Water Resources Management efforts for best water allocation in the Lake Poopo basin, Bolivia

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Doctoral Thesis

WATER RESOURCES MANAGEMENT EFFORTS FOR BEST WATER ALLOCATION IN THE LAKE POOPO BASIN, BOLIVIA

by

Andrés Calizaya Terceros

November 2009

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In memory of my wonderful mom "Mami Julia",
who will truly be missed but never forgotten…
to my great father, who taught me the way of science,
to my beloved family, Melina, Khiara Andrea and Andresito,
for their love, understanding and support,
to my lovely Giada and Dina in the distance.

Preface

"In the end what counts is not wisdom, but action. To be half-right at the right moment can be more important than reaching the truth too late"

Aristotle

In Bolivia, the year 2000 was marked by a water-related conflict, a *"water war"* that generated such an important coordination of the affected parties that it gave way to the conformation of an organization named the *"Coordinadora del Agua"* in Cochabamba. This organization was instrumental in the defense of peasant´s rights against private interests. Three years later, the city of El Alto saw a similar, though less violent conflict. The citizens marched and protested, promoting the expulsion of the company that provided potable water to La Paz and El Alto, claiming the company was not complying with its contract. Although Bolivia is a country rich in water resources in general, there is more water where there is the least amount of population, and this situation is worsening due to global changes and increasing migration. Water scarcity is especially severe in the Altiplano and the valleys, where most of the population lives, especially rural population with a high rate of dispersion. It is to be expected that, if water scarcity continues to increase at current rates, social conflicts in Bolivia will also become more and more severe.

In this context, I have devoted more than 20 years of professional work to the development of the country's rural area, implementing several rural development projects based on the planning and use of water resources. I have built many potable water systems for rural communities where women and children had to walk enormous distances in order to collect the water to satisfy their basic needs. Witnessing these situations drove me to desperately search for low-cost alternatives to deal with water scarcity. Finding water for consumption was not the only challenge, but also water for production, which was achieved in many cases through the design and construction of irrigation and micro-irrigation systems, pumping systems, taking advantage of springs, earth dams or small water reservoirs and their distribution systems.

Also, I have had the opportunity to contribute to the development of hydro-energy and the satisfaction of having constructed small hydraulic turbines of my own design and fabrication to provide electricity to more than 40 rural communities. All of these projects related to water resources are of integral management and related to other sciences, such as hydrology, hydraulics, and economy. In order to guarantee their sustainability, and in line with integral management principles, the projects have included training and empowerment of the beneficiaries to ensure they make the projects their own and are capable of eventually maintaining and operating them themselves. The organization of beneficiaries was key to this process, since it established their rights and obligations in terms of managing the projects.

Through the execution of these projects I was able to develop abilities and to learn about the diverse local water management visions, strengthening this process within the communities in a democratic way. The goal was always to achieve an improvement in the quality of life of all the beneficiaries. The appreciation of the people who benefitted from these projects and their smiles of satisfaction have been more than enough retribution for this work. Providing light, installing a tap or using a spring to increment the local agricultural production and, therefore, food security, translates into the personal satisfaction of contributing to improve the quality of life in the rural area.

The acts of opening a potable water tap, flowing the water in an irrigation system or providing electricity cause a very particular satisfaction for one who has undertaken the challenge of working for development in a sustainable and ecologically-compatible manner. Seeing the gratitude in the eyes of the children, women and men that benefit from these projects after years of suffering is a motivation to go on. These experiences have given me the possibility to conduct scientific research in water resources management, with the full participation of the stakeholders, as it must be done in order to set the foundations and provide solutions for integrated water management in the Lake Poopo basin.

I hope this Thesis contributes to a practical implementation of an integrated water resources management strategy in the Lake Poopo basin. Hopefully this strategy can be started in the short-term in order to deal with climate change and stop the migration, environmental degradation and poverty that are beating down on this very vulnerable region of Bolivia.

Acknowledgements

First and foremost, I would like to thank my supervisors, Professors Lars Bengtsson and Ronny Berndstsson, for their understanding, helpful support and patience during my seemingly endless doctoral studies. I also wish to extend my gratitude to all the staff of the TVRL (Department of Water Resources Engineering at the University of Lund-Sweden) for having allowed me to get to know closely the customs and traditions of Swedish society and having shared with me so many precious moments during my short but unforgettable visits to Sweden.

During my doctoral studies I confronted two critical situations which required my utter attention. First, my son was born and faced health problems due to medical negligence and later my mother passed away, also due to a case of medical negligence. This loss, along with my son's process of recovery, was ultimately an incentive for me to accomplish the goal of concluding this research. My deepest appreciation is extended to all those who supported and encouraged me through those difficult times.

Thanks are also due to the Swedish International Cooperation Development Agency (Sida) for their financial research support to the University of San Andres (UMSA), under which I carried out my doctoral studies.

I would also like to acknowledge my colleagues at the Institute of Hydraulic and Hydrology, and its head, C. Herbas, for their understanding and patience during my studies, to *tovarich* R. Pillco for several useful discussion day and nights, insight and feedback during the cold winter in Lund and J.L. Montaño and A. Aliaga for their permanent encouragement.

I want to express my thanks to the UMSA's authorities, to the Department of Research in Social Interaction (DIPGIS), to the Dean of the Engineering Faculty M. Teran, to the Director of the Civil Engineering Department M. Calla and to everyone who made it possible for me to continue and finish my doctoral studies.

My profound and sincere thanks to all the people of the Lake Poopo basin (indigenous authorities, Tacagua Association of Irrigators (ARPT), local farmers, and municipal authorities) for generously sharing their time. Special thanks to the local authorities of the towns of Quillacas, Challapata, Pazña, El Choro, Huacani and Sevaruyo for making it possible for me to bring the stakeholders together and secure their participation in the meetings and workshops in order to understand the issues, the local water vision, propose solutions and participate in facing the challenge of driving an adequate management of water resources.

Last, but not least, I want to thank my mother$^{(\dagger)}$ and father for their permanent guidance and inspiration. To my siblings dispersed around the world; my sisters, Virginia in Belgium and Irene in USA, my brother Ivan in Belgium, my daughters Giada in Italy and Dina in Russia. Finally, I would like to express my gratitude to my wife Melina for her love, permanent support and help, especially during my absences, and of course to my beloved children Khiara Andrea and Andresito. I love all of you so much.

Andrés Calizaya Terceros

Abstract

The Lake Poopo basin, located on the Bolivian Altiplano, is extremely vulnerable to environmental degradation. The basin displays extreme spatial and temporal variations of water resources and rapidly decreasing water quality due to anthropogenic and natural pollution. The region's population lives in extreme poverty, and the authorities' efforts to manage the water resources efficiently have been insufficient. The poor environmental and socio-economic conditions, made worse by water scarcity and extreme weather events, are causing migration from the basin to increase rapidly. Although Integrated Water Resources Management (IWRM) is a relatively new approach in Bolivia, it is now generally accepted that this approach needs to be established in order to find sustainable solutions for development. The present study proposes a strategy to implement IWRM in the Lake Poopo basin on the basis of analyzed hydrologic and water-demand data and a model of Multi-Criteria Decision Analysis.

This research analyses climate and hydrological data from a newly established observational network at the Lake Poopo basin, as well as information from local and regional stakeholders. The data is analyzed using Geographical Information System (GIS), resulting in the assessment of temporal/spatial variability of water balance components and the availability of freshwater resources throughout the basin.

The present study assesses also the use and availability of water in the basin and determines the minimum water necessary for increasing the people's quality of life. A questionnaire was carried out and the data was used to elaborate a model for the determination of rural domestic water demand and the parameters this demand depends on.

This study includes the application of the integrated Water Sustainability Index (WSI) to the Lake Poopo watershed. The WSI incorporates hydrologic, environmental, life, and water policy issues and responses for a specific watershed. By analyzing different scenarios, the thesis develops an integrated view of which water-related issues are the most critical for sustainable development.

A Multi-Criteria Decision Analysis (MCDA) was also developed in the Lake Poopo basin, based on economic, social and environmental criteria in an uncertain decision environment. The purpose of this was to support stakeholders in managing their water resources, as stakeholder participation is at the heart of successful water resources management. Saaty's analytical hierarchy process (AHP) theory was applied to solve the MCDA and to identify the alternatives using the highest expected utility value. Thanks to the participation of stakeholders, the study was able to determine the most pressing conflicts, most adequate solutions and best-suited implementing actors. This model forms a basis for the development and execution of an IWRM strategy in the Lake Poopo basin.

Finally, this research proposes a stepwise implementation of an IWRM strategy, based on key issues, such as active stakeholder participation, and an institutional arrangement structure. This strategy is designed to improve the management possibilities of the basin's scarce freshwater resources and the feasibility of planned water harvesting projects. The study assesses the opportunities and challenges in the implementation of the strategy and proposes steps to achieve successful results. In addition, it explores the potential benefits from the development of local capacity and stakeholder participation.

The main conclusion of this study is that the water resources in the Lake Poopo basin are subject to extreme variability and scarcity, and that the only way to face this situation sustainably is the immediate implementation of an IWRM strategy with the full participation of stakeholders and the support of local and regional authorities.

List of appended papers

The following papers are appended:

Paper 1
Calizaya, A., Bengtsson L. and Berndtsson R., 2008. Spatial and temporal distribution of water resources in the Lake Poopo basin, Bolivia.
Open Hydrology Journal accepted for publication. In press.

Paper 2
Calizaya, A., Bengtsson L. and Berndtsson R., 2008. Water use related to the water resources in the Lake Poopo basin, Bolivia.
International Water Resources Association (IWRA) Journal. (Submitted)

Paper 3
Calizaya, A., Chaves H., Bengtsson L. and Berndtsson R., 2008. Application of the Watershed Sustainability Index to the Lake Poopo Watershed, Bolivia.
Open Hydrology Journal. (Submitted)
The paper has been presented at UNESCO/PHI International Conference in Water and Global Change ("Agua y Cambio Global") held in Montevideo, Uruguay 8-10 September 2008.
Conference proceedings Unesco/ihp-LAC, 2008.

Paper 4
Calizaya, A., Bengtsson L., Meixner O. and Berndtsson R., 2008. Multi-Criteria Decision Analysis (MCDA) for Integrated Water Resources Management (IWRM) in the Lake Poopo basin, Bolivia.
Water Resources Management Journal by Springer. (Submitted)
The paper has been presented at UNESCO/PHI International Conference in Water and Global Change ("Agua y Cambio Global") held in Montevideo, Uruguay 8-10 September 2008.
Conference proceeding Unesco/ihp-LAC, 2008.

Paper 5
Calizaya, A., 2009. Approach for Implementing an Integrated Water Resources Management (IWRM) Strategy in the Lake Poopo basin, Bolivia.

The paper, translated to Spanish, was sent to the Prefect of Oruro and diffused among the main municipalities and indigenous authorities in the basin in order to have them debate and analyze its inclusion in their Annual Operating Plan and propose changes and suggestions. Most importantly, as stakeholders, they are expected to promote its implementation.

Table of Contents

1. INTRODUCTION

Integrated management means that all the different uses of water resources are considered together. Water allocations and management decisions consider the effects of each use on the others. They are able to take account of overall social and economic goals, including the achievement of sustainable development. The basic Integrated Water Resources Management (IWRM) concept has been extended to incorporate participatory decision-making. Different stakeholders (water-user) groups (farmers, communities, environmentalists, etc.) can influence strategies for water resource development and management. This brings further benefits, as informed users apply local self-regulation to issues such as the conservation, catchment and protection of water much more effectively than central regulation and surveillance can. Thus, integrated water resources management is a systematic process for the sustainable development, allocation and monitoring of the use of water in line with economic, social, and environmental goals. According to Koch and Grunewald, 2008, for "an integrated water resources management (IWRM), as demanded for instance by the European Water Framework Directive (EU-WFD 2000), the ecological, social, and economic functions of the water cycle have to be taken into consideration". When one entity is responsible for the management of drinking water, another for irrigation water and another for the environment, the result is inevitably uncoordinated water resource development and management, which results in conflict, waste and unsustainable systems (Cap-Net and others, 2005).

Currently, the paradigm of Integrated Water Resources Management has worldwide recognition as the only feasible way to ensure a sustainable approach in planning and managing water resources systems (Castelleti and Soncini, 2006). It is the main reference for all water-related activities in developing countries, where access to water supply is one of the most important factors for social and economic development. "As pointed out by the United Nations (UN), one third of the Millennium Development Goals (MDGs) depend on water." (Phumpiu and Gustafsson, 2009). However, most attempts to implement IWRM often fail due to the use of inadequate tools and methods to address the complex issues of integrated water-management and also due to the lack of stakeholder involvement.

The equitable allocation of water resources implies an improved decision-making process, where stakeholders are empowered to actively participate and make decisions regarding the management of their water resources. The empowerment of stakeholders implies raising water-management awareness, providing training and encouraging the formation of stakeholder organizations. This process can facilitate the resolution of conflicts balancing water demand and water availability, while guaranteeing the sustainability of water resources management.

The need to manage any resource is directly related to its degree of scarcity. In the case of water, which is a national good of public use, what management tries to maximise is social benefit. Scarcity is a key notion and can refer to aspects of water quantity and quality, with both temporal and spatial dimensions. This scarcity may be caused by limitations of the physical water resources, the access to them, or by inadequate management of the resources, or a combination of these. In the Lake Poopo basin, for example, access to water is one of the most important factors contributing to water scarcity. In other words, scarcity is often not determined by amount of water or rainfall, but by access to the water, which is sometimes impossible.

The management of water resources has three general objectives:

- The optimal and efficient use of water, with focus on the basin's development;
- The sustainability of water in time,
- Social peace and active and informed participation of the stakeholders

There are also several specific objectives of water management, such as a) sustainable agricultural production, b) energy production, c) alleviation of poverty, d) mitigation of extreme weather events, e) pollution control, f) impact on laws and policies, g) institutionalized stakeholder participation, h) cooperation between government and non-government agencies, i) monitoring and information management, etc.

From these objectives stem three clear ideas that allow us to approach the practical application of water resources management:

1) Recognizing the unitary character of the water resource in the unit called a basin. In other words, acknowledging that the water resource in a basin is one, and that all the users share the same resource and, therefore, must act supportively in its use.
2) The need for the existence of a local administration entity at the river basin level to manage the water resources in the basin.
3) The need to understand water as an economic agent, inserted as another productive factor in the national activities. This means recognizing that the value of water can translate into a price, inherent characteristic of any scarce good. With relation to water, the distinction must be made that the scarce good can be:

    - The right to water, in exhausted basins;
    - The quantity of flow of water, in times of drought;
    - The quality of water where there is a much pollution;
    - The opportunity of water supply from ephemeral rivers.

Where local water resources are limited, it is necessary to value water and decide how to allocate it. In some circumstances, price is an efficient mechanism to promote the conservation or increase the efficiency in the use of water. Nevertheless, this option must not be imposed on the poorest groups in benefit of private interests or through anti-democratic means. As recent Bolivian history has proven, problems are bound to arise when large private interests are satisfied without paying due consideration to the needs of rural communities and ecosystems.

In the Bolivian countryside, water resources are fragile. In general, more than half the country experiences a deficit of fresh water (Van Damme, 2002). The Andean region, in particular, is suffering several social and environmental changes which affect the access to water. These changes range from an explosive growth of some cities to the constant expansion of industrial activity and the possible change of the climatic pattern. Water resources in the Andes are being over-exploited in order to satisfy growing internal and external demand. As the water supply becomes more uncertain and conflicts emerge, local users and the related institutions try to find solutions.

Integrated Water Resources Management (IWRM) is a relatively new approach in Bolivia, and few or no attempts have been made to apply it. However, it is now an accepted fact that this approach must be established in order to find sustainable solutions for development. Integrated Water Resources Management is currently promoted by the Ministry of Environment and Water through a five-year (2008-2012) National River Basin Plan (PNC). The main objective of this national program is to develop and to strengthen the local operational capacities for Integrated Water Resources Management (IWRM) and the Integrated River Basin Management (IRBM).

The Lake Poopo basin is one of the poorest and most arid regions in the Bolivian Altiplano. It is confronted with severe water scarcity during the dry season, leading to low water quality, a high water-poverty index and low values of the watershed sustainability index. Furthermore, salinization and environmental degradation of soil and water are forcing people to migrate to faraway urban areas. The water bodies and regional rivers in the basin have, for a very long time, been polluted both naturally and by heavy metals from mining activity. The Lake Poopo basin is extremely vulnerable to environmental degradation. The basin displays extreme spatial and temporal variations of water resources and rapidly decreasing water quality due to anthropogenic and natural pollution from the mining industry.

The basin's population lives in extreme poverty, and the authorities' efforts to manage the water resources efficiently have been insufficient. The Lake Poopo basin is part of the bi-national (Peru-Bolivia) TDPS system, which includes the Lake Titicaca, Desaguadero River, Lake Poopo and the Salt marsh. The TDPS system authorities concentrate on the management of the bi-national Lake Titicaca, relegating the southern part of the river system, where Lake Poopo is located. These are some of the factors underlying an ever-increasing complexity in integrated water resources management in the region.

1.1 Objective of the research

The main objective of this study is to assess the water resources of the Lake Poopo basin, involving the stakeholders in a decision-making process to design a sustainable strategy for water resources management in the water-scarce Lake Poopo basin.

The specific objectives of this research are:

- To assess water resources and their spatial and temporal distribution in the basin through a water budget for a 42-year period.
- To assess the use of water resources in the basin, forecasting and investigating the current demand through inventories, questionnaires, workshops and meetings carried out in 68 small towns, in native languages, with the basin's local and indigenous authorities.
- To apply the HELP model in order to compute the Watershed Sustainability Index (WSI) in the Lake Poopo basin, and generate water-storage scenarios in order to demonstrate the fragile social, economic and environmental situation of the 20 watersheds.
- To propose a strategy for integrated water resources management with active enrolment of stakeholders at all levels in order to generate feedback and to support them in a decision-making process aimed at achieving the basis for sustainable development of the Lake Poopo basin.

1.2 Overall methodology

To achieve the objectives described above, field work, activities and processes were carried out, which allowed the consolidation of a close relationship with the watershed's stakeholders (national, regional and local authorities, indigenous authorities, irrigation organizations and other institutions) in order to listen to and understand their needs and priorities. The processes also helped to secure the stakeholder's support and participation in the research, which included their help in the collection of hydro-meteorological information. After specific training, local people were also involved in the measurement activities, as part of the study's objective of raising awareness regarding the care, protection and efficient use of water.

In order to express the availability of water in terms of space and time, data from 14 meteorological stations was analyzed for a 42-year period. The measurement of climate variables and discharge was carried out in order to apply the rainfall-runoff model *Simula* (developed by the *Center for Hydrological Studies of Spain*) in the regional rivers (Pillco and Bengtsson, 2006), with the objective of computing a water budget of the basin. Finally, GIS tools (ArcGis) were used to build thematic maps and to build a database.

After that, interviews and surveys were conducted, and inventories of the water use were taken throughout the Lake Poopo basin, covering even the farthest communities in order to obtain basic information. These activities were always carried out together with local authorities in an attempt to avoid misunderstandings with the people. The interviews and surveys allowed the systematization of information and the computing of current and future use of the water in the Lake Poopo basin. Based on that information, the necessary variables were selected to elaborate a model of domestic water-demand for the rural area suggested by (Calizaya *et al*., 2008b). This model can be useful for the continuous monitoring and assessment of domestic water-demand in the rural area of the basin.

Introducing to the Integrated Water Resources Management tools, the HELP model was applied to determine the Watershed Sustainability Index of each sub-basin, assessing the hydrology, environment, life quality and policy, thus assessing the situation of the regional river sub-basins in the Lake Poopo basin.

Several especial and coordinated meetings were carried out with local authorities and indigenous people to understand their water vision and promote the consolidation of a "water action" based on that vision. Several principles and statements on water resources management were taken into account for an equitable allocation of water resources, which requires an improved decision-making process. Thus, it was decided to give the stakeholders the opportunity to play the part of decision-makers in an Integrated Water Resources Management strategy.

Saaty's analytical hierarchy process (AHP) theory was applied here to solve the Multi-Criteria Decision Analysis and to identify the alternatives using the highest expected utility value. The study identifies the best solutions for existing conflicts, while promoting interaction with stakeholders and Instruments in order to reach a sustainable strategy for water resources management in this water-scarce region.

1.3 Organization of the thesis

This thesis synthesizes a series of recent studies conducted on the hydrological behaviour of the Lake Poopo basin and is presented in two parts: (a) the summary and (b) appended papers. The individual studies focus on water resources assessment, water resources management and water resources strategies for the sustainable development of the Lake Poopo basin. Research results have been presented at an international conference and have resulted in the formulation of scientific papers. The five papers included in this thesis are given as follows:

Paper 1

This paper forms the first part of the research background of the thesis. It discusses the main issues related to the spatial and temporal distribution of water resources in the Lake Poopo basin.

Paper 2

This paper forms the second part of the research background of the thesis. It discusses the water use related to the water resources in the Lake Poopo basin. The research included a survey that was carried out in more than 68 small communities in order to understand and get important information regarding water use in general (consumptive and non consumptive uses were defined) and the forecast of the water consumption up to 2015.

Paper 3

The objective of this paper is to apply and compute the integrated Water Sustainability Index (WSI) to the Lake Poopo watershed, with data from the five years between 1997 and 2001. The WSI incorporates hydrologic, environmental, life, and water policy issues and responses for a specific watershed. By analyzing different scenarios, the objective is to develop an integrated view of which water-related issues are the most critical for sustainable development. Three scenarios were analyzed: 1) a year-long drought, 2) a dry season with a dam in the upstream river branches, and 3) the dry season without the dam.

Paper 4

This paper proposes and develops a Multi-Criteria Decision Analysis (MCDA) in the Lake Poopo basin, based on economic, social and environmental criteria in an uncertain decision environment in order to support stakeholders in managing their water resources. Saaty's analytical hierarchy process (AHP) theory is applied here to solve the Multi-Criteria Decision Analysis and to identify the alternatives using the highest expected utility value. The paper identifies the best solutions for existing conflicts, while promoting interaction with stakeholders and Instruments in order to reach a sustainable strategy for water resources management in this water-scarce region.

Paper 5

This paper aims to guide a stepwise approach for implementing Integrated Water Resources Management strategy, based on Integrated Water Resources Management functions and key issues and institutional arrangement structure according to the results of the Multi-criteria Decision Analysis in order to find the best way for integral water resources management in the Lake Poopo basin.

2. THE LAKE POOPO WATERSHED

2.1 Geographical settings

The Lake Poopo watershed lies in the Bolivian Altiplano, a high- altitude plateau. The Desaguadero River links Lake Titicaca to lakes Uru Uru and Poopo and, in wet years, to the Coipasa Salt Flat. This system, conformed by four subsystems, is known as TDPS system (Titicaca-Desaguadero-Lake Poopo-Salares) which belongs to Bolivia, Peru and Chile, but most of the area is in Bolivia (Fig. **1**). The TDPS system covers an area of 143900 km^2, equivalent to 75% of the territory of Uruguay, and drains into interior basins (Revollo, 2001).

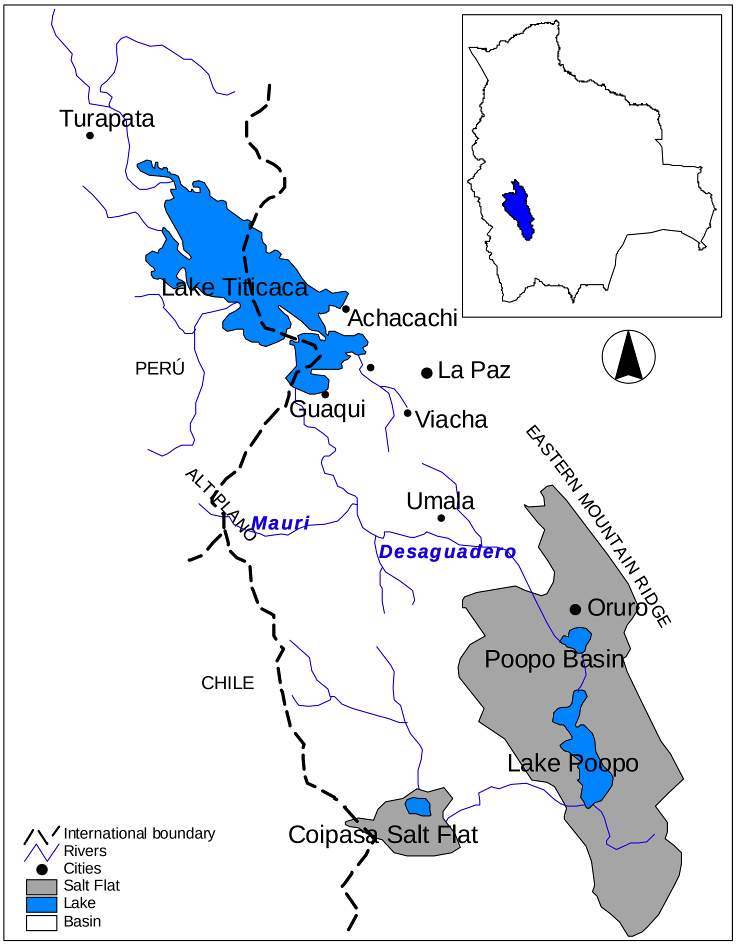

Fig. (1). The TDPS system and location of the Lake Poopo watershed.

The biggest subsystem is the Titicaca Lake; the lake itself has an average surface area of 8500 km^2 with a depth of 280 m, and is at a mean elevation of 3810 m a.s.l. (Pillco and Bengtsson, 2007). This entire system is enclosed by the Royal Andes mountain range. The Lake Poopo watershed has an area of 24000 km^2 and is one of the world's highest basins. Its main source of water is the Desaguadero River. The highest peak in the region is Mount Azanaque, which stands 5500 m above sea level, and the lowest point is the lake bottom, at 3670 m above sea level. Consequently, Lake Poopo is basically a water and salt sink. Spill-over occurs very seldom; the last spill-over occurred in 1986. The Lacajahuira River links Lake Poopo with the Coipasa Salt Desert (3550 m high).

The Lake Poopo watershed is constituted by 22 ephemeral river sub-basins, from 23 to 2577 km^2, and there are two shallow lakes (Fig. **2**): Lake Poopo (max. depth 3.5 m) and Lake Uru Uru (max. depth 1 m).

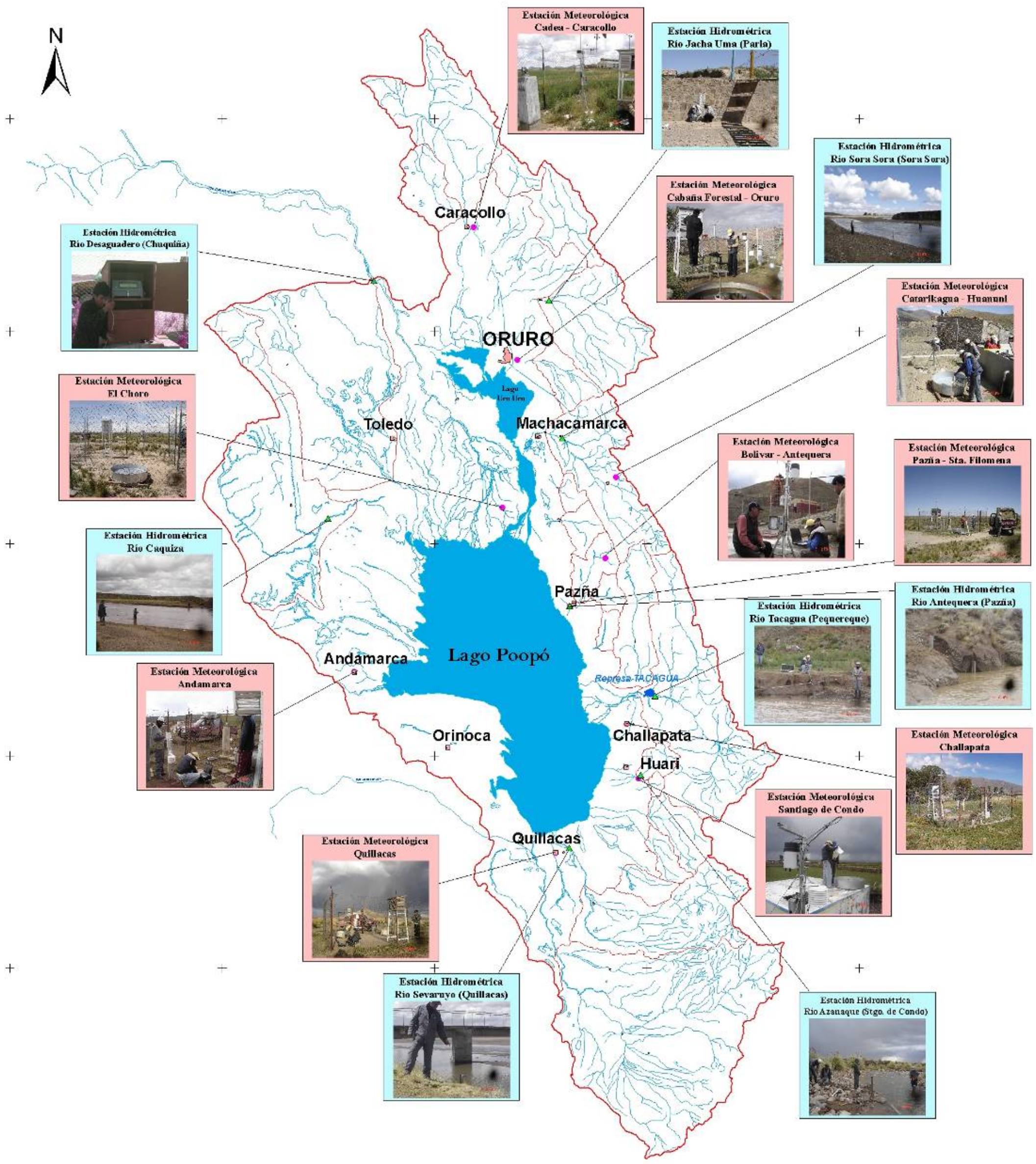

Fig. (2). The regional river basins of the Lake Poopo watershed and the recently implemented hydro meteorological network.

Lake Poopo can be as large as 3000 km^2, at spill-over level, after consecutive years with high precipitation, but may also dry up after consecutive years with prolonged dry seasons. Lake Uru Uru dries up every year during dry season, but during the rainy period it can be as large as 350 km^2. Lake Poopo and Lake Uru Uru are connected to Lake Titicaca through the Desaguadero River, which has a length of 400 km. In the wet season, the surface area of the lakes Poopo and Uru Uru can cover almost 15% of the total Lake Poopo river basin. As Lake Poopo is a closed and terminal lake, it is extremely sensitive to climate changes and water pollution.

The annual mean flow in all the regional rivers varies much from year to year, but is within the range of 10-40 m^3s^{-1} and at the inlet of the basin, in the town of Chuquiña, the average flow of the Desaguadero is 66 m^3s^{-1} (Pillco and Bengtsson, 2006).

Almost 30% of the total area of the Lake Poopo river basin is a mountainous range (Upland), especially the east (Fig. **3**), where the regional rivers originate and flow to Lake Poopo during the rain period, from December to March. The flat-land (flooding area) covers more than 30% of the area. The lakes are in the flat land surrounded by the flooding area.

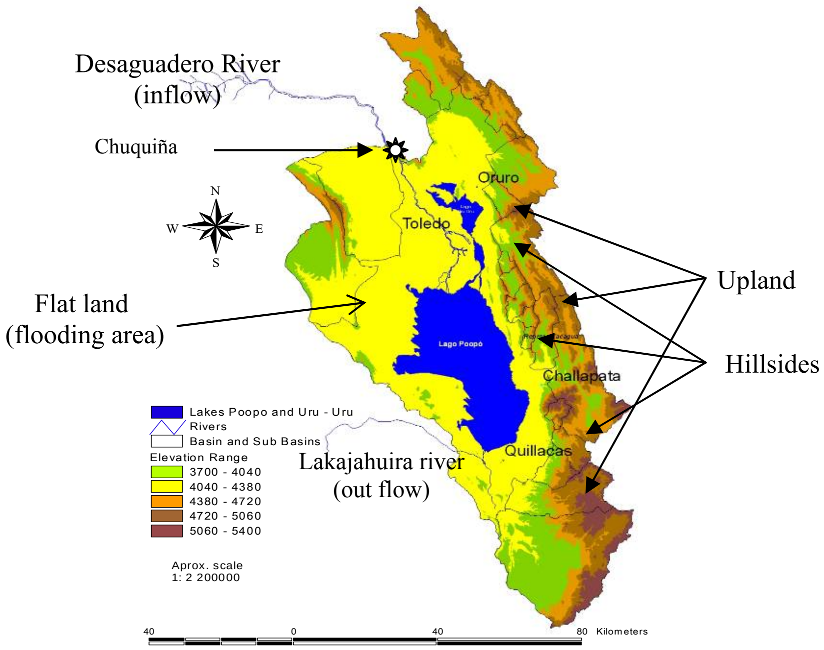

Fig. (3). Topography configuration and regional river sub-basins of the Lake Poopo

2.2 Geology and vegetation of the Lake Poopo basin

The Lake Poopo basin is a relatively young geologic system. The Nazca continental plate collided with the South America plate, resulting in geological disruption and the formation of the folded mountain range. The existing geology of the Altiplano is shaped by weathering working on tectonic features. The bedrock in the Lake Poopo basin consists mainly of folded, fragmental Paleozoic sedimentary rocks; shale, siltstone, sandstone, and quartzite. These rocks have been affected by the tectonic events such as folding. The Poopo-Uyuni fault system divides in two parts, differing in geology and morphology. The western region is covered with Cenozoic deposits on the older, Paleozoic layers. The Eastern region is characterized by Paleozoic bedrock with some younger deposits. Two major Cenozoic volcanic plateaus are located east of the town of Challapata. These extensive plateaus consist mainly of acid pyroclastic rocks. (Troëng and Riera, 1996).

Due to the texture of the soil and the high salinity in some sectors of the basin, certain species have developed morphological and physiological adaptations, which allow them to live in environments that are hostile to other species. Many species of animals live in close interaction with this vegetation. Extensive dry pastures predominate on the degraded soils, which are used as grazing land for herds of llama (*Lama glama*), alpaca

(*Lama pacos*), vicuña (*Vicugna vicugna mensalis*) and sheep (*Oves aires*). To a lesser degree, the land is used for the cultivation of potato (*Solanum tuberosum*), barley (*Hordeum vulgare*), quinua (*Chenopodium quinoa*), cebadilla (*Bromus catharticus*), etc. (Montes de Oca, 1997).

The vegetation in the basin is sparse, with occasional native copse of *polylepis tarapacana, parastrephia lepidophylla, bachiris incarum, azorella compacta, stipa ichu y festuca orthophylla,* (Beck, 1988). In the lowlands on the shores of Lake Poopo, where the salinity in the soil is very high, the typical vegetation is *troglochin sp., deyeuxia curvula* and *distichlis humilis* (Zeballos *et al.,* 2003). As aridity increases from north to south, the vegetation decreases. According to Rivera *et al.,* (1996), the soils in the Altiplano are shallow and not well developed, while along the rivers and on the hillsides there is a higher level of evolution. Along the lakeshores, one can find saline soils with a thin layer of salt deposits on top of the sediments.

2.3 Environmental and conflict setting of the basin

In the past, the ancient cultures in the Altiplano respected nature and practiced the rational use of natural resources, which helped them to live in harmony with the environment. Since the times of the Incas and later, with the coming of the Spaniards, mining has been one of the main economic activities in the region. Silver, gold, tin, tungsten, antimony and lead are the main metals exploited, and their exploitation began the anthropogenic pollution of the natural resources. Since the mining started, the water bodies and the landscape of the Lake Poopo basin have been under heavy natural and anthropogenic pressure. The acid and heavy-metal contamination is due to natural sources, as well as to the mining and metallurgic industries and the high salinity levels of the soil, surface waters and shallow groundwater (Risacher and Fritz, 2000).

In the north-east of the basin, inventories established the existence of around 120 mines, of which 60% are still active. The most important are Huanuni, Antequera, Poopo, Santa Fe, Kori Kollo, Bolivar and the Vinto tin foundry (Zabaleta *et al.,* 1993 and EALPyRT, 2007). The most important minerals, mined and exported in high quantities, are lead, silver, zinc, tin, gold and copper (Capriles, 1997); much mineral residuals reach into Lake Poopo. According Garcia *et al.*, (2007), the impact of mine activities on the environment is extensive in the northern part of the Lake Poopo region. The pH values are very acid or very alkaline, such as in the Poopo River, and heavy-metal concentrations are high both in the water and the sediment. There is also a high concentration of sulphur and lead in Lake Poopo, which increases during the wet period, showing how mining residues are carried into the regional rivers and then into Lake Poopo. In the southern regional rivers, where there is no mining activity, the water has a neutral pH, low heavy metal concentrations, sometimes lower than detection levels, with the exception of the lake’s outlet, Lakajahuira River, which carries high sulphur and heavy metal concentrations into the downstream Salt Marshes of the TDPS-system, the rare times that Lake Poopo spills over.

In addition to contamination from the mining activity, the basin has suffered from the contamination from an oil spill. In the year 2000, a spill of crude petroleum occurred in the Desaguadero River, which practically exterminated the native species of fish existing in Lake Poopo. Fishing was the means of survival for the native culture of *Uru-Muratos*, who have since been forced to leave their lands. Although the lake has partially recovered and fish are again present, the negative consequences of this event will impact the local environment for many years to come (Montoya and Mendieta, 2006).

The waters of the regional rivers are seasonal. The rivers are ephemeral, flowing from December to April and dry the rest of the year. Although drought is the most common phenomenon, both droughts and floods have had significant environmental, social and economic impact on the basin. The droughts of the 1990s caused economic losses estimated at US$30 million, while the great flood of 1986-1987 inundated more than 4000 km^2 of the shores of lakes Poopo and Uru Uru and caused losses totaling US$20 million throughout the basin (Revollo *et al.,* 2003). Both the droughts and the floods are linked to natural rainfall and water-flow patterns but, they are also influenced by the imbalances caused by the basin's diminished regulating capacity which results from poor land use and the inappropriate location of the productive activities and infrastructure.

The imbalance of water resources availability in the Lake Poopo basin between the 4-month long wet period and the 8-month long dry period causes a process of water-stress, provoking the deterioration of fresh-water resources in terms of quantity and quality, as well as land degradation, desertification and unsustainable eco-life conditions (Calizaya *et al.*, 2008a). The inflow from the Desaguadero River must be guaranteed for the conservation of the biota and to prevent Lake Poopo from drying up during the dry period. The inflow required to sustain the lake is 46 m^3s^{-1} (Calizaya *et al.*, 2008a). Unfortunately, the inflow from both regional rivers and the Desaguadero River is not guaranteed due to the extreme variability of the climate.

The increasing development of agriculture and livestock demands a greater quantity of water in order to supply for an increase in production, especially during the dry period. As the water resources become more and more scarce, conflicts among different users may intensify, especially between the mining and farming sectors. These major problems are further aggravated by the generalized lack of water management awareness and by the dearth of clearly established water policies, all of which leads to conflicts between sectors. Due to increasing water demand, different groups compete for access to water resources, and simultaneous water use from different sectors is often not compatible and can generate conflicts (Crespo and Mattos, 1999).

Conflicts relating to the water resources in the basin occur at different levels and between different stakeholders, take diverse forms, involve a wide range of issues and have many dimensions (legal, institutional, socio-cultural, and so on). The water-conflict issues in the basin have been grouped into 5 main categories: extreme weather events (water quantity), socio-economic situation, deficient water regulations, environmental degradation (including water quality) and the lack of organized stakeholder involvement (Calizaya *et al.*, 2008a, b, c and d).

One example of conflict deriving from deficient water regulations and environmental degradation is the one between the mining and farming sectors in the north-east of the basin (Calizaya *et al.*, 2008b). In general, the mining sector receives more political support in the definition of water rights. Most cases of water conflicts between stakeholders are on the exercise of water rights, which require adequate water laws and regulations in order to be peacefully resolved.

Table 1. Water related conflicts and consequences in the Lake Poopo basin

Category	Conflict	Indicators	Consequences
Extreme weather events	highly variable climate	ENSO phenomena	drougth, water scarcity, desertification
	low precipitation high evaporation	200-400 mm 1200-1800 mm	drougth, water scarcity, desertification
	drougths	16 devastating events since 1906	
	floods	11 devasting events since 1906	agricultural losses, starvation, livelyhood threatened, roads and train railway destruction
	frost	frecuent in winter	
	hails	50 days between 1971-1977	
Socio-economic situation	education	25% average illiteracy rate	few opportunities to improve quality of life
	poverty & extreme poverty	73% ; 30% ; HDI=0,52	pressure on the natural resources
	access to water	low water poverty index (WPI=28)	low quality of life
	income	< 600 $us/year	subsistance economy
	land fragmentation	insufficient data available	farmers can not make the transition to more efficient agricultural production
	health: life expectancy	farmers 58 years miners 45 years	low quality of life
	child mortality rate	10%	
	migration from the basin	-25% (INE, 2001)	farmland abandoned
Deficient water regulations	deficient regulation of WR		conflicts among users
	obsolete and ambiguos law	water law passed in 1906 unmodified to date	conflicts among users
	lack of instances to enforce laws	enivronemental law 1333 constantly violated	environmental degradation
Environmental degradation	pollution: natural & antropoghenic	RAD, salinization, sediments	
	Intense mining activity	120 mines (big & small)	Diseases in humans, loss of plant and animal life, environmental degradation
	heavy metals in water bodies, plants and soils	acid pH; alkaline pH concentrations of As, Pb, Cd, and Zn are over permissible level	
	deforestation	increase of arid zones	decrease of arable and grazing land (food security threatened)
	overgrazing and overharvesting	natural pastures are depleted	low recovery capacity, erosion and desertification
	salinization: water and soils	(2-100 grl^{-1}) ; (4 - 10 dSm^{-1})	decrease of arable and grazing land (food security threatened)
	environmental degradation	low watershed sustainability index (WSI=0.42)	decrease of arable and grazing land (food security threatened)
Stakeholder involvement	lack of environmental education		People lack training to manage water efficiently
	lack of participation		People are not willing to cooperate in "common good" activities without perceived direct benefit
	isolation of communities from eachother	aprox. 6.5 inhabitants per km^2	communication between communities is difficult
	limited economic resources		limited resources (time, etc.) to participate in activities

Table **1** was elaborated mainly based on information from the National Statistics Institute (INE, 2001), PPO-2 and PPO-3 (1996), Revollo (2001), Pillco and Bengtsson (2006), ALT (1999 and 2003) and Calizaya *et al.*, 2008a, b, c, and d.

This table details each of the conflicts that fall under the conflict categories. Where it was possible, indicators and numbers were given to illustrate the severity of the conflict. Nevertheless, statistics and indicators were not available in some of the cases, such as “land fragmentation” and “deforestation”. Finally, the table shows the consequences of each conflict. This table largely describes the current situation of the Lake Poopo basin tied to the water-related conflicts.

Extreme weather events such as floods and drought have devastating impacts on the region because of the fragile economy and the degradation of the environment. Since 1906, the Lake Poopo basin has experienced 16 droughts and 11 floods. The drought of 1990 caused economic losses worth US$30 million, while the flood occurred between 1996 and 1997 meant at least US$ 20 million in losses (Revollo *et al.*, 2003). As a consequence of these events, poverty is aggravated, which in turn causes added pressure on the natural resources. The implementation of an IWRM strategy would enable the basin to regain some of its natural regulating capacity. In other words, it would decrease the impact of these events. For example, reforestation could help control floods, and the construction of dams would decrease the impact of droughts.

