

AQUATIC FAUNA IN THE DRIEST DESERT ON EARTH: FIRST REPORT
ON THE CRUSTACEAN FAUNA OF THE LOA RIVER (ATACAMA DESERT,
ANTOFAGASTA REGION, CHILE)

BY

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ABSTRACT

The longest river in Chile, the Loa, is in fact found in the Atacama Desert in the far north of the country. Being an important resource for the dry Antofagasta region, this river experiences high anthropogenic impacts due to water use for mining, urban, and agricultural activities. Unfortunately, few biological surveys have been conducted in the Loa, and the invertebrate fauna in particular is poorly known. The aim of this study is to characterize the microcrustacean species associations at various sites of the Loa River and some of its tributaries. Unexpectedly high species richness was detected at high-altitude sites, where the amphipods *Hyalella fossamanchini* and *H. kochi* were reported. At low-altitude sites only the ostracod *Heterocypris panningi* was found. No significant correlation was detected between species richness and salinity, nor between richness and conductivity. Although a null model community analysis indicated that the microcrustacean species associations in the Loa are largely random, species richness and altitude were significantly and positively correlated. Potential causes of this pattern include the accumulation of nutrients and pollution along the course of the river, as well as increasing temperatures in the lower-altitude zones of the river. The biogeography of the constituent members of the Loa fauna is discussed.

RESUMEN

El río Loa, es el más largo de Chile, y se encuentra localizado en la región de Antofagasta, en el desierto de Atacama, este río tiene mucha intervención antrópica debido al uso de sus aguas por industrias mineras, así como usos domésticos y agrícolas. Desafortunadamente hay pocos estudios sobre sus componentes biológicos. El objetivo del presente trabajo consistió en estudiar los ensamblajes de crustáceos en diferentes zonas del río Loa y algunos de sus afluentes. Los resultados revelaron una alta riqueza de especies principalmente en zonas altas del río, donde se reportaron principalmente los anfípodos *Hyalella fossamanchini* y *H. kochi*, mientras que en zonas bajas solo se reportó el ostrácodo *Heterocypris panningi*. No obstante, no hubo correlaciones significativas

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entre el número de especies con salinidad, hubo una correlación débil pero no significativa entre riqueza de especies y conductividad, y una correlación significativa entre riqueza de especies y altitud. Los resultados del modelo nulo indicaron la presencia de factores aleatorios en la regulación de las asociaciones de especies. Una posible razón, sería la potencial acumulación de nutrientes y contaminantes, así como altas temperaturas en zonas bajas del río. Se discutieron tópicos ecológicos y biogeográficos.

INTRODUCTION

Northern Chile contains the Atacama Desert, which is characterized by rare, shallow, saline lagoons, small intermittent streams, and a few rivers (Niemeyer & Cereceda, 1984). One of the principal rivers in this region is the Loa, the longest river of Chile with a length of 440 km. Situated in the Antofagasta region, it originates in the Andes mountains, close to Bolivia, receives three tributaries, and contains one reservoir (Pumarino, 1978; Niemeyer & Cereceda, 1984; Gutiérrez et al., 1998). Studies of the native aquatic fauna to date have only described the presence of the freshwater prawn *Cryphiops caementarius* (Molina, 1782) (cf. Jara et al., 2006), amphipods such as *Hyalella fossamanchini* (Cavalieri, 1959) and *H. kochi* (González & Watling, 1991) (cf. González, 2003), and the native silverside, *Basilichthys* (?*B. semotilus* Cope, 1874) (cf. Dyer 2000a, b; Ruiz & Marchant, 2004; Vila et al., 2006). In addition, the introduced fishes *Oncorhynchus mykiss* (Walbaum, 1792) (rainbow trout) and *Salmo trutta* (Linnaeus, 1758) (brown trout), have been reported from the Loa River and its tributaries (Pumarino, 1978; Wetzlar, 1979; Silva et al., 1985; Iriarte et al., 2005). However, data on species distributions and associations in the Loa River are currently lacking.

The Loa River basin experiences a heavy impact from water use for mining and domestic needs, as well as for agricultural activities (Niemeyer & Cereceda, 1984; Gutiérrez et al., 1998). Elements of the biota are also under pressure from fishing, particularly in the case of the prawn *Cryphiops caementarius* (cf. Meruane et al., 2006a, b), as well as sport fisheries for rainbow and brown trout (pers. obs.; Pumarino, 1978). However, the status and composition of the crustacean fauna of the Loa River is unknown due to a lack of study, stemming largely from the inaccessibility of water bodies in northern Chile (Chong, 1988). The present study aims to partially rectify this lack of knowledge by determining the crustacean species inhabiting the Loa, characterizing species associations along a spatial gradient within the river, and testing for potential regulating factors of community composition.

