Description of the Elqui River Basin

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1 INTRODUCTION

The United Nations Framework Convention on Climatic Change was enforced at the UN office in New York on May 9, 1992. The signing of this document was in response to the warnings made during the 80's on the basis of scientific data concerning a predicted global climatic change due to the effects of GHG (Greenhouse House Gases). The outcome of this convention evolved into worldwide action on March 24, 1994. In Chile this convention was enforced in April 13, 1995 committing Chile to a series of actions toward climatic change stabilization through gradually lowering the GHGs in a way that ecosystems may adapt and sustainable economic development can occur (CONAMA, 2004).

This commitment involves the following actions:

1. To provide systematically updated inventories of GHGs with respect to their amount and absorption from waste deposits
2. To develop regional / national programs aiming at diminishing and preventing potential effects and fostering adaptation.
3. To strengthen technical and scientific research, climatic system surveillance, and to encourage the development of technologies, training and processes to control, reduce or prevent human generated GHGs.

In 1997 Chile also participated in the elaboration and enforcing of the Kyoto Protocol, in order to comply with its strict reduction and limiting of the amounts of GHGs.

There are two governmental entities in charge of national measures regarding global climatic change: the Environmental National Commission (CONAMA) and the Ministerio de Relaciones Exteriores (Ministry of Foreign Affairs). CONAMA is in charge of carrying out national studies, programs and strategies while the Foreign Affairs Office is in charge of the engagement in international activities regarding Global Climatic Change (CONAMA, 2004).

In 1996 Chile created the "Comite Nacional Asesor sobre Cambio Global" (CNAC), whose main functions are to advise the CONAMA on how to carry out the commitments of the Climatic Change Conference, and advise the Ministerio de Relaciones Exteriores regarding national viewpoints on the decisions adopted by the Conference.

In 1999 and consistent with its commitments, CONAMA elaborated the 1993 and 1994 GHGs national base inventory. A study was carried out in order to analyze possible alternatives to reduce GHGs for the energy and non-energy sectors, along with measuring vulnerabilities and adaptation to climatic change effects on the hydrological resources, agriculture, land use change and forestry (CONAMA, 2004).

Bilateral cooperation was established between the CONAMA and the EPA from USA, regarding the analysis of the benefits (non environmental) of mutual cooperation concerning climatic change matters; the study of climatic change gains from national environmental measures, the analysis of flexible mechanisms of the Kyoto Protocol, and broadcasting and training.

2 STUDY AREA

The study area is Chile's fourth Region (Figure 1); also know as the Coquimbo Region. This Region is characterised by a semiarid climate, and a series of transverse valleys that go from the Andes to the Pacific Ocean with an East to West orientation

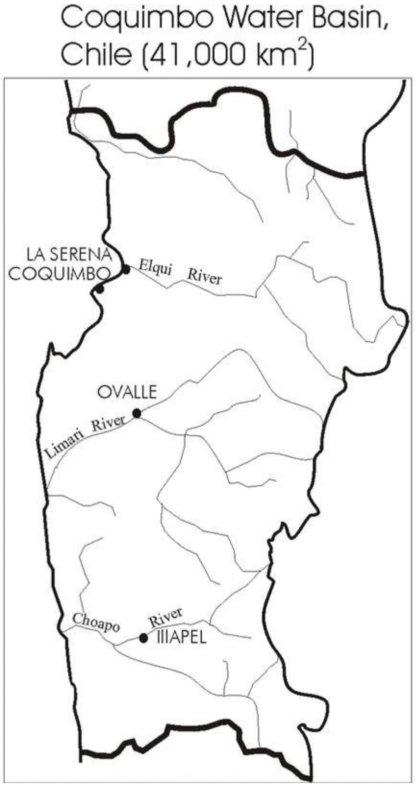

Figure 1.- The Coquimbo

The Region has a population density of 12.4 habitants per Km^2. In spite of the small water flow (caudal), the regularity of its water courses in the valleys explain concentrated populations along the valleys. In the Coquimbo Region the main cities are usually linked to other minor urban centres (Vicuña, Ovalle and Illapel), through the communication corridor of the East-West valleys (Elqui, Limarí and Choapa), which end at shipping ports (Coquimbo, Los Vilos). The cities also are concentrated at the margins of the national interstate (Carretera Panamericana). Nearly 75% of the regional population is classified as urban, concentrated at the most important cities: Coquimbo, La Serena and Ovalle. Negative rates of population change and a high degree of social risk are especially found at the comunas Punitaqui, Canela, Paiguano and La Higuera (Soto G. & Ulloa F., 1997).

2.1 General Description

Although there have been many descriptions of the fourth Region's landscape, Paskoff's geomorphological description is the most accepted (Bodini, H. & F. Araya. 1999). It consists of the following categories: High Mountain, Middle Mountain, Coastal Band and the Transverse Valleys.

The High Mountain is described as the eastern sector linked to the Andes where there are uniform elevations and absence of volcanoes. Altitude is 3,000 meters and above, with the presence of peaks, mountainsides and valley flows of the main rivers where glacier activity can still be seen. At these High Mountain valleys snow and ice accumulation feeds the Region's main rivers and gives them a stable water flow.

The Middle Mountain region presents altitudes between 600 and 3,000 meters above sea level. It is characterized by the presence of minor mountain ranges. Far from the coastal influence, atmospheric humidity, and groundwater, this area presents a very high aridity. These interfluvial landforms have always been marginal land whose population and agriculture has been focused on subsistence. Here we find one of Chile's most devastating examples of vegetation destruction due to wood chopping for mining purposes, coal production and overgrazing, among other activities.

The Coastal Band is a very typical regional landscape. Altitudes vary between the sea level and 600 meters, where wide marine terraces are associated at its eastern margin with alluvial cones, debris near the base of mountains and debris cones. Due to direct contact with oceanic air masses, fog and abundant cloudiness, a higher precipitation and relative humidity can be found, supporting a typical steppe shrub. Human population is usually found at specific locations where ports are present and tourism has developed in the last few years.