Land fragmentation is also a contributor to water conflicts. Agriculture and livestock breeding, the main sources of income for the peasants in the Lake Poopo basin, are carried mainly on small-scale and dispersed parcels of land. The land is fragmented generation after generation, as farmers inherit the land from their parents, and the already small parcels are divided amongst siblings. This impedes farmers from adopting more efficient means agriculture and irrigation. Thus, they are condemned to subsistence farming, and a ceiling is set on their income-generating capacity and opportunity for growth.

Some of the more severe conflicts between the farming and mining sectors in the basin derive from deficient water regulations and environmental degradation. For example, the Huanuni Mine has been in conflict with the 40 communities located along the Sora Sora River for many years. The water reaching downstream communities is heavily contaminated by waste discharges from the mine. In the beginning of 2009, these 40 communities demanded their sub-basin be declared an environmental disaster zone because the pollution had degraded the soil and elevated the acidity of the water to pH levels of between 2.6 and 6.5. The conflict has not yet been solved.

Water-supply is also a cause of conflict, especially between the private sector and the population. The town of Santiago de Huari, for example, is home to one of the largest beer-producing companies. The company pays four nearby indigenous communities in exchange for the right to deviate water from the springs in their territory. Yet, these springs are the only source of water for the town's water-supply system. As a result, around 60% of the available water is used by the beer industry, while the population of Huari has access to water only 6 hours a day.

Finally, anthropogenic and natural pollution of the water is another of the most important factors aggravating water-related conflicts (ALT, 2003). For a long time, rivers and lakes have been contaminated by heavy metals from the mining companies and foundries. As a consequence, the concentration of heavy metals in Lake Poopo is reported to be between 300 and 3500 times that of other lakes around the world (PRH, 1989). The consequences of pollution are diseases in the population, such as lung silicosis, heavy-metal poisoning, mental alterations, anemia, nervous and renal problems, high blood pressure, reproductive problems, etc., according to Garcia *et al.*, (2005). On the other hand, salinization causes desertification and diminished fertility of soils (Montoya, 2006). The salinization values in the basin's lakes and rivers are between 2 and 100 grl^{-1}. In the soil, the salinization values range from 4 to 10 dSm^{-1}.

2.4 Socio-economic setting

The pre-Hispanic ethnic groups in the altiplanic region maintain ancestral cultural patterns which are unlike those of Western culture. Due to their strong cultural traditions, which play an important role in the lives of peasants, it is necessary to understand, assimilate and appreciate their way of life before any attempt at introducing changes can be successful.

Although there are only three main indigenous groups in the Lake Poopo basin (*Aymara, Quechua* and *Uru-Muratos*), these are organized into 200 *Ayllus,* or traditional territorial, cultural and political organizations. Each *Ayllu* has a different name, particular traditions and festivities, and its authorities are elected periodically by traditional means. The population surrounding the Lake Poopo is mostly made up of *Aymaras* and *Uru Muratos*. Spanish and *Aymara* are the main languages spoken in the region.

The Lake Poopo watershed has a population of 360000 inhabitants (Calizaya *et al.*, 2008a), the majority of which is indigenous. 50% of the population remains without access to improved sources of water, and 60% lack hygienic sanitation. The exposure to disease caused by this contributes to 10% of the cases of infant mortality every year. The life expectancy is only of 58 years and drops to 45 in the mining towns. According to the census carried out by the National Institute of Statistics (INE) in 2001, 73% of the total population lives under the line of poverty, of which 30% lives in extreme poverty. Close to 50% of the population of Oruro, the most important city in the basin is poor. Mining has always been a main source of income in the region, but the profits from this activity have not improved the people's quality of life in the long term. This is due to many factors, such as unsustainable social responsibility projects and the lack of policies to deal with fluctuations in the international price of minerals.

Migration to cities is increasing in Bolivia, due mainly to poverty. In 1950, the ration of urban to rural population was 40 to 60. The last census (INE, 2001) shows a reversed relationship, with approximately 60% of the people living in cities and 40% in the countryside. Given that the Lake Poopo basin is one of the poorest regions, migration from the basin is high.

As stated above, agriculture in the basin is mainly carried out on small and dispersed parcels of land. This is due to the Land Reform of 1953, whereby community ownership of rural land was abolished and replaced by individual ownership. Thus, with each new generation, the parcels of land become smaller and efficient farming is a more elusive goal. In this context, only subsistence agriculture is possible. Thus, the current system of land ownership, coupled with poverty, causes a great waste of effort and resources. In addition, floods, droughts and frost cause the loss of animals and cultivations. In general, the region has a highly fragmented landscape, with many farm lots, overgrazing, poor vegetation cover, salinity and low productivity, as shown in Table **1**.

2.4.1 The Andean vision of water from an indigenous and peasant point of view

Involving the water vision, the principle of water as an "economic" good, (Dublin Statement on Water and Sustainable Development, 1992), may not be in line with all cultures and may be, therefore, a source of conflict. For South America, reference can be made to the Andean Water Vision, where indigenous people understand water as a sacred and in some sense "living" entity (World Water Council, 2006). Often, in western cultures, water is viewed as a purely material substance. Consequently, there are contrasting understandings of what water actually represents, creating a source of conflict with respect to water rights, water use, and water management. In general, the rural population of Bolivia, especially in the Altiplano, has a holistic view of the use of water, which to them represents a source of life, in coherence with the general Andean water vision. People do not exclude water from the remaining natural surroundings, and they reject the idea that water can be managed through a mercantilist point of view. For the Andean peoples, water can be much more than a natural resource. In the indigenous communities there are common beliefs that define an Andean vision of water:

- Water is a living entity which is a source of life capable of animating the universe;
- Water is a divine being that comes from the god creator of the Universe, the *Wirakocha,* to fertilize mother earth, *Pachamama,* thus allowing the continuity of the cycle of life.
- Water is the basis for reciprocity that gives unity to all living beings, connecting nature with human society, generating links within the family, family groups and Andean communities;
- Water is a universal and community right that is distributed with equity according to the needs, traditions and norms of the community and respecting the water's natural cycles;
- Water is an expression of flexibility that adapts to ecosystems, circumstances and opportunities without adhering to rigid norms;
- Water is a transforming being that obeys the laws of nature, is ruled by the cycles of the seasons and the conditions of the terrain;
- Water is a force of cohesion that allows the self-determination of the peoples and the communities, respecting nature;
- Water is a common patrimony that belongs to the earth and to all living beings and;
- Water is a public good that is governed through local common law.

In the Lake Poopo basin, the beliefs around water are very strong. In certain communities, if the rain does not come before the sowing season, the indigenous authorities and spiritual leaders walk several kilometers in search of the sacred spring water in the up-land for the rituals to guarantee the rains. In this case the ritual is very deep and mystical, as it involves not only to the indigenous authorities but also to all the beneficiaries in rituals related to the *Pachamama*. The understanding of water of indigenous people in the Lake Poopo basin manifests itself also in the rejection of water provision from private companies and in resistance to assigning a price to water. When a price is assigned to water from a water-supply system, the indigenous communities must be satisfied that the proceeds are invested entirely in the sustainability and maintenance of the water system. No economic profit is allowed to be had from the provision of water. Finally, their vision of water favors the idea of integrated management of water resources, as it implies the conception that humans, water and the environment are connected and dependant on each other.

3. CLIMATE AND HYDROLOGY

3.1 Climate over the basin

The Lake Poopo basin is characterized by the extreme variability of its climate. It is semiarid and cold, and its temperature ranges from 8ºC to 10ºC as annual average. Daily temperature fluctuations are extreme. In the summer, the temperature ranges from -2ºC to 25ºC, and in winter from -15ºC to 14ºC (Troëng and Kilibarda, 1996). Garreaud *et al.,* (2003) described the climate as having two well-defined seasons: one wet period of four months, from December to March, in which most of the yearly precipitation occurs (>70%). In the Lake Poopo basin the precipitation, temperature and humidity are very variable. Annual rainfall in the basin fluctuates more than 50% from the mean. The average yearly precipitation amounts to about 370 mm over the watershed, and varies from about 420 mm in the north to about 270 mm in the south. Evaporation is very high, reaching annual means exceeding 1800 mm at Lake Poopo (Pillco and Bengtsson, 2006) and almost 500 mm for the Lake Poopo river basin (PPO-3, 1996; Calizaya *et al.,* 2008a). These marked variations explain the flooding and droughts.

In the Lake Poopo watershed, precipitation occurs from December to March. The average yearly precipitation amounts to about 370 mm over the watershed, and varies from about 420 mm in the north to about 270 mm in the south.

The climate is related to the atmospheric circulations of the Inter-tropical Convergence Zone (ITCZ) (Ronchail, 1995; Garreaud *et al*., 2003) and the El Niño Southern Oscillation (ENSO) effect (Thompson *et al.*, 1984; Aceituno, 1988; Lenters and Cook, 1999; Vuille *et al*., 2000; Arnaud *et al*., 2001; Francou *et al.,* 2003). The first mechanism causes intense precipitation during the southern hemisphere summer, when it contributes vapor mass (Pillco *et al*., 2007). The ENSO effect has an impact on the behavior of the Lake Poopo basin and the availability of the water resources (e.g. Aceituno, 1988; Garreaud, 1999; Vuille, 1999; Pillco *et al*., 2006).

Droughts and floods are not only linked to extreme weather events and conditions. Another important factor that has considerable impact on extreme flow events is the basin's lack of natural regulation capacity due to steep slopes and poor land use (Revollo, 2001). The basin does not fulfill the function of a water reservoir, retaining water in the wet period and ensuring water availability during the dry period. Frost during nights is also a frequent phenomenon. Its frequency is very variable, and it occurs with more intensity between June and August (WMO, 1994).

3.2 Hydrology

The Lake Poopo watershed consists of 22 ephemeral river sub-basins. Its two main lakes are Lake Poopo (max. depth 3.5 m) and Lake Uru Uru (max. depth 1 m). Lake Poopo can have an area of up to 3000 km^2 after consecutive wet year, but may also dry up after several years with prolonged dry seasons. Lake Uru Uru dries up every year during the dry season, but can have an area of 350 km^2 during the rainy season. The Desaguadero River connects lakes Poopo and Uru Uru to Lake Titicaca.

The runoff generated within the Lake Poopo basin from the regional rivers varies largely throughout the year, from practically zero during the dry season to 10 times the average discharge during rain season. The regional rivers disperse into many streams, forming small deltas before reaching the lake. Some water filtrates into the shores. At the end of the dry season the rivers are mostly dry. Melt-water from the mountain areas in the north-west drains into the plains, where the western branch of the Desaguadero River flows. The south-western part of the watershed, which borders the Coipasa Salt Desert, is part of the flat-land. Diffuse groundwater flow into the lake from coastal aquifers is believed to be negligible.

According to Calizaya *et al.,* (2008a), the mean annual water balance for the Lake Poopo watershed is composed of 372 mm precipitation, 468 mm actual evaporation, and

96 mm water inflow from the Desaguadero River. The water balance of the Lake Poopo is composed of: precipitation equal to 340 mm per year; evaporation 1800 mm per year; inflow from Desaguadero River equal to 1152 mm per year and inflow from regional rivers about 286 mm per year, Table **2**.

Table 2. Annual water balance

	Whole basin	Lake Poopo	Up land & Flat land	Up land
Area (km^2)	2400	2000	22000	12500
P (mm/y)	372*	340*	375*	380*
E (mm/y)	468**	1800	349**	334**
Q_{Des} (mm/y)	96*	1152		
Q_{Reg} (mm/y)		286	-26***	-46***
Error term		-22		

*value from observations; **value from water budget; ***value from computations

4. POVERTY AND WATER POVERTY

"Managing water sustainably is essential to eliminating poverty and it enables people to live healthier and more productive lives" Clare Short, Secretary of State for International Development, UK.

The water crises are critical issues for governments and society worldwide, but poor people face this crisis on a daily basis in the Lake Poopo basin. The sustainable management of water is crucial to efforts to eliminate poverty. Poor people's lives are closely linked to their access to water and its multiple uses and functions.

Water poverty affects all poor people, but particularly women and children in the Lake Poopo basin. The poor elderly woman in a remote village in Huacani (Fig. **4**) has to devote a large amount of her time and energy to collect even salted-water from well. This task also is assigned to the children in absence of parents (Fig. **5**). The consequences are huge in terms of human development. At the heart of this crisis is an imbalance between the availability and demand for fresh water. In this increasingly tense contest, it is the poorest people who most frequently lose.

Fig. (**4**). Elderly woman collecting water from salty well in Huacani sub-basin, south east of Lake Poopo basin

Fig. (**5**). Uru-Murato children collecting water from 7 m well in the flat-land (Llapallapani town).

An indicator used to measure water stress and water poverty at household and community levels is the Water Poverty Index (WPI). The WPI is designed as a composite, interdisciplinary tool, linking indicators of water and human welfare to indicate the degree to which water scarcity impacts on human populations (Sullivan, 2001). The WPI has a range from 0 to 100. The highest value, 100 is taken to be the best situation, while 0 is the worst. It can be used to show that improvement within the water sector would help decrease poverty. The poverty index and WPI of the Lake Poopo watershed are compared with those of other parts of Bolivia and South America in Fig. **6**. The comparison shows that the situation of extreme poverty in the studied region is closely related to the lack of water, especially during the 8-month dry season, with its consequential disadvantage in temporal and spatial water allocation.

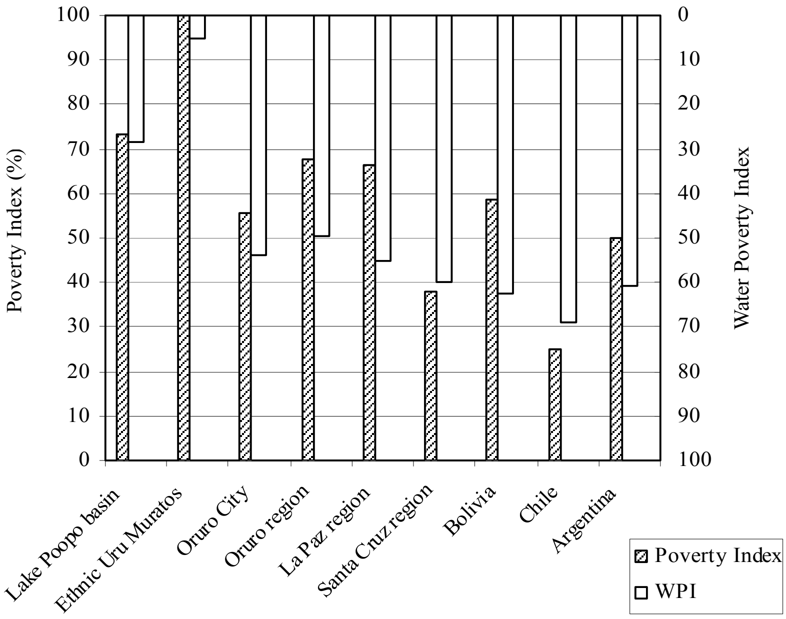

Fig. (6). Poverty Index and WPI for the Lake Poopo watershed compared to other places in South America (INE, 2001; ECLAC, 2002; CEH, 2002).

4.1 The vicious cycle; poverty-environmental degradation

A first aspect that emerges is the fact that poorest of the poor occupy the areas with most restrictions, limitations and of greater environmental fragility, areas that exist throughout the Lake Poopo basin. These are ecosystems with very little flexibility, which means that their options of productive use and their natural capacity of production are low. Furthermore, any alterations of the variables result in the acceleration of the degradation dynamics. Whenever an imbalance in these ecosystems takes place, regardless of the causes, the population exerts a higher pressure on the water resources to satisfy its basic needs, thus harnessing the process of environmental degradation. The degradation of the environment increases poverty which, in turn, causes the population to put even more pressure on the fragile water resources, in a process that truly constitutes a vicious cycle.

5. WATER RESOURCES IN THE LAKE POOPO BASIN: AVAILABILITY, CONSUMPTION AND SUSTAINABILITY

5.1 Spatial and temporal water distribution

The spatial and temporal distribution of the water resources in the Lake Poopo basin and the water use are discussed in depth in papers 1 and 2. In these papers, it is established that the availability of the water resources in the basin depends on the extreme climate variability. The assessment of the availability of water resources has been determined on the basis of an annual water budget over a period of 42 years (1960 to 2002), rainfall-runoff modeling of regional rivers, GIS tools and thematic maps (soils, vegetation and land use).

It is important to highlight that the Desaguadero River is the most important inflow to lakes Poopo and Uru Uru. Its potential is almost 10 times bigger than the inflow of regional rivers. The temporal water inflow distribution shows that, during the wet period, the regional rivers flows is $1.49x10^6$ m^3day^{-1} (17.24 m^3s^{-1}) and from Desaguadero River 7.79 $x10^6$ m^3day^{-1} (90.16 m^3s^{-1}), meanwhile during the dry period are 0.09 $x10^6$ m^3day^{-1} (1.04 m^3s^{-1}) and $3.74x10^6$ m^3day^{-1} (43.29 m^3s^{-1}) respectively. The annual average inflow from regional rivers is $0.56x10^6$ m^3day^{-1} (6.48 m^3s^{-1}) and the Desaguadero River is $6x10^6$ m^3day^{-1} (69.44 m^3s^{-1}). Temporally and spatially, the distribution of water resources in Lake Poopo (Fig. **7**) shows the gradient from the north to the south of the basin.

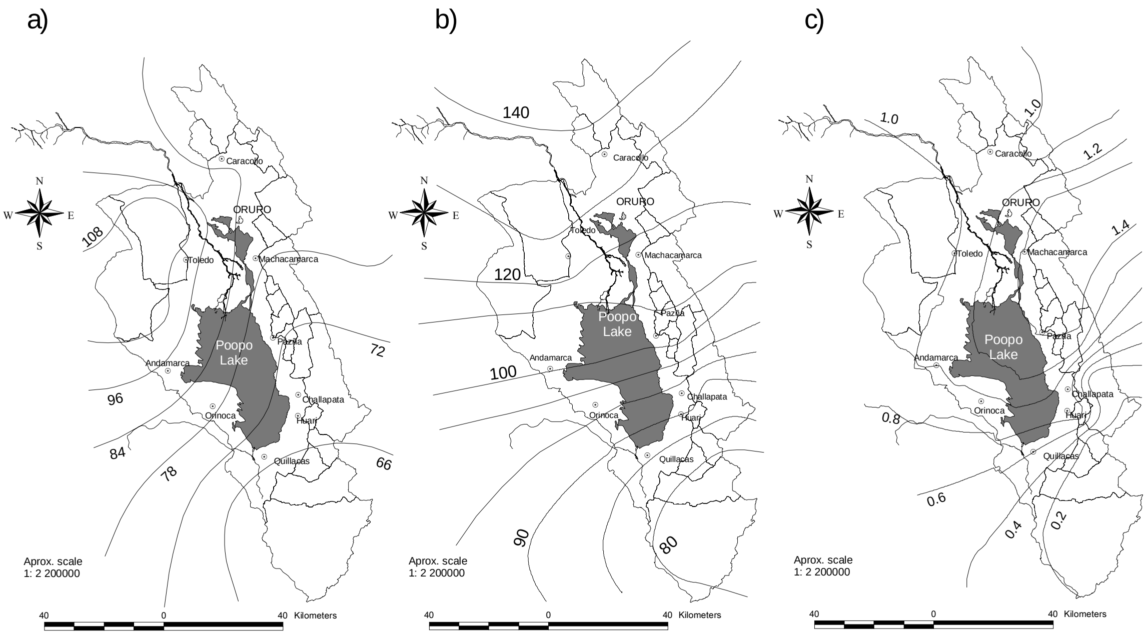

Fig. (7). Spatial surface runoff availability in the Lake Poopo basin:
a) Annual average based on 18 sub basin water budget in mm, b) Wet period in mm/4 months and c) Dry period in mm/8 month.

Figures (**7a**,) (**7b**), and (**7c**) show a useful map of water resources availability, in which the spatial distribution, in general, decreases from the northeast to the south. The difference between the spatial runoff availability during the wet and dry period is large. The spatial runoff availability during the dry period is practically zero in the south of the basin, making water unavailable. These maps can be used as a first overview of the water availability in the sub-basins when decision-makers are to identify related pre-feasibility development of water resources projects.

The water use in the basin, from a water-source point of view, can be divided in two systems: the Desaguadero River system and the regional rivers system. The water from the Desaguadero River can only be used for irrigation in the very low lands north-west of the flat-land area by traditional gravitation irrigation systems. Pumping the water to the uplands is not sustainable for agriculture due to the high cost of electricity and water-quality related problems (dissolved salt, sodicity and heavy metals). The most important irrigation system in this area is El Choro, which irrigates almost 4000 ha with water from the Desaguadero River. Every year, around one hundred stakeholders or beneficiaries must open the deviation channel manually for withdrawal due to the sedimentation problems. This work is carried out by men and women in well-organized communal work-days, which include traditional communal lunches (*apthapi*).

Meanwhile, the water from regional rivers must be used, especially the headwaters, before it becomes polluted in the mining areas, especially in the north east of the basin where the most important mines are located. Of the 22 river sub-basins, only the Tacagua sub basin, a 1300 km^2 catchment area, is regulated with a 25 m dam for agricultural proposes. The dam irrigates almost 5000 ha. Currently, this reservoir, of $45x10^6$ m^3 of initial volume and 60 km^2 surface area, has lost close to 50% of its storage capacity, due to sediments flowing from the unmanaged, eroded basin and is under pressure of the surrounding hills. To reduce the sedimentation to the reservoir sandtraps have been designed, but not yet implemented (Calizaya and Cespedes, 2008).

During the investigation, at least 4 sites with adequate characteristic for the implementation of dams were identified. The regional rivers also re-charge the groundwater aquifers. Thus, groundwater must be considered as another water-source for water supply and, in some cases, for irrigation under economic valuation. Here, the challenge must be to find the financial support for materializing these projects.

5.2 Water consumption in the Lake Poopo basin

The total water use was assessed based on inventories and questionnaires carried out throughout the basin. In general, in the rural area of the Lake Poopo basin there are no water meters. In the municipalities and in some large towns, the water service is handled by the Municipality, and this entity does not emit invoices for this service. Neither do they keep record or statistics of water consumption. In most of the communities located farther into the countryside, there are no water systems and no records of how much water is taken from sources such as wells and rivers for consumption.

Due to the lack of abstraction data regarding water demand and consumption in the Lake Poopo basin, it was necessary to obtain this information from an inventory and questionnaire. The inventory was carried out of all the existing irrigation and water-supply systems. In the case of irrigation, basic information was obtained regarding irrigation area, agricultural production, type of irrigation system, water source and water consumption. Likewise, the inventory was able to determine the number of livestock and mines operating in the basin.

On the other hand, in order to determine human consumption of water, questionnaires were conducted in a representative sample of 68 communities and towns, from a universe of 260. The sample was not random, but rather determined by factors such as location, population, environmental conditions and socioeconomic factors. The selection of the 68 towns and communities ensured that the Lake Poop basin would be represented in all its environmental and socio-economic characteristics. The results obtained from the questionnaires were compared with the scarce data from the Bolivian Information System of Water and Sanitation (SIAS), 2001, a nation-wide inventory of water systems and regional consumption tendencies. Specifically, these results were compared with the data of the consumption of water in the entire Altiplano region in order to verify their accuracy. The results of the questionnaire allowed the elaboration of a model to assess rural domestic consumption of water. This model is a first attempt at the scientific assessment of water consumption in the rural area, and is expressed as:

$$Q = 9.15 + 0.23X_1 - 0.66X_2 - 0.27X_3 + 0.02X_4 - 0.43X_5 + 2.38X_6 - 0.22X_7 + 2.96X_8 - 0.04X_9 \qquad [1]$$

In Eq. [1] the variables are: Q-average quantity consumed (l/c/d); X_1-Nº of adults; X_2-Nº of children; X_3-Nº of rooms; X_4-lot size (m^2); X_5-Nº of animals; X_6-Nº of taps; X_7-microirrigated area (m^2); X_8-type of water source(river, spring, well, etc.); X_9- monthly income ($us). The correlation coefficient has obtained as r=0.79.

The results show that the overall demand for water throughout the Lake Poopo basin is 9.0 m^3s^{-1}, of which 0.2 m^3s^{-1} is used for domestic consumption, 8.1 m^3s^{-1} for irrigation (2.3 m^3s^{-1} in winter, which lasts from June through August and 5.8 m^3s^{-1} in summer, which lasts from December through February) and 0.5 to 0.6 m^3s^{-1} for other uses including mines, small industry and watering places for livestock (MAGDR, 2000; Calizaya *et al.*, 2008b). According to the inventory and the flow measures of thermal waters, the overall flow is almost 30 ls^{-1} in 6 sites offering tourists small-scale natural hydrotherapies for medical uses.

The demand forecasting for overall water uses depends on the population growth. The population growth rate average was estimated at 2.4%. In some sub-basins of the Lake Poopo basin, the population growth rate is negative due to migration. In 2001, the population in the basin was 340000 inhabitants. According to the results of our investigation, the population is estimated at $360x10^3$ and $420x10^3$ for 2006 and 2015 respectively, computed based on information from the INE's census of 2001 and adapted to the basin.

Having established both the overall volume and overall demand of water in the basin, the water seems to be quite sufficient to cover at least the current demand. The water flow brought to the basin is 76.5 m^3s^{-1}, from which the ecological flow 45 to 50 m^3s^{-1} must be guaranteed in order to preserve Lake Poopo and Lake Uru Uru (Pillco and Bengtsson, 2007; Calizaya *et al*., 2008a) or 54 m^3s^{-1}, as established by Quintanilla and Martinez, (1992). In addition, and as stated above, the water inflow from Desaguadero River can only be used for irrigation in the very low lands north-west of the flat-land area. Therefore, the regional water systems must cover the water demand of the entire basin. So, not counting the inflow from the Desaguadero River, there is a deficit of almost 2.5 m^3s^{-1}.

The Peruvian Government has a plan to transfer water from the Mauri River, which is an international river and a tributary to the Desaguadero River. If executed, this diversion of water will greatly affect the Desaguadero Rivers inflow to Lake Poopo.

Peruvian authorities plan for even greater transfers in the mid-term. This situation could result in as yet unevaluated threats to the stability of Lake Poopo (Pillco and Bengtsson, 2007).

An alternative solution for coping with the water scarcity in the basin is the harvesting and storage of fresh water coming from the regional rivers. In some sub-basins, (i.e. Huacani, 23 km^2 of catchment area) a groundwater dam is considered as a solution to confront water shortage. The Huacani is an ephemeral river and it presents poor conditions for a surface dam due to the high slope of the main river channel, erosion and sediment transport. Yet, there is an underground flow, continuously fed by headwaters (springs), of between 1.5 to 3 ls^{-1} in the dry period. In addition, the bed rock is 10 m deep, allowing it to be closed to create a groundwater reservoir of approximately 4000 m^3 (Calizaya *et al.,* 2009b). It is necessary to implement water-harvesting projects throughout the basin in order to face the 8-month dry period.

5.3 Watershed sustainability assessment in the Lake Poopo sub-basins

One of the goals of watershed management is to achieve development that "meets the need of the present generation without compromising the ability of future generations to meet their needs" (WCED, 1987). Despite the fact that the sustainability of the water resources in a watershed depends on its hydrologic, environmental, life, and policy conditions, few have attempted to integrate these elements into a single, comparable indicator (Chaves and Alipaz, 2007). Integrated indicators are useful for survey and planning purposes. An example of integrated indicators is the Human Development Index (HDI), which the United Nations has been using for many years (UNDP, 1998). The HDI integrates educational, life expectancy, and income data from municipalities, states and countries.

Lawrence *et al.,* (2002) developed a Water Poverty Index (WPI) in order to estimate the water scarcity in countries. A variation of the WPI is the Climate Variability Index (Meigh and Sullivan, 2005), which estimates the vulnerability of countries, regions, and communities in terms of water resources. Both indicators are integrative, yet they are not watershed specific, because they neglect to consider cause-effect relationships, or the policy responses that are implemented in a watershed in a given season (Chaves and Alipaz, 2007).

Considering that the management of water resources is a dynamic process, and assuming that the sustainability of a watershed is a function of its hydrology (H), environment (E), human life (L), and policy (P), a dynamic, Pressure-State-Response (PRS) model was applied to these four indicators (H, E, L, P) in a matrix scheme. The Pressure-State-Response (PRS) model was developed by the OECD (2003) to structure its work on environmental policies and reporting. It considers that human activities exert pressures on the environment and affect its quality and the quantity of natural resources. Society responds to these changes through environmental, general economic and sectorial policies and through changes in awareness and behavior ("societal response" OECD, 2003). As a result, a Watershed Sustainability Index - WSI was developed, and is given by the following equation (Chaves and Alipaz, 2007):

$$WSI = \frac{H + E + L + P}{4} \qquad [2]$$

Where WSI (0-1) is the watershed sustainability index; H (0-1) is the hydrologic indicator; E (0-1) is the environment indicator; L (0-1) is the life (livelihood) indicator; and P (0-1) is the policy indicator. As seen from Eq. [2], all indicators have the same weight, since there is no evidence to the contrary (Harr, 1987). The linear and additive structure of Eq. [2] allows for error compensation in the indicators, reducing the potential of under and overestimation of the WSI (Chaves and Alipaz, 2007). The logic behind this is the fact that, if one of the indicators of Eq. [2] is overestimated, there is a good chance that another would be underestimated, compensating at least part of the overall error.

Since watershed management at the local and regional level is more effective in watersheds of up to 2500 km^2 (Schueler, 1995), this is the upper limit suggested for the application of WSI in the estimation of watershed sustainability. In the Lake Poopo basin, it was found that about 80% of the 18 sub-basins have low watershed sustainability, when the period analyzed is the whole year. The percentage increases if the dry season is considered, and is significantly reduced if artificial water storage is implemented. In average, the bottlenecks for the 18 watersheds are environment (0.41), policy (0.42), life (0.55) and hydrology (0.46).

Figure 8 shows the classification of WSI for each sub-basin, in the 3 scenarios studied. If water storage is implemented in the headwaters of the watersheds, all of them will experience a significant improvement in watershed sustainability, moving from the low to the intermediate level.

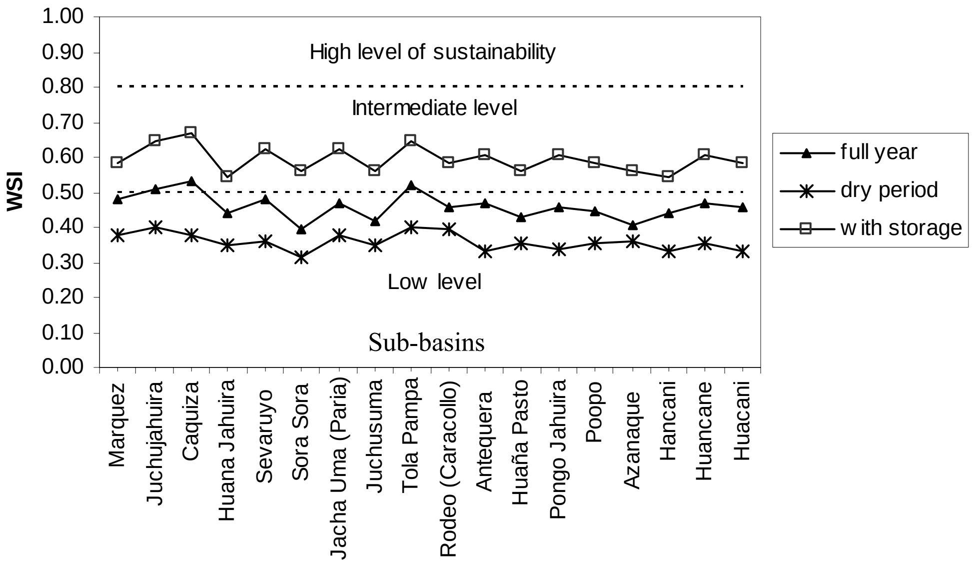

Fig. (8). Variation of the calculated Water Sustainability Index (WSI) for each watershed within the Lake Poopo basin.

6. STAKEHOLDER ENROLLMENT IN THE DECISION-MAKING PROCESS OF IWRM IN THE BASIN

It is widely acknowledged that stakeholders should play an important role in the public decision-making process. Consultation and participation of stakeholders in watershed management is seen as good practice (WWF 2001; Chaves 2001; Water Policy 2001). Such participatory practices help “to define problems, set priorities, select technologies and policies, and monitor and evaluate impacts and in doing so is expected to improve performance" (Johnson *et al.,* 2001).

Since the main problems in water resources management occur at the local level, their solutions depend on strong participation of stakeholders at all levels. Nevertheless, sometimes local people are not very motivated for participation. It is said that the main reason is a "local prisoner's dilemma" stemming from basic poverty in the basin (ALT, 2003) and the related low environmental awareness. The people cannot afford the more effective irrigation systems, and even if they could afford them, they lack the capacity to operate them. They are often unwilling to invest for a common good, such as reafforestation, if no direct personal benefit is to be obtained. Furthermore, changing habits is difficult, as people are unlikely to implement changes unless their neighbors are making those changes, as well.

Given that the management of water resources involves various stakeholders with multiple objectives, the decision-making process should include all individuals, groups and community-based organizations. The issue is how to best support stakeholders in managing their water demands in a context of increasing competition, interdependency and land fragmentation in order to guarantee sustainable management of water resources (Feng, 2001). According to FAO 2006, "supporting stakeholders in managing their water resources means supporting stakeholders to make choices and to reach a common understanding on the necessary arrangements for sharing and equitable allocating water related goods and services". Evaluating different strategies in water management (water valuation) is implicit to this process.

According to Feas *et al.,* (2004), a decision-making process implies the following steps:

a) Identification of alternatives that can solve the problem;
b) Selection of the criteria on the basis of which alternatives or instruments are going to be compared;
c) Estimation of the priorities of the alternatives related to the criteria;
d) Selection of the information derived from performances;
e) Relative importance of criteria must be clear in order to be able to select an alternative.

These steps are comparable with other models of decision processes, like Davis and Cosenza's (1993) model, where each decision (and evaluation) process starts with identification of problems and conflicts, followed by information search, problem analysis, alternative evaluation and finally the decision, i.e. the phase of implementation.

This study considers stakeholders to be all individuals, communities, irrigation organizations, local and municipality authorities, etc., that had have interest (stake) in the use or the management of water resources (households, peasants, companies, and others). The participation of the Lake Poopo basin's stakeholders was essential in this study, as it was the basis for the Multi-Criteria Decision Analysis (MCDA) that was carried out, which is the cornerstone of the Integrated Water Resources Management strategy we propose for the Lake Poopo basin.

The stakeholders received support in the decision-making process, as recommended by

FAO (2006). This process consisted of workshops held in three municipalities (El Choro, Challapata, and Quillacas) chosen for their ecological and socio-economic diversity and large populations. The workshops were held with the participation of: inhabitants of each municipality, peasants from the surrounding communities, indigenous and municipal authorities, and members of relevant stakeholder organizations from each region (agricultural unions, irrigation organizations, water supply committees, etc.). Between 250 and 800 people participated in each of the workshops, which were organized with the help of indigenous and municipal authorities. The workshop's main objectives were to provide information regarding Integrated Water Resources Management and to obtain feedback from the stakeholders regarding their water knowledge, traditions related to water management, and priorities. The goal was to elaborate a Multi-Criteria Decision Analysis model based on that information, shown in Figure 9.

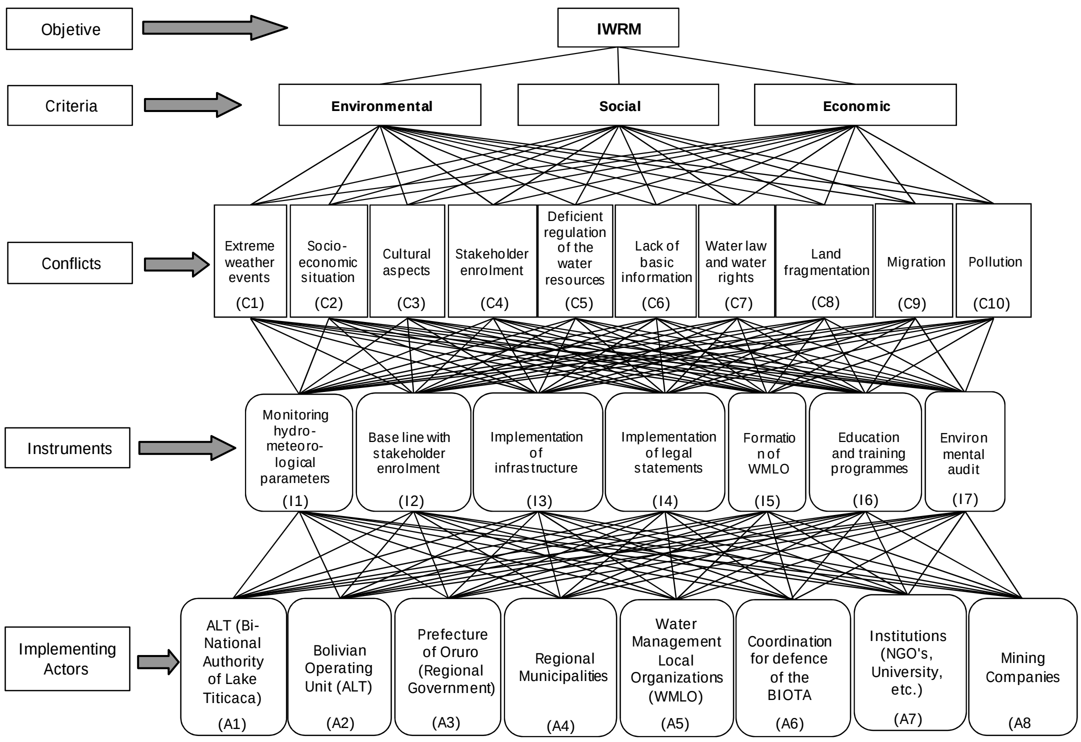

Fig. (9). Proposed structure of multi-criteria decision analysis model for Lake Poopo basin.

The workshops were divided into two stages. The first stage was an orientation regarding the hydrological cycle, situation of the water resources in the region and the importance and benefits of managing water resources in a sustainable and integrated manner. The second stage started with a discussion regarding the importance of stakeholder participation in the decision-making process. Then, the participants were asked to identify the water-related conflicts in their regions, in terms of three main criteria: social, economic and environmental. The conflicts identified were grouped into categories, such as Extreme Weather Events, and placed under the corresponding criterion. The data obtained was then discussed and processed. The same steps were followed in order to identify the best possible implementing actors and instruments.

Once the participants had identified a set of conflicts, instruments and actors, they were asked to relate them to each other in order to evaluate them in terms of importance (hierarchy analysis). Thus, conflicts were ranked in terms of their severity, instruments were ranked in terms of their effectiveness in solving the conflicts, and actors were ranked according to their ability to wield the instruments. Later, this data was processed and organized in matrixes, and Saaty's Analytical Hierarchy Process (AHP) theory was applied using pairwise comparisons (Saaty, 1980; 1985; 1990). This resulted in the design of the structure of the suggested Multi-Criteria Decision Analysis model (Calizaya *et al.*, 2008d), which shows a hierarchy of the most important perceived conflicts, instruments and actors from the point of view of the stakeholders.

7. STRATEGY FOR SUSTAINABILITY OF INTEGRATED WATER RESOURCES MANAGEMENT

The development of decision-making processes and implementation strategies is a very complex issue. According to von Winterfeldt (1980), the structuring of a decision problem is a creative process which involves converting a complex problem into a set of specific elements, relations and operations. In the case of Integrated Water Resources Management, the decision-making process is especially complex, as it involves numerous decision-makers who operate at different levels and several stakeholders with conflicting interests and needs.

The design of a step-by-step strategy for implementing Integrated Water Resources Management in the Lake Poopo basin was based on an Multi-Criteria Decision Analysis model, elaborated with the participation of stakeholders at all levels of decision-making. As described above, stakeholders were asked to rate conflicts (in terms of their severity), instruments (in terms of their effectiveness in addressing the conflicts) and possible implementing actors (in terms of their ability to wield the instruments). This allowed the identification of the most important elements of the Integrated Water Resources Management strategy, and the steps that need to be taken in order for it to be sustainable.

7.1 Structure of the decision hierarchy of water management in the Lake Poopo

The structure of the suggested model for Multi-Criteria Decision Analysis was elaborated on the basis of three principal criteria: economic, social, and environmental. This involved the identification and selection of 10 conflicts:

Table 3. Conflicts

Abbreviation	Description
Co1	Extreme weather events
Co2	Socio-economic situation
Co3	Cultural aspects
Co4	Stakeholder involvement
Co5	Deficient regulation of the water resources
Co6	Lack of basic information
Co7	Water law and water rights
Co8	Land fragmentation
Co9	Migration
Co10	Pollution

along with the identification of 7 Instruments to address the conflicts:

Table 4. Instruments

Abbreviation	Description	
I1	Monitoring hydro-meteorological parameters	Participatory/multidisciplinary data, collection analysis and process of database
I2	Base line with stakeholder involvement	Integral diagnostic with active participation of the stakeholders of basin
I3	Implementation of infrastructure	Identification/selection of sub-project (dams, rainwater harvesting, irrigation, etc.)
I4	Implementation of legal statements	Enabling environment (policies, legislation, regulation)
I5	Formation of WMLO	Formation of Water Management Local Organization (WMLO)
I6	Education and training programs	Education, training and diffusion programs in the whole basin on Water Resources Management
I7	Environment audit	Environment audit, especially of mining activities

and a hierarchy of possible implementing Actors:

Table 5. Actors

Abbreviation	Description
A1	ALT (Bi-National Authority of Lake Titicaca)
A2	Bolivian Operating Unit (ALT)
A3	Prefecture of Oruro (Regional Government)
A4	Regional municipalities
A5	Water management local organizations
A6	Recently conformed basin coordination for defense of the BIOTA
A7	Institutions (NGO's, University, etc.)
A8	Mining companies

The Analytical Hierarchy Process (using pairwise comparisons to get subjective judgments where objective data is not available; Saaty, 1980; 1985; 1990) was selected as a method for computing the preferences for the Multi-Criteria Decision Analysis model (comparable to the evaluation process by Zhang, 2009).

At the first level of the decision hierarchy, the stakeholders consider mainly environmental criteria ($w_{Env} = 0.62$) and (with less intensity) social criteria ($w_{Soc} = 0.33$) to be crucial for the implementation of IWRM principles. Economic variables seem to be of much less significance ($w_{Eco} = 0.06$).

The results obtained from the Multi-Criteria Decision Analysis show that Extreme weather events (Co1) is the most severe conflict under the Environmental criteria (W_{Env}), Cultural Aspects (Co3) was ranked highest under the Social criteria (W_{Soc}), and Migration (Co9) was ranked as the most important conflict under the Economic criteria (W_{Eco}). The most effective Instruments for addressing the most pressing conflicts are: Education and Training programs (I6) related to Integrated Water Resources Management, Conformation of Water Management Local Organizations (I5), and a Base Line with stakeholder involvement (I2). Concerning the implementing actors, the Prefecture of Oruro (A3) is ranked as the most appropriate actor to be in charge of the Instruments. However, it must be assumed that cooperation among all actors is a key element in order to introduce and sustain Integrated Water Resources Management principles in the Lake Poopo basin.

