Water allocation strategies and their implications – A Drought in the Limarí Watershed, Chile

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Abstract:
Chile's water allocation is driven by water rights which can change the owner and location of use with the facility of a permanent and spot water market, which is more active in the semi-arid north than in the south of Chile, due to less water availability and therefore higher pressures on the resource. Private regulation, collective management inside and between organizations of water rights possessors are prevailing.
Studying the characteristics of the droughts and furthermore the resistance and possible strategies regarding an allocation system driven by physical, legal and social constraints against extreme hydrological events will serve to improve decisions making for water allocation during future climate pressures. The strategies and its impacts due to the drought period from 1993-1997 in an agriculture dominated catchment is being presented.
Due to different levels of vulnerability and different access to responses, the necessity exists of identifying different levels of risk (vulnerability due to a drought), their indicators and possible mitigations and methods of resolution for similar future events, taking the physical and social constraints into consideration
The study includes the analysis and evaluation of indicators of decision, diverse strategies (individual and organizational), their motivation and impacts. Different indicators of vulnerability and resistance were considered: perceptive indicators, demand satisfaction, irrigation security among others; the aim was to define different levels of a drought (depending mainly of the duration), their affiliated risks and possible management reactions. Furthermore the resilience of the system under the historical operation has been studied and evaluated.
Site drought identification and characterization has been carried out based on the run method by the REDIM software (developed by the department of the Civil and Environmental Engineering of Catalania University).It allows an objective at site and regional drought identification and characterization and therefore represents a methodology for an analysis oriented to define best drought mitigation alternatives The results of the historical operation (simulated between 1999 and 2004) is been analysed for the drought period of 1993-97). The simulation has been conducted with the model MAGIC: "Modelación Integrada de Cuencas y Acuiferos"; a generic, object oriented model developed by the national water authority (DGA).
Data on private strategies were collected from a questionnaire conducted with 108 Water Rigths owners. In order to access the strategies of different decision making levels two members of the main stream organizations were interviewed.

Keywords: *Drought characterization and management, risk, vulnerability, modelling, mitigation strategies, water rights, organizational aspects, Chile*

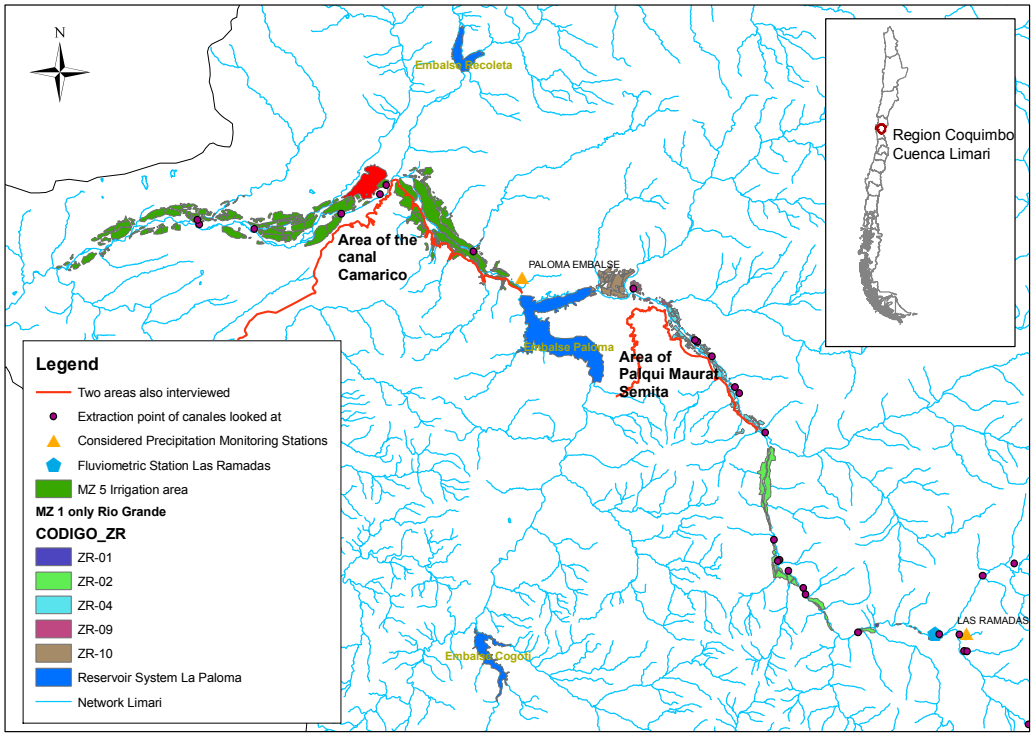
1. Introduction : Drought: Risk and vulnerability

Natural risk exposure can be measured by frequency and gravity of natural events and by the degree of the negative impacts or effects on "stakes" or resources. The drought characteristics (e.g. intensity, duration) are depending on physical properties (elevation), hydraulic structures (e.g. conveyance, reservoir) of the area as well as demand in the area under consideration. Therefore it differs among the irrigation sectors. For a similar event, levels of impacts are different and thus the vulnerability associated to each sectors.
The degree of negative impacts can be mitigated by stakeholders' capabilities (farmers and organizations) to confront the event. The risk is determined by the probability to be exposed to an event and by the capabilities to adapt conducts in front of this event. The resources that one can develop in order to protect or mitigate the negative effects can help to determine the degree of vulnerability in front of drought. One only can speak of a risk in case there is an event with negative impacts upon resources. Vulnerability represents the internal component of risk and can be described by a combination of economic, environmental and social factors (Iglesias and al, 2007).
Drought indices facilitate detection of drought conditions and thresholds to activate drought responses. They differ due to the kind of droughts, e.g. meteorological, agricultural, hydrological o social drought. It is important to underline that the vulnerability, and so the risk levels, can change with time and location. Vulnerability is also linked to other technical and organizational aspects. The question

now is what other variables could be taken under consideration in order to consider the multidimensional aspect of vulnerability, and, indeed, of risk.
A lot of different indicators or component to evaluate vulnerability has been developed and used. Here only indicators directly to the exposure to the drought under analysis are being discussed in more detail; these are for example: historical precipitation and discharge data, irrigated area, demand and demand-satisfaction, supply (allocation) system, access to other sources of water (in particular to subterranean water), possibility for participation in the spot water market, the storage capacity – individual as well as organizational – for each analysed sector. Furthermore economic considerations are incorporated, which are explained in more detail in the methodology.

2. Limarí Catchment in Northern Chile

The province of Limarí is located in the semi-arid North of Chile. Here the normal average annual rainfall does not exceed 120mm and the potential evapotranspiration exceeds 1,000mm. Additionally the region has to cope with strong inter- and intra annual variations of water availability. Nevertheless, the main activity in the catchment is irrigated agriculture which is possible through a regulated hydrological and social system known as the "La Paloma System". This technical and social system of water allocation is in operation since 1972. It is physically composed by three reservoirs, storing together 1,000MCM, and the associated channel network.
An important part of the irrigated area dedicates its production to pomiculture for exportation; just a small part is used for annual crops; the cultivated area below the cannel network sums up to 65.000ha (CNR, 2005). Nine different private organizations as well as the State are participating in the management of the system; in this context integrated water management is quite complex. This study only concentrate on the main river course (Rio Grande), from the headwater until the reservoir (unregulated) as well downstream the reservoir (regulated) [map1].



