232/row 78 was used to classify scene path 232/row 79 after modifications for the water and upland classes. The signature set developed for scene 233/row 79 was used to classify scene path 233/row 78 without modifications.

After executing the maximum likelihood classification for all nine scenes using the final signature set, the output was recoded to the seven classes. A majority neighborhood function was then executed on each scene using a 3 × 3 window. All classes were input into the majority function, but the function was not applied to the shallow water, wet mud/salt, or *vega*/agriculture/forest classes, meaning that no pixels in these three classes were modified. Manual cleanup, using raster recode while referring to pixels identified with the inquire cursor option, was used to correct obvious conflicts in the classification. The primary conflicts were between salt and cloud/snow and between water and shadows. Finally, the nine classified scenes were joined together to form a single mosaic.

Limited global positioning system (GPS) ground truth (GT) data, which were not used during the classification process, were used to evaluate the results of the classification.

Results

Multivariate analysis of bird community and environmental data

Detrended correspondence analysis (Gauch 1982) showed statistically that the most important variable separating the lakes was related mainly to a salinity gradient among lakes, from *vegas* with fresh water, then brackish lakes to hypersaline lakes. Figure 2 shows the position of the fresh water *vegas* on the left of axis I and brackish lakes in the middle of the axis. The remainder of the lake were hypersaline and were positioned on the right end of the axis. The second most important set of variables distinguished among different habitat types within hypersaline lakes, mainly related to differences in depth.

We identified six habitat groups in Figure 2 listed by frequency as:

(a) Shallow water in hypersaline lakes concentrate James flamingos and Andean avocets.
(b) Shallow and deep water in brackish lakes used by coots, ducks, and podiceps.

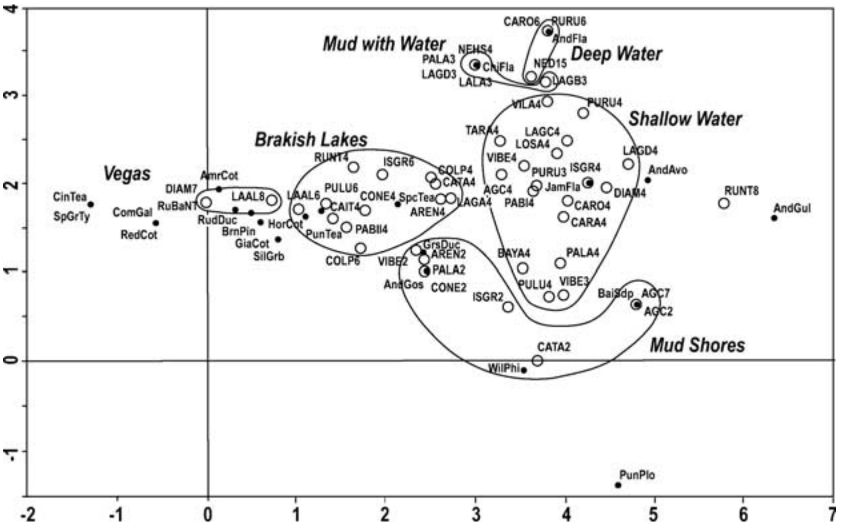

Figure 2. DCA ordination for waterbirds and lake. Open circles are lakes; closed circles are individual species of birds. See Table 2 for summary statistics. Lakes: AGC, Aguas calientes; AREN, Arenal; BAYA, Baya; CAIT, Caiti; CARA, Carachipampa; CARO, Caro; CATA, Catal; COLP, Colpayoc; CONE, Cerro Negro; DIAM, Diamante; ISGR, Isla grande; LAALLa, Alumbrera; LAGA, Laguna Grande A; LAGC, Laguna Grande C; LALA, La Laguna; LOSA, Los Aparejos; NFDI, Negro Fco. I Dulce; NFIIS, Negro Fco. II Salty; PABI, Pabellon I; PABII, Pabellon II; PALA, Palar; PULU, Pululos; PURU, Purulla; RUNT, Runtuyoc; TARA, Tara; VIBE, Vilama Bahía Escondida. Waterbirds: AmrCot, American Coot; AndAvo Andean Avocet; AndFla, Andean Flamingo; AndGos, Andean Goose; AndGul, Andean Gull; BaiSdp, Baird's Sandpiper; BrnPin, Brown Pintail; CinTea, Cinnamon Teal; ComGal, Common Gallinule; CrsDuc, Crested Duck; ChlFla, Chilean Flamingo; GiaCot, Giant Coot; HorCot, Horned Coot; JamFla, James Flamingo; PunTea, Puna Teal; RedCot, Red-gartered Coot; RudDuc, Ruddy Duck; SilGrb, Silvery Grebe; SpcTea, Speckled Teal; SpGrTy, Puna ground tyrant.