The Multi-Criteria Decision Analysis model represents a critical line to follow in order to achieve the sustainability of water resources in the Lake Poopo basin. Moreover, applying the Multi-Criteria Decision Analysis to the Lake Poopo basin proved to be a practical and effective way to start a real master plan towards the Integrated Water Resources Management strategy because it allowed the identification of key actors, instruments and conflicts. Having this information was essential for laying the ground for the design of a step-by-step strategy to implement Integrated Water Resources Management in the region based on stakeholder participation.

8. STEPWISE APPROACH FOR IMPLEMENTING AN INTEGRATED WATER RESOURCES MANAGEMENT STRATEGY IN THE LAKE POOPO BASIN

Today, the Bolivian State has little participation in the integrated management of water resources (Van Damme, 2002). In other words, no central government has ever elaborated a national or regional strategy to manage water resources in an integrated way. In the last ten years, the process of decentralization in the country assigned the responsibility for water management to regional governments and municipalities. Specifically, there has never been a strategy for integrated management of water resources implemented in the Lake Poopo basin. In the communities, the indigenous *Ayllu* authorities allocate water as equitably as possible for irrigation and domestic consumption, according to their customs.

There have been few projects executed with local and external (international cooperation) funds to build infrastructure in the countryside in order to meet the particular water-related needs of specific communities. Yet, these projects were not framed within an integrated water management strategy, and therefore lacked sustainability. Also, as they were not the result of consensus of all stakeholders, these projects often had unwanted consequences on upstream or downstream communities, and thus generated conflicts.

In order to implement an Integrated Water Resources Management strategy in the Lake Poopo basin, some conditions must exist. First, there must be an actor identified and willing to implement the strategy at the regional level, with sufficient funds available to it to guarantee efficiency and sustainability. Second, there must be solid and trained stakeholder organizations to implement the strategy at the sub-basin level and coordinate efforts with the main implementing actor and local indigenous and municipal authorities (Calizaya, 2009a).

The first of these conditions is in place. The Prefecture de Oruro is an entity interested in the implementation of Integrated Water Resources Management in the Lake Poopo basin and able to plan and execute the strategy. In fact, the participation of the Prefecture's Secretary of Water, Secretary of Biodiversity and Environment and Secretary of Planning and Development was instrumental in the elaboration of the Institutional Arrangement Structure for the implementation of an Integrated Water Resources Management strategy in the Lake Poopo basin. In a meeting with these entities, it became clear that, in order for the Prefecture to implement an Integrated Water Resources Management strategy in the Lake Poopo basin, it would need to create a Main Lake Poopo River Basin Bureau (MLPRBB) within its administrative structure, with autonomous and decision-making faculties, a budget and a multi-disciplinary team of professionals. Prefecture authorities also agreed to elaborate a Project that would allow them to obtain international cooperation funds for the implementation of Integrated Water Resources Management in all its stages.

The proposed institutional arrangement shown in Figure 10 was elaborated in coordination with the Prefecture's Secretary of Water with the objective of making viable the implementation of an Integrated Water Resources Management strategy. This institutional arrangement was designed to incorporate all the important institutions and entities and describe their hierarchy and decision-making power in relation to Integrated Water Resources Management in the Lake Poopo basin.

Figure 10 shows the institutional arrangement in function of the implementation of an Integrated Water Resources Management strategy in the Lake Poop basin. As no strategy is currently being implemented, the different institutions and entities work in an uncoordinated manner with each other and with municipal and indigenous authorities as far as water management is concerned. Of course, the Main Lake Poopo River Basin Bureau and Local Basin Organizations do not exist, as their creation is part of the strategy we propose for the implementation of Integrated Water Resources Management in the region.

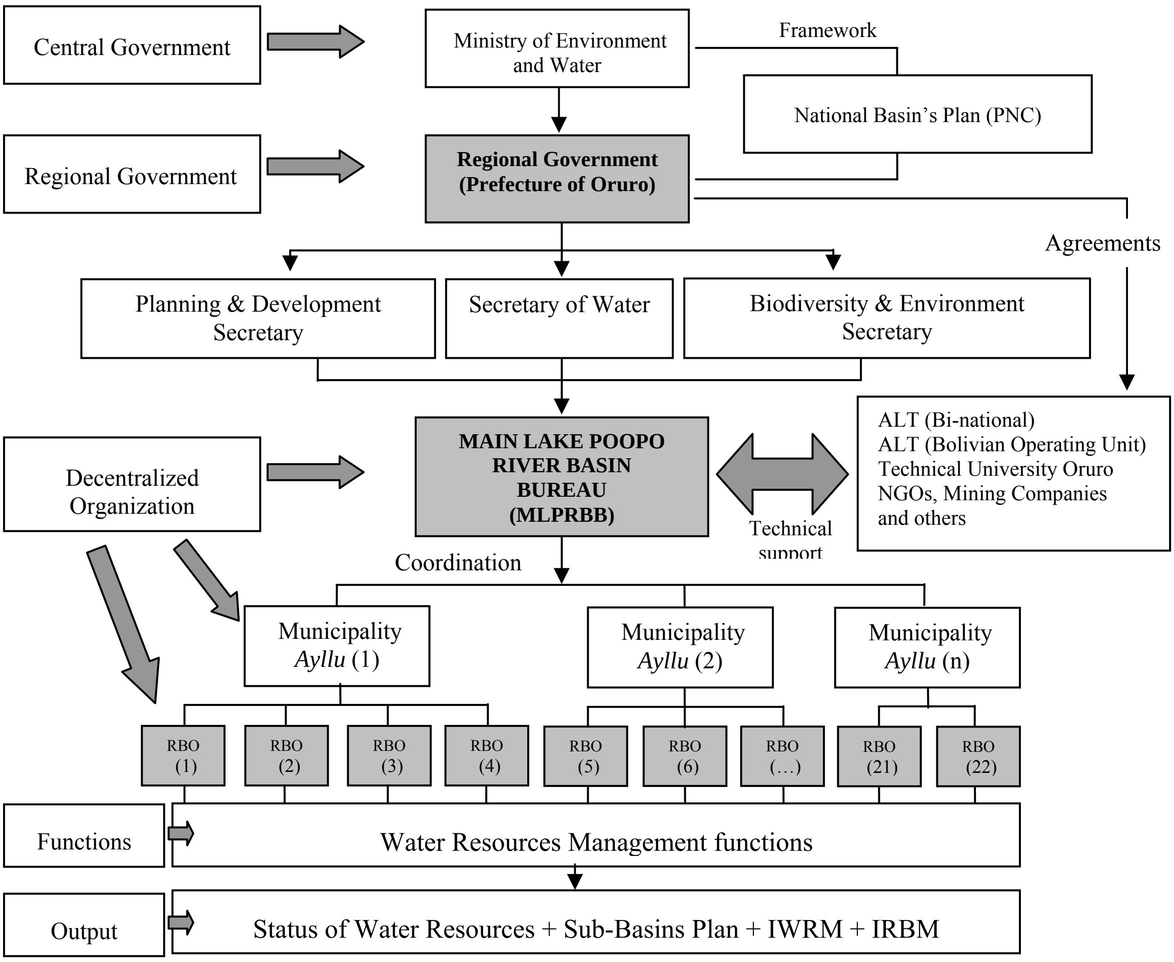

Fig. (10). Proposed institutional arrangement for performing the Integrated Water Resources Management (IWRM) strategy in the Lake Poopo basin.

For the second condition (strong stakeholder organizations) to exist, the conduction of a training campaign is essential. It is the most important step for empowering women and local authorities to make informed decisions and take action regarding water management. To carry it out, the Main Lake Poopo River Basin Bureau (MLPRBB) should hire a team of training consultants to design the curricula in subjects such as water management, conflict resolution, climate change and efficient use of water. The training will also lay the ground for the creation of Local River Basin Organizations (LRBO), as it will include training in management and will be a good opportunity for natural leaders to emerge. The conformation of Local River Basin Organizations should be carried out after the workshops and seminars organized in each of the 22 sub basins that make up the Lake Poopo basin.

As women are key actors in the management of water at household level, both the training campaign and the conformation of the Local River Basin Organizations should take gender issues into serious consideration in order to be successful. It is crucial to empower women in this process and give them a central role. Women generally have very few opportunities to occupy political positions or become authorities. Yet, they are influential, especially regarding the household use and allocation of water resources. The training campaign, for example, should make special concessions in order to secure the participation of women. These should include holding the training sessions in *Quechua* or *Aymara*, having women-only groups, and making sure the sessions do not interfere with housework hours. The conformation of the Local River Basin Organizations should be carried out with the full participation of women, and they should hold 50% of the positions of authority within these organizations.

Once conformed, it is the responsibility of each of the Local River Basin Organizations to conduct a diagnostic and formulate its water management objectives, which will be included in the Local River Basin Plan (LRBP). This plan, elaborated by each Local River Basin Organization, should comprise a diagnosis of the situation of the river sub-basin, identify the most pressing water-related conflicts, and propose possible solutions. This process must be carried out in coordination with local actors and the Main Lake Poopo River Basin Bureau, which will provide technical support and orientation throughout this stage.

The Local River Basin Plan must then be presented to the Main Lake Poopo River Basin Bureau for evaluation and for the implementation of an integrated strategy to manage water resources in an integrated manner in the Lake Poopo basin. Based on the needs and priorities of stakeholders, the strategy will coordinate the implementation of projects to solve the most pressing water-related conflicts, as well as elaborate and enforce long-term policies to guarantee the sustainability of the water resources in the region.

The implementation of the Integrated Water Resources Management strategy is an on-going and dynamic process that does not conclude with the elaboration of the first Local River Basin Plan or the execution of the first set of projects. Thus, the last two stages (elaboration of the Local River Basin Plan and the execution of projects) must be periodical and adapt to a constantly changing reality. For example, new Local River Basin Plans must be elaborated periodically to respond to the effects of climate change, increase or drop in population, new industries operating in the area, new sources of pollution, etc. Likewise, new projects and policies will need to be executed and enforced periodically to meet the dynamic needs of the Lake Poopo basin.

9. CONCLUSIONS AND RECOMENDATIONS

The situation of water resources in the Lake Poopo basin is critical, as shown in the low Watershed Sustainability Index (WSI) value for the basin, the annual value of which is 0.46 and 0.36 for the dry season. The basin experiences large variations in the spatial and temporal distribution of the water resources, partly as a result of extreme weather variations. Furthermore, even when water is available, its quality is poor due to salinization and pollution from the mining activity. The basin's Water Poverty Index (WPI) is 28, a very low value compared to other basins in Bolivia and Latin America. The severe water scarcity during dry period aggravates poverty, making small-scale subsistence farming the only option for the peasants in the basin.

The WSI calculated for the water-storage scenario reached 0.59, indicating that storage dams or reservoirs in the upstream areas of the watershed would significantly improve watershed sustainability and provide a solution to water scarcity during dry season. Yet the implementation of isolated projects, such as the construction of dams, reservoirs and canals, has been done in the basin without obtaining sustainable results.

Therefore, this study recommends the application of an Integrated Water Resources Management (IWRM) strategy in the Lake Poopo basin to provide long-term solutions to the situation of water scarcity and low water quality. For the purpose of this study, an IWRM strategy means the coordination of efforts of government and non-government organizations and stakeholders to identify specific water-related problems, design solutions and implement them in a coordinated and efficient manner. With sufficient funds and trained professionals, many projects could be carried out to improve the quality and availability of water in the basin. For example projects could be executed to store fresh water and redirect it to dry sectors. Programs for promoting water saving techniques, such as drip irrigation, or the recovery of the ancient "raised bed cultivation" technique (*Suka Kollus)* could also be included. This would allow the sustainability of agricultural activity in the region and secure water for human consumption and agriculture throughout the year.

The benefits of an Integrated Water Resources Management strategy vs. the implementation of isolated projects along the basin are many. First, an integrated strategy involves education and training and enrolls the participation of stakeholders at all levels of decision-making, ensuring the sustainability of the projects. Second, an integrated strategy raises awareness regarding the "unitary" character of water resources. In other words, it makes stakeholders conscious that how they use the water in their communities or towns affects the quality and quantity of water throughout the basin. Third, an integrated strategy pulls local and regional authorities together and increases the overall access to financial resources to execute the necessary projects and activities.

The participation of stakeholders and stakeholder groups is the key element for the success of an Integrated Water Resources Management strategy. The most sustainable ways to motivate grassroots stakeholders to participate are education and the creation of

Local River Basin Organizations, through which the stakeholders take active part in the management of their water resources. Also, stakeholder groups, such as irrigating organizations, NGOs and mining companies should work together with the main implementing actor, the Prefecture of Oruro, at all stages of the implementation of the IWRM strategy to ensure it is a product of consensus and ensure its applicability.

This study proposes an institutional arrangement structure and the steps to follow towards the implementation of an Integrated Water Resources Management strategy in the Lake Poopo basin. The institutional arrangement shows the position of the main implementing actor in the implementation of the strategy and takes into consideration all the actors and institutions at national, regional and local level which will influence the strategy's implementation. The steps begin with the creation of a special bureau within the Prefecture of Oruro to implement IWRM in the Lake Poopo basin. The culmination is the implementation of the strategy by the Prefecture of Oruro on the basis of the planning documents elaborated by the Local River Basin Organizations.

The success of the strategy will greatly depend on the ability of the main implementing actor, (i.e. the Prefecture of Oruro) to regard the strategy as a dynamic process, one that takes into account and adapts to, not only the basin's cultural, political and socioeconomic characteristics, but also to the country's political climate, the existence or lack of environmental policies, etc. The strategy must be conceived not as a goal in itself, but as a process which can and must be adjusted to meet emerging challenges in the context of rapid change.

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PAPER 1

Spatial and temporal distribution of water resources in the Lake Poopo basin, Bolivia

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Abstract: The Lake Poopo basin, located on the Bolivian Altiplano, is extremely vulnerable to environmental degradation. The basin displays extreme spatial and temporal variations of water resources and rapidly decreasing water quality due to anthropogenic and natural pollution from the mining industry. The region's population lives in extreme poverty, and the authorities´ efforts to manage the water resources efficiently have been insufficient. Although Lake Poopo is part of the bi-national (Peru-Bolivia) TDPS system, which also includes Lake Titicaca, Desaguadero River and the Salt deserts, the TDPS system authorities concentrate on the management of the bi-national Titicaca Lake, relegating the southern part of the river system, where Lake Poopo is located.

This paper collects climate and hydrological information from a newly established observational network at the Lake Poopo Basin, along with information from local and regional stakeholders, in order to improve the management possibilities of the basin's scarce freshwater resources. The collected information was analyzed using Geographical Information System (GIS), and its results were presented to local authorities in order to improve the feasibility of planned infrastructure projects. This paper presents the main results for the temporal/spatial variability of water balance components and the availability of freshwater resources throughout the basin.

INTRODUCTION

Water is a fragile element of the Bolivian rural landscape. In general, there is a deficit of fresh water over more than half of the countryside (Van Damme, 2002) [1]. Yet the Lake Poopo basin on the Bolivian Altiplano, located south of the Titicaca – Desaguadero – Poopo – Salares (TDPS[1]) river system (Fig. **1**), is especially vulnerable to environmental degradation. With a semi-arid climate, the basin presents water scarcity during the prolonged dry season, which lasts from 8 to 9 months. Most of the rivers are intermittent, and both the dry and wet periods are very pronounced. The basin's population has a high poverty index, and migration from de basin has increased greatly in the last few decades.

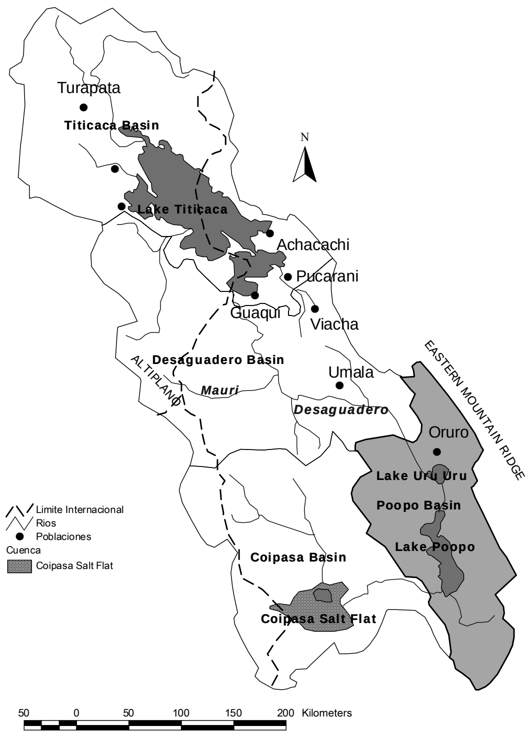

Fig.1 Geographical overview of the TDPS System and location of the Lake Poopo basin.

There are two lakes in the basin: Lake Poopo and Lake Uru Uru. The latter dries up every year during dry season. Lake Poopo, on the other hand, can be as large as 3000 km^2 after consecutive wet years, but may also shrink significantly in years of drought. In many parts of the basin the water quality is poor as a result, not only of mining activities, but also of high amounts of natural leakage of metals from the soil to groundwater and stream water.

These major problems are further aggravated by the generalized lack of water management awareness and by the dearth of clearly established water policies, all of which leads to conflicts between sectors. Due to increasing water demand, different groups compete for access to water resources, and simultaneous water use from different sectors is often not compatible (Crespo, 1999) [2].

The majority of conflicts in the basin may stem from the different conceptual understandings of water. Peasants, for example, often have an integrated view of water, seeing it as a symbol of life and a deity, in coherence with the Andean idiosyncrasy. They do not separate water from its natural surroundings and reject the idea that it can be managed with a commercial focus. In the north-eastern parts of the basin there is a serious water-related conflict between farmers and miners. Generally, the mining sector receives more political support regarding water rights.

The main sources of water in the Lake Poopo basin are the underground streams, which supply for the 240,000 inhabitants of Oruro city. In the rural area, the water supply comes from springs and wells. Some water wells are salty, especially in the southern part of the basin. The low quality of river water, combined with the water scarcity during the 8 or 9 months of dry season, has forced the population to exploit the spring and groundwater for domestic consumption.

The pollution in the region has severe negative effects on the land and soil, and is one of the factors contributing to the people's migration away from the basin. Specifically, the salinization and environmental degradation of soil and water are forcing people to migrate to urban areas. For a very long time, the lakes and rivers in the basin have been polluted by heavy metals from mining and foundries. Yet the worst case of pollution in the region happened at the beginning of year 2000, when 30,000 barrels of crude petroleum were spilled on the main stream of the Desaguadero River, contaminating hundreds of acres of farmlands and killing fish and birds. The episode also devastated a 5000 year-old native tribe of fishermen, the Uru Murato, the oldest

[1] TDPS-Lake **T**iticaca, **D**esaguadero River, Lake **P**oopo and **S**alt marsh river system. The Lake Poopo basin belongs to the TDPS system, challenged with water scarcity for a large part of the year and very poor water quality.

native pre-Inkan tribe. Today they live in a small group of 94 families in the town of Llapallapani located on the flat land very close to Lake Poopo (see Fig. **2**).

Water scarcity is a problem that hinders the basin's development. The fact that mining is declining as the most important economic activity in the region is another reason why it is important to achieve efficient water management in the region. The present government, which came into office in 2006, has recognized the importance of water rights in general and, in January of 2006, a Water Ministry was created. This historic event took place six years after the eruption of the so-called *water war* in the city of Cochabamba. The purpose of formulating policies having to do with water resources at all levels, through the National Basin Plan (PNC) which promotes and implements Integrated Water Resources Management (IWRM) and Integrated River Basin Management (IRBM) .

Both the urban and the rural economies of the Lake Poopo basin strongly depend on the availability of water resources in time and space, which is why it is urgent to apply water resources planning and management in an integrated way based on the active participation of stakeholders, such as native population, farmers, municipalities, and small water supply system operators. Efforts should be devoted to making existing water resources more reliable and available, and to using them in a more efficient way.

The objective of this paper is to assess the availability of water resources in the Lake Poopo basin as a first step towards developing a strategy for sustainable water resources management.

In the year 2001, a hydro-meteorological observation network was established in the Lake Poopo basin. The information from this network was collected with the active participation of different groups of major stakeholders, who also contributed in the collection of data. We present the main results of the research (temporal and spatial variability of water balance components and water resources availability throughout the basin) and we close with a discussion on the practical implications of the results.

THE LAKE POOPO BASIN

Natural resources

The Lake Poopo basin belongs to the enclosed basin of the Altiplano – Bolivian-Peruvian TDPS system (Lake **T**iticaca, **D**esaguadero River, Lake **P**oopo and **S**alt desert). The TDPS system, confined by the Eastern and Western Cordilleras mountains, covers a total of 144000 km^2. The Altiplano has a mean altitude of 3800 m above sea level and an area of 1000000 km^2 (World Survey of Climatology, 1976) [3]. Lake Poopo is connected to Lake Titicaca by the Desaguadero River, which measures 400 km in length and is the main inflow into Lake Poopo.

Lake Titicaca and Lake Poopo, the two main lakes in the Altiplano, have very different characteristics. Lake Titicaca, which lies at 3,808 m above sea level, is 200 to 300 m deep, while Lake Poopo lies at 3,686 m above sea level and is a shallow lake with maximum depth at spill-over of about 3.4 m (Pillco & Bengtsson, 2007) [4]. Lake Poopo is mainly a salt terminal lake, and spill-over occurs very seldom; the last spill-over occurred in 1986. The Lacajahuira River links Lake Poopo with the Coipasa Salt Desert, located at 3550 m above sea level. According to Pillco and Bengtsson, this river carries water only when the water depth in the Lake Poopo is above 3.0 m. Since Lake Poopo is a closed lake, it is extremely sensitive to climate variations and pollution.

The total Lake Poopo catchment area, downstream from Chuquiña on the Desaguadero River, is about 24000km^2 including Lake Poopo and Lake Uru Uru. Just downstream from Chuquiña (see Fig. **2**) the Desaguadero River divides into two branches, one to Lake Poopo and another to Lake Uru Uru (Iltis, 1993) [5]. Lake Uru Uru, which has an area of 260km^2, receives all the waste water from Oruro, the largest city in the basin. The water from Lake Uru Uru discharges into Lake Poopo.

The Lake Poopo basin's water resources are degraded as a result of organic and microbiological pollution from the sewage from Oruro and other towns (ALT, 1999) [6]. The heavy metal contamination is due to natural sources, as well as to the mining and metallurgic industries and the high salinity levels of the soil, surface water and shallow groundwater (Risacher and Fritz, 2000) [7]. The salinity on Lake Poopo´s surface water increases from north to south. The salinity varies with the seasonal fluctuations between 2 and 100 gl^{-1} (ALT, 1999; Garcia, 2006 [8]; PPO, 1996 [9]).

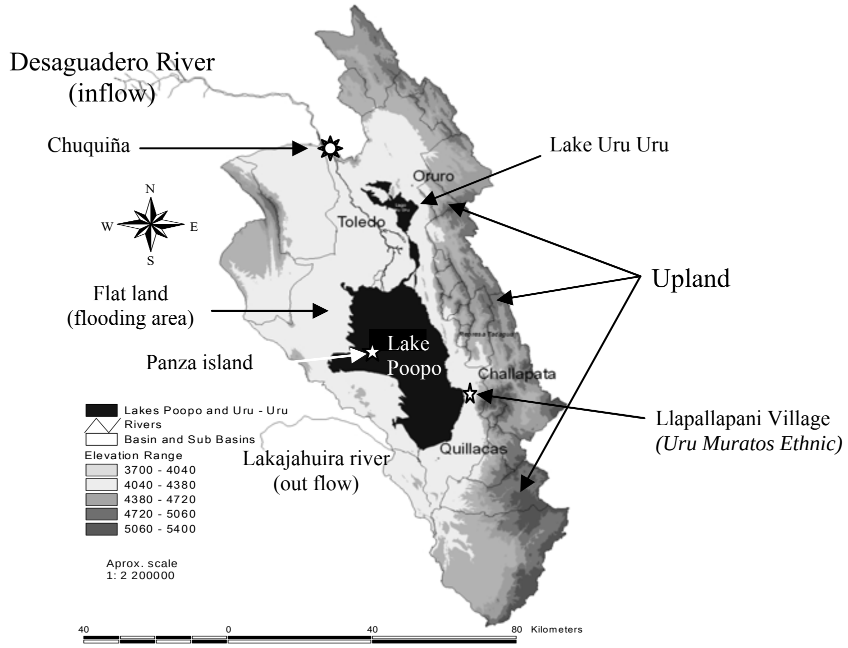

Fig. (2). Sub-basins and topography of the Lake Poopo basin

The climate of the Lake Poopo basin is semi-arid and cold; between 8º C and 10º C average, and daily temperature fluctuations are extreme. In the summer, the temperature ranges from -2º C to 25º C, and in winter from -15º C to 14º C (Troeng and Kilibarda, 1996) [10]. The climate is characterized by a rain season between November and March, and a dry season from April to October (TDPS, 1993 [11]; Garreaud *et al*., 2003 [21]). The main source of moisture is the continental lowland east of the Andes (Garreaud, 2000) [13]. The seasonal variability of precipitation over the region is related to changes in the upper troposphere circulation.

As a result of the transitory circulation phenomenon, the precipitation over the region is sensitive to variations in the large scale circulation patterns. These variations are expressed as inter-annual variability in the precipitation over the region. The effects of El Niño-Southern Oscillation (ENSO) on the atmospheric circulation are observed as variations in the amount of precipitation in the region, so that El Niño years are related to below-normal precipitation and La Niña years to above-normal precipitation (e.g., Aceituno, 1988 [14]; Lenters and Cook, 1999 [15]; Garreaud, 1999 [16]; Vuille, 1999 [17]). However, the ENSO-effect is rather weak in the Oruro-Poopo region.

The mean annual rainfall in the Altiplano basin varies between 200 mm and 800 mm in a north –south direction. In the Lake Poopo basin, the mean rainfall varies from about 420 mm in the north to about 270 mm in the south, with a mean of about 372 mm (Pillco and Bengtsson, 2006) [18].

The meltwater from the eastern mountain ranges drains into Lake Poopo through 22 regional rivers (Fig. **3**). The largest tributaries, the Marquez and Sevaruyo rivers, feed the lake from the south. The small regional rivers are actually connected to Lake Poopo only during peak flows. At any other time they discharge diffusely on the flat area surrounding the lake. The regional river water is distributed into many small river arms before reaching the lake. At the end of the dry season, the rivers are almost dried up. The mountain areas in the northwest drain into the plains, where the western branch of the Desaguadero river flows. The south-western part of the basin, which borders the Coipasa Salt Desert, is part of the flat-land. From this region there is an inflow to Lake Poopo from only one regional river.

Fig. (3). Digital Terrain Model of the Lake Poopo basin

Small rivers in Fig. **3** disperse into delta system, and that the groundwater level comes close to the ground surface. Table **1** gives the details of the 22 Lake Poopo sub-basins, such as morphometric parameters, area of the flat land and the bodies of water. The biggest river in the basin is the Marquez River, with a basin area of 2600 km^2, and the smallest one is the Huacani River, with a basin area of 23 km^2. Approximately 130,000 inhabitants live on the flat-land region of the Lake Poopo basin, excluding the city of Oruro. The most populated sub-basin is Tacagua, with 24,000 inhabitants, and the most scarcely populated sub-basin is Huacani, with a population of 320. Oruro City has 216,000 inhabitants.

Table **1**
Sub-basin population and characteristics

Name of river (Subbasin)	Population (inhab.)	Watershed			River		Drainage	
		Area	length	slope	length	slope	order	density
		km^2	km	%	km	%	Nº	km/km^2
Marquez	7268	2577	96.9	0.9	94.5	1.0	5	0.5
Juchuy J.	8105	1740	82.3	1.5	80.7	1.5	2	0.4
Caquiza	8900	1381	102.3	0.5	101.3	0.5	3	0.4
Tacagua	24370	1374	57.9	1.1	56.1	1.1	5	0.6
Huana Jahuira	5638	862	66.5	1.1	65.4	1.1	4	0.3
Sevaruyo	3600	852	80	1.1	78.3	1.2	4	0.7
Sora Sora	25600	735	54.4	1.4	52.4	1.5	4	0.8
Jacha Uma	4200	706	47.2	0.9	44.8	0.9	4	0.3
Juchusuma	1500	381	58.7	1.3	56.4	1.3	3	0.3
Tola Pampa	3367	314	39.5	1.8	36.3	1.9	4	0.3
Rodeo	5500	259	30.9	1.0	29.5	1.0	4	0.3
Antequera	5300	227	23.8	3.0	22.7	3.1	3	0.3
Cortadera	380	223	25.6	3.1	23.9	3.4	3	0.4
Huaña pasto	3500	182	24.1	3.8	23.4	3.9	3	0.5
Pongo Jahuira	2028	121	17.6	2.6	15.4	3.0	3	0.3
Chillari	550	116	17.8	3.9	15.4	4.6	3	0.4
Poopo	6036	109	17.5	4.1	13	5.5	2	0.2
Urmiri	3600	98	20.2	3.5	16.3	4.3	3	0.4
Azanaque	10221	82	16.2	6.1	15.1	6.5	2	0.3
Hancani	600	57	10.6	6.9	6.7	10.9	2	0.2
Huancane	100	57	13.7	5.2	9.3	7.6	1	0.2
Huacani	350	23	5.3	10.8	4.2	13.6	2	0.3
Flat área	228000	10000						
Water bodies	-	2000						
Desaguadero River	Mean river to the Lake Poopo							
Laka Jahuira	Lake Poopo river outflow							

Socioeconomic conditions

The Lake Poopo basin belongs administratively to the Department of Oruro and it is one of the poorest regions in Bolivia. About 70% of the population lives in poverty, 40% of the population lives in extreme poverty and 2% lives in complete marginality. The life expectancy is of 58 years, the infant mortality rate is 10%, and 60% of the population is indigenous (INE, 2001) [19]. Close to 50% of the population in the city of Oruro lives below the line of poverty. As for the indigenous population, the tribe Uru Muratos is extremely poor and less than 20% of its members have access to water and sanitation. Until recently, the mining sector generated high incomes, although the profits resulting from these resources did not succeeded in improving the quality of life for the people in the region.

In 1950, the population's urban to rural ratio was 40/60. The last census (INE, 2001) showed a reversed relationship, with approximately 60% of people living in cities and 40% in the country. These figures clearly demonstrate a high rate of migration from rural to urban areas in the last 50 years.

The Water Poverty Index (WPI)[2], which is a holistic tool to measure the water stress at household and community levels, shows that improvement within the water sector would decrease poverty in the region. In Fig. **(4)**, the poverty index and WPI are compared for other parts of Bolivia and South America.

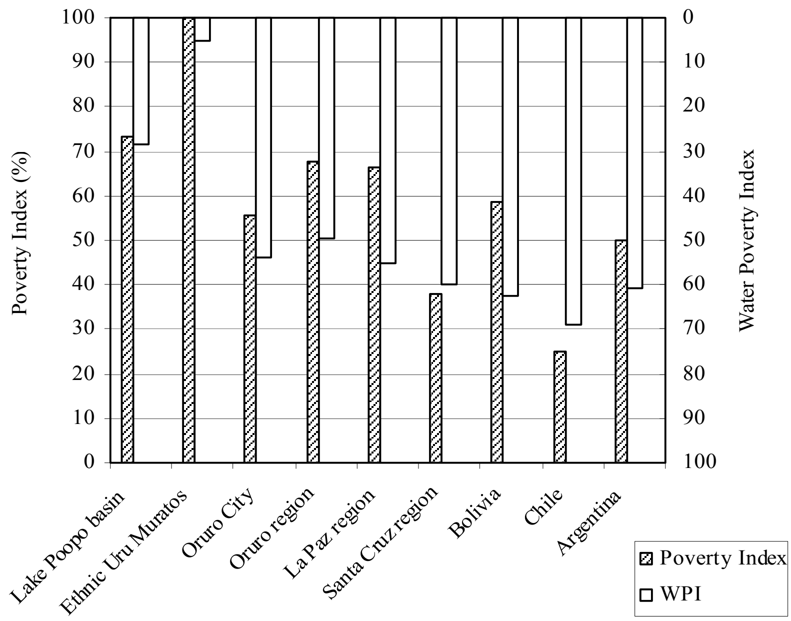

Fig. (4). Poverty index and WPI for the Lake Poopo basin compared to other South American locations (INE, 2001; ECLAC, 2002 [20]; CEH, 2002 [21]).

The main areas of cultivation are located on the flat-land and soft relief hills bordering the two lakes. In general, the region has a highly fragmented landscape, parcel division, overexploitation, poor vegetation, low productivity of the soil, and a lack of fertilizers and machinery; the latter is linked to the rudimentary technological levels in the local agricultural systems.

Development in agriculture and livestock breeding requires an increase in production by means of more water for irrigation during the dry period and better water quality. This would also benefit the fishing activities in the area. Traditionally, fishing was the means of survival for the native Uru-Muratos. The fishing reached a maximum production of 2500 tons of fish per year between 1989 and 1991. The major catch was *pejerrey* and *karache* (Van Damme, 2002). In 1992, when Lake Poopo dried up, the fishing activity was completely halted. Today it is considered unhealthy to eat the fish due to the water pollution.

[2] The WPI is designed as a composite, interdisciplinary tool, linking indicators of water and human welfare to indicate the degree to which water scarcity impacts on human populations (Sullivan, 2001). The WPI has a range from 0 to 100. The highest value, 100 is taken to be the best situation, while 0 is the worst.

Water quality

The water quality of Lake Poopo and Lake Uru Uru is affected by both natural and anthropogenic contamination. In the north and north-east area, where the mining activity is most important, the water in general has a pH of between 2.5 and 4.0 and its the heavy metal concentrations, depending on the wet and dry seasons, are above the permissible limits (Law of Environment of Bolivia and OMS. 1995) [22]. This area is also affected by high levels of pollutants emitted to the air by foundries, as well as acidic surface water originating from carbonates and sulphur dioxide (Garcia, 2006). There is a general dilution effect during the rain period, which helps to somewhat improve the water quality.

The heavy metals with the highest concentration are cadmium, zinc, iron, arsenic and lead. Approximately 65% of the loading of the heavy metals in the rivers come from anthropogenic sources (Garcia, 2006). Lake Poopo is also affected by heavy metals (arsenic, lead, and cadmium) coming from river water. The concentration in the lake is above the permissible levels according to Bolivian regulations (PPO-6, 1992 [23]; Garcia, 2006) [24].

The water that flows into Lake Poopo from the Desaguadero River is also heavily polluted. One of the biggest contributors to this pollution is the gold and silver mine Kori Kollo, located near the town of Chuquiña (see Fig. **3**). This mine has operated for 23 years and it has severely affected soil and water in the region. Salinization has accelerated and there is an increased transport of heavy metals and sediments. The pH in the Desaguadero River is slightly alkaline during most of the year (around 8.1 – 8.6), and the arsenic, cadmium and lead concentrations are 5 to 6 times above the permissible level (Montoya and Mendieta, 2006) [25]. From Oruro City, about 200 l/s of treated waste water are released into the eastern branch of the Desaguadero River (Villarroel, 2001 [26]; INE, 2001). The estimate for 2020 is a release of 230 l/s.

The southern part of the Lake Poopo basin, where the Sevaruyo and Cortadera rivers flow, shows a better water quality than the northern part (Garcia, 2006). The pH level is neutral throughout the year and the concentration of heavy metals does not exceed the allowed limits. The concentration of metals and sulphates in the southern part is lower than in the central part of Lake Poopo, but higher than in the surrounding southern rivers.

RESULTS

Water balance

The water balance of the Lake Poopo basin has been quantified for different parts of the basin considering its distribution in time. There is no river outflow, so the precipitation for the basin together with the inflow from the Desaguadero River balances the evaporative loss. The main physical conditions and the hydrological system have been determined using geographic information system (GIS), with digitized cartographic maps on a 1:50000 scale.

Rainfall and evaporation

The majority of the data used in this study were obtained from the *Servicio Nacional de Meteorología e Hidrología de Bolivia* and *Proyecto Piloto Oruro* (PPO, 1996). Rainfall was measured at 14 points within and close to the Lake Poopo basin. Only five of them have records extending some decades back (1960-2002). The average annual rainfall for the 42-year period is 372mm. According to Pillco and Bengtsson (2006), there are some gaps corresponding to between 2% and 13% for the daily rainfall data for different years. These gaps were filled by interpolating data from neighbouring stations.

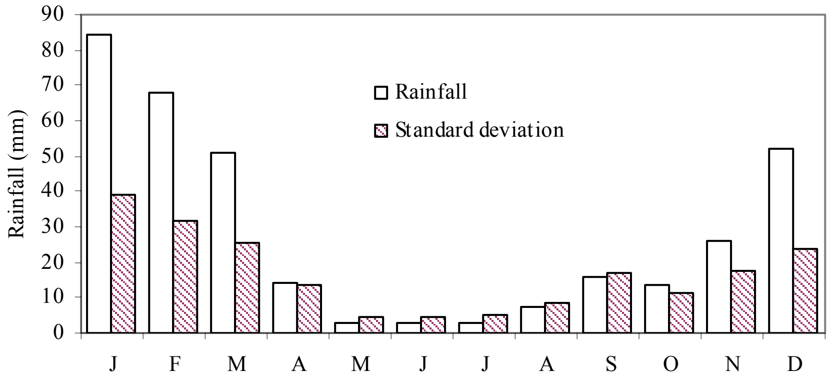

Fig. (5). Long-term monthly average rainfall in the Lake Poopo basin (Pillco and Bengtsson, 2006).

The average monthly rainfall as shown in Fig. **5**, was computed as the mean of five gauges with 40-year records. Most of the precipitation falls between December and March. The inter-annual precipitation is best described by comparing 12-month precipitation for the hydrological year (1 Oct. - 30 Sep.).

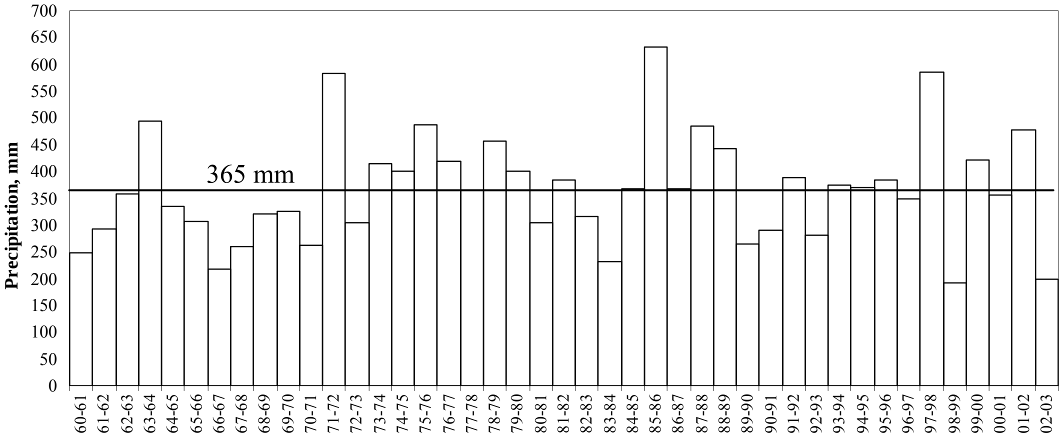

Fig. (6). Annual average rainfall in the Lake Poopo basin 1960-2003

The annual rainfall for the hydrological years from 1960 to 2003 is shown in Fig. **6** with an average of 365mm. There were five years with precipitation of less than 250mm and three years with precipitation exceeding 500mm. The observed annual rainfall over the basin displayed some influence of ENSO, even though the correlation between annual rainfall and the Southern Oscillation Index (SOI) is not significant. The ENSO can be characterized by the dry El Niño 1965/66, 1982/83 and 1997/98 years. The wet years of 1996//97 and the middle of 1970 correspond to La Niña years. However, the large precipitation in 1984/85 is not related to La Niña. The spatial rainfall distribution is shown in Fig.**(7)**.

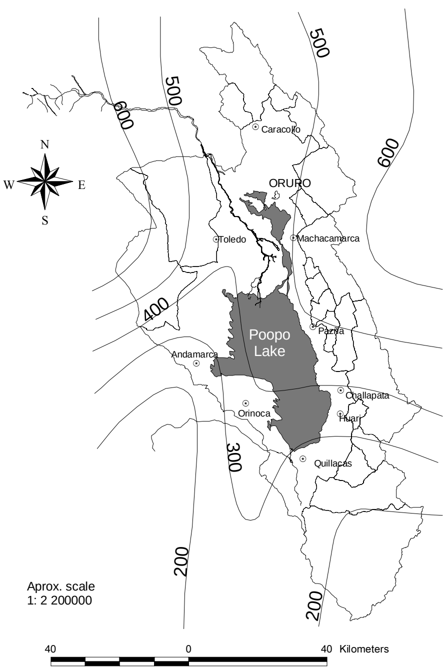

Fig. (7). Spatial rainfall distribution (mm/year)

The mean annual potential evaporation (Ep) rate over the whole Altiplano is estimated at more than 1500mm per year (Roche et al., 1992) [27], and it varies from 1500 to 2000mm per year from north to south

(TDPS, 1993). Pan observations are available from six stations near or within the Lake Poopo basin for the period between 1990 and 1995. Comparing the pan-observation data with the evaporation computed Penman equation, a pan coefficient of 0.87 was estimated. The monthly corrected pan evaporation values vary between 110 and 170mm per month, with an annual value close to 1800mm (Pillco and Bengtsson, 2006).

Inflow from the Desaguadero River and regional rivers

Since measurements of regional river flows are available only from 2001-2002, it was necessary to simulate the river inflow to Lake Poopo over a longer period of time. The monthly runoff from the entire Poopo basin was simulated using a conceptual rainfall-runoff model, SIMULA. This model was developed in the *Center for Hydrological Studies of Spain* and adapted to Visual Basic in the *Institute of Hydraulics and Hydrology of La Paz*. The model distinguishes between surface flow and groundwater. The input parameters are monthly rainfall, rainy days and monthly potential evapotranspiration. Calibration parameters are soil storage capacity, monthly maximum infiltration, and the recession coefficient. The model was calibrated for two rivers for two years only. Two sets of parameters were determined, one set being representative for the northern and one set for the southern rivers.

The regional flows peak early in the year and there is very little flow, if any, between April and December. The mean annual regional flow is only 5m^3/s, but in years of extremely high precipitation the monthly peaks can exceed 100m^3/s.

The measured average annual discharge of the Desaguadero River at Chuquiña was 73m^3/s between 1960 and 2001; the maximum annual discharge was 230m^3/s and the minimum was 16m^3/s. The inflow to the lakes from the Desaguadero River strongly depends on the water level in Lake Titicaca. The inflow from the Desaguadero to Lake Poopo usually starts to increase in early December and is high during the first three months of the year; then it drops to low values from April onwards. The highest monthly discharge on record is 504m^3/s, recorded in March, 1986, which produced high floods. The lowest monthly flow, 3m^3/s, was recorded in October of 1998.

Table **2** shows a summary of the computed and measured results for water balance components depending on sub-basin. The values are in mm and they are annual averages for periods of between 10 and 25 years. The rainfall is an annual average for each area of the sub basins, actual evaporation (E) and discharge (R) are output from the model application. The storage values obtained in the water balance are close to zero for long term average in each sub-basin. Fig. (**10**) shows the spatial distribution of water balance components.

Table **2**

Regional rivers budget and water availability per capita in the 18 sub-basins.