Map 1: The study area under consideration to analyze the measures taken during the drought of 1994-97
Source: Elaborated from Rodhos (2006), CEAZA Data base and fieldwork sampling.

The following sectors are studied in detail and therefore the cultivations are described in bit more detail:
In the "Camarico" sector, which are supplied by the canal Camarico the following crops prevail: permanent crops for the Chilean market, grapes for Pisco (national alcohol of Chile), combined with vegetables/annual crops and pasture plantations, a small part is dedicated to wine grapes and high-value export permanent crops, mainly table grapes.

In the part of the Rio Grande upstream more pasture plantation, traditional permanent crops (e.g. walnut) and pisco grapes can be found, few plantations with high value permanent crops. The area of the Palqui Maurat Semita (map 1) in contrary has a high percentage of high value permanent crops and only a few annual crops (vegetables). The sector ZR 01only has natural pasture and pasture plantations, few private gardens and also few permanent crops. Downstream the reservoir, permanent crops and vegetable crops are prevailing. But not only the irrigation security is the driven force for the different plantations, furthermore the Palqui Maurat Semita area also has a different micro climate which favours the cultivation of grapes for example since the harvest period is in general the first in this section and therefore the revenue is very high.
During the last ten years after the drought an increase of high value permanent crops can be witnessed, en particular in Rio Grande sector (upstream as well as downstream).
The Paloma reservoir was designed in order to compensate the inter and intra- annual variations of water availability. It secures water for three consecutive years with less rainfall. This new regulation/allocation system permits, with appearance of foreign capital and the new Water Code during the 80's, the implementation of high value permanents crops (table grapes). The Paloma System does not coincide with the watershed limits; effectively it is in the first place an agreement between different Water Organizations. The participation is voluntary: four tributaries for example decided to refuse the participation (in the unregulated area). Unregulated - or uncontrolled - areas (organizations which accept participate but can't use stocked water volumes) receive an indirect benefit of the system (less shifts, agreement to contribute to the reservoir filling).

Water Rights and Water Markets

The 1981 Water Code allows that water transactions are realized separately to land selling; it permits then a certain Water Rights mobility (limited by legal and physical constraints). Furthermore it conserves the Water Organizations competence: They are private organizations of Water rights owners, which can be distinguished in three different types, geographically connected/bounded and embedded: 1. The *Juntas de Vigilancia*, are in charge of water distribution and the control of the allocation based on water rights in natural streams; 2.Water Communities and 3.*Asociaciones de Canalistas*, are responsible of water repartition in artificial streams (canals or reservoirs). The competence of these two types of water organizations begins with collective points of extraction, generally of a shared canal. The decision makers of the *Juntas de Vigilancia* are representatives of the Water Communities and *Asociaciones de canalistas.*
Three different categories of Water Rights exist, due to its source and use: a. Superficial or subterranean; b. permanent or eventual; c.consumptive or no-consumptive. The Water Right identity is based on a point of extraction in the river and the organization related to its distribution in the associated canal; it has to include the measure in l sec^{-1}, that is to say the number of fraction or part that corresponds to this water right in the river. In the Rio Grande y Limarì, a fraction (or share) corresponds to 1 l sec^{-1}.
The fact that water is connected/ bounded to a physic point of extraction is an important legal and physical constraint upon a change of this point: it is the legal case of "*traslado*", or permanent movement of this point of extraction, that needs State's institutions authorization. Some Water Rights owner's organizations permit a temporary movement of this point, in particular in the spot water market.
The spot water market is a water volume market (m^3). This market has been evolved downstream of all reservoirs: the Huatulame valley, Camarico sector, Recoleta sector and Rio Grande y Limarì sector, downstream La Paloma reservoir. The climatic and production differences between these irrigation sectors (as describes above) stimulate the water volume market. And the temporary change of the point of extraction makes it possible.
The *Junta de Vigilancia* of Rio Grande and Limarì holds 28,6% of the permanent water rights in the Paloma System. This is one reason why the Rio Grande is considered as a water supplier to other organizations trough the spot market. Due to Cristi, 2001 a part of the water user of The *Junta de Vigilancia* of Rio Grande and Limarì has a higher percentage of recuperation of river water than the rest of the Organizations and therefore also the potential to act as a water supplier.

3. Methods for the drought characterization and assessment of mitigation strategies

Indices of drought characterization

Since in the Limarí Basin agricultural activities prevail, in the Following only the agricultural implications of the last severe drought will be tackled. Furthermore only the management of the irrigated land is being studied.

There are a lot of methods and indices available for characterization of droughts. A method based on drought-trigger indices should a. provide criteria for declaring the beginning and the end to a drought, b. represent the concept drought in a particular region and c. correlate to drought impacts over different geographical and temporal time scales (Tsakiris et al., 2007). In the present study only the lower part of the Limarì catchment has been investigated in more detail; nevertheless to identify the thresholds which where used to characterize the droughts over 50 years on two different sites the whole main river valley (Rio Grande) were considered. Looking at a. and b. they can be categorized as general indices which give an overview over the draft occurrence and its severity. The following parameters for characterization where considered: i. Frequency (how many droughts occur in the period of study); ii. Timing; iii. Intensity (ratio between cumulated deficit and duration); iv. Cumulated deficit: sum of the negative deviation throughout the drought duration; v. Duration Number of consecutive intervals where the variable is below the threshold, vi. Predictability. The run method was chosen for the described analysis. It allows an objective at site and regional drought identification and characterization and therefore represents a methodology for an analysis oriented to define best drought mitigation alternatives. The method is based on the relationship between drought and negative runs in rainfall time series considering a hydrological variable and a critical threshold level. (Yevievich, 1967; Rossi et al., 2003 cited in Tsakiris et al., 2007). The advantage of the run method consists furthermore in the possibility of deriving the probabilistic features of a drought characteristic (duration, cumulated deficit) analytically or by data generation. Due to developed procedures to access the return period of droughts according to the run method (Cancelliere and Salas, 2004 in Tsakiris et al., 2007) it is ideal to perform also drought risk analysis.

Drought analysis: Indicators and strategies

In order to complete the drought risk analysis, after the characterization of the 1993-1997 the private drought management realized in response to this drought is being assessed. This assessment is coupled with an analysis of modeling results of the yearly demand satisfaction of the same period of time and of the same irrigation sectors (map1 and 2). This simulation was carried out with the program MAGIC (DGA, 2005). MAGIC is an analytical, generic model which integrates water resource issues on the catchment scale. The inputs and results from the study by Rodhos (2006) were modified for the studied sub-catchments. The gross demand for the field which is considered in the model has been calculated from the potential evapotransparation of the plants as well the efficiency of irrigation and conduction has been integrated.