MATERIAL AND METHODS

The Loa River, which originates in the Andes Mountains close to the border with Bolivia, flows first from north to south, then continues in a westerly direction, changes to a northerly direction, and finally flows west before emptying into the Pacific Ocean (fig. 1). Nine sites were sampled along the Loa (fig. 1, table I), the first being Quillagua, a small agricultural village with small reservoirs for recreational use. The second site was Sloman Reservoir, which is a former hydro-electrical power station used before 1930 during the period of Chilean nitrate mining; this station no longer functions for power generation. The third site was a zone of the Loa River close to “oficina salitrera Iberia”, a ghost town from the period of Chilean nitrate mining. This site is apparently used for poultry grazing (pers. obs.). The fourth and fifth samples were taken from the fluvial beach at Chacance, where the Loa receives the Salvador River, its last tributary. The Salado River, our sixth site, is an affluent of the Loa located close to the small town of Chiuchiu. This river is characterized by its relatively high content of dissolved minerals (Niemeyer & Cereceda, 1984). The seventh sampling locality is the Loa River close to the town of Chiuchiu, before the confluence with the Salado River. Conchi Reservoir, which provides potable water for cities, represents our eighth

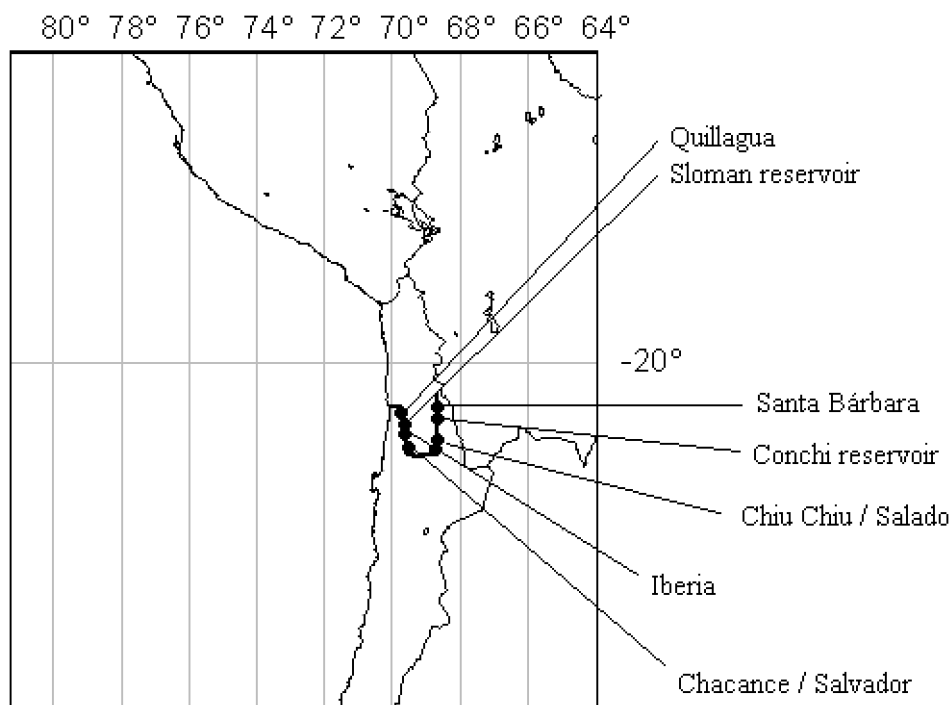


Fig. 1. Geographical location of the studied sites in northern Chile.