Sub basin	A, km^2	P, mm	E, mm	R, mm	Population inhab	Q, m^3/per c year	Q, m^3/per c day
Antequera (Urmiri)	227	385	323	62	9600	1459	4
Azanaque	82	388	323	66	10221	527	1
Caaquiza	1381	444	324	122	8900	18949	52
Rodeo	259	440	356	85	5500	3982	11
Tola Pampa	314	431	347	85	3367	7897	22
Huacani	23	403	336	66	350	4259	12
Huana Jahuira	862	440	356	85	3638	12937	35
Huancane	57	432	341	93	200	26524	73
Hancani	57	448	345	93	600	8872	24
Juchu Jahuira	1740	444	324	122	8105	26219	42
Juchusuma	381	432	336	95	1500	24195	66
Marquez	2577	325	307	22	7268	7624	21
Jacha Uma	706	377	305	73	4200	12266	34
Pongo Jahuira	121	440	356	85	2028	5037	14
Poopo	109	448	345	105	7800	1470	4
Huaña Pasto	182	418	312	105	3500	5446	15
Sevaruyo	852	305	379	26	3600	6130	17
Sorasora	735	445	311	137	25600	3925	11

The regional inflow from 22 rivers and the Desaguadero River flow are compared in Fig**. (8)**. The seasonal variations are clear, as is the inter-annual variation. The inflow from the regional rivers to Lake Poopo starts to increase in early December until April, when it decreases. The average inflow from both the regional and Desaguadero Rivers was 108m^3/s during the wet period and 56m^3/s during the dry period. Generally, dry and wet periods last from December to March and from April to November, respectively.

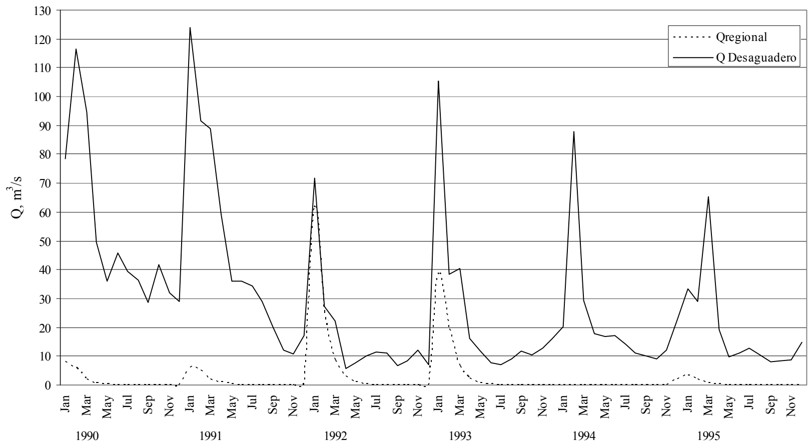

Fig. (8). Seasonal discharge of Desaguadero and regional rivers from 1990 to 1995

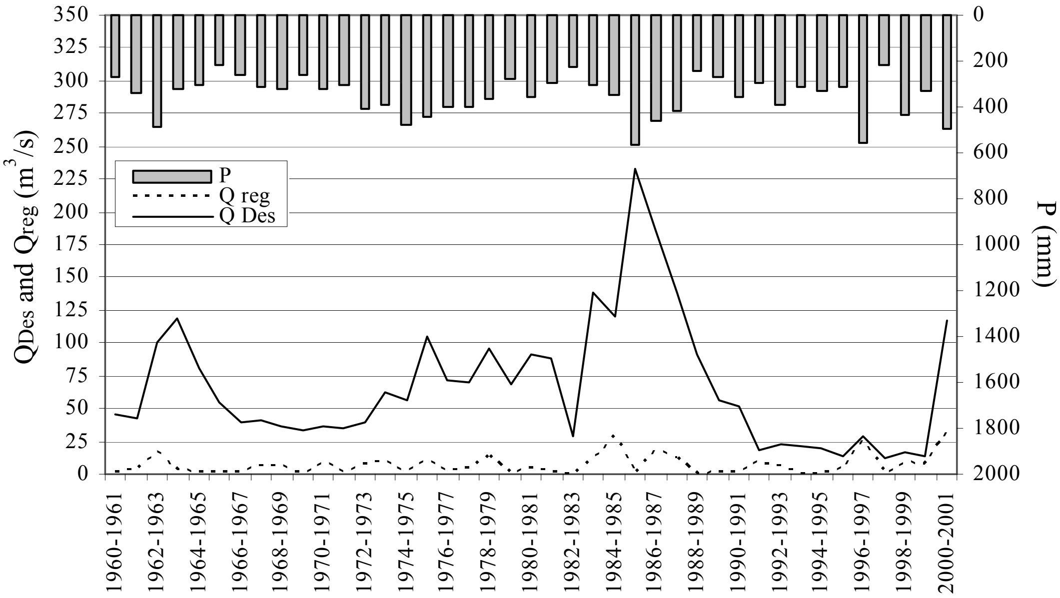

Fig. (9) Annual variation of inflow from the Desaguadero, regional rivers, and annual precipitation

The inflow to Lake Poopo over a long period including precipitation is shown in Fig. (**9**). The maximum annual inflow from the Desaguadero to the lakes was 233m^3/s between 1985 and 1986 and the minimum inflow was 12m^3/s between 1997 and 1998; the average inflow between 1960 and 2001 was 73m^3/s.

Annual water balance

The Lake Poopo basin was divided into three areas: the lakes, the flat-land between the hill sides and the lakes and the hill sides or mountain sides. The river water is of decent quality up in the mountains, however, not so further down. The rivers disperse into deltas and much water infiltrates into the flat-land and is not easily available for use. The lake water is salty. The lake evaporation and the precipitation distribution were determined from measurements. The river flow was measured in two rivers and, through the model, used to estimate regional flows in all rivers when the water from the river enters the flat land from hill slopes. The model computations gave actual evaporation from precipitation and potential evaporation as input. For the lake, Table **3** shows a residual term which gives the error of computations.

Table **3**
Annual water balance

	Whole basin	Lake	Up+flat land	Upland
Area (km^2)	24000	200	22000	12500
P (mm/y)	372 (obs)	340 (obs)	375 (obs)	380 (obs)
E (mm/y)	468 (wb)	1800	349 (wb)	334 (wb)
Q_{Des} (mm/y)	96 (obs)	1152		
Q_{Reg} (mm/y)		286	-26 (comp)	-46 (comp)
Error term		-22		

Within the flat-land area the water is not easily available; however there is a possibility of harvesting rainwater further upstream. The temporal river flows in the wet and dry periods are shown in Table **4**.

Table **4**
Temporal water inflow

Inflow	Unit	Annual average	Wet period Dec - Mar	Dry period Apr - Nov
$Q_{Regional}$	m3/day	$0.56x10^6$	$1.49x10^6$	$0.09x10^6$
$Q_{Desaguadero}$	m3/day	$6.0x10^6$	$7.79x10^6$	$3.74x10^6$

The water from the Desaguadero River can be used for irrigation in the north, but is mostly important as environmental flow for maintaining Lake Poopo's water level. The inflow from regional rivers is mainly of interest upstream, where the water quality has not yet deteriorated and the water can be collected during the wet period.

Environmental inflow consideration

From an environmental point of view, the inflow from the Desaguadero River is necessary in order to guarantee the conservation of the biota and to prevent Lake Poopo from drying up during the dry period. Thus, considering that the minimum area for the lake is 1000 km^2, corresponding to 0.5 m of depth, according to the hypsographic curve (Pillco and Bengtsson et al., 2007) [28], the inflow required to sustain this area is:

$$(E_{Lake} - P_{Lake})A_{min} = Q_{in} \qquad (1)$$

Therefore, calculating the lake's potential evaporation to be about 1800mm and its precipitation 340mm, the minimum inflow required to prevent Lake Poopo from drying up is $46m^3/s$. Unfortunately, the inflow from both regional rivers and the Desaguadero River during the analyzed period was higher than $46m^3/s$ only 25% of the time, as shown in Fig. (**9**). Consequently, it may be difficult to maintain this minimum environmental flow.

Available water for different consumption

After calculating the estimated required environmental inflow to Lake Poopo, the available water for different consumption (domestic water supply, irrigation, industrial use and water for livestock), is the difference between inflow from the Desaguadero and the regional rivers and the environmental flow. However, the inflow from the Desaguadero can be used only in the north-west of the basin for irrigation, but not for domestic consumption due high salinity and lower water quality.

The water from the Desaguadero River can be used for irrigation only in the very low lands north-west of the flat-land area by traditional gravitation irrigation systems. Pumping the water to the uplands is not sustainable for agriculture due to water-quality related problems. The water from regional rivers can be used, especially the headwater before it becomes polluted in the mining area. The challenge, as an alternative solution, is the storage of fresh water coming from the regional rivers and, in some regions, the groundwater. This, however, depends on the financial benefits.

The available water for different water use can be expressed as:

$$Q_{\mathrm{Re}\,g} + Q_{Des} - Q_{Envir} = Q_{Available} \qquad (2)$$

If the river inflow is expressed as water availability per capita from both Desaguadero and the regional rivers in the dry and wet periods, and considering the 360,000 urban and rural inhabitants, results are shown in Table **5**.

Table **5**
Water availability per capita in the entire basin

Inflow	Unit	Annual average	Wet period Dec - Mar	Dry period Abr - Nov
$Q_{available}$	1/per c day	$10x10^3$	$24x10^3$	$9x10^3$

According to Falkenmark and Winstrand (1992) [29], water stress in a basin occurs when total water availability (for domestic consumption, livestock, irrigation and industry) falls below 4.6 m^3/per c day (1,700 m^3/person/yr). In this case, the annual average of available water is really higher due the Desaguadero River inflow even in dry period. But, the water scarcity takes place throughout the 8 or maybe 9 dry months of the year.

The temporal and spatial runoff availability over the Lake Poopo basin is shown in Fig. (**10**). To obtain these runoff values, data from Table **2** was plotted for the wet and dry periods.

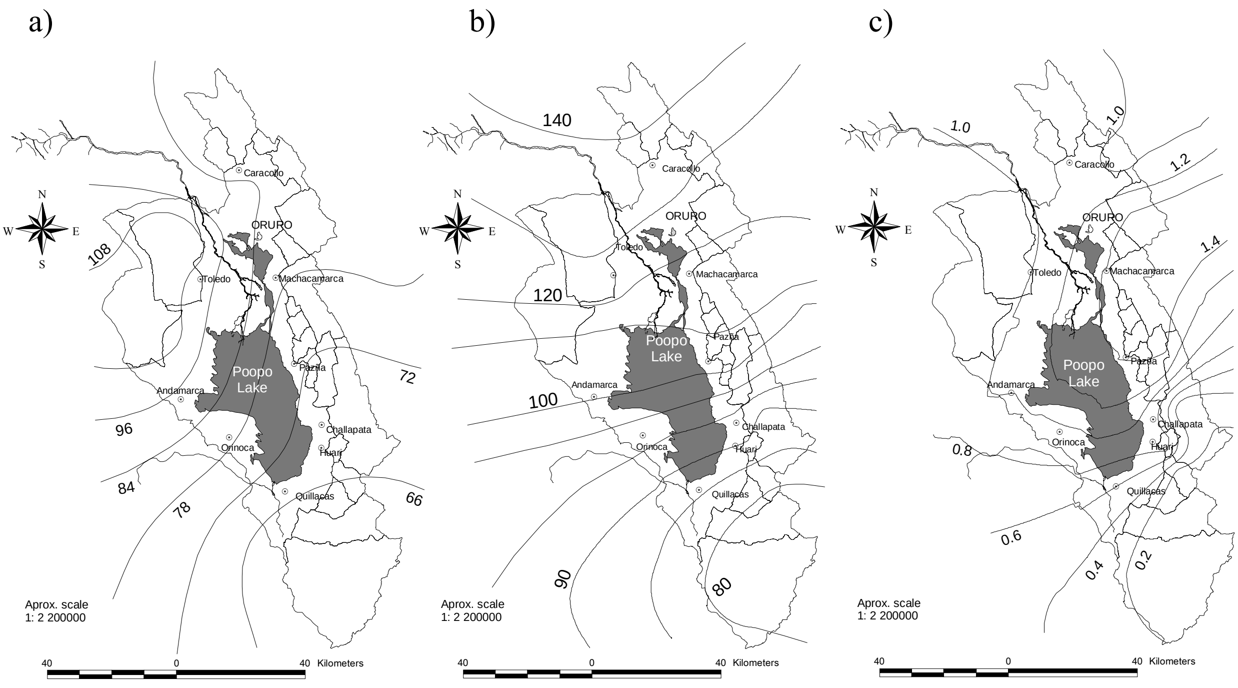

Fig. 10 Spatial surface runoff availability in the Lake Poopo basin:
a) Annual in mm, b) Wet period in mm/4 months and c) Dry period in mm/8 months

Figures (**10a**,) (**10b**), and (**10c**) clearly show a useful water availability map, in which the spatial distribution, in general, is decreasing from the northeast to the south, according to the spatial rainfall distribution over the basin. The difference between the spatial runoff availability during the wet and dry period is large. The spatial runoff availability during the dry period is practically zero south of the basin, making water unavailable.

These maps can be used as a first overview for the water quantity availability in the sub-basins when decision-makers are to identify related pre-feasibility development of water resources projects.

The severe water scarcity is directly related to the situation of poverty, which is increasing continuously due the population growth and land fragmentation. The water scarcity promotes small-scale subsistence agriculture without any extra income. Even if the wet period water availability is high, it is not enough for irrigation and sometimes can cause floods in flat-land areas. To avoid this, it is urgent to store fresh water and redirect it to relevant sectors. Programs for promoting water saving techniques, such as drip irrigation, or recovery of the water-efficient ancient “raised bed cultivation” technique, or *Suka Kollus*, are needed.

CONCLUSION

The sustainability of Lake Poopo basin’s development has several obstacles, such as severe water scarcity and environmental problems. The 372 mm of precipitation are not enough to reduce the water poverty index and this results in the population’s mass migration from rural to urban areas in search for a better future.

An integrated plan for managing both the environment and the water resources is desperately needed to improve the socioeconomic situation for the people living in the basin, based on the active participation of stakeholders at all authority levels. In this context, the participation of the native population and farmers is especially critical. The information policy is clearly insufficient.

There is also a need to promote and conduct activities in order to communicate the results of the research and the data base information more efficiently and increase people’s awareness of water resources management to protect both the environment and the water resources in general.

ACKNOWLEDGEMENTS

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PAPER 2

Water use related to the water resources in the Lake Poopo basin, Bolivia

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Abstract
The Lake Poopo basin is extremely vulnerable to water deficit and environmental degradation. It faces water scarcity, pollution and low water quality, and its population is extremely poor. This paper analyzes the use and availability of water in the basin and determines the minimum water demand necessary for increasing the people's quality of life. The assessment period is 2000-2006 and the forecast applies to the period 2007-2015. The assessment of water consumption was conducted through a questionnaire, with the participation of the authorities of over 60 communities. This facilitated the development of a model for the determination of domestic water demand and the parameters this demand depends on. The objective is also to create awareness regarding sustainable water use and promote decision-making in water resources management.

Key words: *water resources management, Lake Poopo, water demand, water forecast, environmental degradation*

Introduction

The semi-arid Lake Poopo basin on the Altiplano, shown in Fig. 1, is considered the most vulnerable region in Bolivia in terms of water deficit and environmental degradation (ALT, 1999; Calizaya, *et al.,* 2008). The basin is confronted with water scarcity and low water quality, all of which contributes to the population's extreme poverty. The lakes and regional rivers are polluted by heavy metals from mining and foundries, and also by natural and anthropogenic factors.

The rural economy of the Lake Poopo strongly depends on the availability and spatial distribution of water resources in time. For this reason, the application of water resources planning and management is urgent and should be conducted with the active participation of all stakeholders (native population, farmers, municipalities, and small water supply system operators).

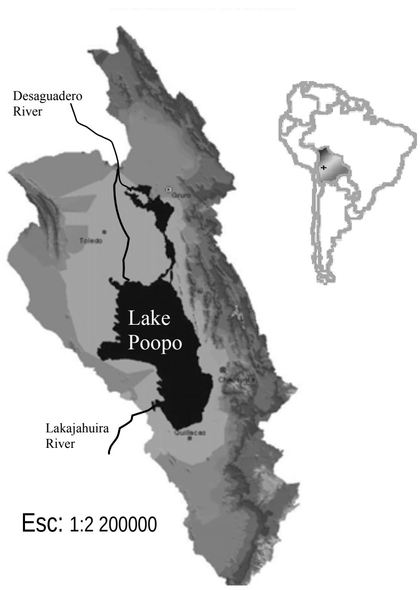

Fig. 1 Lake Poopo basin

The imbalance of water resources availability in the Lake Poopo basin between the 4 month long wet period and the 8 month long dry period causes a process of water-stress, provoking deterioration of fresh water resources in terms of quantity and quality, as well as land degradation, desertification and unsustainable eco-life conditions (Calizaya, *et al.,* 2008). The increasing development of agriculture and livestock

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demands a greater quantity of water in order to supply for an increase in production, especially during the dry period. As the water resources become more and more scarce, conflicts among different users may intensify, especially between the mining and farming sectors.

The aim of this paper is to analyze the use of water and water quality in the Lake Poopo basin, as well as to determine the minimum water demand necessary in order to insure an increase in the quality of life for the basin's population. The paper also aims at raising awareness and promoting decision making processes regarding the sustainable management of water resources.

The country and the region

In Bolivia, the total renewable water resources availability is 623 km^3/year (AQUASTAT-FAO, 2006). This means that the water resources availability is $70x10^3$ m^3 per capita. According to the Center for Ecology and Hydrology (CEH 2002), the Bolivian Water Poverty Index (WPI) is 63. This is rational if one compares the score with that of other countries, as shown in Table 1. The WPI is a holistic tool, designed to improve the effectiveness of water resources management. A higher value of WPI indicates less water poverty.

Table 1: Water resources availability and WPI in some countries

Country	Precipitation	Volume	IWRA* per capita	Population	WPI**
	mm/yr	km^3/yr	m^3 x 10^3	inhab x 10^6	
Argentina	591	814	20	40	61
Bolivia	1146	623	69	9	63
Chile	1522	922	58	16	69
Peru	1738	1913	68	28	64
Israel	435	1.67	0.3	6.3	54
Sweden	624	174	19	9	74

*Internal water resources availability (Aquastat-FAO,2006)

** Water poverty index (Centre for Ecology&Hydrology CEH, 2002)

The Lake Poopo basin belongs to the Titicaca–Desaguadero–Poopo-Salinas (**TDPS**) system (Fig.1). The basin has two lakes systems: Lake Poopo and Lake Uru Uru. It is located in the Department of Oruro and comprises more than 15 municipalities. Lake Poopo, located at an altitude of 3686 meters above sea level, is connected with Lake Titicaca-in turn located at 3810 meters above sea level- through the Desaguadero River, which measures 400 km in length.

The Desaguadero River, which has a very low gradient (about 45 cm/km) is the most important inflow to Lake Poopo. The outflow from Lake Titicaca to Lake Poopo and the water level are regulated by 4 gates. The gates are operated when the water level reaches 3810 masl, allowing water to flow out of the lake. The eastern mountains drain into the Lake Poopo through 22 regional rivers. The water from regional rivers disperses and infiltrates before the water reaches Lake Poopo, which covers an area of 3000 km2 (Pillco & Bengtsson, 2006).

The Lake Poopo basin constitutes a unified geomorphologic system, with distinct plains, valleys and depressions, hills and flat-land areas, mountains and water bodies, distributed as shown on Table 2. The eastern mountains drain into the Lake Poopo through 22 regional rivers. The water from regional the rivers disperses and infiltrates before reaching Lake Poopo, which covers an area of 3000 km2 (Pillco & Bengtsson, 2006).

The climate in the region is related to the atmospheric circulation of the Intertropical Convergence Zone –ITZC (Ronchail, 1995; Garreaund *et al.*, 2003). There are two main seasons: the wet period (Dec-Mar), during which most of the 70% yearly precipitation occurs, and the rest of the year is practically dry (Garreaund *et al.*, 2003). The yearly precipitation amounts to about 420 mm in the northern parts of Lake Poopo basin, while it is only 270 mm in the south, with a mean of about 372 mm. There is a higher potential evaporation. It was estimated at 1800 mm by Roche et al. (1992) and PPO, 1996.

Due to the high seasonal and annual variability of precipitation, severe floods and droughts occur in the Lake Poopo basin. Also notorious is the variation in temperature and humidity. Frost during the night is frequent, especially in winter, which lasts from May to July (PPO, 1996). These weather conditions often cause economical damages, weakening an area that already suffers from poverty. As shown in Figure 2, the poverty and the water stress (measured by the WPI) in the Lake Poopo basin will only get worse unless measures are taken in order to reverse this situation.

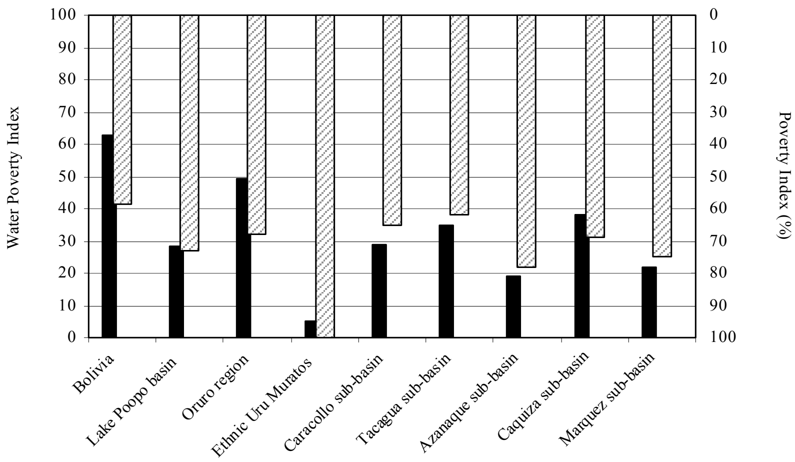

Fig.2. WPI for the country, Lake Poopo basin and other sub-basins

The department of Oruro, where the basin is located, is known to be one of the poorest regions of Bolivia (INE 2001). Until recently, mining was the sector generating the most important income for the region, although the profits resulting from these resources have not succeeded in improving the quality of life of the population.

Currently, the population distribution is 60% urban and 40% rural, a reverse relationship from 1950, when the urban population was only 40% and the rural population was 60%. In the basin, more than 70% of the population lives under the line of poverty, extreme poverty and marginality. This scenario partly explains the high rate of migration from rural areas to urban areas in the basin. The inventory and the distribution of population in sub-basins carried out recently are shown in Table 3.

Excluding Oruro's 216,000 inhabitants from the total population of 370000, almost all of the remaining 154000 inhabitants of the Lake Poopo basin live in the rural area. Even though there are small urban concentrated villages, e.g., Challapata, Pazña and Urmiri, they are considered rural due to the life conditions and lack of basic services.

The Lake Poopo Basin is not a densely populated area, as shown on Table 2. The population density in the biggest sub-basin, Marquez, is just 3 inhabitants per km^2, while the sub basin with the highest population density index is Azanaque, with 125 inhabitants per km^2. Curiously, the biggest sub-basin has the greatest amount of water resources and the least amount of people.

Table 2: Population, density and area of the Lake Poopo sub basins

	River sub basin	Catchment area	River		Population		
			length	slope	Total	Density	Rural
		km^2	km	%	miles	Nº/km^2	% of total
	All basin	24013.4			368534		
	22 sub basin				152637		
1	Marquez	2577.4	94.5	0.95	6950	2.7	100
2	Juchu Jahuira	1739.7	80.7	1.49	12540	7.2	85
3	Caquiza	1609.0	101.3	0.54	6240	3.9	95
4	Tacagua	1373.5	56.1	1.11	26450	19.3	75
5	Huaina Jahuira	861.8	65.4	1.07	7612	8.8	90
6	Sevaruyo	851.9	78.3	1.15	6300	7.4	80
7	Sora Sora	734.6	52.4	1.49	21560	29.4	75
8	Paria	705.7	44.8	0.92	5200	7.4	80
9	Juchusuma	380.6	56.4	1.33	1400	3.7	90
10	Conde Auque	314.1	36.3	1.93	4930	15.7	80
11	Caracollo	258.8	29.5	1.02	21650	83.6	60
12	Antequera	226.5	22.7	3.13	3820	16.9	85
13	Cortadera	222.6	23.9	3.35	720	3.2	75
14	Sepulturas	181.5	23.4	3.89	4860	26.8	85
15	Pongo Jahuira	120.7	15.4	2.98	2980	24.7	90
16	Pauma	116.2	15.4	4.55	229	2.0	100
17	Poopó	109.3	13.0	5.47	6059	55.4	100
18	Chillari	98.2	16.3	4.28	830	8.5	75
19	Azanaque	82.1	15.1	6.49	10240	124.8	80
20	Irancani	57.1	6.7	10.86	600	10.5	100
21	Huancane	56.9	9.3	7.57	1100	19.3	80
22	Huacani	22.7	4.2	13.57	367	16.1	90
	Flat area	9771.5					
	Oruro city				215898		5
	Water bodies	1540.9					
	Desaguadero river						
	Laka Jahuira river						

The spatial and temporal distribution of water resources does not match that of real demand in the basin. Most of the population is concentrated in the flat land. 80% of the renewable water resources along the study area come from Eastern (Amazon) rainfalls, the local source is 10% and the others come from western (Pacific) rainfalls. The annual precipitation in the basin is 372 mm (1960-2002). Thus, it is surprising the large amount of life depending on small quantities of fresh water resources, considering the arid and semi-arid conditions of the Lake Poopo basin. The closed basin is whipped mainly by the global changes and the El Niño Southern Oscillation (ENSO) phenomenon, that are causing severe droughts, floods, hailstorms, frosts, soil salinity, erosion, landings, etc.

Sources of water-related conflicts

There are 5 main of sources of water-related conflicts in the region: extreme weather events, poverty, deficient water regulations, environmental degradation and lack of sufficiently organized stakeholder enrolment.

North-east of the basin, for instance, there is a serious water conflict between farmers and miners. In general, the mining sector receives more political support in the definition of water rights. Most cases of water conflicts between stakeholders are on the exercise of water rights, which require adequate water laws and regulations in order to be peacefully resolved.

Currently, agriculture and livestock are the main sources of income for the rural population, and are mainly carried out on small and dispersed parcels of land. The main areas of cultivation are located on the flat-land and soft relief hills bordering the lakes.

There are several factors that hinder the productivity of the land in the region. One is land fragmentation. After the land reform of 1953, the rural property was fragmented to a large extent, and land parcels were at times limited to a few square meters. In such conditions, only small-scale subsistence agriculture is possible. Another issue is the lack of access to irrigation and farming equipment. In the basin, there is only one community that, due to international cooperation, can afford the newer water saving irrigation technique (dripping), and very few farmers can afford modern land cultivation equipment.

Pollution is another factor to take into consideration. The rivers and lakes have been polluted for decades by heavy metals from the mining region (Fig.3). Recently, the almost 30000 barrels of crude petroleum that were accidentally spilled into the Desaguadero River have practically exterminated the native species of fish in Lake Poopo. Fishing was how the native tribe of Uru Muratos made their living. Thus, the Uru Muratos have been forced to work as servants for the local farmers. The social and environmental consequences in general will last for many years (Montoya, 2002).

Surface water

The Lake Poopo basin is composed of 22 sub-basins, a flat-land highly populated area and water bodies. The temporal and spatial surface water availability in the Lake Poopo basin has been discussed by Calizaya *et al* (2008), and is summarized in Table 3.

Table 3: Water resources availability over the entire Lake Poopo basin

	Unit	Annual average	Wet period Dec - Mar	Dry period Apr - Nov
P	mm	372	300	75
Q Des	mm	96	118	46
Qregional	mm	20	45	3

The dry period is 8 months long, lasting from March to November. During this time, the water scarcity dramatically affects the biota in general, but specially the agriculture. Along with the lake's altitude and low humidity, low air pressure and high radiation causes almost 100% of the water inflow to evaporate.

Groundwater

The Lake Poopo basin is a water-stress basin regarding its surface water availability. Groundwater seems to be one of the options available to cover the water-demand during the dry period, especially for domestic consumption, but the sustainability of its exploitation is still in doubt.

An inventory carried out has identified more than 150 wells, mostly located around the flat-land, but only 93 groundwater taps are in actual exploitation, from which 75% involve shallow wells of no more that 10 m in depth. In Challapata, a town located southeast of the basin, the production of 6 wells of 60 m in depth is only 3.6 l/s. Fig. 3, Spatial distribution and depth of groundwater wells show these are mostly distributed around the lakes in the flat-land area of the basin. In the sub-basins, the basic water necessities are satisfied by spring water, but in the flat-land, the only alternative is to draw groundwater.

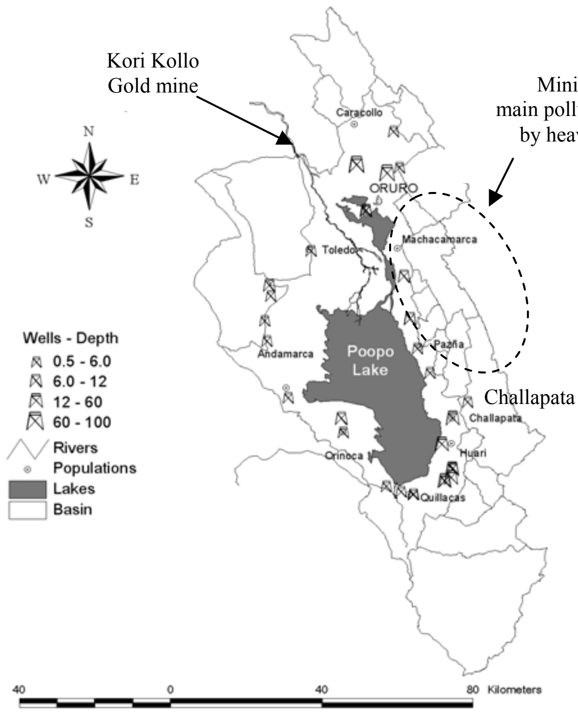

Fig. 3 Spatial distribution of groundwater wells and its depth

According to the Water Supply System Company SELA, 2002, (Fig.4), the largest volume of groundwater for the city of Oruro's water supply system, based on the average of 11 annual observations (1996 to 2006), is 250 l/s. The drilling wells are more than 100 m in depth. In this area, the water level is decreasing at a rate of 0.5 cm per year (SELA, 2006). It is urgent to promote the monitoring and protection against pollution, and guarantee the recharge of aquifer systems to ensure the water supply to the city of Oruro.

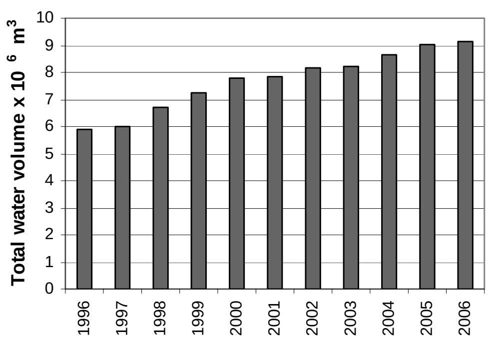

Fig.4 Annual production of groundwater wells to cover the
Water supply of Oruro City (SELA, 2006)

The mining activities in the Lake Poopo basin have caused severe disturbances in the ecological equilibrium. The damage can be attributed to the acid mine drainage, generated by the mining waste. These effluents have contaminated and continue to contaminate the groundwater and lakes with heavy metals. In the northeast there are more than 100 small and large mines and the biggest one, the "Kori Kollo" gold and argent mine, is located in the north western region of the basin (Fig. 3).

Results: Water use and water demand in the Lake Poopo basin

The water use in the Lake Poopo basin has been separated into two categories: consumptive and non-consumptive, as shown in Table 4.

Table 4: Different water uses in the Lake Poopo basin

Consumptive uses	Non consumptive uses
Water supply (domestic)	Recreational use
Irrigation use	Fishing use
Livestock use	Navigation use
Industrial use	Environmental use
Mining use	

The domestic consumption and the irrigation uses of water are the main focus of this paper. A survey was carried out in order to obtain basic information, as were inventories and interviews with the water stakeholders, native people and civilians from municipalities throughout the basin.

Domestic consumption

The availability of water for domestic consumption is the top priority to be achieved in the region. According to the national census carried out by the National Institute of Statistics (INE, 1992-2001), detailed on Table 5, the water supply systems have extremely low values and have grown very slowly. In this analysis, some information was included from municipalities and the data base of the Bolivian Information System of Water and Sanitation (SIAS, 2001).

Table 5: Water supply cover in the country, in some regions and in the Lake Poopo basin

	Bolivia		Oruro		Lake Poopo basin			La Paz		Santa Cruz	
	1992	2001	1992	2001	1992	2001	2006 (*)	1992	2001	1992	2001
Population, inhab.*106	6.42	8.27	0.34	0.4	0.28*	0.31*	0.37	1.9	2.35	1.36	2
Water supply sources	%	%	%	%	%	%	%	%	%	%	%
Pipe line	47.1	62.3	55.9	57.5			59	47.6	65.5	64.5	77.7
Public tap	8.2	7.4	8.1	8.3			5.5	11.9	6.6	5.7	4.7
Cistern	3.1	2.1	1.2	0			0	3.1	1.4	1.3	0.4
Shallow well with pump	20.4	3.5	23.8	3.1			6.3	22	1.8	18.1	6.1
Shallow well without pump	0	10.6	0	18.8			22.2	0	13.2	0	5.7
River, spring, irrig. channel	19	11.3	8.3	8.5			5.8	13.7	8.8	7	2.9
Lake, pond	0	0.9	0	0.6			0.4	0	0.5	0	0.9
Others	2.2	1.9	2.7	3			1	1.8	2.2	3.4	1.7

The growth rate in the Oruro region between 1992 and 2001 was 0.6% for the urban area and the almost 3.0% for the rural area. These rates can be considered the same for the basin, which includes Oruro City. Currently, the city of Oruro is served in almost 85% by the pipe line water-supply system with an estimated average water use of 220 l/day/person.

Analyzing the water-coverage situation in the Lake Poopo basin, Table 6 shows that the two most important sources of water are: the pipe-line gravity system, or pumping system, (including the public taps) and the shallow, hand-drawn wells without a pump (manual or engine pump). The third most common source is the water from the rivers (when these are not dry), or head waters (spring water), and sometimes the water is diverted from the closest irrigation channel.

Table 6: Sources of water-supply in the Lake Poopo basin

Water supply source	Lake Poopo basin *
	%
Pipe line	33.5
Public tap	14.5
Cistern	0.01
Shallow well with pump	6.4
Shallow well without pump	32
River, spring, irrig. channel	12
Lake, pond	1.2
Others	0.5

In the southern part of the lake and in the north-western part of the basin, small farms often use the water from the lake or ponds, especially during the rain period. In recent years, with the help of international cooperation, the use of private and communal manual water pumps has become common, including some wind pumps. Unfortunately, the wind pumps were not sustainable due to the operation and maintenance cost, and many of these wind pumps are no longer functional. A low percentage of the people store small amounts of rain water. On the other hand, some people receive water in compensation for labor in agriculture.

The quantity of water used for domestic consumption and main sources of water were determined from the inventory and survey carried out in 68 of the 260 small towns, villages and farms with a total population of 6500 inhabitants.

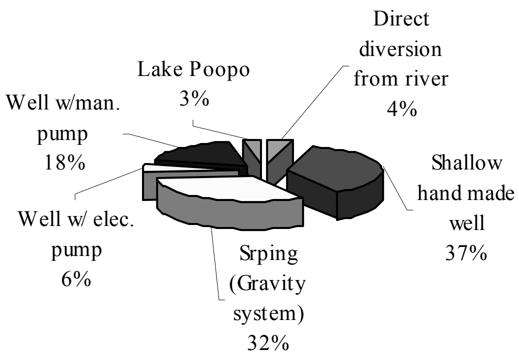

Fig. 5 Water supply source of the sample

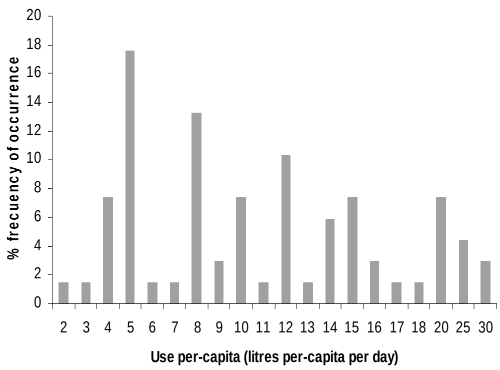

Fig. 6 Water use per capita (sample)

Fig. 5 shows that 32% of the population uses water from springs through a gravity water-supply system and 37% uses water from open shallow wells (manually drawn) from 3 m to 7 m depths. 18% uses concrete closed wells with damaged manual pumps, and 6% of the water-supply systems use electrical submersible water pumps. Only 4% of the sample takes water directly from the river, when it is available, and the other 3% takes the water directly from the Lake Poopo, specially the people who live on Panza Island.

From the same sample, it has been determined that in some villages the rate of water-use does not exceed 5 l/per capita/day and, in the best case the rate is 30 l/per capita/day, with a 3% of occurrence frequency in a typical 5-member household, as shown in Fig. 6. The occurrence frequency percentage shows how often the quantity of water in liters per capita per day is used in the sample of the Lake Poopo basin's population, where the water (5 l/per capita/day) is mostly used for cooking and for drinking, not including hygiene.

The rural domestic water-demand model was developed from the questionnaire, assessing the variables which influence the domestic use of water in the countryside and determining the parameters that help manage the demand. 9 variables were selected for their impact on rural domestic water consumption. The linear equation of best-fit solving by multiple regression model has been defined as:

$$Q = 9.15 + 0.23X_1 - 0.66X_2 - 0.27X_3 + 0.02X_4 - 0.43X_5 + 2.38X_6 - 0.22X_7 + 2.96X_8 - 0.04X_9 \quad (1)$$

In Eq. (1) the variables are: Q-average quantity consumed (l/c/d); X_1-Nº of adults; X_2-Nº of children; X_3-Nº of rooms; X_4-lot size (m^2); X_5-Nº of animals; X_6-Nº of taps; X_7-microirrigated area (m^2); X_8-type of water source(river, spring, well, etc.); X_9- monthly income ($us). The correlation coefficient has obtained as r=0.79.

Regarding the quality of water in general, almost 30% of the water was found to be potable drinking water and 70% not suitable for human consumption. If the locals can drink this water, it is because they have developed natural defenses to the microbial and bacterial contamination. But this contamination affects the infant and child population severely, producing diarrhea, dysentery, typhus and hepatitis, and is one of main causes of the high child mortality rates in the basin. Chlorination is the traditional form of water-treatment for those systems that the people pay for, or for systems where the municipality is in charge of operation and maintenance (O&M).

Irrigation

Agriculture is the main source of income for the rural population, and as stated above, is mainly carried out on small and dispersed parcels. 307 irrigation systems were investigated, based on the report MAGDR/PRONAR, 2000; data base 2001/2003 and field inventory IHH, 2005/2006. According to our inventory, from these 307 irrigation systems, only 267 are still operating, and the rest have left due to the soil salinity in the flat-land area, soil erosion in the regional basins and mining pollution in the irrigation system in the basin's north-eastern region.

The current surface under irrigation is 132 km^2, which represents $6x10^{-3}$ % of the total land in the basin. It benefits 8400 users directly and 5000 families indirectly. There are only two big irrigation systems. One of them is the Tacagua system, in the regional river basin with a reservoir, and the second one is the Choro irrigation system, using the water inflow from the Desaguadero River.

The Tacagua reservoir, built in 1950, has lost 50% of its storage capacity due to the sedimentation and erosion problem in the upstream of the river. Currently, the maximum storage capacity is $20x10^6$ m^3, covering the $5.4x10^3$ ha and $1.5x10^3$ users. The Choro irrigation system, withdrawal from the Desaguadero River, covers $4x10^3$ ha and $1.7x10^3$ users.

Due to the high level of salinity in the soil and the climatic conditions in the basin, characterized by variability and occurrence of extreme events mentioned before, the main agricultural product is forage. This product represents 78% of the total production, as shown in Fig. 7. The low economic potential has motivated the people to herd fast reproducing cattle and sheep, especially in the north western region of the basin, in addition to the traditional *llama*, that is widespread in the south part of the basin, where *llama's* meat is a part of the people's daily diet.

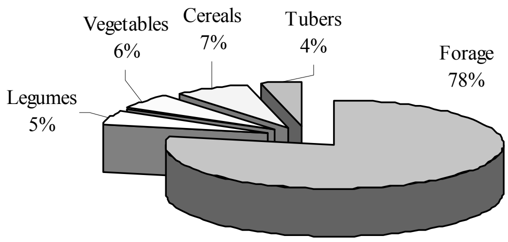

Fig. 7 Actual agricultural production

Table 7: Water irrigation source

Source	Area	
	km^2	%
River	72	57.7
Srpings	4.5	3.6
Reservoirs	46	37.2
Wells drawn	2	1.5

According to the water irrigation source, the regional and Desaguadero Rivers are the main sources of water for irrigation, as shown in Table 7. From the river sources, the regional rivers are used almost 40% of the time and the Desaguadero River is used 60% of the time. The total water used for irrigation was computed at $70x10^3$ m^3.

Water for recreation (thermal waters)
The water for recreation is the lake itself, which can be used for fishing and navigation. In order to guarantee those tourist-related activities, it is necessary to ensure the environmental inflow to the Lake Poopo from the Desaguadero River, established at a minimum of 50 m^3/s. Another source of tourist activities comes from the thermal waters. In the basin there are hot springs which flow naturally from artesian aquifers. More than 20 such sites were found in the entire basin, and the 6 most important are detailed on Table 8.

Table 8: Thermal water in the basin

Site name	Sub basin	Flow	Location		Altitude
		l/s	y	x	Z
Obrajes	Jacha Uma	10	8028279	713128	3805
Urmiri	Antequera-Urmiri	7			3725
Capachos	Flat area	4.5			3783
Poopo	Poopo	4.5	7966602	716224	3782
Pazña	Antequera-Urmiri	1.5	7942802	719580	3729
Tacagua*	Tacagua	1	7915631	748120	3785

Currently, 5 of the sites offer tourists small natural hydrotherapies, as for medical uses, in small scale. The biggest one is located in Obrajes and has a good infrastructure, including a swimming pool. The others are much smaller but, well managed, they can be an interesting way to generated extra income to the region. The flow from this source is almost constant throughout the year. The temperature is also constant over the year. In Obrajes and Capachos, the average water temperature varies between 50 and 75°C.

Water for mining and industrial activities
It is very difficult to determine exactly the total volume of water for the mining and industry activities in the basin. In the urban area, including Oruro City, the water for these uses is very little due to the small amount of activities. In the rural area, where the mines are located, the water use for mining can be estimated as close to 400 l/s. According to Van Damme (2002), the biggest ore mine, Huanuni- Ingenio Santa Elena, uses 240 l/s deviated from the Huanuni River, from which 60% is recycled.

One of the most important industrial activities identified in the rural area of the basin is the beer production in the town of Huari. Yet, the exact quantity of water it uses is unknown, as is the total production of beer. The only thing known is that approximately 3 l/s are taken from the Huari water supply system. Currently, this deviation is generating a conflict between the beer factory and the town's water supply system due to the forced rationalization which reduce availability of water to two times a day.

Water for livestock

The quantity of livestock has been estimated from MAGDR, 2000 and adapted to the Lake Poopo basin. As shown in Table 9, the consumption of water for livestock is close to $2x10^6$ m^3 per year.