The lower and middle parts of the valleys, which host the Elqui, Limarí and Choapa Rivers, the Transverse Valleys that give the Coquimbo Region the name of "Green North". The flows of these rivers, in spite of being irregular, join one another in the Middle Mountains and marine terraces (westward) are significantly distinct from the rest of the arid and semiarid landscape that surrounds them (Bodini, H. & F. Araya. 1999).

The spatial relationship between adequate soils, low slope fluvial terraces, high solar radiation, and permanent surface and subsurface water, constitute the most outstanding geographical-physical pattern of the Coquimbo Region.

2.2 Economic Activities

According to the 2002 census, the population of the Coquimbo Region consists of approximately 605,000 inhabitants. The economic activities are more diverse than the adjacent regions, where gold and steel mines are the most important, representing 36% and 60% of the country's total production.

Almost 43% of the region's surface dry land is dedicated to agricultural development. The main products are fruits, wine vineyards for “pisco” production (a Chilean brandy), horticulture and flowers all of which have a high workforce demand. The agricultural production mentioned before is very dependent on water availability derived mainly from snow and glaciers in the Andes.

Livestock production in the Region is basically caprine (goats), which has an important desertification effect over the region's surface due to its feeding habits.

There is also an important industrial fishery related to the rich waters of the Humboldt current. A very interesting activity that has been gaining importance is tourism, mainly concentrated in the two largest cities: La Serena and Coquimbo.

Poverty is mainly focused on the rural sector: approximately 20% of rural families are classified as poor. The rate of urban poverty, in comparison, is 11%. In these terms, poverty is a regional issue that should be considered in the study.

3. CLIMATE CHANGE VULNERABILITIES AND ADAPTATION

3.1. Introduction

There is scientific evidence indicating that global climate is changing, mainly due to processes induced by anthropogenic activities (Akin, 1991; Folland et al., 2001). Revelle (1986) has noted that climate change could gravely alter the existing geographic patterns related to seasonal temperature, precipitation and evapotranspiration with disastrous consequences for some agricultural zones and with beneficial outcomes for others. The rate of the climate change would be slow enough as to allow human communities to adapt to it, perhaps by large scale migrations (Revelle 1986). However, the actual rate of climate change is greater than those recorded in the past. In addition, the impact generated by humans upon the natural communities portrays a scenario, which has not been observed previously in this planet. Consequently, the species and natural communities will not have sufficient time to adjust to the new conditions (Arroyo el al., 1993; IPCC, 2001).

Water resource scarcity is one of the greatest problems that humanity will confront in the next decades (PHI, 2001). It is foreseen that this issue will generate serious conflicts between neighboring nations (Fernández-Jauregui, 2001). In Chile, water availability per capita in the North is less than 1,000 m^3/hab/year, in some instances decreasing to 500 m^3/hab/year. These ranges are considered internationally to be restrictive for the economic development of nations (DGA, 1999).

Regional water resource availability depends upon the system's hydrologic balance, which depends upon the interannual dynamic of the region's hydrologic cycle. The hydrologic cycle depends upon a constant water interchange between the oceans, ice layers, the atmosphere and the earth surface. The evapotranspiration from the earth surface depends upon the atmosphere temperature, incidence radiation, wind, atmospheric humidity and plants' transpiration (Maidment, 1993; Brutsaert, 1982). The water vapor distribution, clouds, precipitation and corresponding energy transport are less understood climatic system components in quantitative terms, despite being studied intensively since 1988 through the global energy monitoring campaign and hydrologic cycle GEWEX. The water vapor concentration increases in the atmosphere, as a consequence of the global temperature increase (greenhouse effect), accelerating climatic processes. The increase of extreme climatic events coupled with high damage potential is the consequence of the intensification of processes inherent to the hydrologic cycle. Thus, hydrologic cycle variations will be highly important regionally (Losan et al., 2001).

Moreover, the desertification or productivity deterioration in arid environments has been recognized as a critical problem around the world (Naciones Unidas, 1978; Conferencia de las Naciones Unidas sobre Medio Ambiente y Desarrollo, 1992; Convención de las Naciones Unidas de Lucha contra la Desertificación y la sequía, UNCCD 1994; UNCCD-Chile, 2000).

Desertification processes involve both natural and human elements, leading to environmental productivity loss as well as to the quality of human life (Naveh & Lieberman, 1993; Soto & Ulloa, 1997; Squeo et al. 2001).

3.2 Regional Climate

Climate of the Coquimbo Region is affected by the interaction of three factors:

a) The southeast Pacific anticyclone, which almost always blocks the frontal precipitation systems. As a consequence of the persistency of this atmospheric circulation system the Coquimbo Region is characterised as an arid climatic zone;
b) the cold Humboldt current along the Pacific coast;
c) the Andes mountains which create a longitudinal barrier to the westerly winds (Kalthoff et al., 2002)

It shows steep climatic gradients from the coastal zone towards the interior, reducing the aridity along the coast, and increasing the aridity towards the interior with fluctuating isohyets between 25 and 300 mm of precipitation, concentrated primarily during the winter season; but during El Nino years there is an important increase in precipitation. The dry season lasts approximately 10 to 12 months yearly. Along the coastal belt, at some few places an abundant condensation accumulates, which constitutes an important water resource for vegetation development, which may exceptionally contribute more than 500 mm of additional precipitation per year (Santibáñez, 1985).

In summary: The climatic characteristics of the Norte Chico include a periodic water scarcity, product of the precipitation variability, which is manifested in long and persistent dry periods (Santibáñez, 1985; Azócar et al., 1990; Romero & Ihl, 1991). But it should be noted, that the ENSO phenomena (see further) has a great influence in the climatological oscillations in this region.