TABLE I
 Geographical location, altitude, conductivity, salinity, and species reported for the studied sites in the Loa River, northern Chile

	Santa Bárbara	Conchi	Salado	Chiuchiu	Chacance	Salvador	Iberia	Sloman	Quillagua
Geographical location (latitude S/longitude W)	21°58.7' 68°36.7'	22°00.5' 68°36.7'	20°20.4' 68°39.2'	20°20.4' 68°39.2'	22°23.8' 69°31.6'	22°23.8' 69°31.6'	21°55.2' 69°33.6'	21°51.2' 69°30.9'	21°39.5' 69°32.2'
Altitude (m a.s.l)	3304	3272	2784	2768	1328	1328	1118	1085	866
Conductivity (mS/cm)	3.7	3.0	7.77	3.8	14.44	8.88	18.45	20.40	20.20
Salinity (g/l)	1.8	1.5	4.2	1.5	8.3	4.8	10.4	11.5	12.0
CLADOCERA									
<i>Ceriodaphnia dubia</i> (Richard, 1894)		X							
<i>Daphnia pulex</i> (De Geer, 1877)		X							
<i>Clydonor sphaericus</i> (O. F. Müller, 1785)			X						
COPEPODA									
<i>Eucyclops serrulatus</i> (Fischer, 1851)		X							
Unidentified Cyclopoida			X						
OSTRACODA									
<i>Heterocypris panningsi</i> (Brehm, 1934)			X		X			X	
<i>Cubacandona</i> spp. (cf. Broodbakker, 1983)							X		X
AMPHIPODA									
<i>Hyalella fossamanchini</i> (Cavaliere, 1959)	X	X	X						
<i>H. kochi</i> (González & Watling, 2001)	X	X	X						

sampling station. Finally, the ninth site was located in Santa Bárbara, a zone close to the international route to Bolivia.

Crustacean specimens were collected using Apstein (20 cm diameter, 100 μm mesh size) and Surber nets (30 \times 30 cm, 100 μm mesh size). The collected specimens were fixed in absolute ethanol, and identified with keys and descriptions provided by Araya & Zúñiga (1985), Reid (1985), and González (2003). Water samples of 300 ml were taken from each site for conductivity and salinity analysis in the laboratory, using an YSI-30 sensor (Wetzel & Likens, 1991), and altitude was recorded for all sites. We tested for relationships between species richness and three physical variables (salinity, conductivity, and altitude) using correlation coefficients (Rho-Spearman), calculated in the software SPSS v.12.

Crustacean community structure was explored using null model analysis, which tests whether species co-occur less frequently than expected by chance (Gotelli, 2000). Based upon an absence/presence matrix, a Checkerboard score (“C-score”) is calculated, which represents a quantitative index of co-occurrence (see Tondoh, 2006; De los Ríos et al., 2008; De los Ríos, 2008). A community is concluded to be structured by competition when its C-score is significantly larger than expected by chance (Gotelli, 2000, 2001). In order to determine whether a particular score is statistically significant, a set of randomizations of the species occurrence data is performed and a null distribution for the coexistence index is created. Gotelli & Entsminger (2004), Tondoh (2006), and Tiho & Johens (2007) suggested the following three statistical models for creating the randomized communities, with the species placed in rows and the sites in columns:

- (1) Fixed-Fixed. In this model, the row and column sums of the matrix are preserved. Thus, each random community contains the same number of species as the original community (fixed column) and each species occurs with the same frequency as in the original community (fixed row).
- (2) Fixed-Equiprobable. In this algorithm only the row sums are fixed, and the columns are treated as equiprobable. This null model considers all the sites (columns) as equally available for all species, which occur in the same proportions as in the original communities.
- (3) Fixed-Proportional. This algorithm holds the species occurrence totals the same as in the original community, and the probability that a species occurs at a site (column) is proportional to the column total for that sample.

All three of these models exhibit fairly reasonable combinations of Type I and Type II error rates, although model #3 has a high Type I error rate (false positives) using the C-score index, but have differences in their underlying assumptions and behaviour (Gotelli, 2000). The fixed-fixed model is suggested to be most appropriate for island species lists, in which species-area effects are expected, while the fixed-equiprobable model would be most appropriate for standardized

samples in a homogeneous environment (Gotelli, 2000). The fixed-proportional algorithm represents an intermediate model, which might be most appropriate in our system due to habitat heterogeneity, as well as to differences in depth and width along the river. Differing results among models can provide insights into community structure. The null model analyses were performed using the software Ecosim version 7.0 (Gotelli & Entsminger, 2004).