Table 9. Livestock and yearly water consumption in the basin

Livestock	Quantity	lpc	water consumption m3/year
Sheep	90000	5	164250
Cows	44040	30	482238
Cows (milk producers)	40000	70	1022000
Llamas and Alpaca	20000	20	146000
Pork	8404	5	15337
Donkey	500	30	5475
Total	202944		1835300

Demand forecasting

According to the census (INE, 2001) and the inventory carried out during the field-work, the average population growth rate for the next seven years will be 2.4%. The population growth in some sub-basins is negative due to the high rates of migration to the urban areas. The population in the basin in 2001 was $340x10^3$, and 360 $x10^3$ and 420 $x10^3$ for 2006 and 2015 respectively has been computed. The forecast of the population behavior, as well as the water consumption in the basin, are shown in Fig. 8.

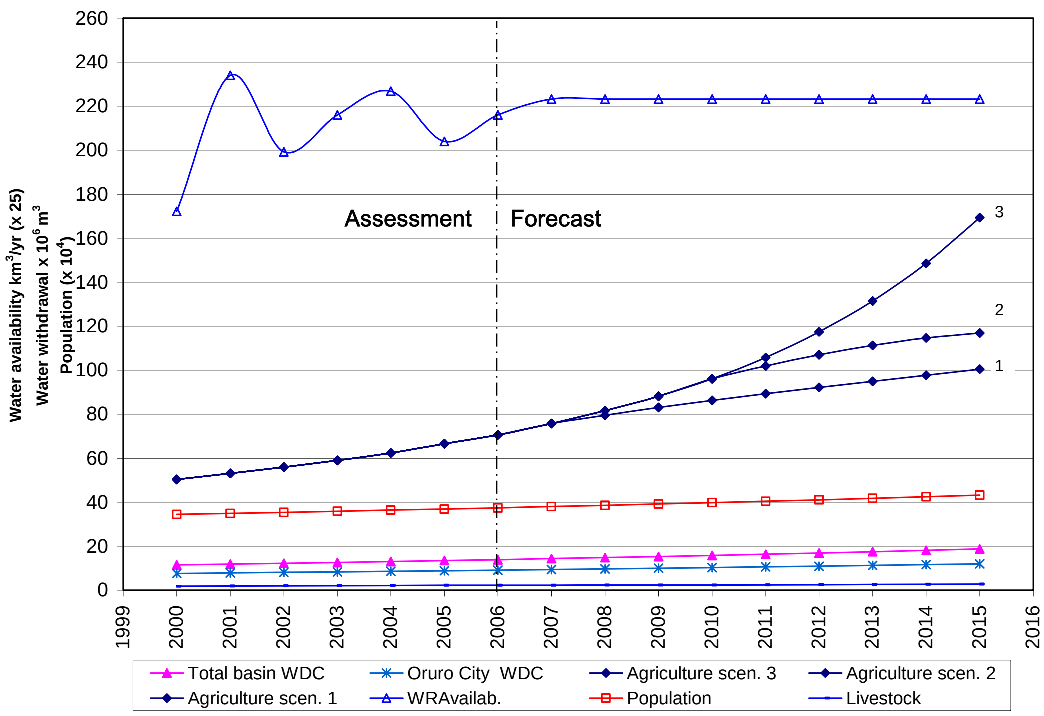

Fig. 8 Assessment and forecast of water consumption in the Lake Poopo basin and scenarios of agriculture possibilities

Three scenarios have been generated in order to analyze the consumption of water for agriculture. The first scenario is the forecast if the water demand growing with the same assessment gradient for water and land use increases. The second one is the case in which a water harvesting would take place through the construction of two new dams, more water deviation from Desaguadero River and the construction of small spring water tanks. The third one would be the best situation, where all the available and adequate land were irrigated through the construction of dams in each of the regional rivers and the government would facilitate machinery to make available land and to irrigate the flat land in the northwest of the basin. The available water was computed from the observed annual precipitation throughout the basin and the forecast was computed from the average precipitation over 40 years: 372 mm.

Conclusions

The results obtained from the assessment and the forecast of water consumption represent a critical guideline in order to improve water resources sustainability in the Lake Poopo basin.

According to the surveys, there are still a large number of people who consume 5 liters of water per day, not because there is a lack of water, but because of the lack of investment in provision of better water supply systems, waste disposal and treatment. This is connected also to the provision of public health services in order to ensure a better quality of life for the population.

The majority of farmlands have no irrigation systems, due in part to land fragmentation caused by the traditional property Rights. This situation contributes to stall productivity, consolidating the poverty in the basin.

Considering that both population and agricultural growth in the region are moderate, due mainly to the fact that the population is migrating at very high rates, the sources of surface and underground water are sufficient to satisfy current and future demand. Nevertheless, it will be necessary to implement the building of water storage infrastructure in order to confront the extreme climatic variability. Also, it is urgent to implement more efficient agricultural technologies to improve productivity and organize producers associations to strengthen their social and economic structures.

Acknowledgements

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Tables

Figures

PAPER 3

Application of the Watershed Sustainability Index to the Lake Poopo watershed, Bolivia

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Abstract: The Lake Poopo watershed, located in the southern Bolivian Altiplano, is subject to low quality and availability of its water caused by pollution from the mining industry, a lack of water policies and a semi-arid climate. Its population lives in extreme poverty.

Moreover, social, economic, environmental, and policy issues affect the sustainability of the sub-basins in the region. Both the urban and rural populations of the Lake Poopo watershed depend on the availability of water resources in time and space, which makes it urgent to apply integrated water resources planning and management tools involving the participation of stakeholders such as peasants, authorities and small water-supply system operators.

The objective of this paper is to apply the integrated Water Sustainability Index, or WSI, to the Lake Poopo watershed, with data from the five years between 1997 and 2001. The WSI incorporates hydrologic, environmental, life, and water policy issues and responses for a specific watershed. By analyzing different scenarios, the objective is to develop an integrated view of which water-related issues are the most critical for sustainable development.

Three scenarios were analyzed: 1) a year-long drought, 2) a dry season with a dam in the upstream river branches, and 3) the dry season without the dam. The value of WSI for the first scenario was 0.46. During dry season, the score without the dam was 0.36, and the score was 0.59, with the dam. The factors that contributed to the decrease in the overall WSI score were environmental and political issues.

INTRODUCTION

The Lake Poopo watershed on the Bolivian Altiplano presents water scarcity and a high index of poverty among its population, leading to a mass-migration toward Bolivian and other Latin American cities. The annual climate is characterized by a short rain season, followed by a long dry season, during which most of the rivers become intermittent. In many parts of the watershed the water quality is poor as a result of mining activities, but also due to high amounts of natural leaching of metals from the soil to groundwater and streams. These major problems are further aggravated by lack of water management policies and control, which generates conflicts between sectors. For all these reasons, water scarcity is limiting the development of the region.

To improve the situation, water resources planning is required, following social and environmental guidelines. When formulating a plan, the cultural factors that affect water consumption in rural communities must be taken into account. Peasants often have an integrated view of water, understanding it as an element that holds both life and cultural values, in coherence with the general Andean understanding of water (Calizaya et al., 2008).

According to Chaves and Alipaz (2007) [1], several issues impact the water sustainability of a watershed. Among them are social, economic, and environmental concerns. These issues are often treated separately, not as integrated parts of an ecosystem, natural resource and a social and economic good (Dietrich and Schumann, 2004) [2]. Integrated and environmentally sustainable water management requires more than environmental impact assessment. It demands integration of policy formulation, project appraisal, clear water management laws and institutions, cutting across the breath and depth of the decision-making process regarding the use of freshwater resources (Smith and Rast, 1998) [3].

The objective of this paper is the application of the integrated Water Sustainability Index, or WSI (Chaves and Alipaz, 2007). This recently developed index incorporates hydrologic, environmental, life and water policy issues and responses for a specific watershed. The index was applied to the Lake Poopo watershed with data from the period between 1997 and 2001. By analyzing different scenarios, the objective was also to develop an integrated view of which water-related issues are the most critical for the sustainable development of the area. Three scenarios were analyzed: 1) a prolonged, year-long drought, 2) a dry season with the existence of an artificial reservoir storage, or dam, in the upstream river branches, and 3) the dry season without the dam. The Lake Poopo watershed is also assigned a UNESCO H.E.L.P. operational watershed in Bolivia. The results can be used to create a basis for multi-criteria analysis (MCA) of integrated water resources management (IWRM) in challenged river watersheds.

THE LAKE POOP BASIN

Geographical background

The Lake Poopo watershed lies in the Bolivian Altiplano, a high- altitude plateau. It is enclosed by the Andes mountain ranges, and its main source of water is the Desaguadero River (Fig. **1**). The Lake Poopo watershed has an area of 24000 km^2 and is one of the world's highest basins. The highest peak in the region is Mount Azanaque, which stands 5500 m above sea level, and the lowest point is the lake bottom, at 3670 m above sea level. Consequently, Lake Poopo is basically a water and salt sink. Spill-over occurs very seldom; the last spill-over occurred in 1986. The Lacajahuira River links Lake Poopo with the Coipasa Salt Desert (3550 m high). Outflows from the lake occur only when the water depth in Lake Poopo is above 3.0 m. (Pillco & Bengtsson, 2006) [4].

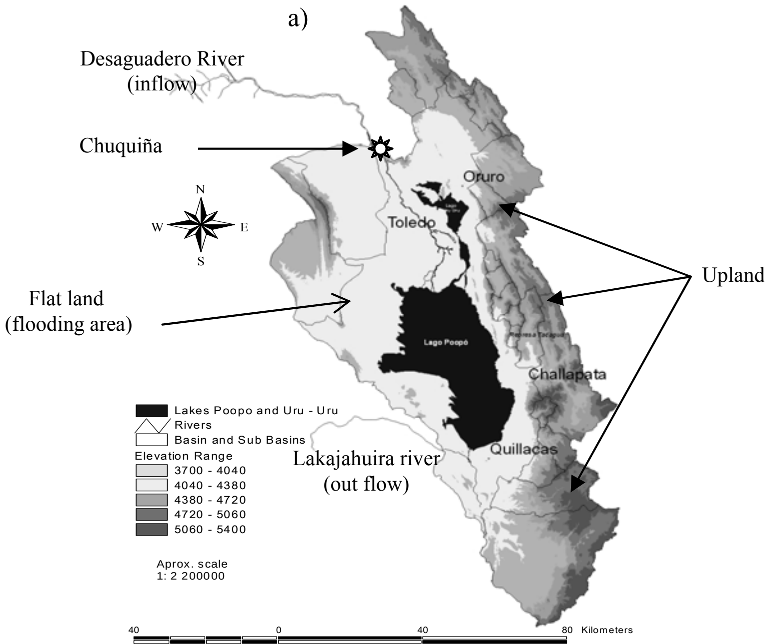

Fig. (1a). Topography of the Lake Poopo watershed.

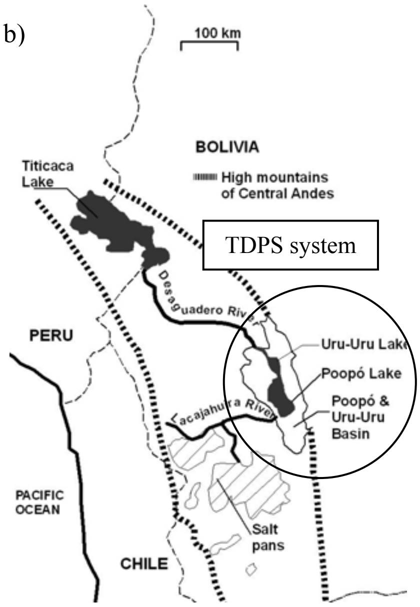

Fig. (1b). Location of the Lake Poopo watershed

Hydrology

The Lake Poopo watershed is constituted by 22 intermittent river sub-basins and there are two shallow lakes: Lake Poopo (max. depth 3.5 m) and Lake Uru Uru (max. depth 1.0 m). Lake Poopo can be as large as 3000 km^2 after consecutive years with high precipitation, but may also dry up after consecutive years with prolonged dry seasons. Lake Uru Uru dries up every year during the dry season, but during rain season it can be as large as 350 km^2. Lake Poopo and Lake Uru Uru are connected to Lake Titicaca through the Desaguadero River, which has a length of 400 km. Since Lake Poopo is a closed lake, it is extremely sensitive to climate changes and water pollution.

In the Lake Poopo watershed, precipitation occurs from December to March. The average yearly precipitation amounts to about 370 mm over the watershed, and varies from about 420 mm in the north to about 270 mm in the south.

The discharge varies largely throughout the year, from practically zero during the dry season up to 10 times the average discharge during rainy season. The regional rivers disperse into many streams forming small deltas before reaching the lake. Some water filtrates into the shores. At the end of the dry season the rivers are mostly dry. Melt water from the mountain areas in the northwest drains into the plains, where the western branch of the Desaguadero flows through. The south-western part of the watershed, which borders the Coipasa Salt Desert, is part of the flat-land. Diffuse groundwater-flow into the lake from coastal aquifers are believed to be negligible.

According to Calizaya et al., (2008) [5], the mean annual water balance for the Lake Poopo watershed is composed of 372 mm precipitation, 468 mm actual evaporation, and 96 mm water inflow from the Desaguadero River. The water balance of the Lake Poopo gives precipitation equal to 340 mm per year; evaporation 1800 mm per year; inflow from Desaguadero River 1152 mm per year and inflow from regional rivers about 286 mm per year.

Socio-economic setting

The Lake Poopo watershed, with a population of 360,000 inhabitants, is one of the poorest regions in Bolivia (Calizaya *et al.,* 2008) [6]. The life expectancy is only of 58 years, the infant mortality rate is 10%, and 60% of the population is indigenous (INE, 2001) [7]. 73% of the total population lives under the line of poverty, and close to 50% of the population of Oruro, the most important city in the watershed, is poor. The indigenous Uru Muratos are extremely poor and less than 20% of them have access to water and sanitation (Calizaya *et al.,* 2008). Until recently, the mining sector generated important income for the population, although the profits resulting from these resources have not improved the people's quality of life. In 1950, the proportion of urban to rural population was 40 to 60. The last census (INE, 2001) shows a reversed relationship, with approximately 60% of the people living in cities and 40% in the countryside.

The Water Poverty Index (WPI)[4], an indicator used to measure the water stress at household and community levels, can be used to show that improvement within the water sector would help decrease poverty. The poverty index and WPI of the Lake Poopo watershed are compared with those of other parts of Bolivia and South America in Fig. (**2**). The comparison shows that the situation of extreme poverty in the studied region is closely related to the lack of water during the 8-month dry season, with its consequential disadvantage in temporal and spatial water allocation.

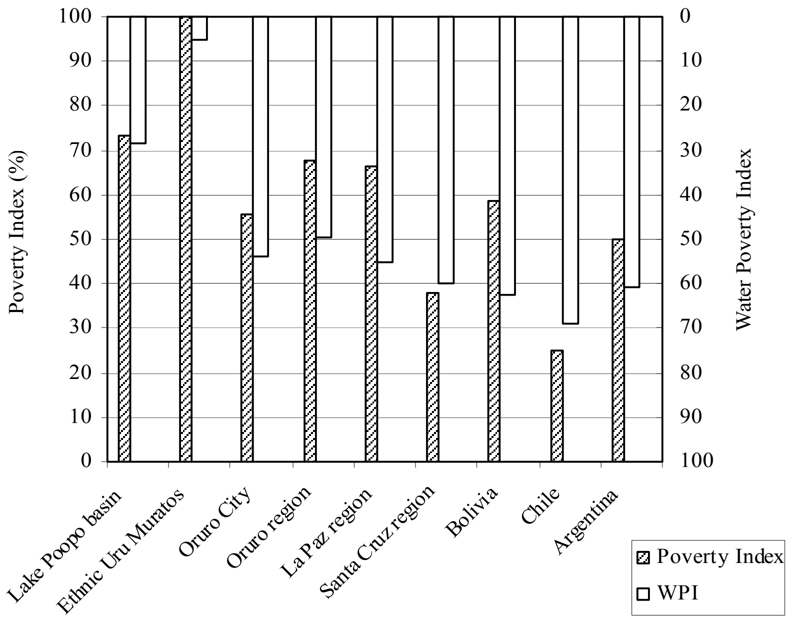

Fig. (2). Poverty Index and WPI for the Lake Poopo watershed compared to other places in South America (INE, 2001; ECLAC, 2002; CEH, 2002) [8].

The main areas of cultivation are located on the flat-land and rolling hills bordering the two lakes. In general, the region has a highly fragmented landscape, with many farm lots, overgrazing, poor vegetation cover, and low productivity. In addition, the farmers rely on rudimentary farming systems.

Traditionally, fishing has been the means of survival for the native Uru-Muratos. Fishing reached a maximum production of 2.500 tons/year between 1989 and 1991. The major catch was *pejerrey* and *karache* (Van Damme, 2002) [9]. In 1992, when Lake Poopo dried up due to drought, the fishing activity halted completely. Today, it is considered unhealthy to eat the fish from this lake because of the high levels of water pollution, particularly from heavy metals (Garcia, 2006) [10].

[4] The WPI is designed as a composite, interdisciplinary tool, linking indicators of water and human welfare to indicate the degree to which water scarcity impacts on human populations (Sullivan, 2001). The WPI has a range from 0 to 100. The highest value, 100 is taken to be the best situation, while 0 is the worst.

METHODOLOGY

The Watershed Sustainability Index (WSI)

Sustainability assessment and development that "meets the need of the present generation without compromising the ability of future generations to met their needs" (WCED, 1987) [11] is now an acknowledged goal of watershed management. Though it is recognized that the sustainability of the water resources in a watershed is directly related to its hydrologic, environmental, life, and policy conditions, few attempts have been made to integrate them in one single and comparable indicator (Chaves and Alipaz, 2007). Integrated indicators are used for survey and planning purposes. The United Nations has been using the Human Development Index - HDI (UNDP, 1998) [12] for several years. It integrates educational, life expectancy, and income information from municipalities, states and countries. Varying from 0 to 1, the HDI is simple to use, and applied worldwide.

To estimate the water scarcity in countries, Lawrence et al. (2002) [13] developed a Water Poverty Index (WPI). A variation of the WPI is the Climate Variability Index (Meigh and Sullivan, 2005) [14], which estimates the vulnerability of countries, regions, and communities related to water resources. Both indicators are integrative but are not watershed specific, as neither take into account cause-effect relationships, or consider the policy responses that are implemented in a given watershed in a given season (Chaves & Alipaz, 2007).

Considering that the management of water resources is a dynamic process, and assuming that the sustainability of a watershed is a function of its hydrology (H), environment (E), human life (L), and policy (P), a dynamic, pressure-state-response model[5] (OECD, 2003) was applied to these four indicators (H, E, L, and P) in a matrix scheme. As a result, a watershed sustainability index - WSI was developed, and is given by the following equation (Chavez & Alipaz, 2007):

$$WSI = \frac{H + E + L + P}{4} \qquad (1)$$

Where WSI (0-1) is the watershed sustainability index; H (0-1) is the hydrologic indicator; E (0-1) is the environment indicator; L (0-1) is the life (livelihood) indicator; and P (0-1) is the policy indicator. As seen from Eq. (1), all indicators have the same weight, since there is no evidence to the contrary (Harr, 1987) [15]. The linear and additive structure of Eq. (1) allows for error compensation in the indicators, reducing the potential of under and overestimation of the WSI (Chaves & Alipaz, 2007). The logic behind this is the fact that, if one of the indicators of Eq. (1) is overestimated, there is a good chance that another would be underestimated, compensating at least part of the overall error. This is an important issue in model development, but often overlooked by modellers (Chaves and Nearing, 1991) [16].

Since watershed management at the local and regional level is more effective in watersheds of up to 2,500 km^2 (Schueler, 1995) [17], this is the upper limit suggested for the application of WSI in the estimation of watershed sustainability. Just one of the sub-basins of the Lake Poopo watershed is larger than that upper limit (the Marquez sub-basin), by only 80 km^2, so it was assumed that this would not limit the application of the WSI in this sub-basin.

Table **1** presents the WSI parameters corresponding to each of the four indicators; H, E, L, and P. These are divided in to three columns, comprising Pressure, State, and Response (PSR). The advantage of using a PSR model is that it incorporates cause-effect relationships, helping stakeholders and decision-makers to see the interconnections between the parameters (OECD, 2003) [18].

[5] The PRS model has been developed by the OECD to structure its work on environmental policies and reporting. It consider that: human activities exert pressures on the environmental and affect its quality and the quantity of natural resources "state"; society responds to these changes through environmental, general economic and sectorial policies and through changes in awareness and behavior "societal response" OECD, 2003.

Table **1**
Indicators and parameters of the Watershed Sustainability Index (WSI).

Indicators	Parameters		
	Pressure	**State**	**Response**
Hydrology	Variation in the basin's per capita water availability in the last 5 years;	Basin per capita water availability	Improvement in water-use efficiency (last 5 years);
	Variation in the basin BOD_5	Basin BOD_5 (yearly average)	Improvement in sewage treatment/ disposal (last 5 years)
Environment	Basin's EPI (rural and urban)	% of basin area with natural vegetation	Evolution in basin conservation (Protected areas, BMPs)
Life	Variation in the basin per capita GDP in the last 5 years	Basin HDI (weighed by county pop.)	Evolution in the basin HDI (last 5 years)
Policy	Variation in the basin HDI-Ed in the last 5 years	Basin institutional capacity in WRM	Evolution in the basin's WRM expenditures in the last 5 years

A value of between 0 and 1 is assigned to each combination of indicators and parameters. A value of 0.25 is assigned to poor conditions, 0.5 to intermediate conditions, 0.75 to good conditions and 1 to optimal conditions. In the WSI hydrology indicator, there are 2 sets of variables: one relative to water quantity and the other to water quality. In the case of water quantity, the parameter is the per capita water availability per year.

Thus, 4 levels of per capita water availability were used: a) WA < 1,700 m^3/inhab.yr., b) 1,700 < WA < 3,400; c) 3,400 < WA < 5,100; and d) WA > 5,100 m^3/person.yr., corresponding to poor, medium, good, and excellent water availability, respectively. In the case of water quality, since biochemical oxygen demand (BOD_5, in mg/l) information is available or can be estimated in watersheds, and due to its high correlation with other important water quality data (dissolved oxygen, turbidity), it was selected as the quality parameter. Since it compares the latest water availability information with the long term average, the hydrologic Pressure parameters have the advantage of incorporating eventual climate variability/change impacts which, in certain conditions, could significantly affect water availability in the watersheds.

In Table **2**, the pressure parameter for the environment indicator is the environment pressure index-EPI, estimated by the averaged changes of the watershed agricultural area and urban population in a 5-year period, in percentages. The proportion of agricultural and urban areas in a given watershed is correlated with water quality (Hunsaker and Levine, 1995), and is easy to obtain from agricultural and population censuses. The environment pressure index-EPI used here is a modification of the Anthropic Pressure Index, developed by Sawyer (1997) [19]. The EPI, estimated for a 5 year period, is given by (Chaves & Alipaz, 2007):

$$EPI = (\%\ VAA + \%\ VUP)/2 \qquad (2)$$

Where VAA is the change of watershed agriculture area and VUP is the change of watershed urban population expressed in %. The environmental pressure index-EPI can be positive, negative, or zero. Positive values indicate higher pressures over the remaining natural vegetation of the watershed (environmental state). This state parameter is, in turn, highly correlated to the flora and fauna biodiversity, being an indicator of the watershed overall environmental integrity (Chaves & Alipaz, 2007).

The life parameters of the WSI are the watershed human development index-HDI (in the state column), and its evolution in a 5-year period (response). The pressure parameter is given by the % change of the HDI-Income, i.e., the change of the watershed income per capita in the 5-year season studied. Negative values of this parameter indicate that the population became poorer, and vice-versa, which would impact the watershed's resources and sustainability.

In the case of the policy parameters, the pressure is given by the change in the watershed HDI-Education indicator in the 5-year period studied. Since this indicator measures the population's educational level, positive values of HDI-Ed would indicate that the watershed population became more participative in WRM, which puts more pressure on the decision-makers.

The state policy parameter reflects the present watershed institutional capacity in WRM, given by the level of adequate legal and institutional framework, as well as participatory management. It is one of the few qualitative parameters of the index, varying from poor (0.25) to excellent (1.0).

The response parameter is estimated by evolution in the watershed WRM expenditures in the 5-year period studied. This reflects the pressure applied by watershed stakeholders on the decision-makers. The greater the spending in WRM, the higher the chances the watershed will meet its water-related objectives.

The WSI is calculated according to Eq. (1) after all indicators are obtained, and selecting a 5-year period for the pressure, state, and responses. The advantage of the WSI is that its framework provides for comparative measurements of the watershed sustainability in different time frames and scenarios, including climate variability.

The WSI was computed for other watersheds in Latin America, as shown in Table **2**. The results indicate that the WSI varies from 0.60 for the Chaguana watershed in Ecuador to 0.70 for the Gatun watershed in Panama. None of them is located in a semi-arid region.

Table **2**
WSI of some Latin American watersheds

Country	Watershed	Area (km2)	Population (inhab)	WSI	Level
Ecuador	Chaguana	320	10000	0.60	Intermediate
Uruguay	Tacuarembo	13000	12000	0.62	Intermediate
Brazil	Verdadeiro	2200	168000	0.64	Intermediate
Panama	Gatun			0.70	Intermediate

Applying the WSI to sub-basins of the Lake Poopo watershed

The WSI uses a Pressure-State-Response model with UNESCO's HELP platform. The PSR model is capable of examining cause-effect relationships, and looks at historical data, current information, and prospects for the future. The time-period selected for the computation of the

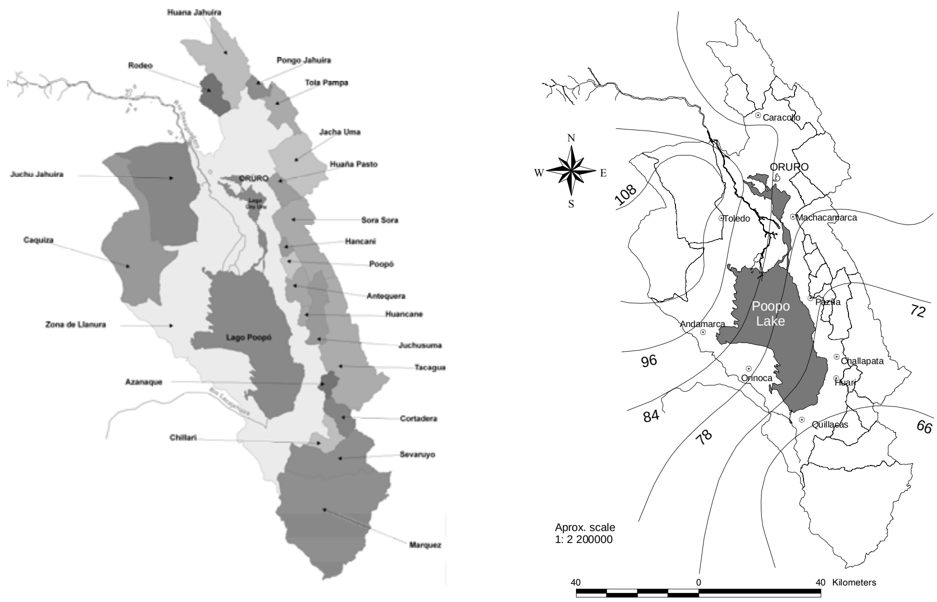

Fig. (3). Watershed division and spatial surface runoff availability (mm) in the Lake Poopo watershed (Calizaya *et al.*, 2008).

WSI in the sub-basins of the Lake Poopo watershed was the 5 years between 1997 and 2001. In total, 18 sub-basins were studied, and they are presented in Table **3** and Fig. (**3**). Since the WSI is formed by four indicators (H, E, L, and P), each of them will be presented separately.

Table **3**
Watershed population and characteristics

Watershed	Population inhab	Watershed			River		Drainage	
		area	length	slope	length	slope	order	density
		km^2	km	%	km	%	Nº	km/km^2
Marquez	7268	2577,4	96,9	0,93	94,5	0,95	5	0,5
Juchu Jahuira	8105	1739,7	82,3	1,46	80,7	1,49	2	0,4
Caquiza	8900	1380,6	102,3	0,52	101,3	0,54	3	0,4
Tacagua	24370	1373,5	57,9	1,07	56,1	1,11	5	0,6
Huana Jahuira	5638	861,8	66,5	1,05	65,4	1,07	4	0,3
Sevaruyo	3600	851,9	80	1,12	78,3	1,15	4	0,7
Sorasora	25600	734,6	54,4	1,43	52,4	1,49	4	0,8
Jacha Uma	4200	705,7	47,2	0,87	44,8	0,92	4	0,3
Juchusuma	1500	380,6	58,7	1,27	56,4	1,33	3	0,3
Tola Pampa (C.A.)	3367	314,1	39,5	1,77	36,3	1,93	4	0,3
Caracollo (Rodeo)	5500	258,8	30,9	0,97	29,5	1,02	4	0,3
Antequera	9600	226,5	23,8	2,98	22,7	3,13	3	0,3
Cortadera	380	222,6	25,6	3,13	23,9	3,35	3	0,4
Huaña Pasto (Sepul.)	3500	181,5	24,1	3,78	23,4	3,89	3	0,5
Pongo Jahuira	2028	120,7	17,6	2,62	15,4	2,98	3	0,3
Chillari	550	116,2	17,8	3,94	15,4	4,55	3	0,4
Poopo	7800	109,3	17,5	4,05	13,0	5,47	2	0,2
Urmiri	3600	98,2	20,2	3,46	16,3	4,28	3	0,4
Azanaque	10221	82,1	16,2	6,05	15,1	6,49	2	0,3
Hancani	600	57,1	10,6	6,88	6,7	10,86	2	0,2
Huancane	200	56,9	13,7	5,24	9,3	7,57	1	0,2
Huacani	350	22,7	5,3	10,84	4,2	13,57	2	0,3

RESULTS

Hydrology indicator

The hydrology indicator is the average of the watershed's quantity and quality parameters. In the case of the quantity sub-indicator, since the dominant water use in the watershed is surface water, the per capita water availability (state) is the long-term river mean flow rate, divided by each watershed population. For this, observed and modeled regional river discharge was used for extension to annual flow from 1960 to 2001 (Fig. **4**).

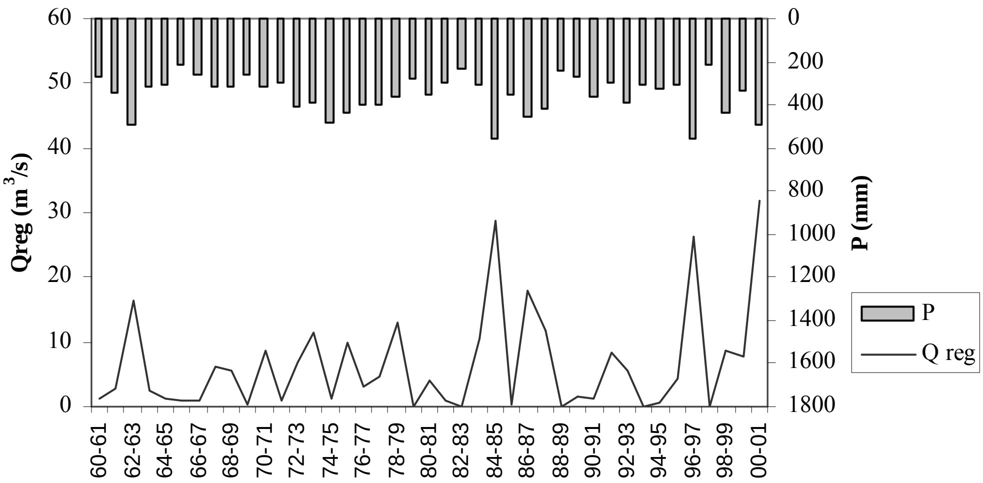

Fig. **(4).** Extending annual variation inflow modelling from regional rivers and annual precipitation of Lake Poopo watershed (Pillco and Bengtsson, 2006).

The mean monthly flow rates from each selected regional river watershed, with a long-term average, were divided by the total watershed population (National Census INE 2001 basis), so that the per-capita water availability (WA) could be computed for each watershed (Table **4**).

Table **4**
The per capita water availability in the watersheds of Lake Poopo watershed

N'	Watershed	A, km^2	Q, mm	Population inhab	Q, m^3/person year
1	Antequera (Urmiri)	226,5	61,8	9600	1459
2	Azanaque	82,1	65,7	10221	527
3	Caquiza	1380,6	122,2	8900	18949
4	Caracollo (Rodeo)	258,8	84,6	5500	3982
5	Tola Pampa (C.A.)	314,1	84,7	3367	7897
6	Huacani	22,7	65,6	350	4259
7	Huana Jahuira	861,8	84,6	5638	12937
8	Huancane	56,9	93,2	200	26524
9	Hancani	57,1	93,3	600	8872
10	Juchu Jahuira	1739,7	122,1	8105	26219
11	Juchusuma	380,6	95,3	1500	24195
12	Marquez	2577,4	21,5	7268	7624
13	Jacha Uma	705,7	73,0	4200	12266
14	Pongo jahuira	120,7	84,6	2028	5037
15	Poopo	109,3	104,8	7800	1470
16	Huaña Pasto (Sepul.)	181,5	105,0	3500	5446
17	Sevaruyo	851,9	25,9	3600	6129
18	Sorasora	734,6	136,8	25600	3925

According to Falkenmark and Widstrand (1992) [20], water stress occurs when water availability falls below 1.750 m^3/person per year. As Table **4** shows, only three of the sub-basins studied experience extreme water stress. This is mainly due to a low population density (inhab/km^2) in the region and the influence of the rain season, which lasts from December to March.

In the case of the quantity pressure parameter, the change in WA in the time-period studied was computed, with respect to the long-term average. In the case of response parameter, improvement in water use efficiency was estimated in each sub-basin, as shown in Table **4**. Consequently, the averaged pressure, state, and response parameters for hydrology-quantity were determined for each sub-basin.

In the case of the hydrology-quality sub-indicator, data are available only in 11 of the sub-basins in the analyzed time-period, mostly from the eastern region (Fig. **5**). Lack of information in the rest of the sub-basins made it necessary to assume BOD_5 values of the nearest areas with available data.

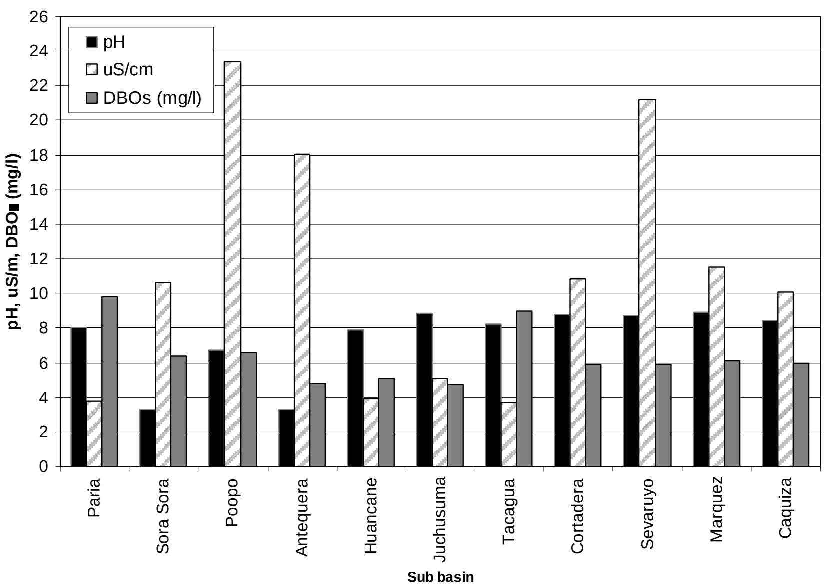

Fig. (5) Watershed quality parameters (mean values)

Environmental Indicator

As with the hydrology indicator, the environmental indicator of the sub basins was computed using its pressure, state, and response parameters. In the case of environmental pressure, the combined watershed increase in agricultural area and the growth of urban population in the season studied were computed by the environment pressure index-EPI (Eq. (2) based on the agricultural and population census (INE 2001).

For the environmental state, the original vegetation cover in 2001 of each sub-basin was determined from the land use and vegetation maps of the Lake Poopo watershed. The environmental response (evolution in protected or conserved areas), Lake Poopo was considered a RAMSAR (1971) [21] site. Therefore, all sub-basins have received a good evaluation in this aspect.

Life indicator

The pressure, state, and response of the life (L) indicator are based on the Human Development Index (HDI). The parameter Life Pressure in the sub-basins was estimated by the increase in the basin's per capita HDI-Income sub index, in the 5-year period (1997-2001), based on the Human Development Report (UNDP, 2002) [22].

The Life State sub-indicator was determined from the HDI for the last year of the period studied (2001). The basin HDI was the weighted average of HDI values of each municipality and its corresponding population of the basin. Life Response, i.e., the evolution of the expenditures in water resources management in the basin, was estimated for a 5-year season.

Policy indicator

The Policy Pressure parameter is based on the Education index (HDI-Ed). Chaves & Alipaz (2007) state that the improvements of HDI-Ed yield improved population awareness with respect to water resources management. For the five years studied, the HDI-Ed improved but still remains low (UNDP, 2006; 2002) [23]. This situation shows the policy pressure level (increase or decrease in the HDI-Ed in the 5-year period) that there was not a significant increase in the educational level, which would not help pressure for responses in WRM in the basin. Capacity building in WRM is needed as a tool in order to improve the awareness regarding the implementation of a water resources master plan.

As for the policy state parameter (basin institutional capacity), although there is a legal framework available (national-level and state-level water and environmental laws and regulations), little was accomplished in participatory water resources management in the period studied. The Lake Poopo watershed still lacks a committee or organization responsible for the water management. As a consequence, the watershed was ranked poor in this parameter. Regarding Policy Response, the evolution in the watershed expenditures in water resources management in the 5-year period was small.

Computing the WSI

The WSI is the global average of the four HELP indicators and the pressure, state and response columns. Therefore, Eq. (1) was applied to each of the 18 sub-basins. Table **5** below presents the levels, values, and the overall WSI (0.47) for the Antequera basin (9600 inhab. and A=226 km^2). Therefore, the WSI of the Antequera basin falls in a low level of watershed sustainability, but close to the intermediate level.

Table **5**

The WSI of Antequera watershed for a full year

Indicator	**Parameter**						**WSI**
	Pressure		**State**		**Response**		
	Level	Value	Level	Value	Level	Value	
Quantity	-4,5%	0.50	WA<WS	0.25	medium	0.50	-
Quality	5.0%	0.50	4.80	0.75	poor	0.25	-
Hidrology (H)	-	0.50	-	0.50	-	0.38	**0.46**
Environment (E)	10.5%	0.25	24%	0.50	5%	0.75	**0.50**
Life (L)	3.5%	0.75	0.52	0.25	4.0%	0.75	**0.58**
Policy (P)	-4.0%	0.50	poor	0.25	-10%	0.25	**0.33**
	Average	**0.50**	Average	**0.38**	Average	**0.53**	**0.47**

In Table **5**, the lowest score was the one related to State and the highest was related to Response. Regarding the combined PRS and HELP parameters, the poorest combinations in Table **5** are Environmental Pressure (0.25), Life State (0.25), Policy State (0.25), and Policy Response (0.25). Therefore, in order to improve the global sustainability in the watershed, stakeholders and decision-makers should work more effectively in the implementation water resources infrastructure, reducing the pressure over the remaining vegetation, improving the agricultural income, enhancing the WRM institutional capacity, and improving the expenditures in the water resources planning and management.

Table **6** presents the results of WSI computed for 18 investigated sub-basins of Lake Poopo, including the three scenarios analyzed.

Table **6**
Summary of WSI for 18 sub-basins of Lake Poopo watershed

WATERSHED	Population	Area	INDICATOR				WSI		
			H	E	L	P	Full year	Dry period	With storage
	(inhab)	(km^2)	Hydrology	Environment	Life	Policy			
Marquez	7268	2577	0.58	0.33	0.42	0.58	**0.48**	**0.38**	**0.58**
Juchujahuira	8105	1740	0.46	0.58	0.50	0.50	**0.51**	**0.40**	**0.65**
Caquiza	8900	1381	0.46	0.42	0.75	0.50	**0.53**	**0.38**	**0.67**
Huana Jahuira	5638	862	0.46	0.50	0.58	0.33	**0.44**	**0.35**	**0.54**
Sevaruyo	3600	852	0.42	0.42	0.75	0.33	**0.48**	**0.36**	**0.63**
Sora Sora	25600	735	0.33	0.33	0.58	0.33	**0.40**	**0.31**	**0.56**
Jacha Uma (Paria)	4200	706	0.38	0.33	0.67	0.50	**0.47**	**0.38**	**0.63**
Juchusuma	1500	381	0.42	0.33	0.50	0.42	**0.42**	**0.35**	**0.56**
Tola Pampa	3367	314	0.50	0.58	0.50	0.50	**0.52**	**0.40**	**0.65**
Rodeo (Caracollo)	5500	259	0.50	0.42	0.50	0.42	**0.46**	**0.40**	**0.58**
Antequera	9600	226	0.46	0.50	0.58	0.33	**0.47**	**0.33**	**0.60**
Huaña Pasto	3500	182	0.46	0.42	0.50	0.33	**0.43**	**0.35**	**0.56**
Pongo Jahuira	2028	121	0.42	0.42	0.67	0.33	**0.46**	**0.34**	**0.60**
Poopo	7800	109	0.46	0.42	0.50	0.42	**0.45**	**0.35**	**0.58**
Azanaque	10221	82	0.38	0.33	0.58	0.33	**0.41**	**0.36**	**0.56**
Hancani	600	57	0.58	0.33	0.42	0.42	**0.44**	**0.33**	**0.54**
Huancane	200	57	0.50	0.25	0.58	0.50	**0.47**	**0.35**	**0.60**
Huacani	350	23	0.58	0.50	0.25	0.42	**0.46**	**0.33**	**0.58**
			0.46	**0.41**	**0.55**	**0.42**	**0.46**	**0.36**	**0.59**

According to Table **6**, about 80% of the 18 sub-basins have low watershed sustainability, when the period analyzed is the whole year. The percentage increases if the dry season is considered, and is significantly reduced if artificial water storage is implemented. In average, the bottlenecks for the 18 watersheds are environment (0.41), policy (0.42), and hydrology (0.46).

Figure **6** shows the classification of WSI for each sub-basin, in the 3 scenarios studied. If water storage is implemented in the headwaters of the watersheds, all of them will experience a significant improvement in watershed sustainability, moving from the low to the intermediate level.

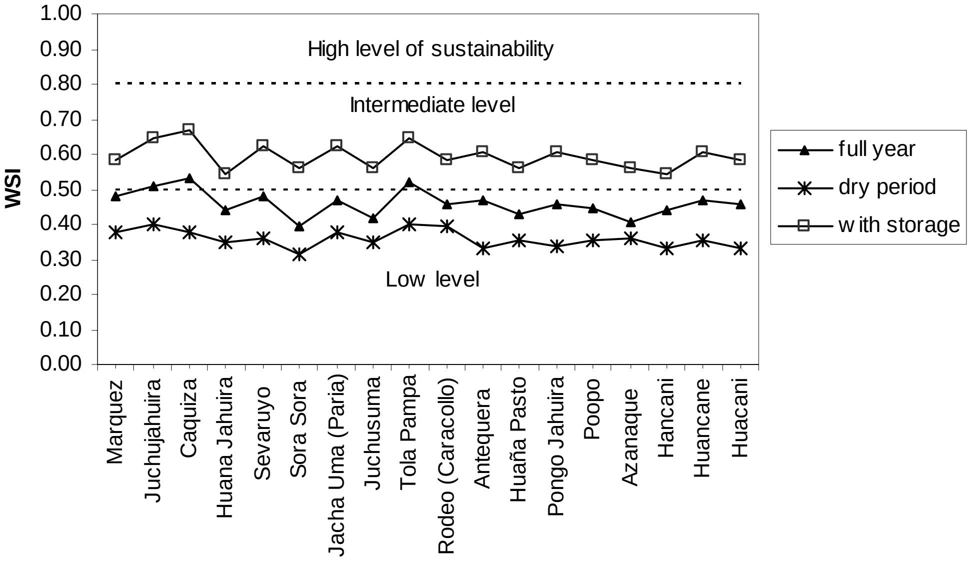

Fig. (6). Variation of the calculated WSI for each watershed within the Lake Poopo basin.