Looking at the private drought management it was first analysed trough the existence or the non-existence of a shared vigilance system. The objective was to describe the management preparedness trough an alert system and the mitigation responses developed at a local and private level. The methodology of the stakeholder, including the description of the different drought indicators to decide on a drought, the drought level and the personal responses is being assessed and described. This work was first focalised in the perception of risk: when do the farmers consider that their fields are threatened and that they should adapt their management to protect it.

The indicators provoke different type of responses. The water rights owners adapt their conduct according to the water availability but also according to their own capabilities (e.g. social, economical) to mitigate the droughts effects. Furthermore post-reactive actions, that is to say strategies that the farmers have developed after the drought, but in reaction to the event are being assessed. The capability to develop strategies is used here as an indicator of vulnerability.

The indicators and responses are illustrated from the individual fields to the entire Paloma System. The field work has been carried out in the end of 2007; this means 10 years after the end of the last severe drought and with the start of a new highly hydrological pressure of the system.

The indicators and the mitigation strategies of the *Junta de Vigilancia* of Rio Grande and Limarí were collected from the study of the directory board reports of three different hydrological years (1994-1995; 1995-1996 and 1996 – 1997). Interviews with two members of the *Junta de Vigilancia* directory

board and the analysis of Paloma System Operational Model permit to complete this information and to access to the decisions at the Paloma System level.
Data on the individual strategies were collected from a questionnaire conducted with 108 Water Rights owners – or its legal representatives - of different canals of the *Junta de Vigilancia* of Rio Grande and Limarì. The sampling was realized from the *Junta de Vigilancia* of Rio Grande and Limarì register: of the 174 canals 28 were chosen, according to the number of fractions they possess in the river. In each canal (and its associated organization), the questionnaire was conducted with 10% of the Water Rights owners. The presidents of all chosen water organizations have been interviewed also. The sampling permits to have a representation of all sectors and all types of farming systems (multinational fruit exporters, Agrarian Reform farmers, peasants and medium-sized entrepreneurs).
The Rio Grande and Limarí was divided in five stretches (sectors): these sectors correspond mainly to the stretches used by the *Junta de Vigilancia,* when introducing the irrigation turns. The first sector corresponds to all the tributaries of the Rio Grande who participates in the Paloma System. This sector is not considerate in the model MAGIC because it is located upstream the first monitoring station. The second sector is not considerate entirely too in the MAGIC model for the same reason. The fifth sector corresponds to the part of the river downstream Paloma reservoir.

4. Results

Site drought characterization

Due to the objective of the study only the site drought identification (not the regional drought identification) and characterization has been carried out based on the run method by the REDIM software (developed by the department of the Civil and Environmental Engineering of Catalania University).
Two sites have been analyzed: One station which is of highest importance in providing water for the catchment, called Las Ramadas. It is located at the headwaters of the main river Rio Grande in a height of 1350 m a.s.l and forms the main source to fill the main reservoir Paloma. As a second site the station next the reservoir La Paloma (downstream the gate) which indicated the boundary of the lower catchment - also called La Paloma - has been chosen. For the headwater station (unregulated part of the catchment) two different time series has been used: historical precipitation records from 1949/1950 until 2005/2006 and measured discharge data records from 1962/63 until 2006/2007 (since the discharge depends mainly the snowmelt of the Andes). For the La Paloma station only the historical precipitation records were available for the framework of this study.
Since precipitation and discharge where used as input parameters and thresholds, one speak from a meteorological and/o hydrological drought. Since the system we are looking at is in the lower part regulated the meteorological drought indices may not correlate well with the historical drought impacts, due to the effects of storage. This has to be considered looking at the results
All time series were tested for normality in the form of the PPCC plot Tukey Lambda and the normal Probability plot to approximately assess graphically if the data are normally distributed. Furthermore the density functions had been plotted. In the probability plots the data are plotted against a theoretical normal distribution. All tests showed that none of the data time series are normally distributed. Furthermore they were all heavily right skewed. The density plot in form of a normal curve confirmed that. This leaded to the choice of nonparametric tests during the modeling. Furthermore Helsel and Hirsch (2002) are stating that as skewness increases ARE (asymptotic relative efficiency) increases also. Therefore in the presence of skewness and outliers, precisely the characteristics commonly shown by water resources data, nonparametric tests exhibit greater power than do parametric tests. Furthermore the existence of non-stationarity in the time series has been tested, since the present of it would lead to misleading drought analysis.
For the model a yearly time step has been used, starting in April for each hydrological year. As a preliminary threshold the median (sample quantile corresponding to a frequency level of 50%) has been chosen, since the median is only minimally effected by the magnitude of a single observation. It could be observed that the results (duration) very well represented the historical droughts of the region. To finally calculate the threshold which best represent the yearly demand of the region, results of demand and demand satisfaction, which were modeled with the program MAGIC of DGA (2005) has been used. MAGIC is an analytical, generic model which integrated water resource issues on the catchment scale. The inputs and results from the study by Rodhos (2006) were modified for the studied sub-catchments. For the station at the headwaters looking at a demand satisfaction of min.

85% of the irrigation zones downstream it has decided that using the median of 267,14 mm is a good choice. It is quite difficult, because, if there has been a drought before much more precipitation is necessary to reach 85% irrigation security; furthermore the yearly average has been taken. Therefore the results have to been looked at critically afterwards. The threshold regarding the discharge has been set also to the 50% quantile which leads to 35,99 m^3/sec. Calculating the demand downstream the number looks quite high, but looking at the yearly demand satisfaction which where calculated with MAGIC the number seems very reasonable.

The results of REDSIM regarding the headwater station can be seen in table 1. Looking at the results from the precipitation input the number of drought are 15 during the last 36 years, but only four quite severe ones. Whereas the worse was in the end of the 60th, which where before the Paloma System went into operation (the reservoir was ready in 1972, but until it could be filled up it needed some more time, since during this period the water availability was quite scarce). Looking at the results of the discharge time series the results are quite similar and follow more or less the same pattern. Since the discharge is highly dependent on the snowmelt the deficit in the first year of a drought is always less severe looking at the discharge then looking at the precipitation; even though there is a deficit in precipitation in the year under consideration, the snowmelt from the last year precipitation of the mountains are contributing to the actual discharge, which therefore leads to less deficit. The precipitation of the year under consideration gives some ideas about the behavior of the next year, whereas the discharge is valid for the consideration of the actual year.