(c) Mud shores, mostly in hypersaline lakes, habitat of Andean geese, phalaropes, and shorebirds.
(d) *Vegas* inhabited by passerines and ducks.
(e) Mud with a film of water, where Chilean flamingo feed and nest.
(f) Deep water in hypersaline lakes with Andean flamingos.

The habitat types were mainly defined by depth differences. For the distribution of waterbirds in the altiplano, not only the depth of the water is important but also the salinity. The classification types that we delineated in the analysis of the Landsat TM images could be directly linked with the distribution and structure of the bird communities. The polygons drawn delineate various habitats within the DCA ordination diagram. The supporting statistics indicate that the first two axes of the ordination explained 33.2% of the variability of the community data; four axes explained 44.4% (Table 1).

We used CCA to determine the individual strength of association of a number of environmental variables with the variation in the community structure (ter Braak and Verdonschot 1995). CCA of the field and laboratory chemical data indicate that five variables (pH, Secchi disk depth, maximum depth of lake, elevation, and latitude) were the most critical variables associated with the variation in the structure of the bird community at the various lakes sampled (Figure 3). The presence of gravel in the bottom was also an important variable. This represents a second set of variables important to summer bird distribution within the area that we sampled. The statistical summary indicates that the community data triplot of the analysis was ecologically and statistically significant. The association community data with the chemical and physical data was very high, 73.5% for the first two axes shown in Figure 3, and 93.6% for all four axes.

Figure 4 shows the RDA of the laboratory analysis of certain heavy metals known to be toxic, the lakes, and the distribution of bird species. The diagram shows a negative correlation of high concentration of specific metals with the occurrence of aquatic avifauna and identifies the lakes

Table 1. Supporting statistics for multivariate analysis.

		Individual effects				Axes				Total inertia
	Variable	Var. N	Lambda A	*P*	*F*	1	2	3	4	
(a) DCA ordination for waterbirds and lake-habitat types, shown in Figure 2.										
Eigenvalues						0.670	0.344	0.203	0.138	3.054
Lengths of gradient						5.777	3.724	3.215	4.266	
Cumulative percentage variance of species data						21.9	33.2	39.8	44.4	
Sum of all unconstrained eigenvalues 3.054										
(b) CCA bioplot of lakes and with field variables shown in Figure 3.										
	Depth	2	0.37	0.005	5.69					
	gravel	9	0.23	0.005	3.94					
	Secchi	5	0.10	0.055	1.81					
	pH	3	0.10	0.055	1.86					
	Latitude	14	0.10	0.035	1.93					
	Elevation	15	0.08	0.085	1.67					
Eigenvalues						0.538	0.185	0.140	0.058	1.933
Species–environment correlations						0.925	0.931	0.833	0.658	
Cumulative percentage variance										
of species data						27.8	37.4	44.7	47.6	
of species–environment relation						54.7	73.5	87.8	93.6	
Sum of all unconstrained eigenvalues 1.933										
Sum of all canonical eigenvalues 0.983										
Summary of Monte Carlo test										
Test of significance of first canonical axis										
Eigenvalue = 0.538										
F-ratio = 7.327										
P-value = 0.0050										
Test of significance of all canonical axes										
Trace = 0.983										
F-ratio = 3.280										
P-value = 0.0050										
(c) RDA of waterbirds and lakes and chemical variables shown in Figure 4										
	B	21	0.11	0.175	1.58					
	Al	28	0.06	0.425	0.97					
	Pb	31	0.07	0.445	0.94					
	Mn	30	0.05	0.685	0.66					
	As	26	0.03	0.825	0.49					

continued on next page

Table 1. Continued.

Variable	Individual effects				Axes				Total inertia
	Var. N	Lambda A	*P*	*F*	1	2	3	4	
Eigenvalues					0.202	0.088	0.023	0.010	1.000
Species–environment correlations					0.861	0.669	0.559	0.422	
Cumulative percentage variance									
of species data					20.2	29.0	31.3	32.3	
of species–environment relation					62.3	89.5	96.7	99.7	
Sum of all unconstrained eigenvalues 1.000									
Sum of all canonical eigenvalues 0.324									
Test of significance of first canonical axis:									
Eigenvalue = 0.202									
F-ratio = 2.274									
P-value = 0.2150									
Test of significance of all canonical axes: trace = 0.324									

where the high levels of metals occurred. While this analysis was compelling in its interpretation, the summary statistics did not indicate that the analysis was highly significant.