CONCLUSION

The watershed sustainability index (WSI) is an important tool for IWRM and it helps to identify the level of sustainability of a certain watersheds, as well as the actions needed to improve it. The WSI was applied to 18 sub-basins within the Lake Poopo watershed in Bolivia, in the time period between 1997 and 2001. The average WSI for the 18 sub-basins was 0.46 and 0.36, for the full year and for the dry season, respectively. In the water storage scenario, the WSI was 0.59, indicating that storage dams in the upstream areas of the watershed would significantly improve watershed sustainability.

The central aspects needing attention from decision-makers in the watershed are those related to environmental pressure, policy state and hydrology response, which where the bottlenecks responsible for reducing the overall WSI.

The lowest obtained WSI of the Lake Poopo watersheds require strong policy measures in order to improve the level of awareness regarding preservation, conservation and adequate exploitation of the water resources.

ACKNOWLDEGEMENTS

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PAPER 4

Multi-Criteria Decision Analysis (MCDA) for Integrated Water Resources Management (IWRM) in the Lake Poopo basin, Bolivia

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Multi-Criteria Decision Analysis (MCDA) for Integrated Water Resources Management (IWRM) in the Lake Poopo basin, Bolivia

Abstract

Integrated Water Resources Management (IWRM) is a relatively new approach in Bolivia. However, it is now generally accepted that this approach needs to be established in order to find sustainable solutions for development and is actively promoted by the Water Ministry, especially in environmentally fragile regions, such as the Lake Poopo basin.

The Lake Poopo basin is one of the poorest regions in the Bolivian Altiplano. It is confronted with severe water scarcity during the dry season, leading to low water quality, a high water-poverty index and low values of the watershed sustainability index. Furthermore, salinization and environmental degradation of soil and water are forcing people to migrate to urban areas. These are some of the factors underlying an ever-increasing complexity in integrated water resources management in the region.

This paper proposes and develops a Multi-Criteria Decision Analysis (MCDA) in the Lake Poopo basin, based on economic, social and environmental criteria in an uncertain decision environment in order to support stakeholders in managing their water resources. Saaty's analytical hierarchy process (AHP) theory is applied here to solve the MCDA and to identify the alternatives using the highest expected utility value. The paper identifies the best solutions for existing conflicts, while promoting interaction with stakeholders and Instruments in order to reach a sustainable strategy for water resources management in this water-scarce region.

Key words: *Integrated Water Resources Management, Multi Criteria Decision Analysis, sustainability, water resources, decision making process.*

1. Introduction

The Integrated Water Resources Management (IWRM) paradigm has been recognized worldwide as the only currently feasible way to ensure a sustainable perspective in planning and managing water resources systems (Castelleti and Soncini 2006). It is the main reference for all water related activities in third world countries. Sufficient water supply might be considered to be one of the most important factors for improving quality of life in these countries. "As pointed out by the United Nations (UN), one third of the Millennium Development Goals (MDGs) depend on water." (Phumpiu and Gustafsson 2009).

However, real-world attempts of implementing IWRM often fail due to the lack of a systematic approach and the inadequacy of adopted tools and techniques to address the intrinsically complex nature of water systems. According to one of the principles of the IWRM, the equitable allocation of water resources implies an improved decision-making process, which is technically and scientifically informed and can facilitate the resolution of conflicts over contentious issues, balancing social, environmental and economic consideration. Because for "an integrated water resources management (IWRM), as demanded for instance by the European Water Framework Directive (EU-WFD 2000), the ecological, social, and economic functions of the water cycle have to be taken into consideration" (Koch and Grunewald 2008).

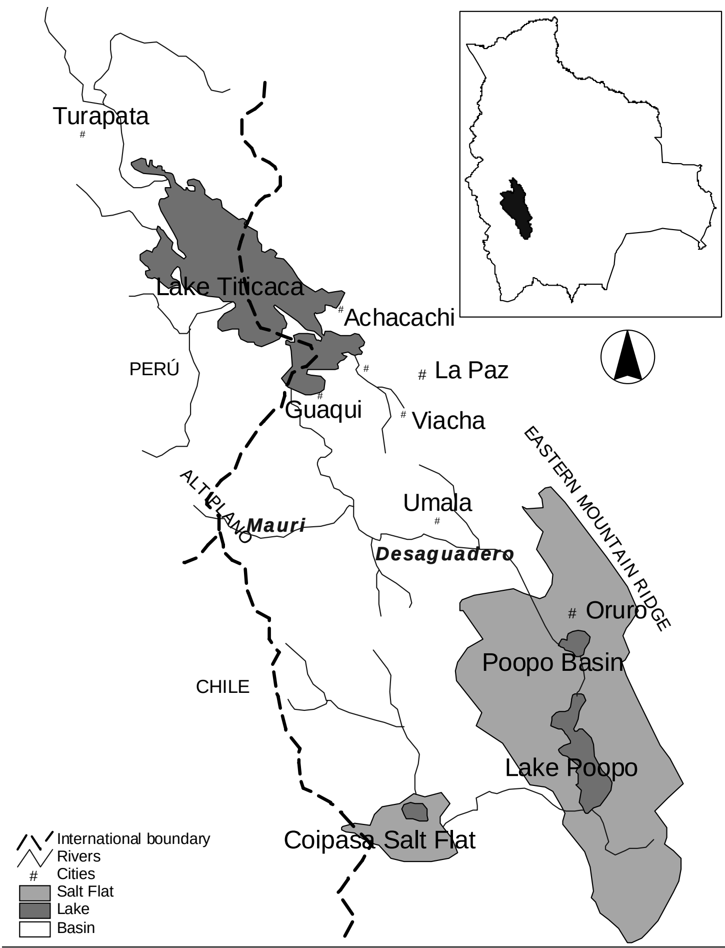


Fig. 1 The TDPS system and Lake Poopo basin

1.1 IWRM in the Lake Poopo basin

In the rural area of Bolivia, water resources constitute a fragile element of the landscape. In general, there is a fresh water deficit spanning more than half of the country (Van Damme 2002). The Lake Poopo basin in the southern Bolivian Altiplano does not escape this reality. The basin is confronted with severe water scarcity during the dry season, which leads to low water quality combined with extreme poverty, a low water poverty index and low values of the watershed sustainability index. Furthermore, salinization and environmental degradation of soil and water are forcing people to migrate to faraway urban areas. The water bodies and regional rivers in the basin have, for a very long time, been polluted both naturally and by heavy metals from mining activity. For example, for early 2000, 30000 barrels of crude petroleum were spilled into the main stream of the Desaguadero River contaminating hundreds of acres of farmlands. These are some of the factors underlying an ever-increasing complexity in integrated water resources management in the region.

The rural economy of the Lake Poopo basin strongly depends on the availability of water resources in time and space, and for this reason it is extremely urgent to apply integrated water resources planning and management based on active participation of stakeholders (native population, farmers, municipalities, and small water supply system operators).

The lack of water and water rights in the Lake Poopo basin lead to water and land conflicts. Due to increasing water demand, different sectors compete for access to fresh water resources. The Simultaneous water use by different sectors is not compatible and can generate conflicts (Crespo 1999). The majority of conflicts in the basin may be delineated from the different vision and conception of the use of fresh water. In the north-eastern parts of the basin, for example, there are serious water and land conflicts between mining and agriculture sectors and in some cases with the domestic users.

Confirming the World Water Vision report, we are actually facing a veritable water crisis. "But the crisis is not about having too little water to satisfy our needs. It is a crisis of managing water so badly that billions of people and environment suffer badly" (World Water Vision Report 2000). In this respect, education at all levels has an important role to play. In general, it is also important to promote the guiding principles for water resources management and best practices. According to the Dublin Statement on Water and Sustainable Development, 1992, these include the followings guiding principles:

1) Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment
2) Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels
3) Women play a central part in the provision, management and safeguarding of water
4) Water has an economic value in all its competing uses and should be recognized as an economic good

The second item above is relevant to integrated water resources management; as it regards water stakeholders and their involvement in the process. The last principle is also very important, as it involves the water vision according to the local native culture. However, this principle of water as an "economic" good may not be in line with all cultures and may be, therefore, a source of conflict. For South America, reference can be made to the Andean Water Vision, where indigenous people understand water as a sacred and in some sense "living" entity (World Water Council 2006). Often, in western cultures, water is viewed as a purely material substance. Consequently, there are contrasting understandings of what water actually represents, creating a source of conflict with respect to water rights, water use, and water management.

In general, the rural population of Bolivia has an integrative view of the use of water, representing a source of life in coherence with the general Andean water vision. People do not exclude water from the remaining natural surrounding. They reject the idea that water can be managed through a mercantilist point of view.

The major problems mentioned above are further aggravated by a general lack of water management awareness by the population and authorities and also a lack of clearly established water rights, generating sector conflicts. To improve the situation, there is a need for the establishment of water resources planning in accordance with environmental sustainability objectives.

In view of the above, efforts should be devoted to increasing the reliability of existing water resources availability and to utilizing these in a more efficient way. With consideration to this point of view, the objective of this paper is to establish a model of multi-criteria decision making and participative interaction by stakeholders towards developing a strategy for sustainable water resources management with the sustainability of the basin's ecosystem in focus.

2. Causal Network (a water-conflict source)

"Water resources management has been widely discussed in the recent years as water scarcity has become a prominent problem with increasing populations suffering from water scarcity and water quality deterioration." (Kampragou et al. 2007). Water is not only important to human beings. Water provides essential living conditions to many different flora and fauna in the basin.

The water-conflict sources related to water resources management issues have been grouped into 5 main categories: extreme weather events, socio-economic situation, deficient water regulations, environmental degradation and the lack of sufficiently organized stakeholder involvement.

One example of conflict deriving from deficient water regulations and environmental degradation is the existing one between the mining and farming sectors in the north-east of the basin. Generally, the mining sector receives more political support in the definition of water rights. This illustrative example shows that most water conflicts between stakeholders are based upon water-using rights. However, this is only one example of why adequate water regulations are strongly necessary.

Figure 2 shows the causal network of water-related processes and problems (Rontentalp et al. 2005), adapted to the conditions of Lake Poopo basin. The causal network was structured on an environmental platform with 2 sub platforms: (a) geography and hydrology and (b) socio-economic. The causal network clearly shows the inter-relation between parameters and indicators and the relevant geographic region with its specific hydrologic, socio-economic and environmental conditions. As a consequence, floods, drought, and salinization are the main impacts on natural resources, while socio-economic behavior in particular aggravates poverty and the fragile environmental situation.

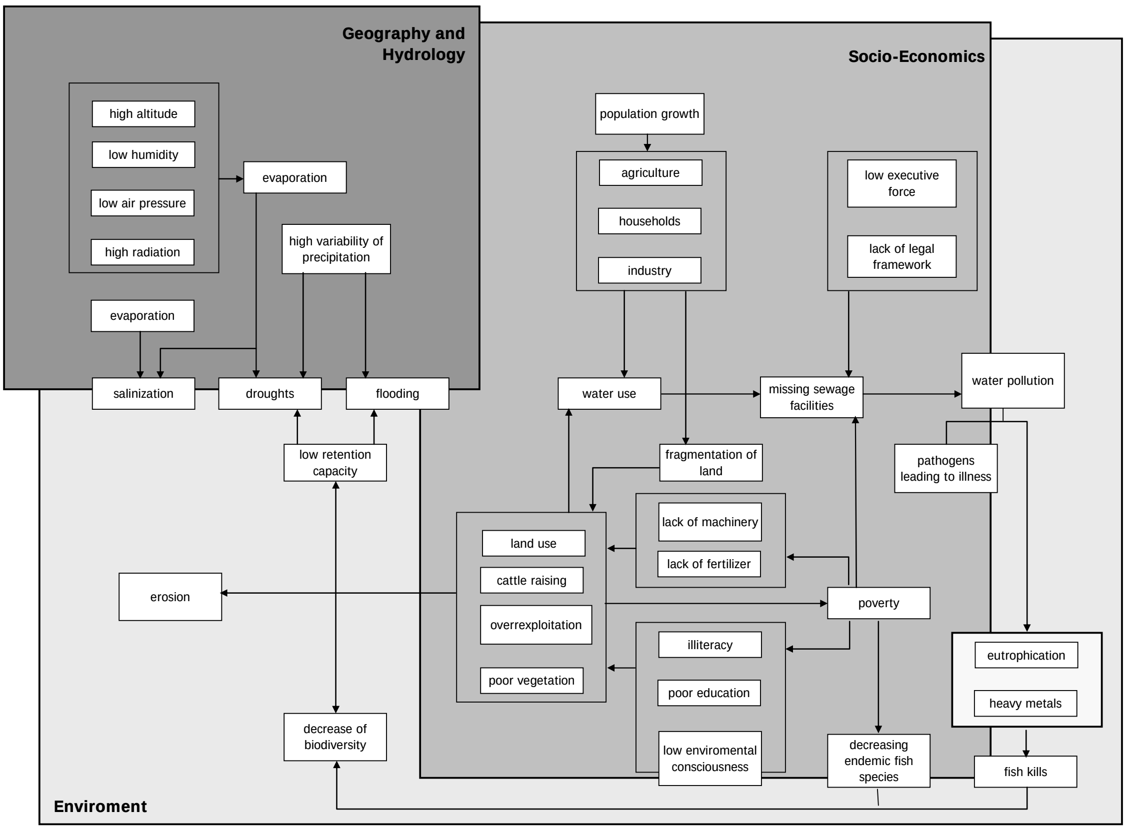


Fig. 2 Causal network of water related process and problems (Rontentalp et al. 2005), adapted by authors to the Lake Poopo basin

Land property and fragmentation in the region contribute to the existence of water conflicts. Currently, agriculture and livestock breeding are the main sources of income for the rural population in the Lake Poopo region, and are mainly carried out on small-scale and dispersed parcels of land. The main areas of cultivation are located on flat land and soft relief hills bordering the lakes. After the land reformation of 1953, the rural property was fragmented to a large extent, and land parcels were sometimes limited to a few square meters. In such conditions only small-scale subsistence agriculture is possible. In the basin, only one small community with international cooperation can afford the newer water saving irrigation technique (spray and dripping) and very few farmers can also afford modern land cultivation equipment.

Pollution of water resources is another of the most important factors aggravating water-related conflicts. Over a long period of time, rivers and lakes have been contaminated by heavy metals from the mining companies. On the other hand, spills of crude petroleum infiltrating the Desaguadero River have practically exterminated the native species of fish existing in Lake Poopo, which had devastating social, economic and cultural consequences. Fishing was the way of survival for the native culture of Uru-Muratos, a tribe that has since had to resort to leaving their land and working for local farmers to secure their livelihood. Negative impact of pollution on the local environment will be felt for many years to come (Montoya and Mendieta 2006).

3. The Decision-making process in Integrated Water Resources Management (IWRM)

Integrated Water Resources Management is defined as: "… a process to promote the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Dublin Principles, 1992). The IWRM should be applied at the catchment level. It can be strengthened through the integration of environmental impact assessment, water resources modeling, and land use planning. It should also be understood that the watershed approach implies that water should be managed alongside the management of co-dependent natural resources: water, soil, air, forest, and all other biota.

Water resources management involves various stakeholders with multiple objectives. Therefore, all individual, groups or community-based organizations should be included in related decision-making processes. The question is how to support stakeholders in managing their water demands in connection with increasing competition, interdependency and land fragmentation in order to guarantee the sustainability of water resources management (Feng 2001). According to the FAO 2006, "supporting stakeholders in managing their water resources means supporting stakeholders to make choices and to reach a common understanding on the necessary arrangements for sharing and equitable allocation of water related goods and services". Evaluating different strategies in water management (water valuation) is implicit to this process. Water valuation means expressing the value of water related goods and services in order to inform sharing and allocation decisions (FAO, 2006).

A decision making process, according to Feas et al. (2004), implies the following steps:

a) Identification of alternatives that can solve the problem;
b) Selection of the criteria on the basis of which alternatives or Instruments are going to be compared;
c) Estimation of the priorities of the alternatives related to the criteria;
d) Selection of the information derived from performances;
e) Relative importance of criteria must be clear in order to be able to select alternative(s).

These steps are comparable with other models of decision processes, like Davis and Cosenza's (1993) model, where each decision (and evaluation) process starts with problem recognition, followed by information search, problem analysis, alternative evaluation and finally the decision, i.e. the phase of implementation.

As described above, the decision makers normally disregard the perceptions of the problem by the stakeholders due to the complexity of related water issues. For this reason, the participation of the Lake Poopo basin stakeholder's at this level has been helpful in the identification of the main relevant criteria and their societal targets in the decision-making process. However, the stakeholders also have problems identifying these criteria and assessing priorities for indicators.

Supporting the stakeholders in this process has been successfully achieved through the conduction of workshops and seminars in the rural communities. In this context, stakeholders are all individuals, communities, irrigation organizations, local and municipality authorities, etc., that had have interest (stake) in the use or the management of water resources (households, farmers, companies, and others). This path of analyzing the problem in the Lake Poopo basin helped to attain a proper structure of the problem. This is a pre-condition of good decision making (Greeno 1976).

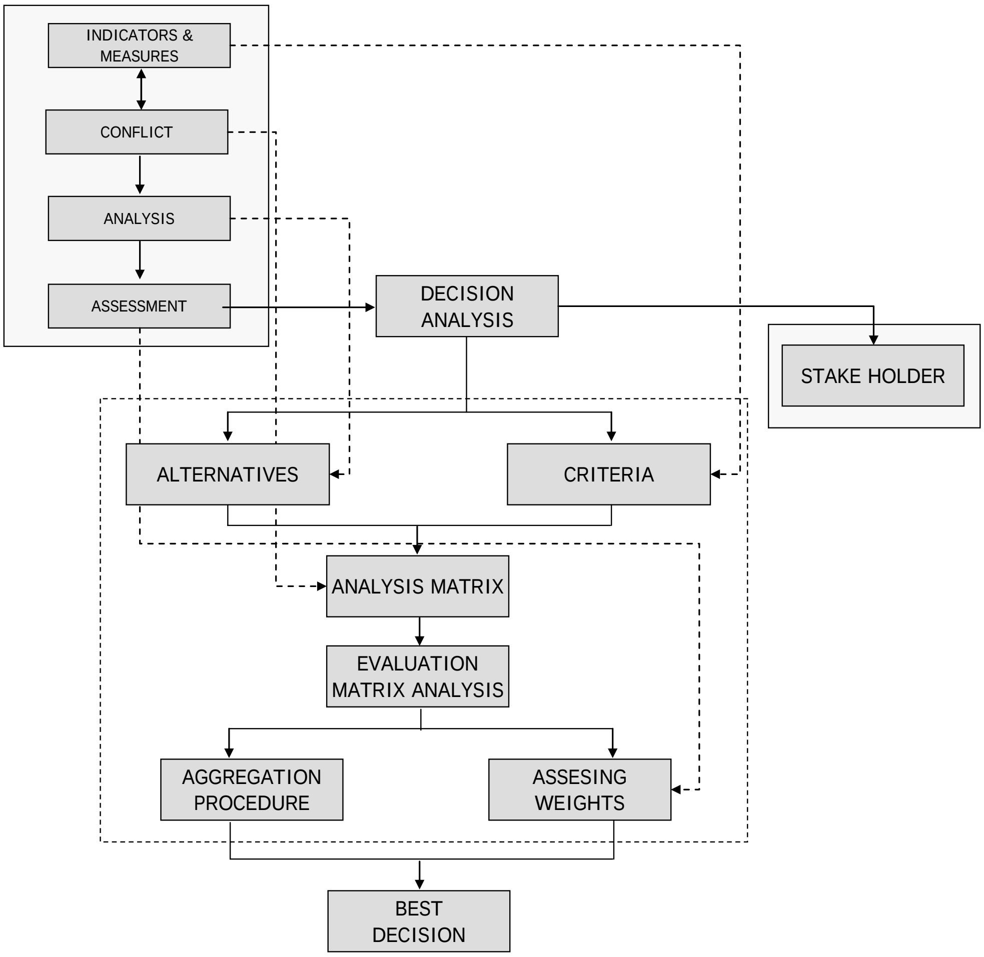


Fig. 3 Decision making process for the IWRM and sustainable development (Feas et al. 2004; modified by the authors)

The lack of water-management awareness is the principal reason for carrying out an MCDA based on the active participation of the stakeholders in order to reach an IWRM strategy in the Lake Poopo basin.

4. Structure of the decision hierarchy of the lake Poopo water management

According to von Winterfeldt (1980), structuring a decision problem may be described as "... an imaginative and creative process of translating an initially ill-defined problem into a set of well defined elements, relations, and operations". According to Feas et al. (2004) IWRM is usually characterized by the involvement of *numerous decision-makers* operating at different levels and a *large number of stakeholders* with conflicting preferences and different value judgments. This makes the development of implementation strategies and decision making a very complex issue.

The structure of the suggested model for MCDA has been set up on the basis of three principal criteria: economic, social, and environmental issues and inter-relation between them. This involved the identification and selection of 10 conflicts, together with the identification and selection of 7 Instruments to confront and solve the conflicts, and a hierarchy of possible implementing Actors of the preference Instruments of the IWRM strategy in the Lake Poopo basin, as shown in Figure 4. The Analytical Hierarchy Process (using pairwise comparisons to get subjective judgments where objective data is not available; Saaty, 1980; 1985; 1990) has been selected as the approximation method for calculating the preferences for the proposed MCDA model (comparable to the evaluation process conducted by Zhang 2009). However, we have to consider that Saaty's is only one possible way of estimating priorities out of pairwise comparison matrixes (even though it seems to be one of the most common). "… several methods have adopted an approximation perspective; i.e., they try to search a reciprocal and consistent matrix, W, that differs from M 'as little as possible', and then obtaining weights from W . Saaty's eigenvector method may be considered one of them." (González-Pachón and Romero 2004). A review of multi criteria decision methods for IWRM purposes is given by Hajkowicz and Collins (2007).

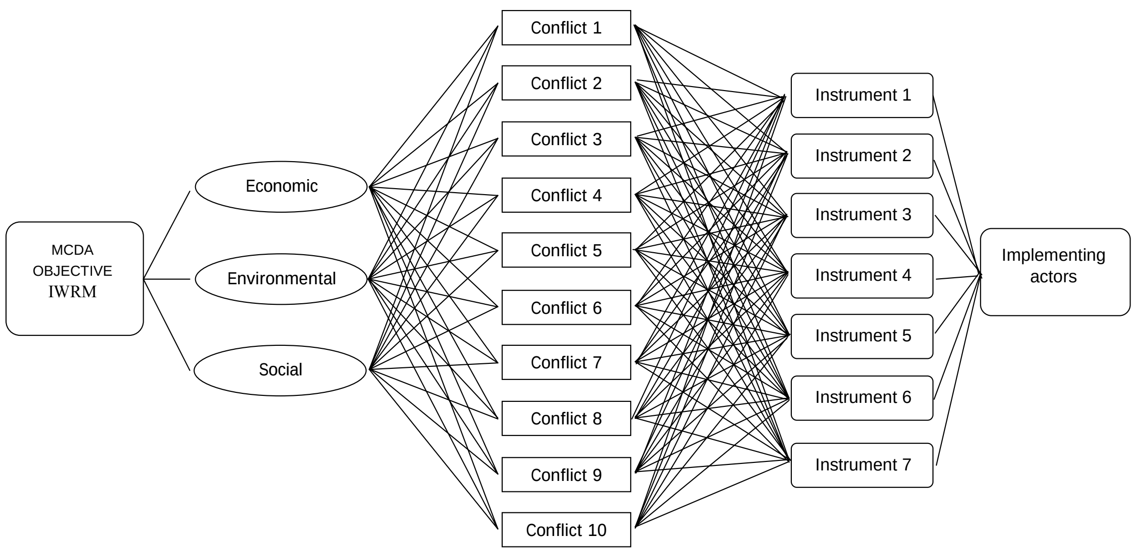


Fig. 4 Proposed structure of multi criteria analysis model for Lake Poopo Basin. A first approach for MCDA

The model (Fig. 4) was designed through various stages and facilitated by workshops with the active participation of stakeholders or groups of key players. The authors have played an impartial role as facilitators in this process. This has involved guiding the stakeholder groups through various stages of the MCDA. The stakeholders were chosen to represent all key perspectives of water interests throughout the basin. The three workshops carried out in the towns of Challapata, Quillacas and El Choro were lively and creative sessions with much exchange and feedback of information between stakeholders whose areas of expertise differ from the traditional to the innovative. Three factors account for this performance: impartial facilitation, a structured modeling process, and use of information technology to provide on the spot modeling and display the results and scenarios.

4.1 Identifying Criteria

For the IWRM strategy in the Lake Poopo basin, three basic criteria were identified: economic, environmental and social. These criteria represent the summarized variables positively or negatively influencing water conditions (in the Lake Poopo basin, but also in general). They relate to the MDGs defined by the UN to be reached by 2015, aiming for a better world in the 21st century. "The MDGs relate to the water sector in regards to poverty reduction, environmental sustainability and development." (Phumpiu and Gustafsson 2009).

Table 1 Criteria

Abbreviation	Description
C1	Environmental: to implement the administration instruments that generate minimal environmental impact in the basin
C2	Social: to implement the administration instruments that generate less social conflict in the basin
C3	Economic: Implementation of administrative instruments that generate an adequate economic well-being in the basin

Other approaches could also be found, which may be considered to be specific concepts that fit inside the three big categories (environmental, economic, and social). Examples of these are: Reduction of poverty, of water poverty and of pressure on natural resources; more water availability for human consumption and for irrigation and semi-industrial uses; promotion for conservation of biodiversity and for diminishing affectation on biodiversity; etc.

4.2 Identifying the Conflicts in the basin

Many authors have been dealing with water conflicts in water resources management (e.g., Babel et al. 2005; McNulty 1986; Just and Netanyahu 1998; Opricovic 2009). As shown in the conflict framework (Fig. 2) the most important conflicts in the basin were identified and discussed by the stakeholders. The identified conflicts include the following:

Table 2 Conflicts

Abbreviation	Description
Co1	Extreme weather events
Co2	Socio-economic situation
Co3	Cultural aspects
Co4	Stakeholder involvement
Co5	Deficient regulation of the water resources
Co6	Lack of basic information
Co7	Water law and water rights
Co8	Land fragmentation
Co9	Migration
Co10	Pollution

4.3 Identifying the Instruments (alternatives)

Seven Instruments were selected (i.e. alternatives within the MCDA which influence the Conflicts) and were intensively discussed by stakeholders in their communities. Consequently, the variables were completely validated by them.

Table 3 Instruments

Abbreviation	Description	
I1	Monitoring hydro-meteorological parameters	Participatory/multidisciplinary data collection, analysis and process of database
I2	Base line with stakeholder involvement	Integral diagnostic with active participation of the stakeholders of basin
I3	Implementation of infrastructure	Identification/selection of sub-project (dams, rainwater harvesting, irrigation, etc.)
I4	Implementation of legal statements	Enabling environment (policies, legislation, regulation)
I5	Formation of WMLO	Formation of Water Management Local Organization (WMLO)
I6	Education and training programs	Education, training and diffusion programs in the whole basin on Water Resources Management
I7	Environment audit	Environment audit, especially of mining activities

4.4 Identifying implementing Actors of IWRM strategy

The actors listed below are the identified organizations implementing the IWRM strategy. They are also key players participating in the design of the MCDA process and involved in evaluating the whole decision hierarchy. Furthermore, these actors have been identified because one main purpose of this study is to reveal those actors who are more or less able to effectively implement the Instruments mentioned above.

Table 4 Actors

Abbreviation	Description
A1	ALT (Bi-National Authority of Lake Titicaca)
A2	Bolivian Operating Unit (ALT)
A3	Prefecture of Oruro (Regional Government)
A4	Regional municipalities
A5	Water management local organizations
A6	Recently conformed basin coordination for defense of the BIOTA
A7	Institutions (NGO's, University, etc.)
A8	Mining companies

5. Decision matrixes for the Analytical Hierarchy Process (AHP)

To carry out the MCDA for the Lake Poopo basin, four basic matrixes were developed. The matrixes were used to determine the importance of the Instruments as possible solutions for the conflicts and to evaluate the possible contribution of the actors. As mentioned above, we used pairwise comparisons in order to estimate the relevant priorities of all elements within the hierarchy, since the "Pairwise Comparison (PC) method is a powerful inference tool that permits the building of a global rank from local ones by using matricial algebra" (González-Pachón and Romero 2004; comp. also Wei 1952). The basic matrixes comprise all necessary pairwise comparisons at each level of the hierarchy:

1) Matrix M_1 – Criteria vs. Criteria. Prospective result: priorities for the selection of Criteria over Criteria for the decision-maker as a function of the relative importance of one criterion over another criterion.
2) Matrixes $M_{2.1}$ to $M_{2.3}$ – Conflicts vs. Conflicts with respect to Criteria. Prospective result: priorities for the selection of conflicts as a function of the relative importance of each conflict over the criteria.
3) Matrixes $M_{3.1}$ to $M_{3.10}$ – Instruments vs. Instruments with respect to Conflicts. Prospective result: priorities for the selection of Instruments as a function of the relative importance of each Instrument over the Conflicts. Expected result: ranking of priority for the selection of Instruments, based on how each Instrument helps to solve each Conflict, and of what element affects each Conflict to maximize or to diminish the general Criteria (Economic, Environmental and Social)
4) Matrixes $M_{4.1}$ and $M_{4.7}$ – Actors vs. Actors implementing Instruments. Prospective result: ranking of priority for the selection of Instruments as a function of the relative importance of each Instrument over the Implementing Actors.

6. Construction and weighting (judgment) of performance matrixes for MCDA

The idea of each MCDA is to construct scales representing preferences for the consequences, to weight the scales for their relative importance, and then to calculate weighted averages across the preference scales (including all relevant criteria within the evaluation process). The setting of weights brings to the fore the question of whose preferences counts the most. The process of deriving weights is thus fundamental to the effectiveness of an MCDA. Pursuant to this, matrixes and weighting were established according to the results of the workshops with the stakeholders. As stated by Dodgson et al. (2000), the criteria weights reflect both the range of option differences, and how much that difference matters. Any numbers can be used for the weights, as long as their ratios consistently represent the valuation of the differences in preferences between the top and bottom scores of the scales being weighted. For this MCDA valuation, Saaty's rating scale was selected (Saaty, 1980; 1985; 1990); ranging from 1 (if two elements are equally important) to 9 (if one element is absolutely dominating another element) including the relevant reversal values down to 1/9.

6.1 Matrix M_1 – Criteria vs. Criteria

The set of Criteria $A_1 = \{C1, C2, C3\}$ was evaluated by the stakeholders using pairwise comparisons (C1 Environmental Criteria, C2 Social Criteria, C3 Economic Criteria). The corresponding matrix M_1 was elaborated according to the preferences for the consequences; thus, the stakeholders have played a central role in the scoring process. The following matrix, M_1, represents the pairwise weighting concerning the three criteria. Of course, only the upper diagonal elements were assessed directly. As we can easily see from these comparisons, the weightings are not completely consistent. We will discuss this point later.

$$M_1 = \begin{pmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 9 \\ 1/7 & 1/9 & 1 \end{pmatrix}$$

The relative weights for the criteria can be approximated on the basis of this matrix. We used the eigenvector method proposed by Saaty (1980; 1985; 1990) to estimate the priorities.

6.2 Matrixes $M_{2.1}$ to $M_{2.3}$ – Conflicts vs. Conflicts with respect to Criteria

The matrixes of 10 selected conflicts (set $A_2 = \{Co1, Co2, \ldots Co10\}$) have been evaluated with respect to the three criteria, in order to determine the importance of each conflict with respect to the environmental, social, and economic criteria. Below we indicate only $M_{2.1}$, i.e. the pairwise comparisons of all conflicts with respect to *environmental* criteria; matrixes $M_{2.2}$ and $M_{2.3}$ provide a comparable picture for social and economic criteria. From these matrixes we may estimate the relevance of each conflict.

$$M_{2.1} = \begin{pmatrix} 1 & 5 & 5 & 5 & 3 & 3 & 5 & 5 & 5 & 1 \\ 1/5 & 1 & 1/3 & 3 & 3 & 3 & 1/3 & 1 & 5 & 1/5 \\ 1/5 & 3 & 1 & 3 & 5 & 1 & 3 & 5 & 5 & 1 \\ 1/5 & 1/3 & 1/3 & 1 & 5 & 3 & 5 & 9 & 7 & 1 \\ 1/3 & 1/3 & 1/5 & 1/5 & 1 & 1 & 1 & 1/3 & 1/3 & 1 \\ 1/3 & 1/3 & 1 & 1/3 & 1 & 1 & 3 & 1 & 1/5 & 1 \\ 1/5 & 3 & 1/3 & 1/5 & 1 & 1/3 & 1 & 1 & 3 & 1/5 \\ 1/5 & 1 & 1/5 & 1/9 & 3 & 1 & 1 & 1 & 5 & 1/5 \\ 1/5 & 1/5 & 1/5 & 1/7 & 3 & 5 & 1/3 & 1/5 & 1 & 1/5 \\ 1 & 5 & 1 & 1 & 1 & 1 & 5 & 5 & 5 & 1 \end{pmatrix}$$

6.3 Matrixes $M_{3.1}$ to $M_{3.10}$ Instrument vs. Instruments with respect to Conflicts

The matrixes $M_{3.1}$ to $M_{3.10}$ represent the pairwise comparisons of the 7 selected Instruments (set $A_3 = \{I1, I2, \ldots I7\}$) under the umbrella of each of the 10 conflicts in order to determine the importance of each Instrument with respect to the conflicts. The estimation of priorities can then show the ability of each Instrument to solve a relevant conflict. The following matrix, $M_{3.1,}$ contains the pairwise comparisons of the Instruments with respect to the conflict "Extreme weather events" (Co1). Here too, we refrain from displaying the other matrixes $M_{3.2}$ to $M_{3.10}$.

$$M_{3.1} = \begin{pmatrix} 1 & 7 & 7 & 9 & 5 & 3 & 5 \\ 1/7 & 1 & 1/5 & 5 & 3 & 3 & 1 \\ 1/7 & 5 & 1 & 7 & 1 & 5 & 3 \\ 1/9 & 1/5 & 1/7 & 1 & 1/5 & 1/5 & 3 \\ 1/5 & 1/3 & 1 & 5 & 1 & 5 & 3 \\ 1/3 & 1/3 & 1/5 & 5 & 1/5 & 1 & 5 \\ 1/5 & 1 & 1/3 & 1/3 & 1/3 & 1/5 & 1 \end{pmatrix}$$

7. Evaluation of the relative importance of the elements of the decision hierarchy

According to the subjective evaluations of the stakeholders, there are 3 principal Instruments which are appropriate for creating the basis for the IWRM of the Lake Poopo basin (global result of the MCDA). We estimated the relevant priorities *w* – as mentioned above – by applying the Analytical Hierarchy Process and Saaty's eigenvector method to approximate the relevant weights (Saaty, 1980). At the first level of the decision hierarchy, the stakeholders consider mainly environmental criteria ($w_{Env} = 0.62$) and (with less intensity) social criteria ($w_{Soc} = 0.33$) to be crucial for the implementation of IWRM principles. Economic variables seem to be of much less significance ($w_{Eco} = 0.06$).

Table 5 Absolute priorities of MCDA (Criteria, Conflicts, and Instruments)

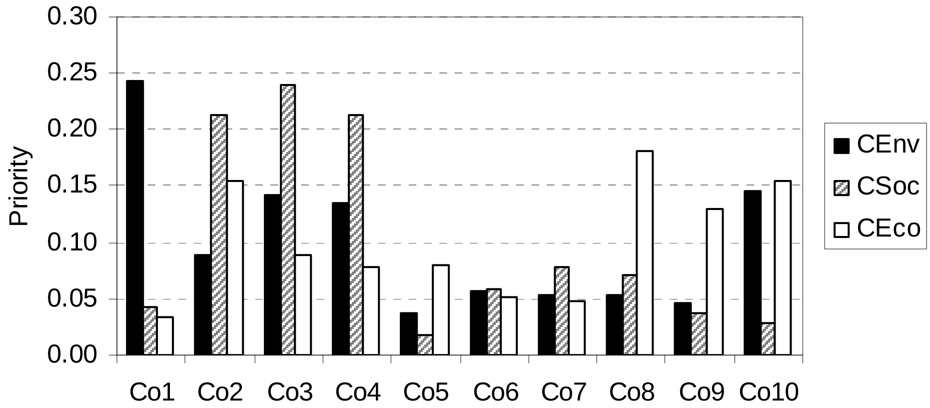
level 1 & 2			level 3						
w_{Ii}			w_{I1}	w_{I2}	w_{I3}	w_{I4}	w_{I5}	w_{I6}	w_{I7}
$w_{C1\ (Env)}$	0.620								
w_{Co1}		0.243	0.429	0.113	0.185	0.033	0.122	0.076	0.041
w_{Co2}		0.089	0.054	0.106	0.414	0.074	0.152	0.138	0.063
w_{Co3}		0.142	0.035	0.189	0.036	0.107	0.357	0.201	0.075
w_{Co4}		0.136	0.042	0.307	0.029	0.062	0.184	0.343	0.033
w_{Co5}		0.037	0.085	0.104	0.330	0.080	0.213	0.151	0.037
w_{Co6}		0.057	0.357	0.184	0.026	0.047	0.102	0.131	0.152
w_{Co7}		0.053	0.017	0.146	0.027	0.461	0.118	0.175	0.056
w_{Co8}		0.053	0.018	0.252	0.078	0.175	0.175	0.201	0.101
w_{Co9}		0.045	0.019	0.119	0.291	0.040	0.146	0.330	0.055
w_{Co10}		0.146	0.017	0.075	0.068	0.161	0.114	0.391	0.174
$w_{C2\ (Soc)}$	0.324								
w_{Co1}		0.042	0.429	0.113	0.185	0.033	0.122	0.076	0.041
w_{Co2}		0.214	0.054	0.106	0.414	0.074	0.152	0.138	0.063
w_{Co3}		0.240	0.035	0.189	0.036	0.107	0.357	0.201	0.075
w_{Co4}		0.213	0.042	0.307	0.029	0.062	0.184	0.343	0.033
w_{Co5}		0.018	0.085	0.104	0.330	0.080	0.213	0.151	0.037
w_{Co6}		0.059	0.357	0.184	0.026	0.047	0.102	0.131	0.152
w_{Co7}		0.078	0.017	0.146	0.027	0.461	0.118	0.175	0.056
w_{Co8}		0.071	0.018	0.252	0.078	0.175	0.175	0.201	0.101
w_{Co9}		0.037	0.019	0.119	0.291	0.040	0.146	0.330	0.055
w_{Co10}		0.028	0.017	0.075	0.068	0.161	0.114	0.391	0.174
$w_{C3\ (Eco)}$	0.056								
w_{Co1}		0.034	0.429	0.113	0.185	0.033	0.122	0.076	0.041
w_{Co2}		0.154	0.054	0.106	0.414	0.074	0.152	0.138	0.063
w_{Co3}		0.089	0.035	0.189	0.036	0.107	0.357	0.201	0.075
w_{Co4}		0.079	0.042	0.307	0.029	0.062	0.184	0.343	0.033
w_{Co5}		0.079	0.085	0.104	0.330	0.080	0.213	0.151	0.037
w_{Co6}		0.051	0.357	0.184	0.026	0.047	0.102	0.131	0.152
w_{Co7}		0.048	0.017	0.146	0.027	0.461	0.118	0.175	0.056
w_{Co8}		0.130	0.018	0.252	0.078	0.175	0.175	0.201	0.101
w_{Co9}		0.181	0.019	0.119	0.291	0.040	0.146	0.330	0.055
w_{Co10}		0.154	0.017	0.075	0.068	0.161	0.114	0.391	0.174

By multiplying the priorities of all elements of the hierarchy by the relevant priorities of the upper hierarchy level elements, we get the relevant weights of the decision hierarchy. By aggregating the priorities at the Instruments' hierarchy level, we can assume that I6 (Education and training programs) and I5 (Formation of Water Management Local Organization (WMLO)) will be the most important for the implementation of IWRM principles, followed by I2 (Lake Poopo basin with stakeholder involvement). Thus, it seems to be advisable that the first step for the IWRM will be to establish training programs for the stakeholders connected to the basin.

Table 6 Relative priorities of MCDA (Criteria, Conflicts, and Instruments) and total weighting of Instruments I1 to I7

Level 1 & 2			level 3						
			w_{I1}	w_{I2}	w_{I3}	w_{I4}	w_{I5}	w_{I6}	w_{I7}
$w_{C1\ (Env)}$	0.620								
w_{Co1}		0.150	0.065	0.017	0.028	0.005	0.018	0.011	0.006
w_{Co2}		0.055	0.003	0.006	0.023	0.004	0.008	0.008	0.003
w_{Co3}		0.088	0.003	0.017	0.003	0.009	0.031	0.018	0.007
w_{Co4}		0.084	0.004	0.026	0.002	0.005	0.015	0.029	0.003
w_{Co5}		0.023	0.002	0.002	0.007	0.002	0.005	0.003	0.001
w_{Co6}		0.035	0.013	0.006	0.001	0.002	0.004	0.005	0.005
w_{Co7}		0.033	0.001	0.005	0.001	0.015	0.004	0.006	0.002
w_{Co8}		0.033	0.001	0.008	0.003	0.006	0.006	0.007	0.003
w_{Co9}		0.028	0.001	0.003	0.008	0.001	0.004	0.009	0.002
w_{Co10}		0.091	0.002	0.007	0.006	0.015	0.010	0.035	0.016
$w_{C2\ (Soc)}$	0.324								
w_{Co1}		0.014	0.006	0.002	0.003	0.000	0.002	0.001	0.001
w_{Co2}		0.069	0.004	0.007	0.029	0.005	0.011	0.010	0.004
w_{Co3}		0.078	0.003	0.015	0.003	0.008	0.028	0.016	0.006
w_{Co4}		0.069	0.003	0.021	0.002	0.004	0.013	0.024	0.002
w_{Co5}		0.006	0.001	0.001	0.002	0.000	0.001	0.001	0.000
w_{Co6}		0.019	0.007	0.004	0.000	0.001	0.002	0.002	0.003
w_{Co7}		0.025	0.000	0.004	0.001	0.012	0.003	0.004	0.001
w_{Co8}		0.023	0.000	0.006	0.002	0.004	0.004	0.005	0.002
w_{Co9}		0.012	0.000	0.001	0.003	0.000	0.002	0.004	0.001
w_{Co10}		0.009	0.000	0.001	0.001	0.001	0.001	0.004	0.002
$w_{C3\ (Eco)}$	0.056								
w_{Co1}		0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000
w_{Co2}		0.009	0.000	0.001	0.004	0.001	0.001	0.001	0.001
w_{Co3}		0.005	0.000	0.001	0.000	0.001	0.002	0.001	0.000
w_{Co4}		0.004	0.000	0.001	0.000	0.000	0.001	0.002	0.000
w_{Co5}		0.004	0.000	0.000	0.001	0.000	0.001	0.001	0.000
w_{Co6}		0.003	0.001	0.001	0.000	0.000	0.000	0.000	0.000
w_{Co7}		0.003	0.000	0.000	0.000	0.001	0.000	0.000	0.000
w_{Co8}		0.007	0.000	0.002	0.001	0.001	0.001	0.001	0.001
w_{Co9}		0.010	0.000	0.001	0.003	0.000	0.001	0.003	0.001
w_{Co10}		0.009	0.000	0.001	0.001	0.001	0.001	0.003	0.002
Total weighting			0.119	0.166	0.137	0.107	0.181	0.214	0.075
Rank			5	3	4	6	2	1	7

A deeper analysis of the results shows that the conflicts are frequently connected to one specific criteria of the hierarchy; e.g., Co1 ("Extreme weather events") is seen to have mainly environmental outcomes while conflicts Co8 ("Land fragmentation") and Co9 ("Migration") are mainly economically relevant. Co2 ("Socio-economic situation") is considered to have impacts on the criterion "Economy" as well as on "Society", while Co10 ("Pollution") has environmental and economic outcomes (for all other details see Fig. 5). Therefore, along with other considerations (like scientific results referring to the water management situation in comparable regions) we now have a picture of the situation confirming the estimation of the stakeholders.