RESULTS AND DISCUSSION

Our results revealed the presence of a small number of crustacean species in the Loa River in northern Chile. In Quillagua, no crustaceans were found, but the introduced fish species *Gambusia affinis* (Baird & Girard, 1853) was abundant, whereas in Sloman and Chacance only the ostracod *Heterocypris panningi* (Brehm, 1934) was detected. By contrast, the Salado River harboured unidentified cyclopid copepods, the cladoceran *Chydorus sphaericus* (O. F. Müller, 1785), *H. panningi*, and the amphipods *Hyaella fossamanchini* and *H. kochi*. Conchi Reservoir supported similarly high species richness, with *H. fossamanchini*, *H. kochi*, *Eucyclops serrulatus* (Fisher, 1851), *Ceriodaphnia dubia* (Richard, 1895), and *Daphnia pulex* (De Geer, 1877) being present (table I). The Rho-Spearman correlation values indicated no correlation between species number and salinity ($r = -0.39$; $P = 0.149$), but a marginally non-significant, negative correlation between species richness and conductivity ($r = -0.50$; $P = 0.087$). However, a significant and positive relationship was detected between diversity and altitude ($r = 0.61$; $P = 0.041$) (table II). The results of the null model analyses, for all simulations, revealed that crustacean community composition seems to be random (table II), but small sample sizes

TABLE II

Results of correlation and null-model analysis. Correlation coefficients are provided between species richness and conductivity, salinity, and altitude, respectively, at nine sites along the Loa River (“ P ” values lower than 0.05 denote significant correlations). The null-model analysis (see text) suggests that crustacean community structure is random ($P > 0.05$)

	Conductivity	Salinity	Altitude	
Number of species	$r = -0.496$; $P = 0.087$	$r = -0.391$; $P = 0.149$	$r = 0.610$; $P = 0.041$	
Results of null model analysis				
Simulation	Observed index	Mean from randomization trials	Standard effect size	P
Fixed-Fixed	1.250	1.132	1.066	0.155
Fixed-Proportional	1.250	1.105	0.443	0.372
Fixed-Equiprobable	1.250	1.873	-2.301	0.982

could mask other underlying patterns (De los Ríos et al., 2008). Unfortunately, further chemical and physical data are not available, but a potential regulating factor could be the kind of human intervention in the river, such as has been observed for central Chilean rivers (Figueroa et al., 2003). For the Loa River, in the high zones human intervention is minimal considering the presence of small villages, in comparison with low zones that are more severely impacted by large towns and mining activities (Alvarez, 1999; Melcher, 2004).

To date, the literature on Chilean rivers only contains descriptions of invertebrate species associations in south-central rivers, which aimed to use them as bio-indicators of water quality (Figueroa et al., 2003, 2007). Differences in macroinvertebrate assemblages (mainly insects and crustaceans) were detected as a function of pollution levels along the course of the river (Figueroa et al., 2003, 2007). From this perspective, the aquatic fauna of Chilean rivers is regulated by deterministic factors, namely water quality as governed by the level of human intervention (Figueroa et al., 2003, 2007). However, Figueroa et al. (2003, 2007) only described the riverine biota at the family level, and this lack of species-level data precludes more precise statistical treatments of community structure (Gotelli & Graves, 1996; Gotelli & Ellison, 2000; Jaksic, 2001). By contrast, this study, as it has included only crustaceans, resulted quite readily in species-level identifications, whereas Figueroa et al. (2003, 2006) studied all benthic invertebrates, including aquatic insects, which are highly diverse compared to crustaceans. In future studies of riverine community structure, it will be important to expand upon our studies in order to include aquatic insects at the species level. This group is likely to have ecological interactions with crustaceans in benthic communities, which would affect abundances and patterns of co-occurrence across both these taxonomic groups (Parra et al., 2001).

In biogeographical terms, the presence of the amphipods *Hyaella fossamanchini* and *H. kochi* in the Loa River has previously been described by Gonzalez (2003) and Jara et al. (2006). However, their descriptions did not specify any details about the localities at which these species were found, and thus the present survey contributes new information regarding their distributions. The absence of specimens of the northern river shrimp, *Cryphiops caementarius*, indicates that this species is under threat from excessive fishing as human food for at least one century (Jara et al., 2006) and probably also from the presence of exotic fishes such as *Gambusia affinis*, which is an active predator on native aquatic invertebrates at sites where this species has been introduced (Leyse et al., 2005). Regarding the presence of ostracods in Chile, there are currently only records of *Heterocypris panningi* and *Cubacandona* spp., which has also been reported for South American inland waters (Martens & Behen, 1994). Spatial differences in community composition were detected, involving the presence of ostracods and the absence of