GIS analysis of Landsat TM images

The nine images covered more than 254,300 km^2 between parallels 22° and 29° south latitude in the southern altiplano of Argentina, Bolivia, and Chile. The composite map of these images with detailed depiction of each habitat type by lake is available on the website: http://rockys20.cr.usgs.gov/argentina/initialpg.htm.

From data collected in the field we chose 28 GT points identified by a GPS receiver with an accuracy of not greater than 5 m to evaluate the classified image. The classification was considered correct if the GPS error circle for the GT point included the GT class. Five GT points were defined as having more than one class and if the GPS error circle included any of these classes it was considered correctly classified. Overall, 25 of the 28 points were classified correctly. There were eight salt flat GT points and one of these was incorrectly classified as mud. Three of five mud GT areas were correctly classified, and two were incorrectly classified as upland. Eleven shallow water GT areas were correctly classified. Two deep water GT areas were correctly classified. Two *vegas* GT areas were classified correctly.

The magnitude of total surface area of six aquatic bird habitats within the nine Landsat TM images is shown in Table 2. The deep-water habitat (>1 m) was the smallest category. Soil over salt flat was the second smallest category. *Vega* was the largest waterbird habitat plotted on the nine images. However, it was impossible to distinguish *vegas* from agriculture that occurred along river valleys at elevations less than ~2.500 m. Since this elevation separated *vega* and agriculture, the location of agricultural areas in these valleys are easily distinguishable on the generated map. Variation in the total availability of shallow water, salt flats, soils over salt flat, and wet mud/salt are expected with annual to decadal changes in precipitation. Moreover, with changes in precipitation and lake level, one habitat may be converted to another.

Some summary descriptions of the data include Table 3, which shows the frequency of lake size

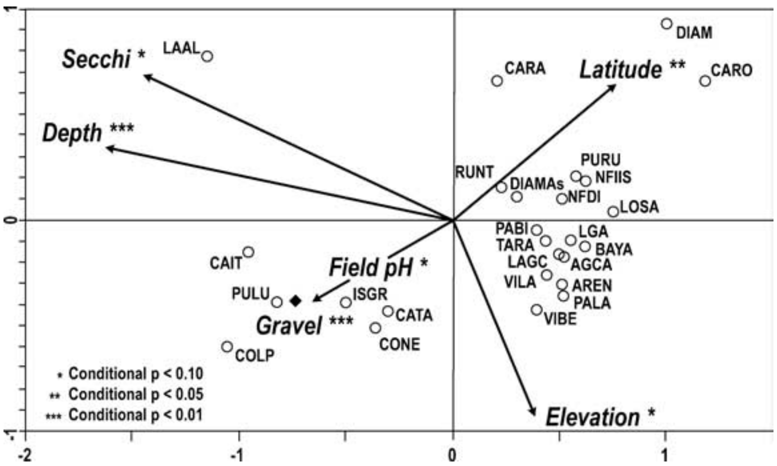

Figure 3. CCA bi-plot of lakes with physical–chemical field data. Open circles are lakes. Vectors indicate statistically significant numerical data; the diamond centroid indicates significant presence absence data. See Table 2 for summary statistics.

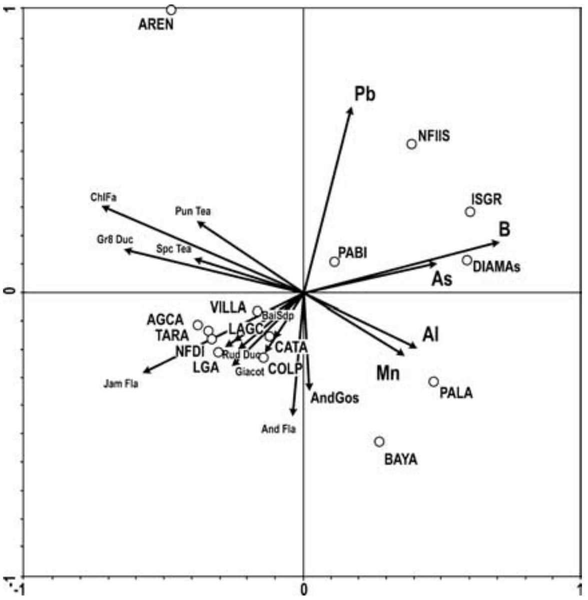

Figure 4. RDA plot of waterbirds and lakes, open circles with chemical variables. See Table 2 for summary statistics.

