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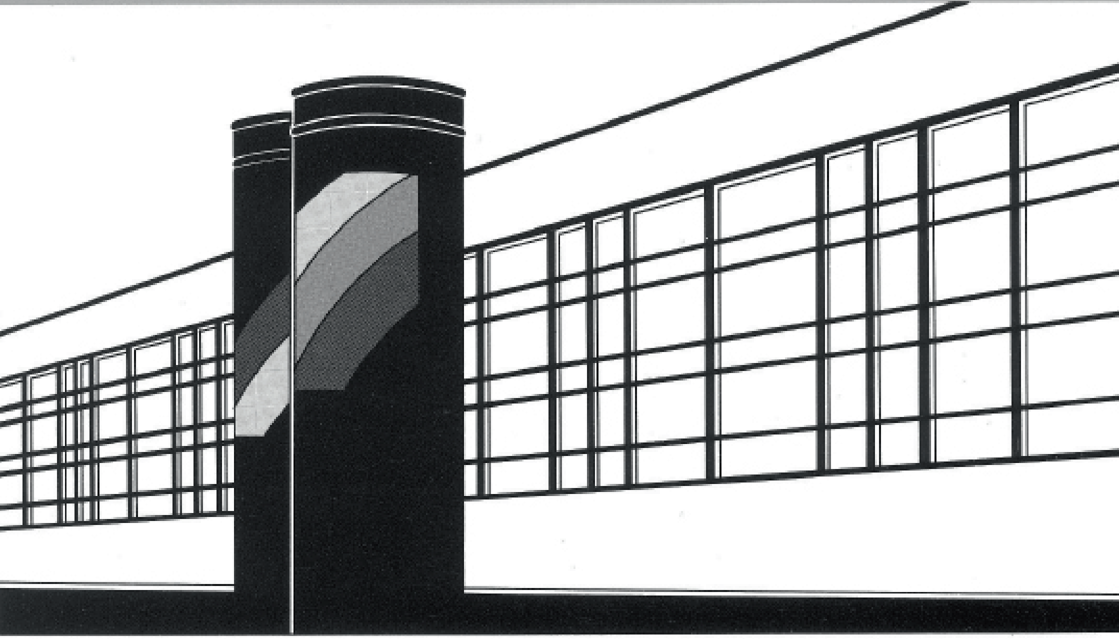

Heft 242 Nicole Kretschmer

Impacts of the existing water allocation scheme on the Limarí watershed – Chile, an integrative approach

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von
Dr.-Ing.
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List of Acronyms and Abbreviations

ACCamarico	Association of the Camarico channel (Asociación de Canalistas de Camarico)
ACCDPunitaqui	Association of the Punitaqui channel, Asociación de Canalistas del Canal Derivado Punitaqui
ACECogoti	Association of the Cogoti reservoir channels (Canalistas del Embalse Cogoti)
ACERecoleta	Association of the Recoleta reservoir channels (Canalistas del Embalse Recoleta)
ACPaMauSe	Association of the Palqui, Maurat-Semita channels (Asociación de Canalistas Palqui, Maurat - Semita)
AI	Interjacent Area [ha]
BES	Beginning Ending Storage [MCM/month]
CASEP	Community of water of the La Paloma reservoir (Comunidades de aguas de embalse La Paloma)
CAZALAC	Water Center for Arid and Semi-Arid Zones in Latin America and the Caribbean (Centro del Agua para Zonas Áridas y Semiáridas de América Latina y el Caribe)
CEAZA	Centre of advanced studies in arid Zones (Centro de estudios avanzados en Zonas Áridas)
CIREN	Information Centre 2of natural Resources (Centro de Información de Recursos naturales)
CNR	National Irrigation Commission (Comissión nacional de Riego)
Co	Cogoti Reservoir
CONAMA	National Environmental Commission (Since 2010: Ministry of Environment MMA)
CP	Control Point
D	Demand [m^3/sec]
D_a	Yearly Demand [m^3/year]
D_i	Demand in month i [m^3/month]
DI	Drought Index [-]
DGA	National Water Authority (Dirección general de Agua)
DMC	Double mass curve
DOH	Chilean Water Work devision (Dirección obras Hidráulicas)
DS	Monitoring station (discharge) under study
E_{irrig}	Efficiency of irrigation technique [%]
ENSO	El Niño and Southern Oscillation
Etc	Crop evapotranspiration (Equation for standard conditions) [mm/month]
Eto	Potential evapotranspiration [mm/month]
FAO	Food and Agricultural Organisation
F_{CL}	Channel Loss Factor [%]
i-CET-ODEPA	Information system for territorial statistics (Sistema de Consulta Estadístico Territorial)
FY	Firm Yield: maximum value of the annual water supply diversion with a computed reliability of 100 %t
IF	Instream Flow [MCM/month]
INE	National Institute of Statistics (Instituto nacional de estadística)
INIA	Institute of Agricultural Investigation (Instituto de Investigaciones Agropecuarias)
IP record	Percentage Index [%]
IS record	Storage Index [MCM]
IWRM	Integrated Water Resource Management
JVRCog	Association of the Cogoti River (Junta de Vigilancia Río Cogoti)
JVRGyL	Association of the Grande River, Limarí River and their affluents (Junta de Vigilancia del Río Grande, Limarí y Afluentes)
JVRHua	Association of the Huatulame River (Junta de Vigilancia Río Huatulame)
JVRHur	Association of the Hurtado River (Junta de Vigilancia Río Hurtado)
kc	Crop coefficent [-]

MCM	Million cubic meter
MMA	Ministerio del Medio Ambiente (Ministry of Environment)
NF	Natural Flow [MCM/month]
NSE	Nash–Sutcliffe coefficient [-]
p	mean daily percentage of annual daytime hours [%]
Pa	Paloma reservoir
PBIAS	Percent Bias [%]
Q_{AI}	Discharge supported by the interjacent area [m^3/sec]
$Qeco_m$	Monthly minimum ecological flow [m^3/sec]
$Q95\%PE_{min}$	Minimum discharge: 95% exceedance probability of the low flow period
R_{DA}	Ratio of the drainage area [-]
Re	Recoleta reservoir
REG	Regulated flow [MCM/month]
RMSE	Root mean square error
Rp	Period Reliability [%]
RSR	RMSE-observations standard deviation ratio [-]
Rv	Volumen Reliability [%]
STDEVobs	observed standard deviation
SWAT	Soil and Water Assessment Tool
T_{mean}	mean daily temperature [°C]
Tr	Tranca reservoir
UC	Use coefficient [-]
UNA	Unappropriated flow [MCM/month]
UNESCO	United Nations Educational, Scientific and Cultural Organization
WEAP	Water Evaluation and Planning System
WP	Watershed Parameter
WR E	Conditioned Water Right
WR P	Permanent Water Right
WR	Water Right
WRAP HYD	Hydrological model of WRAP (Water Right Analysis Package)
WRAP SIM	Allocation model of WRAP (Water Right Analysis Package)
WRAP	WaterRight Analysis Package
Monitoringstations:	
CEC	Rio Cogoti en entrada embalse
CUE	Rio Mostazal en Cuestecita
CUY	Rio Grande en Cuyano
FRG	Rio Cogoti en Fragüita
GPSJ	Rio Grande en Puntilla de San Juan
HAP	Rio Hurtado en Angostura de Pangue
LR	Rio Grande en las Ramadas
MC	Rio Mostazal en Caren
MOA	Rio Los Molles en Ojos de Agua
MOC	Canal Central Los Molles en Camera DGA
PAM	Rio Pama entrada Cogoti
PAN	Rio Limarí en Panamericana
RAM	Rio Combarbala en Ramadillas
RJ	Rio Rapel in Junta
TD	Rio Tascadero en Desembocadura
TOM	Rio Huatulame en Tome

Summary

The research is motivated by an interest in evaluating the special Chilean water management framework, relating to the 1981 Water Code legislation, introduced by the military government. This law mainly strengthened private property rights and increased private autonomy in water use. In particular, it is of interest to assess the impacts of this legislation in the context of the current highly stressed water availability situation in central and northern Chile, combined with intensive and increasing agricultural demands. The reason to look at this region first is to test a catchment with a more or less vivid water market.

The purpose of this research is to investigate the influence of water rights on water management practices under the present situation as well as changing situations. Here changing situation refer on one hand to improvement and extension of infrastructure, on the other hand to different use of the water in magnitude and further time and space. The latter one mainly based on the water market.

It will be analysed if the chosen model which has been developed and is being used for water management in Texas, based on the legal water right framework of Texas, can be used for the chilean context and is able to respond to the questions, which have to be solved in the Chilean water management.

The study region which is the Limarí River basin of the Coquimbo Region, Chile covers 11,666 km², spanning 30º 10’ to 31º 20’ S and 70º 15’ and 71º 45’ W comprising almost the entire Limarí Province (which has an area of 13,553.2 km²). Approximately 48% of the agricultural land in the whole Coquimbo region is in the Limarí Valley and 70% of the regional exports are produced there (Oyarzún, 2011). Climate conditions favour agriculture, but as the region is classified as semi-arid, hydrological resource availability is a potential problem. Local climate is influenced by El Nino Southern Oscillation (ENSO) which can cause multi-year periods of drought prone conditions during a La Nina event. Until 2014, the basin gained water for its reservoirs on average every 8 years through strong El Niño events (results of an analysis of monitored data, DGA), but the last major El Nino event occurred 12 years ago. The Limarí Valley experiences one of the most active water markets in Chile (Hearne and Easter, 1995; Christi, 2001), and the occurrence of extreme precipitation or drought events are a further catalyst for water market movements.

This study analyses how the integrated approach to water management is being understood in the Chilean private policy setup and its impact on a catchment which is highly regulated and ruled by thirteen private single entities and one newly constituted macro organisation, *Community of water of the La Paloma reservoir* (CASEP). Four of the private organizations do not participate in the so-called La Paloma System, which poses another challenge and pressure on the system, especially with new developments in these catchments. The main reservoir has been used since 1972, when the La Paloma system was established, with unregulated upstream sub-catchments and regulated catchments downstream of the three reservoirs: La Paloma (V_{max}=750 MCM), Cogoti (V_{max}=150 MCM) and Recoleta (V_{max}=100 MCM), including a natural and channel conveying system of nine private organisations, which have operated since then with a ratified operational model. Thus the basin's management system is a complex one, with multiple reservoirs, regulated and unregulated components, multiple management organisations and no basin-wide operational simulation model in place.

The main objective of this study is to investigate if the proposed WRAP Modelling System (**W**ater **R**ights **A**nalysis **P**ackage) which is used in the whole state of Texas, is able to model the consequences of the allocation scheme in the present, as well changing situations, incorporating the Chilean legal framework, here especially the allocation according to water rights. The main changes are subject to

i. new legislation to incorporate in the allocation of water resources
ii. further development, like new reservoirs in the upstream sub-catchments,
iii. water right transfers as well as
iv. different operation policies

WRAP was chosen to investigate the impacts of the water management practices. It combines detailed information describing water resource development, management, allocation and use with natural river system hydrology represented by naturalized streamflows, assuming that the hydrological pattern of a catchment stays the same in the future (Wurbs, 2011). The primary objective of the model is to provide capabilities for assessing hydrologic and institutional water availability and reliability within the framework of a priority-based water rights system. It has been developed as a flexible generalized computer modelling system for simulating the complexities of surface water management. The following sub-goals were defined:

(i) Derive natural flows out of the monitored discharges, to determine the basin hydrology in the absence of any management and regulation. This "zero" condition is a prerequisite to model different scenarios, including different structural (here mainly reservoirs) and operational set up. Furthermore it is needed for estimating the minimum ecological flows. After pre-processing the monitored time series of streamflows, naturalized flows were developed for 15 stations from 1946 until 2010. In total 27 points of interest (control points, CP) in the basin are defined for modelling, thus for the missing control points, streamflows were calculated by distributing the natural flows from the gauged to the ungauged control points. Here different methods incorporated in the WRAP modelling system were used.
(ii) Determine which allocation target might be better to face the possible new infrastructure and developments in the basin.
(iii) Testing the developed ecological minimum flows against the simulation results in the basin of the most interesting control points individually and further aggregated to sub-catchments.
(iv) Simulation and evaluation of different system operational policies

Beside the development of the spatial configuration of the system, which has been defined as a set of control points (CP) that represent pertinent sites in the river basin, geospatial data, time series data, census data, operational data sheets of the organisations as well as information and data about the water rights of each stakeholder have been statistically and spatially pre-processed in order to be able to estimate agricultural water demand, understand the legal system in general and of the basin under study in particulary. Further information of the Food and Agricultural Organisation (FAO), monitored data of the National Water Authority (DGA), elaborated data of the National Centre of Natural Resources (CIREN) and historical and actual regional as well as local studies were consulted to elaborate all the needed information to model the system.

With this information and preprocessed data the WRAP modelling system was implemented, to quantify the impacts of decision making and its consequences on the whole system. Furthermore the development of diferent scenarios could be elaborated with all the information and data gathered.

The base model was developed step by step with a time period of 20 years to test the configurations of the system with all the input data. To evaluate the model, general model evaluation guidelines, for monthly time steps, which were developed, based on performance ratings for recommended statistics by Moriasi, and others (2006) have been applied. As quantitative model evaluation statistics, the Nash - Sutcliffe-coefficient (NSE), the root mean square error (RMSE) - the observations standard deviation ratio (RSR) as well as percent bias (PBIAS) are evaluated. The results range from very good (upstream) until satisfactory (last station downstream). Furthermore the hydrographs were analysed graphically and it was confirmed that they correspond well to the observed records.

Alternative usage scenarios were developed and tested with the whole time period of 64 years historical streamflows. Starting with real supply data (where available) and modelling a new planned reservoir upstream in one sub-catchment of the La Paloma system, also developments of independent sub-catchments were simulated and analysed. The simulation was done with two different supply scenarios: 1. the real diversion targets and 2. the legal allocation volumes. The different scenarios include additionally direct or indirect changes in water rights, transfers from upstream to downstream and vice versa.

Model results include water supply reliabilities (including reliability indices) as well as flow and storage frequency statistics developed from the simulation results representing long-term probabilities or percent-of-time estimates. Furthermore shortage metrics have been developed by the model and evaluated for each scenario. The model includes the following frequency statistics for concisely summarizing modelling results: (a) volume and period reliability tables for water supply diversion, (b) frequency tables for naturalized, regulated and unappropriated flows, reservoir storage volumes, as well as instream flow shortages and (c) reservoir storage-reliability tables.

The main results can be summarised as follows: Regarding a new reservoir (La Tranca) upstream of the Cogoti reservoir and part of the Paloma system, a best location, with final extraction points and best allocation volume per water right from the reservoir, as well as possible operational policies were determined. Comparing it with scenarios in which the independent upper parts also were further developed, with and without the new reservoir La Tranca, the consequences for the downstream users were that the Cogoti river - reservoir - system provides more reliable water supply, when introducing the La Tranca reservoir.

Thus it is recommendable for the association of the Cogoti River to construct a reservoir and keep participating in the La Paloma system. This scenario, according to the model results, will provide benefits to all, when implementing the amounts and management as suggested and tested so far (certainly more management possibilities should still be tested to make sure to implement the most convenient).

Results of the firm yields (FY) show clearly that the impact of the further development of the upstream catchments of Pama and Combarbala might be quite high since it lowers the firm yield and 85% exceedance reliability by about 12 MCM annually, which is between 40% and 26% respectively.

Evaluating the real (current), legal and mixed (real upstream, legal downstream) target scenarios, in different sub-catchments different scenarios were preferable, which finally lead to the mixed targets to be used for further scenario development. In some sub-systems the difference between legal and real targets is very high, especially in the Cogoti sub-system; keeping here the original legal assignation in the future, when further upstream development gets real, decreases the negative impact to the downstream users essential. Furthermore the real targets in the upper catchment of the Limarí reservoir (Grande River) results in slightly better reliabilities for the downstream users of the La Paloma reservoir. Further water transfers and changes of extraction points have to be studied in detail, different examples shows that the benefits and negative consequences can not been always easily foreseen, but can be well evaluated by the model and model result can provide a useful basis for decisions.

Ecological minimum flows are evaluated in two manners: (i) with instream flow target (required existent legal condition for a conditioned water right); (ii) comparing the regulated flows with the before calculated minimum flows according to the 2002, 2008 and 2012 regulation of the other CPs. None of the historic and recent legal requirements for the minimum ecological flow (Qeco) can be satisfied in total, neither in the present nor in future scenarios. The results with the requirement of 2008 are better than with the more recent regulation of 2012. The legislation of 2012 gives more attention to the high flow events, and less to the average or water poorer years, thus for this semi-arid catchment the regulations of 2008 are more suitable. Nevertheless forcing the fulfilment of Qeco (2008) in the evaluated CPs would consequently result in severe shortages in the supply of the water rights (WR).

A common operational rule as used (more or less consequently) since the system is in operation is not working efficiently for the sub-systems, the three reservoirs react differently, a common operational rule can be recommended, between the La Paloma and Cogoti reservoir in only one scenario. The Recoleta reservoir always needs an individual rule expressed with a drought index, specially tested for the sub-system.

Finally looking again on the main results of the different scenarios considering the further upstream development, it can be stated that according to the model the basin as a common system holds sufficient resources to deal with these changes. Nevertheless, this would imply that the distribution between the organisations has to be reviewed and adapted to the new conditions.

Although it has been confirmed during this investigation that in some cases the organisations already use assignations that differ from those originally agreed upon during some periods, a redistribution of the volumes is not very likely to occur. In general it is almost impossible to transfer an already-granted benefit from one organisation to another. But the model results show the possibilities and consequences of such actions and thus serve as a good basis for discussions. The pressure of the scarce water resources is increasing for all actors within the basin, thus, rethinking some water allocation and management practices is timely.

After all the different scenario simulations and analysis of the results it can be stated that the WRAP modelling system is applicable for the questions under study based on the legal Chilean water management framework. Flexibility is provided for adaption of a broad range of modelling approaches. A huge variety of management records can be combined in many different ways to be able to model any application. Ingenuity is required from the modeller to achieve the incorporation of sometimes quite complex allocation rules, apply different target options, demands, administrate a variety of users and include new developments within a multiple and multipurpose reservoir-river management system. Although some simplification of the independent sub-catchments was necessary, the achieved results show that the consequences of allocation decisions, including water transfer and future development are simulated in a satisfactory manner and can therefore be much better understood. The model system is adequate to serve as a basis for decision making within the chilean legal framework.

Zusammenfassung

Die Motivation des Forschungsthemas basiert auf den speziellen chilenischen Rahmenbedingungen der Wasserwirtschaft, deren rechtliche Grundlage das Wassergesetz von 1981 (Codigo de agua) bildet. Es wurde von der Militärregierung eingeführt und stärkt private Eigentumsrechte sowie die private Autonomie in der Wassernutzung; jeder Nutzer benötigt Wasserrechte. Von besonderem Interesse ist die Untersuchung der Rahmenbedingungen im Kontext mit dem hohen Druck auf die Wasserverfügbarkeit im zentralen und nördlichen Chile, kombiniert mit intensiver Landwirtschaft.

In der Studie wird untersucht, wie integrierte Wasserwirtschaft unter den vorliegenden Rahmenbedingungen von den Akteuren verstanden und umgesetzt wird, sowie deren Auswirkungen auf das betrachtete Untersuchungsgebiet.

Da die gesamte Wasserverteilung auf Wasserrechten beruht und es in Chile noch kein Model gibt, dass die Wassernutzung auf der Grundlage der Wasserrechte und deren Prioritäten modelliert, wird in der vorliegenden Studie das Modelsystem WRAP (**W**ater **R**ights **A**nalysis **P**ackage), welches für die legalen Rahmenbedigung von Texas entwickelt wurde unter chilenischen Bedingungen getestet. Als Studienregion wurde ein Einzugsgebiet im semi-ariden Norden gewählt, welches sich durch eine starke Regulierung und viele Stakeholder auszeichnet.

Dabei handelt es sich um das Limarí Einzugsgebiet, gelegen in der Coquimbo Region, Chile, zwischen 30º 10’ bis 31º 20’ und 70º 15’ bis 71º 45’ W mit einer Fläche von 11.666 km². Etwa 48 % der landwirtschaftlichen Fläche der Region werden im Limarí Tal kultiviert und 70 % des Regionalexports werden dort erzeugt (Oyarzún, 2011). Dies ist das Resultat der dort herrschenden bevorzugten Klimabedingungen, andererseits stellen die hydrologischen Bedingungn des semi-ariden Gebiets auch eine Gefahr dar. Das Klima steht unter Einfluss der El Niño - Southern Oscillation (ENSO), welche unter anderem auch längere Trockenperioden mit größerem Wassermangel, zur Folge hat. Im Durchschnitt ist alle acht Jahre im Einzugsgebiet ein El Niño Ereignis zu verzeichnen (Ergebnisse einer Analyse von gemessenen Niederschlagsdaten der nationalen Wasserbehörde, DGA, 1949-2014), allerdings liegt das letzte große Niederschlagsereignis zwölf Jahren zurück. Das Limarí Tal stellt einen der aktivsten Wassermärkte in Chile dar (Hearne and Easter, 1995; Christi, 2001), vor allem katalysiert durch die extremen hydrologischen Bedingungen.

Das Einzugsgebiet, das durch drei Talsperren stark reguliert ist (La Paloma System), wird von 13 privaten Organisationen betrieben, von denen aber nur neun dem La Paloma System angehören, die anderen vier sind unabhängig und können daher ihre Wasservorkommen ohne weitere Einschränkung (soweit es ihre Wasserechte zulassen) nutzen. Zudem zählt seit kurzem die für die Haupttalsperre La Paloma neu gegründete Makroorganisation: Nutzergemeinschaft der La Paloma Talsperre (CASEP), deren Direktorium aus den Organisationen zusammengesetzt ist, zu den Akteuren, die dem La Paloma System angehören. Die unabhängigen Organisationen stellen eine weitere Herausforderung und einen zunehmenden Druck auf das System dar, vor allem mit möglichen neuen Entwicklungen bezüglich der Wasserregulierung (neue Stauseen) und somit möglichen Landnutzungsveränderungen, bedingt durch höhere Bewässerungssicherheiten. Die Haupttalsperre, La Paloma, wurde 1972 als letzte in Betrieb genommen und damit summiert sich das Stauvolumen der drei Talsperren auf 1.000 Mio. m^3 (La Paloma: V_{max} = 750 Mio. m^3; Cogoti: V_{max} = 150 Mio. m^3 und Recoleta: V_{max} = 100 Mio. m^3). Die Talsperren sind nicht alle miteinander verbunden, werden jedoch mit einem gemeinsam ratifizierten, betrieblichen Modell gesteuert. Ein weiterer Bestandteil des Gesamtsystems ist ein Kanalsystem von ungefähr 700 km Länge. Es existiert kein Simulationsmodell, das als Basis zur Wasserverteilung dient und zudem auf Wasserrechten basiert und somit zur Transparenz beitragen könnte.

Das Hauptziel der Forschungsarbeit besteht darin, zu untersuchen ob das vorgeschlagende WRAP Modellierungsystem (**W**ater **R**ights **A**nalysis **P**ackage), welches ursprünglich für die legalen Rahmenbedingungen der Wasserwirtschaft von Texas (USA) entwickelt wurde, auch die legalen Rahmenbedingungen von Chile berücksichtigen kann, um damit folgende Fragestellung zu untersuchen: Die Folgen der aktuellen Wasserverteilung im gegenwärtigen System und unter veränderten Bedingungen auf das gesamte System. Hier werden allgemein gültige Veränderungen in einem chilenischen Einzugsgebiet, welches hohem Druck ausgesetzt ist berücksichtigt:

i. Neue legale Rahmenbedingungen, die für die Wasserverteilung berücksichtigt werden müssen
ii. weitere Stauseen in den oberen noch unregulierten Teileinzugsgebieten,
iii. Wasserrechtübertragungen und
iv. verschiedene Bewirtschaftungsregeln

für das gesamte Einzugsgebiet zu analysieren und zu bewerten.

Zu diesem Zweck wurde daher ein Modell für das Einzugsgebiet mit dem WRAP Modellierungsystem entwickelt, um die Konsequenzen der Wassermanagement-Praxis zu untersuchen. Es kombiniert Informationen über Wasserressourcenentwicklung, Management, Verteilung und Nutzen mit der natürlichen Flusssystemhydrologie, repräsentiert durch wiederhergestellte natürliche Abflüsse. Dabei wird vorausgesetzt, dass die historischen hydrologischen Zeitreihen als Grundlage für die Zukunft gelten können (Wurbs, 2011).

Mit dem Modell wird somit das primäre Ziel verfolgt, hydrologische und institutionelle Wasserverfügbarkeit und Versorgungszuverlässigkeit innerhalb eines auf Prioritäten basierten Wasserrechtsystems in einem Einzugsgebiet zu bewerten. Im vorliegenden Fall wird dies auf das Oberflächenwassermanagement beschränkt, da dieses die Hauptressource darstellt. Folgende Hauptunterziele können formuliert werden:

i. Entwicklung der natürlichen Abflüsse aller Abflussstationen, die im Einzugsgebiet relevante gemessene Datenreihen besitzen. Somit erhält man die natürliche Hydrologie, auf die man dann die verschiedenen Szenarien aufbauen kann. Desweiteren wird aus den natürlichen Abflüssen, nach chilenischem Wasserrecht der ökologischen Mindestabfluss berechnet. Es wurden natürliche Abflüsse von 15 Monitoringstationen in einem Zeitraum von 1947-2010 modelliert, und diese dann mit Hilfe des Modells auf die anderen relevanten Kontrollpunkte verteilt.
ii. Definition des maximal zu nutzenden jährlichen Wasservolumens (weiterhin der Durchschnitt der letzten Jahre oder die legal festgelegte Verteilung), wenn der Druck auf die Ressource steigt, z.B. durch neue Bauwerke, wie Staudämme, in den Teileinzugsgebieten im Oberwasser. Ziel ist es, die negativen Auswirkungen auf die Nutzer flussabwärts zu minimieren.
iii. Evaluierung der minimalen ökologischen Abflüsse durch den Vergleich der Simulationsergebnisse mit den nach den Richtlinien geltenden berechneten Minimalabflüssen, sowohl an einzelnen ausgewählten Kontrollpunkten, als auch aggregiert nach Untereinzugsgebieten.
iv. Simulation und Evaluierung verschiedener Bewirtschaftungsregeln für das Gesamtsystem im Hinblick auf die Versorgungssicherheit.

Zunächst wurde die räumliche Struktur des wasserwirtschaftlichen Gesamtsystems erarbeitet und durch Kontrollpunkte, die die wichtigsten Bauwerke, wie Talsperren und Entnahmepunkte sowie andere für die Modellierung relevante Standorte darstellen, definiert. Es wurden Geodaten, Zeitreihen und Zensus Daten ausgewertet und bearbeitet, sowie verschiedene Datenbanken konsultiert, sowie Informationen einzelner Nutzerorganisationen erhoben (Landwirtschaftlicher Zensus, FAO, hydrologische Daten der DGA, Daten vom nationalen Zentrum für natürliche Ressourcen, CIREN sowie historische und aktuelle regionale und lokale Studien um z.B. die detaillierte Verteilung der Wasserrechte und den landwirtschaftliche

Wasserbedarf aller Untereinzugsgebiete zu analysieren und zu berechnen, sowie die natürlichen Abflüsse zu modellieren.

Das Modell wurde Schritt für Schritt mit dem WRAP Modellierungssystem implementiert. Das Grundmodell wurde mit Zeitreihen von zunächst zwanzig Jahren (1990-2010) und tatsächlich verteilten Wasserversorgungsdaten (soweit vorhanden) gespeist, um die Konfigurationen des Systems mit allen notwenigen Eingabedaten zu testen. Folgende Bewertungskriterien für die Evaluierung der Modelleffizienz des Basisszenarios sind genutzt worden: Nash-Sutcliffe-Koeffizient (NSE), RMSE-observations standard deviation ratio (RSR) und absoluter Modell-BIAS (PBIAS%). Hierzu wurden die Kontrollpunkte genutzt, die gleichzeitig auch Abflussmessstationen darstellen. Die Resultate reichen von sehr gut (obere Einzugsgebiete) bis befriedigend (am untersten Kontrollpunkt des Einzugsgebietes). Zudem wurden die Ganglinien grafisch analysiert, was bestätigt, dass sie sich in den meisten Fällen sehr gut mit den gemessenen Werten decken.

Die weiteren entwickelten Szenarien wurden dann mit dem gesamten vorliegenden hydrologischen Zeitraum von 64 Jahren simuliert. Hier wurden zunächst die Durchschnittswerte der realen Wasserverteilung der letzten zwanzig Jahre zur Modellierung genutzt, und damit eine neue mögliche Talsperre im Paloma System (Cogoti Fluss) simuliert. Zudem wurden Szenarien mit weiteren möglichen Talsperren in den unabhängigen Zuflüssen der Cogoti Talsperre modelliert und analysiert. Alle Szenarien wurden ebenfalls mit der legal festgelegten Wasserverteilung simuliert, um die Unterschiede aufzuzeigen.

Die wesentlichen Ergebnisse können wie folgt zusammen gefasst werden: Für die am Cogoti Fluss geplante Talsperre konnten die günstigste Lage und das günstigste Szenario bezüglich der Verteilung der Wasserrechte und des maximalen jährlichen Volumens mit dem Modell herausgearbeitet werden. Dafür wurden auch verschiedene Bewirtschaftungsstrategien getestet.

Die Simulation weiterer Szenarien, die einerseits einen abhängigen Talsperrenbetrieb mit der schon bestehenden Talsperre im Untereinzugsgebiet und andererseits weitere maximale Wassernutzung der unabhängigen oberen Untereinzugsgebiete durch neue Talsperren berücksichtigt, lassen folgende Schlussfolgerungen zu: Die Resultate des Cogoti-Fluss-Talsperren-Systems sind günstiger, wenn die mögliche neue Talsperre des Systems (La Tranca) berücksichtigt wird, mit und auch ohne den weiteren Ausbau der unabhängigen oberen Einzugsgebiete (Flusssysteme Combarbala-Pama). Laut den Ergebnissen ist es empfehlenswert für die Organisation des Cogoti Flusses die Talsperre zu bauen und auch im La Paloma System verankert zu bleiben. Wenn die Mengenwirtschaft und Bewirtschaftung so wie vorgeschlagen ausgeführt wird (weitere Simulationen werden empfohlen), ergibt sich für alle ein Nutzen.

Die Ergebnisse der Berechnung der jährlichen Mindestergiebigkeit (*Firm Yield*, also die Ergiebigkeit, die in 100% der simulierten Fälle erlangt wird) zeigt deutlich die negativen Auswirkungen einer weiteren Entwicklung in den unabhängigen Flussgebieten von Pama und Combarbala; das *Firm Yield* wird um ungefähr 40% vermindert, das zu 85% der Fälle bereitgestellte Wasser (85% supply reliability) um ca. 26% reduziert (das entspricht jeweils ca. 12 Mio. m^3/Jahr).

Die Auswertung der Szenarien mit den verschiedenen maximalen jährlichen Verteilungsvolumina (legal und Durchschnitt der letzten 20 Jahre) führt zu dem Ergebnis, dass für verschiedene Untereinzugsgebiete unterschiedliche Volumina genutzt werden sollten, um das Gesamtsystem letztendlich zu bewerten. Es konnte teilweise ein großer Unterschied zwischen legal zugeteilten und tatsächlich genutzten Volumina ermittelt werden. Vor allem im Cogoti-Teilsystem minimiert die ursprüngliche legale Zuteilung die negativen Auswirkungen der möglichen neuen Nutzungen in den oberen Teileinzugsgebieten auf die Nutzer, vor allem in Anbetracht der wasserknappen Jahre, die wiederholt auftreten. Die realen Nutzungen des Grande Flusses, im Gegensatz zu den legal möglichen Nutzungen, wirken sich leicht positiv auf die

Verteilung unterhalb der Haupttalsperre (La Paloma) aus. Weitere Übertragungen von Wasserrechten und damit Volumina sowie Verlagerung der Entnahmestellen sollten nach Bedarf im Detail simuliert werden. Beispiele zeigen, dass die Vorteile bzw. negativen Konsequenzen nicht immer einfach vorauszusehen sind, aber sehr gut durch WRAP modelliert werden können.

Der Vergleich des berechneten ökologischen Mindestwasserabflusses nach den Vorschriften von 2002, 2008 und 2012 mit den Simulationsergebnissen in den Kontrollpunkten führt zu folgenden Schlussfolgerungen: Die Regulierung von 2012 berücksichtigt durch ihren Ansatz die höheren Abflussvorkommen und weniger die Durchschnittsabflüsse oder wasserknapperen Jahre. Daher werden für das Studiengebiet (semi - arides Klima) die Vorschriften von 2008 als angemessener betrachtet. Dennoch kann in 30% der simulierten Monate der Mindestabfluss nicht eingehalten werden. Würde man diesen nun mit dem Modell forcieren, würde dies zu starker Reduzierung der Wasserverteilung der Nutzer führen.

Die weitere Analyse bezüglich der gemeinschaftlichen Bewirtschaftungsregel der drei Talsperren, die seit der Inbetriebnahme des La Paloma Systems gilt und seit dem mehr oder weniger konsequent ausgeführt wurde, ergab, dass alle drei Talsperren sehr unterschiedlich reagieren und nur in einem Szenario kann eine gemeinsame Regelung zwischen der La Paloma und Cogoti Talsperre empfohlen werden. Die Recoleta Talperre benötigt eine individuelle Betriebsregelung, vor allem in wasserknappen Jahren, wenn das Stauraumvolumen stärker zurückgeht. Diese kann im Detail mit Hilfe des Modells entwickelt werden.

Als abschließendes Resultat ist festzuhalten, dass durch die verschiedenen Szenarien herausgestellt werden konnte, dass auch mit dem möglichen weiteren Ausbau der Zuflusseinzugsgebiete der Cogoti Talsperre, die verbleibenden Oberflächenwasserressourcen ausreichend sind, um die Wasserrechte in dem gemischt zugeteilten Szenario (legal und real) weiterhin hinreichend zu versorgen. Allerdings beinhaltet dieses, dass die Verteilung zwischen den Organisationen überdacht, neu bewertet und an die möglichen neuen Verhältnisse angepasst werden muss.

Das Modell zeigt die Möglichkeiten und Konsequenzen einer Nicht-Umverteilung. Genauso können zukünftig verschiedene Umverteilungen leicht simuliert werden und somit als transparente Diskussionsbasis dienen. Der Druck auf die sehr knappen Wasserressourcen steigt in dem Einzugsgebiet und wird für alle Akteure grösser, was bedeutet, dass es an der Zeit ist, ein Umdenken voranzutreiben.

Obwohl in der vorliegenden Studie bei der Umsetzung einige Vereinfachungen des Systems angenommen wurden, können mit dem entwickelten Modell die beschriebenen Situationen zuverlässig simuliert und bewertet werden. Der Einsatz des Modellsystems kann für die Zukunft als Entscheidungsunterstützung uneingeschränkt empfohlen werden.

Es ist in der Lage die legalen chilenischen Rahmenbedingungen zu berücksichtigen und somit auch für andere Einzugsgebiete in Chile, vor allem dort wo die Oberflächenwassernutzung im Vordergrund steht, geeignet.

1 Background and motivation

1.1 Location and Climate

Arid and semi-arid zones, i.e., where potential evapotranspiration surpasses rainfall, cover over 30% of the earth surface, and are typically found between latitudes 15-35º (both northern and southern hemisphere), immediately north and south of the major tropical convergence zones (Simmers, 2003). An increased demand for water on these vulnerable zones is already occurring worldwide, due to factors such as population growth and economic development based on water demanding activities such as agriculture and mining (Oyarzún et al, 2015). This increased demand is further complicated by water shortage trends due to climate change, a common situation in several basins in North–Central Chile (CONAMA, 2006; Souvignet et al, 2010).

The Limarí River watershed, which has been selected as the case study of this research is located in the semi-arid north-central region of Chile and is highly dependent on the annual snowfall in the Andes. Precipitation alterations from El Niño and Southern Oscillation (ENSO) events have a high influence on water availability at inter-annual scales. The mountainous areas host the headwaters and guarantee the supply of water to downstream communities for irrigation, human consumption and ecosystem sustainability in dry spring and summer periods.

The basin is located at 30º 10’ - 31º 20’ S latitude and 70º 15’ - 71º 45’ W longitude and has an area of 11,666 km². It covers almost the entire Limarí Province (which has an area of 13,553.2 km²) and belongs to the Coquimbo Region (IV Region, part of the so called "Norte Chico"). Approximately 48% of the agricultural surface in the whole Coquimbo region is cultivated in the Limarí Valley and 70% of the regional export is produced there (Oyarzún, 2011).

The average annual rainfall does not exceed 130 mm in the lower Limarí basin, whereas the evapotranspiration exceeds 1,000 mm. The average discharge (including all extreme events) of the main river (Grande River) is 4 m³/sec, with a maximum recorded of 50 m³/sec, but is highly variable, both spatially and temporally (Kretschmer et al, 2012).

1.2 Sustainable water resources management

Integrated water resource management (IWRM) and its evolution in Chile have been extensively described in Kretschmer et al. (2012). While there has been more than 20 years of discussion of management concepts until now they have not been implemented satisfactorily. The management is ruled by a relatively rigid legal and institutional framework. Nevertheless the main issues of development of IWRM or watershed management will be reviewed since its main principles are also mentioned in the Chilean context.

The following “events” laid the historic foundations of the main international guidelines for sustainable water resources management, which is the main pillar of integrated watershed management: (a) the United Nations Water Conference, held in Mar del Plata, Argentina in 1977. This conference in particular is regarded by many researchers as a landmark event in watershed management (and management of water resources in particular). Special attention was paid to the growing threat faced by water resources as a result of the conflict between the needs of economic development and environmental protection; (b) the International Conference on Water and the Environment: Development Issues for the 21st Century, held in Dublin, Ireland, in 1992. The Dublin Conference established four guiding principles for the management of water resources; these four “Dublin Principles” are at the heart of what is known as IWRM; (c) the United

Nations Conference on Environment and Development, held in Rio de Janeiro, Brazil, in 1992; (d) the International Conference on Water and Sustainable Development, held in Paris, in 1998; (e) the United Nations Millennium Declaration (September, 2000), which set eight goals for development (Millennium Development Goals or MDGs) (Kretschmer et al, 2012)

Chile has adopted these concepts, and has recently modified the environmental assessment process that has been in place since 1994 (Lostarnau, 2011). Moreover, Chile has recently joined the Organization for Economic Cooperation and Development (OECD), triggering the development of new government plans related to natural resource management. One area that has begun to receive increasing attention and importance is integrated watershed management and water resources protection, as illustrated by the formulation of the National Strategy for Integrated Watershed Management (CONAMA, 2007), the National Glacier Policy (CONAMA, 2009), and the Secondary Surface Water Quality Regulations (CONAMA, 2004). In addition, the National Water Authority (Dirección General de Aguas, DGA) fostered the formation of Regional Water Round Tables aimed at establishing a public-private forum for coordination, understanding and agreement among different stakeholders and water users at the basin scale (DGA, 2007).

Nevertheless none of these initiatives have made significant or lasting progress to date; ideas and concepts exist but the implementation has not been successful so far. Different factors are responsible for that, including legal and institutional limitations.

1.3 Legal/social framework of Chiles water management

In the legal political framework, catchment management issues are mainly expressed through the national water policies. Water in Chile is defined as a national good with public and private use, applying economic market principles (Francke, 2003). This is established in the Water Code of 1981 (Código de Agua) and further allowing the transfer of private property rights for water use (Alvarez et al, 2006).

The 1981 Water Code introduced by the military government mainly strengthened private property rights and increased private autonomy in water use. With the implementation of the Water Code, for the first time in the history of Chile, water rights were separated from landownership. The aim was to foster a commercial and market-oriented economic mentality among water users. This was the total opposite to the 1967 agrarian reform, which had expanded the governmental authority in issues of water use and water management (Bauer, 1998, 2004).

Bauer (2004) points out that the Chilean model (here referred mainly to water markets) raised crucial questions among international water experts, from which he highlights two: first in how successful those markets have really been; and secondly what is the relationship between water markets and other issues of water management in Chile: what are the consequences of its legal and institutional framework for solving water management problems other than allocation of resources?

The second point has attracted much less attention, that leads to the conclusion that "*the Chilean experience offers a unique opportunity to examine the fundamental issue about the 4th Dublin Principle: Is the free market approach to recognize water as an economic good, like the narrow economic perspective associated with this approach, compatible with the broader and long-term goals of integrated water resources management*" (Bauer, 2004) and thus with the idea of integrated watershed management?

Based on several publications, including the pros which are pointed out by the World Bank and the Inter-American Development Bank as well as the more critical views of the United Nations agencies and a paper about water governance for the Global Water Partnership, Bauer (2004) argues that "*the positive* *assessments of the Chilean Water Code are simplistic or mistaken in several crucial respects, and in consequence it is misleading and dangerous to present the Chilean case as a model of success whose few problems other countries can avoid*". In his opinion "*the Chilean experience offers broader lessons by demonstrating the critical limitations of a narrow approach to water economics and the failure of such an approach to adequately address the legal and institutional arrangements that are essential to integrated water resources management*".

The Chilean Water Code comprehends among other things the legal basis of the national water policy whose last modification was made in 2010 (Ley 20417, 2010). The main modification, which will be addressed in this work, is the introduction of an ecological minimum flow. According to Riester (2011) already in 1999 it was established that a minimum flow should respected when new water rights are granted, but changes in the Water Code was made only in 2005.

Following Bauer (2004) the Chilean model is the world's leading example of a free-market approach to water law, water right, and water management. Since the 1990s, the frame of the Chilean model – usually referred to simply as "Chilean water markets" has spread among international and Latin American water experts; the World Bank for example has actively publicized the Chilean case as a model of success and an inspiration for water policy reforms in other countries (Bauer, 2004).

The article I of the Water Code separates superficial waters and groundwater, and applicants for new water rights no longer have to specify or justify their intended water uses. There are no legal priorities among different types of water use stipulated, its left to private parties and the market. Also, water rights holders do not have the obligation to use their water and in accordance to the original code they face no penalty or cancellation for lack of use; however in 2005 a fine for non use was introduced.

As stated in Solanes (1996) and Bauer (2004) the unconditional nature of private water rights in Chile subject to the 1981 Water Code differs from all previous legislation in Chile and also from the water laws around the world even those who incorporated the concept. These principles allow unrestricted speculation in water rights, and have been the most controversial aspects.

In the context of watershed management, the Water Code which is the only legally regulating base does not give a framework since the code's main concern when it was established was agricultural use, especially irrigation. Later the concept of non-consumptive use was incorporated as well as the difference made between non-consumptive and consumptive use rights was introduced, specially to stimulate hydroelectric development. However at this point it is important to note the following: 1. it was intended to stimulate hydroelectric use in the upper part of a catchment without harm/affect negatively farmers downstream with pre-existing consumptive water rights, 2. the term non-consumptive implies that the owner may divert water from a stream and use it, as long as the water is returned in the same condition (both in quantity and quality) to its original channel, for further downstream use.

Most changes to the original 1981 Water Code had been done in 2005 through the law 20017, Art. 1 (Ley 20017, 2005). The main changes with consequences to water management are the titles X and XI: *Title X: Protection of the water and river courses, Title XI: Fine in case of not utilizing of the water.* Article X states that a minimum environmental flow has to be considered when new water rights are granted, it does not affect by law already existing water rights. The law does not establish a new approach or method to determinate minimum flow, thus the manual of the DGA of 2002 keeps valid. Nevertheless the law stipulates that the minimum ecological flow does not have to be higher than 20% of the average annual discharge of the respective surface water; however in specific cases if new knowledge about environmental needs of particular places leads to different requirements it can be increased to more than 40% of the average discharge (this has to be agreed upon by the President of Chile). It is worth noting that the term:

"minimum ecological flow" is introduced and used, but finally just a maximum flow of the ecological flow is newly defined. The introduction of a minimum flow included in the approval of new water rights was quite ambiguous and according to DGA officials the need is high for further investigation to establish these ecological flows (Riester, 2011).

The main idea behind article XI about the implementation of fines is to give incentives to use the granted water rights and not provoke a negative impact with not using/transferring it. Differences are made mainly by region (administrative division of Chile), by type of water right and quantity of original constitution (l/s).

Finally in July 2013 a new amendment, No. 014, of the Environmental Ministry (MMA) which has effects on the respective article in the Water Code has been ratified. This implies a more explicit definition of environmental flow taking into account not just the annual average of river flow, but the monthly. Following discussions with public stakeholders the minimum environmental flow was set at 10% (after the DGA manual of 2008), but is not reflected in the above mentioned amendment of 2013.