Station name: LasRamadas
Hydrological variable: Precipitation
Aggregation time scale: year
Drought Characteristics
Number of drought events: 15

Initial month: April
From year: 1950/1951 To: 2005/2006
Threshold (Quantile 50%):267.14 mm

N	Begin.	End	Durat.	Cum. Def.	Drought Int.	Tr(L=l)	Tr(L=>l)	Tr(D>d)	Tr(L=l,D>d)	Tr(L=>l,D>d)
			[years]	[mm]	[mm/year]	[years]	[years]	[years]	[years]	[years]
1	1967/68	1971/72	5	845.15	169.03	128.00	128.00	303.44	3274.46	248.11
2	1973/74	1976/77	4	494.70	123.67	64.00	64.00	37.92	131.61	45.20
3	1958/59	1960/61	3	205.95	68.65	32.00	32.00	8.14	32.53	16.13
4	1994/95	1996/97	3	354.95	118.32	32.00	32.00	17.43	58.03	21.14
5	1955/56	1956/57	2	267.00	133.50	16.00	16.00	10.99	43.26	12.18
6	1998/99	1999/00	2	246.10	123.05	16.00	16.00	9.89	33.54	11.08
7	1951/52	1951/52	1	124.35	124.35	8.00	8.00	5.66	17.94	5.58
8	1962/63	1962/63	1	106.75	106.75	8.00	8.00	5.28	13.68	5.06
9	1964/65	1964/65	1	124.65	124.65	8.00	8.00	5.67	18.03	5.59
10	1979/80	1979/80	1	148.65	148.65	8.00	8.00	6.27	28.11	6.40
11	1981/82	1981/82	1	73.85	73.85	8.00	8.00	4.70	9.53	4.35
12	1985/86	1985/86	1	143.25	143.25	8.00	8.00	6.13	25.27	6.21
13	1988/89	1988/89	1	203.85	203.85	8.00	8.00	8.06	99.85	8.59
14	1990/91	1990/91	1	111.45	111.45	8.00	8.00	5.38	14.64	5.19
15	2003/04	2003/04	1	38.75	38.75	8.00	8.00	4.24	8.12	4.03

General Characteristics of Drought Events

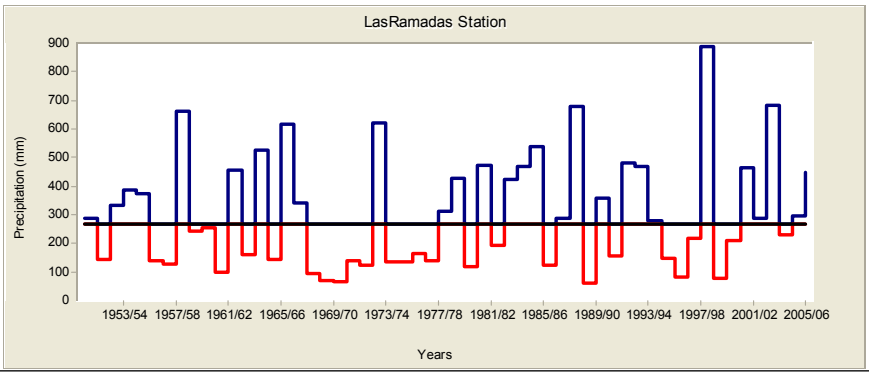


Table 1:
Results of the drought identification – Site analysis (though REDIM) of the headwater station in the uncontrolled sub - catchment (Input: precipitation time series)

Station name: LasRamadas
Hydrological variable: Streamflow
Aggregation time scale: year
Drought Characteristics
Number of drought events: 12

Initial month: April
From year: 1962/1963 To: 2006/2007
Threshold (Quantile 50%):35.99 m³/sec

N	Begin.	End	Durat.	Cum. Def.	Drought Int.	Tr(L=l)	Tr(L=>l)	Tr(D>d)	Tr(L=l,D>d)	Tr(L=>l,D>d)
			[years]	[m³/sec]	[m³/sec/year]	[years]	[years]	[years]	[years]	[years]
1	1967/68	1971/72	5	106.36	21.27	106.41	93.11	334.47	6092.79	286.44
2	1973/74	1976/77	4	49.39	12.35	56.75	49.66	24.17	93.12	33.65
3	1994/95	1996/97	3	57.07	19.02	30.27	26.48	33.99	289.33	36.00
4	1985/86	1986/87	2	7.94	3.97	16.14	14.13	4.75	16.22	7.55
5	1998/99	1999/00	2	26.38	13.19	16.14	14.13	9.16	33.31	10.30
6	1962/63	1962/63	1	8.84	8.84	8.61	7.53	4.87	11.97	4.63
7	1964/65	1964/65	1	5.72	5.72	8.61	7.53	4.46	9.63	4.23
8	1979/80	1979/80	1	14.64	14.64	8.61	7.53	5.89	22.84	5.84
9	1981/82	1981/82	1	12.30	12.30	8.61	7.53	5.44	17.06	5.30
10	1988/89	1988/89	1	9.25	9.25	8.61	7.53	4.94	12.41	4.70
11	1990/91	1990/91	1	17.35	17.35	8.61	7.53	6.49	33.37	6.56
12	2004/05	2004/05	1	11.73	11.73	8.61	7.53	5.34	15.98	5.17

General Characteristics of Drought Events (in m³/sec)

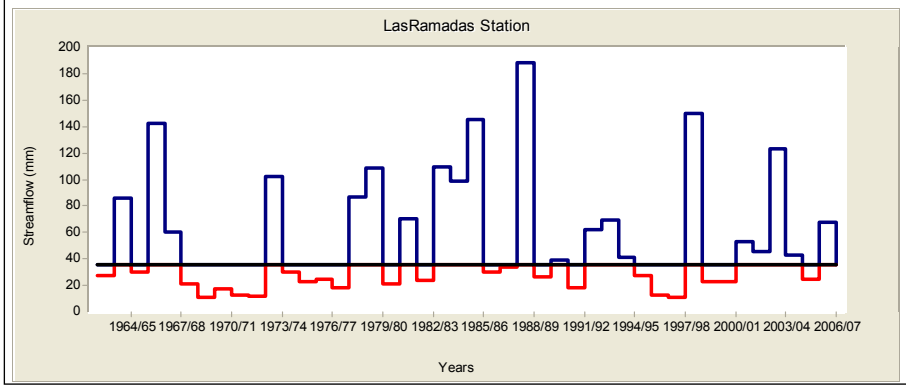


Table 2: Results of the drought identification – Site analysis (though REDIM) of the headwater station in the uncontrolled sub-catchment (Input: discharge time series)

The tables have been ordered by the drought duration, which show that actually the drought from 1994 until 1997 which is studied has been the severest after the Paloma System has been gone into operation. But not only is the duration of importance but also the cumulated deficit and the drought intensity, which is the intensity per year. Looking of the drought intensity the drought under consideration was almost as severe as the drought from 1967 – 72, but it was less in duration. The accumulated deficit shows that it was higher during the 1994 – 97 drought than in the seventies, although the seventies one was longer. Looking at the drought intensity of the precipitation one can see that it was highest in 1988/89, even higher than in the end of the sixties. Since the area is not controlled it might have also a high negative impact although just for one growing and harvest period depending one the type of cultivation.

Looking at the second station under evaluation next to the reservoir La Paloma the threshold for calculation has been set as well to the median of the samples, which leads to 115.6 mm/year.