3.3 Regional Climate Change

Calculations based on global climatic models, with a hypothesis of doubling the CO_2 concentration in the atmosphere relatove to the 1990's condition (CONAMA, 1999), indicate for the Coquimbo Region the following climatic scenarios: 1) A warming of 2ºC to 3ºC (Beniston, 1994; Novoa & Cortés, 1997) during the second decade of the XXI century; 2) a 10% increase in precipitation the mountains and foothills (Halpin, 1994), with a 20% to 25% liquid precipitation decrease (Azócar et al., 1990; CONAMA, 1999); 3) A flow increase in the short and/or medium term, subject to the melting of some snow and ice reserves from the river basins as a consequence of the temperature increase.

Current evidence indicates changes in some of the climatic parameters. The temperatures and relative humidity show a trend towards increases for a 100 year data base located in La Serena-Coquimbo (30ºS) area (Novoa & Cortés, 1997). The average precipitation in La Serena has been dramatically reduced in the past 100 years. The 30-year running mean has decreased from 170 mm in the early XX century to values currently under 80 mm (Santibáñez, 1997; Soto & Ulloa, 1997; Novoa & López, 2001). This represents a 100 mm/year movement of the isohyets towards the south, which has caused a desertification of approximately -0.7 mm/year.
However, it is important to note that those regions located east of the Andes Range, have registered an opposite trend in the precipitation time series (Soto & Ulloa, 1997; IPCC, 2001, see Fig. 1).

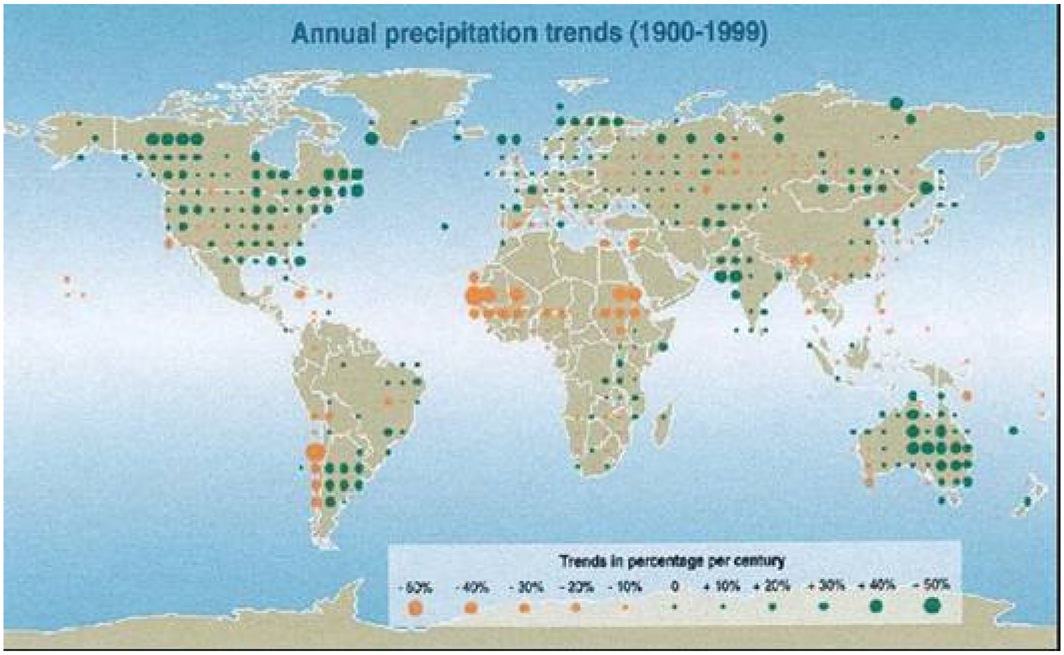

Figure 1. Global annual precipitation trends (1900 – 1999) (IPCC, 2001). The North-Center of Chile shows a 50% precipitation decrease in the last century.

3.4 Regional Hydrology

In the Coquimbo Region the river flows show an enormous variability from one year to the next (Downing et al., 1994). For instance, the average flow of the Elqui River annually varies between 2.4 m^3s^{-1} and 33 m^3s^{-1} (DGA, 1991;), Some mountain watersheds in the the Coquimbo Region show a trend of natural flows that increase, both monthly and annually (Novoa et al., 1995, 1996). The Elqui River, one of the main rivers in the Coquimbo Region, showed a trend of flow increase on the basis of 40 year data between 1950-1990 (Novoa et al., 1996). The Elqui, Limarí and Choapa Rivers' high flow also show an increase, but in different order of magnitude (Novoa et al., 2000). The flow increase may be considered contradictory with the Norte Chico aridization trend shown by the models applied in this zone, which have taken into account the precipitation decrease (Santibáñez, 1985; Romero & Ihl, 1991; Gwynne & Meneses, 1994). Today, the causes of the flow increase are still unknown; however, the melting of snow and ice resources in the Andean region of the basin is suspected (CONAMA, 1999).

The aquifers play a significant role in the global hydrologic cycle. However, systematic studies of the aquifers and existing research related to the dynamics of this resource do not exist at representative scales of the Coquimbo regional reality (Mapa Hidrogeológico, 1989). There are some more detailed hydrological studies for the lower part of the Elqui River basin, focused on the hydrological resource volume estimation (CORFO, 1955; Celedón, 2001). In addition, a study on the aquifers isotopic characterization is being developed. The first results have been obtained for some sectors of the Coquimbo Region (Strauch et al, 2002).

There are few studies related to the Andean zones that show permafrost characteristics and/or the temporal/spatial evolution of such zones (Lliboutry, 1956; Marangunic, 1976; Trombotto et al., 1997; Francou et al., 1999; Novoa & Robles, 1999): but in the Coquimbo region there are not information about the hydrological relevance of the permafrost.

One of the problems emphasized by CONAMA (1999) is related to the risk of the future water availability in the long term as well as to the adverse climate change implications on the hydrologic cycle of the Andean ecosystem. A recommendation of this report is the urgent elaboration and implementation of a monitoring and surveillance system for the understanding, management and potential regulation or control of the hydrologic cycle.