In summary the only legal basis for water management (here better named: water allocation) is the Chilean Water Code of 1981, and thus mainly left to the water right holders, which means to the private stakeholders. The agricultural water use was and is the dominant priority and concern; the legal and instructional arrangements for other water management issues were either overlooked or simply left to the free market (Bauer, 2004).

1.4 Institutional framework

Water is declared as public property in the Water Code and the National Government may grant private rights, which are called: the rights of use or water rights. Since they are legally separated from landownership, these rights can be freely bought, sold, inherited and transferred like any other real estate. The DGA has the mandate to grant all requests for new water rights, free of charge, whenever the water is physically and legally available.

A water right (WR) is governed by private law, e.g. civil law, rather than administrative, public law, after its constitution, which gives them significantly more protection from governmental regulation (Bauer, 2004). In general terms, the DGA has minor regulatory entitlement or power concerning private use. Primary decisions are taken by private stakeholders, or by private user organizations. Even conflict resolution is out of the DGA's mandate. They can try to intervene but stronger conflicts normally end in the civil court.

The Water Code recognises several kinds of private water user organizations, but all of them were designed solely for purposes of irrigation and to distribute water, but not for settling conflicts with non-irrigators.

Although water management, for example for irrigation is mainly a private issue, the state, represented by the DGA, can intervene in cases of emergency and dispute between parties and make decisions which are normally made by private organizations. For example in the end of March 2008, 34 zones in 59 municipalities were declared as water deficient areas in Chile. Through this declaration, the DGA is allowed to take decisions regarding allocation in these catchments, furthermore declared water deficient areas can receive funds and other benefits. In four rivers the DGA had to intervene, mainly due to disputes between private organizations (Galleguillos, 2008). Disputes are often induced by mistrust, which is often a result of poor information, no controls and none existence of a sound basis of decision making or the ignorance about the impacts of the decision.

In compliance with recommendations of a World Bank study (World Bank, 2011) the DGA developed detailed requirements, responsibilities and rights for the constitution and administration of water user organization. Historically these organizations have been founded by private initiatives with rules and status advised by advocates and different kind of professionals. Often the law came afterwards.

There are some other state agencies than the DGA participating in water resources issues, but mainly for control and improvement of new projects (e.g. reservoirs, canal improvement). Needs of new projects are formulated often by the private user organisations first.

Especially in the Limarí basin, which is the case study of this research, the organizations have been historically established from smaller user groups. The organizations in the basin with the longest tradition are the ones belonging to the Paloma system (nine organizations), as well the state agencies (DOH, DGA). Indeed, the Chilean Water Work division (DOH) has been responsible for the largest reservoir, La Paloma for almost 40 years, as well as for the main distribution channel (Matriz channel). In 2008 a first memorandum of understanding (La Paloma, 2008) was signed between the state agencies, DOH and National Irrigation Commission (CNR) and the private farmer organizations to be agreed upon to prepare the final transfer of the reservoir from state administration to the private organizations. This has been finalized in September 2012; the private organization had to find a form to manage (both administratively and financially) the system. Now the *macro-organization* is called Community of water of the La Paloma reservoir (CASEP). All organizations of the system finally concluded an agreement although not all are participating actively. Following private conversations between some of the stakeholders, until now no final definition exists which legal status the macro organization should hold.

1.5 Problem statement

Water management in semi-arid/arid zones is becoming more and more a high concern issue for multiple stakeholders. Especially the availability of water resources is a crucial limitation of water management planning and development. These even more since the pressure of resources increases due to more export oriented agriculture and high investments in this sector.

The Coquimbo Region is the one that has the most important agricultural activity in north-central Chile, with *ca*. 75,700 ha of irrigated crops (INE, 2007). Within the Coquimbo Region, the Limarí basin is the most important agricultural area, where a sustained increase in irrigated area through the years has occurred. This situation, as well as the change of crop types and the introduction of new ones, such as avocado and sweet orange, has further modified seasonal water consumption patterns and added additional stress on limited water resources. Analysing the agricultural census of 2007 the irrigated area of the Limarí province equals 41,760.44 ha.

In the region a growth of 300% of food product exportation during 2006-2010 was projected (Plan regional del Gobierno, 2006-2010). Therefore one priority area of the regional development plan of 2006-2010 was the sector of food production, which leads to change in land use, land management and consequently more pressure on the water resources. Here already a shift in the direction of drip irrigation could be observed by analyzing the census concerning fruit cultivation in 2005. Out of this 87% for mayor fruit trees in the Region of Coquimbo (ODEPA and CIREN, 2005) are now irrigated by water saving technologies.

The Limarí Basin represents 33 % of the surface of the Region of Coquimbo (about 1.3 million hectares). In this river basin 42 % of the regional agricultural surface and 70 % of the regional exports are concentrated. Considering the climate and those productive activities a sustainable and balanced development of this territory is required.

Due to high pressure on the resource by the agricultural sector, the basin was declared in 2005 as over allocated ("agotada") for its surface water availability by the DGA and no new consumptive surface water rights could be obtained. The only way to obtain rights is from the water market. These are offered as permanent or temporal (spot market) transfer of the right. The decision on whether a transaction can be approved is mainly the responsibility of the private organization where the applications for transactions are being submitted. The DGA gives final approval, but always in consultation with the organisations. In case of conflict a civil court has to decide.

The Limarí Valley, experiences one of the most active water markets in Chile (Hearne and Easter, 1995; Christi, 2001). Furthermore extreme events, here referring to low precipitation and drought events, are a high catalyst for water market movements. The water scarcity is without doubts the main factor that motivates the operation of an efficient water rights market; it is an incentive to participate in the market in order to achieve a reallocation of the scare resource (Harris, 2003). Due to its reservoir storage and flexible allocation system, water is delivered to farmers on demand.

Briscoe (1998) argues that “in well – regulated river basins in arid areas of Chile the water markets function as on would wish”. Following his study the water is traded from lower-value uses to higher value uses and prices are responsive to seasonal water scarcity as well as long-term scarcity.

Several studies have been elaborated in regard to the water market and its functionality in the Limarí Valley, e.g. Hadjigeorgalis et al (2004); Harris (2003); Zegarra (2002); Cristi (2001) among others. All of them looked at the water market as a function of legal and economic considerations. Cristi (2001) also comprised some hydrological consideration with it, since he analysed the market during the major drought period from 1994-1997. Most of the studies executed were motivated by this severe drought, to study the changes in the market with this high pressure of water scarcity.

A study elaborated in 2007/2008 in the catchment classified and characterized the different drought periods which have been witnessed so far in the Limarí Valley and looked at mitigation strategies at the organizational level as well as the individual level during the last severe drought from 1994 – 1997 (Kretschmer et al., 2008). The study was based on the results of Rhodos et al. (2006), which determined the efficiency of water use in the whole region with a model developed from the DGA. As input data the registered distribution data from the different organizations were used, but not actually looked at the water rights and its distribution among the different water user organisations.

As shown, the Limarí basin has been often used as an example of a good working water market, but nonetheless the detailed rules, consequences, uncertainties for management etc. have not been extensively studied or discussed.

Thus an integrated study looking at the impact of the water allocation scheme based on water rights and thus the water market on the watershed has not been performed yet and becomes more and more important while the demand keeps increasing and the region is exposed to higher vulnerability than before. This is valid for the other catchments, too, not only for the semi-arid north. Furthermore since 2009 the region suffers again a period of less water availability. Organisations manage the system mainly based on historical experiences, but their decisions cannot be supported by a model until now. Due to higher pressure new projects, mainly smaller reservoirs in the upper catchments are being discussed; the difficulties to evaluate the changing conditions for management decisions and their impact without a flexible model are increasing.

Looking at the high pressure on the water resources, and the shift of even more responsibility towards the private user organisation (which is common in Chile), increases even more the need for a transparent decision basis including the re-evaluation of operational policies.

1.6 Objective of the research

The concept of water rights is the foundation of the Chilean water policy, thus water allocation is mainly driven by water rights.

The purpose of this research is to investigate the influence of water rights on water management practices under the present situation as well as changing situations. Here changing situation refer on one hand to improvement and extension of infrastructure, on the other hand to different use of the water in magnitude and further time and space. The latter one mainly based on the water market.

Further changing situations which are examined include changes in legislation refering to modifications which have been executed in favor of the environment, respecting the environment as a demand sector, expressed in minimum ecological flows.

It will be analysed if the chosen model which has been developed and is being used for water management in Texas, based on the legal water right framework of Texas, can be used for the chilean context and is able to respond to the questions, which have to be solved in the Chilean water management.

To be able to compare and evaluate changes in water management via water rights, natural conditions have to be reastablished. On the basis to set the system to zero (natural conditions), the impact of different and new structures, here especially reservoirs can be tested. Furthermore the often complicated allocation rules, especially in case of the presence of multiple stakeholders in the basins or interbasin transfers, have to be able to be reflected and simulated by the model.

Assuming the model is able to comply which these requirements new operational policies including all necesary associations can be tested and in the best case an overall optimal water allocation achieved and compared to the current one.

The Limarí basin has been decided upon to use for the case study. This is mainly due to the high pressure on the resources in the semi-arid region and its complexity assessing the management system which its mannigfold associations and reservoirs as well future developments as mentioned in the problem statement.

Until now no model simulating water allocation based on water rights exists in Chile. The hypothesis is that with the known response of the system to certain decisions of the involved decision makers, based on the water rights and known trade off of different operation rules, the system is able to compensate better natural and manmade changes or adapt to them. Furthermore better decisions for new infrastructures and trading of water right can be taken.

In addition the impact of the current and possible future system on the water availability according to the legal requirements for the environment is investigated.

The conceptual approach can be described as follows:

- Analysing how much surface water is potentially available without any human use for meeting a quantifiable objective for surface water allocation and minimum ecological flow requirements
- Investigating the legal and institutional framework for water allocation in the catchment under study to incorporate the findings in the model including in the scenarios to be developed.
- Analysing the demand of the different sub-catchments for agricultural use
- Evaluating the impact on the system by making “x” change at “y” location? Here “x” is referred to changes in water rights, water conservation activity (ecological flow), extraordinary inflow to reservoirs, and construction of new reservoirs in the upper sub-catchments). This will be mainly done by analysing different indices (reliabilities and shortages).

Background and motivation

- Simulating different allocation strategies and thus changes in the operation rules of the system (including the re-evaluation of the operation policies for the existing reservoir system); evaluating the reliability and the possible shortages of water supply for different scenarios

In general the study will analyse the impact of water allocation decisions on the different user groups, based on water rights, agricultural demand as well as legal frameworks, during the historical natural hydrological sequence and thus provide a sound decision basis for more sustainable water resource allocation.

In case suitability for the Chilean legal framework can be approved the model might be used in more catchment to support transparency and better decision making in water management issues.

2 Methodology

In the following chapter the general methology of the research is presented. It can be seen as a guideline for catchments where water management strategies have to be tested, evaluated or adapted to changes due to natural and legal conditions, as well as changes forced through development; a special focus is given to the legal and social Chilean framework.

2.1 Water rights and information

For better understanding first general issues regarding Chilean water rights and their assigned volumes of water are summarised.

The Water Code of 1981 classifies the use of rights in functions and opportunities as shown in Figure 1. Surface water and groundwater are considered as two different sources which are independent of each other, have different procedures to apply for and are approved in different units. Thus dependent of the main water source in a catchment, the focus can be either on surface water, ground water or both.

As explained before the main classification is done according to consume (consumptive or non consumptive), further according to the execution (permanent and conditioned) and to continuity. The last classification refers to low flow years, were water for irrigation traditionally is offered by turns.

Of this classification, the model system used in this study simulated the permanent, the consumptive permanent and conditioned rights, which are continuous.

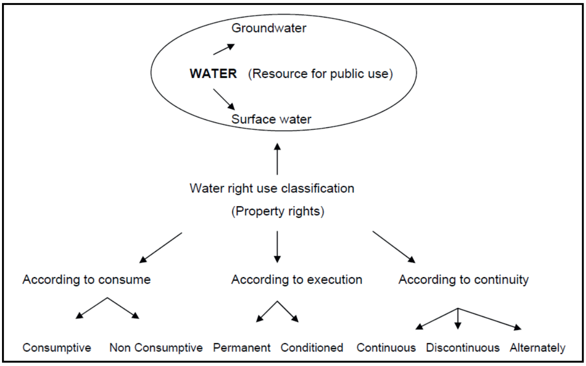


Figure 1: Classification of water rights (taken from: Alvarez et al, 2006)

The established measuring unit of a water right is expressed in volume per unit of time. Each water right (WR) is quantified in most of the times in litres per second (in unregulated river courses) and volume per year in regulated sub-catchments (receiving water from reservoirs). This discharge rate or assigned volume is a function of the volume of water available in the system, that varies in time and therefore it could be less than the defined amount at the time of its constitution. The permanent and conditioned assignment of water is related to scarcity and applies certain rules of priority, whereas the continuous or discontinuous condition of the water right is related to the time of use.

A maximum volume of water is assigned to a WR, for downstream users receiving water from the reservoirs a maximum volume per season is allocated to the association, who administrate the distribution of the water. The amount distributed to its users depends on the amount of WR they hold. Permanent water rights are proportional, so that in the event of water shortfall, water volume is reduced equally among all associations and thus all users.

Water rights are the legal base for water allocation, and therefore have to be studied first to develop an adequate allocation model. Data sources are manifold: The DGA holds all water rights which are approved to the single users, the most actual and extensive data base hold in general the user association, responsible for the different sub-catchments. Chapter 4.1 summarizes the detailed information about the water rights and allocation rules of the study area subdivided by catchment.

2.2 Estimation of agricultural water demand

As a method and tool for the estimation of agricultural water demand also the FAO software "AquaCrop", the new version of CROPWAT has been revised. The tool, which is also recommended from the United Nations Framework Convention on Climate Change as a tool to evaluate impacts of, and vulnerability and adaptation to, climate change, is a crop water productivity model developed by the Land and Water Division of FAO. AquaCrop results from the revision of the FAO Irrigation and Drainage Paper No. 33 “Yield Response to Water”, a key reference for estimating the yield response to water (FAO AquaCrop, 2013; Raes, D. et al, 2012). It is designed to simulate biomass and yield responses of field crops to various degrees of water availability. The model runs on daily time-steps, and is particularly suited to address conditions where water is a key limiting factor in crop production. Thus this model is a tool for: a. Predicting crop production under different water-management conditions (including rain fed and supplementary, deficit and full irrigation) under present and future climate change conditions; b. Investigating different management strategies, under present and future climate change conditions (FAO AquaCrop). Thus indirectly also estimating the water demand analysing a lot of different parameters, simulating the soil water balance. This involves a quite high data input need, which is not available for the whole basin and furthermore running on a daily time step detailed irrigation scheduling is determined which is not necessary for the questions to solve. For the present research it is satisfactory to know the average monthly agricultural demand per sub-catchment.

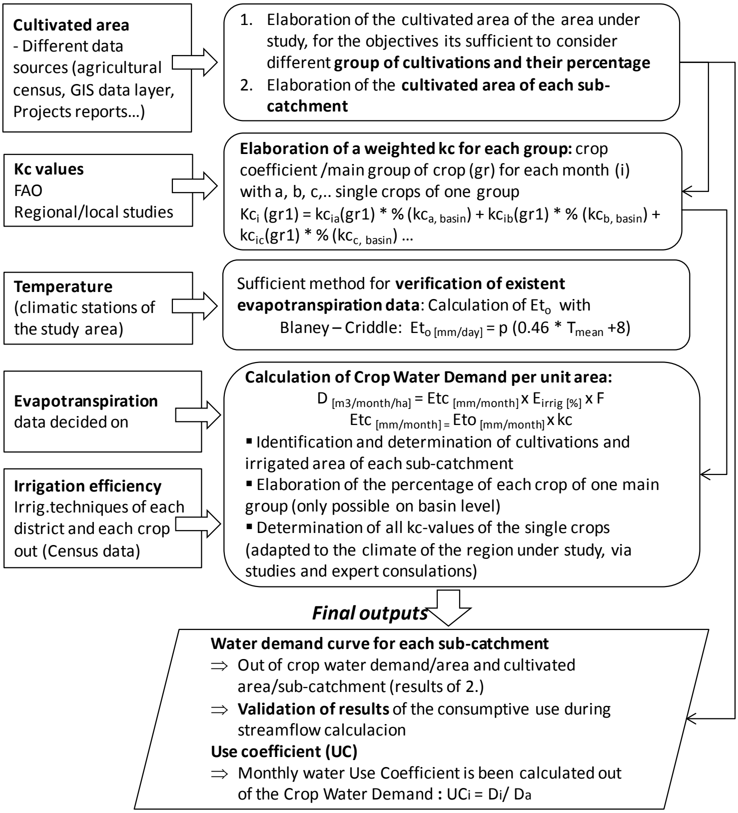
Assessing data sources and compiling available information mainly on basis of the VIIth national agricultural and forest census (VII Censo Nacional Agropecurario y Forestal; Instituto nacional de estadisticas, INE (2007)) it was decided to use the methodology which is outlined and summarized step by step in Figure 2 and in the following.

1. Elaboration of cultivated area of each sub-catchment of the basin considering the main groups and their percentage
2. Elaboration of a weighted crop coefficient (kc) for each group and each month. The weighting results corresponding to the percentage distribution of the single crop in the whole basin. The different kc values are adopted from FAO information, regional and local studies (details in chapter 4.2.2 Determination of the crop coefficients and irrigation efficiency)
3. While assessing the existent information for the area, a detailed national data base for evapotranspiration for all regions has been located. Data were verified with the Blaney - Criddle equation, which is the one which requires less data input. Temperature data were compiled from the climatic stations of the study area.
4. Calculation of the weighted crop water demand of each group per unit area, taking into account the results of the previous steps (equation in Figure 2). Irrigation efficiencies were elaborated by the census data per cultivation group and sub-catchment.

5. Finally these demands of the unit area (here Ha), are multiplied with its percentage of occurrence in each of the sub-catchments and the area of the sub-catchment to get the monthly demands (D_i) per sub-catchment:

   $D_{i\ (\text{sub-catchment})} = D_{i\ (\text{gr1})} * \%\ (\text{gr1/sub-catchment}) + D_{i\ (\text{gr2})} * \%\ (\text{gr2/sub-catchment}) + \dots + D_{i\ (\text{gr8})} * \%\ (\text{gr8/sub-catchment})$

6. The final use coefficient per month UC_i is calculated by the coefficient of the monthly demand (D_i) and the annual demand (D_a): $UC_i = D_i/D_a$



Cultivated area
- Different data sources (agricultural census, GIS data layer, Projects reports…)

1. Elaboration of the cultivated area of the area under study, for the objectives its sufficient to consider different **group of cultivations and their percentage**
2. Elaboration of the **cultivated area of each sub-catchment**

Kc values
FAO
Regional/local studies

Elaboration of a weighted kc for each group: crop coefficient /main group of crop (gr) for each month (i) with a, b, c,.. single crops of one group
$Kc_i\ (gr1) = kc_{ia}(gr1) * \%\ (kc_{a,\ basin}) + kc_{ib}(gr1) * \%\ (kc_{b,\ basin}) + kc_{ic}(gr1) * \%\ (kc_{c,\ basin}) \dots$

Temperature
(climatic stations of the study area)

Sufficient method for **verification of existent evapotranspiration data**: Calculation of Et_o with
Blaney – Criddle: $Et_{o\ [mm/day]} = p\ (0.46 * T_{mean} + 8)$

Evapotranspiration
data decided on

Irrigation efficiency
Irrig.techniques of each district and each crop out (Census data)

Calculation of Crop Water Demand per unit area:
$D_{[m3/month/ha]} = Etc_{[mm/month]} \times E_{irrig\ [\%]} \times F$
$Etc_{[mm/month]} = Eto_{[mm/month]} \times kc$
▪ Identification and determination of cultivations and irrigated area of each sub-catchment
▪ Elaboration of the percentage of each crop of one main group (only possible on basin level)
▪ Determination of all kc-values of the single crops (adapted to the climate of the region under study, via studies and expert consulations)

Final outputs

Water demand curve for each sub-catchment
⇒ Out of crop water demand/area and cultivated area/sub-catchment (results of 2.)
⇒ **Validation of results** of the consumptive use during streamflow calculacion
Use coefficient (UC)
⇒ Monthly water Use Coefficient is been calculated out of the Crop Water Demand : $UC_i = D_i / D_a$

Figure 2: Flow chart describing steps to develop the water use coefficient of each area under study

2.3 Estimation of environmental water demand

In Chile the concept of minimum flow or minimum ecological flow is known officially already since the eighties, but treated without any associated legal mean. During the decades until 2002, some minimum flows were established and required only in resolutions for special project approvals. More recently in the last decade the legislation (Chilean Water Code) underwent some changes, as already mentioned in the first chapter in favour for a minimum ecological flow. In the following the legal framework is outlined, which is afterwards used to calculate the respective minimum ecological flows.

Methodology

Legislative Chilean framework for minimum ecological flow

The following milestones are an approach to define ecological flows in Chile; they are based on historical flow records and expressed as percentage of annual or monthly mean flows or flow frequency distribution with no limnological considerations.

1) Resolution of the DGA N°63 of 1982 (Hydroelectric power plant Itata and Manual of 2002[1]

Resolutions were established for cases in which an area had to be protected or controversial discussions occurred, as it was the case for the hydroelectric power plant Itata (source: DGA). Ecological flows here are based on hydrological patterns (percentage of river flow) in different river stretches. The discharge applied is permanent and continuous during the whole year and calculated mainly as 10% of the average yearly streamflow ($Qaver_a$). Two methods are used, the second of which was added in 2002 in the manual of standards:

a. $Qeco_m = 10\%$ of $Qaver_a$ *(1982-2002/2002)*
b. $Qeco_m = 50\%$ of $Q95\%PE_{min}$ *(2002)*

With:

$Q95\%PE_{min}$: the minimum discharge which results out of the 95% exceedance probability of the low flow period

$Qeco_m$: monthly ecological minimum flow

2) Modification of the Water Code in 2005:

The DGA has to establish a minimum ecological flow when new water use rights are approved. The maximum value of the minimum flow cannot generally exceed 20% of the average annual discharge. In special cases justified by environmental needs, the maximum can reach 40% of the average annual discharge. Detailed calculation methods refer to the Manual of 2002.

3) Manual of standards and specifications for the administration of water resources (2008):

This manual requires the establishment of an ecological flow for all new water use rights, as well those which are being processed and water rights which are already established, but which are transferred/changed to another extraction point. For the first time it is established to consider the seasonal variation of the streamflow on the monthly base of the natural flow regime.

The minimum flow is defined as being 50% of the monthly natural streamflow with a 95% exceedance probability (Q95%PE), with the following restrictions:

a) River stretches with established water rights with a minimal flow equal 10% of $Qaver_a$.

If Q_m: 50% of Q95%PE < 10% $Qaver_a$ => $Qeco_m = 10\%\ Qaver_a$

If Q_m: 10% $Qaver_a$ < 50% of Q95%PE < 20% $Qaver_a$ => $Qeco_m = 50\%$ *of Q95%PE*

If Q_m: 50% of Q95%PE > 20% $Qaver_a$ => $Qeco_m = 20\%\ Qaver_a$

b) River stretches with established water rights with a minimal flow of the minimum of 50% of Q95%PE.

If Q_m: 50% of Q95%PE < 20% $Qaver_a$ => $Qeco_m$ = 50% of *Q95%PE*

If Q_m: 50% of Q95%PE > $Qaver_a$ => $Qeco_m = 20\%\ Qaver_a$

c) River stretches without established water rights or with rights, without an established minimum ecological streamflow: case b) is applied.

---

[1] Manual of standards and specifications for the administration of water resources (DGA, 2002)

With:

Q_m: monthly flow [m3/sec]

$Qaver_m$: monthly average streamflow [m3/sec]

$Qaver_a$: yearly average streamflow [m3/sec]

$Qeco_m$: monthly minimum ecological flow [m3/sec]

4) Standard to determine a minimum ecological flow (Regulation 'decreto' N°14/2012):

- The maximum values are kept: normally 20% $Qaver_a$, in special cases until 40% $Qaver_a$
- The monthly variability is also maintained but with a different criterion:
  $Qeco_m = 20\% \ Qaver_m$
- For calculations a minimum of 25 years of hydrological data should be used.

Summarized it can be stated:

Chilean legislation emphasizes the need to account additionally for environmental needs (already in the manual of 2002), which, although difficult to quantify, would be added to the calculated ecological minimum flow. However, this decision has to be made case by case, and in the Limarí basin no such assessment is existent so far.

Since 2008 the legislation was changed to account more for the natural variation, by considering the monthly differences of the natural streamflow pattern. The legislation of 2012 demands still a higher minimum ecological flow. All permanent water rights were constituted prior to these years, and environmental flow did not have to be taken legally into account. Nevertheless from the point of view of the environment selected sites are tested to find out how the system complies with this regulation.

2.4 Development of natural streamflows

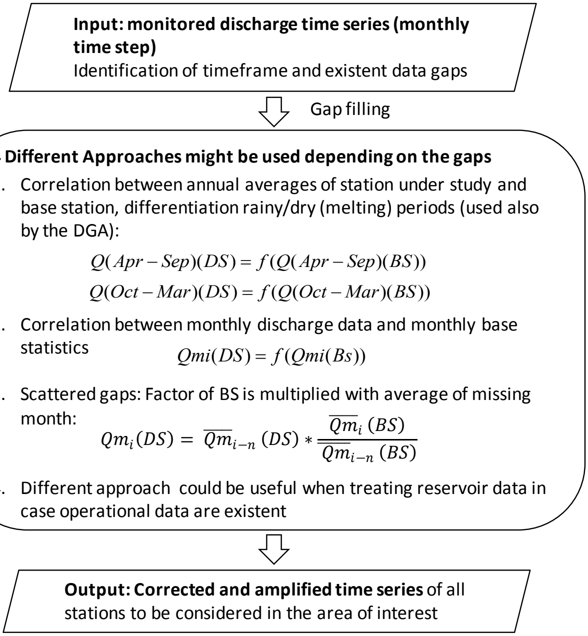
Sequences of monthly naturalized streamflows representing historical natural hydrology unaffected by people are fundamental to many modelling applications addressing various aspects of river basin management (Wurbs R., 2006). In the catchment a general need for elaboration of natural flows and their current as well as future alterations, subject to new constructions and intervention of mining companies and other ongoing developments is existent. Furthermore the minimum ecological flow, which are also subject of evaluation are calculated on the basis of monthly naturalized streamflows according to the Chilean water regulations and legislations.

Flow-naturalizing adjustments consist primarily of removing the effects of historical reservoir storage and evaporation, water supply diversions and return flows from surface and groundwater supplies (Wurbs, 2006). As the majority of data required naturalizing the measured streamflows are missing, an alternative approach was used for the main part of the time series, based on historical data and following the methodology of an earlier study (Ingendesa, 1992).

2.4.1 Gaps filling and amplification of selected monitoring stations

Methods applied

As shown in the flow chart four different methods for data gaps filling and amplifying were used, three are explained in the following:



Input: monitored discharge time series (monthly time step)
Identification of timeframe and existent data gaps

4 Different Approaches might be used depending on the gaps

1. Correlation between annual averages of station under study and base station, differentiation rainy/dry (melting) periods (used also by the DGA):
$$Q(Apr-Sep)(DS) = f(Q(Apr-Sep)(BS))$$
$$Q(Oct-Mar)(DS) = f(Q(Oct-Mar)(BS))$$
2. Correlation between monthly discharge data and monthly base statistics $Qmi(DS) = f(Qmi(Bs))$
3. Scattered gaps: Factor of BS is multiplied with average of missing month: $Qm_i(DS) = \overline{Qm}_{i-n}(DS) * \frac{\overline{Qm_i}(BS)}{\overline{Qm}_{i-n}(BS)}$
4. Different approach could be useful when treating reservoir data in case operational data are existent

Output: Corrected and amplified time series of all stations to be considered in the area of interest

Figure 3: Flowchart of steps for monthly discharge data correction and amplification

1. Using correlations between two stations:

For the amplification it was considered that it is more valid (correct) to amplify first the average annual discharges (m^3/sec) which will be assumed to be fixed and not matter of change. The annual discharge was taken from the hydrological year, starting in April until March; the seasonal and monthly discharges (as described in the paragraphs (a) to (d) had to be adjusted.

(a) Determination/Selection of a base statistic (BS)
(b) A correlation between the annual discharge statistics (m^3/sec) under study (Q_a (DS)) and the base statistic (BS) has to be established:

$$Q_a\ (DS) = f\ (Q_a\ \ (BS)) \qquad (1)$$

(c) Correlation between the rainy periods and the melting periods between the selected stations:

$$Q(Apr-Sep)(DS) = f(Q(Apr-Sep)(BS) \qquad (2.a)$$

$$Q(Oct-Mar)(DS) = f(Q(Oct-Mar)(BS) \qquad (2.b)$$

With:

$$Q(Apr-Sep) = Q(Apr) + Q(May) + Q(Jun) + Q(Jul) + Q(Aug) + Q(Sep) \qquad (3.a)$$

$$Q(Oct-Mar) = Q(Oct) + Q(Nov) + Q(Dec) + Q(Jan) + Q(Feb) + Q(Mar) \qquad (3.b)$$

Fulfilling the following Equation:

$$Q(Apr\ -\ Sep)\ +\ Q(Oct\ -\ Mar)\ =\ 12 * Q_a \qquad (4)$$

Results in the following (with exceptions):

$$Q(Apr - Sep) + Q(Oct - Mar) = 12 * Q_a + Dif \tag{5}$$

If the correlations and the statistics are of good quality, the last term (Dif) will be small. To eliminate it, it is proportional divided between the left side:

$$Q_c(Apr - Sep) + Q_c(Oct - Mar) = 12 * Q_a \tag{6}$$

The sub index c indicates the corrected values.

(d) In the same way the correlations of the monthly discharges are being established:

$$\begin{gathered} Q(Apr)(DS) = f(Q(Apr)(BS)) \\ \ldots \\ Q\,(Mar)(DS) = f(Q(Mar)(BS)) \end{gathered} \tag{7}$$

As in (c) we have:

$$Q(Apr) + Q(May) + Q(Jun) + Q(Jul) + Q(Aug) + Q(Sep) = Q_c\,(Apr - Sep) + dQ \tag{8}$$

$$Q(Oct) + Q(Nov) + Q(Dec) + Q(Jan) + Q(Feb) + Q(Mar) = Q_c\,(Oct - Mar) + dQ \tag{9}$$

The value of dQ will be proportional divided between the different months (each proportion to the seasonal total), with the following results [Equation (10), (11)]:

$$Q_c\,(Apr) + Q_c\,(May) + Q_c\,(Jun) + Q_c\,(Jul) + Q_c\,(Aug) + Q_c\,(Sep) = Q_c\,(Apr - Sep) \tag{10}$$

$$Q_c\,(Oct) + Q_c\,(Nov) + Q_c\,(Dec) + Q_c\,(Jan) + Q_c\,(Feb) + Q_c\,(Mar) = Q_c\,(Oct - Mar) \tag{11}$$

2. The method describes above can be simplified, in case the correlation terms and scatter plots are similar for all month, this leads to the direct correlation of each month, not considering the annual and seasonal discharges:

$$Q_{mi}\,(DS) = F(\,Q_{mi}\,(BS)) \tag{12}$$

3. The last method is applied for just monthly gaps: The corresponding base station (BS) for filling the gaps has to be determined. Then the following Equation is going to be applied:

$$Q_{mi}\,(DS) = \overline{Q_m}_{i-n}\,(DS) * \frac{\overline{Q_m}_{i}\,(BS)}{\overline{Q_m}_{i-n}\,(BS)} \tag{13}$$

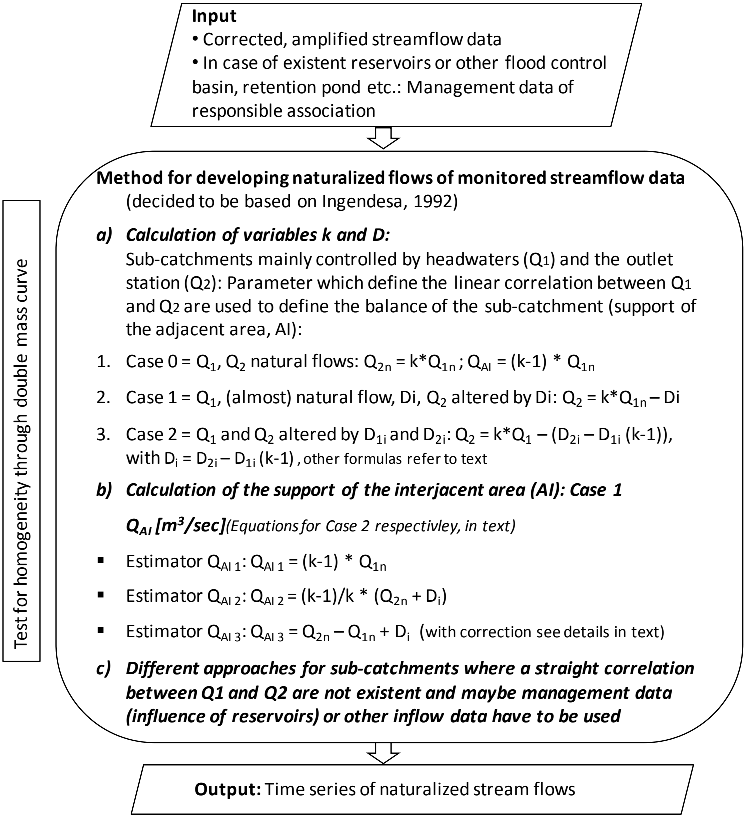
For the quality test, better test of homogeneity, the method of the double mass curve was used. In general the time series were compared with the base station to determine any significative change in slope, or break, which might be a sign for e.g. change in equipment and errors in monitoring.

2.4.2 Developing naturalized flows at gauged sites

Naturalized refer to sequences of past streamflos adjusted to represent a specified condition of river basin development that includes either no human impact or some defined lever of development. The objective is to develop a homogeneous set of flows at pertinent locations; these sets of adjusted streamflows are assumed to capure the relevant characteristics of climate and natural river bains hydrology (Wurbs, 2006).

They are different methods to obtain natural flows, ranging form hydrological models as for example SWAT, WEAP, etc.. to adjusting monitored flows with known distribution amounts, recharge, existent storage volumes, evaporation rates and more. Having almost an ungauged basin or very little information the swat model might be a good approach. In case a lot of management data are available distribution models, inluding adjustment approaches might be a good decision, for example one modul of the WRAP model (Wurbs, 2006).

Since in the catchment under study not sufficient information is existent to adjust monitored flows with available models, it was decided to use the approach of Ingendesa, 1992, which is summarized and outlined which its principle methods in Figure 4.



Input

• Corrected, amplified streamflow data

• In case of existent reservoirs or other flood control basin, retention pond etc.: Management data of responsible association

Method for developing naturalized flows of monitored streamflow data
(decided to be based on Ingendesa, 1992)

a) Calculation of variables k and D:
Sub-catchments mainly controlled by headwaters (Q_1) and the outlet station (Q_2): Parameter which define the linear correlation between Q_1 and Q_2 are used to define the balance of the sub-catchment (support of the adjacent area, AI):

1. Case 0 = Q_1, Q_2 natural flows: $Q_{2n} = k*Q_{1n}$; $Q_{AI} = (k-1) * Q_{1n}$
2. Case 1 = Q_1, (almost) natural flow, Di, Q_2 altered by Di: $Q_2 = k*Q_{1n} - Di$
3. Case 2 = Q_1 and Q_2 altered by D_{1i} and D_{2i}: $Q_2 = k*Q_1 - (D_{2i} - D_{1i} (k-1))$, with $D_i = D_{2i} - D_{1i} (k-1)$, other formulas refer to text

b) Calculation of the support of the interjacent area (AI): Case 1

Q_{AI} [m^3/sec]*(Equations for Case 2 respectivley, in text)*

- Estimator $Q_{AI\,1}$: $Q_{AI\,1} = (k-1) * Q_{1n}$
- Estimator $Q_{AI\,2}$: $Q_{AI\,2} = (k-1)/k * (Q_{2n} + D_i)$
- Estimator $Q_{AI\,3}$: $Q_{AI\,3} = Q_{2n} - Q_{1n} + D_i$ (with correction see details in text)

c) Different approaches for sub-catchments where a straight correlation between Q1 and Q2 are not existent and maybe management data (influence of reservoirs) or other inflow data have to be used

Test for homogeneity through double mass curve

Output: Time series of naturalized stream flows

Figure 4: Method adopted for developing natural streamflows

Main method applied

Considering that a sub-catchment is defined in most of the times by two monitoring stations, one controlling the headwaters (Q_1) and one the outlet more downstream (Q_2), it can be demonstrated that the two parameters which define the linear correlation between the discharges Q_1 and Q_2 are sufficient to define the variables which enter in the Equation to define the balance of the sub-catchment, specifically the support of the interjacent area (AI) between these two points and the consumptive use, here mainly through irrigation (Ingendesa, 1992).

In all three cases, which will be explained and analysed in detail in the following, the inclination of the regression line k, defines the AI and the constant D_i, the consumptive use which is expected in each month i.

Calculation of variables to define the balance of sub-catchments

Three cases are considered, which are explained in the following.

Case 0

"Case 0" is the ideal one: Q_1 and Q_2 with Q_{1n} and Q_{2n} as natural regime. This means, that no upstream and downstream (down of Q_1) consumptive use exists. This case does not occur in reality but is mentioned here from the conceptual point of view. For both stations, which are located in the same river a linear relationship between the discharges is being expected, going through the origin with the following form:

$Q_{2n} = k*Q_{1n}$ (14)

And the support of the AI with Q_{AI} or ΔQ (Q_1,Q_2) in [m^3/sec] would be given by:

$Q_{AI} = (k-1) * Q_{1n}$ (15)

Where k > 1 resulting in the representative parameter of the AI

Equation (1), represent in innumerable situations a true feasibility with certain dispersion depending on the quality of measurements.

Case 1

Case 1 defines that Q_1 reflects more or less the natural regime and Q_2 is altered by a consumptive use D_i, looking at Equation (1) this lead to:

$Q_2 + Di = k* Q_{1n} \Leftrightarrow \quad Q_2 = k* Q_{1n}-D_i$ (16)

Important to mention is that the variables k and D are only derived from the measured, gap filled time series, but without the years which are completely derived from correlation with other stations.

The parameter k which represents the inclination of the regression line defines the interjacent area (AI). The variable D_i represents the extracted discharge (demand) for an average consumptive use in month (i). The Equation (3) shows that the correlation of the observed discharge preserves the factor k and has a parallel displacement to the correlation of the natural regime of a quantity of D_i (Illustration see Figure 6).

Case 2

The discharge Q_1 and Q_2 are altered by a consumptive use of D_{1i} and D_{2i}, looking again at Equation (14) for this case it can be rewritten as follows:

$Q_2 + D_{1i} + D_{2i} = k (Q_1 + D_{1i})$ (17)

$\Leftrightarrow Q_2 = k*Q_1 – (D_{2i} – D_{1i} (k-1))$ (18)

And $D_i = D_{2i} – D_{1i} (k-1)$ (19)

Again here the coefficient k of the correlation of the natural streamflow conserves the relation between the observed time series, just that the displacement of the linear line has now a value which is a bit lower than the consumptive use of the intermediate area D_{2i}.

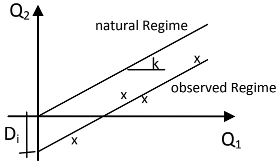


Figure 6: Schema of variables defined by the correlation (case 1 and 2) of the discharge

To separate the two consumptive uses the following additional relationship is used:

$\frac{D_{1i}}{D_{2i}} = \alpha = \frac{s1}{s2}$ resulting in: $D_{2i} = \frac{Di}{1-(k-1)*\alpha}$ (20)

with s1 = surface of the first demand area D_1 and s2 = surface of D_2

The calculations of the support from the interjacent area (Q_{AI})

As explained before the coefficient of the correlations defines the natural inflow of the interjacent area. In the following, three independent calculations of the AI estimator are presented. They can be considered independent since they are calculated in function of data which were generated independently.

The estimators for **case 1** are calculated as follows:

Estimator Q_{AI1}: $Q_{AI1} = (k-1) * Q_{1n}$ (21)

This estimator just considers the discharge Q1n, which enter in the interjacent area:

Estimator Q_{AI2}: $Q_{AI2} = (k-1)/k * (Q_2 + D_i)$ (22)

Combing the Equations (15) and (16) the AI can be expressed in function of Q_2 and the expected monthly consumptive use.

Estimator Q_{AI3}:

$Q_2 = Q_{1n} + Q_{AI3} – Di$ => $Q_{AI3} = Q_2 – Q_{1n} + D_i$ (23)

The estimators for **case 2** are calculated respectively:

Estimator Q_{AI1}: $Q_{AI1} = \frac{k-1}{k} * (Q_1 + \frac{\alpha * D_i}{(\alpha+1)- k*\alpha})$ (24)

Estimator Q_{AI2}: $Q_{AI2} = \frac{k-1}{k} Q_2 + D_i(\frac{1}{(\alpha+1)- k*\alpha} - \frac{1}{k})$ (25)

Estimator Q_{AI3}: $Q_{AI3} = Q_{2-} Q_{2i} - Q_1$ => $Q_{AI3} = Q_2 - Q_1 + \frac{D_i}{(\alpha+1)-k*\alpha}$ (26)

The last estimator Q_{AI3} (Equation 23, 26), might exaggerate the errors which already exists in the measurement of Q_{1n}, Q_1 and Q_2, since they are transmitted also to the difference of them. This implies possible corrections of Q_{1n}, Q1 and Q_2 in case the calculation results in values which do not have a physical significance, as for example when AI results in a negative value in a terminated month.

If ***Q_{AI3} < 0***, the following corrections to the measurements are made:

The assumption is that both variables x (Q_1 or Q_{1n}) and (Q_2), origin from the same error and comply the relation:

$Y = kX - D$ (27)

Both have to be corrected in the way that the new values $\hat{X}$ and $\hat{Y}$ conserve the average of the original values:

$\frac{\hat{X}+\hat{Y}}{2} = \frac{X+Y}{2}$ (28)

A combination of (27) and (28):

$$\frac{X+Y}{2} = \frac{\hat{X}+k\hat{X}-D}{2} = \frac{(k+1)\,\hat{X}-D}{2}$$

$\hat{X} = \frac{X+Y+D}{K+1}$ (29)

$\hat{Y} = K * \hat{X} - D$ (30)

If Q_{1n}, Q_1 or Q_2 are very high:

This can happen in years of exceptional rainfall (“El Niño”) that the discharge curve can’t be measured exactly due to missing measurement possibilities of high level discharges, thus values might be estimated. Therefore a limit for the dispersion of the correlation of 3*SD (Standard Derivation) was decided for the measured Qs.

Q_{AI} *adopted*

There are no objective reasons to determine which of the calculated areas should be preferred.

The results have to be examined with caution. The advice is to adopt the average value of the three calculated Q_{AIs}, in case the difference to the Q_{AI3} has not been more than 25 -35%. The Q_{AI3} is considered to represent best the intermediate discharge in the case of extremely high discharge, compared to the average (rainy or highly snowmelt month) (Ingendesa, 1992).

The following threshold was adopted to decide which AI was most compatible to the observed and natural generated discharges:

$Q_{AI\ adopt\ ed} = \overline{Q_{AI}}\ if\ Q_{AI3}/\overline{Q_{AI}} < 1+\varepsilon$ (31)

$Q_{AI\ adopted} = Q_{AI3}\ if\ Q_{AI3}/\overline{Q_{AI}} \geq 1+\varepsilon$ (32)

ε: changes between 0.3 and 0.5 and has to be decided upon depending on the case.

The following Equations were used for recalculating and testing of X (Q_1) and in case necessary calculating $\hat{Y}$ (Q_{2new}):

$Q_{AI\ adopted} = \hat{Y} + Di - \hat{X} <=> \hat{Y} = Q_{AI\ adopt} - D_i + \hat{X}$ (33)

And $\frac{\hat{X}+\hat{Y}}{2} = \frac{X+Y}{2}$ (34)

$$\frac{X+Y}{2} = \frac{\hat{X}+\hat{X}+Q_{AI\ adopt} - Di}{2} <=> \hat{X} = \frac{X+Y-Q_{AI\ adopt} + D}{2}$$

In the cases of a new $\hat{X}$ (Q_1) value of natural flow, the $\hat{Y}$ (Q_2) had to recalculate by Equation (30), too.

For case 2 this results in:

$\hat{X} = (x+y-Q_{AI\ adopt} + D_{2i})/2$ (35); $\hat{y} = Q_{AI\ adopt} - D_{2i} + \hat{x}$ (36)

Methodology

With this the natural flows of the upstream and downstream stations are calculated as follows:

Upstream: $Q_{1i}NF = \widehat{X} + D_{1i}$ (37)

Downstream: $Q_{2i}NF = Q_{1i}NF + Q_{AI\ adopt\ i}$ (38)

In the most of the cases this approach has been valid for the study area (details and results see chapter 4.3.2.). Just for the time series of three monitoring stations (or sub-catchments) a slightly different approach had to be considered and is explained, when applying it to the case study.