amphipods in the lower reaches of the Loa River, zones exhibiting relatively high salinity and conductivity (table I). By contrast, the high-altitude zones of the Loa, as well as the Salvador River, have relatively lower salinity with species associations comprised primarily of the amphipods *H. fossamanchini* and *H. kochi* (table I). The presence of microcrustaceans, specifically copepods and cladocerans in Conchi Reservoir, agrees with the distributions reported in the literature (Araya & Zúñiga, 1985; Reid, 1985). Although the data denote a segregation of species into low and high altitude zones (table I) with significantly higher diversity detected at higher altitudes, the results of null models suggested that species associations are random (table II). These results are seemingly in disagreement; however, the low total species richness and small number of study sites may preclude the detection of a true underlying pattern (De los Ríos et al., 2008). Further work on the crustacean fauna of northern Chile is clearly needed. Nevertheless, the present results contribute to our understanding of the community ecology of inland water invertebrates in northern Chilean streams, which unfortunately have been understudied to date due primarily to problems of accessibility.

ACKNOWLEDGEMENTS

The present study was financed by a grant to PR from the Research Direction of the Catholic University of Temuco (Funding for development of Limnology Project DGI-DCA 2007-01), a NSERC (Natural Sciences and Engineering Research Council of Canada) Discovery Grant to JDSW, and by a NSERC post-doctoral fellowship to SJA. Also, we gratefully express our appreciation to Eliana Ibáñez, Elizabeth Escalante, the Family Escalante-Astudillo, and Elisa Pistán for their helpful logistic assistance during the field work.

REFERENCES

- ALVAREZ, A., 1999. Geo biografía: 1-176. (Impresos Universitaria S.A., Santiago de Chile).
- ARAYA, J. M. & L. R. ZÚÑIGA, 1985. Manual taxonómico del zooplancton lacustre de Chile. Boletín Limnológico, Universidad Austral de Chile, **8**: 1-169.
- CHONG, G., 1988. The Cenozoic saline deposit of the Chilean Andes between 18°00 and 27°00 south latitude. Lecture Notes on Earth Sciences, **17**: 137-151.
- DE LOS RÍOS, P., 2008. A null model for explain crustacean zooplankton species associations in central and southern Patagonian inland waters. An. Inst. Patagonia, **36**: 25-33.
- DE LOS RÍOS, P., N. RIVERA & M. GALINDO, 2008. The use of null models to explain crustacean zooplankton associations in shallow water bodies of the Magellan region, Chile. Crustaceana, **81**: 1219-1228.
- DYER, B., 2000a. Systematic review and biogeography of the freshwater fishes of Chile. Est. Oceanol., **19**: 77-98.