In addition to climate change, the trend towards population and regional production increase should be considered. First, the most significant productive factors relate to mining (copper, gold, iron and silver), agriculture (pastures, fruits and vegetables) based on intensive highly technical irrigation system, tourism and ocean fishery activity. Primarily, the first three productive areas depend mostly upon hydrological resource availability. Tourist and agricultural activities are expansion areas, which will require in the future a larger availability of water. (CONAMA 1999). Additionally, the demographic growth is highly differentiated within the Region, with communities or cities with trends of swift transformation, both increased and decreased population, as shown by numerous documents on census analysis made by the National Statistics Institute. Therefore, this behaviour also will result in varying demand for hydrological resource availability.

The extensive irrigation system, by which water is extracted from the rivers and distributed by a channel system and dripping technology into the agriculture areas in the Coquimbo Region, plays an important role within the hydrological cycle. Some studies (DGA, 2002) suggest an increasing pressure on water resources, which is expected to have direct and perceptible effects on the regional hydrologic cycle in the short run. Additionally, circulation or interaction patterns within the hydrologic cycle are modified, which may have implications in the long run, establishing different equilibrium points. Furthermore, irrigation development generates return flows inducing both quantitative and qualitative changes: an efficiency increase implies modifications of aquifer recharge, changing their balance. The increased pumping of the aquifers leads to their depletion, which in turn will modify river-aquifer relationship in the fertile plain zones. According to these studies, in those areas of extreme aridity the recharge issue is a crucial factor; in this case the recharge related to high water events may be significant. In addition, the role of the saturated zone is relevant due to the way it allows flow transportation to saturated zone and in a way that may induce "losses" of the quantity of water that is "trapped" in such zone. In order to define recharge rates, it is fundamental to know the recharge transit times of those zones without superficial drainage, but with contributions in aquifer head (DGA, 2002).

Another very important aspect to be considered in the regional hydrology is the geological factor, because in the "Norte Chico" regions (III and IV), besides of the climatic condition, is the mountainous character and a high

degree of hydrothermal mineralization. This has the following implications:
a) a high percentage of precipitation falls over rocky mountains and part of this precipitation infiltrates in fractures and other permeable structures, in such a way that rocks store, transmit and interact chemically with the infiltrated water.
b) The economic development has allowed the existence of numerous fallow lying or active mine resource exploitation. These excavations and residual products provide additional opportunities for the contamination by toxic heavy metals, especially due to acidic drainage. Despite the absence of mine exploitation, such phenomena may reach significant magnitude ((Oyarzun et al., 2004; Fleet,1984; Jambor & Blowes, 1994).

Taking into account scientific studies, demographic development and trends in production , the conclusion that decreases in precipitation (although during some periods there are flow increases) and increases in water consumption are opposite factors, allow a forecast of potential scarcity of regional hydrologic resources. Thus, it is imperative to study systematically the hydrologic cycle, in order to understand the interrelationships between different components involved in the dynamics of the resource. This study is one of the main objectives for the recently established Center for Advanced Studies in Arid Zones (CEAZA; www.ceaza.cl).

3.5 Use of Mathematical Models for the Study of Hydrologic Cycle

Modelling is a useful tool because numeric models of natural phenomena tend to be a synthesis of the scientific understanding of complex systems. This tool allows the understanding of the system's total behavior (relationship between causes and effects), and it constitutes a sort of theoretical laboratory for the analysis of the interrelationships between the components of the system in a study; they are very useful for the study of the effects produced by changes of individual processes on complete systems (scenario studies). In addition, they allow the forecasting of future conditions, as a consequence of changes produced by relevant processes (naturals or anthropogenic) (Graedel and Crutzen, 1995).

Mathematical models have been used in the last decades, for instance, for the study of effects produced by changes in land uses in hydrologic basins (see Hookey, 1987, Bulton et al., 1990, Bathurst et al., 2000), global climate change, and also they have been used in the forecasting of the effects of climate change on the hydrology of a basin or a region (Caspary 1990, David and Golstein 1988).

The availability of the hydrologic resource depends on the dynamics of the hydrologic cycle. The latter mainly depends on the characteristics of the atmospheric circulation and of temperature (Graedel and Crutzen, 1995); specially over lands with hilly topography, the atmosphere is an extraordinary complex system (Kalthoff et al., 1998: Kossman et al., 1998) whose study, through numeric models, only has been approached in a practical way during the last two decades.

Based on the aforementioned considerations, the Hydrology and Models Group (H+M) from CEAZA has focused on the study of the hydrologic cycle, using the monitoring and modelling approach. This allows the inclusion of all relevant components in relation to the hydrologic balance of the Coquimbo Region .