2.4.3 Distribution of natural streamsflows from gauged to ungauged sites

The last step to get in all points of interest the natural streamflow (NF) the calculated flows from the gauged locations (primary control points) of the last section have to be distributed to the ungauged secundary control points (CP). The different steps are summarized in the flow chart (Figure 7).

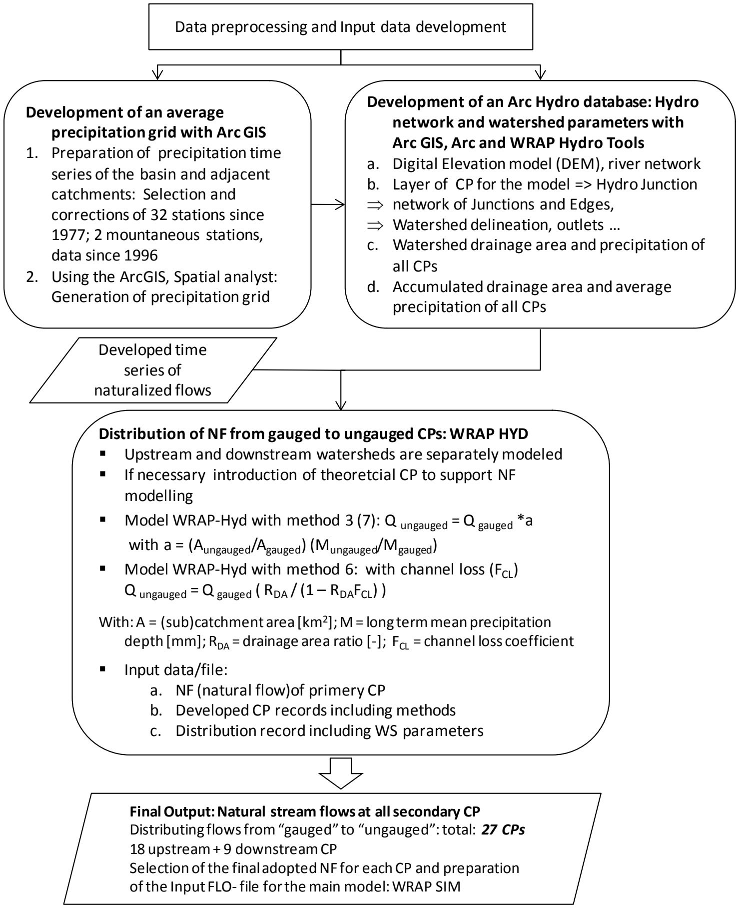


Figure 7: Work flow for preparation and modelling to get the natural flows in ungauged CPs

For transferring these flows different preliminary steps of data processing and watershed parameter development had to be performed before modelling the flow distribution, which has been decided to be done also with the WRAP modelling system[2] (further explication chapter 2.5), here in particular with the HYD Model.

Development of a Hydro Network and Watershed Parameter

The necessary parameters were generated through several work flows with different software to prepare and analyse geospatial information[3]. First an average precipitation grid was developed out of precipitation data of 21 climate station (data since 1977) in the basin and 13 further off its limits for better interpolation. Additionally two mountainous stations with data since 1996 of the basin were considered. The time series were corrected, gaps filled and a precipitation grid with the spatial analyst of Arc GIS created. As an interpolation method, finally ordinary kriging has been used, since it reflected most the known reality of the watershed.

Other input data are the river network, which had been corrected, digital elevation model, GIS layers of monitoring station and developed control points. With all necessary data an Arc Hydro database was built. After terrain processing, applying network and watershed processing tools, the correct network with hydro edges (rivers) and hydro junctions (all necessary control points) as well the corresponding sub-watersheds were developed. With WRAP Hydro finally the necessary watershed parameters (WP), i.e. watershed drainage area and average precipitation as well as the accumulated precipitation and drainage area, were calculated (Annex, Table-A 16).

Modelling natural flows at all sites of interest

The following methods facilitated by the model have been used:

- Distribution of flows in proportion to drainage area (method 7) also named the DAR Method, simple ratio of drainage areas:

$$Q_{\text{ungauged}} = Q_{\text{gauged}} * a \qquad \text{with} \qquad a = R_{DA} = A_{\text{ungauged}} / A_{\text{gauged}}$$

- Incorporation of the channel loss coefficient F_{CL} in the drainage area method (method 6)

$$Q_{\text{ungauged}} = Q_{\text{gauged}} (R_{DA} / (1 - R_{DA}F_{CL})$$

  The channel loss (CL) has to be given as a normalized share of the CP record and should range from 0.0 – 1.0. Here it corresponds to the reach below the indicated CP with CL factor (F_{CL}).

$$CL = F_{CL}\, Q_{\text{upstream}}$$

- Flow distribution equation with ratios for various watershed parameters (method 3), in this case, just with A (area) and M (average precipitation in mm).

$$Q_{\text{ungauged}} = Q_{\text{gauged}} * a$$

$$a = (A_{\text{ungauged}} / A_{\text{gauged}})^{N1} (M_{\text{ungauged}} / M_{\text{gauged}})^{N2}$$

Assuming that all exponents are unity, the constant a can be related to the watershed characteristics as:

$$a = (A_{\text{ungauged}} / A_{\text{gauged}}) (M_{\text{ungauged}} / M_{\text{gauged}})$$

The factor "a" had to be calculated manually and integrated as parameter in the model.

---

[2] Water Rights Analysis Package, developed at the Texas A&M University, since the mid-1980 (Wurbs, 2010)

[3] The core software of the geographic information system used is Arc GIS (ESRI) with spatial analyst. Furthermore additional tools, as ArcHydro Tool9 (ESRI), and WRAP Hydro Tool (Texas Water Resources Institute).

Furthermore judgment is required in selecting gauges and incremental watersheds for transferring flows to ungauged sites.

2.5 Model used to answer the research questions

2.5.1 General description

After a detailed revision of models to come into consideration (Wurbs, 1993; Wurbs, 2005; Wurbs, 2011; Sieber, 2007; DGA, 2005) it was decided to use the WRAP Modelling System[4], for the study proposed. The Chilean legal water system is similar to the system in Texas, wherefore the model was developed in the first place.

The WRAP model is a river-reservoir system water allocation model designed for assessing reliabilities for water supply diversions, environmental instream flow needs, hydroelectric power generation, and reservoir storage (Wurbs, 2006). The basic principle of water supply is based on water rights. The model provides capabilities for simulating a system involving essentially any stream tributary configuration. Furthermore multiple-reservoir system operations and off-channel storage can be simulated. Flexibility is provided for modelling the various rules specified in water rights permits and/or other institutional arrangements governing water allocation and management.

Primary objective of the model is to provide capabilities for assessing hydrologic and institutional water availability and reliability within the framework of a priority-based water rights system. It is developed as a flexible generalized computer modelling system for simulating the complexities of surface water management. The model evaluates water supply feasibility associated with alternative water resources development projects, water management plans, water use scenarios, demand management strategies, regulatory requirements, and reservoir system operating procedures. Thus basin basin-wide impacts of changes in water management and use, during a hypothetical repetition of historical hydrology, are assessed.

2.5.2 Methods

The water rights analysis package is public domain software using an ad hoc algorithm, which means that the computational progress through sets of water management requirements and water balance computations is performed in each time step (month, day and any sub-monthly). It is a merely simulation model.

The model combines detailed information describing water resources development, management, allocation and use with natural river system hydrology represented by naturalized streamflows, assuming that the hydrological pattern of a catchment stays the same in the future (Wurbs, R. 2011).

The spatial configuration of a river-reservoir-water use system is defined here as a set of control points (CP) that represents pertinent sites in the river basin (Figure 11, Figure 12). Reservoirs, diversions, return flows, instream flow requirements, streamflows, evaporation rates, and other system features are assigned to CP denoting their locations. Control points provide a mechanism to model spatial connectivity. Various computational routines in the model include algorithms allowing the computations to cascade downstream by CPs. Spatial complexity in actual applications may range from a system modelled with a single CP to those of thousand of CPs. Each water right (WR) must be assigned a main CP indicating the location at which the right has access to available streamflow. Any number of WRs can be assigned to the same CP, rights can also be grouped.

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[4] Water Rights Analysis Package, developed at the Texas A&M University, since the mid-1980 (Wurbs, 2010)

Methods are provided also for naturalizing streamflows, which are the basis for WRAP simulation; for different reasons natural flows had to be determined outside of the WRAP model environment and therefore these WRAP methods are not further commented here.

The alternative flow distributing methods to transfer naturalized flow from gauged to ungauged locations can be applied to either local incremental streamflows or the total flows at the pertinent CPs. Watershed parameters (WP) for distributing flows are provided on flow distribution coefficient and watershed parameter records. The WRAP methodology allows the user to select the gauged CP from which to distribute flows. Different methods can be selected (details, Wurbs, 2010); the ones selected in the study are described in more detail in chapter 4.3.3.

The WRAP-SIM simulation can be outlined as follows (adopted from Wurbs, 2010):

- Input data are read and organized
- Yield - reliability analysis, BES (Beginning-Ending-Storage) options involve iterative repetitions of the simulation
- Annual Loop (repeated for each year of simulations)
    - Naturalized flows and net evaporation rates are read or activated
    - Naturalized flows are transferred from gauged to ungauged sites (here the Hyd-Model, has been used) and put as input flow in the SIM-Model
- Monthly Loop (repeated for each month of simulations)
    - Net evaporation-precipitation adjustment option
    - Spills associated with monthly varying storage capacity option
    - Flow adjustment for constant inflow/outflow option
    - Water Right Loop (repeated for each right in priority order)
      (First and second pass though loop for instream flow options)
        1. Diversion, instream flow, or hydropower target is set
        2. Water availability is determined from available flow array
        3. Operation decision (diversions, reservoir releases, return flows) are performed (includes reservoir water balance with iterative net evaporation-precipitation and hydropower computations.
        4. Available streamflow array is adjusted for effects of rights at all CPs (Channel losses are considered in adjusting available flows)
        5. Water right output records are developed and written.
- Control points and reservoir output records are developed and written.

WRAP works exclusively with total streamflows, which is the total flow available in one specific point of interest. These flows are checked to determine water availability and adjusted to reflect the basin wide effects as computations are performed for each water right in priority order or upstream-downstream. The WRAP simulation program can be applied in three different modes:

1. A single long-term simulation mode (applied in the present study)
2. A yield - reliability analysis option (based on the repetitions of the long-term simulation to develop a diversion target versus reliability table, including a firm yield if it is feasible (applied in the present study)
3. Conditioned reliability modelling option (CRM), based on many short-term simulations starting with the same initial storage condition (not applied)

Methodology

Water accounting procedures

The computations are performed for each water right in priority order; an accounting is maintained from the amount of regulated[5] and unappropriated[6] flow remaining at each CP location. As each water right is considered in priority order, the amount of streamflow available to the right is determined as the minimum of this flow to each of the individual downstream CPs and the CP of the water right. After the streamflow depletion, return flow and other variable values are determined for a water right, the water availability array values for that CP and each downstream CP are adjusted appropriately.

The water accounting computations for a storage right include computation of reservoir net evaporation-precipitation volume. An iterative algorithm is used since evaporation volume depends on end-of-period storage, which is a function of evaporation.

The end-of-period storage content (S_T) for a particular period becomes the beginning storage content for the next period in the period computation loop. It is computed in the model based on the water volume balance equation (Wurbs, 2010):

$$S_T = S_{T-1} + D_{SF} - W_{WS} - R - E$$

With:

S_{T-1}	reservoir storage content at the end of the previous time period T-1
S_T	reservoir storage content at the end of the current time period T
D_{SF}	streamflow depletion [7]during time period T
W_{WS}	water supply withdrawal or diversion from the reservoir during time period T
R	release for hydropower, instream flow, or other downstream requirements
E	net reservoir surface evaporation less precipitation during time period T

Drought Index (DI)

There is a set of information specifying the water management and use requirements defining a particular water right. One record is the *drought index*. This record is used to vary targets as function of reservoir storage. Targets are diversions, instream flow and possible hydropower requirements.

The term *drought index (DI)* is adopted because depleted storage is viewed as an indicator of prolonged dry conditions with diminished water resources (Wurbs 2010.1).The DI may be used as a mechanism for modeling reservoir system operations and furthermore to allow any water use target to vary as a function of storage content, including instream flow, run-of-river diversions and other water use requirements not met by releases from the reservoirs included in the drought index.

Each drought index consists of a drought index reservoir DI record, drought index storage IS versus percentage record. The DI record specifies the selection of reservoir upon which to base the index. The IS and IP record provide a table of reservoir storage versus percentage. These are the factors by which the targets are multiplied.

Other types of applications are also possible; for example, a drought index may be used to specify targets as a function of cumulative flows or diversions.

---

[5] Regulated streamflows: physical streamflow after accounting for all water rights. Regulated flows may be greater than unappropriated flows because a portion of the regulated flows may be committed to meet instream flow requierements or downstream diversion.

[6] Unapproriated streamflows: portion of the naturalized streamflows still remaining after ste streamflow deplitions are made and return flows are return flows are returned for all the water rights included in the simulations

[7] Streamflow depletion: amount of streamflow appropriated by a water right to meet water use requirements and refill reserovir storage, while accounting for net evaporation-precipitation

2.5.3 Results

2.5.3.1 Statistics used for model evaluation

To evaluate the model, general model evaluation guidelines, for monthly time steps, which were developed based on performance ratings for recommended statistics by Moriasi, D.N. et al (2006), described below, are used.

1. **The Nash–Sutcliffe coefficient (NSE)**

The NSE or coefficient of simulation efficiency indicates how well a plot of observed versus simulated data fits the 1:1 line (Sing J., et al, 2004). It is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (“information”) (Nash and Sutcliffe, 1970). NSE is computed as shown in equation:

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(q_i^{obs} - q_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(q_i^{obs} - q^{mean}\right)^2}$$

where q_i^{sim} is the i*th* simulated value for the constituent being evaluated, q_i^{obs} is the i*th* observation for the constituent being evaluated, q^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

NSE can range from −∞ to 1, with NSE = 1 being the optimal value, corresponding to a perfect match of modelled discharge to the observed data. An NSE of 0 indicates that the model simulations are as accurate as the mean of the observations, whereas an NSE less than zero occurs when the observed mean is a better predictor than the model, which indicates an unacceptable performance.

General performance ratings for recommended statistics for a monthly time step for that statistics method is given in Table 1.

2. **RMSE-observations standard deviation ratio (RSR)**

RSR standardizes the RMSE (root mean square error) using the $STDEV_{obs}$ (observed standard deviation) and it combines both an error index and the additional information recommended by Legates and McCabe (1999). Based on the recommendations by Singh et al. (2004), which have published a guideline to qualify what is considered a low RMSE based on observations standard deviation Moriasi et al. (2007) developed the RSR. It is calculated as the ratio of the RMSE and standard deviation of measured data, as shown in equation:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(q_i^{obs} - q_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(q_i^{obs} - q^{mean}\right)^2}\right]}$$

RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower RSR, the lower the RMSE, the better the model simulation performance.

3. Percent bias (PBIAS)

Percent bias (PBIAS), measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). PBIAS is calculated with the following equation:

$$PBIAS = \left[\frac{\sum_{i=1}^{n} \left(q_i^{obs} - q_i^{sim} \right) * (100)}{\sum_{i=1}^{n} \left(q_i^{obs} \right)} \right]$$

The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999, cited in Moriasi, 2007).

Table 1 presents the value ranges and performance ratings for recommended statistics which were reviewed and summarised by Moriasi, D.N. et al, 2006. These model evaluation guidelines apply to the typical case of continuous, long-term simulation for a monthly time step.

Table 1: General performance ratings for the used statistics for a monthly time step

Performance rating	*RSR*	*NSE*	*Streamflow PBIAS%*
Very good	0.0 ≤RSR≤ 0.5	0.75≤NSE≤1.00	<± 10
Good	0. 5 ≤ RSR ≤ 0.6	0.65≤NSE≤0.75	± 10 - ± 15
Satisfactory	0.6 ≤ RSR ≤0.7	0.50≤NSE≤0.65	± 15 - ± 25
Unsatisfactory	RSR >0.7	NSE<0.50	>± 25

[Source: Performance rating due to Moriasi et al. (2007)]

Visual agreement between observed and simulated constituent data is also an indicator of adequate calibration and validation of the range of the constituent being simulated (Singh et al., 2004 cited in Moriasi, 2007). The same statistics were successfully used within a study of a mountainous catchment in Venezuela where the SWAT model was used (Barrios A, Urribarri L, 2010), NSE was also used to evaluate the flow series in the upper Betwa basin (Chaube, U.C et al, 2011). Besides the recommended performance rating of the guidelines they should be adjusted by the modeller based on additional considerations such as: quality and quantity of measured data, model calibration procedure, project scope and magnitude (Moriasi, 2007).

Graphical techniques provide a visual comparison of simulated and measured constituent data and a first overview of model performance and are essential to appropriate model evaluation according to Legates and McCabe (1999). In general two techniques are commonly used for comparison: the hydrographs and percent exceedance probability (Moriasi et al., 2007). Here just the hydrograph were used, percent exceedance probability curves are used more with daily flow duration curves.

Water supply reliabilities (including reliability indices) as well as flow and storage frequency statistics developed from the simulation results represent long-term probabilities or percent-of-time estimates. Furthermore shortage metrics can be developed by the model; they are detailed below.

The model includes the following frequency statistics for concisely summarizing modelling results: (a) volume and period reliability tables for water supply diversion, (b) frequency tables for naturalized, regulated and unappropriated flows, reservoir storage volumes and water surface elevations, as well as instream flow shortages and (c) reservoir storage-reliability table.

2.5.3.2 Reliability calculations

Reliability tables here will be constructed for meeting water supply diversion targets in any randomly selected future month, but can alternatively also defined for a particular month.

- Period reliability

Period reliability (R_P) is based on counting the number of periods of the simulation during which the specific demand target is either fully supplied or a specified percentage of the target is equaled or exceeded.

$$R_P = \frac{n}{N} * 100\ [\%]$$

with:

n: number of periods during the simulation for which the specific percentage of the demand is met

N: total number of periods considered

- Volume reliability

Volume reliability is the percentage of the total target demand amount that is actually supplied. For water supply diversions, the amount are volumes. Volume reliability (R_V) is the ratio of the total diversion volume supplied (v), to the target volume (V) during a specific period of time:

$$R_V = \frac{v}{V} * 100\ [\%]$$

2.5.3.3 Shortage metrics: Definition of indicators (Wurbs et al, 2010.3)

The shortage volume in a particular month of the simulation is the diversion target less the actual diversion as constrained by water availability. Shortage represents failures to fully meet water supply diversion requirements. A shortage period is defined as one or more consecutive months of a simulation during which a failure to meet the full diversion target occurs in each of the months.

The following indicators: Vulnerability (MCM/sequence), Resiliency (month^{-1}), average severity (MCM/sequence), and shortage index (month^{-1}) are calculated for each water right and then analysed by aggregating them depending on their supply source (results are presented and discussed during the different scenarios simulations in 6.2 until 6.5).

Maximum Shortage: $S_{max\ tot}$ [MCM] [8]

The maximum shortage in any month during the entire simulation.

Vulnerability: $\overline{S_{max}}\ (sequ_{i-n}) = \frac{1}{n} * \sum_{sequ\ i}^{n} S_{max}$ [MCM/sequ]

with n = number of sequences (sequ) when shortage occurred

The average maximum shortage that occurred during each sequence in which a shortage occurred. In the case of a conventional long-term simulation, sequence length is defined on an April-March basis.

Resiliency: $(\frac{1}{n} * \sum_{sequ\ i}^{n} \overline{L_{SPi}})^{-1}$ [month^{-1}]

with n = number of sequences (sequ) when shortage occurred

---

[8] MCM = $10^6 m^3$

The inverse of the mean of the average length of the shortage periods (L_{SP}) that occurred during each sequence, counting only those sequences for which shortages occurred (the lower value is worse)

Average Severity: $\frac{1}{n} * \sum_{sequ\ i} S_{consec}$ [MCM/sequence]

with n = number of sequences (sequ) when shortage occurred

The average sum of consecutive shortages that occurred during each sequence, counting only those sequences during which shortages occurred.

Shortage Index: A smaller index implies less shortage. Through the power, the difference between less and higher shortage gets bigger, thus shows that higher shortage might have an higher impact.

$$Shortage\ Index = \frac{100}{mont\ h} \sum\left(\left(\frac{annual\ \ or\ sequence\ \ shortage}{annual\ \ or\ sequence\ \ target}\right)^2\right)\ [\text{month}^{-1}]$$

Maximum number of consecutive shortages: maximum number of consecutive months with shortage that occurred during the simulation

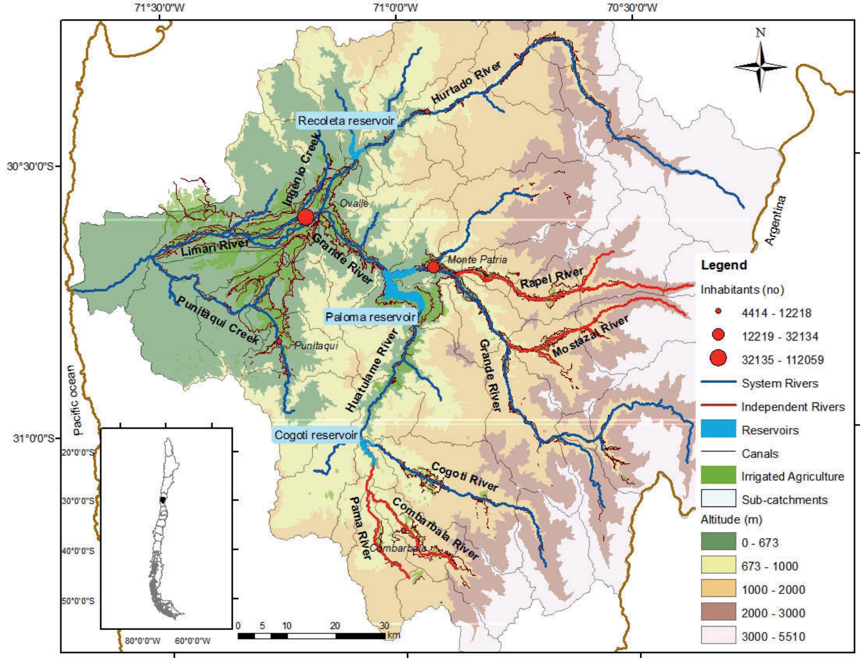
During the yield-reliability analysis the long-term simulation is iteratively repeated multiple times with specified water use targets incremented each time to develop a table of diversion target versus period and volume reliability. The table ends with a firm (100% reliability) yield if a firm yield can be obtained.

3 The river basin under study and its actors

3.1 Main facts of the Limarí River basin

The Limarí basin is in the semiarid north-central Coquimbo Region of Chile. The province has around 170,000 inhabitants (INE, 2011) whose distribution is quite heterogeneous, with about 65% of the population living in the Commune of Ovalle, where the provincial capital is located (Map 1).

Three climate types are found in the Limarí basin: (a) Coastal semiarid extends up to 40 km inland along the W-E valleys and minor gulches. It is characterised by frequent cloudy conditions, mild temperatures, high humidity, and average annual rainfall of 130 mm with an extended dry season of 8 to 9 months (September - April/May). (b) Moderate semiarid climate of the Limarí River valley, which experiences winter precipitation, but generally dry conditions with evaporation in excess of rainfall, and annual average temperatures reaching 18º C; (c) Cold semiarid of the Andean Cordillera (above 3,000 m.a.s.l.), with high winter precipitation, low temperatures and permanent snow cover (Kretschmer et al, 2012)..



Map 1: Limarí River Basin: Base map with main cities (no of inhabitants from the commune), river network (independent and system network, reservoirs and canal network (source: own elaboration)

The Limarí River is formed by the confluence of the Grande and Hurtado Rivers (Map 1). The Grande River drains the central and south parts of the basin (Commune of Monte Patria), whereas the Hurtado drains the northern part (Commune of Hurtado) (administrative limits refer to Map 2). Both rivers originate in the Andean Cordillera, with headwaters around 5,000m.a.s.l, thus snowmelt as well as rainfall contributes to their discharge. The Hurtado River does not have any major tributaries, and its course is intercepted by the Recoleta dam. The Grande River has the Rapel, Mostazal and Huatulame as sizeable tributaries. The discharge of the Huatulame is regulated by the Cogoti reservoir, and La Paloma dam is located at the confluence of the Huatulame and the Grande Rivers. The Grande and Hurtado Rivers merge about 4 km upstream from Ovalle, the catchment’s main city. From this point, the river is called Limarí, and reaches a further 60 km down the Pacific Ocean at Punta Limarí. Two tributaries, fed by rainfall from the Coastal Cordillera, join the Limarí River between Ovalle and the river mouth: El Ingenio and Punitaqui Creeks. These are of minor importance in terms of discharge, but impact the water quality of the Limarí River, since it receives some drainage water of mining activities (Kretschmer et al, 2012). In general the basin does not suffer major water quality problems. The only other concern in the lower part is a higher conductivity, most probably mainly provoked by the geology and marine terraces. The variation since 1972 has been studied in the basin and results in the worst case (lower catchment) in an increase of about 5% during the last 10 years (Kretschmer et al, 2011). Thus it can be expected that it might increase slightly more in future.

Their spatial and temporal variability of the discharge is high. Figure 8 shows the average yearly monitored discharge of the main tributary of the Paloma reservoir (Grande River at GPSJ-Grande Puntilla en San Juan station), the extremes are considerably. Average monitored discharges of the Grande, Hurtado, and Limarí

Rivers are approx. 8.8, 2.5, and 9.3 m^3/s, respectively (at the outlet of their sub-catchments). The yearly discharge here is calculated per hydrological year, which runs from April - March.

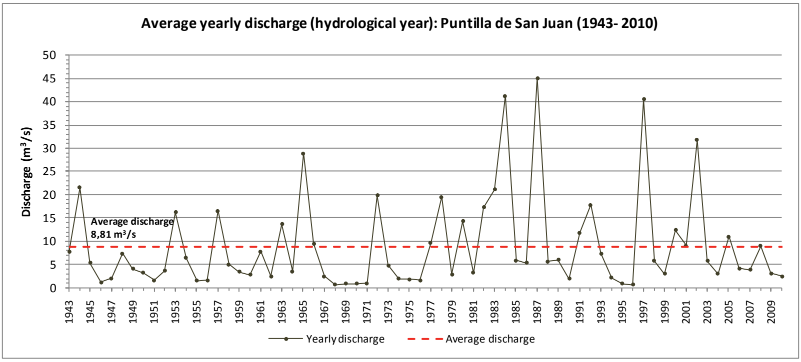


Figure 8: Mean yearly discharge, Grande Puntilla de San Juan (GPSJ) station (1943-2010), DGA station at the entrance of the reservoir La Paloma

The monthly mean precipitation of different stations of all sub-catchments are illustrated in upstream - dowstream order in Figure 9 (refer to altitude). The highest Las Ramadas Station measures as expected the highest precipitation. The station in the Cogoti River sub-catchment (Cogoti 18) is lower located as the station in the Hurtado catchment, but monitors higher precipitation. The Ovalle monitoring station counts with the lowest precipitation, it is sited in the lower part of the basin with an altitude of 234 m.a.s.l.

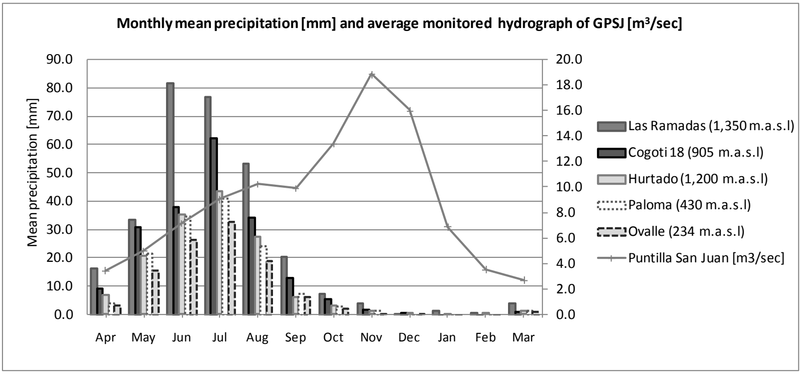


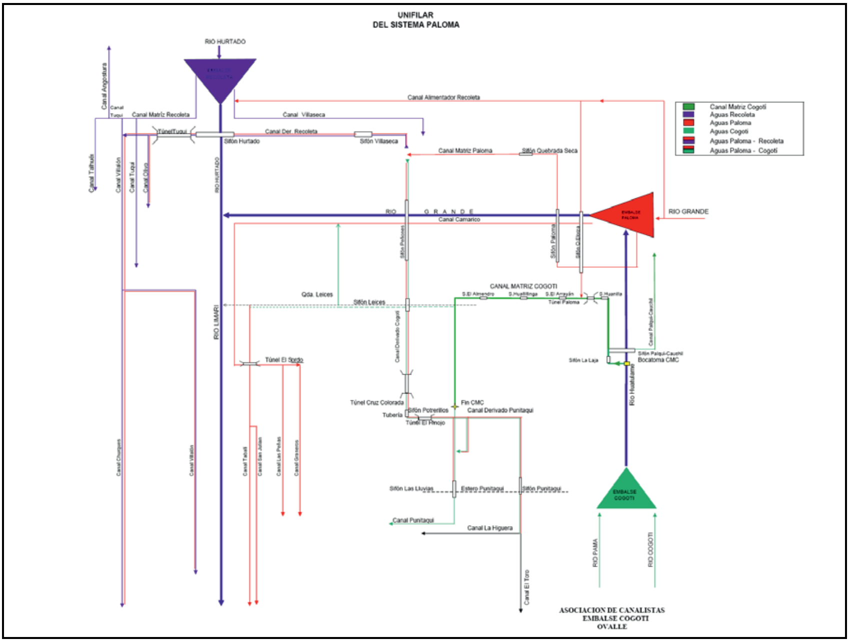
Figure 9: Monthly mean precipitation of five stations and monitored mean annual hydrograph at the Grande Puntilla de San Juan (GPSJ) station

The secundary axis presents the monitored mean annual hydrograph of the entrance station of La Paloma in the Grande River. The highest peak can be obsered in the summer month generated by snowmelt, having its peak in the late spring in November. Furthermore a little increase and peak can be obsered in July and August, produced by precipitation in winter.

Natural discharges are presented at the end of chapter 4.3 (Natural streamflows, Figure 37, Figure 38).

3.2 Management of the “La Paloma System”

The Limarí basin is the best regulated basin in the northern part of Chile, with reservoirs which are operated together with total capacity of 1,000 MCM, the so called "Paloma System". The system is comprised of a set of three reservoirs: La Paloma (capacity of 750 million cubic meters, MCM), Cogoti (150 MCM) and Recoleta (100 MCM). A canal (Alimentador Recoleta) with its intake in the Grande River, just above the La Paloma reservoir, was created to facilitate sub-basin water transfers to the Recoleta reservoir, but was only used for this purpose from 1973-1978. While not all reservoirs are connected, they operate in a coordinated fashion, and a dense irrigation channel network extends for more than 700 km throughout the basin. The system of channels fed by the reservoirs is shown schematically in Figure 10.



🟩	Canal Matriz Cogotí
🟪	Aguas Recoleta
🟥	Aguas Paloma
🟩	Aguas Cogotí
🟥🟪	Aguas Paloma - Recoleta
🟥🟩	Aguas Paloma - Cogotí

Figure 10: Scheme of the La Paloma distribution system [source: Associación de canalistas de embalse Cogoti].

The different colours of the channels indicate the source of water: blue = Hurtado reservoir, red = La Paloma reservoir, green = Cogoti reservoir; channels with two colours have two sources, thus some channels can get water out of different reservoirs, therefore in some parts of the catchment the distribution can be more flexible than in others.

Short history of the private actors

One of the most important advances that have been introduced with the Law of Associations of channels of 1908 was to grant a legal entity to the water communities and to establish a practical way of linkage between the water rights of every associate. Later the Code of 1951 added other forms of organization named as water communities and river associations, organisations that still persist in the current Code (Alvarez P, 2005 in Oyarzun R. et al, 2011).

The river basin under study and its actors

Title III of the Water Code of 1981 states that "if two or more people have the water rights of the same channel or reservoir.....they will be able to regulate the community resulting out of this, be constituted in channel association or any type of society, in order to take the waters of the main channel and distribute it between the water right holders...... In case of natural river beds they will be able to organize themselves as, River association. As soon as they are registered in the records of the DGA they are accepted legally (Alvarez P, 2005 in Oyarzun R. et al, 2011).

The following nine associations are part of the Paloma system (English names and abbreviations for further use):

1. Association of the channels Palqui, Maurat- Semita, fed by the upper Grande River: ***ACPaMauSe***
2. Association of the Grande River, Limarí River and their affluents: ***JVRGyL***
3. Association of the channels of Recoleta reservoir: ***ACERecoleta***
4. Association of the channels of the Cogoti reservoir: ***ACECogoti***
5. Association of the channel Camarico: ***ACCCamarico***
6. Association of the Huatulame River: ***JVRHua***
7. Association of the Punitaqui channel: ***ACCDPunitaqui***
8. Association of the Cogoti River: ***JVRCog***
9. Association of the Hurtado River: ***JVRHur***

The four upstream rivers (marked in red, Map 1) are not obliged to contribute to the reservoirs, nor downstream water irrigation, since their respective river associations refused to be part of the Paloma system, when it was built.

- Association of the Mostazal River
- Association of the Rapel River
- Association of the Combarbala River
- Association of the Pama River

Responsibilities of the actors

Within the Paloma irrigation system, works constructed by the registered proprietors belong to the community. In the same way, the expenses associated with maintaining and improving of the common works will be paid proportionally according to the rights that correspond to each of the associates (Alvarez P, 2005 in Oyarzun R. et al, 2011).

The participation in decision making of the users' organizations takes place by means of the elections of the board of directors and of the participation in the general and extraordinary meetings. Among its tasks the river organization will have to: distribute the waters, declare its scarcity and in this case, define any extraordinary distribution measurements. Furthermore, they can make a request to the director of the DGA to declare the depletion of the channels.

The declaration of water scarcity refers to the physical availability of the resource whereby the water is not sufficient to supply the granted water rights. The declarations used to instigate one of two possible responses;(1) proportional distribution or (2) if water is even more scarce, a process of "shifts" may have to be initiated in order to maintain conduction and distribution of water in the channels. Nevertheless in both cases the assigned conditioned water rights are not been exercised anymore.

A declaration of water depletion prevents the constitution of new permanent water rights. This can only be executed by the State (Director of the DGA).

If an area is declared as “area of scarcity” and there is no agreement of the farmers to distribute the water, the DGA will become the primary decision maker, and can suspend the activities of the river associations. This might take place for example if there is a very prolonged drought and the private stakeholders can not come to a solution to assure the potable water supply.

With regard to groundwater there exist two aspects that can lead to the constitution of water communities, the exploitation of an aquifer by means of different points of extraction or the joint exploitation of the same point of extraction for several holders of groundwater rights. When an aquifer is exploited by means of several wells, and every well is regulated, that is to say with the respective constituted rights, the holders can constitute a groundwater community to protect the common source of water or aquifer. In this case the structure work for withdraw is a property of every proprietor and the aquifer they have in common. Furthermore natural or artificial persons can join to exploit one well and constitute a water right that later is divided among the members of this group. In this case there exists a common source, a common groundwater right and a common withdrawal structure and it is additionally possible to constitute a water community for protection of the group interests. These communities are not stipulated in the actual Water Code of 1981, but assistance and facilitation is been given for those who want to establish one (more details refer to: Comunidades de AguasSubterráneas, 2011).

In this study the focus is placed on the management of surface waters, since this is the main water use in the basin under study.

4 Preparation of data and information for modelling

This chapter deals with all data and information and their further development and analysis, including data pre-processing, necessary for modelling the basin with the WRAP modelling system. Section 4.1 describes the basis and details of the water rights and operational rules for further model input development. The detailed WR analysis is separated in upstream and downstream sub-catchments, incorporating the previously defined control points (CP) of interest. The agricultural demand is calculated in section 4.2 and finally in section 4.3 the natural streamflows out of the monitored time series are developed. The last section of this chapter determines the minimum ecological flows in selected points of interest according to Chilean water legislation and as basis for modelling and comparison with simulation results in chapter 6.4.

4.1 Water rights, operational setup and rules

Figure 1 of chapter 2 shows the classification of the different water rights according to the Water Code of 1981. The model system simulates the consumptive permanent and conditioned rights, which are continuous for this study.

In section 4.1.2 and 4.1.3 the WR per river course and reservoir are further specified and aggregated to the previously defined points of interest (control points, CP). They are separated in upstream and downstream sub-catchments and constitute the basis for the model configuration. The last sub-section deals with some operational issues of the system.

4.1.1 Water assignation in the Paloma system

The operation of the so called "*Paloma system*", composed of three reservoir and canal systems is based on a framework which was established in 1977, as the "Operational model of the La Paloma reservoir"[9], and entered permanent usage in 1980 (conversation with Muñoz, Manuel, Administrator of the main river association). Due to Article 2, the annual maximum volume assigned to all associations downstream of the reservoir sum up to 320 MCM, if the total volume of the three reservoirs is equal or greater than 500 MCM. In case the total volume of reservoir water is less than this threshold, half of the stored volume is assigned.

Article 3 defines how this total 320 MCM volume is typically divided between the three reservoirs and states that this amount has an exceedance probability of 85%, thus a reliability of 85%:

- Recoleta reservoir: 40 MCM
- Cogoti reservoir: 40 MCM
- Paloma reservoir: 240 MCM

The detailed percentage of the volume assigned to each of the associations and the source of water supply, is defined in Article 4 and 5 summarized in Table 2 and Table 3.

Table 2: Annual volumes assigned to each association downstream of the reservoirs

Organization	% of total	Volume annual: m^3
1. ACERecoleta	35.75	114,400,000
2. ACECogoti	31.09	99,488,000
3. JVRGyL	19.83	62,816,000
4. ACCCamarico	7.90	25,280,000
5. JVRHua	2.96	9,472,000
6. ACCDPunitaqui	2.67	8,544.000
Total	100.00	320,000,000

Table 3: Sources of water (name of the reservoir) and percentage to supply the assigned volumes to each association

Organization	Recoleta	Cogoti	Paloma
1. ACERecoleta	35%	-	65%
2. ACECogoti	-	30.69%	69.31%
3. JVRGyL	-	-	100%
4. ACCCamarico	-	-	100%
5. JVRHua	-	100%	-
6. ACCDPunitaqui	-	-	100%

In the following section, and tables, the WR per river or reservoir and association are summarized, including the correspondent control points (CP) and maximum target. The information about WR and canals are manifold (geographic information of canals, datasheets of associations, and information of resolutions of the DGA). To model the system they were grouped while defining the CPs. For the modelling purpose this simplification is permitted.

For a more detailed distinction of defined water rights groups of each CP refer to Annex Table-A 1-Table-A 8:).

In the upper, unregulated catchments, the annual maximum target has been calculated and further the monthly ($\text{target}_{\text{month}} = \text{target}_{\text{annual}}/12$). Thus a maximum final target and the maximum monthly target are

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[9] Operational model of the La Paloma reservoir (original title: "el modelo operacional del embalse Paloma"): Legally based regulation, approved and ratified by all associations, which are part of the Paloma System, received by the JVRGrYL (Junta Vigilancia del rio Grande y rio Limarí)

presented; in this metric, the supply depends not only on the water rights, but also on the monthly demands, which is later modelled with the corresponding use coefficients for the area. The maximum diversion target/year is calculated in general with: 1 Water Right (WR) = max. 1l/sec. In case a river association uses another factor it will be mentioned and is included in the model.

For the regulated parts of the catchment, the maximum target/assignation is calculated by the multiplication of the amount of WR for one specific area/association with the yearly maximum volume of assignation, which varies. The amount assigned to one WR is calculated referring to article 4 and 5 of the La Paloma operation model (Table 2,Table 3) and considering the number of WRs for one modelled water right group. Depending on the source and number of WRs, it gets between 6,000 - 10,000 m^3/year. The lower boundary value of 6,000 m^3/year is the minimum volume assigned to the water rights downstream of La Paloma, which are managed by the JVRGyL (Limarí River association); some canals receive 10,000 m3/year and more out of historical reasons. For clarity, a sample calculation of the Huatulame River association is presented here:

In legal terms the operation model assigns the Huatulame River association 2.96% out of the La Paloma System, which equates to maximum 9,472,000m^3, divided through the amount of 1,011 water rights (WRs) of the association results in a maximum share of 9,368.94 m^3/WR/year. Of this assigned share, the amount of water reaching the individual might be much less, depending on the conveyance system.

The details which constitute the base for the model are presented in the following section, subdivided in upstream and downstream sub-catchments (Figure 11, Figure 12) and further per river. Here also the priorities used for the different WRs in the model (aggregated for the control points) are shown.

4.1.2 Upstream sub - catchments

The following scheme presents the sites of the control points (CP) in the upstream catchments where water is extracted and water balance calculations are performed, as well the connections between the different CPs and the corresponding associations.

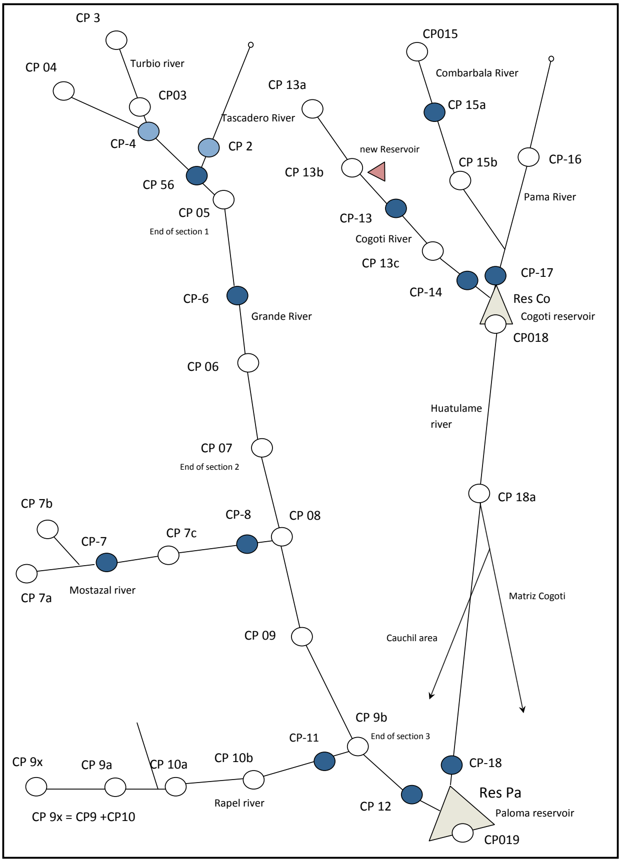

Figure 11: CP-scheme of the upstream sub-catchments with correspondent associations (Blue: Primary CPs; White: Secondary CPs; grey: reservoirs)

Grande River

The Grande River has an average regulated (measured) discharge of 279 MCM/year (~9m^3/sec),until reaching the La Paloma reservoir. However the effect of El Niño/La Niña phenomenon has a high impact on water availability (see Chapter 2), and therefore, the median yearly discharge of 255 MCM/year might be a more accurate metric than the average to characterize the river.

The sections of the Grande River are defined by the river association of the Grande and Limarí River and its confluences (JVRGyL) and administrated by them; the sections are also regarded as management sections and if convenient water rights have been summed up of the canals which constitute one section.