- —, 2000b. Revisión sistemática de los pejerreyes de Chile (Teleostei, Atheriniformes). *Est. Oceanol*, **19**: 99-127.
- FIGUEROA, R., A. PALMA, V. RUIZ & X. NIELL, 2007. Análisis comparativo de índices bióticos utilizados en la evaluación de la calidad de las aguas en un río mediterráneo de Chile: río Chillán, VIII Región. *Rev. Chilena Hist. nat.*, **80**: 225-242.
- FIGUEROA, R., C. VALDOVINOS, E. ARAYA & O. PARRA, 2003. Macroinvertebrados bentónicos como indicadores de calidad de agua de ríos del sur de Chile. *Rev. Chilena Hist. nat.*, **76**: 275-285.
- GONZÁLEZ, E. R., 2003. Los anfípodos de agua dulce del género *Hyaella* Smith, 1874 en Chile (Crustacea: Amphipoda). *Rev. Chilena Hist. nat.*, **76**: 623-637.
- GOTELLI, N. J., 2000. Null models of species co-occurrence patterns. *Ecology*, **81**: 2606-2621.
- —, 2001. Research frontiers in null model analysis. *Glob. Ecol. Biogeogr.*, **10**: 337-343.
- GOTELLI, N. J. & A. M. ELLISON, 2000. A primer of ecological statistics: 1-510. (Sinauer Associated Inc. Publishers, Sunderland, Massachusetts).
- GOTELLI, N. J. & G. L. ENTSMINGER, 2004. EcoSim: null models software for ecology. Version 7. (Acquired Intelligence Inc. & Kesey-Bear, Jericho, VT 05465). <http://garyentsminger.com/ecosim.htm>
- GOTELLI, N. J. & G. R. GRAVES, 1996. Null models in ecology: 1-357. (Smithsonian Institution Press, Washington, D.C.).
- GUTIÉRREZ, J. R., F. LÓPEZ-CORTES & P. A. MARQUET, 1998. Vegetation in an altitudinal gradient along the Rio Loa in the Atacama desert of northern Chile. *Journ. arid Env.*, **40**: 383-399.
- IRIARTE, A., G. A. LOBOS & F. M. JAKSIC, 2005. Invasive vertebrate species in Chile and their control and monitoring by governmental agencies. *Rev. Chilena Hist. nat.*, **78**: 143-151.
- JAKSIC, F., 2001. Ecología de comunidades: 1-233. (Ediciones Pontificia Universidad Católica de Chile, Santiago de Chile).
- JARA, C. G., E. H. RUDOLPH & E. R. GONZÁLEZ, 2006. Estado de conocimiento de los malacostráceos dulceacuícolas de Chile. *Gayana, Concepción*, **70**: 40-49.
- LEYSE, K., S. P. LAWLER & T. STRANGE, 2005. Effects of an alien fish *Gambusia affinis*, on an endemic fairy shrimp, *Linderella occidentalis*: implications for conservation of diversity in fishless waters. *Biol. Conserv.*, **118**: 57-65.
- MARTENS, K. & F. BEHEN, 1994. A check list of the Recent non-marine ostracods (Crustacea, Ostracoda) from the inland waters of South America and adjacent islands: 1-84. (Travaux Scientifiques du Musée National d'Histoire Naturelle de Luxembourg, Luxembourg).
- MELCHER, G., 2004. El norte de Chile, su gente, desiertos y volcanes: 1-149. (Editorial Universitaria, Santiago de Chile).
- MERUANE, J., J. RIVERA, M. MORALES, C. MORALES, C. GALLEGUILLOS & H. HOSOKAWA, 2006 (cf. a). Juvenile production of the freshwater prawn *Cryphiops caementarius* (Decapoda: Palaemonidae) under laboratory conditions in Coquimbo, Chile. *Gayana, Concepción*, **70**: 228-236.
- MERUANE, J., J. RIVERA, M. MORALES, C. MORALES, C. GALLEGUILLOS, M.A. RIVERA & H. HOSOKAWA, 2006 (cf. b). Experiencias y resultados de investigaciones sobre el camarón de río del norte *Cryphiops caementarius* (Molina, 1782) (Decapoda: Palaemonidae): historia natural y cultivo. *Gayana, Concepción*, **70**: 280-292.
- NIEMEYER, H. & P. CERECEDA, 1984. Hidrografía: 1-320. (Colección Geografía de Chile, VIII. Military Geographical Institute, Chilean Army, Santiago de Chile).
- PARRA, O., N. DELLA CROCE & C. VALDOVINOS, 2001. Elementos de limnología teórica y aplicada: 1-303. (Microart's Edizioni, Italy).
- PUMARINO, H. 1978. El Loa de ayer y hoy: 1-203. (Editorial Universitaria, Santiago de Chile).

- REID, J., 1985. Chave de identificação e lista de referencias bibliográficas para as espécies continentais sudamericanas de vida livre da orden Cyclopoida (Crustacea, Copepoda). Bolm. zool. Univ. São Paulo, **9**: 17-143.
- TIHO, S. & J. JOHENS, 2007. Co-occurrence of earthworms in urban surroundings: a null model analysis of community structure. European Journ. Soil Biol., **43**: 84-90.
- TONDOH, J. E., 2006. Seasonal changes in earthworm diversity and community structure in central Côte d'Ivoire. European Journ. Soil Biol., **42**: 334-340.
- RUIZ, V. & M. MARCHANT, 2004. Ictiofauna de aguas continentales chilenas: 1-356. (Dirección de Docencia, Universidad de Concepción).
- SILVA, A., L. FRANCO & N. ITURRA, 1985. Antecedentes sobre la reproducción y alimentación de la trucha arco iris *Salmo gairdneri* del Embalse Conchi, Antofagasta, Chile. Biol. Pesq., **14**: 32-39.
- VILA, I., R. PARDO, B. DYER & E. HABIT, 2006. Peces límnicos: diversidad, origen y estado de conservación. In: I. VILA, A. VELOSO, R. SCHLATTER & C. RAMÍREZ, Macrófitas y vertebrados de los sistemas límnicos de Chile: 73-102. (Editorial Universitaria, Santiago de Chile).
- WETZEL, R. & G. LIKENS, 1991. Limnological analysis: 1-391. (Springer Verlag, New York).
- WETZLAR, H., 1979. Beiträge zur Biologie und Bewirtschaftung von Forellen (*Salmo gairdneri* und *S. trutta*) in Chile: 1-264. (Ph.D. Thesis, Universität Freiburg).

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