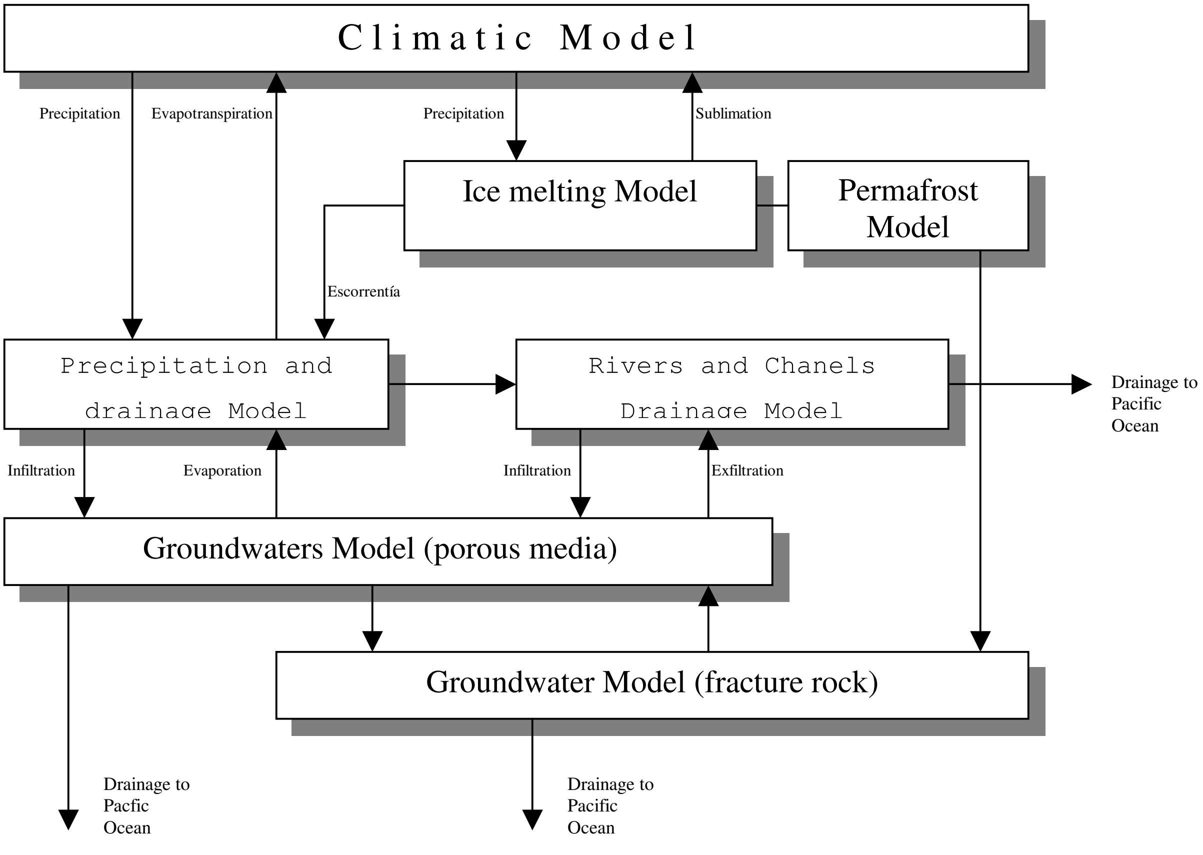

Figure 2. Concept of Integrated Models

Currently, there are models able to simulate the different partial processes of the hydrologic cycle, that is to say, climate models at regional scale such as MM5 (Grell et al., 1995), and hydrologic simulation models such as FEFLOW (Kaden and Diersch 1998), SHETRAN (Bathurst et al., 1995), MIKE11 (Havno 1995. However, the major difficulty is centred on coupling these models in order to achieve the development of an integrated model system, as is illustrated in Figure 2, that is valid in the interaction amongst the climate, atmospheric and hydrologic models at meso-scales. This is mainly the result of different time scales, which characterize those processes. Also, this is the product of the difficulty that emerges due to the fact that different numeric algorithms are inherent to each model, using discreet spatial steps with very uneven magnitudes (BMU, 1998).

The hydrologic models above mentioned are integrated systems of superficial/subsurface drainage, of physical basis and spatially distributed, where the flow component is the main part of the hydrologic cycle terrestrial phase (interception, evaporation, ice melting, superficial drainage (channels and hillsides and underground drainage). These processes are described by systems of partial differentiated equations; the solutions of the systems are approximated numerically. These systems have been applied in Chilean basins (Bathurst el al.,1998, González & Bathurst, 1998), particularly the application done on Elqui basin (González et al., 2001).

Currently, a more detailed study is being conducted on the atmospheric component of the Coquimbo region, based on atmospheric monitoring and modelling, in the context of the CEAZA activities. Special attention is made on a refined transport modelling of water vapor in the regional atmosphere (evapotranspiration product), by using the atmospheric mesoscale KAMM (Karlsruhe Atmospheric Mesoscale Model) with multiple nesting. Currently, a first draft of KAMM is being used in a study on wind regime for the Coquimbo Region (Kalthoff et al., 2002).

In order to made forecast for the Elqui basin under different future climate scenarios, it will be necessary to work with downscaling techniques, because the usual step sizes of the global climate models are so large (200 km and larger) that the results can not be applied directly to subscale phenomena, like precipitation in the Elqui river basin or even in the Coquimbo region.

3.6 El Niño – South Oscillation (ENOS)

El Niño– South Oscillation (ENSO) oceanic phenomena, due to a large scale coupling between ocean-atmosphere, for decades has been an important focus of study within the Pacific region in both hemispheres. The physical processes involving the phenomena are relatively known (eg., Rasmusson & Wallace, 1983; Blanco & Díaz, 1985). One of the main agreed interpretations is that El Niño events occur as an internal cycle of positive and negative returns within the tropical Pacific ocean-atmosphere coupled system. Ecuatorial Kelvin waves are generated and expanded from East towards South America, suppressing the thermocline and increasing sea level. The results of these changes are translated into an increase of sea surface temperature between 3ºC-5º C, and sea level increase up to 20 cm from Peru up to North of Chile (Enfield, 1989).

Large regions around the world are influenced by ENSO. ENSO events occur irregularly but typically once every three to six years (Allan et al., 1996). During a given El Niño episode, in some regions of the world rainfall increases dramatically, meanwhile in other regions severe dryness occurs. Throughout El Niño years rainfall may be four to ten fold higher than average, this phenomena lasts approximately a year. The following phase, known as La Niña, induces the opposite climatic pattern to El Niño. El Niño events bring significant ecological (Glynn et al., 1990) and economic implications (Bouma et al., 1997). Comprehensive studies have been conducted on El Niño effects in marine environments, where this climatic phenomena is correlated with dramatic changes in abundance and distribution of many organisms, and fisheries collapse (Tegner & Dayton, 1987; Jordan, 1991; Vásquez & Vega, in press). The effects on terrestrial ecosystems have been studied the least. One of the phenomena's most noticeable effects is the greening and flowering of deserts (Dillon & Rundell, 1990; Armesto et al., 1993), and agricultural crop losses (Taylor & Tulloc, 1985). Long range systematic studies have increased in recent years, which are revealing how the ENSO events may have sharp effects on vegetative and animals communities in a wide range of terrestrial ecosystems (Gutiérrez et al., 1997; Holmgren et al., 2001; Siegert et al., 2001).