The results presented in table 3 are expressing the characteristics of the hydrological drought, but since the area is controlled by three reservoirs, the majority of the drought which are listed (the one year droughts for example) are of less importance for the negative impacts to the area. Nevertheless there are important when thinking of refilling the reservoir and certainly for the water markets and its prices. The drought characteristics follow also more or less the pattern as described before. Looking at the values for cumulated deficit and drought intensity for the drought under study it has almost the same percentage of the threshold value like in the headwater station. The duration nevertheless is calculated here with four years, starting one year earlier than in the upper catchment. It can be concluded that the lower catchment suffered therefore, although controlled, more than the headwater area. The Cogotí reservoir for example has been totally empty during the last year

Station name: LaPaloma
Hydrological variable: Precipitation
Aggregation time scale: year
Drought Characteristics
Number of drought events: 15

Initial month: April
From year: 1948/1949 To: 2005/2006
Threshold (Quantile 50%):115.6 mm

N	Begin.	End	Durat.	Cum. Def.	Drought Int.	Tr(L=l)	Tr(L=>l)	Tr(D>d)	Tr(L=l,D>d)	Tr(L=>l,D>d)
			[years]	[mm]	[mm/year]	[years]	[years]	[years]	[years]	[years]
1	1967/68	1971/72	5	285.90	57.18	128.00	128.00	117.84	533.20	145.24
2	1993/94	1996/97	4	223.20	55.80	64.00	64.00	51.49	226.88	64.35
3	1973/74	1975/76	3	113.60	37.87	32.00	32.00	12.79	47.35	19.70
4	1988/89	1990/91	3	179.30	59.77	32.00	32.00	29.16	135.73	33.96
5	1950/51	1951/52	2	38.00	19.00	16.00	16.00	5.41	17.08	8.27
6	1985/86	1986/87	2	116.40	58.20	16.00	16.00	13.24	56.95	14.82
7	1998/99	1999/00	2	141.40	70.70	16.00	16.00	18.04	105.90	19.55
8	1956/57	1956/57	1	11.10	11.10	8.00	8.00	4.25	8.55	4.13
9	1958/59	1958/59	1	9.10	9.10	8.00	8.00	4.19	8.37	4.09
10	1960/61	1960/61	1	91.60	91.60	8.00	8.00	9.82	82.23	10.16
11	1962/63	1962/63	1	27.60	27.60	8.00	8.00	4.89	11.44	4.74
12	1964/65	1964/65	1	10.40	10.40	8.00	8.00	4.23	8.48	4.12
13	1979/80	1979/80	1	102.60	102.60	8.00	8.00	11.20	122.56	11.64
14	1981/82	1981/82	1	7.30	7.30	8.00	8.00	4.14	8.23	4.06
15	2005/06	2005/06	1	32.50	32.50	8.00	8.00	5.12	12.83	4.99

General Characteristics of Drought Events

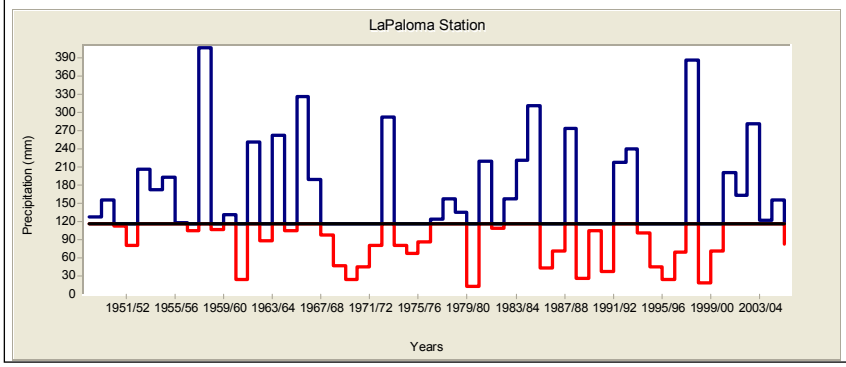


Table 3: Results of the drought identification – Site analysis (though REDIM) of the La Paloma station in the controlled part of the catchment (Input: precipitation time series)

As described before the run method performs also the return period (Tr) of drought and the associated risks. The results of that can be found in the second part of the tables, which gives an estimation of the return period based on the calculation of the occurrence probabilities of a special drought event. The probabilities have been derived considering only the duration of the drought, regardless the accumulated deficit [Tr(L=I) or Tr(L=>I)], by the drought accumulated deficit [Tr(D>d)], as well as drought accumulated deficit conditioned on drought duration [Tr(L=I, D>d) or Tr(L=>I, D>d)]. Here the parameters of the probability distribution have been determined according to a non parametric approach (for more details refer to Cancelliere A. et al, 2005).

From the results can be said, that in generally the possible return period considering the accumulated deficit is lower than considering only the duration. On the other hand, the return periods which are conditioned on drought accumulated deficit and drought duration (which could be even greater than the event under consideration), have higher return periods as the ones where only the deficit is considered. Looking specifically at the drought of 1994-97, the lowest return period looking at the duration and the accumulated deficit can be found in the analysis of the precipitation of Las Ramadas with 21, 14 years. One should be careful to take the numbers as absolute values, but they give an idea of the probability of occurrence.

Drought management and private strategies: The 1993 – 1997 drought and its implications

Drought management, in the distribution part, is Water Organizations competence. Before the 1951 Water Code, decisions relative to drought management were taken by tribunals. State intervention generally limited to compensation actions (post-reactive actions). Only in the case that Chile's president declares the province, a river basin or sub-basin as "*zona de escasez*" (scarcity zone), the National water association (DGA) intervenes in the distribution (for the duration of drought). This public institution allocates water resource if a water organization or agreements about the distribution during the drought do not exist.

In the case of Paloma system, the state intervenes in the distribution through the DOH (State institution for hydraulic structures) since the Paloma reservoir and the superficial eventual water rights associated to the reservoir are State property.