CEnv – Environmental Criteria (C1), CSoc – Social C. (C2), CEco – Economic C. (C3)

Fig. 5 Absolute priorities of Conflicts referring to Criteria

Comparable conclusions can be made concerning the Instruments. From Table 5 we can learn that Instrument I1 ("Monitoring hydro-meteorological parameters") is especially useful for improving negative impacts of conflict Co1 ("Extreme weather events"; $w_{I1}(Co1) = 0.43$) and Co6 ("Lack of basic information"; $w_{I1}(Co6) = 0.36$). The same may be said for:

- I3 (Implementation of infrastructure) for Co2 (Socio-economic situation) and Co5 (Deficient regulation of the water resources)
- I5 (Formation of WMLO) for Co3 (Cultural aspects)
- I4 (Implementation of legal statements) for Co7 (Water law and water rights)
- I6 (Education and training programs) for Co10 (Pollution)

(For all other details connected to Instruments and Conflicts see Table 5.)

Therefore, we may assume that, depending on the problem we are considering, different Instruments seem to be more or less appropriate. Moreover, one must take into account which problem-field should be dealt with in general. For instance, if we want to improve mainly the environmental situation, I1 may be assumed to be the most effective Instrument (together with I5, I6 and I2). However, one main research question still remains unsolved: we have to also consider the different actors when referring to specific Instruments. The MCDA analysis proved that not all actors are equally suitable to implement specific Instruments in water management. The following analysis will present the relevant results concerning Actors.

8. Matrixes $M_{4.1}$ and $M_{4.7}$ – Actors vs. Actors implementing Instruments

To evaluate the Actors' ability to participate in the implementation process, the same pairwise comparison valuation was done, as described in the above chapter. As mentioned, 8 different Actors relevant to this specific decision problem were identified. From this set of Actors $A_4 = \{A1, A2, \ldots A8\}$ we need 7 different matrixes in order to estimate the relevant priorities referring to the implementation of Instruments. The following, exemplary matrix, $M_{4.1}$, was also produced by the participating stakeholders; matrixes $M_{4.2}$ and $M_{4.7}$ can be assumed to provide a comparable illustration.

$$M_{4.1} = \begin{pmatrix} 1 & 1 & 1/3 & 1/5 & 3 & 3 & 1/3 & 5 \\ 1 & 1 & 1/3 & 1/3 & 3 & 3 & 1/3 & 7 \\ 3 & 3 & 1 & 7 & 9 & 9 & 7 & 9 \\ 5 & 3 & 1/7 & 1 & 3 & 5 & 3 & 7 \\ 1/3 & 1/3 & 1/9 & 1/3 & 1 & 1 & 3 & 5 \\ 1/3 & 1/3 & 1/9 & 1/5 & 1 & 1 & 3 & 7 \\ 3 & 3 & 1/7 & 1/3 & 1/3 & 1/3 & 1 & 5 \\ 1/5 & 1/7 & 1/9 & 1/7 & 1/5 & 1/7 & 1/5 & 1 \end{pmatrix}$$

The relative importance of each actor may be estimated from these pairwise comparisons (here also, we used Saaty's eigenvector method for the approximation of priorities). The following table represents the absolute priorities for the actors with respect to the relevant Instruments.

Table 7 Absolute priorities of MCDA (Actors, Instruments)

	w_{A1}	w_{A2}	w_{A3}	w_{A4}	w_{A5}	w_{A6}	w_{A7}	w_{A8}
I1	0.085	0.090	0.414	0.183	0.063	0.064	0.086	0.016
I2	0.021	0.056	0.091	0.162	0.282	0.308	0.053	0.028
I3	0.041	0.063	0.095	0.195	0.375	0.137	0.077	0.017
I4	0.152	0.110	0.371	0.203	0.028	0.045	0.068	0.023
I5	0.033	0.032	0.133	0.127	0.296	0.297	0.064	0.018
I6	0.047	0.137	0.495	0.069	0.031	0.029	0.111	0.082
I7	0.073	0.138	0.460	0.081	0.036	0.089	0.060	0.062

According to this table, we may assume, for example, that if I1 is considered appropriate for implementation, then one should mainly rely on Actor 3 (Prefecture of Oruro). Instruments I6, I5 and I2 may be considered of highest relevance for IWRM in the Lake Poopo basin. To make use of these Instruments, different actors should be taken into account: A3 (Prefecture of Oruro) may be assumed to be the main actor for the application of I6 (implementation of education and training programs) which is the Instrument with the highest priority. The priority vector amounts to $w_{A3} = 0.495$. Only A2, (Bolivian Operating Unit, ALT) and A7 (organizations such as NGOs, Universities, etc.) are seen to be of moderate importance concerning education and training; all other authorities are below $w_{Ii} < 0.1$, which is an unmistakable signal of their relative unimportance for I6. For both, I5 (Formation of WMLO) and I2 (Base line with stakeholder involvement) the most important Actors are A5 (Local Organizations) and A6 (Basin Coordination for Defense of the BIOTA), respectively.

Independent of the Instruments considered above, Actor A3 (Regional Government – Prefecture of Oruro; total $w_{A3} = 0.282$; see Table 8) seems to be the actor with the highest "authority" with respect to IWRM, followed by A5 (local organizations) and A6 (Basin Coordination for Defense of the BIOTA). This result confirms findings by Phumpiu and Gustafsson (2009): "WSS [water and sanitation service] partnerships at local level have demonstrated to be efficient and to bring the best of abilities at very high levels of equity". However, from our experience, the lack of sustainable financial support, capacity building and implementation ability could be permanent obstacles for A5 to really play an important role within the implementation process. Furthermore, A4 (Regional Municipalities) are of significant importance, and all other actors are considered to be significantly inferior when concerning IRWM.

Table 8 Absolute priorities of MCDA (Actors, Instruments)

	w_{Ii}	w_{A1}	w_{A2}	w_{A3}	w_{A4}	w_{A5}	w_{A6}	w_{A7}	w_{A8}
I1	0.119	0.010	0.011	0.049	0.022	0.008	0.008	0.010	0.002
I2	0.166	0.003	0.009	0.015	0.027	0.047	0.051	0.009	0.005
I3	0.137	0.006	0.009	0.013	0.027	0.052	0.019	0.011	0.002
I4	0.107	0.016	0.012	0.040	0.022	0.003	0.005	0.007	0.002
I5	0.181	0.006	0.006	0.024	0.023	0.054	0.054	0.012	0.003
I6	0.214	0.010	0.029	0.106	0.015	0.007	0.006	0.024	0.017
I7	0.075	0.005	0.010	0.034	0.006	0.003	0.007	0.004	0.005
Total weight		0.057	0.086	0.282	0.141	0.172	0.149	0.077	0.037
Rank		7	5	1	4	2	3	6	8

9. Sensitivity and Consistency Analysis

Finally, one must consider that MCDAs are usually connected to some methodological problems. Therefore, it is especially necessary to finally analyze the stability of these results (sensitivity analysis) and the consistency of the subjective judgments (connected with pairwise comparisons and the transitivity of the ranking of the analysis). These problems are broadly discussed in relevant literature (e.g. Linares, 2009); examinations in this regard help us to assure that analytical results are not generated on the basis of random decisions.

Concerning the sensitivity analysis, it might be concluded that the generated results are robust and stable. Even if we shift the weighting of the first level of the hierarchy significantly, the final ranking of Instruments and Actors would not change. This is a reliable signal for stability.

Concerning consistency, the results are much more problematic. To prove the consistency of the pairwise comparisons, we used Saaty's standard solution for evaluating consistency of AHP decision matrixes (Saaty, 1980), following Perron's Theorem that any positive matrix has a maximum, real and positive eigenvalue λ_{max} (Stein and Mizzi, 2007). If $\lambda_{max} = n$ (number of elements of the relevant pairwise comparison) a consistent matrix is available. If $\lambda_{max} > n$ then the matrix is not consistent. The referring Consistency Index (CI) is defined by $(\lambda_{max} - n)/(n - 1)$ (Saaty, 1980). However, the metric amount of CI depends on the size of the matrix; therefore, CI is not useful for evaluating the consistency of a matrix but the *ratio* of CI divided by CI of a random matrix should be used (i.e. Consistency Ratio CR). We took the Random Consistency from Saaty (1995, p. 83), as shown in Table 9:

Table 9 Random Consistency

Size of Matrix	1	2	3	4	5	6	7	8	9	10
Random Consistency	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

To confirm his suggestions, CR should not exceed the level of 0.1 (a consistent decision matrix has a CR of 0). It might also be interpreted that a small proportion of inconsistent judgments is not harmful, but a typical concept of human behavior. However, if this proportion exceeds a relevant level (0.1 for Saaty's CR) one should rethink the whole decision process. Unfortunately, we calculated a CR far beyond 0.1 for some of the pairwise comparison matrixes analyzed above. The reasons for the inconsistencies of the decision are likely to be due to high complexity and cultural aspects. Therefore, we had to find ways of evaluating the results with respect to the criteria "consistency".

Table 10 Consistency Ratio (original matrixes and modified)

	Original matrix CR	Modified matrix CR ≤ 0.1
	Criteria	
M_1	0.198	0.096
	Conflicts	
$M_{2.1}$	0.256	0.097
$M_{2.2}$	0.138	0.098
$M_{2.3}$	0.284	0.096
	Instruments	
$M_{3.1}$	0.244	0.094
$M_{3.2}$	0.148	0.097
$M_{3.3}$	0.112	0.097
$M_{3.4}$	0.105	0.085
$M_{3.5}$	0.195	0.099
$M_{3.6}$	0.088	0.088
$M_{3.7}$	0.138	0.098
$M_{3.8}$	0.351	0.094
$M_{3.9}$	0.087	0.087
$M_{3.10}$	0.141	0.099
	Actors	
$M_{4.1}$	0.196	0.097
$M_{4.2}$	0.113	0.097
$M_{4.3}$	0.268	0.098
$M_{4.4}$	0.177	0.099
$M_{4.5}$	0.067	0.067
$M_{4.6}$	0.110	0.091
$M_{4.7}$	0.184	0.095

For this purpose, we transformed each inconsistent pairwise comparison matrix with CR > 0.1 step by step, by reducing or augmenting the most inconsistent value to the next evaluation point (as long as it did not exceed the maximum scale value of 9 and 1/9 respectively; when it did, we took the second most inconsistent evaluation) until we reached the required level of CR ≤ 0.1. For the first matrix (pairwise comparisons of C1, C2, C3) the original matrix shifted from

$$M_1 = \begin{pmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 9 \\ 1/7 & 1/9 & 1 \end{pmatrix} \text{ to } M_1' = \begin{pmatrix} 1 & 2 & 7 \\ 1/2 & 1 & 9 \\ 1/7 & 1/9 & 1 \end{pmatrix}.$$

In this case, only one change in one cell was necessary in order to reach a consistency level of CR ≤ 0.1 (CR = 0.096). To get all matrixes to a sufficient consistency level, we had to make more iteration in many cases. Subsequently, we recalculated the final results and asserted, via this approach, that the shift of the total weighting of Instruments and actors can be neglected. The maximum deviation between the original weighting and the weighting calculated with matrixes fulfilling the condition CR ≤ 0.1 was much lower than ± 0.01 (for Instruments; see Table 10) and even beyond that level for the Actors' priorities (Table 9).

Table 11 Consistency analysis – Instruments

	w_{I1}	w_{I2}	w_{I3}	w_{I4}	w_{I5}	w_{I6}	w_{I7}
Original	0.119	0.166	0.137	0.107	0.181	0.214	0.075
CR < 0.1	0.121	0.167	0.131	0.108	0.181	0.222	0.069
Deviation	-0.002	-0.001	0.006	-0.001	0.000	-0.008	0.006

Table 9 Consistency analysis – Actors

	w_{A1}	w_{A2}	w_{A3}	w_{A4}	w_{A5}	w_{A6}	w_{A7}	w_{A8}
Original	0.057	0.086	0.282	0.141	0.172	0.149	0.077	0.037
CR < 0.1	0.056	0.085	0.283	0.143	0.172	0.146	0.077	0.038
Deviation	0.001	0.001	-0.001	-0.002	0.000	0.003	0.000	-0.001

On the basis of these results, we may conclude that the evaluation within this analysis fulfills both conditions:

(1) The results are stable (sensitivity analysis). The results do not change even if we change part of the weightings of higher hierarchy levels.

(2) The inconsistencies are not harmful. The inconsistent matrixes within this evaluation process, which are rather high for part of our pairwise comparisons (and probably connected to the complexity of the decision problem and to a cultural approach), do not damage the explanatory power of the evaluation via the Analytic Hierarchy Process presented herein. No intransitivity was found, a pre-condition for rational decision making, or – in other words – "cornerstone of rational preference" (Linares, 2009).

10. Concluding remarks

The values obtained through application of the MCDA model, represent the critical line to follow in order to confront the sustainability of water resources in the Lake Poopo basin. The results acquired from the MCDA allow water resources managers to search for efficient instruments, which take into account ecological, social and economic criteria. These instruments were evaluated according to the preferences of decision-makers, based on the active participation and validation of stakeholders. In this case, the most effective instruments should be education and training programs (I6), formation of WMLO (I5) and base line with stakeholder involvement (I2), or a combination of these (see Fig. 6).

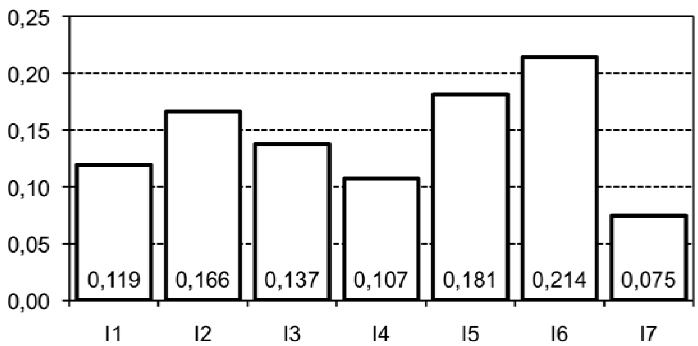


Fig. 6 Priorities of Instruments

Concerning the implementing actors identified in the first section of this paper, the local government (A3) seems to be the most appropriate to implement the Instruments. However, it should be discussed to what extent a co-operation between several or all actors could bring even better results concerning IWRM. This point cannot be solved via this evaluation process, as the methodological basis of the MCDA (the pairwise comparisons) does not consider combinations of hierarchy elements (which would be an interesting question). However, we may assume that co-operations are unconditionally necessary in order to introduce IWRM principles in the Lake Poopo basin.

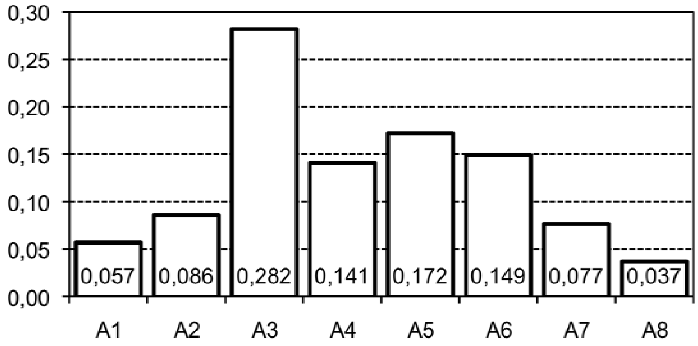


Fig. 7 Priorities of Actors

There is a clear need for methodologies and tools to put IWRM principles into practice. This is required in an application context in which decisions and choices are assessed in terms of their sustainability, not only over the long term, but also with regards to their day-to-day contribution to the perspective of sustainable development.

Applying the MCDA to the Lake Poopo basin proved to be a practicable and effective way to start a real master plan towards the IWRM strategy. This first approach forms a basis for all further developments and should be empowered and consolidated by the active intervention of stakeholders at all levels, especially in the conformation of the water management local organization (WMLO) in each sub basin.

Finally, an important latent question, "Is the MCDA the best way to serve the decision making process for our purpose?" The analysis can be framed in different ways, in some instances directly supporting the eventual decision, and in some less. Therefore, the MCDA might be structured, according to Dodgson et al. (2000), into:

a) Showing the decision maker the best way forward
b) Identifying the areas of greater and lesser opportunity
c) Prioritizing the options
d) Clarifying the differences between the options
e) Helping the stakeholders to understand the situation better
f) Indicating the best allocation of water resources
g) Any combination of the above

Following this, the results of the research indicate a good direction for the introduction of IWRM principles in the Lake Poopo basin; all of the points a) to g) were included in the above analytical approach. Of course, some problems occurred (e.g. consistency of the pairwise comparisons); however we were able to show that these problems should not be harmful concerning the explanatory power of the conclusions. Finally, the results have already been widely spread throughout the Lake Poopo basin, obtaining positive response and identification of the stakeholders with these results. This should facilitate involvement of all affected institutions and organizations (even if they have opposed points of view), which is probably the key factor for successfully introducing the principles of integrated water resources management.

11. Acknowledgements

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PAPER 5

Approach for Implementing an Integrated Water Resources Management (IWRM) Strategy in the Lake Poopo Basin, Bolivia

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Abstract
The Lake Poopo basin, in the Bolivian Altiplano, is confronted with large variability of limited water resources over time and space. The implementation of an IWRM strategy is urgently required to face this situation and allocate water wisely and sustainably. This paper guides a stepwise implementation of an IWRM strategy, based on key issues and an institutional arrangement structure according to the Multi-Criteria Decision Analysis (MCDA). The study assesses the opportunities and challenges in the implementation process of such a strategy and proposes steps to achieve successful results. In addition, it explores the potential benefits obtained from the development of local capacity and stakeholder participation as one of the most important factors.

Key words: Multi-Criteria Decision Analysis, IWRM strategy, Bolivian Altiplano, poverty, institutional arrangements, local capacity building

Introduction
Since the International Conference on Water Resources and the Environment in Dublin 1992, Integrated Water Resources Management (IWRM) has become a key concept in the management of water resources. The Global Water Partnership (2000) defines the IWRM as "a process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".

Although the concept of IWRM has been accepted by many countries around the world, the implementation of IWRM has not been easy, and there is evidence to suggest that the performance of recently conformed river basin organizations (RBOs), the objective of which is to implement IWRM, has been disappointing. Some of the factors in the below-expected performance of the RBOs are: limited autonomy and excessive political influence, limited resources and capacity to achieve goals, and low participation of stakeholders, especially women. Furthermore, uncertainty seems to prevail regarding the role and functions of river basin organizations when it comes to implementing IWRM (Cap-Net *et al*., 2008)

All over the world, many practices adopted to manage water for human consumption, industry, and farming have led to surface water pollution, over-exploitation of groundwater resources and trans-boundary disputes over water-sharing. While some progress has been achieved in the last decade, increasing competition for scarce water resources among various domestic, industrial, and agricultural uses, and an inevitable rise in the cost of providing water and sanitation services will bring more severe challenges for the future. Effective development and management of water resources are essential for facing these challenges, securing sustainable growth and reducing poverty in all developing countries.

Integrated water resources management is a systematic process for the sustainable development, allocation and monitoring of water resources use in the context of social, economic and environmental objectives. For example, when the responsibility for drinking water rests with one operator, for irrigation water with another, and for the environment with yet another, the lack of cross-sector linkages leads to uncoordinated water resource development and management, resulting in conflict, waste of resources and unsustainable systems.

The main objective of this paper is to propose a comprehensive strategy for the implementation of IWRM in the Lake Poopo basin with the active participation of stakeholders, based on an already developed model of multi-criteria decision making, in concordance with the National Basins Program (PNC), created by the Ministry of Water in 2007. In 2009, the Ministry of Water became the Ministry of Environment and Water, an organization that promotes the Integrated Water Resources Management (IWRM) and the Integrated River Basin Management (IRBM) at national level.

Overview of the region

The Lake Poopo basin, comprised by 22 sub-basins, is located in the southern Bolivian Altiplano, at an altitude of 3700 m, see Fig. 1. According to Van Damme (2002) and Revollo (2001) the Altiplano and the Lake Poopo basin are confronted with a) uneven spatial and temporal rainfall, requiring water harvesting infrastructure, b) low efficiency in the utilization of developed water resources for irrigation and rural water supply due to insufficient operation and maintenance and lack of technical assistance, c) inter-sector competition, particularly between mining activity and irrigation and between water irrigation, water supply, and industry, d) catchment degradation and poor management coordination. This situation demands efforts devoted to increasing the reliability of available water resources and to utilizing these in a more efficient way.

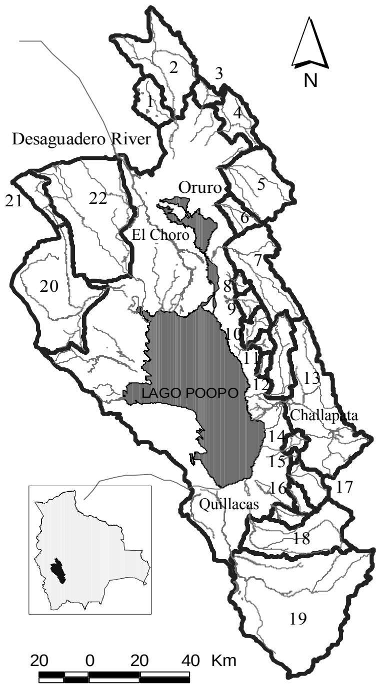


Fig. 1 The 22 river sub-basin systems of Lake Poopo basin in the Southern Bolivian Altiplano

The surrounding environment is fragile, subject to droughts, floods, frost, and increasingly, pollution. The basin is one of the poorest regions in the world (Li Pun, 2007; ALTAGRO, 2004), with very low human development indexes, including per capita gross domestic product, life expectancy, literacy, and infant mortality. Poverty in the basin is predominately rural, and is closely linked to lack of water, pollution and other factors which are forcing people to migrate to faraway urban areas (ALT, 1999; Revollo, 2001; Rotentalp et al., 2005; UTO/INCO, 2007).

The lakes Poopo and Uru Uru comprise the second most important enclosed system in the Altiplano (second only to the Lake Titicaca system), due to their unique biodiversity and large surface area: 3000 and 260 km^2, respectively. The lakes are also of great importance in the conservation of several water birds, some of them endemic, like the Andean flamingo (*Phoenicoparrus andinus* and *Phoenicopterus chilensis*) and Jame's flamingo (*Phoenicoparrus jamesi*), and some endangered like the horned coot (*Fulica cornuta*) (Rocha *et al.*, 2002). According to UTO *et al.* (2007), there are only two fish species: Karachi

Amarillo (*Orestias agassizii*) and Pejerrey (*Odontesthes bonariensis*). Every year Lake Uru-Uru dries up in the dry period and Lake Poopo is reduced to about half its area. The lake which is 3000 km^2 at spill-over level may even dry out (Pillco and Bengtsson, 2006).

In the Bolivian countryside, population is organized into rural towns and communities. The rural towns in the Lake Poopo basin have populations of maximum 5,000, and they have running water and electricity. Their inhabitants are both indigenous and *mestizo*. The highest authority in a town, or municipality, is the Mayor. Although technically part of the municipality, the communities are scattered throughout the countryside and usually inhabited by no more than 100 families. Communities have no water supply system and most of them have no electricity. The houses are usually made of adobe, a brick made of a special dry mud, and their population is indigenous. Often, communities are far from the highways and roads, and access to them can be extremely difficult. Each community has an authority, or *Jilakata,* elected by traditional means. Several communities make up an *ayllu*, and the *ayllu* authority, is responsible for all the communities in his territory.

The *ayllu* is the pattern of territorial and socio-economic organization of pre-Columbian indigenous communities. It comprises several communities with specific ethnic and cultural identity, and a system of authorities elected by traditional means. Thus, communities belong to both *ayllus* and municipalities.

Many different peoples and organizations coexist in the Lake Poopo basin. It is home to various indigenous communities, the largest of which are the Aymara, Quechua, and Uru-Murato, a pre-Columbian ethnic group that settled in the region between 2000 and 1500 BC, (Delgadillo, 1998). It is also home to a considerable *mestiz*o, or mixed race population. The main languages spoken are Spanish, Aymara, Quechua, and Uru-Murato. At least 16 pre-Inca archeological sites have been found in the region (Catacora *et al.*, 2002), especially in the north-west, offering great touristic potential. Both private and public sector organizations operate in the area; at least 120 mines, a tin foundry, agricultural industries, a beer factory, and several NGOs. The basin's territory is divided into 15 municipalities and more than 100 *ayllus* (Jatun Quillaca Asanajaqi, Indigenous organization that represents the *ayllus* in the region.).

In pre-colonial times, the *ayllu* played a very strong role in the management of water resources within its territory. Since land and water resources were collective property, the *ayllu* authorities were able to organize the people to irrigate crops and ensure that everyone had access to water for consumption and irrigation. To this day, *ayllu* authorities still play a role in the allocation of water resources within their territories, but their influence is limited by several factors, such as lack of education and resources.

The role of municipalities in the management of water resources is to identify conflicts and solve them through the construction of infrastructure such as improvement of canals, water supply systems, irrigation systems, etc. Thus, municipalities are key actors because they have the funds and means to execute infrastructure projects. Yet these projects are usually isolated and not part of an overall, regional or even municipal water management strategy.
This uncoordinated handling of the water resources generates a situation characterized by the lack of clearly established water rights and inefficiency in dealing with issues such as extreme weather events, water scarcity, environmental degradation, etc. This, in turn, leads to water and land conflicts. Due to increasing water demand and decreasing water quality and availability, different sectors compete fiercely for access to fresh water. The simultaneous use

of water by different sectors is not feasible and can generate conflicts (Crespo and Mattos, 1999).

Water related conflicts in the basin

Conflicts relating to the water resources in the basin occur at different levels and between different stakeholders, take diverse forms, involve a wide range of issues and have many dimensions (legal, institutional, socio-cultural, and so on). The water-conflict issues in the basin have been grouped into 5 main categories: extreme weather events, socio-economic situation, deficient water regulations, environmental degradation and the lack of organized stakeholder involvement (Calizaya & Bengtsson, 2008).

Table 1. Water related conflicts and consequences in the Lake Poopo basin

Category	Conflict	Indicators	Consequences
Extreme weather events	highly variable climate	ENSO phenomena	drougth, water scarcity, desertification
	low precipitation high evaporation	200-400 mm 1200-1800 mm	drougth, water scarcity, desertification
	drougths	16 devastating events since 1906	agricultural losses, starvation, livelyhood threatened, roads and train railway destruction
	floods	11 devasting events since 1906	
	frost	frecuent in winter	
	hails	50 days between 1971-1977	
Socio-economic situation	education	25% average illiteracy rate	few opportunities to improve quality of life
	poverty & extreme poverty	73% ; 30% ; HDI=0,52	pressure on the natural resources
	access to water	low water poverty index (WPI=28)	low quality of life
	income	< 600 $us/year	subsistance economy
	land fragmentation	insufficient data available	farmers can not make the transition to more efficient agricultural production
	health: life expectancy	farmers 58 years miners 45 years	low quality of life
	child mortality rate	10%	
	migration from the basin	-25% (INE, 2001)	farmland abandoned
Deficient water regulations	deficient regulation of WR		conflicts among users
	obsolete and ambiguos law	water law passed in 1906 unmodified to date	conflicts among users
	lack of instances to enforce laws	enivronemental law 1333 constantly violated	environmental degradation
Environmental degradation	pollution: natural & antropoghenic	RAD, salinization, sediments	Diseases in humans, loss of plant and animal life, environmental degradation
	Intense mining activity	120 mines (big & small)	
	heavy metals in water bodies, plants and soils	acid pH; alkaline pH concentrations of As, Pb, Cd, and Zn are over permissible level	
	deforestation	increase of arid zones	decrease of arable and grazing land (food security threatened)
	overgrazing and overharvesting	natural pastures are depleted	low recovery capacity, erosion and desertification
	salinization: water and soils	(2-100 grl^{-1}) ; (4 - 10 dSm^{-1})	decrease of arable and grazing land (food security threatened)
	environmental degradation	low watershed sustainability index (WSI=0.42)	decrease of arable and grazing land (food security threatened)
Stakeholder involvement	lack of environmental education	aprox. 6.5 inhabitants per km^2	People lack training to manage water efficiently
	lack of participation		People are not willing to cooperate in "common good" activities without perceived direct benefit
	isolation of communities from eachother		communication between communities is difficult
	limited economic resources		limited resources (time, etc.) to participate in activities

Table 1 was elaborated mainly based on information from the National Statistics Institute (INE, 2001), PPO-2 and PPO-3 (1996), Revollo (2001), Pillco and Bengtsson (2006), ALT (1999 and 2003) and Calizaya *et al.*, 2008a, b, c, and d.

The conflicts that fall under each conflict category were detailed. Where it was possible, indicators and numbers were given to explain the severity of the conflict. In some cases, statistics and indicators were not available, for example for “land fragmentation” and “deforestation”. Finally, the consequences of each conflict were given. This table largely describes the current situation of the Lake Poopo basin tied to the conflicts.

Extreme weather events such as floods and drought have devastating impacts on the region due to environmental degradation and the fragile economy of its inhabitants. Since 1906, 16 droughts and 11 floods have devastated the Lake Poopo basin. The drought of 1990, for example, caused economic losses worth US$30 million, while the flood occurred between 1996 and 1997 meant at least US$ 20 million in losses (Revollo *et al.*, 2003). These events aggravate poverty, which in turn causes added pressure on the natural resources. The implementation of an IWRM strategy would enable the basin to regain some of its natural regulating capacity A source control action such as reforestation could be vital for frost, flood and drought protection.

Land fragmentation, one of the most important conflicts in the category of socio-economic situation, also contributes to the existence of water conflicts. Agriculture and livestock breeding are the main sources of income for the rural population in the Lake Poopo region, and are mainly carried out on small-scale and dispersed parcels of land. As each generation of farmers inherits the land from its predecessor, the already small parcels are divided amongst siblings. This prevents farmers from being able to adopt more efficient means of agricultural production and renders efficient use of water for irrigation unlikely, condemning them to subsistence farming. Thus, a ceiling is set on their income-generating capacity and opportunity for growth.

There are several conflicts deriving from deficient water regulations and environmental degradation between the mining and farming sectors in the north-east of the basin. For example, the Huanuni Mine, which produces approximately 6,000 tons of tin concentrates (PPO-2, 1996), has been in conflict with the 40 communities located along the Sora Sora River for many years. The water reaching downstream communities is heavily contaminated by waste discharges from the mine. In the beginning of 2009, these 40 communities demanded their sub-basin be declared an environmental disaster zone because the pollution had degraded the soil and elevated the acidity of the water to pH levels of between 2.6 and 6.5. They made their request to the Ministry of Civil Defense, who promised a team of scientists would conduct a diagnosis of the situation. The conflict has not been solved to date.

There is also conflict regarding the water supply, especially between the private sector and the population. The town of Santiago de Huari (3,500 inhab.) for example, is home to one of the largest beer-producing companies. The company pays an undisclosed amount of money to four nearby indigenous communities in exchange for the right to deviate water from the springs in their territory. These springs, however, are the only source of water for the town’s water-supply system. As a result, around 60% of the available water is used by the beer industry, while the population of Huari has access to water only 6 hours a day. The law states that human consumption is priority when defining water use, yet there is no instance able to enforce the law in this case. The lack of adequate water and environmental regulations and the entities suited to enforce them prevent conflicts such as these to find timely resolution in line with integral water management principles.

Anthropogenic and natural pollution of the water resources is another of the most important factors aggravating water-related conflicts (ALT, 2003). Over a long period of time, rivers and lakes have been contaminated by heavy metals from the mining companies and foundries.

As a consequence, the concentration of heavy metals in Lake Poopo is reported to be between 300 and 3,500 times that of other lakes around the world (PRH, 1989). The consequences of pollution are diseases in the population, such as lung silicosis, heavy-metal poisoning, mental alterations, anemia, nervous and renal problems, high blood pressure, reproductive problems, etc., according to Garcia *et al*. (2005). Salinization, on the other hand, causes desertification and diminished fertility of soils (Montoya, 2006). In water bodies, the salinization values are between 2 and 100 grl^{-1}. In the soil, the salinization values range from 4 to 10 dSm^{-1}. This has a negative impact on the environment and on productive capacity, reflected in the low Water Poverty Index (WPI=0.28) and Watershed Sustainability Index (WSI=0.46). (Calizaya *et al.*, 2008).

Decision-making process applied to the Lake Poopo basin

In order to elaborate an IWRM strategy for the Lake Poopo basin, a Multi-Criteria Decision Analysis (MCDA) was carried out based on the active participation of the stakeholders, who received support in the decision-making process, as recommended by FAO (2006). This process consisted of workshops held in three municipalities: El Choro, Challapata, and Quillacas. These were chosen for several reasons. First, they are the municipalities with the highest populations in the basin. Second, their locations (north, east, and west) reflect a natural and cultural diversity. Third, each of these municipalities has very distinct economic characteristics. In El Choro, for example, the inhabitants are overusing water from the Desaguadero River, resulting in the soil salinity and sodicity, heavy metals transport and sedimentation in canals. Challapata, on the other hand, is the most productive agricultural municipality in the basin, and most of its inhabitants rely on farming for income. Quillacas is the poorest of the three, and faces the most severe consequences of water scarcity.

The workshops were held with the participation of: inhabitants of each municipality, peasants from the surrounding communities, indigenous and municipal authorities, and members of relevant stakeholder organizations from each region (agricultural unions, irrigation organizations, water supply committees, etc.). The objective of the workshops was to a) provide basic information to stakeholders regarding integrated water management issues and b) obtain information from the stakeholders regarding their water priorities in IWRM in order for us to elaborate an MCDA model based on that information.

The organization of the workshops followed several steps. We first traveled to the communities neighboring El Choro, Challapata, and Quillacas (Fig. 1). In each community, we spoke to the indigenous authorities about our plans to hold a workshop on water management in the neighboring municipality, and asked them to help us coordinate this workshop in order to obtain the participation of their community. The enthusiasm of the indigenous authorities was a key in achieving the participation of peasants from surrounding communities. Then, in the municipalities, we held meetings with the authorities and gained their support as well. They facilitated the place where the workshops were to be held, and aided in calling the population to participate. It was also established that we would give away prizes (buckets, jars, etc.) to workshop participants selected at random. The process of organizing each workshop took between two and four weeks.

The first workshop was held in El Choro with the participation of members from 14 neighboring communities. In total, 400 people participated in this workshop, which lasted 5 hours. The second workshop was held two weeks later, in Challapata, with the participation of members from 22 neighboring communities. This workshop had the highest participation, with 800 people, and lasted 6 hours, with a lunch and coffee break. The last workshop was in

Quillacas, two weeks later. This workshop was carried out with the participation of 12 communities and 250 people in total, and lasted five hours.

The workshops were divided into two stages. The first stage was an orientation regarding to hydrological cycle, water resources situation (quantity and quality) in the region and the importance of an integrated water management, with subjects such as the objectives and benefits of water management and the requisites for its implementation. The content was based on the knowledge of the availability of water, through the computation of water balance (Calizaya *et al.,* 2008) and water demand, obtained from inventories carried out in 60 communities. In each of the workshops, this stage lasted an average of two hours.

The second stage started with a discussion regarding the importance of stakeholder participation in the decision-making process when it comes to IWRM. Then, we asked the participants to identify the water-related conflicts in their regions, related to three main criteria: social, economic and environmental. For example, the participants identified frost, hail, floods, drought¸ etc., as important conflicts, and these were grouped into the category of extreme weather events and placed under the environmental criterion. The data obtained was then discussed and processed. The same steps were followed in order to identify the best possible implementing actors and instruments.

Once we had a set of identified conflicts, instruments and actors, we proceeded to relate them to each other (see Fig. 2). First, the participants were asked to rate the severity and importance of each conflict. When we had the conflicts arranged in order of importance, the participants were asked to rate the capacity of each instrument to solve each conflict, assigning values ranging from 1 to 9 (1 if two elements are equal in importance and 9 if one element is the most important, including the relevant reversal values down to 1/9). These data were used to fill the elaborated tables. Thus, we had a hierarchy of the most important perceived instruments.

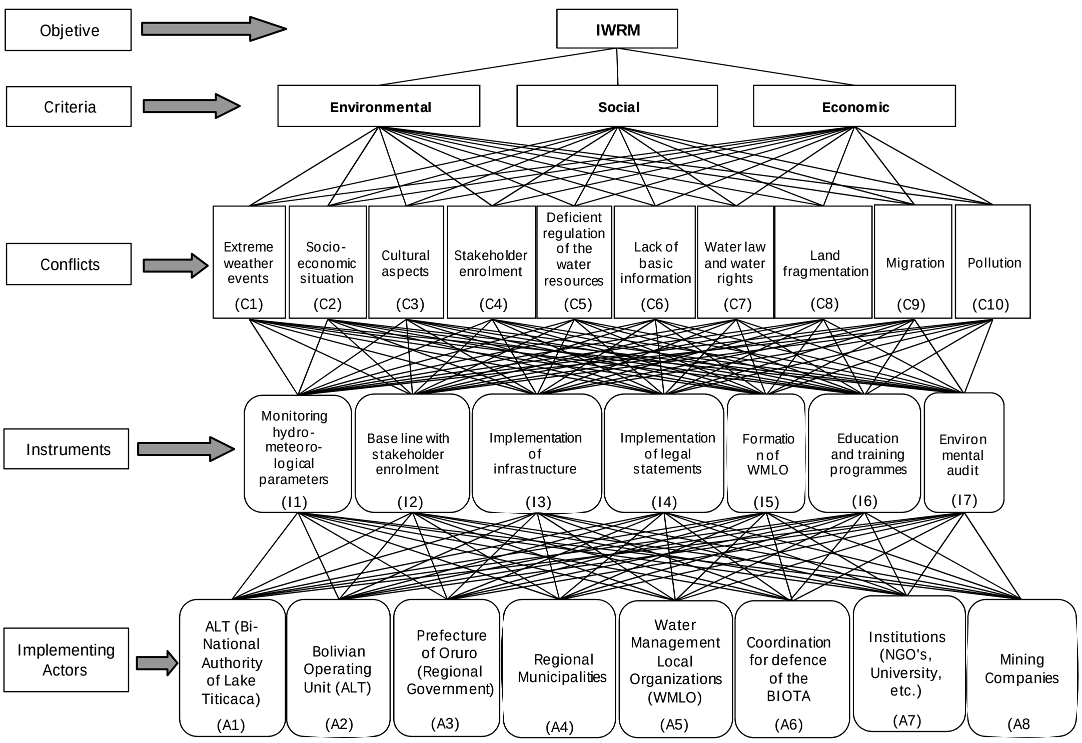


Fig. 2. Proposed structure of multi-criteria decision analysis model for Lake Poopo basin

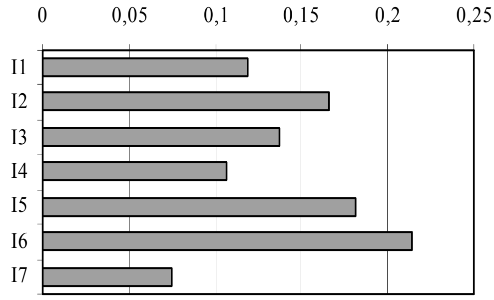
Next, we displayed all the identified instruments and possible implementing actors, and asked participants to rate actors in their perceived capacity to wield the instruments effectively, assigning the same range of values as before. This gave us a hierarchy of the best-suited implementing actors. In assigning the values, the participants had the opportunity to back up their opinion and discuss the values given. Later, this data were processed and organized in matrixes, and Saaty's analytical hierarchy process (AHP) theory was applied using pairwise comparisons (Saaty, 1980; 1985; 1990. See Annex I)). This resulted in the design of the structure of the suggested MCDA model (Calizaya *et al.*, 2008). Figure 2 shows the 10 most pressing conflicts, together with the 7 identified Instruments to solve the conflicts, and the possible implementing actors.

Results of the decision hierarchy for IWRM implementation

Applying Saaty's AHP theory, the seven instruments were given a value to determine their hierarchy. The results, presented on Table 2 and detailed in Annex I (a and b), show that three of the instruments would be the most efficient: "Education and training programs", "Creation of local water management organization or Local river basin organization (LRBO)", and "Basin's base line with stakeholder involvement". By aggregating the priorities at the Instruments' hierarchy level, we can assume that these instruments will be the most important for the implementation of an IWRM strategy at catchment level.

Table 2. Results of MCDA - Instruments

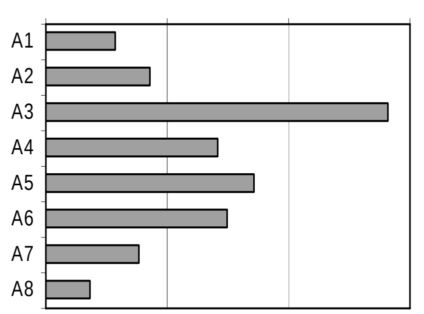
Instrument		Value
I1	Monitoring hydro-meteorological parameters	0,12
I2	Base line with stakeholder involvement	0,17
I3	Implementation of infraestructure	0,14
I4	Implementation of legal statements	0,11
I5	Creation of Local Water Resources Management Org.	0,18
I6	Education and training programs	0,21
I7	Environment audit	0,08



The same process was followed to determine the most suited implementing actors, the results of which are shown in Table 3. Actor A3 "Regional government – Prefecture of Oruro" received the highest value, being the actor with the highest regional "authority" with respect to IWRM, followed by A5 "Local organizations" and A6 "Basin coordination for defense of the BIOTA". Despite the high value placed on A5 "Local organizations", experience shows that the lack of sustainable financial support, capacity building and implementation ability could be permanent obstacles for this actor to play an important role in the implementation process. In order to thrive, Local organizations would need constant technical assistance and financial support from A4, Municipalities, and A3, the Prefecture of Oruro.

Table 3. Results of MCDA – Implementing Actors

Implementing Actor		Value
A1	ALT (Peruvian and Bolivian Authority of Lake Titicaca)	0,057
A2	Bolivian Operating Unit (ALT)	0,086
A3	Prefecture of Oruro	0,282
A4	Regional Municipalities	0,141
A5	Water Management Local Organizations	0,172
A6	Recently conformed organization for defense of biota	0,149
A7	Institutions (NGOs, Universities, etc.)	0,077
A8	Mining companies	0,037



When the data was processed and the MCDA model designed, a second set of workshops was carried out with the stakeholders, this time to present and discuss the results. There were some disagreements among stakeholders that held different views. For example, some indigenous authorities insisted Local organizations (A5) should be the main actor for the implementation of IWRM. Municipal authorities argued against this, stating that Local organizations (A5) did not have the conditions to lead this strategy without the support of municipalities and the regional and central government. Nevertheless, there was a general approval of the results on the part of the majority.