Table 4: Water rights Grande River upstream of the La Paloma reservoir with theoretical target and mean real diversion

Control Point ID	Priority	Return Flow CP	Amount of WR 1 WR = 1l/sec	Theoretical Diversion Target max.MCM/ year/month	New Calc Target (UC) MCM/ year	Real Diversion e.g. S1[10] MCM/a
CP3	1000	CP03	414	13.06/1.091	9.29	5.5
CP3	2000	CP03	57.5	1.81/0.15	1.29	
CP03	1000		152	4.79/0.40	3.41	8.0
CP03	2000		11.45	0.36/0.03	0.36	
CP04	1000		221	6.97/0.58	4.96	3.88
CP04	2000		20	0.631/0.053	0.450	
CP4	1000		107	3.374/0.282	2.398	2.18
CP4	2000		95	2.996/0.250	2.132	
CP2	1000	CP56	479	15.11/1.262	15.11	5
CP56	1000		77	2.428/0.203	1.728	1.38
CP05	1000	CP-6	210.51	6.639/0.554	4.722	6.876
CP05	2000	CP-6	40	1.261/0.105	0.897	
CP-6	1000		270.49	12.95/1.08	9.21	1.768
CP-6	2000		32	1.0/0.08	0.72	
CP06	1000	CP07	405.6	12.79/1.07	9.114	8.245
CP06	2000	CP07	15	0.473/0.040	0.335	3.65
CP07	1000	CP08	167.3	5.276/0.441	4.510	4.5
CP08	1000	CP08a	361+*714*	11.38+ 22.517	22.517	16.38
CP08	1000	CP08a	401.58	12.66/1.058	9.01	8.101
CP08a	1000	CP09	641.92	20.24/1.691	14.40	9.5
CP08a	2000	CP09	15	0.473/0.04	0.335	
CP09	1000	CP09b	87.5	2.759/0.231	1.964	1.6
CP09	2000	CP09b	15	0.473/0.04	0.335	
CP9b	1000	CP-12	312.5	9.855/0.824	7.011	5.5
CP-12	1000	CP019	172.79	5.449/0.455	3.875	1.3
CP019	*38051.75 Refilling rights, this doesn't influence the model*					
Sum			P =4,621.1 *+714 Palqui* E =300.95 +38,051.75	Tot: 177.727 MCM/year E =9.49	**130.07 MCM/year** **E =7.02**	**93.36 MCM/ year**

For this sub-catchment, including Turbio and Tascadero Rivers, 14 CPs has been decided upon, four of which are stations (CP-4, CP-2, CP-6 and CP-12), thus primary CPs, the others are different extraction points of interest (secondary CP). The following table shows an overview of the rights and its targets (more details in Annex, Table-A 1), in the sequence up – to downstream. The whole section is unregulated; therefore water availability is dependent on instantaneous flow in the watercourse. The priority is differently subject to permanent rights (P) and conditioned rights (E); permanent rights get higher priority (1000) as the conditioned (2000).

The new calculated target considers the maximum monthly possible diversion according to the WR, and thus a recalculation of the use coefficients. The yearly target is then again calculated using the adjusted UC depending on the maximum monthly volumes.

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[10] S1: base scenario and other

Additionally the average current (real) supply amount used for the calibration/evaluation of the model (in case available) is aggregated in the final column of the tables. Most of these data were received during various meetings and working sessions with the different associations.

In this sub catchment the WR of the organisation of Palqui-Maurat-Semita canal, (first WR of CP08) are in discussion and thus not that easy to decide about the target amount to use in the model. The original permanent WR before the reservoir was build sums up to 361 WR, and further 4,500 conditioned WR. With the reservoir a benefit of 714 WR were assigned. This would lead to a total of almost 34 MCM, in years of 100% assignation. When less water is available it can be reduced by more than two thirds. The data of the responsible association of the Grande and Limarí River show that the average use since 1973 is 15.598 MCM /year with a maximum of 26.761 MCM. The average of the last 20 years which were used to evaluate the model was 16.38 MCM/year. It was decided to leave the real data scenario for modelling within the whole time span also with a target for Palqui of 16.38 MCM, whereas for the legal model scenario the target was assumed with the amount of 22.517 MCM, which represent the 714 WR.

All of the above mentioned WR are so called run-of-river diversions, which are represented in the model as a Type 1 WR with no reservoir.

Mostazal River

The Mostazal River has its confluence with the Grande River after the CP-8 (Monitoring Station: Rio Mostazal in Caren). The amount of WR constituted sum up to 3,670 permanent WR (details Annex, Table-A 2), with sum up to the maximum target diversion of 115.74 MCM.

The Mostazal River association is not part of the La Paloma system; they are independent, which implies they do not have any obligation to contribute water to the lower catchment.

For the model all WR were assumed to be supplied in CP-8, considering a return flow to the river course of the Grande River. This leads to a bit less water than monitored, since the different distribution of rights and different availability of water within the catchment is not considered within this simplification. Nevertheless, the model evaluation showed this to be a reasonably reflection of the natural system. The potential impact of this bias is that the modelled results provide a more pessimistic estimate of water availability than reality, which is preferable over optimism in a region where future scenarios project deteriorate water availability conditions.

Rapel River

The sub-catchment of the Rapel River counts with 3,672 permanent WR, which sum up to the maximum diversion target of 115.8 MCM/year (details Annex, Table-A 3). Thus the Rapel River sub-catchment (824 m^2) and the Mostazal sub-catchment (640 km^2) have almost the same amount of WRs to supply.

For simplification, and because the details of the catchment for this work are not relevant, the use of the water has been set all in the last CPs at the outlet (CP-11), with return flow which is considered at the CPs downstream.

Cogoti River

The Cogoti River is the most important confluence to the Cogoti reservoir. It is the river with the highest natural discharge of the three inflow rivers with an average of 71 MCM (median: 60 MCM) in the gauged station over the last 20 years. The mean of all monitored years result in 89 MCM (median: 71 MCM). In comparison, the neighbouring Combarbala and Pama River sub - catchments had mean discharges of 22 MCM (median: 13.5 MCM) and 11 MCM (median: 3.11 MCM) over the last 20 years respectively (calculated out of monitored Data, DGA). Due to the possible high inter annual differences caused by the climate of this region, median discharges are considered more robust for discussing the yearly water availability.

The amount of water rights sum up to 1615.5 permanent and 418.5 conditioned WR, in total 2,034 WR[11]. The water is extracted by 32 water intakes channels; However, DGA official data, GIS data and the database of the user organisation of the Cogoti River (MN Ingenieros Ltda., 2008) show slightly different information. For this study, the decision was made to use the data base of the organisation, with registered 36 channels and a total of 2,138.91 WR. These data were chosen because (a) it is the most updated dataset (transactions are often later registered with the DGA) and (b) the sum of the WRs is the highest, thus it represents a worst case scenario for the users downstream.

In total the water rights are, depending on the channel location, distributed to four different CPs. Two of them represent the two possible locations for the new reservoir. The final WR distribution adapted for the model for the base scenario S1 is shown in Table 5.

The maximum diversion target has been calculated with: 1 WR = 1.2 l/sec. This amount is given by the president of the association, it differs to the DGA, who assume 1 WR = 1l/sec. The last column shows the target used in the model, recalculated according to the use coefficient and is always smaller, since not in all month the maximum WR target is needed. Here no real data were available, thus in all scenarios the legal target is been used.

Table 5: Water rights Cogoti River - reservoir system with theoretical targets and real diversion (actual situation)

Control Point ID	WR ID	Prio	Return Flow CP	WR type	Number of WR (acciones)	Theoretical Diversion Target max.MCM/ year	New Target (UC) MCM/ year
CP13a	WRCo13aP	998	CP13b	1	105.0	3.974	2.869
CP13a	WRCo13aE	999	CP13b	1	175.0	6.623	4.782
CP13b	WRCo13bP	998	CP-13	1	74.0	2.800	2.487
CP13b	WRCo13bE	999	CP-13	1	15.0	0.568	0.410
CP-13	WRCo13P	998	CP13c	1	962.21	36.413	26.292
CP-13	WRCo13E	999	CP13c	1	172.0	6.509	4.700
CP13c	WRCo13cP	998	CP-14	1	521.2	19.724	14.242
CP13c	WRCo13cE	999	CP-14	1	114.5	4.333	3.129
Sum					**2,138.91**	**80.944**	**58.911**

Combarbala River

The Combarbala River sub-catchment is also independent of the La Paloma system and holds a total of 3606 WR, with 3,410.5 WR for agricultural use, and 195.5 WR for potable water (details in Annex, Table-A 4).

During simulation the results of water distribution from the gauged to ungauged CPs in the Combarbala and Pama sub-catchment did not reproduce the expected volume of water in the upper area of the catchment.

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[11] Data of a register, 1992, CNR (Chilean irrigation agency), source: Alfaro, 2001

Preparation of data and information for modelling

Thus, some different assumptions were made for the Combarbala catchment to simulate the base scenario, and the following target volumes were recalculated.

Table 6: Water right Combarbala River and targets as used in the base scenario 1

Control Point ID	Water right ID	Priority	Return Flow Location	WR type	Diversion Target (max. MCM/year; MCM/month)
CP15a	WRCombar1P	1000	CP15b	1	32.29/2.7
CP15b	WRCombar2P	1000	CP-17	1	50.52/4.21
Sum					**82.81**

The upper part of the river, which was excluded from the analysis, possesses 23% of the agricultural target, thus the sum of 82.81 MCM was left to distribute downstream. Further it was calculated that downstream of CP15b, 61% of the water can be used according to the distribution of the WR.

Pama River

As mentioned before Pama River at his gauging station has an average discharge of 11 MCM/year and a median discharge of 3.11 MCM/year. The permanent rights sum up to 1,453 WR, the conditioned rights to 581.6 WR (details in Annex,

Table-A 5).

In this sub-catchment the same problem occurred as in the Combarbala catchment while distributing the discharge from the gauged to the ungauged stations. Since most use occurs above the *Pama en valle hermoso* monitoring station, and the monitored discharge there is very low, these discharges were put in the model and the WR ignored.

Both of these assumptions used in the Combarbala and Pama Rivers resulted in the base scenario in good statistical indicators for CP-17, the entrance of the Cogoti reservoir, thus this simplification was adapted for further scenarios, too, with the exception when assuming a development of these sub-catchment and thus a total use of their rights, Table 7).

Table 7: Combarbala-Pama River sub-catchment: Diversion target assumed for total use scenario (at the catchment outlet)

Control Point ID	Water right ID	Priority	Return Flow Location	Diversion Target (max. MCM/year; MCM/month)
CP-17	WRUpPamaComtotP	996	Assumed to be used as a monthly constant use in the catchment	159.529
CP-17	WRUpPamaComtotE	997		18.341
Sum				**177.87**

Cogoti Reservoir

The Cogoti reservoir serves to the river association of Huatulame River and to their own users (Association of the channels of Cogoti: Canalistas Cogoti); the association of the channels of Cogoti posseses 12,000 WR. The Cogoti reservoir serves 4,550 WR, and 7,450 WR are served by the La Paloma reservoir (see details to the La Paloma reservoir: Table 9)

The following table summarizes the rights according to the associations (further details Annex, Table A-5)

Table 8: Cogoti reservoir: Summarized WR and diversion targets (Huatulame association and Canalistas Cogoti)

Control Point ID	Owner/Water management organization	Number of WR rights (acciones)	Diversion Target (max. MCM/year)	Real diversion (S1 and more)
CP018	ACECogoti	637.3921	4.27 (6702.94 m3/WR/year)	3.57
CP018	JVRHua	416.34	3.9 (9.368.94 m3/WR/year)	5.35
CP18a	ACECogoti	3,917.7504	26.26	38.43
CP18a	JVRHua	594.66	5.57	7.65
Sum	**Cogoti reservoir**	**5,566.14**	**40.00**	**55.00**

4.1.3 Downstream sub - catchments

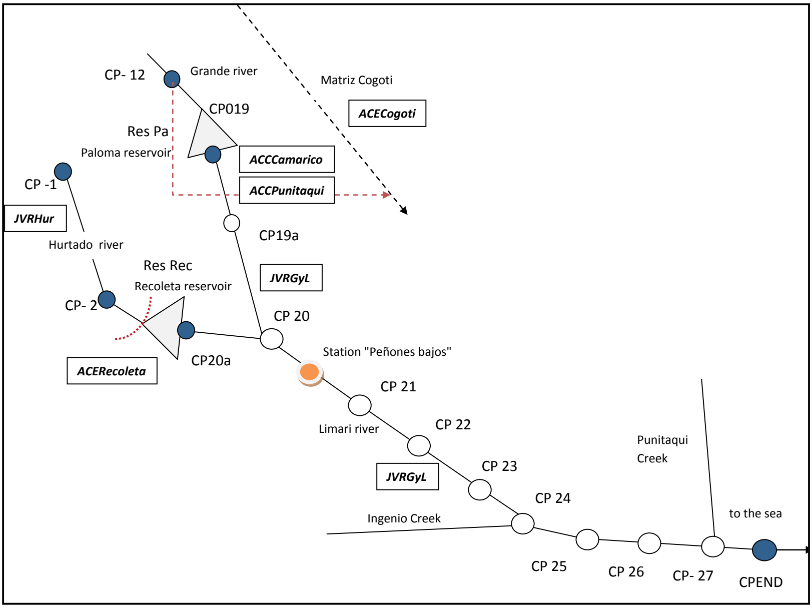

Figure 12: CP-scheme of the downstream sub-catchments with correspondent associations (Blue: Primary CPs; White: Secondary CPs; grey: reservoirs)

La Paloma reservoir

Analysing the information about WRs and canals of the register and data sheets of the JVRGyL with its administrator, changes which are not formally specified were revealed and considered in grouping the WR and assigning the right targets.

Preparation of data and information for modelling

It is very important to note that due to differences in the water sources before and after the construction of the reservoir, the assignation of maximum amount of water per right of the previous existent WR is much more, than to the WR, which were assigned with benefits of the reservoir.

For example: The WR which are provided by the reservoir have a maximum volume per year (average year) of 6,000 m^3/year/right, whereas the natural regime a maximum of 1l/sec. The canals which were inundated by the reservoir, which means were existent before the reservoir was built receive 10,000 m^3/year/right as a compensation for the loss since before they had rights to max 1l/sec = 12,614 m^3/year (790.55 water rights).

The following table summarizes the WR and their maximum assignation depending on the different associations (details Annex Table-A 7).

Table 9: La Paloma reservoir: Summarized WR and diversion targets of the different association

Control Point ID	WR type	Owner/ Water management organization	Number of WR	Diversion Target (max. MCM/year)	Real diversion (S1 and more)
CP019	1	JVRGyL	1,953.34	18.408	18.577
CP019	1	ACCDPunitaqui	803.5	8.544	10.00
CP019	1	ACCCamarico	3,000	25.28	37.00
CP019	1	ACECogoti	7,444.8574	68.9552	54.00
CP019	1	ACERecoleta	14,544.8	73.661	60.455
CP19a	2	JVRGyL	1160	6.96	7.08
CP20-26	2	JVRGyL	6,356.71	38.14	50.652
CP20	2	Agua delValle	300l/sec	(9.46)	(9.46)
Sum		**La Paloma system**	**21,401.95**	**240 MCM (+9.46)**	**237.76 MCM (+9.46)**
Conditioned WR and non-consumptive WR for Hydroelectric power plant					
CP26	2	JVRGyL Conditioned WR	Just a part: 630 l/sec (tot: 980l/sec)	19.86 (continuous, just from streamflow...)	-
CPEND	2	JVRGyL Conditioned WR	350 l/sec (tot: 980l/sec)	11.037 (continuous, just from streamflow...)	-
CPEND	IF	IF of WR Tal1Eventot	1 m^3/sec	31.539 (continuous, just from streamflow...)	-
CP26	2	JVRGyL Conditioned WR	200 l/sec	6.307 (continuous, just from streamflow...)	-
CP26	2	JVRGyL Conditioned WR	4 m^3/sec	126.14	-
CP19	6	Private/ Hydroelectric	Non-consumptive	946.08	-

The sum of the theoretical diversion target for the Paloma association sums up to 240 MCM as stipulated in the operational model, it represents the maximum assignation of La Paloma reservoir; the base scenario, which uses real data diverts almost the same amount of water (237.8 MCM). Nevertheless the diversion among the associations is quite different. Two associations draw special attention when analysing the differences between legal maximum assignation and real average diversion between 1990 and 2010:

- First the ACERecoleta, which uses almost 15 MCM less from the La Paloma reservoir
- Secondly the ACCCamarico who got 12 MCM more in average than legally (around 25 MCM) stipulated. Looking in more detail to the management of the Camarico rights the following can be observed: Officially they possess 3,000 WR of the La Paloma system, but inside the association this amount has to be distributed to 5,499.37 WR. This in times of maximum distribution leads to 4,596.89m^3/WR/year. In case of the distribution of 37 MCM, this would lead to an internal share of 6,728.45m^3/WR/year, which is similar to the other shares of the system. Thus it might be concluded that this is the result of a mutual understanding, but nothing is stipulated formally.

ACERecoleta

The association of the Recoleta reservoir channels as well as the association of the Hurtado River, which administrate the upper part of the catchment of the Hurtado River, is also part of the La Paloma system, but in the model just the Recoleta reservoir will be considered with its monitored inflow.

Table 10: Summarized WR and diversions for the Recoleta association (diverted by the La Paloma and Recoleta reservoir)

Control Point ID	Return Flow Location	WR type	Owner/Water management organisation	Number of rights (acciones)	Diversion Target (max. MCM/year)	Real diversion (S1 and more)
CP20a	CP24	1	ACERecoleta	8,044.2	40.74 Just Recoleta, 5064.4m3/WR/year	38.00
CP019	CP25	1	ACERecoleta	13,714.26	73.66 served by La Paloma, canal Matriz and some could be served by Recoleta, too: Canal Villalon/Canal Matriz Recoleta	60.455
Sum				**22,589**	**114.4**	**98.46**

As shown in Table 2 and Table 3, the “Canalistas de Recoleta” has a right of 37.75% of the share which is diverted per season, from which 65% is served by the La Paloma reservoir: 74.36 MCM and only 35% by the Recoleta reservoir: 40.04 MCM. Analysing the historical data from the La Paloma reservoir an average of 60.4 MCM has been diverted to the association and 38 MCM by the Recoleta reservoir (Table 10). According to this data from the organization less water than stipulated was supplied.

The total sum of WR served be the Recoleta reservoir is 22,589 WR (more details Annex, Table-A 8:), which leads to a maximum share of 5064m3/WR/year, calculation 30% losses, would led to 3,545 m3/WR/year. This is coherent with the information from interviews with the administrator of Recoleta.

Verifying the total supply of all reservoirs (analysing the last 20 years), the average supply of the three reservoirs adds up to 330 MCM. As mentioned before according to Article 2 the annual maximum volume assigned to all associations downstream of the reservoir sum up to 320 MCM. Therefore in average 10 MCM more were supplied annually and this from the Cogoti reservoir.

ACCDPunitaqui

The water allocated from the La Paloma reservoir to the Punitaqui irrigation area is conducted through the *Canal Matriz Paloma*, *Canal Derivado Cogoti* and further *Canal Derivado Punitaqui*. Due to the channel network and siphons, this area is able to get water from the La Paloma reservoir and also from the Cogoti reservoir. But according to the operational model the association of the Canal Punitaqui gets its total share from the La Paloma reservoir. As shown in the Table 2 the share is 2.67% of the available water of the system La Paloma, which in normal years leads to 8,544,000 MCM/year. The information given by the association is coherent with this; Punitaqui association holds 803.5 WR, which leads to 10,633.48 m^3/WR/year, counting from the valves. Due to measurements of the associations of the canal Punitaqui the system from the valves of La Paloma until the property counts with losses of 50%, thus the real share which enters the properties with the maximum assignation is: 5,316.74 m^3/WR/year.

4.1.4 Operational rules of the system incorporated in the model

The Paloma system is operated with a common operation rule, stipulated in the regulation about the operation of the Paloma reservoir: IF the volume of the three reservoirs falls below 500 MCM, the annual assignation is equal to 50% of the whole volume stored. Thus the assignations to each association and thus each WR will be shortened proportionally. For the model this was translated in a percentage of targets and implemented with the drought index (DI) record of the WRAP model.

Furthermore article 6 of the operational model releases the upstream users from contributing water to the downstream users, as long as 40% of the maximum assignation can be supplied from the reservoirs. This can be translated to the following individual critical volumes:

- V_{cri40} Paloma: 96 MCM
- V_{cri40} Recoleta: 16 MCM
- V_{cri40} Cogoti: 16 MCM

With the sum V_{tot40} = 128 MCM

When reaching these volumes, the upstream users are obliged to contribute water to the downstream users. Additionally the individual associations are allowed to implement their own rules in case desired or necessary.

Actually this occurred in the upper Grande River basin; they agreed upon a partial contribution from the upstream users to the reservoirs between May and September, in case the reservoirs are reaching a volume to just supply 80% of the maximum assignation:

- V_{cri80} Paloma: 192 MCM
- V_{cri80} Recoleta: 32 MCM
- V_{cri80} Cogoti: 32 MCM

With the sum V_{tot80} = 256 MCM

According to Article 7 the critical volume is reached as described above with V_{critot} = 128 MCM. The amount of upstream contribution is proportional to the reduction of the annual assignation for the downstream users and to available streamflow of the different water courses.

Operational model of the Cogoti reservoir

Beside the system operation model the Cogoti reservoir has its internal rules, with its tributary Cogoti River and the Huatulame River. Since they are partial incorporated in the model they will be described in the following. Depending on the volume stored in the Cogoti reservoir, first the upstream water allocation to the conditioned WR is curtailed, and secondly the upstream users have to contribute a certain percentage of available streamflow (this is according to the common La Paloma system rule):

- V_{cog} < 75 MCM: no conditioned rights will be served anymore upstream

- V_{cog} ≤16 MCM: JV Rio Cogoti has the obligation to deliver 53h 50min/week to feed the reservoir and supply ~1/3 of the available water to the Huatulame River (details below)

The system starts in crisis, when the minimum volume of 16 MCM is reached (in compliance with the common operation rule). This implies that the Huatulame River association does not receive any more water from the reservoir and the river system Cogoti-Huatulame returns to a situation of natural operation, as though the reservoir were not there.

It has been achieved to implement the operational rules in the model as follows for the downstream part:

- In general these operational rules have been implemented with different *Drought Index records (DI)*. Here the modeller is able to define when the system, or a single reservoir, or a combination of them, and furthermore also single WR (*Flow-Shift record, FS*) have to curtail their water allocation, and further specify the percentage of curtailing.
- The rights of the Huatulame association do not have access to the Cogoti reservoir, when it reaches the dead storage of 16 MCM, this will be counted as shortages to their rights; in case shortages are provoked they are served (in case sufficient flow is available) proportionally by flow of the Cogoti River (before reaching the reservoir).
- The rights of the Cogoti association will be served by the Cogoti reservoir as long as water is available.

4.2 Agricultural water demand

The methodology as described in chapter 2.2 has been adopted

Different data sources (international, national, as well as regional and local) have been identified and worked with to elaborate the necessary information for the water demand calculation of the study area. First the cultivated area of the basin has been derived from national census data as well as geospatial data of a previous project (details refer to chapter 4.2.1).

With the percentage distribution of the different crops of one sub-group of cultivations (on basin level) weighted crop coefficient were elaborated for each sub-group (chapter 4.2.2). The single values of the crop coefficients valid for the study region were worked out from data of the FAO as well as from regional and local studies. The crop water demand is then calculated with further data on evapotranspiration and irrigation efficiencies and presented with the main results of demand curves for each sub-catchment and water use coefficient in chapter 4.2.3.

4.2.1 Cultivated area of the main sub-catchments

The demand was calculated mainly on basis of the VIIth national agricultural and forest census (VII Censo Nacional Agropecurario y Forestal; Instituto nacional de estadisticas, INE (2007)). Different levels of aggregation were available and comparing the county level with results summing up the district levels yielded in some cases inconsistent results. Nevertheless the base of the work is the data of the district level[12]. With this detailed data the different sub-catchments and defined stretches of the river system could be analysed and a more exact demand picture was achieved. In general the administrative district polygons (provided with the census data) coincide quite well with the sub-catchments (see Map 2), thus the tabular

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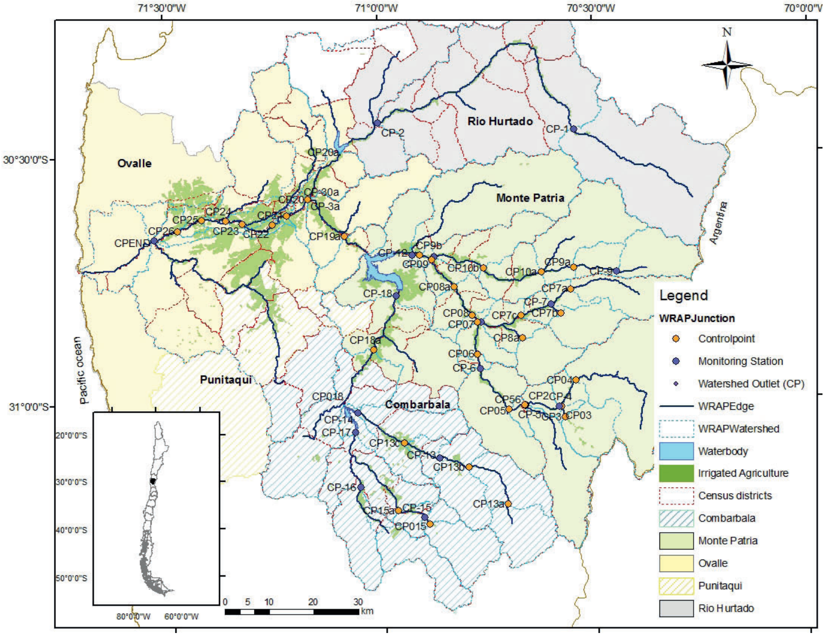
[12] source: could be assessed for a short time on the webpage of the request system for territorial statistics (I-CET Sistema de Consulta Estadistico Terretorial ODEPA)

data could be associated to them and detailed knowledge about the cultivated area between different monitoring stations identified.



Map 2: Overview of all control points and the natural as well as administrative limits in the Limarí basin [own elaboration]

These data have been verified with data of Cazalac (2006), where GIS Layers with information on agricultural cultivation were provided. With GIS tools this data were disaggregated to the district level for further comparison.

Furthermore the results were verified with some image classification in this area (preliminary results of Tapia, 2014), which confirmed that elaboration out of the census data can be considered as representative for this study. The resultant irrigated cultivated area per sub-watershed and the corresponding county is presented in Table 11 (Details about district and their corresponding area refer to Annex, Table-A 9).

Table 11: Irrigated cultivated area per sub-catchment elaborated with data on district level (Census 2007)

Province/County	Sub-catchment	Cultivated area [ha]
Combarbala	Pama River	417.6
Combarbala	Combarbala River	588.0
Combarbala	Cogoti River	1046.1
Monte Patria	Grande River upstream until Mostazal River	767.5
Monte Patria	Mostazal River	721.0
Monte Patria	Grande River between Mostazal and Rapel River	1484.8
Monte Patria	Rapel River until Puntilla en San Juan station	2163.3
Monte Patria	Puntialla de San Juan until La Paloma reservoir	252.9
Combarbala, Monte Patria	Huatulame River until La Paloma	5390.3
Hurtado	Hurtado River until Hurtado en Angostura Station	1494.9
Hurtado	Hurtado en Angostura until Recoleta reservoir	185.2
Ovalle	Grande River, La Paloma until Hurtado River	1596.2
Ovalle	Hurtado River until Limari River	998.0
Ovalle	El Ingenio Creek until Limari River	4620.8
Ovalle	Limari until El Ingenio	4316.5
Ovalle	Quebrada upstream Ingenio	2393.7
Ovalle	Rest of Limari River until Panamericana station	10563.5
Punitaqui, Combarbala	Punitaqui above Camarico and Chalinga irrigation area	2814.0
Ovalle	Monitoring station until mouth of Limari River	480.1
Total Limarí Basin		**42294.4**

A total area of 42,294.4 ha is irrigated in the Limarí province; natural permanent foraging non-irrigated land in the county of Ovalle is about 12,500 ha. Thus the area used for agriculture sum up to around 55,000 ha in total in the basin.

4.2.2 Determination of the crop coefficients and irrigation efficiency

Further analysis of the cultivated areas lead to the following sub-groups in the Limarí basin: a. Fruits, b. Legumes, cereals and tuber, c. Vegetables and flowers, d. Vineyards and vine grapes and e. Allotments.

It was decided to include the following crops in each sub-group to calculate the unit demand area:

a. Fruits: citrus, walnut/almonds, olives, avocados
b. Legumes, cereals, tuber: maize, potatoes, cereals
c. Vegetables and flowers: artichokes, pepper, beans, maize, sweet cucumber
d. Vineyards, Pisco grapes and table grapes

Group a. has the majority area of all groups with 34%, wine, Pisco, which is the typical Chilean Brandy, and table grapes (group d) add another 39%, which are together almost 2/3 of the cultivations. The detailed distribution of all groups in the whole basin is shown in the following diagram.

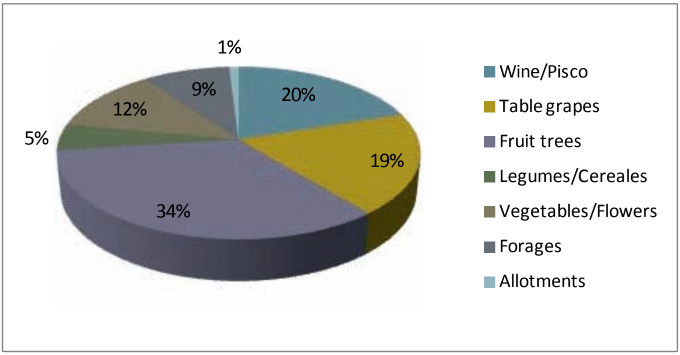
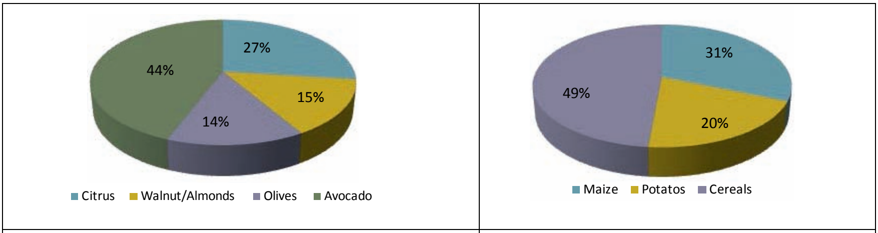


Figure 13: Distribution of main crops/crop groups in the Limarí basin (in percentage), elaborated from Census data

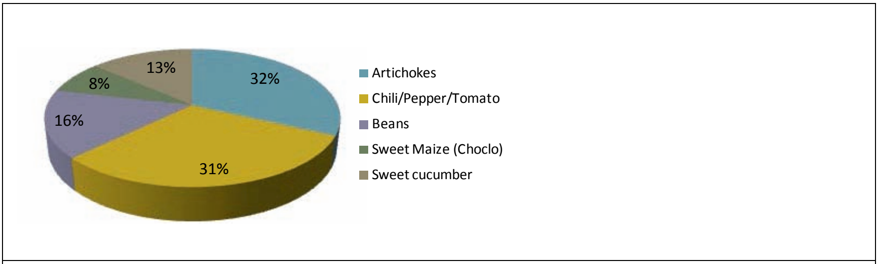
The decision which crop to consider in the different groups was made subject to the percentage of cultivated crop per group in the whole basin. Herewith a representative crop coefficient for each group will be calculated for use in the different sub-catchments. The different percentage of single crops in each group is presented in Figure 14.

With regard to the grapes the decision was made to distinguish between Pisco and wine grapes, since they have different demands and the distribution of both is not uniform. In most of sub-catchments the grapes which serve to make the Chilean brandy Pisco are in the majority.



a. Percentage used of the mayor fruits to calculate the weighted kc of the unit area

b. Most common cultivated Legumes and Cereals and industrial crops for weighted kc



c. Percentage of the most common cultivated vegetables, as adapted for the weighted Kc calculation

Figure 14: distribution of most common cultivations of main groups of crops; a: Fruits, b: Legumes and cereals, c. Vegetables [own elaboration, based on Census data, 2007]

Elaboration of weighted crop-coefficient (kc) for each sub-group

According to the percentage distribution a weighted kc value for each group has been elaborated.

The crop coefficient integrates the effect of characteristics that distinguish a typical field crop from the grass reference, which has a constant appearance and a complete ground cover (Allen et al, 1998), defined as kc = 1. Consequently, different crops have different kc coefficients; furthermore the growing stage and therefore the changing characteristics of the crop as well the climate influence the coefficient. These were the reasons why different sources have been consulted to assume crop coefficients (kc) which are adapted to the climate of the semi-arid region under study and the different seasons of the southern hemisphere (final weighted Kc values in Table 12).

Table 12: Weighted and single kc values elaborated for the Limarí watershed [own elaboration]

Crop/ Month	Grapes (Wine)[13]	Grapes (Pisco)[14]	Table Grapes[15]	Weighted kc Fruits	*Weighted kc Vegetables*	*Weighted kc Legumes*	*Forages (mainly Alfalfa)[16]*	*Allotment (private houses)[17]*
Apr	**0.45**	**0.6**	**0.5**	**0.64**	**0.29**		***0.9***	**0.38**
May	**0.35**	**0.2**	**0.2**	**0.58**	**0.19**		***0.9***	**0.60**
Jun		**0.18**	**0.2**	**0.51**	**0.19**	***0.21***	***0.9***	**0.45**
Jul		**0.15**	**0.2**	**0.48**	**0.19**	***0.32***	***0.9***	**0.55**
Aug		**0.15**	**0.2**	**0.48**	**0.26**	***0.41***	***0.9***	**0.7**
Sep	**0.25**	**0.23**	**0.3**	**0.68**	**0.42**	***0.75***	***0.9***	**0.64**
Oct	**0.45**	**0.52**	**0.8**	**0.7**	**0.6**	***1***	***0.9***	**0.71**
Nov	**0.65**	**0.63**	**0.85**	**0.72**	**0.8**	***0.9***	***0.9***	**0.89**
Dec	**0.75**	**0.72**	**0.85**	**0.78**	**1.04**	***0.8***	***0.9***	**1**
Jan	**0.75**	**0.78**	**0.85**	**0.81**	**0.97**	***0.55***	***0.9***	**0.98**
Feb	**0.7**	**0.8**	**0.7**	**0.71**	**0.84**	***0.25***	***0.9***	**0.98**
Mar	**0.55**	**0.7**	**0.5**	**0.66**	**0.59**	***0.16***	***0.9***	**0.67**

- Weighted kc fruits: Avocado[18] (44%), Citrus[19] (27%), Walnut[20] (15%), Olives [21](14%)

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[13] Values has been adapted to the FAO paper 56 (Allen et al. 1998) after comparing it with the study of CAZALAC, 2012

[14] Since differences could be detected in the different studies (Mutarello, 2009; Cazalac, 2012), an average of values which has been assumed to be the best approach

[15] mainly adapted to the study of CAZALAC, 2012, with the difference of reducing the highest demand to the highest demand given in FAO paper 56 (Allen et al. 1998)

[16] Recommended by FAO 56 paper (Allen et al. 1998) for dry climate and light/median wind: 0.95, since in MN MN Ingenieros LTDA., 2008 the highest value was given with 0.9 (but just in summer), here the continous kc was adapted as suggested in FAO 56 paper, but with the maximum value of the regional study

[17] For private house allotments an average of Maize, Beans, Potato, Artichokes and Pepper was taken

[18] The change of coefficient during the different growing stations were adapted to two studies of the region (Rivera, 2009; Rhodos, 2006). One expressed the whole year the same value of 0.78, which was considered to be averaged. The different values of Kc_{ini}, Kc_{mid} and Kc_{end} were adapted from Rivera, 2009.

[19] different growth stages has been consulted in two studies which has been done for the region (Rhodos, 2006, MN Ingenieros LTDA., 2008), Consulting the FAO paper 56 (Allen et al. 1998), the single values were adapted from Citrus without ground cover and 50% of canopy and averaged

20 Since differences could be detected in the different regional studies and the FAO 56 paper, another study has been consulted and its crop coefficients used (Ferreyra et al. 2001);two months have been adjusted to the work of MN Ingenieros LTDA., 2008 which worked in one valley of the Limarí catchment

[21] Values had been adopted to the study of Cazalac, 2012 and FAO 56 paper (Allen et al. 1998).

- Weighted kc vegetables: Artichokes[22] (32%), Pepper[23] (31%), Beans[24] (16%), Sweet Cucumber[25] (13%), Maize[26] (Choclo) (8%)
- Weighted kc group: Legumes and Cereals (and industrial crops): Cereals[27] (49%), Maize[28] (31%) and Potato[29] (20%)

Since the cultivations of table grapes have a high portion of the overall cultivated fruits (38% of all fruits, 43% of major fruits), they were considered in the calculation as single crop. The kc-values of the rest of the cultivation in the sub-group of fruits have been weighted due to the percentage of plantations in the catchment. Citrus, olives and avocados have similar kc values, the only which is significantly different is the kc values of walnut - orchards, but since they are distributed in all the sub-catchment, they have been included to be part of the weighted kc.

The most common cultivated legumes, without considering the minor cultivations, resulted in the following distribution: 49% cereals, 20% potatoes and 31% maize. The weighted kc value for the group of vegetable has been taken of the 5 mayor crops as shown in Figure 14 and Table 12

These presented final coefficients have been used for each sub-catchment, together with the values of the potential evapotranspiration to get the water demand curves.

Furthermore the efficiency of the irrigation technique had to be considered. Here values differ depending on the source: the regional information is not further specified (); the FAO, gives indicative values for field application efficiency (Table 13).

Table 13: Indicative values of the field application efficiency (Source: FAO, Irrigation Water Management)

Irrigation methods	Field application efficiency
Surface irrigation	**60%**
Sprinkler irrigation	75%
Drip irrigation	90%

On the following page the estimated irrigation efficiencies for the study are presented and further exemplified. Subject to the low efficiencies in some of the sub-catchments the return flow is higher and has been estimated and distributed monthly according to the water applied. In most of the presented water right tables (Table 4 - Table 10, as well in Annex Table-A5 and A7), the control point is been given where the return flow enters the system again.

As field application efficiency for different irrigation techniques of surface irrigation FAO suggests 0.6, whereas in a regional study (CAZALAC, 2006), as well in the agricultural census of 2007 the following efficiencies are given for different surface irrigation methods:

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[22] Values were taken from the Rhodos, 2006 (coincided with the values of the FAO 56 paper, Allen et al. 1998)

[23] Values taken from Mutarello, 2009, adapted to the values of FAO 56 paper and the grow stages in the region

[24] all studies were compared (Rhodos, 2006; Cazalac, 2012, MN Ingenieros LTDA., 2008 and values of Cazalac, 2012 adapted to the FAO values of Kc_{ini}, Kc_{mid}, Kc_{end}. The last month since both had a huge different it was decided to take the average of both studies

[25] Values taken from Rhodos, 2006

[26] Values of Allen et al, 1998 and Rhodos, 2006 adapted, starting with K_{ini} in the middle of spring as the study in Huasco and the FAO 56 paper recommend, which is in Septiembre

[27] Elaborated out of the kc values which were assumed in the study of Rhodos, 2006, adjusted with the Kc_{ini}, Kc_{mid} and Kc_{end} of the FAO 56 paper (Allen et al. 1998)

[28] see previous page

[29] adapted to the values of the study in the Huasco watershed, CAZALAC, 2012 and FAO 56 paper (Allen et al. 1998)

Table 14: Efficiencies of surface irrigation methods and the average used, based on local data

Surface Irrigation Methods	Efficiency (E_{irrig})
Basin	30%
Furrow	45%
Method 3 ("*tazas*")	65%
Average	***47%***

Assuming that the regional efficiency data represent the total efficiency ($E_{irrigtot}$) with:

$Eff_{tot} = Eff_{field} * Eff_{Conveyance}$

Further assuming an average value of conveyance efficiency due to the earthen canal in the catchment results in the following average value for different surface irrigation techniques:

$Eff_{tot\ sur} = 0.6 * 0.75 = 0.45$

And for drip irrigation and lined canals as conveyance structure:

$Eff_{tot\ drip} = 0.9 * 0.95 = 0.85$

Where drip irrigation has been reported in the census the channel was assumed to be lined. Thus for the traditional surface irrigation according to the census a value of overall efficiency of 0.45 and for drip irrigation of 0.85 was assumed to be representative. The detailed results of cultivated area per sub-group and its irrigation efficiency listed by sub-catchment for further calculation are presented in Annex, Table-A 10 and Table-A 11)

4.2.3 Demand curves and water use coefficients of the single sub-catchments

Knowing the pattern of the cultivated areas of the single sub-catchment in the study area, the demand curves are developed. They are used to validate the results of the consumptive use out of the regression analysis during natural streamflow calculations and furthermore required inputs in the model, in form of monthly water use coefficients (UC).

The method used is the calculation of crop water demand per unit area according to

$$D_{[m3/month/ha]} = Etc_{[mm/month]} \text{ x } E_{irrig\ [\%]} \text{ x } F$$

Where $Etc_{[mm/month]} = Eto_{[mm/month]} \text{ x } kc$

Etc: Crop evapotranspiration (Equation for standard conditions)

E_{irrig}: Efficiency of irrigation technique

F: Factor for unit transformation, here: 10

Eto: Potential evapotranspiration (mm/day) as an average for a period of 1 month

kc: Crop coefficient

Thus the evapotranspiration (Eto) of the different areas had to be determined. It was finally decided upon to adopt the values from CIREN, 1997. Nevertheless an estimation of Eto values according to Blaney - Criddle (FAO Blaney, Criddle, 2012), using only measured temperature data were done to verify the other data base.

$$Eto\ [mm/d] = p\ (0.46 * T_{mean} + 8)$$

Preparation of data and information for modelling

T_{mean} = mean daily temperature (°C);   p = mean daily percentage of annual daytime hours[30]

Eight different climate stations with temperature data, which represent eight sub-catchments, were used for the calculations. They register daily maximum and minimum temperatures, which resulted in Grande Puntilla San Juan station in the following representative monthly temperatures (for the medium and lower altitude area of the basin): maximum T = 30 °C, minimum T = 5 °C and the overall average of the year about: T = 16.5 °C. The different monthly maximum, minimum and mean temperatures of this station are presented in Figure 15. The temperatures of the other stations are similar (details of all stations Annex, Table-A 12), since no values of high altitude stations were available, there the temperature are much lower, mainly in the winter season.

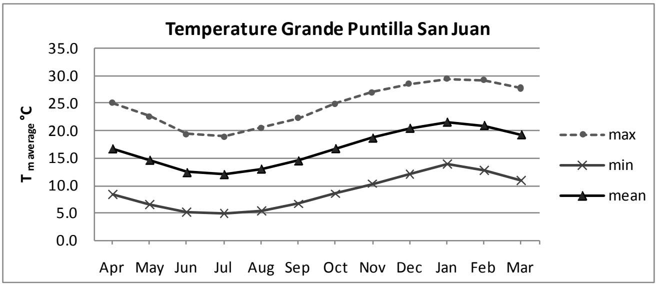

Figure 15: Monthly maximum, minimum and mean temperatures of Grande Puntilla San Juan station

The mean daily percentage of annual daytime hours is given by the FAO for different latitudes (FAO, Blaney Criddle).

The final detailed results of the Eto per month and station are summarized in Table-A 13, Table-A 14 Annex. The mean evapotranspiration over the different stations, as well the maximum (el Tome) and minimum (Las Ramadas and Recoleta embalse) are presented together with the respective Eto values extracted from data provided by CIREN (Centro de Informacíon de Recursos Naturales): the mean is the mean of the different sub-catchments, the maximum is in the Huatulame valley and the minimum in the lower catchment (Figure 16).

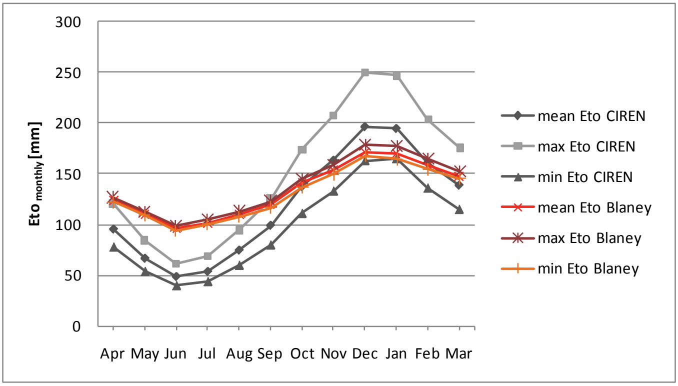

Figure 16: Comparing monthly Eto [mm] after Blaney Criddle with the national database of CIREN

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[30] FAO (web page): The Limarí basin is located at Latitude 30° S, corresponding values are given by FAO, http://www.fao.org/docrep/S2022E/s2022e07.htm#3.1.3 blaney criddle method

The calculated values are especially very different in the winter and summer month to available published values. It is known that in “extreme” climatic conditions the Blaney – Criddle method is inaccurate: in windy, dry and sunny areas the Eto is up to 60% underestimated and in calm, cool and humid areas overestimated (FAO web page). It appears in general that in most of the cases the winter months are over estimated and the summer months are under estimated, thus coincide with the observations about the method.

Therefore for further calculation, the values developed by CIREN are adopted (CIREN, 1997); these Eto values, are based on Merlet y Santibañez (1989), Santibañez y Caldentey (1987), Caldentey y Pizarro (1980). Depending on data availability, the study used the following methods to derive the dataset (here listed from less data necessity to most data need): a. Pan Evaporation method, b. Equation after Ivanov, c. Equation after Turc, d. modified Method after Blaney and Criddle, e. Penman Equation.