3.7 Climatic effects in Latin America

Numerous researchers have shown a significant relationship between El Niño-South Oscillation (ENSO) occurrence and hydrology of countries on the Pacific Ocean basin (Waylen & Caviedes, 1986; Quinn et al., 1987; Aceituno, 1988; Chiew et al., 1997). Previous to El Niño years, winter rainfalls are heavier in North-Central Chile and West of Argentina. In Mendoza snow fall increases in the mountain region, combined with ENSO warm events, resulting in substantial flow increases during summer periods (Simonelli & Heredia, 2001). In some years, towards Northeast Brazil dry events occur during summer and austral fall, which preside El Niño phenomena in the tropical Pacific. During December until March heavy rainfall occurs in the West coast of South America. In the mountain range interior and Peruvian/Bolivian Altiplain, dry events occur during the same period. During the same period, in the low lands of Bolivia's East, Paraguay, Brazil's Southeast heavy rainfall occurs. During austral fall months high precipitation occurs in the low area of La Plata River basin and southeast of Brazil. In the Amazon basin and Ecuador's low lands towards the eastern Colombia and Venezuela rainfall during these years are less intense, and the same phenomena occurs in Colombia's high lands. The Pampa and Patagonia Regions do not response to El Niño impulses. Also, the coastal regions of central Brazil appear to act independently with regard to the phenomena (Caviedes & Waylen, 1998).

Throughout La Niña years severe dry events occur along the South America West coast, from Ecuador to South of Chile. The regions of La Plata River basin experience low winter temperature and little precipitation during fall and winter. The opposite occurs in the whole Amazon basin, East of Ecuador, Colombia, Venezuela and Guyanas, with heavy rain-fall. Also, the continent's Caribbean coast registers high pluviality during La Niña years (Caviedes & Waylen, 1998).

3.8 ENSO effects on hydrologic cycle with emphasis in Norte Chico

In Chile there is little information related to ENSO effects on the hydrologic cycle. Some research have been conducted on the impact of this phenomena in Central Chile (Aceituno & Vidal, 1990; Escobar & Aceituno, 1998), but there are no similar studies in Norte Chico or Coquimbo region. However, significant precipitation events during El Niño years are related directly with an inmediate increase of river flows (and creeks with usually no superficial drainage), temporary lagoons ("vernal pools"), aquifers recharge, erosion of dry land, among others, are important aspects of regional hydrologic cycle. Some of the effects of ENSO have been demonstrated, on some local components of Coquimbo Region hydrologic cycle. In fact, it was shown that ground water of El Romeral basin's middle and upper part (few kilometers

North of La Serena) comes from local recharge generated during heavy rainfall years associated with El Niño events (Jorquera et al., 2003).

Taking in account the lack of information and the importance of the ENSO events, the main goal of the recently created research center "Centro de Estudios Avanzados en Zonas Aridas, CEAZA" is the study of the hydrological cycle and the ecosystems of the Coquimbo region under the climatological oscillations induced by ENSO.

4. Natural Systems in the Elqui River Basin

4.1. Basin general description

Elqui river basin in region IV, Coquimbo, has a total surface of 9,600 km^2. It has two main tributaries: a) the Turbio River, with a sub-basin of 3,895 km^2, which drains the high mountains in the northern side of the main basin with an average flow of $6.48m^3$ /sec.; and b) the Claro River with a sub-basin of 1,515 km^2, which drains the high mountains in the southern side of the main basin with an average flow of $3.9m^3$ /sec. Elqui basin has climatic, physiographic and ecological features (Bodini & Araya 1998, Nova & López 2001, Cepeda 2003) which apparently make of it a natural and human system of high vulnerability to the climate changes.

Rainfall is subject to frontal systems and incursions in the continent of El Niño events. The average rainfall is low (120 mm) and very variable from one year to another , with a clear altitude gradient: 83mm on the coast, 86 mm at 640 m above sea level and 200 mm at 3.750 m above sea level, according to the last 50 years of record. The basin average slope is steep, elevation rises, in less than 150 linear kms, from 0 m. above sea level (milestone El Faro of La Serena on Coquimbo Bay) to 4,800 m above sea level (Agua Negra border junction), with mountains at about 6,300 mts. above sea level on the Argentinean border. To the extent that topography and geology are heterogeneous, watercourses, particularly those from middle and high mountains, are fast and contain an important amount of mineral salts. The main intake of water for Elqui basin comes from snowfall on high mountains. It is very variable from one year to another (CV 113%). Water stored on the Andean tops is gradually released during spring and summer time.

Dominant vegetation is steppe, mainly represented by bushes of sparse distribution; they grow in poor soils on steep slopes. Sunshine is strong particularly at middle and high elevations, and there are strong winds and an intense and rapid desertification. The highest biological activity period is from the end of spring to the beginning/middle of summer, depending on winter duration.

The ecosystem has a low natural productivity, both primary and secondary; biodiversity distribution and ecological production are especially heterogeneous, linked to spatial units with availability of surface or underground water (Anonymous 1997, Squeo et al. 2001, Cepeda 2003). Under ENSO events, the basin is subject to oscillatory periods of droughts and intense, but short, precipitation events. On these last occasions, the volumes that drain the basin transform into torrents with a destructive power, producing considerable damage, which destroy roads and cuts off inland villages, causing flooding, casualties and rural and public property damage. These torrents can eventually cause environmental emergencies when eroding down tailings of mining plants. Severe droughts generate strong pressure for extraction on underlying aquifers. During the last years this pressure has began to weaken with the operation of the Puclaro reservoir, with a capacity of 200 million m^3 of water. The ecosystem primary productivity fluctuates between these two extremes. Under these conditions, groups of wild animal species can, in occasions, make demographic eruptions that have the characteristics of pests.