Each year, at the end of the hydrological year (end of April), the DOH does an estimation of the assignation for the nine organizations which compose the Paloma System. This estimation is done according to the stored volume in the three reservoirs. After the winter, in September, the final decision of assignation is taken, taken also under consideration the simulated water contribution out of the snow melt. Farmers adjust its conducts in May and then in September. The level of storage (sum of all three reservoirs) indicates different types of assignation (due to the Operational Model).
Also during the analysed drought, the water organizations followed the Paloma system operational model. In the 1995-1996 period, the Paloma System allocated 60% of the assignation for the *Junta de Vigilancia* of Rio Grande and Limarì. In 1996-1997, half of the stored volume in the three reservoirs was distributed, as it is stipulated in the Operational Model.
It's also based on these data what the *Junta de Vigilancia* decides what to do in its unregulated sector: if it is necessary or not to contribute in refilling the reservoir or to the downstream Paloma reservoir Water Rights, when should they start with irrigation in turns according to the different stretches
Water Organizations start speaking of drought employing the term of "escasez" that could be translated as "scarcity". It is possible to speak of drought when water availability could not supply the totality of superficial permanent water rights. The legal demand does not correspond to the agronomical demand.
As for the Paloma System, and in relation to the assignation, the *Junta de Vigilancia* of Rio Grande and Limarì is using different thresholds to decide on the water management. Each level leads to a new decision about the river management. When the volume available per fraction is lower to 1 l s^{-1} the *Junta de Vigilancia* initiates the proportional distribution. When the level is below 0.8 l s^{-1}, the *Junta de Vigilancia* initiates the distribution in turns. For distribution effects, the *Juntas de Vigilancia* are divided the course in various stretches, which were used for the sampling. This division is based upon a "know how", an empirical knowledge of the river.
The water distribution in the *Junta de Vigilancia* of Rio Grande and Limarí starts to change in the 1994-1995 season: during this year, Paloma System assignment was normal and so each water organization received its maximum assignment. The water distribution was normal in the Rio Grande y Limarí downstream Paloma. In the upstream part of the river, the precipitation decrease yet had an impact. However the distribution was regular. The *Junta de Vigilancia* "drained" the river during summer period (December to February).
During the 1995-1996 season, the *Junta de Vigilancia* of Rio Grande and Limarí received only 60% of its assignment. It started with the draining upstream Paloma in September and with turns in the first days of November. The downstream area distribution was affected too: the organization had to drain during summer months.
In 1996-1997, half of the stored volume was distributed as mentioned in the operational model. In the Junta de Vigilancia, draining starts at the end of August and turns in October. Upstream Paloma, the flow reach 0.1 l s^{-1} in January and February, and the turns were of three days of water for fifteen without water. Two stretches decide by agreement to give away a part of its fractions during this year. The upper stretch gave away a part of its fractions during December and January, because its agronomical demand was less in this period, whereas the second stretch gave away its part during February and March, for the same reasons. The *Junta de Vigilancia* decided also not to drain the fertile plain, in order to conserve their regulation capacity. Downstream Paloma, in the regulated area, the flow reached 0.4 l s^{-1} during the peak period (summer).
At an individual level, it is possible to say that most of the farmers do not understand the functioning of the Paloma System: the different thresholds and the decisions they imply are mostly well-known by the different directory boards. However all the farmers change their irrigation management of field level in accordance with the different thresholds that are used by the Water Organizations. They adapt their conducts in response to these different thresholds.
The farmers located downstream Paloma reservoir can more easily anticipate the volume that should be available and adapt their plantations according to the estimation of the annual assignation. The situation for the farmers upstream is more complicated as they have to base their conducts on insecure information about the precipitations and the level of snow. The storage of the Paloma System has an effect in the *Junta de Vigilancia*'s management, but this influence is not perceived by the majority of the farmers, in particular in the upstream area. Some of the farmers do not understand the benefit of the Paloma System.

27% of the interviewed farmers consider the non-satisfaction of the agronomical demand as an indicator of drought. That is to say when there is an impact in their plantations and a possible damage. 19,4% of them think that the levels of precipitation and snow indicate in a better way a drought: they adapt their management to the lack of precipitations and snow. It is particularly the case of the farmers of the first sectors; only 13,9% consider that changes in the water assignation and in the water distribution indicate a drought situation. These farmers take under consideration the legal demand as an indicator of drought. The other farmers combined the indicators: 15,7% start to modify its irrigation management according to the precipitation levels and to the non-satisfaction of the agronomical demand; 13% consider precipitation levels and the non-satisfaction of the legal demand as a drought indicator; finally, 7,4% of the farmers think that it is the non-satisfaction of the legal and agronomical demand that imply a change in the irrigation management and only 2, 8% take under consideration all three indicators.

The individual Strategies

Once the drought was perceived, it triggered different types of responses. The farmers developed different strategies to cope with the drought according to the irrigation sector and the type of crops of the farming systems:

16% of the interviewed farmers declared that they have not developed any strategy. They are located next to urban canals - where the water is used generally to irrigate gardens - and in the upstream part: located in the upper tributaries. In the gardens, the production is used for subsistence and for the local market, but this part does not represent the principal income of the family (the production is used as a complement). It is relevant to notice that 56% of the farmers under assessment respond that they do not develop any strategy after the drought period and that 15% told that they could not develop any strategy if a new drought occurs.

Most of the farmers of the tributaries have cattle (mainly goats); this zone is a mainly composed of pasture plantations. It is the area where fewer strategies were developed. The capacity of response is quite limited. The farmers are obliged to make an investment to maintain the cattle, renting pasture and/or buying hay. It's the only group of farmers who had in some case to sell a part of its patrimony.

But there were also farmers who decided on responses: 58 % of them decided to reduce its planted area; 21% farmers used only this strategy and 37 % together with other strategies. Reduction of the plantation surface was the strategy most developed mostly because it is not necessary to realize an investment. Some farming systems (pasture plantations, vegetable crops and traditional crops as wheat and potatoes) permit to adjust plantation superficies to the annual assignation. In the same way, it is possible to let dry plantations which represent less profitability. The possibility to reduce the irrigated surface gives the system elasticity. 34% of the farmers combined reducing their irrigated surface with a "maintenance irrigation" - whose aim is to "keep alive" or to maintain permanent crops (fruit trees) that represent more investment and added value.

16 % of the interviewed farmers bought water rights during the drought but do not mention it as a strategy (about four as a first investment). Selling water rights or part of one's water assignation has never been mention as a strategy. Only one farmer sold water rights during the drought, but do not mention it as a strategy too.

15,3 % of the farmers designed the participation to the spot water market as a strategy against the drought. Spot water market can't be used as a strategy in the unregulated sector (except for the Palqui association who have got two sources of water and can participate in spot water market from the Cogotì reservoir). The spot water market is concentrated in the regulated area and in the case study particularly in the Camarico sector.

Interesting is the fact that most of the farmers who started dealing with the Spot Water market during the drought period are still participating today. The participation in the Spot Water market was a punctual strategy to cope with a drought. It is now a permanent strategy, used to increase the irrigated surface and/or to secure the irrigation during the peak period. Many of the new investments done in the Limarí catchment have sustained their irrigation system on volumes they acquire trough the Spot Water market. However, this strategy is partially called into question. The temporary movements of the points of extraction are not contemplated in the Water Code. Some farmers 'conflicts are questioning these movements. At the end, it is the flexibility of the system which is called into question.

From the interviewed farmers 14% declared they used drilling (access to groundwater) as a strategy during the drought. They are located mainly in the same zone where the spot water market takes place: Camarico and sector downstream Paloma reservoirs and only one sector upstream, in the Palqui zone.

The time of the drought until now (individual strategies)

Searching for an alternative source of water (subterranean water in particular) as well as accessing to the spot water market are concentrated in high value permanent crops areas. It is evident that the incomes due to these crops permit investing in individual and organizational levels. The losses due to a drought – and thus the vulnerability - associated to these farming systems are also higher and justify these investments.