The Eto values are available for each point of interest, defined as geographic areas with similar monthly distribution. The differences between the different areas of the basin can be clearly observed (Figure 16), furthermore when comparing the maximum and the minimum total annual Eto (Figure 17). The calculated annual Eto are all very similar.

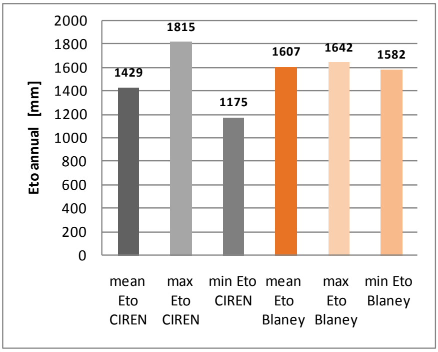


Figure 17: Total annual Eto [mm] (CIREN and calculated due to Blaney-Criddle)

Analysing the Eto values of the twenty sub-catchments, sometimes bigger river stretches, which were extracted out of the CIREN data (Annex, Table-A 14), highest totals are upstream of the Hurtado River, Rapel and Mostazal Valley, as well Huatulame and around Puntilla San Juan. The lowest values are in the downstream part of the Limarí River, as well as in the Pama and Combarbala valley and in the upper part of the Grande River.

Resulting demand curves and use coefficients

The following diagram shows the final results of demand in m^3/sec per sub-catchment calculated based in Equations (3.4a and 3.4b). The demand per ha (unit area) was calculated for each main crop group with the weighted Kc (Table 12). The final demand per sub-catchment was calculated with the percentage area of each sub-group present in the sub-catchment under study and finally multiplied with the total area of the sub-catchment. The results show all very similar demand patterns; a selection of water demands in m^3/sec during one hydrological year is presented in Figure 18. Both demand curves of the downstream reaches of the Limarí River, Limarí until Ingenio and Ovalle until Panamericana station, represent the highest demands with around maximum 4 m^3/sec and 10 m^3/sec respectively in summer (secondary axis). The differences are mainly based on the size of cultivated area in the different valleys.

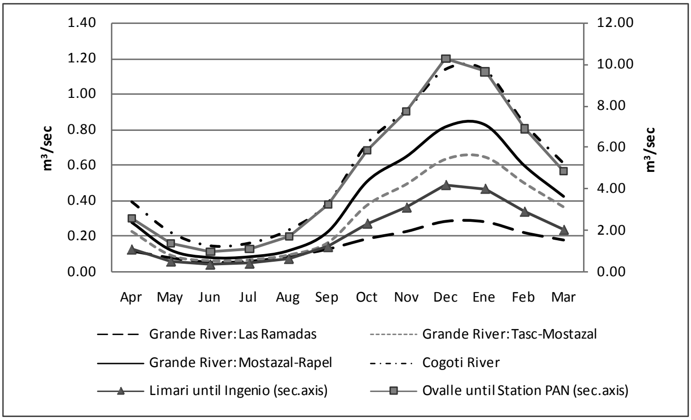


Figure 18: Final demands of selected sub-catchments in m^3/sec

The monthly demands are further used for validation of the consumptive use calculated with linear regression in chapter 0 (Calculation of naturalized streamflows).

Out of the monthly demand per sub-catchment the use coefficient (UC), which is a percentage of the annual demand, was calculated (the sum of them equal to 1). An example is presented below in Table 15 and Figure 19, the UC of the other sub-catchments are almost identically.

Table 15: Calculated use coefficients (UC) for some selected sub-catchments as an example

	Grande River Tasc-Mostazal UC [-]	Cogoti River UC [-]	Huatulame area total UC [-]	Puntilla until La Paloma UC [-]	La Paloma until Hurtado UC [-]	Ovalle until Panam Station UC [-]
Apr	0.06	0.06	0.05	0.05	0.06	0.05
May	0.03	0.03	0.02	0.02	0.03	0.02
Jun	0.02	0.02	0.02	0.01	0.02	0.02
Jul	0.02	0.02	0.02	0.02	0.02	0.02
Aug	0.03	0.04	0.02	0.02	0.03	0.03
Sep	0.04	0.06	0.05	0.04	0.05	0.06
Oct	0.10	0.11	0.11	0.11	0.10	0.10
Nov	0.13	0.13	0.14	0.14	0.13	0.14
Dec	0.17	0.16	0.18	0.19	0.17	0.18
Jan	0.17	0.16	0.18	0.18	0.17	0.17
Feb	0.13	0.12	0.13	0.13	0.13	0.12
Mar	0.10	0.09	0.08	0.09	0.09	0.09

The presentation of the monthly UC of three different areas shows that the highest differences can be observed in the summer time, when the need is highest, too. Two upstream areas and one downstream area have been selected for demonstration (Figure 19). In general all of them are very similar.

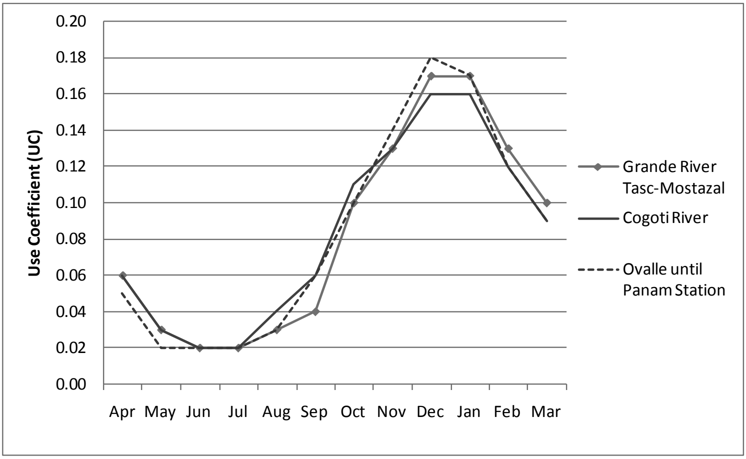


Figure 19: Monthly Use coefficient (UC) of selected demand areas

4.3 Natural streamflows

The first subchapter 4.3.1 covers the gap filling and amplification process, thus the preparation of the historical time series for further modelling. In chapter 0 the historical natural streamflows are reconstructed by different approaches. Most of the time series were modelled, by first estimating the use and lateral additional flows of the adjacent catchment through linear correlation and then calculating the natural additional flows by different estimators. Additionally some series had to be reconstructed with operational data which were available from some water management associations. As mentioned before the approaches of an earlier study were followed (Ingendesa, 1992), additional for two stations new approaches had to be defined (El Tome station and Panamericana station). Natural streamflows are reconstructed starting in 1946 until 2010 for the primary control points (CP). Furthermore they are required for all other points of interest (secondary CP) which are being modelled. Thus sub-chapter 4.3.3 deals with the distribution of natural streamflows from gauged to ungauged stations. In total 27 CP are modelled.

4.3.1 Gaps filling and amplification of selected monitoring stations

The inventory of discharge monitoring stations in the basin resulted in 48 stations, with high differences in monitored years. Nineteen of them are still in use and sixteen were relevant for the study; they are presented in Map 3. and Figure 20)

Most of the stations had been studied in two former projects for the La Paloma system (Brown, Ferrer, 1976; Ingendesa, 1992). These studies were consulted and all data manipulation compared with original data of the DGA, which resulted in the details of the time series, presented in the following flow chart (Figure 3). Furthermore three new stations were included.

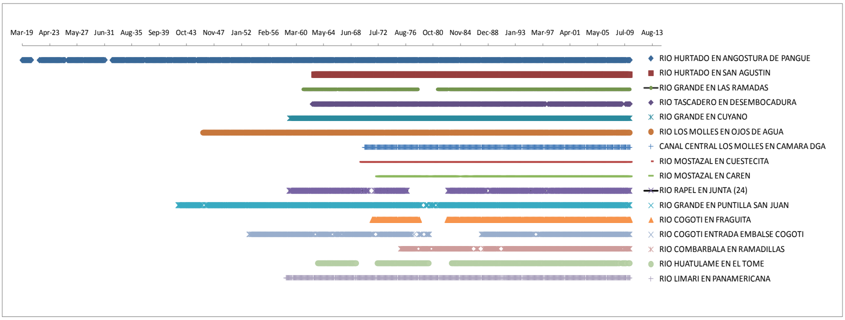
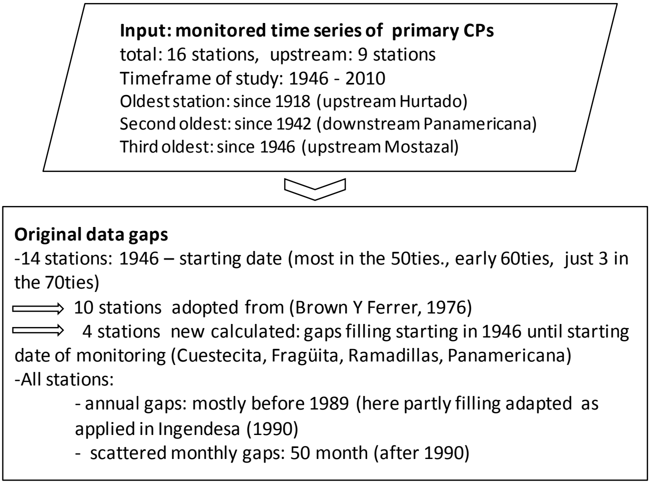


Figure 20: Data availability of the 16 stations selected to use for the study

Thus the time series of 16 stations in the basin had been revised and when necessary gap filled and amplified. The details of the stations and data gaps are presented in Figure 21.

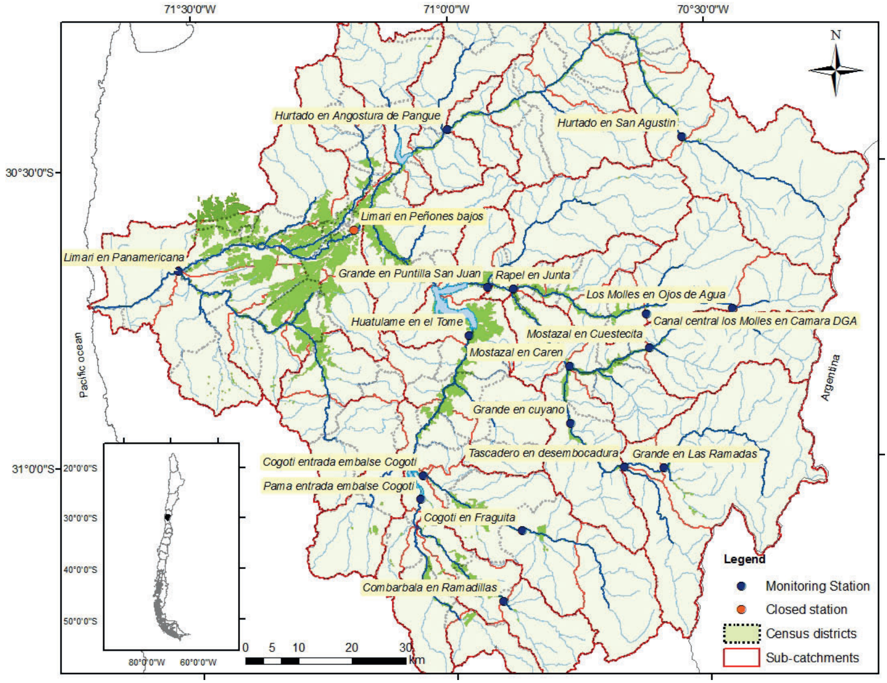
The different approaches are shown in chapter 2.4.1.



Input: monitored time series of primary CPs
total: 16 stations, upstream: 9 stations
Timeframe of study: 1946 - 2010
Oldest station: since 1918 (upstream Hurtado)
Second oldest: since 1942 (downstream Panamericana)
Third oldest: since 1946 (upstream Mostazal)

Original data gaps
-14 stations: 1946 – starting date (most in the 50ties., early 60ties, just 3 in the 70ties)
⇒ 10 stations adopted from (Brown Y Ferrer, 1976)
⇒ 4 stations new calculated: gaps filling starting in 1946 until starting date of monitoring (Cuestecita, Fragüita, Ramadillas, Panamericana)
-All stations:
- annual gaps: mostly before 1989 (here partly filling adapted as applied in Ingendesa (1990)
- scattered monthly gaps: 50 month (after 1990)

Figure 21: Summary of existent stations used and gap filled for the study



Map 3: Discharge monitoring station considered for calculation of natural flow

The names of the stations are the following:

Upstream (nine stations):

1. Grande River sub - catchment:
   Rio Grande en las Ramadas **(LR)**+ *Rio Tascadero en Desembocadura* **(TD)**
2. *Rio Los Molles en Ojos de Agua* **(MOA)** + *Canal Central Los Molles en Camera DGA* **(MOC)**
3. Mostazal River sub - catchment: *Rio Mostazal en Cuestecita* **(CUE)**
4. Cogoti River sub - catchment: *Rio Cogoti en Fragüita* **(FRG)**
5. Combarbala River sub - catchment: *Rio Combarbala en Ramadillas* **(RAM***)*
6. Hurtado River sub - catchment: *Rio Hurtado en Angostura de Pangue* **(HAP)**
7. Pama/Combarbala sub-catchment: *Rio Pama entrada Cogoti* **(PAM)**

Downstream (eight stations):

1. Grande River sub - catchment:
   a) *Rio Grande en Cuyano* **(CUY)**, *b) Rio Grande en Puntilla de San Juan* **(GPSJ)**
2. Rapel River sub - catchment: *Rio Rapel in Junta* **(RJ)**
3. Mostazal River sub - catchment: *Rio Mostazal en Caren* **(MC)**
4. Cogoti River sub - catchment:
   a) *Rio Cogoti en entrada embalse* **(CEC)** *b) Rio Huatulame en Tome* **(TOM)**
5. Limarí River sub - catchment: *Rio Limarí en Panamericana* **(PAN)**

<u>*Preparation of data and information for modelling*</u>

Decision for one main base station

As a base station for amplification or filling of the time series for most of the headwater stations, the *Rio Los Molles en Ojos de agua (MOA)* station with time series starting from 1946 is used. It is the longest record in a representative sub-catchment of the Rapel River without any upstream use. The natural regime is composed of the flow of two monitoring stations, since 1952 a small hydro station went into operation and water is conveyed through a canal to the hydropower station. The second monitoring point is in the canal (canal Central los Molles). Thus the sum of both monitoring points represents the natural flow in the upstream catchments.

Different sources of data were used (Brown and Ferrer, 1975; Ingendesa, 1992; original data of DGA). Most of the time series were adapted until 1989 from Ingendesa (1992). Exception are the following stations: "Rio Mostazal en Cuestecita (CUE)" station, "Cogoti en Fragüita station (FRG)", "Rio Limarí en Panamericana (PAN)". All stations had been actualized and further corrected until 2010.

In the following are four example stations looked at in more detail. The resulting annual correlation coefficients are all very satisfying (Table 16), the homogeneity test by the double mass curve resulted in general in a straight line. It can be concluded that the resulting time series are representative.

More detailed illustration of two examples of the headwater stations, the outlet station and one river using a different approach (Pama River)

In general the correlations of the time series were tested, before deciding on the respective base station for a time series which had to be amplified or gap filled. The MOA station was used mainly to get correlations with other headwater stations and to test homogeneity of the developed time series.

Table 16: Correlation coefficients of different base station (operational values) and station to be amplified

Sub-catchment	Name of Stations	Annual correlations coefficient R^2
Hurtado River	MOA (BS)/ HSA	$R^2 = 0.889$
Grande River	LR (BS)/ TD	$R^2 = 0.901$
Mostazal River	MOA (BS)/ Cue	$R^2 = 0.849$
Cogoti River	MOA (BS)/ FRG	$R^2 = 0.766$
	CUY (BS) /FRG	**$R^2 = 0.957$**
Combarbala River	TD (BS)/ RAM	$R^2 = 0.93$
	FRG (BS)/ RAM	**$R^2 = 0.97$**
Pama River	Tot Inf Cog[31]/PAM	$R^2 = 0.877$
Limarí River	PEÑ (BS)/ PAN	$R^2 = 0.985$[32]

Mostazal River

Its headwater has been monitored historically in two different points. The first station was named Mostazal en Chacay (2,410 m.a.s.l), here the data have been monitored from May 1949 until March 1966. Then the monitoring station was changed more downstream and named Mostazal en Cuestecita (1,250 m.a.s.l). This station is located downstream of the confluence with the San Miguel Creek. Monitoring started in November 1969 until present. Therefore it was decided in contrary to the previous studies mentioned, to

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[31] Annual correlation of the total inflow of the Cogoti reservoir (tot Inf Cog, operational sheets of the reservoir) with the station at the outlet of the Pama River (PAM), linear regression equation: Qa Pama = 0.309 * Qa inf + 0.037

[32] Monthly correlation, worst in June: R2= 0.866 until best in December: R2= 0.989

use the present monitoring stations even though it is influenced through an irrigation use above the station. But still the data are more reliable than generating data from 1966 until present. Due to this decision the first years from 1946 until 1969 had to be amplified. This had been done with data from the MOA with the method which is indicated above (Equation 1-11); correlation and associated scatter plot compare (Table 16 and Figure 22). In general the monthly correlations (Equation 7) are straight forward.

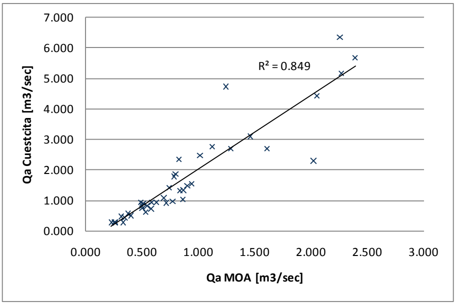

Figure 22: Scatter plot of the annual average observed discharge of MOA station (Rapel River) and CUE station

Cogoti River

The monitoring of the Cogoti en Fragüita head station of the Cogoti River sub – catchment started in 1971, gaps in the original data had been detected from November 1977 – October 1982; in different data bases the gaps had been filled differently and unsatisfactory. Furthermore the data from 1946 until 1971, had to be synthesized. Previous historical studies worked with the correlation between the MOA station and FRG station (Figure 23). Furthermore the correlation in the winter months (precipitation season) resulted even worse, whereas the summer months (melting period) resulted in better correlation coefficients. Testing the correlation with other stations, the best correlation coefficients in both seasons were achieved with the Rio Grande en Cuyano station (CUY, Grande River, Figure 24), annual correlations coefficients in Table 16.

The heights of their location might explain partly these results, since there are quite similar of the two last mentioned: MOA of Rapel River is located at 2,355 m.a.s.l, whereas the station Fragüita of Cogoti River at 1,065 m.a.s.l and the Grande en Cuyano station at a height of 870 m.a.s.l. This might explain that the summer months get better results with the correlation of the Grande en Cuyano station; the hydrological regime, depending very much on temperature, is more similar and probably also the water use have an influence.

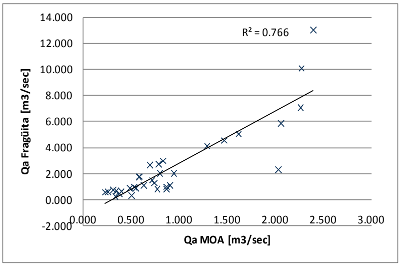

Figure 23: Scatter plot of the annual average observed discharge of MOA station and FRG station

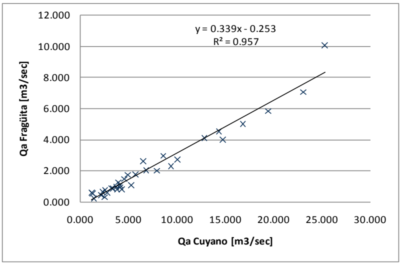

Figure 24: Scatter plot of the annual average observed discharge of CUY station and FRG station

Preparation of data and information for modelling

The correlation of the used station of CUY and FRG station resulted in the summer season (Oct - Mar) in R^2= 0.95 and in the winter season (Apr – Sep) in R^2 = 0.89. The error between the monthly calculation and the seasonal is corrected proportionally. In few cases when monthly calculated discharge had to be corrected and resulted in a negative value, the minimum registered value of that month of all years was used.

Limarí River en Panamericana station

The lower part of the catchment was not considered in the historical studies. Analysing the stations two stations have time series which have to be considered. The basin outlet station, *Rio Limarí en Panamericana* station (PAN), where monitoring started in October 1958, and the Peñones Bajo station (PEÑ), which operated from October 1941 - March 1983, thus they have 25 years of common measurements. The correlation of the annual discharge of the common years resulted in R^2 = 0.985.

The test of the correlation of the single month got similar results, the worst was calculated in March with R^2 = 0.853 and the best in November with R^2 = 0.989. Therefore method 2 was used to amplify the time series of PAN station from 1946 to 1958 with the monthly correlations of PEÑ station, both in the Limarí River.

Pama River

For amplifying and correcting the time series of the Pama River as the base time series, the total inflow to the Cogoti reservoir has been used. These data are not monitored by the DGA, but obtained out of the operational sheets of the Cogoti reservoir, starting in 1945 and provided from the association of the Cogoti reservoir. Streamflow data from the Pama River station had to be extended from 1989 until 2010; earlier data were adopted from Ingendesa (1992), after verifying that they had been using the same data base.

The total affluent to the reservoir (MCM/month) was calculated out of the operational data from the balance of the reservoir as follows: $Q_{in} - Q_{out} = \pm R$

Q_{in} = Inflow to the reservoir, with $Q_{in} = Q_{Afl} + Q_P$

Q_{out} = Outflow of the reservoir, with $Q_{out} = Q_F + Q_C + Q_S + Q_{EV}$

Q_{Afl} = Inflow of the reservoir by affluent and lateral inflow

Q_P = Inflow by direct precipitation

Q_F = Discharge due to leakage

Q_C = Discharge to the canals and downstream association (canal: Matriz Cogoti and Huatulame Association)

Q_S = Discharge which spills

Q_{EV} = Discharge which evaporates by the surface of the reservoir

$\pm R$ = Regulated discharge of the reservoir: positive (increase) or negative (decrease) of the reservoir level.

The time series of the Pama River have been amplified in three step: first the annual discharge has been estimated with the yearly regression equation (see Table 16) of the total inflow into the reservoir with the observed years of the Pama River (1953-1979, $Q_{a\ aver}$ = 0.832m^3/sec, $Q_{a\ max}$ = 2.949m^3/sec.), secondly the monthly distribution has been elaborated with the average monthly discharges of the observed time period. Finally they were tested and readjusted with the total monthly discharges which enter the reservoir

(Q_{Afl}), due to the operational sheets and the monitored inflow of the Cogoti River at the entrance of the reservoir, following the method described in Ingendesa, 1992:

$$Q_{1i} + Q_{2i} = \beta Q_{3i} \qquad (26)$$

Q_{1i} = Discharge of Cogoti River in month i

Q_{2i} = Discharge of Pama River in month i

Q_{3i} = Discharge of total inflow to the reservoir (due to the operational sheets) in month i.

In the Equation "β" results in $\beta \leq 1.0$; in the years of observation it takes in average the value of 0.962. The additional lateral flow mainly occurs in years with more rainfall, which lead to the assumption to use β = 0.86 in the following rainy years: 53/54, 57/58, 65/66, 72/73, 77/78, 78/79, 82/83, 84/85, 87/88, 91/92, 92/93, 97/98, 00/01, 02/03.

If the discharges do not fulfil the Equation above, they are modified with the following condition[33]:

$$\widehat{Q_{1i}} + \widehat{Q_{2i}} + \widehat{Q_{3i}} = Q_{1i} + Q_{2i} + Q_{3i} \qquad (27)$$

Comparing the corrected time series of the Cogoti River at the entrance of the reservoir with the ones which were corrected now to get the amplified time series of Pama River they have a difference of about 3% in average (Table 17). Thus it can be concluded that the corrections result in reliable time series.

Table 17: Average flows of Cogoti after 1. amplifying and 2. adjustment calculation for Pama River inflow

Version	Cogoti (entrance of res), current calc (m³/sec)	Comment
2	2.109	observed - corrected
3	2.179	Compatible with Inflow reservoir

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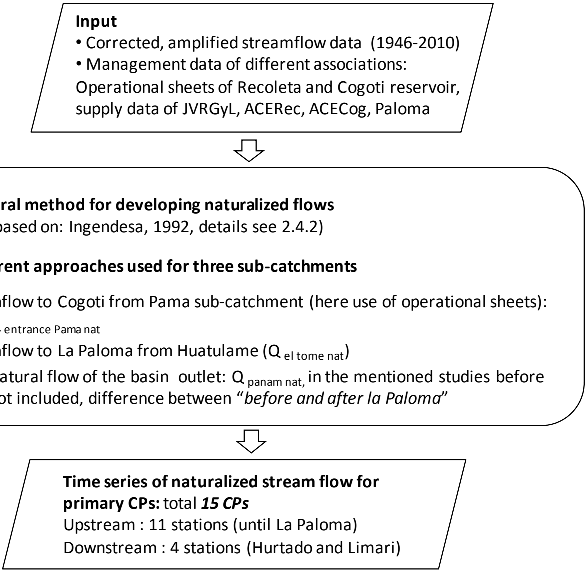
[33] further details in Ingendesa (1992)

4.3.2 Development of naturalized streamflows of monitored (primary) CPs

In the study area the natural flow for 15 preliminary CPs had to be modelled (methods are summarised in Figure 4 and Figure 25). For the calculation the method of Ingendesa (1992) is adapted in most of the CPs. For the outlet Limarí in Panamericana (PAN) station a new approach had been developed, in the historical study the downstream part of the basin was not considered.

Furthermore the natural inflow to the Cogoti reservoir from the Pama sub-catchment as well the inflow to the La Paloma reservoir from Huatulame River has been developed differently.



Input
- Corrected, amplified streamflow data (1946-2010)
- Management data of different associations:

Operational sheets of Recoleta and Cogoti reservoir, supply data of JVRGyL, ACERec, ACECog, Paloma

General method for developing naturalized flows
(based on: Ingendesa, 1992, details see 2.4.2)

Different approaches used for three sub-catchments

- Inflow to Cogoti from Pama sub-catchment (here use of operational sheets): $Q_{\text{entrance Pama nat}}$
- Inflow to La Paloma from Huatulame ($Q_{\text{el tome nat}}$)
- Natural flow of the basin outlet: $Q_{\text{panam nat,}}$ in the mentioned studies before not included, difference between "*before and after la Paloma*"

Time series of naturalized stream flow for primary CPs: total ***15 CPs***
Upstream : 11 stations (until La Paloma)
Downstream : 4 stations (Hurtado and Limari)

Figure 25: Flow chart for developing natural streamflows for the study area

Method tested and verified with the sub-catchment Rio Hurtado: AI (Hurtado en San Agustin – Hurtado Angostura de Pangue)

The test and verification of the method has been done with the sub-catchment of the Hurtado River, since it illustrates the simplest case (case 1, Equation (3)).

To derive the variables k and D through the regression equation, only the time series of the observed time span (1963-2010) is used, excluding years with high residuals (outliers caused mainly by high precipitation years, here Aug 87; Sep 87, Nov 84/87). The final results for the variables k and D are summarised in Table 18, with the historical values until 1988/89 (Ingendesa, 1992); the actual ones starting 1989 until 2010. The highest differences can be observed in the consumptive use, which is much higher in the last 20 years in the main irrigation period (Oct-Dec).

Table 18: Variables k and D, historical and actual for AI: Hurtado San Agustin - Angostura Pangue

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
k hist	1.3	1.5	1.49	1.46	1.5	1.35	1.3	1.2	1.2	1.15	1.13	1.1
D hist	0.75	0.55	0.5	0.4	0.45	0.7	0.8	0.9	1	0.9	0.9	0.9
k act	1.3	1.37	1.64	1.72	1.64	1.24	1.19	1.2	1.29	1.04	1.06	1.15
D act	0.79	0.26	0.41	0.5	0.48	0.61	1.04	1.37	1.93	0.93	1.05	1

For verification of the demand/consumptive use curves derived from Table 18, the demand considering census Census data (agricultural use) as calculated before are compared.

The interjacent area has a drainage area of 1,148.7 km^2 and a cultivated irrigated area of 1,495 ha the details of the demand calculation can be retraced in chapter 4.2. Historical and current demand are very different in the summer months, here the demand calculated with census data and the current use calculated by the regression parameters are similar until December, then the use decreases faster than the demand according to the census, but the use pattern is similar (compare Figure 27).

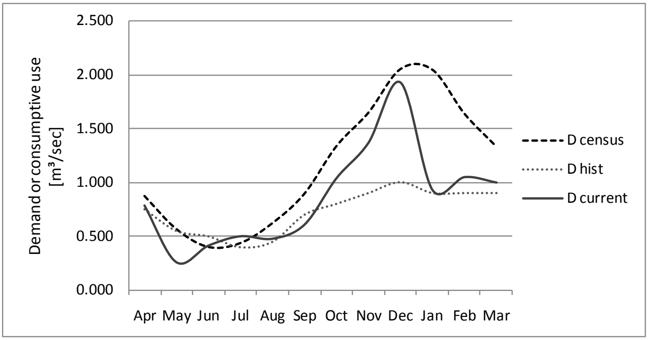


Figure 27: Demand and consumptive use curves for the AI between HAS and Angostura de Pangue (D hist as in Ingendesa, 1992)

Q_{AI} adopted

Conform with the described methodology the first two estimators (Q_{AI1} and Q_{AI2}: Equation 8, 9) are calculated for all years (1946-2010). The third estimator (Equation 10) is calculated with both discharges (entrance and outlet of the intermediate watershed), which might lead to the fact that possible errors in the single measurements are transferred in an exaggerated way to the difference of both of them. Therefore during the calculation of this estimator the two time series of Q_1 and Q_2 are corrected: In the case of a negative value in a calculated month: $Q_{AI3\ mi} < 0$, the Equations (16) and (17) are used to correct the discharges. The other case where error values might occur can be referred to very humid years with very high precipitations (as occurred in 1965, 1972, 1984, 1987, 1991, 1997/98, 2002/2003). Here it was decided to accept a maximum dispersion of 3*σ.

For the Q_{AI} adopted, the average value of Q_{AI1}-Q_{AI3} was used in case the difference to the Q_{AI3} was not more than 25 -35% (percentage as suggested in Ingendesa, 1992). In case that the difference was higher, Q_{AI3} is considered to represent best the intermediate discharge. The natural flow (NF) of HAP station is calculated according to Equation (25).

Verification of the results

For verification of the corrected discharges (with Q_{AI3} and Q_{AI} adopted) the sum of all discharges in m^3/sec has been calculated for each version. The results of the delta between the version of the historical and actual time series is very similar, which leads to the conclusion that the calculation applied seems to be correct and will be applied to all station (Table 19).

Table 19: Comparison between the different version of calculated Q_{AI} of the upstream catchment of Hurtado (sum of all monthly discharges, in m3/sec)

Version	H. San Agustin Σ Q [m^3/sec]	H. A. de Pangue Σ Q [m^3/sec]	Q_{AI} adopt [m^3/sec]	Q_{AI} prom [m^3/sec]
1 (until 89)	1290.52	1260.96		
2 AI3(until 89)	1221.66	1322.81		
10 (until 89)	1227.28	1314.85	483.63	396.73
Δ V.1. and V.10: HAS = 4.8 %		HAP = 4.3%	Δ AI = 18% (due to rainy years)	
1 (all years)	1978.57	1948.56		
2 AI3 (all years)	1895.48	2022.54		
10 (all years)	1901.50	2014.18	736.63	609.22
Δ V.2. and V.10: HAS = 4.0 %		HAP = 3.4%	Δ AI = 18% (due to rainy years)	

Further the double-mass-curve of both time series in natural regime was calculated and shows a straight line, with some very small acceptable derivations, but no breaks or other deviations (Figure 28).

This confirms that is was correct using different time spans for parameter calculations. Clearly the demand changes during the time frame under study.

Not all of the sub-catchments can be calculated in exactly the same way as in the methods stated; there are several details, which need some additional considerations. These details are mentioned in the following paragraphs, where the single calculations are summarised; an example is showed with detailed results.

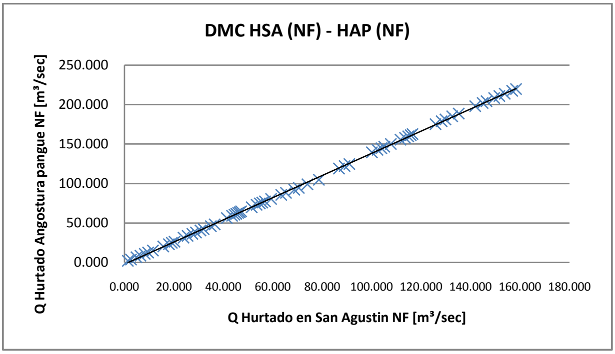


Figure 28: Double mass curve of the natural flow of HSA and HAP.

AI between Hurtado Angostura Pangue and the dam of the Recoleta reservoir

The catchment between Angostura de Pangue station (HAP) and the Recoleta reservoir drains about 735 km², precipitation is very low. Due to the last census the cultivated area in this stretch is about 185 ha. The time series of the inflow into the reservoir had to be obtained to be able to derive from regression the necessary variables for further calculation.

With operational data sheets[34] of the Recoleta reservoir the inflow (IN) to the reservoir could be calculated with the following parameters: $\Delta V = In + P - Out_{canal} - S - EV - Sp$

With
Δ V: Change in volume of the reservoir
In: total inflow to the reservoir (river and lateral)
P: Precipitation
Out: Discharge through canals (outflow)
S: Seepage
EV: Evaporation
Sp: Spill

The values of the historical years (1946-1989) have been taken from Ingendesa (1992). All received demand/use curves show the same pattern, the actual ones are higher as before in the summer months.

Estimation of Q_{AI}

Since this small sub-catchment will not reach 10% of the discharge of HAP, the additional flow of the Q_{AI} has been estimated as described in the methods as case 1 (Q_{AI1}: Equation 8) with the variable k of the correlation. Adjustment as described before had been made when necessary (here just in winter months and mainly in rainy years: 65/66; 84/85; 87/88; 97/98. The final result of the average discharge of the AI is 0.268 m^3/sec, compared to the historical one of 0.240 m^3/sec. The natural flow of HAP resulted in an average discharge of 3.69 m^3/sec, the historical calculation in 3.55 m^3/sec.

The DMC between the natural affluent of the Recoleta reservoir in comparison with the natural flow of MOA station is quite satisfactory, just some dispersion around the linear regression line.

Natural inflow to the La Paloma reservoir

The main reservoir of the system and the basin is the La Paloma reservoir which has two tributaries. The main one is the Grande River, the smaller one and highly altered by an upper reservoir and a canal intake is the Huatulame River (compare upper scheme Figure 11). First the Grande River calculations until the reservoir will be presented and analysed.

The Grande River can be subdivided in different sub-catchments as presented in Map 2. The following head stations are controlling the upper part of the sub-catchments, as described before: Molles en Ojos de Agua (MOA) – Rapel River, Mostazal en Cuestecita (CUE) – Mostazal River, Grande en las Ramadas (LR) – Grande river, Tascadero en desembocadura (TD). For the lower part the following stations had been used for analysis: Grande en Cyano (GC) – Grande River, Mostazal en Caren (MC) - mouth of Mostazal River, Rapel in Junta (RJ) - mouth of Rapel River and finally the Grande en Puntilla San Juan station (GPSJ), which is just some kilometers upstream of the La Paloma reservoir located and just downstream the confluence which the sub-catchment of the Ponio River.

With the mentioned monitoring stations the following four interjacent areas are analysed and the natural flows with the assigned method calculated:

- Upper Grande River: Sum of LR and TD station until GC station: ***Method case 2***
- Mostazal River: CUE until MC station: ***Method case 2***
- Rapel River: MOA until RJ station : ***Method case 1***
- Middle Grande River catchment: GC – RJ – MC until GPSJ: ***Method case 1***

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[34] provided be ACER, association of the Recoleta reservoir and its canals

Case 2 AI: Upper Grande River and Mostazal River

For both areas case 2 of the methodology was adopted, since Q_1 is influenced by an upstream use. Here the Equations (11) until (13) are used to estimate Q_{AI}, and additionally Equation (7).

Cultivated areas were estimated again through the Census and further geospatial data of (CAZALAC, 2006). Thus the upstream area could be estimated and the following values for factor α were received:

Table 20: Factor α for the AI of the upper Grande, Mostazal River and Cogoti River

Location of AI (between monitoring stations)	A_1 (ha)/ A_2 (ha)	α
AI (LR+TD) - (GC)	185.32/463.8	α = 0.4
AI (CUE) - (MC)	98 /894	α = 0.11
AI (FRG) - (COG)[35]	148/898.13	α = 0.165

Following the method the resulting three estimators of Q_{AI} for the upper Grande River show a good compliance. The estimator Q_{AI3} gets higher values with the starting of the melting period in September/October, which indicates that this is more important in the intermediate watershed than in the upstream stretches. The peak in September shows that the Q_{AI} is mainly influences by snowmelt, but also in June/July (the winter and rainy season) an increase can be observed (Figure 29) and explained further down.

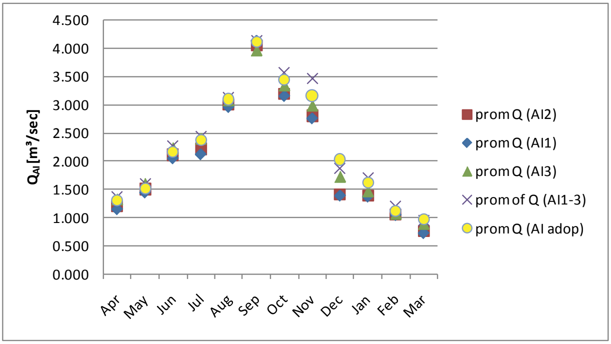

Figure 29: Seasonal difference of different estimators for the support of the discharge (Q_{AI}) of the AI in the upper Grande River

Again discharges were adjusted together with the final adopted average Q_{AI}. The test of the differences of the discharges between the original and the final used, once again is very low, in the upper Grande River case delta = ±1.4%. Furthermore the test with the DMC, comparing the new natural streamflow series with the observed natural flows of MOA, indicates the homogeneity of the elaborated time series.

Looking at the results of the AI CUE station until MC station in the Mostazal River where $\bar{Q}_{AI}$ was adopted, a new Q_1 had to be calculated and tested against the already newly corrected one during the calculation of the third estimator. In case the difference was in the 10% range, that former Q_1 was used, if not also Q_2 had to be recalculated.

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[35] calculation of AI Cogoti River in next sub-chapter: Natural afluent streams to the Cogoti reservoir

Actually this sub-catchment showed some results which were not quite satisfactory and unexpected, too. Following the method, the Q_{AI3} was adopted in the first step for calculating the natural flow, since the calculations resulted in high differences between the average Q_{AI} and the Q_{AI3}. Following this calculation a global change of the discharge time series of almost 10% were observed, furthermore the DMC of the Q_{AI} adopted and the natural flow of CUE station as well the test with MOA station, got results which were quite unsatisfactory. Thus the average value of the Q_{AIs} was adopted. Following up all the calculations, the global change of the time series could be reduced to ±3.8 %.

Since also the test with the DMC got very satisfying results, specially looking at both natural flows of the catchment as well as looking at the natural regime of MC and MOA, the new approach using CUE station is being evaluated as given reasonable results. Furthermore testing the Q_{AI} adapted versus the different calculated natural flows, resulted in a much better approximation to a single line than with the first approach in the historical study.

Case 1 AI: Rapel River and Middle Grande River catchment

If necessary, drainage areas were calculated with GIS software[36]. First the natural flow of the monitoring station Rapel in Juntas had to be calculated to further calculate the middle Grande River catchment.

As stated before, upstream of the MOA station exists no consumptive use, thus case 1 was used for further calculation. The natural flow upstream consists of the sum of the discharge measured in the station and the extraction diverted to the canal for the hydropower plant los Molles. Estimators for the AI are calculated with Equations (8) - (10).

Verifying the results with the previous calculated out of Ingendesa (1992), some small variations can be detected, but minor. The average discharges recalculated for the historical and also for the more current years are slightly higher, highest difference about 0.05m3/sec (about 2-3%). Furthermore the double mass curves of the natural flow of the station MOA and the natural flow of Rapel en Juntas, as well of MOA and the interjacent area (AI) show a high consistency.

Thus with the calculated naturalized entrance flows in the middle catchment of the Grande River: $Q_{1n} = Q_n$ (GC) + Q_n (MC) + Q_n (RJ) again the method of case 1 could be used to get the natural streamflow of the main entrance of the La Paloma reservoir at GPSJ monitoring station. This time the input time series of the outlet of the sub-catchment (GPSJ station) had to be corrected, since the diversions to two canals[37], which transport water to other irrigation areas are added. The new calculated monthly sum from 1973 – 2010 and the previous adopted years were used as the outlet time series (Q_2) of the AI.

With these time series of Q_1 and Q_2 the regression equations were developed, (always excluding the extreme residuals, if necessary) and thus the k and D values obtained, for further calculation of the AI. Comparing as before the pattern and values of the theoretical demand and the consumptive use of the different time ranges, they are similar (use, hist/act: between 2 - 4.5 m^3/sec, demand: 0.5 - 5m^3/sec), just more water is used in the winter month and a bit less in the summer. This time the AI3 resulted in values out of the range. Therefore this estimator was ignored and the average of AI1 and AI2 calculated and further corrected, to make the measured and corrected discharge Q_2 at GSJP station compatible with the calculated natural flow $Q_{1,}$ which enters the AI. This has been done with an iterative approach until the new value Q2 was higher than the calculated value which resulted out of the Equation of AI3. Finally the overall

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[36] Software used: GIS of ESRI version 9.2, with ArcHydro and WRAPHydro tools

[37] 1. canal *Maurat Palqui Semita* since 1973, 2. canal *Alimentador de Recoleta:*July 1947 until May 1977: data aquired of JVLRyG since 1973, before of Ingendesa, 1992

change of the statistics between the observed values of GPSJ and the final corrected version has been 3.4%. The average annual discharge of the natural flow in GPSJ station sums up to 13.09 m³/sec.

The test of the double mass curves of the calculated natural flow of Q_{1n} with the natural Q_{2n} as well as with the flow of the AI resulted in homogeneous time series (Annex, Figure-A 1).

Furthermore the natural discharge of GPSJ and the flow of the AI were tested against the time series of MOA. Both graphs of DMC give very good results, considering that this is the outlet of various calculated sub-catchment (Annex, Figure-A 2 and Figure-A 3). Herewith main natural inflow of the La Paloma reservoir is calculated.

Case 2: AI Cogoti River: FRG until CEC station

Due to some agricultural activity upstream the head station FRG, method of case 2 is used and thus Equations (11)-(13) for the estimators for AI1-3. The agricultural areas and the necessary factor α (presented in Table 20) were estimated and calculated through the analysis of the agricultural area in the previous chapter.

Comparing consumptive use curves (current and historical) with the demand resulting out of the Census data, the curves show for the first time not the same pattern, there is another peak in the winter time, June/July . Nevertheless the decision was made to use the calculated parameters out of the correlations for further calculation. A reason could be that the assumed demand pattern in reality might be a bit different, that water is not used due to the demand and further that in some years the canals stay open in winter to receive all their rights, even though the water is not needed.

The calculation was also here straight forward, just in case AI3 was negative, Q_1 and Q_2 were corrected according to Equation (16) and (17). These new values are used to recalculate a new AI3. Following Equations (18) and (19), for this sub-catchment it was decided on $\varepsilon = 0.5$ in all months.

As before, different DMC have been tested here gain: Double mass curve of the time series of MOA and the natural inflow of the entrance of the Cogoti reservoir (CEC) as well as MOA with the finally adapted AI between FRG and CEC. Both look very reasonable, the statistics of the natural flow of the entrance of the reservoir show a very small oscillation around the straight line. Natural affluent streams to the Cogoti reservoir: Pama River

The Cogoti reservoir receives water of the sub-catchments of the Cogoti River and the Pama River. The latter has its confluence with the Combarbala River further upstream. The Cogoti River represents the main inflow to the reservoir and the calculation of the AI (FRG)-(CEC) is straight forward, for the sub-catchment of Pama and Combarbala River another approach had to be used, since no reliable monitoring stations upstream of both rivers exists.

Aside from the inflow of the two rivers there is an intermediate catchment which can be allotted mainly to the lateral inflow into the reservoir, with a quite low flow with an average discharge of about 600l/sec. This represents about 14% of the average affluent to the reservoir (Ingendesa, 1992). About 50% of this contribution can be explained by high precipitation years. The before mentioned numbers were calculated by statistics until 1989 and confirmed by calculating the values with statistics until 2010, though the tendency is getting lower flows.