Applying the MCDA to the Lake Poopo basin proved to be a practical and effective way to set the basis for an IWRM strategy, the implementation of which should be consolidated by the active intervention of stakeholders at all levels, especially in the conformation of the river basin organization or local water management organizations in each of the 22 sub-basins.

Having carried out this MCDA process, it was agreed with the stakeholders that the second step was to design a strategy for implementing IWRM in the Lake Poopo basin. The third step was to execute the strategy, which depends strongly on the political will of the Prefecture of Oruro and the central government. As the primary beneficiaries of integrated water management, the stakeholders agreed that their participation would be important in terms of pressuring the municipal and regional authorities to give priority to and allocate resources for the implementation of such strategy.

Integrated Water Resources Management key issues and functions

The key issues in water management, according to the Manual of IWRM for Water Local Management Organization (WLMO) or River Basin Organization's (RBO's), published by the Cap-Net (2008), are: a) water governance crisis (leading to fragmented and uncoordinated management of water; b) securing water for people (this is the most serious challenge for the future; c) securing water for food production (here IWRM offers the prospect of increased efficiency, water conservation and management of water demand so it is equitably shared among users); d) protecting vital ecosystem (IWRM helps to preserve an "environmental reserve" of water); and e) gender disparities (as stewards of family health and providers of domestic water and food, women are the most important stakeholders in household water and sanitation. Here, a crucial element of the IWRM philosophy is that the water users, rich and poor, male or female, are able to influence decisions that affect their daily lives.

Water resources management is but one part of the overall management of the environment and the preservation of ecosystems, which is a prerequisite for sustainable development. Therefore, it needs to be coordinated with other disciplines and sectors that affect the water resources or are affected by how well the water is managed. In the Lake Poopo basin these disciplines include: the environmental sciences, due to the high levels of pollution, environmental degradation and climate change; mining engineering, due to the presence of 120 mines; agricultural engineering, because a large sector of the population's income comes from farming and/or cattle raising; sociology and anthropology, due to the rich cultural and ethnic diversity of the region's population; biology and zoology, due to the need to preserve the many species in danger of extinction. Professionals from each of these disciplines, and others, should be involved in the implementation of the IWRM strategy.

At the river basin scale there are many actors that have roles and responsibilities in the management of society and the environment, linked to the status of the water resources. Examples of these actors are the Prefecture of Oruro and municipalities, the indigenous authorities, NGOs and universities, mining companies, industries, etc. For a successful implementation of IWRM, all these actors must be considered and involved.

IWRM at the river basin scale should be focused on a set of basic water resources management functions. The 8 basic functions, which need to be performed by the main implementing actor, according to Cap-Net (2008), are the following: 1) stakeholder participation, 2) river basin planning, 3) monitoring of water resources, water use and pollution, 4) water allocation, 5) flood and drought management, 6) pollution control, 7) information management, and 8) economical management. The 8 functions are detailed in Annex II.

Annex II, Functions of water resources management and related activities (Cap-Net, 2008), shows the eight functions and a non-exhaustive list of activities necessary to exercise these functions. The table was adapted to the Lake Poopo in the activities column, where activities that apply specifically to this region were added, such as “Creation of the LRBOs”.

The water resources management functions comprise a logical framework for implementing IWRM at any river sub-basin in the Lake Poopo basin. In an inhabited river basin with competing water demands, all these functions need to be performed in order to achieve sustainable management of the water resources and to improve livelihoods. Water allocation and pollution control are direct examples of regulatory functions. The other functions may be partly regulatory but also serve as support for each other. For example, the functions of financial and information management are essential to enable the implementation of all regulatory functions.

The functions of water resources management are very complex tasks and may involve different activities conducted by many different players. For example, both the MLPRBB and the LRBOs will hold these functions. The implementation of IWRM is best done in a step-by-step process, with some changes taking place immediately and others requiring years of planning and capacity building. They can also be implemented at different levels of ambition. To successfully perform these functions with limited resources requires careful planning.

Implementing an IWRM strategy for the Lake Poopo basin

To this date, the Bolivian State has virtually no participation in integrated water resources management (Van Damme, 2002). This means that no central government has ever elaborated a national or regional strategy to manage water resources in an integrated way. In the last decade, the process of decentralization in the country assigned the responsibility for water management to regional and local governments. The Law Nº1551 of Popular Participation, which gives annual funds to municipalities, has allowed them to develop activities in the area of environmental management in general and, specifically, management of the water resources. Yet municipalities and regional governments often have severe limitations, such as competition between different groups of stakeholders, lack of information and education, and limited administrative capacity (Hoogendam and Vargas, 1999).

No strategy for integrated management of water resources has ever been implemented in the Lake Poopo basin. The community and *ayllu* authorities are traditionally in charge of allocating water as equitably as possible for irrigation and domestic consumption, according to their customs. They control how much water each family and community takes from the existing water sources. Yet, indigenous authorities face serious challenges in the management of the water resources. Too often, for example, they miscalculate the amount of water required for a certain crop to thrive, which leads to inefficient use of the resource. Thus, theirs is essentially an allocating and monitoring role, as they are not able to implement more complex solutions to issues such as water scarcity and pollution. In rural towns, it is the responsibility of the municipality to ensure access to water for domestic consumption, and to build and maintain water supply and sewer systems.

There have been few projects executed with local and external (international cooperation) funds to build infrastructure in the countryside in order to meet particular water-related needs. Yet, these projects were not framed within an integrated water management strategy, and therefore, often had unwanted effects. One example of such projects is the Tacagua Dam, which was built with state funds in 1946. The Dam caused the land to flood, destroying the farmland in upstream communities. This caused a still unresolved conflict between downstream and upstream communities, who demand compensation for the loss of their land. In the last decades, the dam has lost over 50% of its capacity due to sedimentation, so the available water for downstream communities has decreased.

The construction of irrigation systems and the impermeabilization of water network canals had mixed effects, as well. For the most part, upstream communities, who feel they have property rights over the water, obtain funds to deviate it through canals and irrigation systems in order to take the most advantage of the resource. This is done without concern for the water needs of downstream communities, who demand the water be allocated equitably among communities along the river.

Laying the ground for the implementation of an IWRM strategy in the Lake Poopo basin

The conditions necessary for the implementation of an IWRM strategy in the Lake Poopo basin are: an actor identified and willing to implement the strategy; sufficient funds available to the actor; and solid and trained stakeholder organizations to support and coordinate the strategy with the main implementing actor.

It has been shown that the actor best suited to implement the IWRM strategy in the Lake Poopo basin is the Prefecture of Oruro, due mainly to its authority over the entire Lake Poopo basin, regional policy-making capacity and its access to funds, established in the MCDA. In order to implement the IWRM strategy, it is thought to be best that the Prefecture of Oruro establish a special bureau in charge of this task. This bureau could be denominated Main Lake Poopo River Basin Bureau (MLPRBB) and its proposed administrative structure is described in Figure 3.

The Prefecture of Oruro has funds available to it from two main sources: the IDH tax and the two decentralization laws that award economic funds directly to the Prefecture and Municipalities. The income from the Direct Hydrocarbons Tax (IDH), created in 2005, is distributed between hydrocarbon producing and non-producing Departments. About 2% of the income is awarded to each of the prefectures of non-producing Departments, such as Oruro, which constitutes approximately US$ 26 million. The decentralization laws, passed in 1994, are: Law Nº1551 of Popular Participation and Law Nº1654 of Administrative Decentralization. The latter regulates the Regime of Administrative Decentralization of the Executive authority at departmental level that consists of the transference and delegation of non-privative attributions of technical-administrative character of the Executive authority at National level. The laws establish the transference of national resources to municipal and regional (departmental) levels, and realign managerial responsibilities among public governmental levels. The laws also decentralize natural resources management, under the logic that the local organizations and communities have better knowledge of the socio-economic situation and resources and are also the most affected by decisions taken on how to manage them. These legal and economic conditions make feasible the Prefecture of Oruro's implementation of an IWRM strategy in the Lake Poopo basin.

Although these laws have been in force for more than ten years, they have not had a strong impact on water management in the Lake Poopo basin. This is mainly because, though the municipalities had funds available, their officials lacked the technical training to use them efficiently. For the last 15 years, technical training programs have been provided to municipal officials in all regions of the country by several NGOs and government agencies, building local capacity to manage municipal funds.

The training of stakeholders and creation of stakeholder organizations are also important instruments for the implementation of the IWRM strategy in the region, according to results of the hierarchy analysis. Currently, stakeholders are unmotivated to participate, poorly educated regarding water management and segregated; people, communities and organizations have specific, often conflicting needs, and coordination among them is difficult. Also, local authorities, municipalities, and key players, such as women, are un-empowered to take action and make decisions regarding the rational management of water resources.

Education was selected by the stakeholders as one of the most important instruments to change the above situation and make possible the implementation of IWRM. During the three workshops conducted with the stakeholders to present and discuss the MCDA results, it was agreed that the training campaign should be carried out by training consultants hired by the Prefecture of Oruro in coordination with local and indigenous authorities. At these meetings, stakeholders expressed their interest for technical training in the areas of: climate change, water valuing and preservation, efficient use of water, water harvesting techniques, efficient irrigation techniques, water management, water economy, pollution, and pollution control. Additionally, both indigenous and municipal authorities stressed the need for training in management and organization skills, conflict resolution and negotiation. They also requested to be guided in the conformation of the Local River Basin Organizations.

Women pointed out the importance of encouraging indigenous women to participate in the training, as they are often left behind due to their housework and to the fact that most of them do not speak Spanish. It was agreed that training specific to indigenous women would need to be in Aymara and Quechua and at an hour that would not conflict with their housework. From experience, it is known that indigenous women are more participative when in groups of only women, and it would be important for the trainers to take this into consideration.

Inhabitants of the municipalities stated that the training should be differentiated for the communities and towns, as the challenges and issues in each are different. It was agreed, then, that, aside from receiving training in all the subjects listed above, communities would receive more specific training on issues such as efficient irrigation, and municipalities would focus more on such issues as pollution control.

The issue of stakeholder organization is a complicated one in the Lake Poopo basin for many reasons. First, some of the 22 sub-basins in the Lake Poopo belong to more than one municipality and to one or more *ayllus*. In this context of multiple authorities and territorial delimitations (political and indigenous), gaining the stakeholder's consensus and participation in any activity or project is relatively complex. Second, as established before, the communities are set far away from each other and motivation to participate is low due to economic and educational factors. This is why the creation of a Local River Basin Organization (LRBO) in each of the 22 river sub-basins is vital to the success of an IWRM strategy. The LRBOs will have the responsibility of dealing with each of the different levels of authority comprised in the sub-basins and gaining consensus and cohesion around their water management activities and projects.

The following strategy for implementing IWRM in the Lake Poopo basin is a result of research in the assessment of the demand and availability of water resources, and IWRM decision-making process, taking into account the vision of the basin's inhabitants and respecting their traditions, customs and beliefs throughout the process.

Institutional Arrangements for performing IWRM

Because of often limited financial and human resources of the institutions responsible for water resources management, the process may be constrained by the institutional capacity. This means that the capacity governs the possible activities to be carried out and, consequently, which objectives can be reached. It should also be noted that, due mainly to political reasons, Prefecture officials are often changed in Bolivia and this can hinder the development and continuity of policies and the consolidation of agreements.

The institutional arrangements should be clearly established and in accordance with the respective regulatory policies. An institutional arrangement structure has been elaborated to implement the IWRM in the Lake Poopo basin, as shown in Fig. 3. This structure was elaborated, first of all, from the results of the MCDA, which established the Prefecture of Oruro as the best suited implementing actor in the stakeholder´s perception. In our view, this translates into a demand of the stakeholders for the Regional government to take charge of IWRM in the region.

The MCDA and hierarchy analysis of implementing actors was made known to prefecture authorities at a meeting held in the prefecture at the beginning of 2009. In light of the information presented, and knowing the results stemmed from stakeholders´ priorities and preferences, both technical and political authorities within the Prefecture manifested their support for the implementation of IWRM. At the meeting, they stated that the most efficient way to carry out an IWRM strategy would be to create a specific bureau within the prefecture for this purpose. This bureau would be dependent on three already-existing bureaus within the Prefecture: the Secretary of Water, Secretary of planning and Development and the Secretary of Biodiversity and Environment, as they work in areas closely related to IWRM.

On the basis of this proposal, the Prefecture of Oruro committed itself to facilitating the creation of a Bureau within its organization for the implementation of an IWRM strategy. Also, Prefecture authorities agreed to elaborate a Project that would allow it to obtain international cooperation funds for the implementation of IWRM in all its stages.

The institutional arrangement shown in Fig. 3 was designed in coordination with the Prefecture´s Secretary of Water with the objective of making viable the implementation of an IWRM strategy. It was designed to take into account all the relevant institutions and entities and describe their hierarchy and decision-making power in relation to IWRM in the Lake Poopo basin.

Figure 3 shows the institutional arrangement desirable strictly in function of the implementation of an IWRM strategy in the Lake Poop basin. Today, as no strategy is being implemented, the institutions and entities, such as the Prefecture of Oruro, the Secretary of Water, the Central Government and the National River Basin Plan work in an uncoordinated manner with each other and with municipal and indigenous authorities. Of course, the Main Lake Poopo River Basin Bureau and Local Basin Organizations do not exist, as their creation is part of the strategy we propose for the implementation of IWRM in the region.

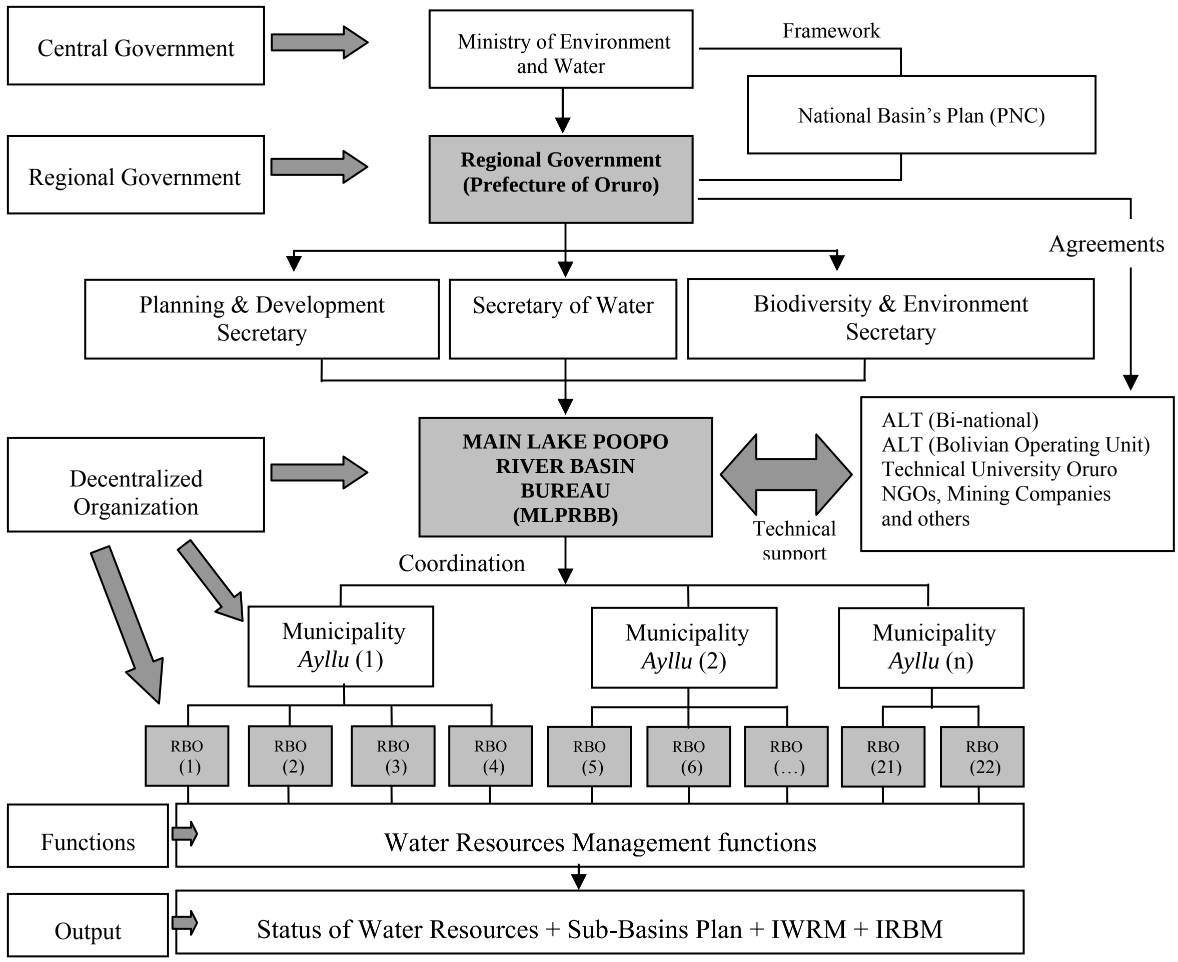


Fig. 3 Proposal of institutional arrangement for performing the IWRM strategy in the Lake Poopo basin.

The proposed structure and organizational framework depends on national and regional policies. Regulatory responsibilities related to the water resources management functions may, however, also be given to institutions other than the regional water authorities, as long as this does not generate dependency or bureaucratic obstacles that could slow the development of activities.

As indicated in Fig. 3, there are also related management areas, which directly influence the water resources but which are not part of the basic water resources management functions. An example is land management guiding, agricultural fertilizer usage and soil conservation measures, all of which affect the quality of water resources. Also, in this case the LRBO must act as a strong stakeholder and interact with the relevant ministry or institution.

One of the most important roles of the MLPRB bureau is to prioritize the objectives of IWRM in the region. This is important, especially when resources are not sufficient to build capacity for all water management objectives. If the MLPRB bureau is able to postpone the least pressing objectives, resources may be released for fulfilling the most exigent ones. This responsibility should fall on the MLPRB bureau because it alone will have the regional point of view and the knowledge of the resources available.

Another of the MLPRBB's first priorities is to coordinate with all involved municipalities and indigenous authorities to create the Local River Basin Organizations (LRBO's). The conformation of smaller LRBO's should be carried out after the training campaign organized in each of the 22 sub basins that make up the Lake Poopo basin. It is important to avoid overlapping of functions; if other institutions have regulatory responsibility, the MLPRBB and LRBO's should act as stakeholders and interact with these institutions in the best way possible.

Steps for performing the IWRM functions and reaching objectives

The steps we propose for the implementation of an IWRM strategy in the Lake Poopo basin are detailed in Table 4 and described in the paragraphs below. The identification and description of these steps are the product of: discussions and agreements with prefectural, municipal and indigenous authorities in the Lake Poop basin; the results of the MCDA and the stakeholder´s perception of these results; our experience in working in the rural area with both indigenous and non-indigenous people; the functions and objectives of IWRM applied to the Lake Poopo basin.

The first column shows the steps in chronological order. The second column details the most important activities that should be carried out within each step. The third column lists the actors that should preferably be involved in each step. The list is not exhaustive, as it is possible for other actors to become involved. The fourth column shows the results that must be achieved by the end of each step, in order to proceed with the next step. The achievement of the results is necessary, as the steps cannot be performed simultaneously; step one must be concluded in order to begin performing step two, and so on. The final column shows the time expected for each of the steps to be completed.

The first step in the implementation of IWRM in the Lake Poopo basin, the conformation of the MLPRBB, implies several stages. First, it is important that the related ministries, especially the Ministry of Environment and Water, and the Prefecture of Oruro reach a consensus regarding the creation of the MLPRBB in accordance to the National Basin Plan. Without consensus between central and regional government, the creation of this special Bureau is not feasible. Second, the institutional arrangement of the MLPRBB should be defined, as well as the roles and responsibilities of the different related local and national institutions. The final stage is for the MLPRBB to follow the process to be legally constituted as an entity within the Prefecture of Oruro, with a budget, equipment and a team of selected professionals.

Once constituted and operating, the MLPRBB should hold meetings throughout the basin with all relevant authorities, stakeholders, and stakeholder organizations in the basin. This will be vital in enabling the institution to a) inform regarding its objectives and functions b) position itself in the basin as an institution working for the well-being of the entire community c) obtain up-to- date information regarding all the authorities and relevant actors operating in the region, and d) lay the ground for its up-coming training campaign.

Table 4. Proposed steps and expected timetable for implementing IWRM in the Lake Poopo basin

Step	Activities	Actors involved	Expected results	Estimated Time (in months)									
				3	6	9	12	15	18	21	24	27	30
Conformation of Main Lake Poop River Basin Bureau (MLPRBB)	- Human resources - Statutes - Legal framework - Designation of funds - Equipment	- Ministry of Environmental and Water - Prefecture of Oruro - Municipalities	The MLPRBB is legally established with a team of qualified professionals. equipment & budget	■	■	■							
Conformation of network of stakeholders	Meetings with: municipal authorities, indigenous authorities. private sector, NGOs and other related organizations	MLRBB Municipalities, local and indigenous authorities	- Data base of sub- basins (GIS) Authorities, NGO's and private sector (companies) operating in en each sub-basin is elaborated - Ground is laid for the training phase			■	■						
Training and capacity building of stakeholders	Training of authorities and population in the following subjects: Climate change. Water management, conflict resolution, sustainable agricultural and industrial practices	MLPRBB Training consultants Universities NGO's	Authorities at different level are trained and capacitated to managed their water sustainably and identify need and obstacles for WRM in their sub-basins (see Annex 1)				■	■					
Conformation of LRBOs	- Selection of LRBO Directive - Legal framework - Statutes - Budget	MLPRBB Municipalities Local and indigenous authorities	22 LRBO's are legally created, have an available budget and ready to operate						■	■			
LRBOs conduct a base line or diagnostic of water management conflicts and needs in each of the 22 sub- river basins and elaborate a Sub-Basin Plan (SBP)	Prepare and regularly update the Basin Plan incorporating stakeholder views on development and management priorities for the basin, and using it to inform the annual work plans of the LRBO's.	LBROs in coordination with the MLPRBB Municipalities Stakeholders	Conflict problems Needs are identified Basin Plan to be updated regularly								■	■	■
Implementation of infrastructure and water management projects based on each of the Sub-Basin Plan *(this phase requieres especial timetable according to the projects to be executed)*	Promotion of norms and regulations Construction of dams, reservoirs. Water- harvesting projects Conflict mediation on the basis of integral water management	MLPRBB in coordination with the LRBO and other stakeholders	Needs identified in the SBPs are meet Conflicts identified in the SBPs are resolved Therefore the quality of life is improved, water allocation is equitable.										■

The training campaign is one of the most important steps for the implementation of a sustainable IWRM strategy in the region. It is the key step for empowering women and local authorities to make informed decisions and take action regarding water management. To carry it out, the MLPRBB should hire a team of training consultants to design the curricula, the material and the best manner in which to conduct the workshops. It can be expected, for example, that several translators will be needed to deliver the content in the people's native tongue, and that the content will need to be accessible to the different stakeholders receiving the training.

The coordination among the MLPRBB, the training consultants, the municipalities and indigenous authorities will be vital in this stage, in which the ground will be laid for the conformation of the 22 Local River Basin Organizations. If the campaign is carried out without coordination among these entities, conflicts could arise between them, and the legitimacy of the entire IWRM strategy could be questioned. For example, the content of the training in the communities should be approved by the relevant indigenous authorities, otherwise the campaign could be perceived as being vertical and imposed. The training consultants themselves should be approved by the municipal and indigenous authorities, as their rejection by either of these entities could jeopardize the success of the campaign.

As the LRBOs are instrumental in the implementation of the IWRM strategy, their conformation must be carefully carried out. For example, they have to be legally constituted entities under Bolivian law, but also incorporate traditional means of selecting officials and representatives to ensure their ability to operate in their particular sub-basin. This will help them remain participative and inter-cultural organizations. Because women are the major stakeholders at household level in terms of water management, and to ensure equal opportunities of participation, gender considerations should be taken into account in the conformation of the LRBOs.

Once conformed, the first responsibility of the LRBOs will be to define clear water management objectives. These objectives should preferably be presented to, discussed with and clarified for the stakeholders of the river sub-basin through seminars and workshops. This is important in order to make the LRBOs into participative institutions and to create ownership and acceptance of their functions and objectives. For the factors, requirements and links necessary for the LRBOs to reach a certain objective, see the Capacity Matrix and the Matrix identifying activities and factors for LRBOs (Annexes III and IV).

The water management objectives set by each LRBO should be part of the Local River Basin Plan (LRBP). This plan, elaborated by each LRBO, should comprise a diagnosis of the situation of the river sub-basin, identify the most pressing water-related conflicts and threats to the region, and propose possible solutions to these. This stage will require that the MLPRBB coordinates with the LRBO, providing technical support, tools and orientation. Cooperation with other stakeholders, such as municipalities and indigenous authorities, will also be essential.

The LRBP should not be understood as a goal in and of itself, but an instrument that must be periodically re-elaborated in order to incorporate dynamic factors such as the effects of rapid climate change, extreme weather events, growth or decrease in population, new industries operating in the region, change in authorities and policies, etc.

The LRBP elaborated by the local organizations must be presented to the MLPRBB for evaluation and for the implementation of an IWRM strategy throughout the Lake Poopo Basin. This strategy, based on the water-related needs, conflicts and threats to each sub-basin (reflected in each of the LRBPs), will most likely comprise a combination of infrastructure projects (water harvesting, reservoirs, etc.), water-management projects (efficient irrigation and allocation of water), source control actions (e.g. reforestation), as well as conflict resolution and water governance (promulgation of regional water management policies and regulations, etc.). Finally, it should be stated that the implementation of the IWRM strategy is an on-going and dynamic process that does not conclude with the execution of one or several projects. To the contrary, it implies constant re-elaboration in order to meet ever-changing environmental, socioeconomic and cultural conditions.

Conclusions

The climate of the world is changing. The Lake Poopo basin is ill-suited to meet changes of all kinds. The region's poor water management leaves it vulnerable to extreme weather events and even to small changes of the hydrological conditions as pointed out by Pillco and Bengtsson (2006). The basin's natural recovery capacity diminishes every day due to environmental degradation and irrational use of the soil and other resources. If this situation is not reversed, migration will continue to rise, desertification will advance and this land, rich in cultural and natural resources, could be barren and uninhabited in the next few decades.

In contrast, if the IWRM strategy is successfully implemented in the Lake Poopo basin, the following results could be obtained: the challenges of Climate change and extreme weather events are met successfully due to water management infrastructure and education projects; the quality and availability of water is better and more predictable, improving the socio-economic situation of people in the basin, thus migration from the basin is reduced; there is a culture of water management which makes the changes and improvements sustainable; there is a culture of inter-sector cooperation and conflict resolution with regards to water management; people and organizations work together to manage water in a sustainable manner; new and improved laws and regulations clearly establish limits and guidelines for water management, and also the entity responsible for the enforcement of these laws and regulations; the Main River Basin Bureau (MLPRBB) and the Local River Basin Organizations (LRBOs) are solid institutions that work together in coordination with other private and public sector organizations, in accordance with the traditions, customs and beliefs of the local people, making the strategy sustainable

The only way to achieve this is to implement an IWRM strategy with the active participation of stakeholders. If the stakeholders are unwilling to work together, or if they feel estranged from the strategy's objectives, there can be no sustainable management of the water resources in the region. Thus, the implementation of this strategy must motivate and educate the stakeholders so they are committed to the strategy's objectives and willing to put their efforts on tasks and activities, the benefit of which may not be felt immediately. Their ability to work together to achieve long-term objectives is key. This can only be achieved through an intensive education campaign.

The basin's rich cultural diversity is a factor that must be taken into account. Although it implies some obstacles, such as the three different languages spoken and different levels of indigenous authority, the cultural diversity can also be an ally in the implementation of an IWRM strategy. For example, the indigenous people's traditional means of organization can be taken advantage of for the conformation of the LRBOs, and their view of the world, which sees humanity as an intrinsic part of the natural world and states that all living and natural resources are connected, can help to consolidate the concept of integrated water management.

Finally, given that *ayllu* and other indigenous authorities have been key actors in the management of water resources in rural areas for hundreds of years, any IWRM strategy implemented in the future must highlight their role and provide these authorities with support from municipalities and the regional government.

The success of an IWRM strategy in the Lake Poopo basin will greatly depend on the ability of the main implementing actor to regard the implementation as a dynamic process, one that takes into account and adapts to not only the basin's cultural, political and socioeconomic characteristics, but also to the country's political climate, the existence or lack of environmental policies, etc. The strategy must be conceived not as a goal in itself, but as a process which can and must be adjusted to meet emerging challenges in the context of rapid climate change.

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Annexes

Annex Ia: Absolute priorities of MCDA (Criteria, Conflicts, and Instruments)

level 1 & 2			level 3						
w_{Ii}			w_{I1}	w_{I2}	w_{I3}	w_{I4}	w_{I5}	w_{I6}	w_{I7}
$w_{C1\ (Env)}$	0.620								
w_{Co1}		0.243	0.429	0.113	0.185	0.033	0.122	0.076	0.041
w_{Co2}		0.089	0.054	0.106	0.414	0.074	0.152	0.138	0.063
w_{Co3}		0.142	0.035	0.189	0.036	0.107	0.357	0.201	0.075
w_{Co4}		0.136	0.042	0.307	0.029	0.062	0.184	0.343	0.033
w_{Co5}		0.037	0.085	0.104	0.330	0.080	0.213	0.151	0.037
w_{Co6}		0.057	0.357	0.184	0.026	0.047	0.102	0.131	0.152
w_{Co7}		0.053	0.017	0.146	0.027	0.461	0.118	0.175	0.056
w_{Co8}		0.053	0.018	0.252	0.078	0.175	0.175	0.201	0.101
w_{Co9}		0.045	0.019	0.119	0.291	0.040	0.146	0.330	0.055
w_{Co10}		0.146	0.017	0.075	0.068	0.161	0.114	0.391	0.174
$w_{C2\ (Soc)}$	0.324								
w_{Co1}		0.042	0.429	0.113	0.185	0.033	0.122	0.076	0.041
w_{Co2}		0.214	0.054	0.106	0.414	0.074	0.152	0.138	0.063
w_{Co3}		0.240	0.035	0.189	0.036	0.107	0.357	0.201	0.075
w_{Co4}		0.213	0.042	0.307	0.029	0.062	0.184	0.343	0.033
w_{Co5}		0.018	0.085	0.104	0.330	0.080	0.213	0.151	0.037
w_{Co6}		0.059	0.357	0.184	0.026	0.047	0.102	0.131	0.152
w_{Co7}		0.078	0.017	0.146	0.027	0.461	0.118	0.175	0.056
w_{Co8}		0.071	0.018	0.252	0.078	0.175	0.175	0.201	0.101
w_{Co9}		0.037	0.019	0.119	0.291	0.040	0.146	0.330	0.055
w_{Co10}		0.028	0.017	0.075	0.068	0.161	0.114	0.391	0.174
$w_{C3\ (Eco)}$	0.056								
w_{Co1}		0.034	0.429	0.113	0.185	0.033	0.122	0.076	0.041
w_{Co2}		0.154	0.054	0.106	0.414	0.074	0.152	0.138	0.063
w_{Co3}		0.089	0.035	0.189	0.036	0.107	0.357	0.201	0.075
w_{Co4}		0.079	0.042	0.307	0.029	0.062	0.184	0.343	0.033
w_{Co5}		0.079	0.085	0.104	0.330	0.080	0.213	0.151	0.037
w_{Co6}		0.051	0.357	0.184	0.026	0.047	0.102	0.131	0.152
w_{Co7}		0.048	0.017	0.146	0.027	0.461	0.118	0.175	0.056
w_{Co8}		0.130	0.018	0.252	0.078	0.175	0.175	0.201	0.101
w_{Co9}		0.181	0.019	0.119	0.291	0.040	0.146	0.330	0.055
w_{Co10}		0.154	0.017	0.075	0.068	0.161	0.114	0.391	0.174

Annex Ib: Relative priorities of MCDA (Criteria, Conflicts, and Instruments) and total weighting of Instruments I1 to I7

Level 1 & 2			level 3						
			w_{I1}	w_{I2}	w_{I3}	w_{I4}	w_{I5}	w_{I6}	w_{I7}
$w_{C1\ (Env)}$	0.620								
w_{Co1}		0.150	0.065	0.017	0.028	0.005	0.018	0.011	0.006
w_{Co2}		0.055	0.003	0.006	0.023	0.004	0.008	0.008	0.003
w_{Co3}		0.088	0.003	0.017	0.003	0.009	0.031	0.018	0.007
w_{Co4}		0.084	0.004	0.026	0.002	0.005	0.015	0.029	0.003
w_{Co5}		0.023	0.002	0.002	0.007	0.002	0.005	0.003	0.001
w_{Co6}		0.035	0.013	0.006	0.001	0.002	0.004	0.005	0.005
w_{Co7}		0.033	0.001	0.005	0.001	0.015	0.004	0.006	0.002
w_{Co8}		0.033	0.001	0.008	0.003	0.006	0.006	0.007	0.003
w_{Co9}		0.028	0.001	0.003	0.008	0.001	0.004	0.009	0.002
w_{Co10}		0.091	0.002	0.007	0.006	0.015	0.010	0.035	0.016
$w_{C2\ (Soc)}$	0.324								
w_{Co1}		0.014	0.006	0.002	0.003	0.000	0.002	0.001	0.001
w_{Co2}		0.069	0.004	0.007	0.029	0.005	0.011	0.010	0.004
w_{Co3}		0.078	0.003	0.015	0.003	0.008	0.028	0.016	0.006
w_{Co4}		0.069	0.003	0.021	0.002	0.004	0.013	0.024	0.002
w_{Co5}		0.006	0.001	0.001	0.002	0.000	0.001	0.001	0.000
w_{Co6}		0.019	0.007	0.004	0.000	0.001	0.002	0.002	0.003
w_{Co7}		0.025	0.000	0.004	0.001	0.012	0.003	0.004	0.001
w_{Co8}		0.023	0.000	0.006	0.002	0.004	0.004	0.005	0.002
w_{Co9}		0.012	0.000	0.001	0.003	0.000	0.002	0.004	0.001
w_{Co10}		0.009	0.000	0.001	0.001	0.001	0.001	0.004	0.002
$w_{C3\ (Eco)}$	0.056								
w_{Co1}		0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000
w_{Co2}		0.009	0.000	0.001	0.004	0.001	0.001	0.001	0.001
w_{Co3}		0.005	0.000	0.001	0.000	0.001	0.002	0.001	0.000
w_{Co4}		0.004	0.000	0.001	0.000	0.000	0.001	0.002	0.000
w_{Co5}		0.004	0.000	0.000	0.001	0.000	0.001	0.001	0.000
w_{Co6}		0.003	0.001	0.001	0.000	0.000	0.000	0.000	0.000
w_{Co7}		0.003	0.000	0.000	0.000	0.001	0.000	0.000	0.000
w_{Co8}		0.007	0.000	0.002	0.001	0.001	0.001	0.001	0.001
w_{Co9}		0.010	0.000	0.001	0.003	0.000	0.001	0.003	0.001
w_{Co10}		0.009	0.000	0.001	0.001	0.001	0.001	0.003	0.002
Total weighting			0.119	0.166	0.137	0.107	0.181	0.214	0.075
Rank			5	3	4	6	2	1	7

Annex II: Functions of water resources management and related activities at a river sub-basin scale (Cap-Net, 2008) adapted to the Lake Poopo basin

Function	Activities
Stakeholder participation – Implementing stakeholder participation as a basis for decision making that takes into account the best interests of society and the environment in the development and use of water resources in the basin.	Develop and maintain an active stakeholder participation process through regular consultation activities. Provide specialist advice and technical assistance to local and indigenous authorities and other stakeholders in IWRM. Creation of the LRBO's.
Water allocation – Allocating water to major water users and uses, maintaining minimum levels for social and environmental use while addressing equity and development needs of all stakeholders.	Promote the creation of norm and regulations regarding the use of water. License of water uses, including enforcement of these.
Pollution control – Managing pollution using polluter fines principles and appropriate incentives to reduce most important pollution problems and minimise environmental and social impact.	Identify major pollution problems. License and regulate polluters. Social control: vigilance of society in matters such as corruption and environmental degradation, holding authorities accountable.
Monitoring of water resources, water use and pollution Implementing effective monitoring systems that provide essential management information and identifying and responding to infringements of laws, regulations and permits.	Carry out hydrological, geographical and socio-economic surveys for the purposes of planning and development of water resources. Develop, update and maintain a climate and hydrometric database required for controlling compliance of water use allocation.
Information management – Providing essential data necessary to make informed and transparent decisions for the development and sustainable management of water resources in the basin.	Create data base for each sub-basin Define the information outputs that are required by the water managers and different stakeholder groups in a river sub-basin. Organise, co-ordinate and manage the information management activities so that the water managers and stakeholders get the information they require.
Economic and financial management – Applying economic and financial tools for investment, cost recovery and behaviour change to support the goals of equitable access and sustainable benefits to society from water use.	Set fees for water use (water supply, irrigation and industrial) Set charges for pollution in compliance with the existing norm and regulations
River basin planning – Preparing and regularly updating the Basin Plan incorporating without any excuses to the stakeholder views on development and management priorities for the basin.	Base line with active participation of stakeholders. Conduct situation analysis with stakeholders. Assess future developments in the basin.
Flood and drought management – Investments in: a) Integrated flood management within basin plans improve the beneficial use of water and minimize losses from floods. b) Drought management brings benefits by reducing the economic, social, and environmental costs associated with drought.	Elaborate a risk map Forecasting and early warning systems Infrastructure to carry water to dried areas Infrastructure to protect the flood areas

Annex III.

Capacity matrix and progress indicator of water resources management functions

Function	Water Management Objectives	Progress indicator	Unit/ definition
WATER ALLOCATION Allocating water to major water users and uses, maintaining minimum levels for social and environmental use while addressing equity and development needs of society.	Major water users are known and are managed through a licensing (or permit) system.	Number of surface and groundwater users licensed according to the regulations.	Number. Number of licenses issued. May be further subdivided by use.
	Water allocation is in line with sustainable use, economic efficiency and social equity principles.	Water allocation criteria include use efficiency, economic benefit and social goals.	Review. Examine allocation criteria for compliance with IWRM principles.
		% of time environmental and social reserve is maintained in major water courses.	%. Number of records from water resource monitoring stations with flows lower than the reserve divided by the total records x 100. A determination of the reserve is required.

Function	Water Management Objectives	Progress indicator	Unit/ definition
POLLUTION CONTROL Managing pollution using polluter fines principles and appropriate incentives to reduce most important pollution problems and minimise environmental and social impact.	The extent of the pollution problem is known and progress being measured.	% of surface water quality samples complying with water quality objectives.	%. Number of samples below set standard. Simplest approach is to base the determination on measurements of a few key water quality parameters.
		% of ground water quality samples complying with water quality objectives.	%. Number of samples below set standard. Most simple approach is to base the determination on measurements of a few key water quality parameters.
	Major polluters are known and managed through a licensing system.	Number of polluters licensed according to the regulations.	Number. Number of licenses issued.

Function	Water Management Objectives	Progress indicator	Unit/ definition
MONITORING Implement effective monitoring systems that provide essential management information and identify and respond to infringements of laws, regulations and permits.	The water allocation system is effective and permits are being complied with.	Proportion of water allocation permit holders complying with permit conditions.	%. From monitoring visits the number not complying with conditions divided by the total number of visits.
	The Pollution control system is effective and permits are being complied with.	Proportion of water pollution permit holders complying with permit conditions.	%. From monitoring visits the number not complying with conditions divided by the total number of visits.
	Knowledge of water resource availability is a basis for management, especially in wet periods to face the dry periods & scenarios.	Number of water resource monitoring stations producing reliable data.	Number. Number of stations with reliable data records.
		Total water storage and harvesting capacity.	The water storage capacity in artificial storage structures above an aprox. minimum size
		% groundwater monitoring stations with declining water levels.	%. Comparison of water levels over a 5 year period.

Function	Water Management Objectives	Progress indicator	Unit/ definition
BASIN PLANNING Prepare and regularly update the Basin Plan incorporating stakeholder views on development and management priorities for the basin, and using it to inform the annual work plans of the RBO's.	Basin planning synthesizes technical and social priorities for the basin and acts as a basis for action and accountability to the stakeholders.	Water management activities driven by Basin plan.	Review. Examine the link between the basin plan and current water management activities.
		Stakeholder priorities reflected in the basin plan.	Review. Examine the basin plan for stakeholder consultation and content.

Function	Water Management Objectives	Progress indicator	Unit/ definition
ECONOMIC AND FINANCIAL MANAGEMENT Applying economic and financial tools for cost recovery and behaviour change to support the goals of equitable access and sustainable benefits to society from water use.	Water use efficiency improving through use of economic and financial instruments.	Charges and fees for water allocation favour the poor and efficient water use.	Review. Examine for the application of economic and financial tools in water allocation.
		% revenue received.	%. Total revenue divided by the total amount billed.
	Pollution reducing through use of economic and financial instruments.	Pollution charges give incentive to reduce pollution.	Review. Examine for the application of economic and financial tools in water pollution.
		% revenue received.	%. Total revenue divided by the total amount billed.

Function	Water Management Objectives	Progress indicator	Unit/ definition
INFORMATION MANAGEMENT Provide essential data necessary to make informed and transparent decisions for development and sustainable management of water resources in the basin.	Essential information is processed and packaged at the right level for specific managers and stakeholders to support transparent decision making and to gain commitment and political support for the decisions made.	Data base is established in formats compatible with other river basin organizations.	Review. Data base is transferable across basins in the country and for transboundary systems.
		Water management information is available to managers and other stakeholders as required.	Review. Examine availability of basin data and reports on water resource management indicators.

Function	Water Management Objectives	Progress indicator	Unit/ definition
STAKEHOLDER PARTICIPATION Implement stakeholder participation as a basis for decision making that takes into account the best interests of society and the environment in the development and use of water resources in the basin.	Effective cooperation between government agencies with responsibilities for water management or water use in the basin.	Number of meetings of water-related Government agencies to consult and collaborate on water management.	Number. Number of formal or ad hoc meetings at interagency level.
	Stakeholder participation is institutionalized in the management of the river basin.	Formal stakeholder structures established with clear roles and responsibilities in water resources management.	Review. Examine basin water management structure for stakeholder organizations and allocated management roles.
		Basin stakeholders (male and female) represented in decision making bodies at all levels.	Number. Representatives from stakeholders serving in government water management structures.

Annex IV.
Matrix for identifying activities and factors necessary for LRBO's

OBJECTIVE	FACTORS			
	Human skills & abilities	**Organizational Support**	**Financial Support**	**External Support**
Water Management Objective (Final activity to meet the objective)	**Capabilities** • Technical skill • Administrative skill • Managerial skill • Knowledge • Conflict resolving and consensus building ability **Efforts** • Will & motivation • Drive & energy • Concentration • Work ethic • Efficiency	**Resources** • Staff • Technical facilities • Office facilities • Equipment • Transport • Spares • Fuel • Service & maintenance **Specified objectives** • Vision • Values • Policies • Strategies • Interests **Management** • Planning • Designing • Sequencing • Mobilising	**Resources** • Government budget • Generated income • Grants from donors **Budget items** • Salaries • Investments - equipment - vehicles - materials - etc. • Running expenses - Fuel - Spares - Communication - Rental, - etc.	**Input from other water organizations** • National and bi-lateral authorities • Water Supply Services • Universities **Stakeholder for a** • Basin committees or councils • Local Governments • Water users **Cross-sector support** • Governmental ministries • International Cooperation • NGOs • Research Centres • Laboratories • Others