Of the farmers who have chosen make a drill during the drought only five are still using the drilling, three in a permanent form and two in a regular form. Contrary to the participation in the Spot Water market, drilling has been identified a strategy more specific for a drought. Most of the farmers indicate the price of the drilling, legal formalities and price of energy as limits to develop this strategy. 13% of the farmers point out financing and energy costs as limits to establish small reservoirs and drilling during a future drought. Furthermore, the farmers add that it is a high and risky inversion as it is not secured in the future: it is impossible to know the real flow that could be used and the time it would be available. Almost 10% did a drill after the drought, but 4% affirms they had difficulties for the financing and 3,5% that they now use it for drinking water. Drilling is a punctual and a rapid solution. Farmers do not considerate drilling in order to secure the permanent irrigation (that's not the case of Spot Water market).This confirms that superficial water rights are still considered as the main source of water and may explain the fact that subterranean water represents only a complement source of water. Drilling is used in case of scarcity of water but it is not a sustainable strategy.

The strategies of maintaining only permanent crops appear quite difficult to develop now due to the decrease of economic profitability of fruit trees. During the drought it was economically sustainable to continue only with permanent crops. It seems quite difficult to maintain the unit production now only with permanent crops, due to the national and international prices. This strategy is now more fragile and cannot have a long duration in the time (but it is one of the most used). It should be less efficient in lowering the vulnerability of the farming system in front of a new drought.

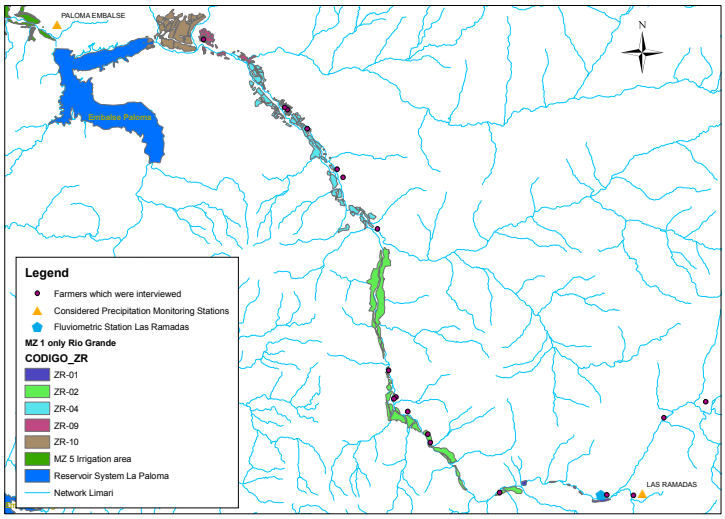
The construction of a reservoir as a drought strategy is been described by 4% of the farmers. However, 7% of them install a reservoir during the drought. 56% of farmers have an access to an individual, a community or both types of reservoirs: 24% upstream - 18% in the last sector of turn upstream Paloma reservoir, MZ09 and 10 in map 2 -and 32% downstream in particular in the Camarico area (21%).

6 % of the farmers install a reservoir after the drought, 9% of them with a drip irrigation system. The technique of the drip irrigation system, which indicates a higher efficiency of water use, has been installed in a lot of cases after the drought and is seen as a responds to the less water availability: 32,5% of the farmers have chosen to establish a drip irrigation system in its field. This conduct is a response to the strong incentive of the State to increase technology in the water management trough the "irrigation law". This law permits to obtain financing for individual and organizational projects. Nevertheless, the individual storage capacity has decreased between 1997 and 2007: the average was of 35 cubic metres per hectares in 1997 and was of 25 cubic metres per hectares in 2007. The efficiency of conduction increases by the effect of the same law, but is concentrated in the areas with high value permanent crops. The concentration or the "crystallisation" of the points with an increase of irrigated surface with high value permanent crops and an increase of technology in these neuralgic points are weakening Paloma System flexibility (Allard and Pailhes, 1999).

Does the MAGIC model show the management decisions taken during the drought in the areas under study?

Analyzing the area under detailed study (as presented in map1 and map2) during the years of drought, which differ at the two stations under consideration it can be found in general that the hydrological drought (without considering the stored water volume) starts earlier in the lower part of the catchment. Looking at the results of the interviews it can be seen that the system was capable to assign the normal amount of water. With MAGIC two indicators of vulnerability has been calculated: the demand satisfaction and the irrigation security (the overall aim has been to model the efficiency of water use). The model is not capable to mirror the different strategies of the individual farmers. For this more than on scenario has to be analyzed (which furthermore has to be much more detailed) and is been

developed in a future work. But even with different scenarios (here the base scenario has been done with the demand equal during the drought years and with the normal used water source), changing the parameters between the years only bigger changes might be obvious, especially when looking at the drilling possibility. The model has used as input real data, so it shows in the best case the results of the mitigations but we don't know how it could have been without that. Furthermore it shows in general the demand satisfaction of an irrigation zone but not in detail the different crops of one farmer and therefore the modeling of the individual farming systems might be interesting to look at with a different model scenario or different model. Nevertheless the different zones with their different capability to respond to the drought are interesting to look. The parts which were analyzed in the frame of this particular study are the part of MZ 1 (Mezozone 1) along the Rio Grande and MZ 5 since these zones are administrated by the JVRL. Along this stretches also the interviews of the farmers were made. The upper uncontrolled part has been divided for the analysis due to the irrigation zones, which coincidence with the possible water distribution per canal and with the water contribution through turns which are being introduced when water is getting scarce. Therefore it was divided in Zones 01, 02, 04, 09, 10 (from the upper to the lower part, see map 2) and also an overall average or min/max has been analyzed.



Map 2: The detailed upper part study area to analyze the measures taken during the drought of 1994-97
Source: Rodhos (2006), CEAZA Data base and fieldwork sampling.

The characteristics of the area, concerning the maximum demand (which were taken from Rodhos, 2006) and the irrigation area, as well as the source of irrigation are been presented in the following table.

Table 4: Characteristics of the irrigated area under study

Region	*Characterisation*	*Max Demand m³/sec*	*Irrigation area (Ha)*	*Water source*
MZ 1 ZR01	unregulated	0,113	42,14	Rio Grande
MZ 1 ZR02	unregulated	1,770	931,87	Rio Grande
MZ 1 ZR04	unregulated	0,680	658,41	Rio Grande
MZ 1 ZR09	unregulated	0,267	155,77	Rio Grande/Rio Rapel
MZ 1 ZR10	unregulated	0,527	591,03	Rio Grande/Rio Rapel /Rio Ponio
MZ 1 sum	unregulated	3,830	2379,22	
MZ 5	regulated	7,043	6010,13	Rio Grande/La Paloma

The following two diagrams present the results concerning demand satisfaction of the single zones as well as the whole unregulated and regulated area. The zones are presented from up- to downstream. When discussing the results it is important to take into consideration the demands which are highly depended of the size of the irrigation area and as well the water source, which is changing in the lower

part since some longer channels are distributing water from the Rio Rapel and as well from the Rio Ponio (which is less important in terms of available flows) to the irrigation zones.
Therefore it is not surprising looking at diagram 1 (average yearly demand satisfaction) that the zone 01 has during all the years 100% demand satisfaction. Zone two is much larger and therefore suffers the first two years more than zone 04 although the demand satisfaction is still over 85% and therefore the first year is not considered as a drought year when characterizing the droughts with REDIM.
Very obvious is that in the MZ 5 which is regulated by the reservoir, the demand satisfaction is much lower than in the upper part, certainly the MZ has also almost double the size. Interesting to see is also the quite rapid loss of demand satisfaction in the third year of almost the whole MZ1, whereas the regulated part doesn't show a very significant decline.