For estimation of the natural streamflow of the Pama River, the approach of Ingendesa, 1992 was adopted, and the demand for agricultural purposes calculated before (by Census data) or the use (calculated by correlation) added to the already amplified and corrected monthly time series:

$$Q_{i\,PamaNF} = Q_{i\,Pama} + D_i \qquad (31)$$

Monthly correlations between the natural flow of Cogoti River in the entrance of the reservoir and the corrected observed/amplified time series of Pama River has been calculated, assuming that the shift of the regression line represents an average use of Pama. Furthermore dry and rainy years were distinguished: years with higher precipitation provide sufficient water to satisfy the theoretical demand, in years with water scarcity the average consumptive use, given by the correlation is been used. The threshold was decided on 100mm per year of the base station precipitation.

Additionally the total natural inflow of the Cogoti reservoir was calculated in two different ways, to test if the time series are in the correct ranges:

a. $Q_{Inf\ res\ NF} = Q_{NF\ COG} + Q_{NF\ Pama}$

b. $Q_{Inf\ tot\ res\ NF} = Q_{Afl\ tot} + UC_{Pama} + UC_{Cogoti}$ with $Q_{afl\ tot}$ according to operational sheets

Again here (as in Table 17) the changes of the different versions have been calculated to see if the difference results in a reasonable ratio, since the data of the Cogoti River, as well the data of the Pama River had been recalculated and adjusted during the process to get the natural flows. Globally the new statistics give a good estimation of the discharge. The last version gets less total flow, because of a decrease of the lateral flow since 1990. As already mentioned this lateral flow can be explained by a minimum of 50% with years of higher precipitation. Until 1989 nine hydrological years had higher precipitation and just five after 1989, from which 50% of the events are less in intensity as in the historical time span.

The DMC of the total natural Inflow to the Cogoti reservoir and the natural Inflow of Cogoti River at the entrance of the reservoir is very reasonable. The homogeneity of both time series is highly acceptable; the test of the DMC of MOA station and the total natural Inflow to the reservoir from Cogoti and Pama also has one straight tendency but oscillates negligibly around this, especially during the last years. Considering all the difficulties in the time series data the results are relatively satisfying.

Natural Inflow to the La Paloma reservoir through the Huatulame River

The Huatulame River is highly intervened through the upstream Cogoti reservoir which cuts the natural streamflow. The average discharge measured in the station is 2.22 m^3/sec, but excluding high precipitation years, it is just 0.31 m^3/sec. Comparing this inflow to the inflow of the Grande River to the reservoir La Paloma, it is of minor importance, therefore a simplified method approach was adapted here.

The natural inflow of Huatulame (since 1989) is calculated as the sum of the calculated natural flows until the dam of the Cogoti reservoir and the flow which is generated in the sub-catchment between the two reservoirs:

$$Q_{Hua\ NF}\ [m^3/sec] = Q_{Inf\ tot\ res\ (NF)}\ [m^3/sec] + Q_{AIHuat}\ [m^3/sec] \qquad (33)$$

The following statistics of time series and demand pattern were used:

a) Discharge of the Cogoti reservoir to the Huatulame River (R_{tot} riv), including spill in case occurred (source: operational sheet of the reservoir association),

b) Statistics of observed time series of el Tome station from 1989 - 2010 ($Q_{Tome\ obs}$.)

3) The agricultural demand of the lower part of the Huatulame River (D_{Huat}).

The support through the AI was calculated as follows:

$$Q_{AIHuat}\ [m^3/sec] = Q_{Tome\ obs}\ [m^3/sec] + D_{Huat}\ [m^3/sec] - R_{riv\ tot}\ [m^3/sec] \quad (34)$$

Preparation of data and information for modelling

The demand was calculated based of the census combined with GIS data of Cazalac, 2006. Demand calculation was made as described in chapter. For calculation of Q_{AIHuat} the demand curve of only 70% was used (subject to comparison with releases to the downstream part); just in the years when precipitation was much higher than average (1991, 1997 and 2002) the 100% demand was considered.

The AI was adapted until 1989 of the historical study, since demand has been different these days. Equation (34) results in an average flow which support the AI: $Q_{AI\ aver} = 0.87 m^3/sec$. The natural flow of the Huatulame River, calculated with Equation (33), sums up to a total average of 5.39 m^3/sec. The DMCs of natural inflows of the Cogoti reservoir with the natural flow of the Huatulame River outlet show a very homogeneous pattern.

Total natural inflow of the La Paloma reservoir

Having calculated the natural flow of the Puntilla de San Juan station (Grande River) and El Tome station (Huatulame River) the total inflow to the reservoir can be estimated. The catchment which is missing until the reservoir dam has an area of about 309.2 km^2. Compared with the AI of Huatulame it is about one third, which a very similar hydrological regime, which implies that the support will not be not much more than 290 l/sec in average. Therefore it was decided to estimate the total natural flow as the sum of the natural flows before mentioned, the average yearly natural flow results in 18.54m^3/sec.

To verify that the observed statistics of La Paloma reservoir are also consistent with the rest of the observed time series, the sum of the statistics of el Tome station and the corrected statistics of Puntilla de San Juan station are being compared with the operational sheets of the La Paloma reservoir. The total inflow to the La Paloma reservoir was calculated as follows:

$Inf_{tot} = \pm \Delta V + (EV + Out_{canal} + Spill + Q_{filt}) – P$

With : Inf_{tot}: total inflow , ΔV: change in Volume, EV: Evaporation, Out_{canal}: Discharge to canals,

Q_{filt}: Filtrations, P: Precipitation

The result of the comparison shows a unique tendency of the DMCs, which implies homogeneity of the time series analysed.

Natural flow of the outlet station: Limarí en Panamericana

For the calculation of the natural streamflow of the Limarí en Panamericana station (PAN) the methods case 1 was used. The time series of the monitoring station at the outlet of the basin (Q_2) have been prepared in the previous step. The time series of Q_{1n} is the sum of all water entering the lower catchment. Since the La Paloma reservoir went in operation just the release to the different associations, thus to the respective cultivated areas, as well as the spill of the Cogoti and Recoleta reservoir enter the lower catchment.

Furthermore two small sub-catchments, Ingenio Creek (Ing) and of the Punitaqui Creek (Pun) (Map 4), contributing to the natural streamflow (especially in rainy years) have to be considered additionally (the modelling of this areas is illustrated in the next paragraph).

The described approach results in the following equations for Q_1 and Q_2:

$Q_1 (1946\text{-}1971) = Q_{GPSJ\ NF} + Q_{elTome\ obs} + Q_{Pun\ NF} + Q_{Ing\ NF}$ (35)

$Q_1 (1972\text{-}2010) = \sum Q_{rel\ Paloma}$[38] $+ Q_{spill\ Cog} + Q_{spill\ Rec} + Q_{Pun\ NF} + Q_{Ing\ NF}$ (36)

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[38] Total monthly release calculated from data provided by JVRLyG

$Q_2 = Q_{\text{Panam obs/corr}}$

The spill of the Recoleta reservoir could just be considered since 1984, no historical data were available.

The final result of the natural flow of the PAN station is calculated for the whole time period by adding the AI adopted to the natural streamflow of Q_1, using the following equation:

$$Q_{\text{Panam NF}}\ [m^3/sec] = Q_{\text{1nat upstream}}\ [m^3/sec] + Q_{\text{AI adop (downstream)}}\ [m^3/sec] \quad (37)$$

With: $Q_{\text{1nat upstream}} = Q_{\text{La Paloma NF}} + Q_{\text{Hurtado NF}} + Q_{\text{Ingenio NF}}$

The calculation of Q_1 of the different time ranges were straight forward, the average release to the lower catchment (Figure 30), without spills sums up to an annual volume, supplied by La Paloma and parts Cogoti of 295 MCM (45 MCM in average supports the Cogoti reservoir to the downstream catchment).

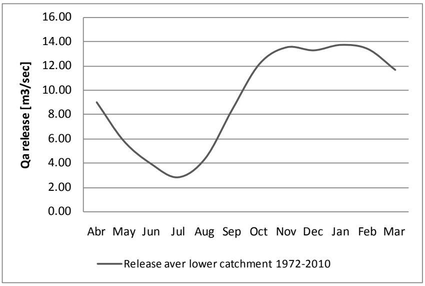

Figure 30: Average monthly release to the downstream catchment from La Paloma and Cogoti reservoir

Natural flow of El Ingenio Creek and Punitaqui Creek

The El Ingenio as well Punitaqui Creeks (Map 4) are non-perennial or intermittent streams which depend on the rainfall pattern. Since no monitoring is existent, the rainfall - runoff model with was developed from the DGA[39] was used to determine the flows upstream. A former study was consulted where the model has been used to simulate various sub-catchments and calibrated parameters for these upper two catchments were obtained (CAZALAC, 2006). They had been validated with simulation results downstream during 1990-2003. Input data and parameters were studied and some changes made, subject to more detailed information available of evapotranspiration, as well different climatic stations were chosen to represent the precipitation of both sub-catchments.

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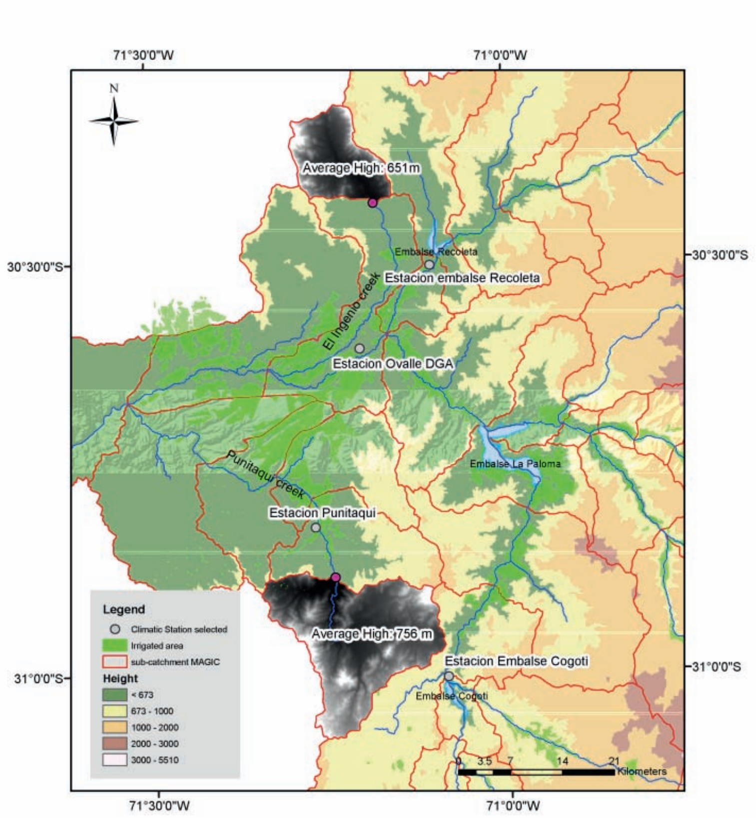
[39] MQM win v.1.0, Simulation of average monthl discharges, DGA, 2004



Map 4: Overview of the contributing sub-catchments to the downstream catchment of the Limari basin

Figure 31 shows the final results simulating the runoff of the Ingenio Creek with the calibrated parameters, and new precipitation time series. The average discharge is slightly lower (before: 0.093 m3/sec), the peaks are higher than in the former model of 2006, but this was expected, since the precipitation is higher, too.

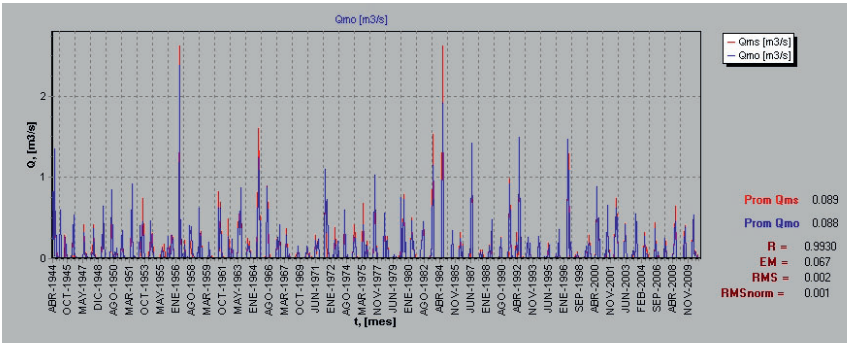


Figure 31: Comparison of the validated time series (Qmo) with the newly calibrated ones (Qms) of El Ingenio

The sub-catchment of the upper reach of Punitaqui has been changed similarly with new precipitation data. The mean runoff of the whole time period (Q_{aver} = 0.133 m^3/sec) is a bit less, than of the calibrated time period.

Looking at the average discharge data of both sub-catchments, the Punitaqui Creek (Qms) seems to have almost the same discharge (final simulation resulted in Q_{aver} = 0.089 m^3/sec). But analysing the results of the low flow years in more detail it can be observed, that El Ingenio (Qms) has in the most of the cases a higher discharge (confirmed by field observations). The contrary is being observed analysing the peaks, here the Punitaqui sub-catchment gets higher runoff. Thus Punitaqui is contributing during high precipitation events an amount which is more significant.

Natural flow of Panamericana en Limarí station

The parameters which are calculated through the correlation of Q_{1n} and Q_2 are determined for time periods when consumption was more or less homogeneous.

Analysing the data the following periods were decided on: 1946 - 1972 (La Paloma reservoir started with operation), 1973 - 1989 and 1990 - 2010. The resulting use curves are presented in Figure 32. The curves show clearly the difference of the consumptive use before and after the dam was constructed, the peak is shifted from June-August (rainy season), before La Paloma reservoir construction to October-February; that means: the cultivation focus has been shifted from the rainy season to the dry (and warmer) season.

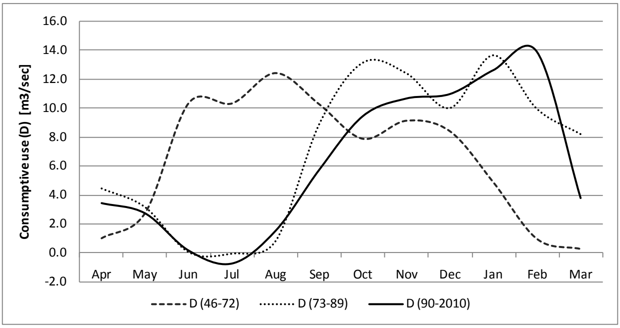


Figure 32: Consumptive use curves (D) downstream la Paloma of the different time periods

With the calculated parameters finally the average of the Q_{AI} estimators 1 - 3 is been used as $Q_{\text{AI adapted}}$ and presented in Figure 33.

The discharge curve of $\bar{Q}_{AI}$ ($Q_{\text{AI1-3average}}$) has higher peaks since here all years have been considered. For the dotted lines, the high flow "el Niño" years (65/66, 84/85, 87/88) has been disregarded.

In the peak month (July, winter season) the average support is Q = 6.3m^3/sec, considering the total monthly average the AI supports 2.5m^3/sec. Clearly the AI has it highest peak subject to precipitation and another much minor peak during November (caused by snowmelt).

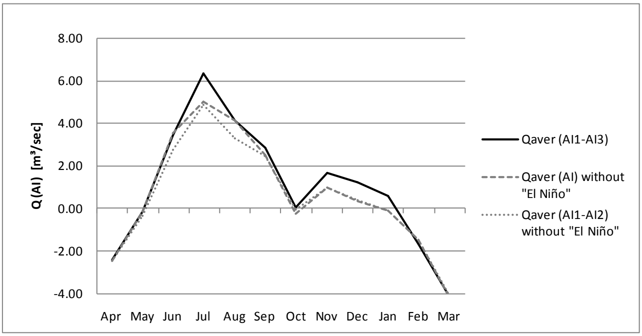


Figure 33: Different estimates (Q_{AI}) of average monthly discharge of the AI of the total lower catchment (La Paloma until Panamericana)

In the end and beginning of the hydrological year, the average AI get negative, which means, that no additional water is entering, water might even disappear. A reason could be for example surface-groundwater interaction. Actually this coincides with the perceptions of people who work in this water management sector, who state that in some month, stretches are quite dry. Furthermore a recent study (Oyarzun et al, 2015) which studied the interaction between surface and groundwater in the lower catchment revealed that there is a high connectivity between both of them; some reaches are gaining reaches, sum reaches are losing reaches. Both phenomena can explain decrease on one hand at the outlet, but also the gaining in some parts of the Limarí River course.

For verifying the results the same approach was used with monitored data in the lower catchment of a closed monitoring station (Peñones Bajo: 1942-1982) to calculate the additional discharge which is being supported by the lower part of the catchment between Puntilla de San Juan/Huatulame and Peñones bajo station (1946-1971). Here the **monitored data** of the station "Puntilla de San Juan" (GPSJ) and **operational data** from Cogoti, together with monitored data of Peñones bajo station, were used. The resulting support of the AI between the reservoir and the Peñones Bajo station is presented in Figure 34.

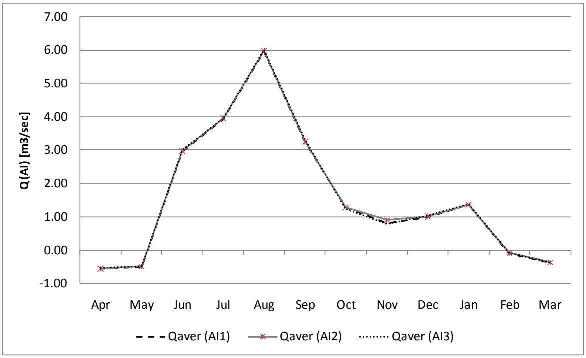


Figure 34: Different estimates (Q_{AI}) of average monthly discharge of the AI between monitoring station *Puntilla San Juan* and *Peñones bajo* using monitored data (1946-71)

It confirms that the lower part until Peñones, mainly support in winter (Jun-Aug) to the discharge. All three calculations have been done and the average is very similar to the previous result. To verify also for the second part of downstream catchment the supporting discharge, the AI between Peñones bajo and Panamericana station was calculated as before with data from 1958-1982.

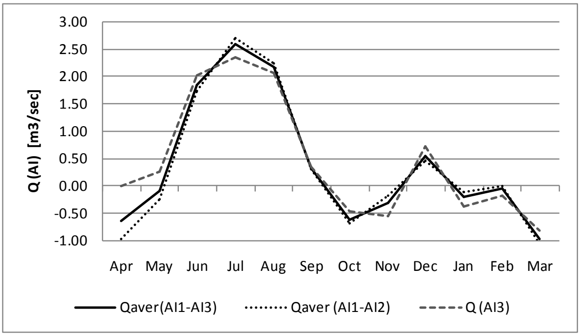


Figure 35: Different estimates (Q_{AI}) of average monthly discharge of the AI between Peñones and Panamericana (1958-1982) using monitored data

Similar results as before has been obtained, showing the same pattern and the peak between June and August, with less magnitude, reaching in average about 2.6 m³/sec. Between January and May almost all months get negative flows again. In general it can be concluded that the results of the final Q_{AI} (Figure 33) is quite reasonable, comparing it with calculation using measured data.

With the final AI adapted, the average annual natural flow of the Panamericana station, calculated with equation (37), resulted in: $Q_{a\ Panam\ NF} = 23.315\ m^3/sec$

The different results of the Panamericana station are presented in the following diagram and as expected the highest peak occurs in summer (snowmelt) and the second peak subject to the rainy season.

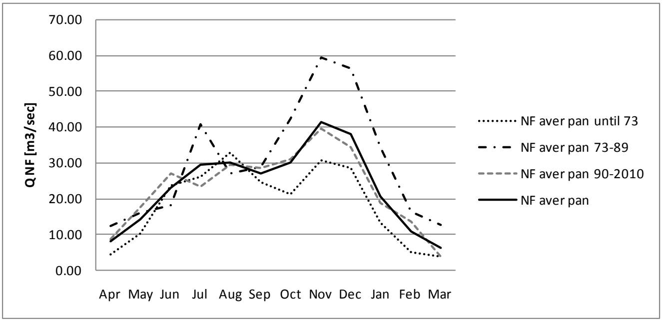


Figure 36: Mean annual hydrograph of natural flows of Panamericana station, different time periods are considered

The different hydrographs of mean natural flow show clearly in which periods the mayor extreme events occurred. Looking at the highest peaks they occurred in between 1973-1989, here especially in 1973, 1984 and 1987. The lowest average hydrograph occurred until 1973, this includes the worst prolonged drought in the studied total time frame. The total average annual hydrograph is very similar to the average of the years 1990-2010, which means that the last 20 years are a good representation of the total average.

Finally the mean and median annual hydrographs of the developed natural flows of selected stations are presented. First the monthly mean values (1943-2010) are presented in Figure 37. The hydrograpghs of the upstream stations (Grande upstream, Hurtado San Agustin and Fragüita) have only one peak produced by snowmelt in the summer month, the ones of the downstream stations show another peak in winter (starting slightly with Grande in Puntilla San Juan (GPSJ) station and more extrem at the outlet Panamericana station.

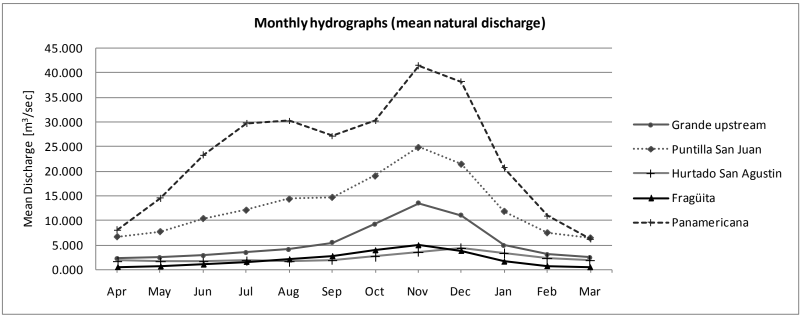


Figure 37: Mean annual hydrograph of natural flows of selected stations

As indicated before the peaks are highly influenced by the years were the "El Niño" phenomennon occured; therefore the median values of the same stations are figured in Figure 38. Since the scale keeps the same the difference appears to be significant, especially in the Panamericana station (here two different time periods were looked at: 1. the whole time period, 2. from 1990-2010).

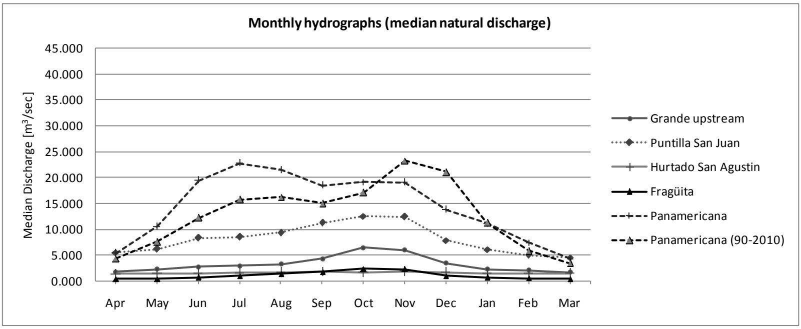


Figure 38: Median annual hydrograph of natural flows of selected stations, three upstream, one before the main reservoir and one at the outlet of the studied basin

The summer peak lowers in average during the whole time period by half, the winter peak also decreases, but less, so that finally the winter peak is higher than the summer peak by snowmelt. Because of this the last 20 years (from 1990-2010) has been tested, and the contrary can be observed; here the winter peak by precipitaiton lowers quite a lot, the summer peak, too, but less, and the peak produced by snowmelt is higher again.

This showns that in the last 20 years, the precipitation as snow was higher than the rainfall precipitation. And further that before 1990 the "El Niño" events were higher and provoked thus a much higher total mean than total median. The median values are more robust against the extrem events.

4.3.3 Distribution of natural streamflows from gauged to ungauged sites

The model WRAP HYD (part of the WRAP modelling package) had then be used with different methods to distribute the flows in order to receive finally the natural streamflows of 27 control points and with this the most proximate natural hydrological condition of the basin.

Following the work flow presented in the flow chart in Figure 7 the natural streamflows of all points of interest are modelled. The resulting watershed parameters (WP), i.e. watershed drainage area and average precipitation as well as the accumulated precipitation and drainage area, were calculated and can be consulted in Annex, Table-A 16.

The upstream and downstream watersheds (Figure 11, Figure 12) are modelled separately. First the upstream catchments of the basin, until the La Paloma reservoir are modelled, in a second step the downstream part. The methods are outlined in detail in chapter 2.4.3.

Furthermore judgment is required in selecting gauges and incremental watersheds for transferring flows to ungauged sites. With all this data and information decisions have been taken, which method and which primary CP is used for each transfer of flow. In the following the results are discussed.

Observations of difficulties, verification of results and final decisions about natural flow (NF) adoption

In the upper area some observations for the sub-catchments of the Pama and Combarbala River have to be pointed out: attempts with different methods of the HYD - Module of WRAP could not obtain reliable natural time series: too much water was distributed in the medium part of the catchment and less in the upper catchment. This will be considered during further modelling by simplifying this area in the model.

CP018 (Cogoti reservoir) and CP18a

The mean natural inflow modelled for CP018 (Cogoti reservoir) is higher than the sum of the natural streamflow calculation calculated before, 5.83 m^3/sec and 3.77 m^3/sec respectively. This coincides with the identification of the problem during simulation of the upper part of the Pama River, which leads to the conclusion, that the natural streamflow calculated could have been a bit underestimated in the upstream catchment of the Combarbala and Pama River. Furthermore the lateral additional flow of the Cogoti reservoir is uncertain, too.

For these reasons the modelling result of CP018 with WRAP-HYD was determined to reflect better the nature and is used for further modelling. For testing purposes both time series had been used in WRAP-SIM and the calculated natural time series resulted in much less supply and higher shortages and further drawdown's of the reservoir as expected according to real data. With the modelled flow, the results coincide highly with the reality.

The other result which had to be look at carefully was the distribution of the NF to CP18a (downstream of the Cogoti reservoir). Two different approaches are tested: first distribution of the flow from the gauged station upstream (CP-14), secondly with flow of the gauged station downstream (CP-18). As expected the results differ from each other. Furthermore with the modelling using the downstream CP-18, the natural streamflow of CP18a resulted minor to CP018, which physically cannot be correct. The calculation through CP-14 resulted in a streamflow much higher than CP018, which also is not very reasonable. Thus for further modelling for both CPs the NF of CP018 is used.

CP019: sum of the previously calculated natural streamflows used for further modelling

Modelling CP019 (Paloma reservoir) the resulting modelled NF is highly overestimated due to the fact that this point is the confluence of two sub-catchments with different hydrological conditions, which cannot be reflected sufficiently in the model since both gauged sites are upstream of the ungauged site. For further modelling the previous calculated naturalized streamflow is used.

CP-20: sum of two new modelled CP-3a and CP30a is further used

For modelling the downstream catchment, some special assumptions had to be taken. Here three primary CPs are used: CP019, CP-3 and CPEND. Furthermore the decision has been made to exclude the upper catchment of the Hurtado River until the reservoir for further modelling. Thus here (CP-3) not the natural flow, but the monitored time series were the input to the model.

CP-20 (the confluence of the Grande River and Hurtado River) is the only downstream CP, which is not calculated based on CPEND. Different trials have been modelled and the most reasonable results were obtained modelling this CP with distributing the flow from the known-flow CPs upstream. Therefore two new CPs were introduced: one just before CP-20 in the Grande River (CP 30a) and one in the Hurtado River (CP 3a). Thus: $Q_{NF\ CP20} = Q_{NF\ CP30a} + Q_{NF\ CP3a}$

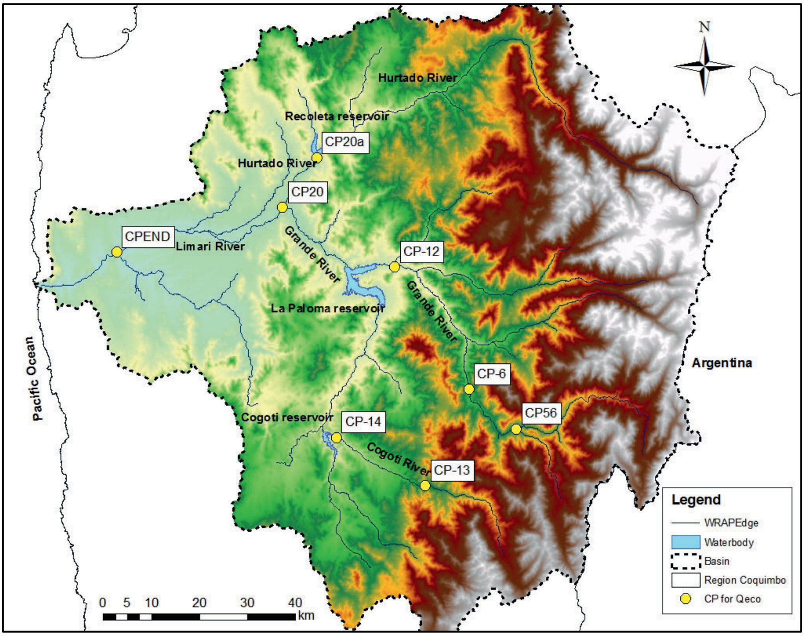
Final conclusion

Distributing flows from known-flow to unknown-flow CPs requires a good knowledge of the area, to be able to choose the correct stations to be used and the most appropriate method. Verifying the results with real data, or testing its plausibility also with previously calculated time series using a different method is of high importance and great help to finally decide upon the most representative flow to reflect nature.

4.4 Minimum ecological flow

4.4.1 Calculation of the minimum flows in the sub-catchments under consideration

Since no previous environmental studies in the Limarí catchment have looked at the minimum flow, the approach here is to analyse how the system complies with the minimum 'ecological flow' as defined in the Chilean water legislation. Thus the ecological minimum flows are calculated according to each of the previously presented regulation and legislation (2002, 2008, and 2012). The different minimum flows as described before are calculated taking into account eight control points in different rivers, as shown in Map 5, using the previously developed natural flows for further calculations.



Map 5: Location of the control points to analyse the ecological minimum flow

Three points were analysed in the upper Grande River (CP56, CP-6, CP-12), two in the Cogoti River (CP-13, CP-14), one at the inflow of the Recoleta reservoir (CP20a) and two downstream of the La Paloma reservoir (confluence of Grande River and Hurtado River, CP20 and CPEND). The evaluation is done comparing the calculated minimum flows with the regulated flows of the simulation results of the different selected scenarios (chapter 6.4).

The first diagram in Figure 39 shows the results of possible case-specific resolutions of 1982, and further of the manual 2002 (the minimum flow as one permanent and continuous value during the whole year); the next diagram shows the results using the manual of 2008 and the last regulation of 2012. Option a. of 2008 gets just a slightly higher minimum flow (min of 10% $Qaver_a$); the rest is exactly the same. The results are from the headwater area of the Grande River (Las Ramadas together with Tascadero).

The results of the 2012 regulation show the greatest difference between summer and winter months, as well as higher values in spring and summer (period of snowmelt), since they include all hydrological events with the same weight (other when looking at the 95% exceedance probability of the flows). Thus, the legislation of 2012 gives more attention to the high flow events, and less to the average or water poorer years.

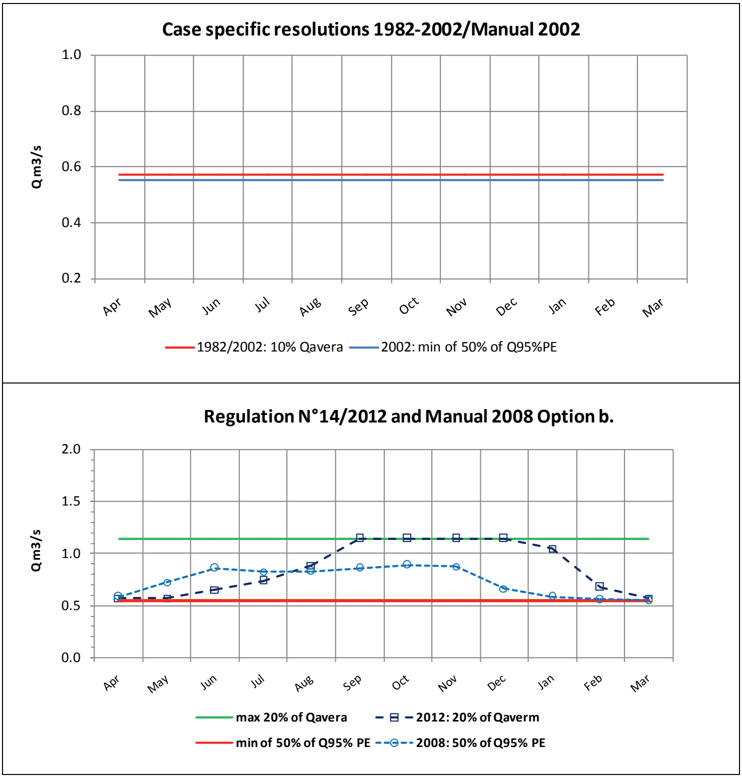


Figure 39: Different ecological minimum flows for CP56, Grande River, according to DGA standards

The following figures show the results of three more stations (Grande: CP-12, Cogoti: CP-14, Limarí: CP-20), per station one diagram with results of the 2008 and 2012 regulations. This includes just option b. In case no ecological flow is established (as almost in the whole basin), option b. is the option to be used according to the law and results in a lower minimum limit.

The higher the natural flow, the higher also the requirement for the minimum ecological flow, thus CP-20 as the confluence of Hurtado River and Limarí River results in the highest requirements.

The regulation of 2008, rarely reaches the maximum value of 20% of average annual discharge. Concluding out of the statement that the regulations of 2012 are taking into account stronger the high flow events, for this semi-arid catchment the regulations of 2008 are more suitable.

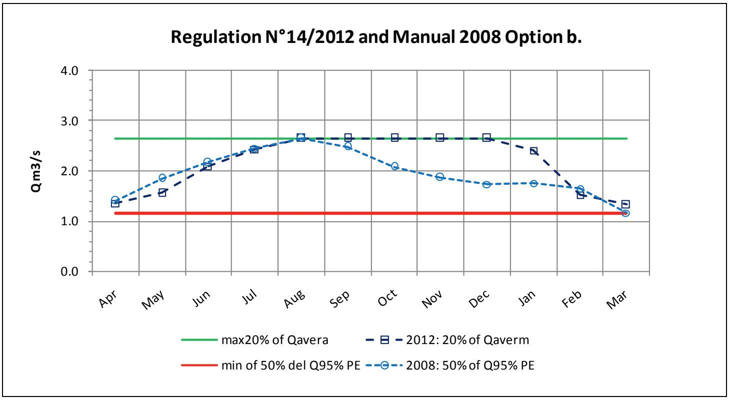


Figure 40: Different ecological minimum flows for CP-12, Grande River, according to DGA standards

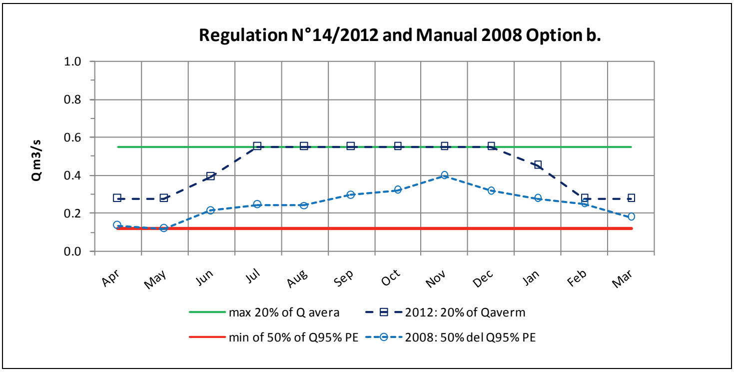


Figure 41: Different ecological minimum flows for CP-14, Cogoti River, according to DGA standards

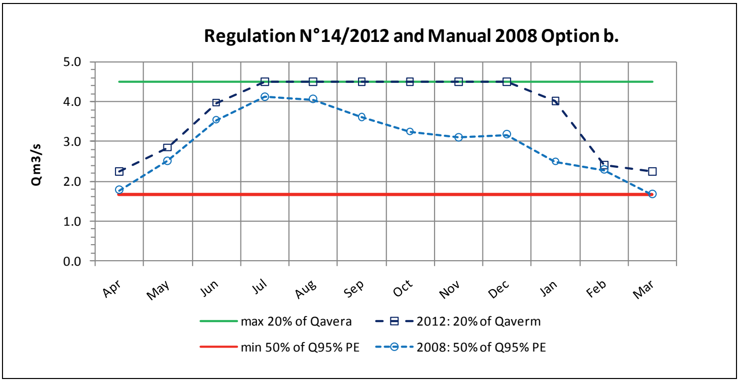


Figure 42: Different ecological minimum flows for CP20, Grande - Hurtado River, according to DGA standards

5 Base scenario and evaluation of the developed model

First some general definitions for the development of the base model scenario are presented. Furthermore assumptions which had to be taken regarding some sub-catchments, hydrological as well management issues are further explained (section 5.1).

To evaluate the model, the recommended statistics by Moriasi, D.N. et al (2006) were used (details: 2.5.3.1 Statistics used for model evaluation). In section 5.2 the results are presented in detail (Table 21, Figure 43 until Figure 45), they range from very good (upstream) to satisfactory (downstream).

All CPs representing monitoring stations are used to test the performance of the simulation model, presented from upstream to downstream. Furthermore the simulated time series of the end-of-month storages of all three reservoirs versus the monitored values are compared.

5.1 Assumptions for definition of the base scenario

The base scenario (S1) was developed to verify the WRAP model set up on the basis of obtaining good agreement between modelled and measured discharge under current conditions. If this is achieved it is assumed that the watershed response to imposed altered scenarios will give reliable outputs.

The period of the simulation was the two decades from 1990 to 2010. This period was selected as prior to 1990, the Association of the Cogoti reservoir (Canalistas de Cogoti), used very different allocation amounts but from the 1990s until 2008, an average value (with some exceptions) could be established, against which modelled values can be compared. In the most recent years of the calibrating time span, the reservoir curves differ more, since allocation was less (Figure 46).

Analysis of all the different hydrological and legal data, and information on supply, demand and management, as well meetings with the main administrators and presidents of the associations, led to some very important preliminary findings, which all guided the definition of the base model, here also referred to as base scenario. Input data as for example relationships between storage volume and surface area of the different reservoirs have been developed from the received information (Annex, Figure-A 4-Figure-A 6). Furthermore reservoir evaporation-precipitation rates were computed with data from the Organisations and the DGA for model input.

The base model was developed step by step to be certain that at the end the entire model represents the main catchment activities. The following decisions have been taken for the different sub-catchments:

- *Hurtado River*

The Hurtado River catchment is isolated from the rest of the La Paloma catchment, which means that influences of possible changes here will primarily affect the Recoleta reservoir and through this, the whole system, and the influence is not expected to be as strong as changes in the Cogoti sub-catchment. According to the main objectives of this study, the upper part of the Hurtado sub-catchment was excluded and the input data of the entrance of the reservoir used for this model.

- *Grande River and its confluences*

Although WR calculations for all CPs of the Mostazal and Rapel River (both independent of the La Paloma system) had been done beforehand, for the final model set up it was decided to put the whole use of WR at their sub-catchment outlet. This decision was made to reduce complexity and uncertainty, which might have resulted from simulating the detailed sub-catchments, while the focus of the study was the La Paloma system.

Given (i) the importance and complexity of the Grande River upstream of the La Paloma reservoir and (ii) the detailed data base of water distribution of the Grande and Limarí River organization, it was decided to use real supply data in the Grande River for the base scenario. The sub-catchment was studied with its canal locations (GIS-data), and the data from the river association to calculate the yearly distribution which sum up the defined CPs. The previously described monthly use coefficient was used to allocate the water according to the average demand pattern in the area.

- *Combarbala and Pama River*

While generating the natural flows it became clear that for the Combarbala and Pama River (i) there is a paucity of monitored data (stations), (ii) main water generation occurred in the upper catchment and (iii) it was not possible to reach a reliable distribution of natural flows from the gauged to the ungauged CPs. Thus, the approach was to build up the model step by step, first the Cogoti reservoir with the downstream part with monitored and corrected inflow time series of CP-17 and CP-14, as described in sub-chapter 4.3.1, as to make sure that this reflects the system without problems. This resulted in a good fit of the Cogoti and La Paloma reservoir curve. Then the Cogoti River sub-catchment was modelled with natural data and the WR as described chapter 4.1.2. Since the Combarbala catchment possesses more water resources than the Pama catchment, it was decided to use the time series of the upper catchment monitoring station, which was already corrected, gap filled and extended to the whole time spam for the final model (1947-2010). Thus detailed analyses of the canals and associated water rights were done to calculate correctly the WR which had to be served down from there (Table 6).

The results shown on Table 21 and later discussed lead to the conclusion that these assumptions represent quite well the reality and will be used further on as simplification, also to simulate the possible impact of new reservoirs and thus maximum water use in these sub-catchments on the Cogoti reservoir and its downstream users.

- *Cogoti reservoir*

Analysing all the yearly average of these 20 years a total of 55 MCM/year has been diverted from Cogoti reservoir (details in Table 8).

- *La Paloma reservoir*

The real average water diversion from La Paloma over the last 20 years was quite different to the legally assumed one. The targets due to legal amounts will be simulated later from scenario 20 (main differences refer to Table 26, details in Annex, Table-A 7). Nevertheless the sum kept almost the same.

- *Limarí River*

The first approach was to just use the WR target for the lower catchment served by the reservoir. But already during the calculation of the natural flow in the lower part, and further analysing the supply data of the river association, led to the conclusion that the outcome will not be reliable. The difference of what was allocated through the dam to the river and finally entered the canals is very high, up to more than 100% more water reached the canals in some month of some years (downstream a mixed supply is used). Thus for calibration of the lower part, first the return flows from the upper parts, use of potable water in the lower part and its return flow, return flow of the Cogoti part to the Limarí, and from Recoleta has been considered. Secondly for the final aggregation of channels to the defined CPs of interest and their target assumption, not only the WR but also the supply data from the association JVRGyL were considered. The target and management options were adjusted to the water volumes which entered in average during the last 20 years the channels.

5.2 Results of model evaluation

The previous selected statistics are applied to evaluate the model during the calibration time span with the use of average real supply data where available. The objective is to assure that the model setup, including natural flows in the gauged and ungauged CPs, calculated real data supply as well as legal WR targets, and the defined management configurations, reflect the current basin management. This was tested by comparing the monitored discharge time series with the resulting regulated flows or inflows of the CPs. The model simulation can be judged as "satisfactory" if NSE > 0.5, RSR ≤ 0.70 and PBIAS ± 25%.

NSE values for monthly streamflow and reservoir volumes range from 0.817 to 1.00. According to the evaluation guidelines the model simulates the trends of the tested time series very well. The same holds for the RSR values, which range from 0.118 to 0.428 (Panamericana before deleting the extreme events with high differences). When considering the simulation of La Paloma with a V_{max} of 750 MCM (which is the maximum capacity) it gets the better results and is more reasonable for long term simulation, it would be 0.399. These values indicate that the model performance for streamflow/reservoir storage residual variation is for the most part very good.

Table 21: Indicators NSE, PBias and RSR of the calibration period

Control point (S 1)	*NSE [-]*	*PBIAS [%]*	*RSR [-]*
CP-4 Inflow (MCM/month)	0.943	-1.61	0.239
CP-6 Inflow (MCM/month)	0.986	-5.79	0.118
CP-12 Inflow (MCM/month)	0.953	3.86	0.216
CP-14 Inflow (MCM/month)	0.966	18.32	0.184
CP-17 Inflow (MCM/month)	0.922	13.40	0.279
CP018 Reservoir Vol (MCM)	0.896	-4.98	0.322
CP019 Inflow (MCM/month)	0.930	2.53	0.265
CP019 Reservoir Vol (MCM) V_{max} = 750 MCM	0.840	-2.12	0.399
CP019 Reservoir Vol (MCM) V_{max} = 700 MCM	0.822	5.74	0.421
CP20a Recoleta Vol (MCM)	0.933	-4.45	0.259
CPEND Inflow Panamericana station (with V_{max} = 700 MCM)	0.817	32.86	0.428
CPEND Inflow: without highest differences during extreme events (9 month of 240 deleted: 3.75%)	**0.913**	**24.45**	**0.294**

Most of the statistical results of NSE and RSR of the different tested CPs show agreement with the graphical results, only CP-14, CP-17 show higher variability instream flows (hydrograph of CP-14, Figure 43). This can be confirmed with the average magnitude (PBIAS), which are 18.3 and 13.4 respectively and thus representing satisfactory and good results. Only the hydrograph of the Panamericana station (CPEND) results in an unsatisfactory PBIAS. The first test resulted in 32.86. This station is influenced by the whole management of the catchment and sums finally all their differences between simulated and real management. Furthermore the developed natural flow of the Panamericana station has its uncertainties (e.g. since 1973, when the entire system came into operation), depending on the reports of three associations, which were not always complete, especially the month with spill, which was often estimated. Thus nine month with the highest differences between simulated and observed values were deleted, the new result shows a PBIAS of 24.45, which is almost the upper range value of being still satisfactory (Hydrograph, Figure 45). Thus, it can be observed that here the model generates conflicting performance ratings for component watersheds.