Table 2. Area report for the entire study area in Argentina (nine Landsat scenes).

Habitat/class	Area in hectares
Deep water	1690
Shallow water	72,954
Salt flat	675,265
Dirt over salt flat	9120
Wet mud/salt	36,293
Vegas/agriculture	222,337

Table 3. Frequency distribution of *laguna* areas within the nine landsat TM scenes in the southern *altiplano* (the entire study area (nine Landsat scenes)).

Size class (ha)	Frequency (number)
0.01–0.99	9076
1–9.9	924
10–99.9	216
100–999.9	59
1000–9999.9	13
≥10,000	1

classifications within the area analyzed. A total of 10,289 water bodies were identified within the nine images that could be of importance in supporting bird habitat. From field observations the large number of smaller lakes (<10 and <1 ha) have value as feeding habitat for both shorebirds and flamingos (Table 3). Many of these smaller lakes appear to be seasonal in their existence, and were probably dry during the winter. Lakes of larger size classes could fluctuate in size among years; however, they appeared to be relatively permanent water bodies. Even lakes within the size class >1000 ha were observed to have great fluctuations. The remains of flamingo nests were observed in lakes as small as 10–100 ha size range. Laguna Guayatayoc, within the 1000–10,000-size range, was completely dry at the end of the rainy season

Table 4. Puna laguna classification system.

Physical factors
  A. Size/physical dimensions
  B. Depth
  C. Hydrological cycle
    (1) Annual filling and drying
    (2) Multiyear cycle of filling and drying
    (3) Permanent
    (4) Position in watershed
      – upper (*lagunas* north of Rinconada)
      – midway (Rontuyoc)
      – terminal (Olaroz)
    (5) Stability of lake level
  D. Elevation
  E. Substrate type on lake bottom (bedrock, gravel, limnoclay)
Chemical factors
  F. Salt type
    (1) $CaSO_4$ dominated
    (2) NaCl dominated
    (3) Concentration/salinity/conductivity
    (4) zonation of salt concentration (i.e., freshwater stream or spring entering salt water)
  G. Metals at toxic concentrations (i.e., As, B, Pb, Al, Mn)
Biological factors
  H. Presence or absence of macrophytes
  I. Location and magnitude of *vegas*

in 1991 and was full of water with two colonies of Chilean flamingos in 1999.

Laguna classification for the altiplano

Lakes in the *altiplano* represent a range of resources to a diverse community of waterbirds. In order to systematically understand the differences in the lakes and their relationship with waterbird distribution, we are proposing a hierarchic set of physical, chemical, and biological attributes that contribute to classification. The variables in this classification scheme are listed in a hierarchic sequence that reflects their importance to bird distribution and their potential variability within a variable climate (Table 4).

Discussion

Differences in size sometimes provided differences in resources for waterbirds. Several lakes less than 10 ha were used as nesting sites by flamingos, although the nests we observed were more than a year old and it was impossible to determine which species made them. The dynamics of these lakes also differs by size. The smaller bodies of water may be only present seasonally. Larger lakes, depending on their depth, may provide habitat for breeding colonies for more than 10,000 flamingos in a season.

The scale for change in these lakes depends on watershed size, and varies seasonally among years, decades, centuries, and geologic epochs (Stoertz and Erickson 1974). The distribution and surface area of the individual habitat types listed in the tables and shown on the composite of TM images are dependent on the amount of precipitation within a year and over the period of several years. The precipitation in the northern portion of the study area fall as summer monsoonal thunderstorms in the form of rain and hail; in the southern areas winter storms are in the form of snow (Vuille 1999; Vuille et al. 2000). The interface between these two weather systems oscillates roughly within the middle of the nine images and the magnitude of precipitation appears to be strongly influenced by the dynamics of El Niño-Southern Oscillation.

Both the analysis of the nine TM images and the analysis of the physical/chemical parameters of bird habitats and lakes will be used by current and future efforts of assessment of critical species such as the present multinational Group for the Conservation of Flamingos and to provide critical information to conservation agencies such as the Argentine National Park Service and the Ramsar Convention which are considering establishing additional protected areas in the altiplano in the future.