Given the arid character of the basin, its steep gradient, altitudinal distribution of rainfall, economic activity concentrated at low and middle elevations, and intense desertification shown by dry barren land, the better preserved natural systems are in the high mountains. Both the river and its tributaries, except for Punta de Teatinos coastal lagoon, next to the Elqui River outlet, are relatively poor in aquatic biota.. The hilly areas and mountainous dry barren land of the basin show a more diverse biota, particularly flora and bird-fauna, although not excellent specialized habitats, except for the case of loreras (Cyanoliseus patagonus, Psittacidae), viscacheras (Lagidium viscacia, Chinchillidae) and chinchilleras (Chinchilla lanigera, Chinchillidae). Most of the significant wild life, biodiversity and endemism are restricted to the humid soils on the basin higher ground, locally known as veranadas (fertile plains used as summer pastures), which are at the present threatened by the intensive use of the vegetation resource by migrating cattle in summer time (see references). Biotic resources of humid soils and its moisture have motivated the need to establish priority for preservation and protection. By now, a significant body of knowledge about high mountain humid soils of Elqui is developing under protection of Nº 19.300 Law, which rules over environmental evaluation of projects, in particular, mining projects carried out in the area (see references).

4.2. Future climate

Using data from Geophysical Fluid Dynamics Laboratory (GFDL), an increase of between 2 and 4º C in surface temperature is expected for Chile (see Schlesinger & Mitchell 1987), between Arica (18º LS) and Chiloe (42 – 43º LS), respectively. More recently estimates project heating of 2º C around 40º South (Mooney et al. 2001), in an atmosphere with 2x more CO_2 than today. For different places in Chile, results of the GFDL model are the most appropriate (see Fuentes & Aviles 1994). Particularly, for the Mediterranean climate of Chile (30-38 ºS), various studies (Villagrán & Armesto, 1993, Arroyo et al., 1993, Contreras, 1993, Mooney *et al.*, 2001) have set out the future scenario and its consequences on the flora and fauna, predicting that the North would show a tendency to drought in the coming years, related to a rainfall decrease (Fuentes & Áviles, 1993). According to the current models there is a high degree of uncertainty, because of the changes in intensity and seasonal/ temporal variability of rainfall events in the coastal zones and Andean zones of northern Chile.

The water supply of the fourth region basins is determined by the pluvio-nival rainfall patterns. For that reason the rise in temperatures of the expected values will generate complex changes in the water cycle. Due to the rainfall decrease, particularly, glacial action decrease, periglaciar process rise (Andrade & Peña, 1993); snow melt will rise, causing a rise in the water level during winter and spring (up to 100 %), in contrast to decrease in the water level during fall and summer (from 10 to 20 %) (CONICYT, 1989. Andrade and Peña, 1993, Peña, 1993). A rise in winter rainfalls would lead to a dramatic rise of the river discharge; the risk of the river level and erosive process in winter would rise (Andrade & Peña, 1993). Also in an environment with a temperature higher by 3ºC (CONICYT, 1989), a rise of the isothermal (0ºC) and snows line elevation of 500 m is expected.

Some experts (CONICYT, 1989), considering the trend to drought in the fourth region, suggest that the expected rise in the temperature in the North of Chile would cause a rise in the intensity and southern extension of the summer rainfall (Bolivian winter). Such rainfall would reach the Andean zone of the North of the fourth region, providing water quantity during the summer.

At a local scale, Novoa *et al.* (1995, 1996a, 1996b), had recorded that the water level of *Valle del Elqui* basin showed a trend to water level rise over the 40 years 1950- 1990, contrary to the decrease expected from the natural rivers in a global change scenario. The authors concluded that those results are a consequence of the local temperature, the relative humidity of the atmosphere (Novoa *et al.*, 1996a, 1996b) and the rise of solid precipitations (Novoa *et al.*, 1995). On the contrary, Aceituno *et al.*, (1993) found that river discharge between 30 ºC and 33 ºC has shown the same variation as the precipitation time series in the S. XIX.

Huenneke (2001) has made a general forecast for the arid and semiarid zones from the world. However, it is undoubtedly that the current models only give estimates for the temperature and precipitation changes, with an important uncertainty for the latter variable. It is suggested that in northern Chile rainfalls/ precipitation quantity will decrease (Fuentes & Avilés, 1993).

4.3. Vulnerable Systems

Temporal seasonal analysis has shown a trend to annual average decrease of the precipitation at the coastal zone of the basin. Raising of the snow line has been related to climate change (Novoa & López, 2001) Information from literature suggests the snow basins such as the *Río Elqui* are among the ecosystems most affected by climate change (Anonymous, 2001). In this particular case, the gravitational energy of *Río Elqui*, rainfall alterations from the ENSO events, the low cover of vegetation, poor mineral soil and a severe drought constitute a set of factors that determine the basin vulnerability in relation to the surface water flow characteristics and the occurrence of alluviums, earth slids and floods. The rise in rate of thaw would release volumes of water and would exceed the retention capacity of the Andean wet terrains. As the water flows, the erosive processes at lower elevations would be accelerated with alterations of water quality. In the middle mountains, the more vulnerable natural systems are the native cactaceas formations, which may still be found in some irrigated land in the middle mountains and gives the landscape its character.

4.4. Strategies and Actions

The two reservoirs in the basin reduce its water scarce vulnerability. *La Laguna* reservoir (at 3,200 m. above sea level and 50 million m^3 of capacity) is a water reservoir for agricultural purposes. The new *Puclaro* reservoir (450 m above sea level and 200 million m^3 of capacity), in the lower part of the basin, works both as a flow regulator and a water reservoir for agricultural purposes. Because of its location in the lower half of the river and its good access, the *Puclaro* reservoir is also an important tourist resource, especially for sailing and windsurfing.

Except for those reservoirs, environmental management for the protection of habitat, biodiversity, recuperation plans and the preservation of wild species are in their initial step. The governmental agency CONAMA is in charge of taking the more relevant actions in the environment area. Among its actions are: to promote a strategy of protection for biological diversity, in order to meet international agreements; to increase the current conservation areas; to promote the creation of private protected areas and also to encourage the studies on specific ecosystems (see references). Most of these are in their planning or initial step. Others governmental agencies (such aa SAG or CONAF) only contribute to CONAMA actions and do not have strategies for planning. *Municipalidad de la Serena* (The local council of La Serena) has an office in charge of environmental education.