In the described CPs of monitoring stations (CP-14, CP-17, CPEND) the PBIAS is positive, signifying a model underestimation of flow, but overall the model is still rated satisfactory to good. The comparison of the hydrographs of simulated versus monitored streamflow confirms the statistical results in CP-14 and CP-17 and reveal the possible inaccuracies of the natural flows (as discussed before), as well as the actual water use (since no real data are available in these upper catchments).

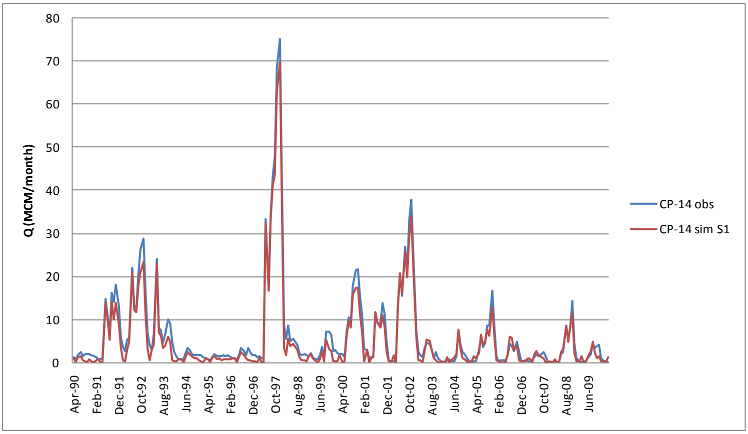


Figure 43: Hydrograph of Q_{aver} obs vs. Q_{aver} sim of CP-14 (Cogoti River)

Evaluating the upper Grande River sub-catchment, the streamflow of the first two control points (CP-4, CP-6), is slightly overestimated (the hydrographs show almost no difference). At the outlet of the upper catchment in CP-12 nevertheless the streamflow is slightly underestimated, especially the peaks (PBIAS is positive, hydrographs in Figure 44).

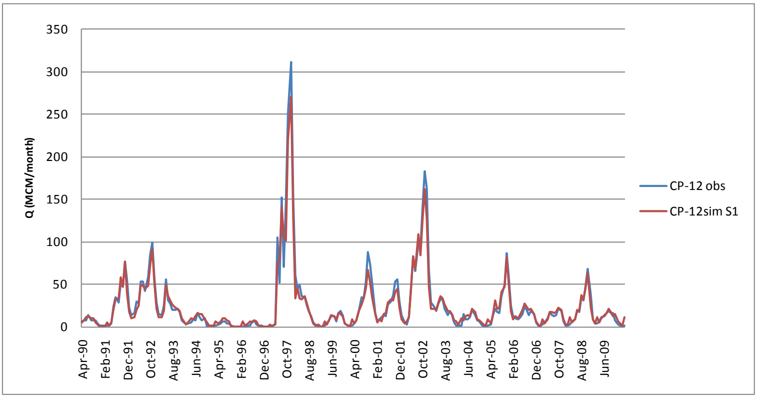


Figure 44: Hydrograph of Q_{aver} obs vs. Q_{aver} sim of CP-12 (Grande River)

This might be also due to the fact of the assumption that the sub-catchment of the Rapel and Mostazal River use always the maximum of their water rights, if water is available. The results at the outlet had been calibrated with the return flow, but especially the higher peaks could not been reached. But it does not have an important impact, which is proved also by the very low PBIAS in CP-12.

As mentioned before the Panamericana station results in a still satisfactory performance when deleting the high differences, which are produced be the extreme el Niño events, representing 3.75% of the data, and simulating with a maximum capacity of 700 MCM of the La Paloma reservoir (Figure 45). Simulating in this time period with a lower maximum capacity, reflect the management mistakes during the high flow event, where the reservoir was emptied much more than necessary and thus important storage was lost and flow higher in CPEND.

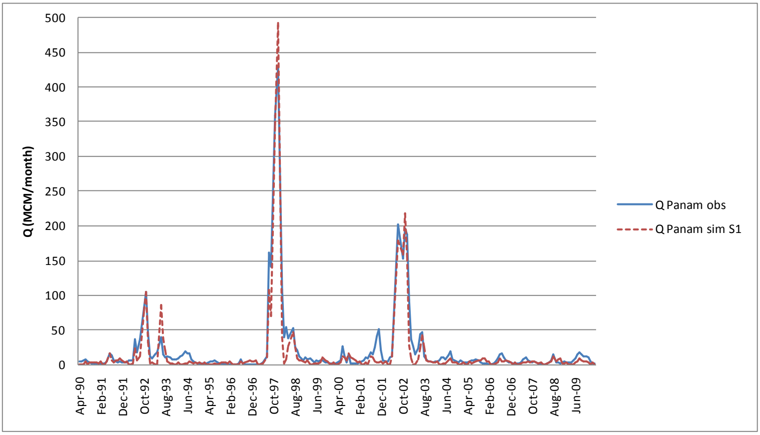


Figure 45: Hydrograph of Q_{aver} obs vs. Q_{aver} sim of CPEND

The reservoirs are all in the very good range, according to the PBIAS, resulting in negative value, which show a slightly model overestimation. This shows that more water is diverted in reality during some month/years than simulated. Although the averages of the last 20 years real data were used, the yearly management differs sometimes. Nevertheless the model shows that it represents very well the reservoirs in the system, thus the setup can be judged as being approved for further scenarios and the whole time span of data.

The graphical interpretation could lead to slightly different conclusions; an example is the Cogoti reservoir curve (Figure 46), since here the differences are the highest compared to the expected in view of the reasonable results from the statistical tests.

Two hydrological years are responsible for the higher differences in the Cogoti storage curves. The first in 1993/94; here due to the observed data of the organisation, 130 MCM has been diverted, including some spill, but nevertheless it is much more than the average diversion for supply. This difference is inherited by the following years, until the reservoir is filled again. The other year 2002/2003 shows a clear management failure: the observed curve is almost 40 MCM lower. That year a spill occurred, because of high precipitation, but just between August and September 30 MCM were additionally released, thus the reservoir level dropped instantaneously and remained lower than the simulated reservoir. The differences in the last years result from the decrease of release to average 37 MCM, the model kept the target of 55 MCM.

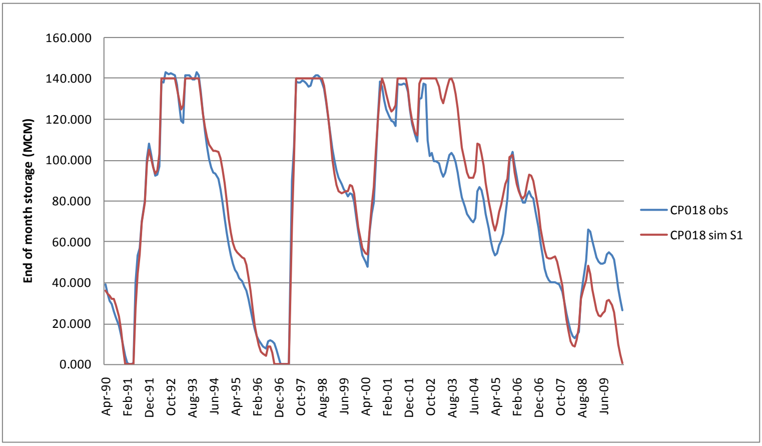


Figure 46: End of month storage (MCM) of the Cogoti reservoir, obs vs. sim S1

The La Paloma reservoir curves could be analysed very similarly, especially the highest differences due to a management failure in 1992/93, where more water was expected than refilled and thus to much water released for security reasons. The best fit results of the Recoleta reservoir curve since the last huge refilling in 1997 after the prolonged drought. It seems that management since then has been stricter.

Some final statements to the simulation of the Limarí River

Different approaches to target changes, setting limits and return flows were necessary to reach a good representation of the lower part of the catchment. A plausibility test was done calculating the amount of water which is served by the reservoir La Paloma to the downstream part of the Limarí River and comparing it with real data. Out of the model results the user can extract how much water was finally served by the reservoir and how much by the river. This resulted in about an average of 30 MCM/year and a maximum of 40 MCM/year served by the reservoir. Assuming that this associations can receive maximum 63 MCM/year by the reservoir for downstream use (Table 2), only 48 - 63% has been allocated for the downstream users, the rest is supplied by the river. This coincides with the numbers given by the associations, they mentioned in average 31-34MCM/year is supplied by the reservoir.

6 Simulation of various scenarios including new reservoirs in the upstream sub-catchments of the Cogoti reservoir, different targets and management strategies

This chapter describes and analyses all scenarios which are modelled in the basin to find answers to the given question, how the system reacts subject to changes in the structural and operational set up, as well to different allocations. Starting with preliminary simulations over the period used for calibration (1990-2010) to analyse and evaluate further development in upper sub-catchments of the Cogoti reservoir and terminating with extended simulations over the whole time span of 63 years, with different focus to examine all catchments which are part of the La Paloma system.

The chapter contains four sub-chapters, each having a slightly different base scenario, which has been developed each time out of the final scenario of the previous section (compare flow charts of all sub-chapter scenarios). Furthermore different periods of time (specially the first sub-chapter) and several model specifications with varying focus for evaluation are simulated. After each section the main conclusions are summarized.

The different scenarios have been developed step by step as follows:

- Chapter 6.1:
    - 12 preliminary scenarios (S1, S1limit, S TR1 - S TR5 and their variations), which inherit from each other and cover the period from 1990-2010, based on the previous elaborated base scenario with real data supply (where available) as target condition. The main objective is to decide on a reservoir site for the La Tranca reservoir (Cogoti River) and assess preliminarily the possible magnitude of a negative impact provoked by further development of all sub-catchments upstream of the Cogoti reservoir (including the independent catchments).

- Chapter 6.2:
    - 9 extended scenarios (S1ext, S1 - S4 and their variations), with the total time span of 63 years (1947-2010) with different operational setups for the new reservoir La Tranca to investigate which conditions lead to the highest firm yield. Here the main findings of chapter 6.1 were incorporated. Furthermore it was looked at the performance indicators (here only 5 scenarios were included for further comparison) of the sub-catchments of Cogoti, upstream as well as downstream. The main objective was to derive the annual assignation for the WR of the upstream users, which constitute a.) Sufficient water per WR and b.) Less impact on downstream users of the Cogoti reservoir. Furthermore the benefits of changing the extraction points from upstream to the new reservoir are being evaluated.
    - 4 extended scenarios (S10 - S13) with the base scenario adopted from the previous best scenario (out of the last five evaluated simulations). These scenarios implement a common management of the areas upstream and downstream of the Cogoti reservoir and the consequences for both catchments, as well incorporating the total use of water in the independent upstream catchments (Pama and Combarbala River). Different setups of development were tested and performance also compared to the independent operations and current situation, simulated before.

- Chapter 6.3:
    - 7 further extended scenarios were developed and simulated, with different targets and different model records to define first the target setup which might be able to resist best the possible structural changes of the system (S20, S21). Secondly with this "best target" scenario evaluate

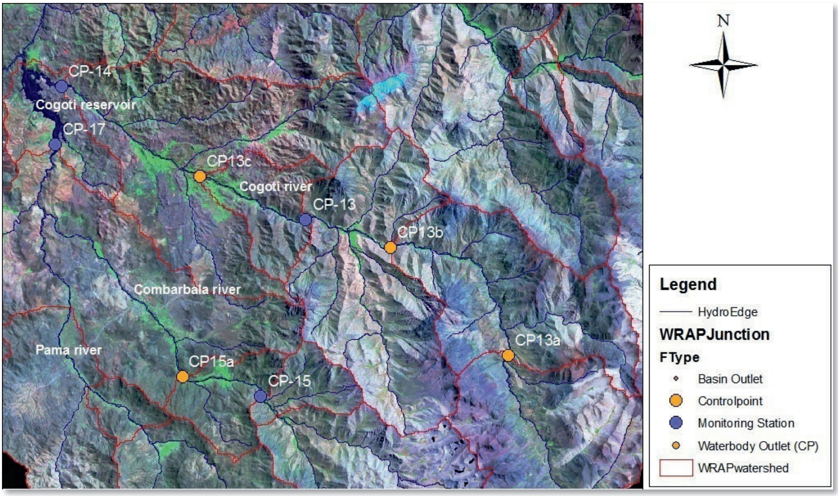
  more recent, conditioned WRs in the downstream catchment (S21a, S21b, S21c), until the last CP under consideration. Based on the last simulated scenario, the consequences of the development upstream of Cogoti are finally evaluated for the whole basin (S22, S23).
  - 2 scenarios (S Trans1, S Trans2) are separated setup to evaluate the current tendency of the downstream Limarí River users wishing to change their extraction point from the downstream part of the river into the reservoir. Base scenario is the same as in the previous simulations. Here the performance of the WRs, which have been changed, as well as the possible impact for the other downstream users is analysed.

- Chapter 6.4: No further scenarios with new targets or WR changes have been set up. The objectives are the following:
  - Further evaluations of five already simulated scenarios (S21c, S23, S1a, S11, and S12) with regard to their consequences on the different legal minimum flows previously calculated (chapter 3.7). Here S21c, thus the "best target" scenario is used to evaluate an instream flow target; S23 and herewith all developments upstream of Cogoti reservoir based on the "best target" scenario and the current scenario S1a are used to evaluate the impact on the minimum flow aggregated per sub-catchment and for the total basin. Furthermore S23, S1a, S11, S12 are used to evaluate the minimum flow for each selected CP, thus considering also the structural variations, simulating with the average real water supply of the last 20 years as target.
  - Advanced simulation of the scenarios S21c, S22 and S23, which are assumed to be better alternatives compared to the current target, are set up having in mind further upstream developments: three different system operational rules/strategies were implemented and again simulated (thus nine different simulations have been analysed in total). The objective is to evaluate three system drought indices (DI) (no rule=System DI 0, current rule=System DI 1, possible new rule=System DI 2) with regard to the current and the future system set up in terms of supply reliability.

Each sub-chapter starts with a flowchart showing the dependencies of the scenarios and their development. A lot of results have been elaborated, but only the main outcomes of each sub-chapter are presented here.

6.1 Evaluation of a new reservoir site and target in the Cogoti River sub-catchment

To evaluate the consequences of a further development in the upper catchments, first the reservoir site in the Cogoti River with a possible target has been assessed. Since this is the only tributary inside the La Paloma system upstream of the Cogoti reservoir, just this possible new reservoir is simulated in more detail, other than the new reservoirs of the Combarbala and Pama River sub-catchments (Map 6). These sub-catchments are independent of the system (Map 1) thus allowed to use all their resources, in compliance with the quantity of water rights they possess. Because of that, in case their development was part of the scenarios, a constant maximum use of all their WRs was assumed and herewith the worst scenario for the downstream users.



Map 6: Sub-catchment of the Cogoti, Combarbala and Pama River with the CPs of WRAP

The upstream CPs in the Cogoti River receive as assignation the maximum calculated annual target, according to their WR, since this represents the worst scenario for the downstream users. In general the maximum target is limited by a monthly maximum target subject to the WRs, as it is carried out by the association of the Grande and Limarí River. The targets of both approaches are shown in Table 5. In the different scenarios the extraction points of the WRs of the upstream Cogoti River are changed as indicated in more detail in Table 22.

Besides another base scenario S1limit has been developed with the recalculated annual targets, incorporating a monthly supply limit. This is used for the extended base scenarios for further simulations, since it represents the legal basis.

The flow chart shows how the scenarios inherit from each other and what has been changed in the new scenarios (Figure 47).

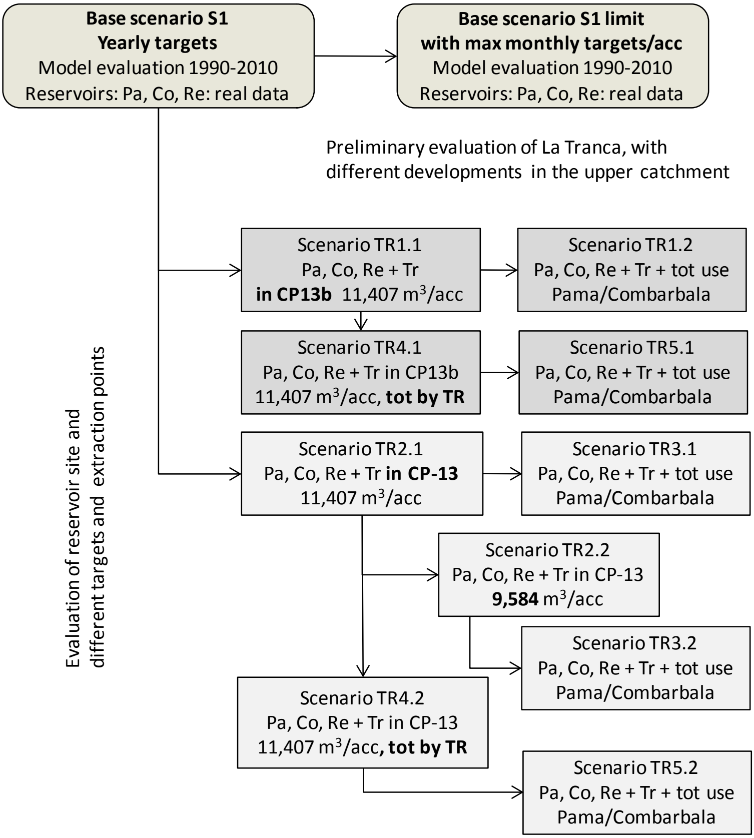


Figure 47: Flowchart of preliminary scenarios to evaluate a new reservoir site in the Cogoti River and its annual target, including development of all upstream catchments of the Cogoti reservoir

The following abbreviations are used:

- Reservoirs: Pa = Paloma, Co = Cogoti, Re = Recoleta, Tr = Tranca; Prio = Priority
- Pama/Combarbala = full water use in their sub-catchments
- Assignation per water right (WR): m^3/acc with acc = acción which correspond to a WR
- Extraction point: tot by TR: the sum of all water rights from upstream of the reservoir is also supplied by the reservoir (change of extraction point to the reservoir)

Simulation of various scenarios: new reservoir site

Table 22: Scenario description for preliminary scenarios for the new reservoir La Tranca (Cogoti River)

Scenario	Description
S1	Base scenario (1990-2010), supply limit is yearly target, with monthly use factors, without a monthly limit, system as it is to date
S1limit	Second base scenario (1990-2010) used as base for the extended final scenario, supply limit is the yearly recalculated target, considering the WRs also as monthly limit and with this a recalculated yearly target; system as it is to date
S Tr1.1	La Tranca at CP13b, Combarbala y Pama normal, higher share given per acc of 11,407 m3/acc/year for Cogoti; upstream extraction point (CP13a) kept as current
S Tr1.2	La Tranca at CP13b, Combarbala y Pama assumed to use all their water due to their water rights, higher share given per acc of 11,407 m3/acc/year for Cogoti, Rio Combarbala/Pama assumed 1l/sec/acc; upstream extraction point (CP13a) kept as current
S Tr2.1	La Tranca at CP-13, Combarbala y Pama normal, higher share given per acc of 11,407 m3/acc/year for Cogoti; upstream extraction points (CP13a, CP13b) kept as current
S Tr2.2	La Tranca at CP-13, Combarbala y Pama normal, lower share given per acc of 9,584.3 m3/acc/year for Cogoti; upstream extraction points (CP13a, CP13b) kept as current
S Tr3.1	La Tranca at CP-13, Combarbala y Pama assumed to use all their water due to their water rights, higher share given per acc of 11,407 m3/acc/year for Cogoti, Rio Combarbala/Pama assumed max. 1l/sec/acc
S Tr3.2	La Tranca at CP-13, Combarbala y Pama assumed to use all their water due to their water rights, lower share given per acc of 9,584.3 m3/acc/year for Cogoti, Rio Combarbala/Pama assumed max. 1l/sec/acc
S Tr4.1	La Tranca at CP13b, Combarbala y Pama normal, higher share given per acc of 11,407 m3/acc/year for Cogoti, but the extraction point of all upstream WRs is in La Tranca at CP13b
S Tr4.2	La Tranca at CP-13, Combarbala y Pama normal, higher share given per acc of 11,407 m3/acc/year for Cogoti, but the extraction point of all upstream WRs is in La Tranca at CP-13
S Tr5.1	La Tranca at CP13b, but the extraction point of all upstream WRs is in La Tranca at CP13b, Combarbala y Pama assumed to use all their water due to their water rights, higher share given per acc of 11,407 m3/acc/year for Cogoti, Rio Combarbala/Pama assumed max. 1l/sec/acc
S Tr5.2	La Tranca at CP-13, but the extraction point of all upstream WRs is in La Tranca at CP-13, Combarbala y Pama assumed to use all their water due to their water rights, higher share given per acc of 11,407 m3/acc/year for Cogoti, Rio Combarbala/Pama assumed max. 1l/sec/acc

A preliminary feasibility study is available (MN Ingenieros Ltda., 2008b) which suggests two different areas for new reservoir construction in the Cogoti River. Different volumes are being discussed, too, but further meetings with the association lead to the final decision to use for the simulation a capacity of 50 MCM. Furthermore the provisional name of the reservoir from the feasibility study is adapted here, too: *La Tranca*.

The following characteristics for the new reservoir were used for modelling: as a maximum capacity V = 50 MCM was assumed; the storage volume (SV) versus surface area (SA) had been adopted from the Cogoti reservoir (Annex Figure-A 5), since the valley of the Cogoti River has a similar formation as the area where the Cogoti reservoir is located, thus it can be assumed that the new reservoir might have similar parameters.

For the first simulation an amount of 20,500,000 m^3/year was allocated, which considers the sum of 2,138.91 WR in an assignation of 9,584.3 m^3/acc/year. The second simulation has been done assuming an amount of 24,400,000 m^3 and thus 11,407 m^3/acc/year. In general the farmers are expecting a volume of about 10,000 m^3/acc water, which can be translated in 10,000 m^3/ha/season.

Results

The differences in drawdown of the reservoir La Tranca River are presented in Figure 48. They are depending first on the assumed reservoir site, and different targets (supply) and secondly on the further development in the other upstream catchments of Pama and Combarbala.

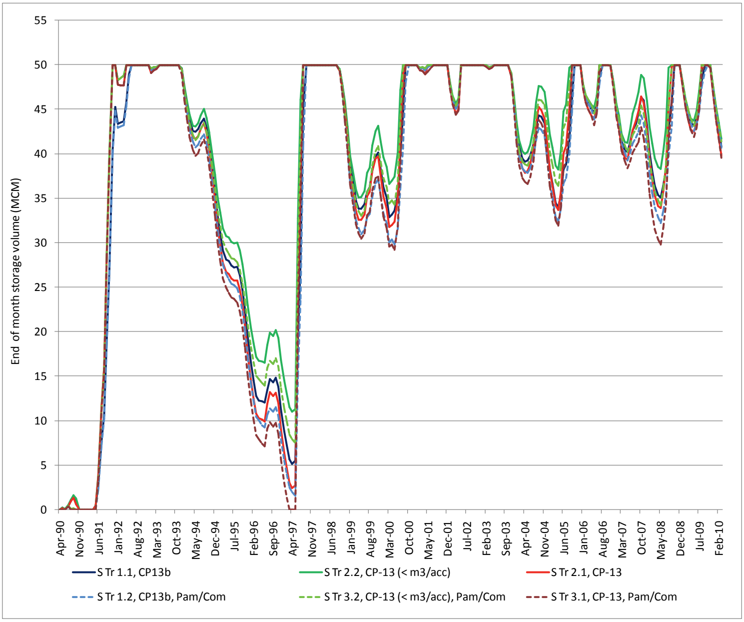


Figure 48: Reservoir storage curve of the end-of-month storages (in MCM) of the new reservoir "La Tranca" simulating two different sites with different targets and further upstream development

Just once in the simulated period during a prolonged drought period in the 90thies the reservoir felt dry in the worst scenario with La Tranca in CP-13, Pama and Combarbala catchments using all their water and a higher amount for assignation per WR (STr 3.1). In general the new reservoir resulted in all scenarios with further upstream maximum use of water in Pama and Combarbala River sub-catchments in a further drawdown in storage (dotted lines). This happens since the same priorities are given for upstream and downstream users. In case less water is available for downstream users out of the Cogoti reservoir, more water is passed to downstream users.

The scenarios with the reservoir site in CP-13b perform slightly better. The differences of the two reservoir sites are mainly provoked by the water use upstream. These WRs get still an instantaneous water supply by the streamflow, according to their amount of rights and the monthly use factors, thus less water reaches the reservoir if more WR are served upstream. Since CP-13 is downstream of CP13b, more upstream WRs are supplied before the water reaches the reservoir.

Since a legal and also physical possibility exists that upstream WRs are also served by the new reservoir, this water transfer has been simulated, too and the results show that here the reservoir site of CP-13 performs slightly better; scenarios with the Pama and Combarbala total water use are presented in red (Figure 49).

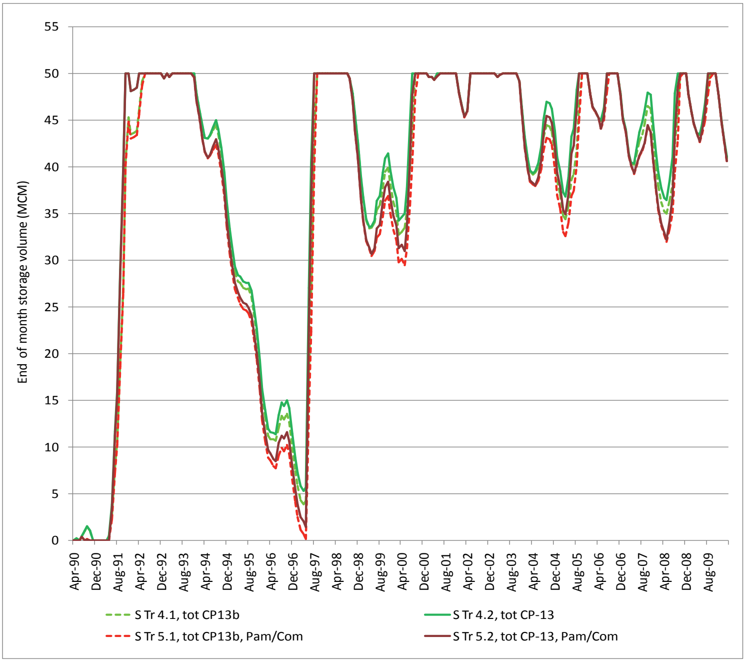


Figure 49: Reservoir storage curve (in MCM) of the new reservoir "La Tranca" simulating different scenarios

The impacts on the storage content of the Cogoti reservoir of the last scenarios where all WR are assumed to be supplied by the reservoir are presented in Figure 50 . The most implications on the performance of the Cogoti reservoir are resulting out of the simulation with the maximum water use in the Combarbala/Pama sub-catchment (S Tr5.1, S Tr5.2: red lines). In water stressed years the storage might drop about 40 MCM compared to the scenario where just La Tranca is considered.

Comparing their different impacts on the end-of-month storages of the Cogoti reservoir (Figure 50) ,the end-of-month storages of the reservoir simulating the scenarios, which only consider la Tranca as new reservoir (S Tr4.1, 4.2: testing two reservoir location), are almost the same.

In most of the drawdowns the results of S1 are below the ones of S Tr4.1 and 4.2. Thus the results of the scenarios incorporating La Tranca are better. Comparing these results with the scenarios where upstream WRs are served still by streamflow, the performance of the Cogoti reservoir is clearly better, when all the WRs upstream are served by the reservoir.

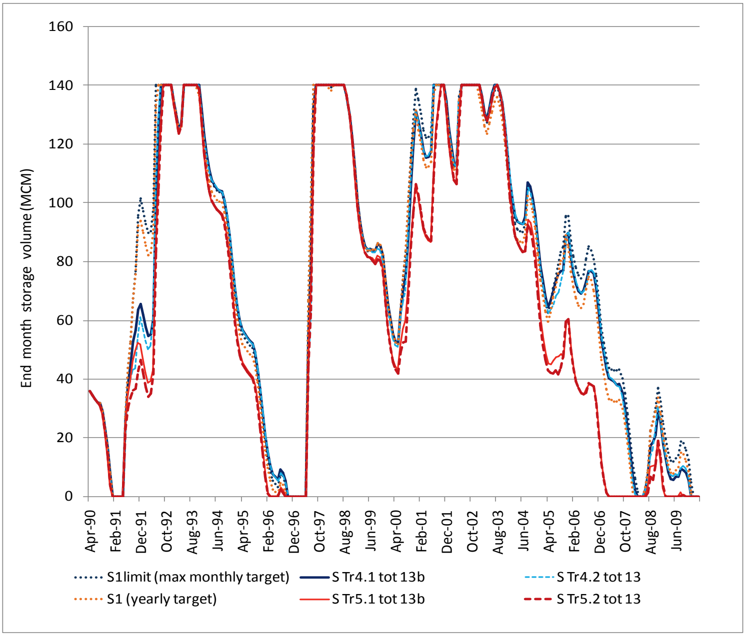


Figure 50: Resulting reservoir storage curves (in MCM) of the Cogoti reservoir with scenarios of total supply by the reservoir in the Cogoti River sub-catchment and total use of water in Pama and Combarbala sub-catchments

Assuming S1limit as the current scenario, the reservoir curves with the new scenarios are lower, thus the scenario without la Tranca is slightly better.

It can be concluded that the construction of La Tranca will have a small negative or slightly positive impact, depending on how strictly the upper sub-catchment users are going to manage their water supply. Furthermore the implications of the total use of Pama and Combarbala resources in their catchments will be a bit less, when serving all WRs from the reservoir, thus transferring the WR from upstream to the reservoir (S Tr5.1, S Tr5.2 instead of S Tr1.2, S Tr3.1), but still very high.

Additionally to the end of month storage curves of the reservoir, the mean end-of-month storage volumes of La Tranca, Cogoti and La Paloma have been elaborated (Table 23). Here all simulation years are considered. The different scenarios are compared to see, if and in case yes, how much the upstream development would have an impact on the mean storage volumes. It can only be interpreted as a qualitative confirmation of the previous discussed figures.

Between the current base scenario S1 (without monthly limits) and the scenarios S4, the Cogoti reservoir mean storage volume keeps almost the same, with about 75 MCM. Comparing the scenario S1limit, the reservoir storage would drop around 6 MCM in average.

Between the scenario S4.2 (only La Tranca) and S5.2 (with all use in Pama and Combarbala sub-catchments) the mean storage drops by 10 MCM.

The La Paloma reservoir is only very slightly affected. The storage drops around 11 MCM, but 2-3 MCM less when assuming the reservoir site at CP-13; the maximum average difference of all scenarios is 16 MCM, which is only about 3%.

Simulation of various scenarios: new reservoir site

Table 23: Mean storage volumes of the preliminary calculated simulations

Scenario	La Tranca (mean Volume MCM)	Cogoti (mean Volume MCM)	La Paloma (mean Volume MCM)
S 1	-	75.4	507
S 1limit	-	81.3	509
S 1.1 (CP13b)	38.4	74.7	496
S 2.1 (CP-13)	38.4	72.8	498
S 4.1 (tot CP13b)	38.3	75.7	496
S 4.2 (tot CP-13)	39.3	75.1	499
S 1.2 (CP13b) with Pam/Com	37.3	64.6	493.4
S 3.1 (CP-13) with Pam/Com	37.3	62.8	496.7
S 5.1 (tot CP13b) with Pam/Com	37.2	65.5	493.0
S 5.2 (tot CP-13) with Pam/Com	38.2	64.8	496.4

In the extended simulations including operational policies, a comprehensive analysis will be done concerning yields, reliabilities of supply and shortages. The results of these preliminary simulations lead to the following conclusions:

- The reservoir should be built in CP-13, since the performance is slightly better analysing La Tranca reservoir, when transferring all WRs to the reservoir.
- Most probably the La Tranca reservoir will not have a major negative impact on the downstream management, in contrary: The preliminary results show that in some month it could result even in a bit higher storage. This mainly depends on the assignation of water in the upper part. Here the highest assignation has been around 11,500 m^3/acc/year, which is higher than the normal assignation of the other reservoirs, but still less than the total water rights in the upstream catchment permit.
- The extended simulations should also include scenarios with the total use of the water resources within the sub-catchments which are not part of the La Paloma system (here especially Combarbala and Pama River). Preliminary results show that this will have a higher impact on the system, especially in prolonged low flow years. Here the mean volume of the Cogoti reservoir could drop about 13% (Table 23).

6.2 Extended simulations and evaluation of different management strategies of the Cogoti river-reservoir sub-system

The main objective is to find a final annual assignation (target) which can be served according to the water rights, and which is sufficient for the farmers and minimizes the negative implications on the Cogoti reservoir and its downstream users.

Different simulations with the new reservoir site (CP-13) of la Tranca, including different extraction points of the WRs in the upper part were executed as before, to evaluate later the possible benefits of WR transfer.

Furthermore the discussion between the associations exists, that the Cogoti River gets independent of the La Paloma system, thus different operational strategies are modelled and evaluated. First the system is simulated independently, thus enabling the holders to use their water rights without any operational rule dependent on the storage volume of the Cogoti reservoir (chapter 6.2.1). Secondly implementing the existent operational rule and thus integrating the new reservoir in the Cogoti sub-system (chapter 6.2.2).

Additionally a drought index for the new reservoir La Tranca (DITR) is implemented to test if this might have a positive affect for the management.

The evaluation will be done with regard to the benefits for the upstream catchment and implications to the performance of the Cogoti reservoir.

6.2.1 Simulation of scenarios for extended modelling of La Tranca with an independent management

First the firm yields[40] of the La Tranca reservoir in different scenarios are calculated, to assume as a result an assignation of water with around 100% probability of supply. Thus yield versus reliability relationships (equation 3.2 for period reliability, as described in the model section), including the firm yield are developed with the model.

The dependencies of the scenarios and their objectives are summarized in the following flowcharts (Figure 51, Figure 52) and a more detailed description in Table 24. The extended scenarios will be simulated, keeping CP13a and CP13b as extraction points (S2) and in the same time changing all WRs supplied by the reservoir (S3). This is possible since the whole area belongs to the same estate (hacienda). The owner is willing to change the extraction points to the reservoir and thus benefit from a regular water distribution of the reservoir. Nevertheless the difference to S2 had to be analysed to quantify the benefit of this water transfer.

Furthermore scenario S1limit (implementing the WRs as monthly limits as explained in 6.1) is simulated as extended S1a/b, to serve as a new base scenario for comparison. Two scenarios with different priorities are simulated: 1. WRs of the upper Cogoti River as senior priorities (S1b) and 2. WRs upstream with the same priorities as downstream (S1a).

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[40] Definition of firm yield: maximum value of the annual water supply diversion with a computed reliability of 100 percent

Simulation of various scenarios: management strategies

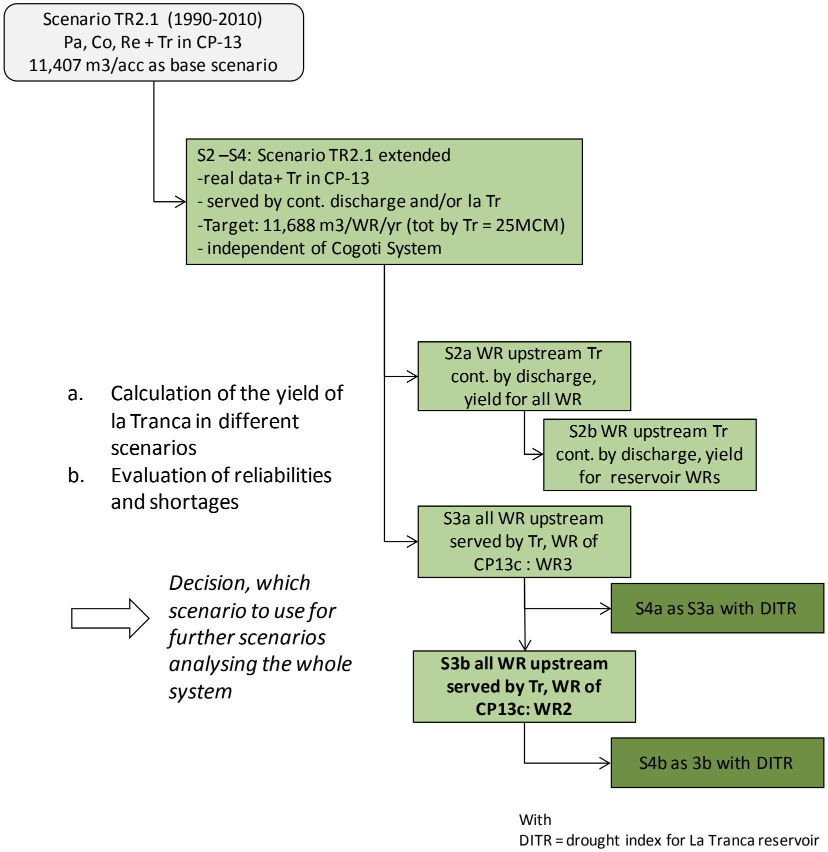

Figure 51: Different scenarios with the main objective to find the firm yield of the new reservoir in the Cogoti River, showing how they are built up on each other

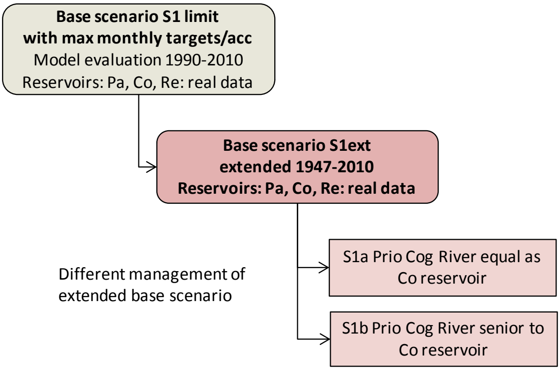

Figure 52: Scenarios for yield simulation of the extended base scenario, with different management strategies

The following abbreviations are used:

> Reservoirs: Pa = Paloma, Co = Cogoti, Re = Recoleta, Tr = Tranca; Prio = Priority; DITR = drought index for the La Tranca reservoir

The different water right types (WR Type 1[41], WR Type 2[42] and WR Type 3[43]) in S3 and S4 were additional used to evaluate the differences in the firm yield, since they define the source of water available for the assigned water rights.

Table 24: Scenario description upstream Cogoti (all scenarios are independent of the Cogoti reservoir)

Scenario	Description
S 1ext	Yield of the diversion to the water rights of Cogoti without la Tranca (here independent of Cogoti: The scenario does not integrate neither a drought index (DI) for the lower part nor a dependence of the upper part on the lower catchment. WRs in the upper part will get different priorities.
S 1a	priority 1000, same as downstream, conditioned rights: junior priority
S 1b	priority 999, priority senior to downstream: inducing that all the water is used when demanded in the upper part, conditioned rights: junior priority
S 2a	With La Tranca in CP-13 (WR Type 1), and above rights are served by the instantaneous discharge of the river as before: without DITR[44] and WR Type 2 in CP13c: calculation of firm yield and 85% period reliability for all water rights
S 2b	With La Tranca in CP-13, and above rights are served by the instantaneous discharge of the river as before: without DITR and WR Type2 in CP13c: yield is only calculated for the rights, which are served by the reservoir
S 3a	With La Tranca in CP-13 and all rights are served by La Tranca: firm yield has been calculated only of the diversion, just served by the reservoir: CP-13c as WR Type 3
S 3b	With La Tranca in CP-13 and all rights are served by La Tranca: and as it is in reality, diversion served by reservoir and streamflow: CP-13c as usual WR Type 2
S 4a	Same as S3, but with drought index of La Tranca (DITR), still independent: as 3a: firm yield has been calculated of the diversion, just served by the reservoir, with DITR: CP-13c as WR Type 3
S 4b	Same as S3, but with drought index of La Tranca (DITR), still independent: as 3b: with DITR: CP-13c as WR Type 2

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[41] WR Type 1: meets its diversion requirement from the reservoir storage if and only if sufficient streamflow is not available, it also refills the reservoir, since it is located at the control point of the reservoir

[42] WR Type 2: same as type 1 except that refilling of reservoir storage with this WRs is not allowed, since this right is not located at the control point (CP) of the reservoir

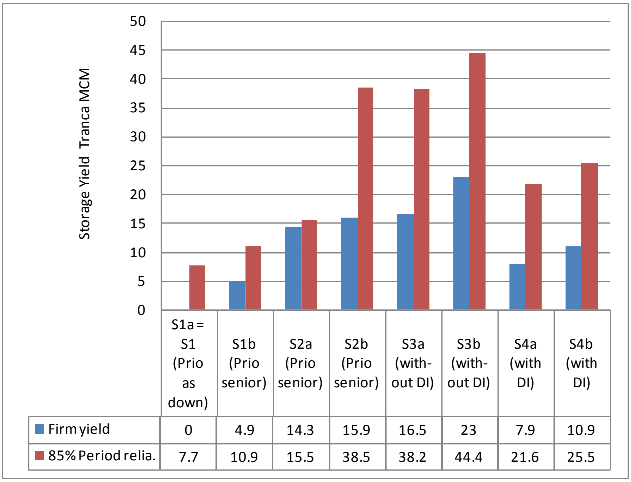
[43] WR Type 3: diversion of a type 3 right can be supplied only from reservoir storage

[44] DITR: Drought index of La Tranca: defining that when the reservoir reaches half of its volume just 50% of the storage which is left, is allocated

Results

Yield calculation

The calculated firm yields (FY) and the 85% period reliability (or 85% exceedance probability) of the different scenarios are presented in Figure 53.



	S1a = S1 (Prio as down)	S1b (Prio senior)	S2a (Prio senior)	S2b (Prio senior)	S3a (with-out DI)	S3b (with-out DI)	S4a (with DI)	S4b (with DI)
🟦 Firm yield	0	4.9	14.3	15.9	16.5	23	7.9	10.9
🟥 85% Period relia.	7.7	10.9	15.5	38.5	38.2	44.4	21.6	25.5

Figure 53: Calculation of the different yields of La Tranca modelling different scenarios

Scenario S1a did not result in a firm yield, because the upstream WRs did not get a higher priority for supply. Comparing thus the current situation of S1a, or better S1b, since this reached a firm yield of 4.9 MCM, with the situation with reservoir (S2a) the firm yield including the upstream WR supplied by the river is almost three times more than the current one, reaching 14.3 MCM. The 85% period reliability reaches a bit more with 15.5 MCM, 40% more than currently. The scenario S2b is theoretical, since the yield of the upstream WRs is excluded; that results in higher yields, which are not realistic, but it shows that the upstream rights has low reliabilities.

The highest yields are reached in scenario S3b, when considering that all the WRs as described before will be served by the reservoir (including the upstream WR) and the available streamflow is considered as further source for the downstream WR (use of WR type 2). Here the firm yield is almost 5 times higher, increasing from 4.9 MCM to 23 MCM (this is not the 100% FY, but 99%). The 85% reliability increases from around 15 MCM to about 45 MCM, thus three times.

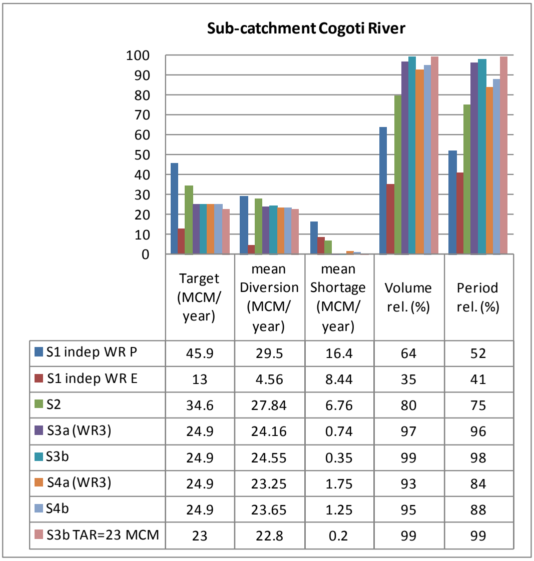
Comparing the scenarios S3 with S4, the latter ones get a lower firm yield (less than 50%) since a DITR is introduced. The same can be observed with the 85% period reliability it also decreases in both S4 scenarios compared to the S3 scenarios.

The reliabilities of 85% with about 45 MCM suggest that more water could be supplied (between 23 MCM and 45 MCM), less reliable but still with a satisfactory probability. The maximum possible legal annual assignation of water to the users of the Cogoti River, corresponding to the upper WR with an instantaneous flow of 1l/sec/acc, results in around 52 MCM. This would mean a very high amount of water per WR (around maximum 20,000 m3/acc/year), which is surpassing the average of the whole basin by 100% and furthermore would result in a very high impact to the Cogoti reservoir and its downstream users. This can be derived from the previous results of the preliminary simulations, where already some consequences of higher assignation could be detected.