Because mineral prospecting in this area is currently intense, it is expected that new mining development is imminent. A habitat map of such a scale ($\sim$254,300 km^2) will aide in knowledge of the habitat availability of the waterbird resources and will be used by current and future efforts of assessment of critical species such as the present multinational Group for the Conservation of Flamingos and to provide critical information to conservation agencies such as the Argentine National Park Service and the Ramsar Convention which are considering establishing additional protected areas in the altiplano in the future. Moreover, the lakes of the *altiplano* are also critical in supporting an array of avian species in that these aquatic ecosystems are important feeding areas for migratory shorebirds that breed in the Arctic and winter in southern South America.

In spite of changes in the magnitude of available habitats due to climatic variations, the value of the map derived from this analysis is important in quantifying existing habitats for comparisons in time. There are still little known areas in Argentina and perhaps Chile that have not been censused for aquatic birds. James flamingo was thought to be extinct until 1960 (Conway 1961). Caziani et al. (2001) discovered a new population of more than 10,000 James flamingos in a remote lake in Catamarca in 1997. Applying remotely sensed imagery in the future to locate areas not currently explored for waterbird fauna will be a major contribution to efforts to protect important ecological habitats. The results of the habitat analysis and all the ancillary chemical, physical, and biological data can be viewed online at http://rockys20.cr.usgs.gov/argentina/initialpg.htm.

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References

Bibby C.J., Burgess N.D. and Hill D.A. 1992. Bird Census Techniques. Academic Press, London.

Blanco D.E. and Canevari P. 1998. Identifying wetlands of critical value to shorebirds in South America. Canadian Wildlife Service Latin American Program Report. 66 pp.

Cabrera A.L. and Willink A. 1980. Biogeografia de America Latina (2 edn). Serie de Biologia Monografia 13. Organization of American States, Washington DC, 122 pp.

Carrasco C. 1999. Indicadores ambientales y vulnerabilidad de los humedales de la puna. Desarrollo Productivo y Conservacin de Humedales de la Puna.

Caziani S.M. and Derlindati E. 2000. Abundance and habitat of High Andean flamingos in Northwestern Argentina. Waterbird 23(Special Publication 1): 121–133.

Caziani S.M., Derlindati E.J., Tálamo A., Sureda A.L., Trucco C.E. and Nicolossi G. 2001. Waterbird richness in altiplano lakes of northwestern Argentina. Waterbirds 24: 103–117.

Collar N.J., Gonzaga L.P., Krabbe N., Madroño Nieto A., Natanjo L.G., Parker T.A. and Wege D.C. 1992. Threatened bids of the Americas: the ICBP/IUCN Red Data Book (3rd edn, part 2). International Council for Bird Preservation, Cambridge, UK.

Conway W.G. 1960. To the highest Andes for the rarest flamingo. Animal Kingdom 63: 34–50.

Conway W.G. 1961. In quest of the rarest flamingo. National Geographic 20: 91–106.

Ericksen G.E. 1993. Upper Tertiary and Quaternary continental saline deposits in the central Andean region. Mineral Deposit Modeling. Geological Association of Canada Special Paper 40: 89–102.

Gauch H.G. 1982. Multivariate Analysis in Community Ecology. Cambridge University Press, Cambridge, UK, 298 pp.

High Andes Flamingos Conservation Group, 2001. Priority Actions for the Conservation of the High Andes Flamingos. Final Report to Migratory Species Convention. High Andes Flamingos Conservation Group, and Fundacin Pachamama.

Messerli B., Grosjean M. and Vuille M. 1997. Water availability, protected areas, and natural resources in the Andean Desert Altiplano. Mountain research and development 17: 229–238.

Ruthsatz B. and Pia Movia C. 1975. Relevamiento de las estepas andinas del noreste de la Provincia de Jujuy, Republica Argentina. Fundacion para la Educacion, la Ciencia, y la Cultura, Buenos Aires, 127 pp.

Stoertz G.E. and Ericksen G.E. 1974. Geology of Salares in Northern Chile U.S. Geographical Survey Paper 811, pp. 65.

Ter Braak C.J.F. and Verdonschot P.F.M. 1995. Canonical correspondence analysis and related multivariate methods in aquatic ecology. Aquatic Sciences 57: 255–289.

Valqui M., Caziani S.M., Rocha O. and Rodríguez E. 2000. Abundance and distribution of the South American altiplano flamingos.In: Baldassarre G.A., Arengo F. and Bildstein K.L. (eds), Conservation Biology of Flamingos (Waterbird 23 (Special Publication 1). pp. 110–113.

Vuille M. 1999. Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation. International Journal of Climatology 19: 1579–1600.

Vuille M., Bradley R. and Keimig F. 2000. Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing. Journal of Geophysical Research 105: 12447–12460.