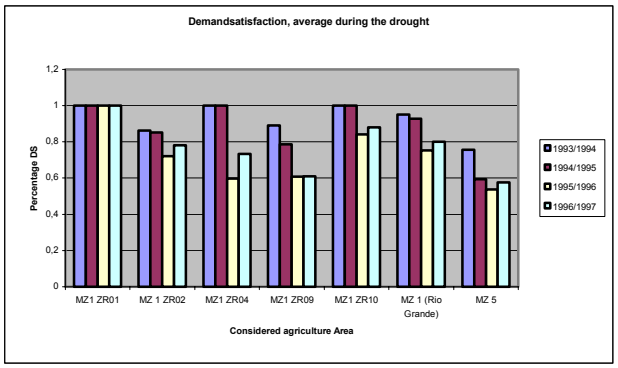


Diagram1: Average demand satisfaction during the drought

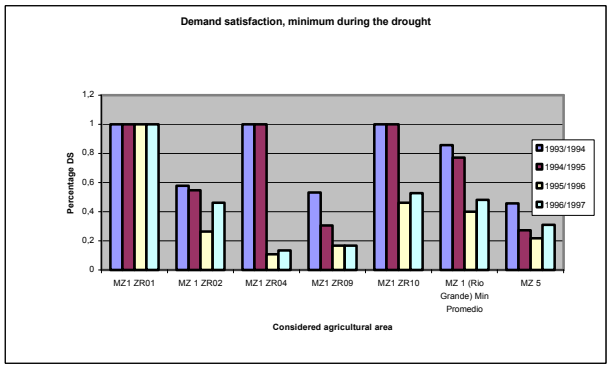


Diagram2: Minimum demand satisfaction during the drought

Comparing the average with the minimum demand satisfaction it gets obvious that also in the regulated part the minimum demand satisfaction is very low, even lower than Zone 10 (here the recuperation is very high). The difference between minimum and average demand satisfaction is caused by inter-annual variations. Comparing Zone 10 with MZ5 it gets obvious why the farmer have also the perception that the lower part of the catchment suffered more. As it can be seen it is very different in time and space and therefore a unique strategy can't be developed. This is one of the conclusions which have been done by the farmers too: in response to the drought, they develop various different combinations of strategies (17 in total).
The economic efficiency calculated with MAGIC can be defined as follow: the economic efficiency of the water use in agriculture depends on the expected revenue and the specific costs. As cost factors have been considered the investment cost for new irrigation technology as well the maintenance and operational costs for some water supply structures. Looking at the economic vulnerability (derived form the economic efficiency), it can be seen in table 5 that the economic efficiency is higher in MZ 1 as in MZ 5, although in this calculation has been integrated the area of Rio Rapel which has been neglected now (the studied areas here are a bit smaller, but the tendency keeps the same).

Table 5: Economic efficiency of the different Mesozones [elaborated from Rodhos (2006)

Mesozone /MZ)	*DS during drought average %*	*DS min during drought*	*DS average of the last 15 years*	*Economic efficiency ($ pro m³)*	*Area (ha)*
1	38	24	66	101,6	4089,63
5	35	22	46	83,7	6010,13

DS = Demand Satisfaction

Looking at the evaluation of the whole catchment it seems that MZ 1 is less vulnerable that MZ 5. Effectively, the economic efficiency is higher in MZ 1; the MZ 1 farmers could develop expensive strategies. Furthermore, the average demand satisfaction in MZ 1 is higher than in MZ 5 and so the MZ 1 hydrological vulnerability may be lower. But this lower vulnerability does not appear clearly in the farmers' perceptions and responses. Other variables should be taken under consideration in order to calculate the economical vulnerability to drought, taking under consideration the high losses

associated to high value permanent crops and the decrease of their profitably. It would be also necessary to acquire more detailed data on land use.

Conclusion and outlook

The capability to develop strategies during the 1993-1997 was higher in the regulated and the high value permanent crops areas. In these areas, the farmers could develop a more various number of strategies to cope with the drought. They had an economic capability associated to the profitability of their farming systems that permitted them to be more resistant against the drought. The risk of loss and the economical impacts relatives to these farming systems stimulate the farmers to develop expensive strategies in order to protect their investment. The Paloma System hydrological and economical vulnerability seems to be concentrated in the high value permanent crops areas where one can witness an increasing water demand known since 1997. The lower profitability of fruit trees is weakening the sustainability of the reduction of irrigated surface strategy and allows fewer farmers to develop strategies that need some kind of investment. The difficulty to access to subterranean water and the uncertainty about the temporary movements of the points of extraction reduces the sustainability of these responses during a drought. The resistance of the upstream farming systems do not really change (e.g. demand satisfaction, response capabilities and economical efficiency) whereas in the high value permanent crops and regulated areas, the resistance to a drought knows a decrease.

During the event 1993-1997, the Paloma system did not experienced a real crisis: the water organizations were successful in the drought management without the appearance of important conflicts and without state intervention in this management. However, the number of disagreements about water management that are resolved with a judiciary process is increasing. The difficulty to come to an agreement between private stakeholders and the necessary intervention of the State institutions are also weakening the flexibility of the Paloma system, at an organizational level. This rigidity should slow down the decision making and a rapid response is important in drought mitigation. With this "judiciary rigidity", the crystallisation of permanent crops areas and the augmentation of the economic vulnerability of most of the farming systems, what should be the resistance (in the time and in the space) of the Paloma system and of the farming systems against a similar drought?

The vulnerability analysis should be described with more details the organizational level, to get a more complete picture. The vulnerability should be studied integrating other factors of vulnerability as socio-demographic factors (socio-demographic vulnerability). It seems also necessary to considerate public institutions related to drought management and their response capabilities against this event.

Furthermore new simulation of a future system will be considered to be able to simulate also different operational models as well as different strategies of individual or organizational level, including the change of point of extraction of water.

Looking at the drought characterization another important issue is the spatial extent of a drought (regional analysis) as well as its severity. The drought classification can be made in correspondence of the event probabilities (from extreme wet to extreme dry) using the SPI (Standard precipitation index) value. For further studies especially for the region under consideration another drought indice should be investigated: The Surface Water Supply Index (SWSI) developed by Shafer and Dezman (1982), which explicitly accounts for snowpack and its delayed runoff (Tsakiris et al, 2007).

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