Recently (2003) the CEAZA (Center of Advanced Studies on Arid and Semiarid Ecosystems) and CAZALAC (International Center of Water for the Arid and Asemiarid zones for Latin America and Caribbean) have been created. (see reference). CEAZA is a research center in charge of the study of the water cycle and its relation with the dynamics and structure of arid and semiarid ecosystems of the Coquimbo region. Universities, the central government, the Regional Government and research institutes help in the management of CEAZA. CAZALAC is a center in charge of coordinating the management of water. Both centres collaborate with the SSHRC/MCRI project.

4.5. Conclusions

1. Elqui basin is arid; rain and snowfall in the high mountains provide water supply and determines the pattern of water flow.
2. The natural ecosystem has low productivity, the biodiversity distribution, and habitats for the wild life and the ecological production is linked to the areas with surface and underground water availability.
3. Biodiversity, wildlife habitat and endemism are in better condition at the high elevations of the basin.
4. The high gravitational energy of the hydrologic system (influenced by ENSO events), the poor vegetation and mineral terrains, marked slopes and severe desertification, constitute a set of factors which define the

degree of basin vulnerability. This is considering its flow characteristics of the water and the frequency of occurrence of droughts and floods.

5. The Andean humid soil and the remaining current cactaceas formations in the basin constitute the more vulnerable habitat to climate change effects.
6. Except for the two reservoirs, protection policies and the studies on humid soil carried out by a mining company, the environmental management of habitat protection, biodiversity, recovery plans and conservation of wild species is in its initial step.
7. Recently two centres in charge of the study of water resources have been established in the Coquimbo Region. Both centres collaborate in Chile on the SSHRC project (Institutional adaptations to climate change: comparative study of dry land river basins in Canada and Chile).

5. S0CIAL SYSTEMS

The social systems of the Coquimbo region are found in an environment characterized by two physical transitions: first, a transition between the arid Atacama desert and the fertile central zone of Chile, from north to south, and second, a gradient from east to west, between the Andes mountains and the Pacific coast. The regional history of human settlements has been marked by different forms of adaptation to this “transitional” territory, to the variations of its weather and to the availability of natural resources.

In this context, a diversity of social systems has emerged from the combination of factors such as:

a. Availability of water (conditioned by climate variability and by access to water sources)
b. Availability of the land (according to the dominant forms of land tenure: estate, small farmsteads, agricultural communities)
c. Availability of natural resources (especially terrestrial or aquatic flora and fauna, and minerals)
d. Accessibility to basic services (health, education, communications)
e. Organizative capability (of local, professional and productive organization: cooperatives, neighbourhood councils, agricultural communities)
f. Accessibility to markets (direct or indirect)

Human settlements of the region can be described according to their territorial situation and productive orientation:

a) Urban systems, services and industries settled in medium cities, in valleys, and in coastal zones;

b) Rural systems, small towns, and villages dedicated to intensive agricultural and cattle production;

c) Mining systems settled in zones of high or medium mountain areas;

d) Livestock and small farmstead systems –such as agricultural communities-- settled in dry land areas (mostly dependent on goat and sheep products);

e) Coastal systems, especially and fishing and aquiculture.

A cultural and technological polarization exists in some of these human and productive systems, which is characterized by an increasing differentiation between:

a) Systems with highly modernized technologies, management systems, intensity and quantity of capitals, and access to capital and commodity markets. Examples of these systems are agricultural production companies (fruits and vegetables), big or medium mining companies (gold, copper, iron), and aquatic farm production (molluscs).

b) Systems with traditional technological and managerial systems related mainly to communal and subsistence rural economies, in areas such as goat meat and cheese production, fruit orchards, wines and traditional spirits, small mining production, and fishing.

Accessibility to resources is affected by this polarization favouring the concentration of large companies in high productive valleys, in places of high quality minerals or in the best fishing areas. These polarizations also impact upon the accessibility to stable water resources (especially in intensive agriculture and in mining), to service networks, to national and international markets, and upon the distribution of risks, especially drought.

The main regional risks and vulnerabilities –at the individual and social levels—, and the responses to them, are related to climatic changes related to the phenomenon of “El Niño”, which could accentuate future global climatic changes:

a) Drought periods, which essentially affect the watershed and non-irrigated systems. These periods have an impact upon limited and fragile water resources, intensive or partially intensive agricultural systems, (which depend on stable water sources such as dams or rivers), the mortality of flocks, the viability of subsistence agriculture, soil degradation, and no less important, the stability of communities and households (an illustration of these impacts is the migration of the adult masculine population to urban or mining places, especially in the north of the country);

b) Extreme weather events, such as intense and concentrated rain periods and associated landslides that affect both households and communities established in the valleys.

c) Social (familiar or communal) and institutional (municipal, regional or national government) responses are determined by the type of disaster or event. Responses are more personal or familiar in the case of droughts and more institutional or governmental in the case of disasters by intense rain.

d) Droughts and extreme weather events impact upon the organization of households (labour migration, which progressively construct a culture of temporal separation and spatial migration), private companies’ capacities to employ people, and the regional population (eradication of families).

e) The existence of technological and business polarities (modern and traditional) causes competition and conflicts about access to resources such as water and land, especially during drought periods when water becomes a scarce resource and there is a higher availability of land.

The social effects of climate changes in the human systems of the Coquimbo region can be considerable:

1. Agricultural communities are at a high level of risks as the result of the effect of prolonged periods of drought upon their local environment (desertification and aridness) and impacts upon their productive processes.
2. The negative impact upon regional water resources could affect regional production systems, especially in the areas of agriculture, mining or fishing, impacting upon the regional economy and regional employment.
3. The combined effects of these processes could lead to the development of a culture of migration and labour changes that may seriously impact on the local economies.

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