Reliability and Shortage analysis of supply (independent of the Cogoti reservoir)

Analysing the results, especially the supply reliabilities are very different. Here the reliabilities of each sub-catchment are calculated proportional to the different targets and reliabilities of the single WRs. Scenario 3b (which resulted in the highest firm yield, FY) gets the best results for the upper part, since all upstream WRs are also served by La Tranca and streamflow and reservoir storage is being used for the water supply of the downstream users of La Tranca (compare reliability indices in Figure 54). The targets are less, since all WRs are served by the reservoir and thus are calculated as annual volume per WR (MCM/year/acc), not as an instantaneous flow (m3/sec/acc). The mean shortages[45] are almost proportional to the targets of the different scenarios.

The mean diversion of S3b reaches 24.5 MCM/year with a reliability of 99% and 98%. In contrary the scenarios without reservoir, thus not regulated, gets reliabilities of supply between 52 and 64% (Permanent WRs).



	Target (MCM/ year)	mean Diversion (MCM/ year)	mean Shortage (MCM/ year)	Volume rel. (%)	Period rel. (%)
■ S1 indep WR P	45.9	29.5	16.4	64	52
■ S1 indep WR E	13	4.56	8.44	35	41
■ S2	34.6	27.84	6.76	80	75
■ S3a (WR3)	24.9	24.16	0.74	97	96
■ S3b	24.9	24.55	0.35	99	98
■ S4a (WR3)	24.9	23.25	1.75	93	84
■ S4b	24.9	23.65	1.25	95	88
■ S3b TAR=23 MCM	23	22.8	0.2	99	99

Figure 54: Aggregated reliability summary of S1-S4 of the Cogoti River (incl. target and diversion)

Furthermore scenario S3b results for the supply of the downstream area of Cogoti in the highest volume with 52 MCM/year, with a volume and period reliability of 95%. But also the reliabilities of the other scenarios are very satisfying, between 92% -94%. The differences are marginal.

Evaluating the shortage metrics (definition page 25) of the Cogoti River sub-catchment (Figure 55), the indicators in general do not have very high values (maximum shortage, vulnerability, severity, number of failures), but the differences between the scenarios can be observed better than with the reliabilities only.

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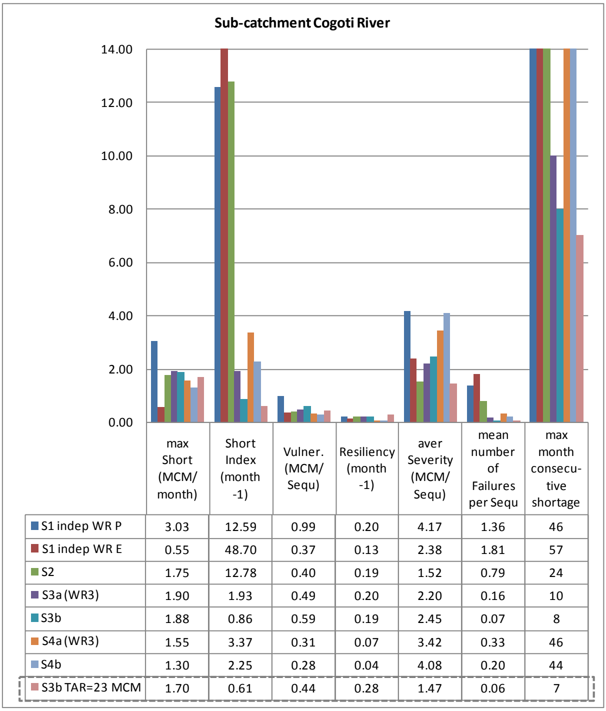
[45] Mean Shortage: Sum of the mean shortages of all WRs of the respective sub-catchment

Simulation of various scenarios: management strategies

Shortage index of S1 and S2, as well the maximum month of consecutive shortages are very high, compared to the other scenarios without DI. The only scenarios which have the same amount of month of consecutive shortages are scenarios S4a, b, where a DI was introduced. These results show that with implementing a reservoir in the sub-catchment, and operating it without a DI will reduce the shortage indices significantly, the average severity for example is also reduced by the half.



	max Short (MCM/ month)	Short Index (month -1)	Vulner. (MCM/ Sequ)	Resiliency (month -1)	aver Severity (MCM/ Sequ)	mean number of Failures per Sequ	max month consecu-tive shortage
■ S1 indep WR P	3.03	12.59	0.99	0.20	4.17	1.36	46
■ S1 indep WR E	0.55	48.70	0.37	0.13	2.38	1.81	57
■ S2	1.75	12.78	0.40	0.19	1.52	0.79	24
■ S3a (WR3)	1.90	1.93	0.49	0.20	2.20	0.16	10
■ S3b	1.88	0.86	0.59	0.19	2.45	0.07	8
■ S4a (WR3)	1.55	3.37	0.31	0.07	3.42	0.33	46
■ S4b	1.30	2.25	0.28	0.04	4.08	0.20	44
■ S3b TAR=23 MCM	1.70	0.61	0.44	0.28	1.47	0.06	7

Figure 55: Shortage metrics for the sub-catchment of the Cogoti River: S1-S4

The final scenario decided upon (scenario S3b, target = 23MCM) gets the best indicators for the catchment downstream of the Cogoti reservoir. All indicators are a bit higher as upstream, but do not differ much between all the scenarios. The highest differences occur in S2 and S4b; the shortage index and the average severity have exactly the same pattern and are highest in these scenarios. The maximum shortage is the same in all scenarios with 6 MCM/month.

The results imply that in average the upper reservoir does not have a negative impact on the lower part, with the assignation used for the simulation (25 MCM). In contrary the scenario 3b with 23MCM target gets in most of the cases in the lower part even slightly better indicators.

Analysing the end-of month storages of La Tranca confirms that the introduction of the DITR did not result in a better management (Figure 56). The dotted lines of S4a and S4b represent the DI-Scenarios and it can be easily observed that higher shortages as desirable are induced, and less water as possible is used. Furthermore it can be observed that in most of the hydrological years more water could be used (the WR would also permit that), but this would result in less available water resources for the lower part, as explained before. The dark blue line represents the best scenario (S3b, TAR 23MCM), which will be used for further simulations to be integrated in the whole model analysis.

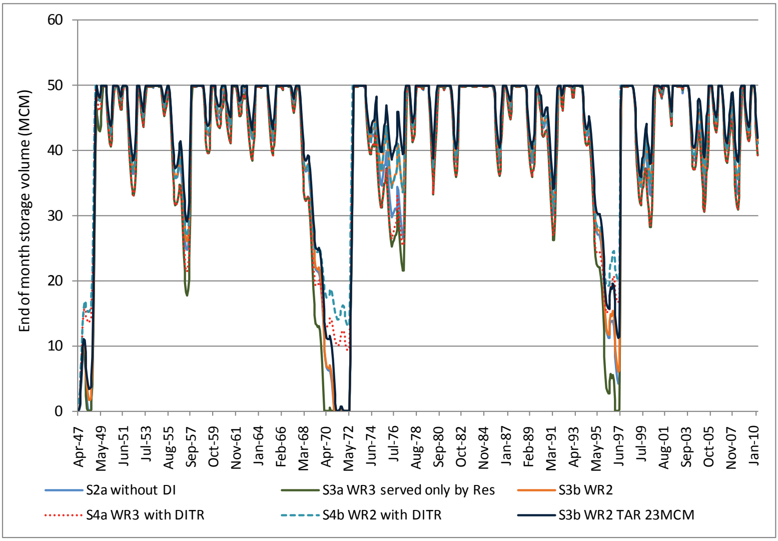


Figure 56: End-of-month reservoir storage curves (MCM) of the planned "La Tranca" reservoir in S2-S4

Analysing the reservoir curves of the Cogoti reservoir it can be observed, that the scenario S3b, which has been decided upon to be the scenario which results in the most reliable supply for both, the upstream and downstream sub-catchment, results most of the time in a similar or even a bit higher storage volume as the current scenario S1; in just a few cases the end - of - month volumes stay slightly below the reservoir storage of S1.

Conclusions

- Based on these results it was decided to divert from the reservoir La Tranca 23 MCM/annually for the upper part of Cogoti, to be simulated in further scenarios, which is similar to the amounts of the preliminary simulations. The respective targets which are allocated to each CP are calculated dependent on the amount of water rights.
- The benefit of changing the extraction point from upstream (S2) to the reservoir (S3) results in an increase of 60% in the firm yield and an increase of 190% of the 85% period reliability (from 15.5 to 44.4MCM/year). Looking at the aggregated results of the reliability metrics this is confirmed (Figure 54): The mean diversion is a bit higher in S2 (since the target is also much higher), but the reliability is less and the max shortage higher than in S3b, too.
- A curtail of diversion induced by the DITR resulted in a high decrease of supply and yields. These results lead to the conclusion that the introduction of the DITR provokes exaggerated supply shortages in the upper sub-catchment and cannot be recommended.

6.2.2 Simulation of further scenarios implementing a common operational management model in the Cogoti sub-system

The following scenarios are incorporating a mutual operational rule for the sub-catchments of the Cogoti River and Cogoti reservoir, using scenario S3b as the new basis for the scenario development. Furthermore scenarios S12 and S13 will introduce total water use in the other upper catchments of the Cogoti reservoir, with and without La Tranca, respectivley.

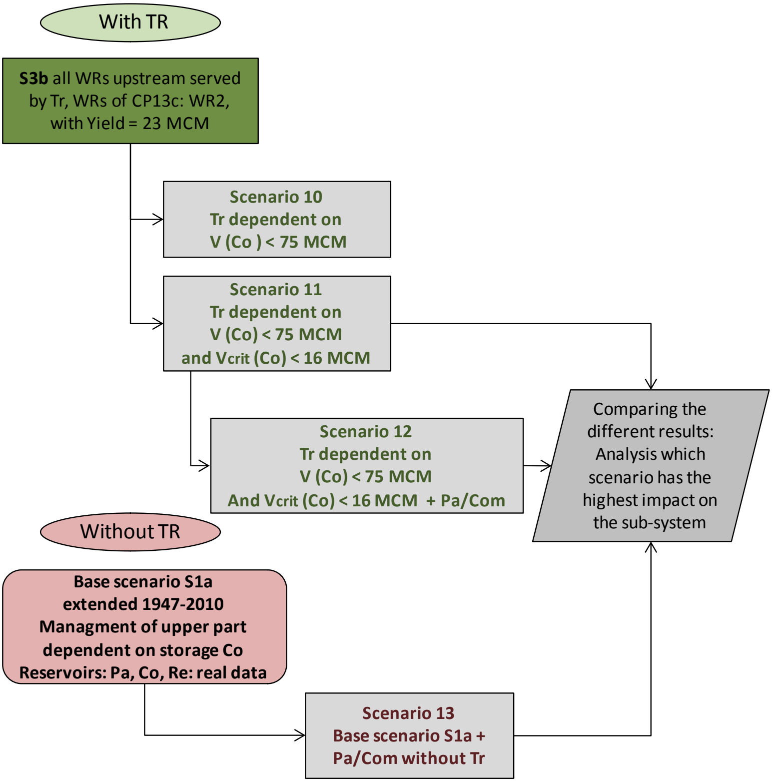


Figure 57: Flow chart of the scenarios simulating in detail the Cogoti River - Reservoir sub-catchment

The management strategies are implemented in two steps

Scenario S10: Conditioned rights will not be served when the storage volume of the Cogoti reservoir reaches a volume of: $V_{Cog} < 75$ MCM, this water will be available for the lower part

Scenario S11: When the Cogoti reservoir reaches the critical volume of $V_{crit} < 16$MCM, a critical management is being implemented: The rights of Huatulame are served by the Cogoti River, assuming the ancient (natural) system, when the Cogoti and Huatulame River were just one river. Thus the rights in the model during this period must have access to the control point above the Cogoti reservoir (here CP-14), the volume of the Cogoti reservoir is being allocated between the water rights of the ACECogoti in a way that more or less 50% of the stored volume is allocated in the respective season.

Simulating the impact of further reservoirs on the sub-system Cogoti

Scenario S12: This scenario uses as the base scenario S11 and includes reservoirs in all upper sub-catchments of the Cogoti reservoir, inclusive the independent Pama and Combarbala River. It is assumed that all the rights are served continuously over the year (worst case scenario) and only the excess water will reach the Cogoti reservoir.

Scenario S13: This scenario has been built up and simulated to determine the influence of the intervention of Pama and Combarbala River without changes in the Cogoti River, the base scenario is S1a.

To analyse and evaluate the different versions, again the shortage metrics, the reliabilities and furthermore the yield of the Cogoti reservoir have been calculated.

In the following table the water rights and their final assumed targets of the upper system: Cogoti River/La Tranca, are summarised. This has been used already for the simulation of S3b (TAR = 23 MCM) and results in an annual supply of around 10,700 m3/WR. Downstream of La Paloma the annual amount per WR various between 6,000 and 10,000 m^3/WR.

The table also gives information of the water right type to be used.

Table 25: Water rights of the Cogoti River upstream with the new reservoir in CP-13 and the management decision of diverting 23 MCM/annually

Control Point ID	Water right ID	Priority	Return Flow CP	WR type	Number of WR (acciones)	Diversion Target max. MCM/ year
CP-13	WRCo13P	998	CP13c	1	1141.21	12.272
CP-13	WRCo13E	998	CP13c	1	362.0	3.893
CP13c	WRCo13cP	998	CP-14	2	521.2	5.605
CP13c	WRCo13cE	998	CP-14	2	114.5	1.231
Sum					**2,138.91**	**23.000**

The maximum refilling of the new planned reservoir is limited to the already assigned water rights in the catchment, but will be further limited to 23 MCM/year based on the annual maximum allocation decision.

Results with La Tranca

Evaluating the reservoir volume curves of the different scenarios with La Tranca most water is supplied by the reservoir in scenario S3b (the drawdown is the highest). It leads to an emptying of the reservoir for 14 month, during a prolonged drought period as it is represented in the end of the 60ties until '72.

When incorporating a common management it results in less use of the stored water in scenario S10, were the conditioned WRs are not served anymore when the Cogoti reservoir reached a certain volume and the additional streamflow is passed for downstream use. With S11 the drawdown is a slightly higher when water is scarce, since the whole management rules of the Cogoti-Huatulame system are introduced. More streamflow is forced to be supplied downstream, provoking higher drawdown.

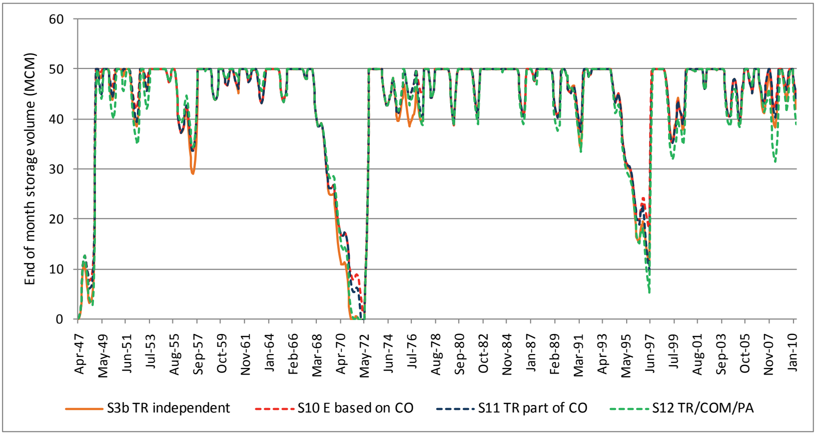
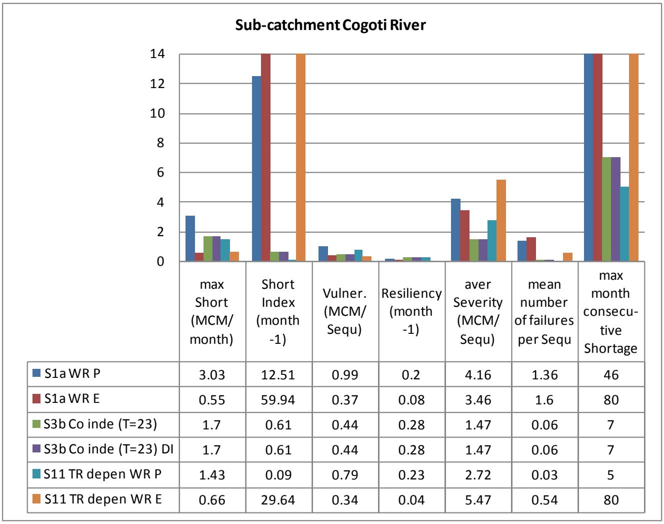


Figure 58: End-of-month storages of La Tranca reservoir implementing different management strategies for the upper Cogoti sub-system

Additional end-of-month storages provoked by the scenario 12 are illustrated, since it also has an impact on the La Tranca reservoir, when the Combarbala and Pama River catchments will use their water in total. It is an indirect impact, since the Cogoti reservoir receives less water, thus results in less storage and with that the reservoir receives more water from the Cogoti River (upstream).

Comparing the shortage metrics (Figure 59) first of the scenarios with only La Tranca (independent and common management) with the actual set up here also simulated as dependent), S1a as well as S11 get the highest shortage index and longest consecutive time of shortage, since the dependent management curtails first the conditioned water rights (WR E).

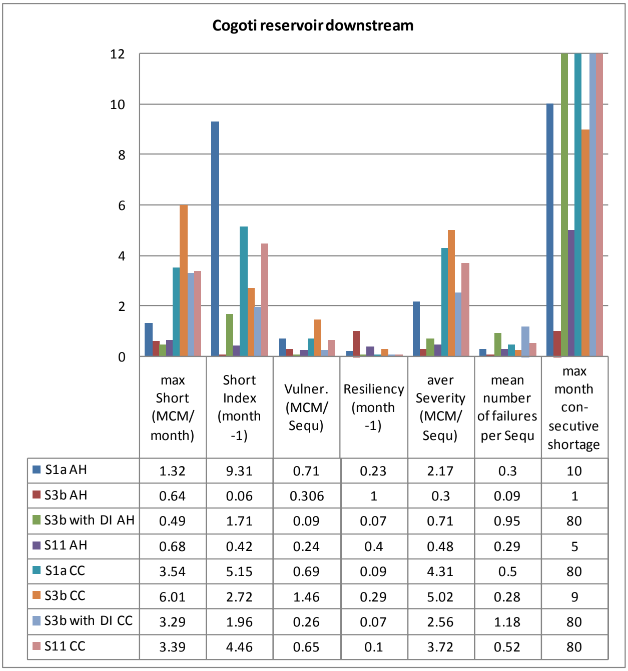


	max Short (MCM/ month)	Short Index (month -1)	Vulner. (MCM/ Sequ)	Resiliency (month -1)	aver Severity (MCM/ Sequ)	mean number of failures per Sequ	max month consecu-tive Shortage
■ S1a WR P	3.03	12.51	0.99	0.2	4.16	1.36	46
■ S1a WR E	0.55	59.94	0.37	0.08	3.46	1.6	80
■ S3b Co inde (T=23)	1.7	0.61	0.44	0.28	1.47	0.06	7
■ S3b Co inde (T=23) DI	1.7	0.61	0.44	0.28	1.47	0.06	7
■ S11 TR depen WR P	1.43	0.09	0.79	0.23	2.72	0.03	5
■ S11 TR depen WR E	0.66	29.64	0.34	0.04	5.47	0.54	80

Figure 59: Shortage metrics for the sub-catchment Cogoti River: comparing S1a, S3b and S11

Considering only the permanent rights, which constitute the main part of WR, S11, results in the lowest shortage index and less month of consecutive shortages. The average severity and vulnerability is a bit higher in S11 WR P than in the S3b scenarios, were conditioned rights and permanent rights are managed equally.

The results of the performance of the Cogoti reservoir for the downstream users (Figure 60) are calculated and presented separately for the association of Huatulame (AH) and the association of the Cogoti reservoir channels (CC), since they receive water from different sources during the critical management.



	max Short (MCM/ month)	Short Index (month -1)	Vulner. (MCM/ Sequ)	Resiliency (month -1)	aver Severity (MCM/ Sequ)	mean number of failures per Sequ	max month con- secutive shortage
■ S1a AH	1.32	9.31	0.71	0.23	2.17	0.3	10
■ S3b AH	0.64	0.06	0.306	1	0.3	0.09	1
■ S3b with DI AH	0.49	1.71	0.09	0.07	0.71	0.95	80
■ S11 AH	0.68	0.42	0.24	0.4	0.48	0.29	5
■ S1a CC	3.54	5.15	0.69	0.09	4.31	0.5	80
■ S3b CC	6.01	2.72	1.46	0.29	5.02	0.28	9
■ S3b with DI CC	3.29	1.96	0.26	0.07	2.56	1.18	80
■ S11 CC	3.39	4.46	0.65	0.1	3.72	0.52	80

Figure 60: Shortage metrics for the sub-catchment Cogoti reservoir downstream S1a, S3b and S11

The downstream supply of the Cogoti reservoir (Figure 60) is not as uniform as in the previous independent scenarios. Summarized it can be stated that with the common management strategy the maximum shortages get less. The shortage index, as well the average severity get very different values in each scenario, but most of the time, the supply to the association of Huatulame (AH) gets better indicators. Analysing the current scenario S1a, simulated with management rules and comparing it with the actual previous one (independent), the shortage index for S1a AH is much higher (9.31 month^{-1}) than without the management (1.98 month^{-1}). Thus the security of the AH supply is granted in the current setup mainly by the Cogoti reservoir.

The average severity of the AH is much lower, the CC gets in S1a and S11 severities a bit higher as before. This might be induced by the DI record of the Cogoti reservoir or just by the separate presentation of both results.

The difference in end-of-month storage considering the DI record of the Cogoti reservoir can be observed in Figure 61. Comparing the reservoir storage lines of *"S3b"* with *"S3b TR with DI Cog"* the reservoir does not empty as fast in the latter one. Furthermore comparing it with the current scenario S1 (river independent) and also S1a (river dependent), the reservoir storage line of the scenario "*S3b with DI Cog*" gets often above the current storage line, thus higher end-of-month storages.

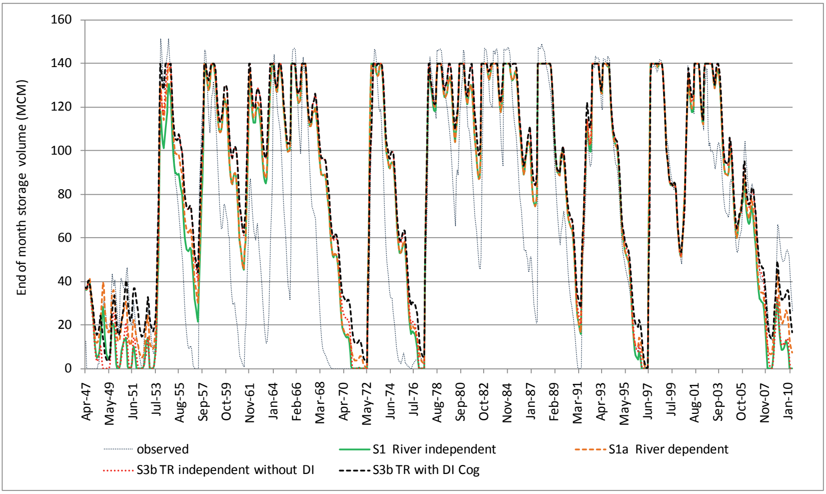


Figure 61: Different end-of-month storages of the Cogoti reservoir modelling S1/S1a/S3b with current supply data

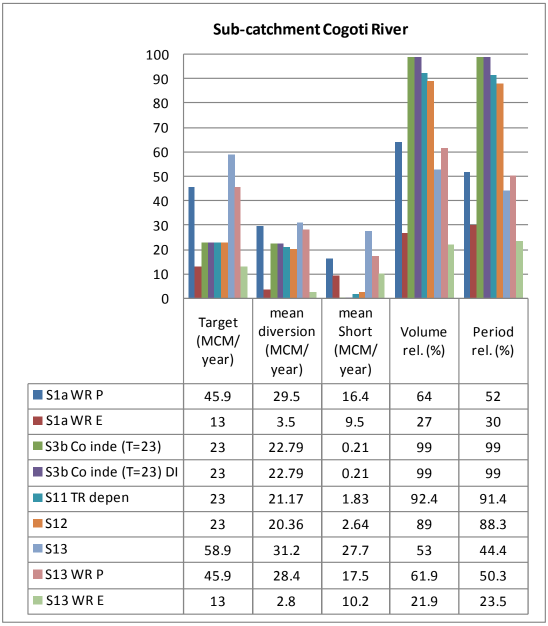
The observed storages were just added to demonstrate the different supply management over the decades and show that with the possible new scenarios it will not be worse than before, when often used much more resources as assigned originally.

Analysing the firm yield of S1a and S11 (results of more scenarios see Figure 66), both scenarios incorporating the current management strategy, result in 39 and 37 MCM respectively, thus the La Tranca reservoir has just a very minor negative impact on the firm yield with the chosen assignation. Even though the firm yield is about 5 MCM less than in S1 and S3b, the max shortage, vulnerability and average severity are lower in S11. The number of failures per sequence and maximum month of consecutive shortages are higher (since due to the DI - record small shortages are induced), thus the shortages occurred during a longer time span, but less severe.

Analysing further the yield with the 85% exceedance probability the volume as well the period reliability are almost the same, with a volume of about 46 MCM.

Results with further use in Pama and Combarbala sub-catchments

The regulated flow of CP-17 (outlet of the upstream catchments and entrance to the Cogoti reservoir at the Pama River, Map 6) in scenario S12 and S13 has been reduced from a total annual mean of 29.98 MCM (S11) to 6.81 MCM, a bit more than one fourth. This average amount is only based on the high precipitation years. In the majority of the years the annual inflow to the Cogoti reservoir from the Pama River (S12/13) is almost zero. Thus the impact of a more extensive water use in these catchments is quite high only evaluating the inflow to the reservoir.



	Target (MCM/ year)	mean diversion (MCM/ year)	mean Short (MCM/ year)	Volume rel. (%)	Period rel. (%)
S1a WR P	45.9	29.5	16.4	64	52
S1a WR E	13	3.5	9.5	27	30
S3b Co inde (T=23)	23	22.79	0.21	99	99
S3b Co inde (T=23) DI	23	22.79	0.21	99	99
S11 TR depen	23	21.17	1.83	92.4	91.4
S12	23	20.36	2.64	89	88.3
S13	58.9	31.2	27.7	53	44.4
S13 WR P	45.9	28.4	17.5	61.9	50.3
S13 WR E	13	2.8	10.2	21.9	23.5

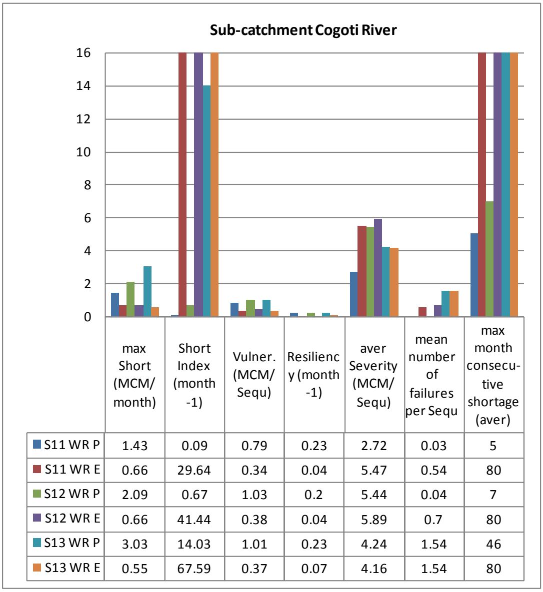
Figure 62: Aggregated reliability summary for S1a, S3b, S11, S12 and S13 (Cogoti River)

Regarding the reliabilities, scenario S12 gets very similar results as S11, slightly worse (Figure 62). The reliabilities drop from about 92% (S11) to 89% (S12), the annual mean diversion of S12 is the worst with 20.36 MCM.

The reliabilities of S13 without La Tranca are worst, just between 45% and 53% in total. For easier comparison with the current S1a scenario the WR of the Cogoti River are presented separated in WR P and WR E. The reliabilities of the permanent WR drop about 3%, of the conditioned WR between 18 and 23%.

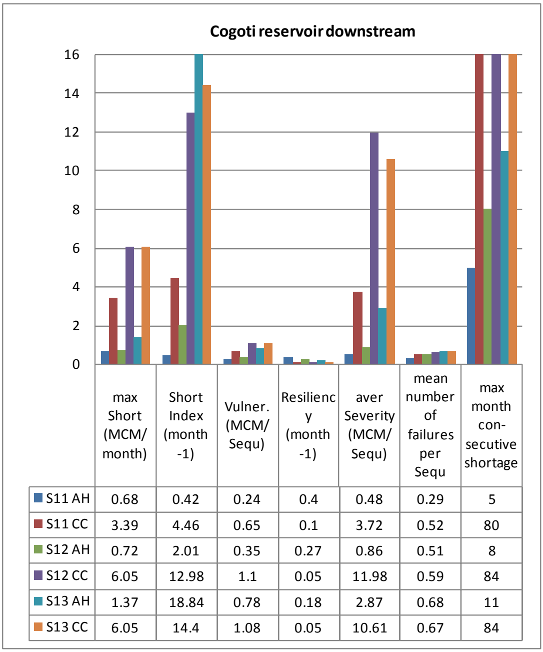
Comparing the shortage metrics of scenarios S11-S13 the results of scenario S11 are the best with the lowest values for the indicators, followed by S12 (Figure 63). An exception is the result of the severity, with the highest value in S12, when all the water resources upstream are regulated.

Further analysing Figure 63, the maximum shortages of WR P, are increasing from S11 to S13, but are still very low. The shortage index as well increases (here both types of WR are affected). Furthermore the high difference of the shortage index of WR P of S12 to S13 is noticeable; it increases from 0.67 to 14.03 month^{-1} respectively, as well the number of consecutive month with shortage increases from 7 to 46. The conclusion can be drawn that the highest negative change is provoked by S13.



	max Short (MCM/ month)	Short Index (month -1)	Vulner. (MCM/ Sequ)	Resiliency (month -1)	aver Severity (MCM/ Sequ)	mean number of failures per Sequ	max month consecu-tive shortage (aver)
🟦 S11 WR P	1.43	0.09	0.79	0.23	2.72	0.03	5
🟥 S11 WR E	0.66	29.64	0.34	0.04	5.47	0.54	80
🟩 S12 WR P	2.09	0.67	1.03	0.2	5.44	0.04	7
🟪 S12 WR E	0.66	41.44	0.38	0.04	5.89	0.7	80
🟦 S13 WR P	3.03	14.03	1.01	0.23	4.24	1.54	46
🟧 S13 WR E	0.55	67.59	0.37	0.07	4.16	1.54	80

Figure 63: Shortage metrics for the sub-catchment Cogoti River: comparing S11, S12 and S13



	max Short (MCM/ month)	Short Index (month -1)	Vulner. (MCM/ Sequ)	Resiliency (month -1)	aver Severity (MCM/ Sequ)	mean number of failures per Sequ	max month con-secutive shortage
🟦 S11 AH	0.68	0.42	0.24	0.4	0.48	0.29	5
🟥 S11 CC	3.39	4.46	0.65	0.1	3.72	0.52	80
🟩 S12 AH	0.72	2.01	0.35	0.27	0.86	0.51	8
🟪 S12 CC	6.05	12.98	1.1	0.05	11.98	0.59	84
🟦 S13 AH	1.37	18.84	0.78	0.18	2.87	0.68	11
🟧 S13 CC	6.05	14.4	1.08	0.05	10.61	0.67	84

Figure 64: Shortage metrics for the for the area served by the Cogoti reservoir downstream: S11, S12 and S13

Analysing the reliability indicators of supply for the downstream area of the Cogoti reservoir of the different scenarios, scenario S13 results in the highest mean annual shortage, almost 3 times higher as in S11. The reliabilities of supply are decreasing as follows: S11, S1a, S12, and S13 from about 90% to about 75%. This reconfirms the results of the Cogoti River catchment, S13 would also result in the worst performance of the Cogoti reservoir.

When assuming a target of 55 MCM/annual of the Cogoti reservoir, the mean actual diversion is about 46 MCM/annually in the worst scenario S13, still more than legally assigned to the association.

Analysing the shortage indicators of the downstream area which is supplied by water from the Cogoti reservoir (Figure 64) the high difference of the shortage index values of S12 AH and S12 CC can be observed, it is much higher than in the other scenarios. In general the WR of the AH are suffering less shortages, the indices are almost all better than the WR CC. Scenario S12 incorporates all reservoirs, thus AH, suffers less impact, concluding that the association clearly benefits from La Tranca reservoir.

Comparing in detail the shortage indicators of the WR which are served to ACECogoti in S12 and S13, they are very similar. Some are slightly better in S12 and some in S13. Thus the differences of both scenarios do not result in different shortage indicators of CC.

Looking at the reservoir curves of the different scenarios of Cogoti (Figure 65), clearly S11 results in a mayor volume of the reservoir (green line), compared to S12 and S13.

Looking at the last years of simulation (2004-2010) it gets obvious that further development of the upper catchments (Combarbala/Pama) will put in water scarce years a higher pressure on the system and a very controlled management is inevitable, since the system will be much more sensitive and vulnerable to allocation changes as with the current system. But in case the current assignation strategies will be adapted, and the hydrological pattern keeps similar, the system will not suffer bigger problems as they suffered already during the 60ties (compare observed reservoir curve with S13, Figure 65).

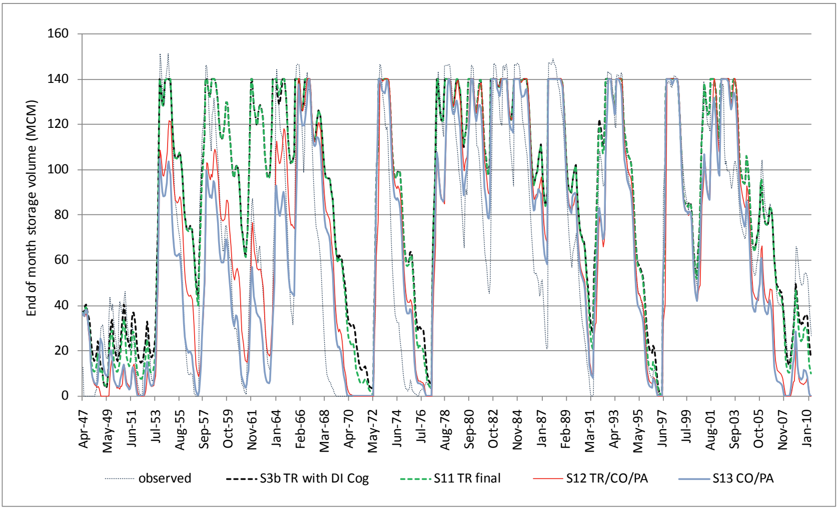
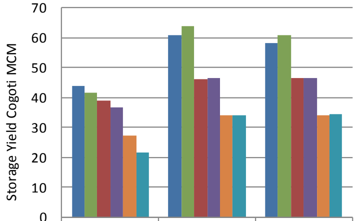


Figure 65: Different end of month storages of the Cogoti reservoir of the different scenarios with current data (S1/S1a/S3b/S11/S12/S13)

Results of yield calculations of the Cogoti reservoir

The current scenario S1 and S3b, which are the only scenarios without any further management rule for La Tranca and the Cogoti reservoir, result in the highest firm yields of the Cogoti reservoir with 44 MCM and 42 MCM respectively (Figure 66), since they can supply all the water which is available (in compliance with their WRs). Scenario S13 (without La Tranca and further development upstream Cogoti reservoir) results in a firm yield of about 28 MCM, the 85% volume and period reliability would be 34 MCM, thus about 6 MCM less than the La Paloma system assigns. Implementing the La Tranca reservoir and assuming further the total use upstream Pama River (S12) results in the worst firm yield but the same 85% supply reliabilities.



	Firm yield (MCM)	85% Vol reliability (MCM)	85% Period reliability (MCM)
🟦 S1 (indepen.)	44	61.1	58.2
🟩 S3b (TR, V = 23 MCM)	41.7	63.9	60.8
🟥 S1a (depen.)	39	46.2	46.5
🟪 S11 (TR depen.)	37	46.5	46.5
🟧 S13	27.5	34.4	34.4
🟦 S12	22	34.2	34.5

Figure 66: Cogoti reservoir yields of different scenarios (S1-S13)

Effect on the storage of the La Paloma reservoir

As can be observed in Figure 67, the reservoir storage curves of La Paloma also get influenced by the new reservoirs of the upper catchments of Cogoti, Combarbala and Pama River.

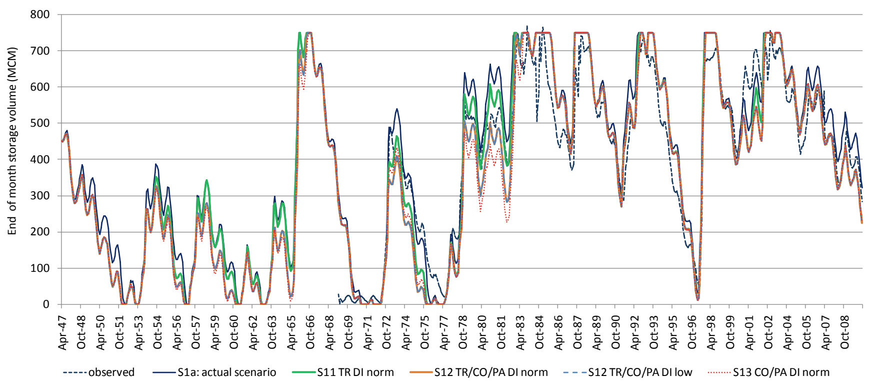


Figure 67: Different end of month storages of the la Paloma reservoir of the different scenarios with current data (S1a/S11/S12/S13)

The blue line represents the present scenario S1a (for comparison also the observed storage is shown, since the reservoir went into operation in 1968, blue-dotted). The new scenario S11 (green) with la Tranca, is in some years below the current reservoir line, here the refilling does not result in the same end-of-month storage and therefore keeps to be lower during the next years, too (72/73, 78/79, 2006).

Scenario S12 shows just in some years even lower results than S11, most of the time the values are similar. As before the peaks for refilling get lower, since the upper catchments of Combarbala and Pama River retain more water. Here two different drought indices for the Cogoti reservoir were tested (DI norm and DI low), but this will not have any influence on the La Paloma reservoir. Scenario S13, which does not consider the development of the Cogoti River, results most of the times in the same storage as with scenarios S12.

Conclusions

- Summarized it can be stated, that with implementation of the management rules in the model the actual scenario S1a gets clearly a lower maximum shortage per month but on the other hand a higher shortage index; furthermore a lower severity for the association of Huatulame (AH) and slightly higher for the association of the Cogoti reservoir channels (CC). Regulations upstream with implementing management rules have in general a positive impact not only for upstream but also on the downstream supply.
- Scenario S12, where all upstream developments are simulated, is preferable. The development of the Pama and Combarbala sub-catchments without the construction of La Tranca (S13), would lead to the worst results for the Cogoti River sub-catchment and further to the worst performance of the Cogoti reservoir.
- The results for the Cogoti river - reservoir - system are better, when introducing the La Tranca reservoir, with and without the further exploitation of the Combarbala and Pama River sub-catchments. Thus it is recommendable for the association of the Cogoti River to construct a reservoir and keep participating in the La Paloma system. This scenario, according to the model results, will ensure benefits to all, when implementing the amounts and management as suggested and tested so far (certainly more management possibilities should still be tested to make sure to implement the most convenient).
- Results of the firm yields show clearly beside the already discussed results that the impact of the further development of the upstream catchments of Pama and Combarbala might be quite high since it lowers the firm yield and 85% exceedance reliability by about 12 MCM annually.
- This might lead to the necessity of a new formulation of the WR assignations in the system with a new maximum assignation of the single reservoirs. But until now just average real data were considered for the lower part. Before new suggestions will be formulated, the system will be modelled with the originally and still valid legal assignations and the results analysed and discussed (chapter 6.3).

6.3 Performance evaluation of the entire La Paloma system (current and future) subject to different WR targets, conditioned WRs and water transfers

With the following scenarios the whole basin with the entire La Paloma system has been analysed. The previous outcomes of the new upstream sub-catchments are part of the new scenarios. The following flow chart explains how the different scenarios are developed from each other with their main differences and objectives on the left hand side.

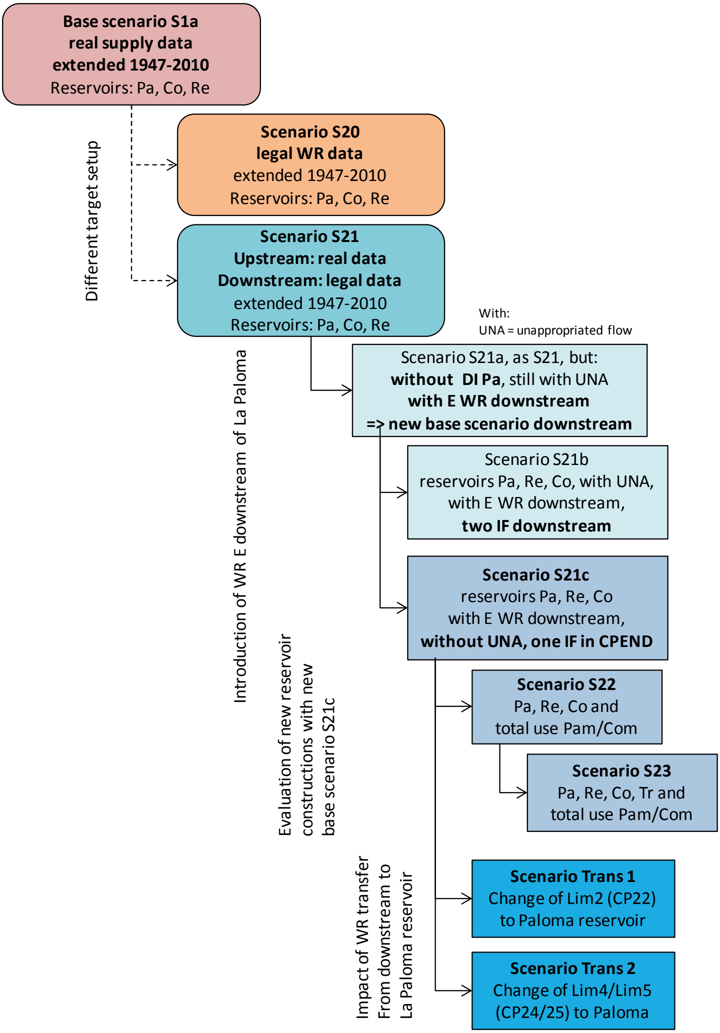


Figure 68: Flowchart of the scenarios with legal and real/legal WR targets, conditioned WRs downstream and new reservoirs upstream

Especially different assignations and their implications are tested. First the legal assignations which are still valid are simulated in S20. This will be evaluated further as water is transfered, here within one reservoir (La Paloma), but also between two reservoirs (La Paloma/Cogoti). The legal assignations in the upper Grande River are simulated in the "legal" scenario, too.

The final target setup (S21) is a combination of S20 and the current S1a scenario, using upstream of the Grande River real supply data, and downstream the legal assignation of WR and volumes.

Finally a water transfer is incorporated into the last two scenarios (S Trans1, S Trans2) evaluating the change of extraction point from the Limarí River to the la Paloma reservoir.

The new scenarios have been set up with the following details:

1. *Scenario S20*:

The current infrastructure (including three reservoirs) with the legal water rights assignation is simulated; especially the following huge differences have been identified (detailed information about the main differences between the legal and real assignation are presented in chapter 4.1, references see footnotes):

- Firstly in the distribution in the upper part of the Grande River[46], upstream of the Paloma reservoir
- Secondly in the distribution of water from the Cogoti reservoir[47], the legal assignation is less than the real distribution, 40 MCM/annually versus 55 MCM/annually.
- Thirdly in the distribution from La Paloma reservoir[48] to Camarico, Cogoti, and as well to Recoleta (main differences see Table 26).

Table 26: Differences of assigned water from La Paloma (real distribution vs. legal WR)

Scenario	To Camarico	To Recoleta	To Cogoti
S1a (real)	37 MCM	60.5 MCM	54 MCM
S20 (legal)	25.3 MCM	74.4 MCM	68.96 MCM

Although the assigned water to various associations of the La Paloma reservoir is different in S1a and S20, the sum of the water assigned is almost the same in both scenarios, of about 240 MCM in average.

Nevertheless the sum of the volumes of water assigned in total from the Cogoti and La Paloma reservoir to the associations ACECogoti and the JVRHua is in both scenarios the same of about 110 MCM, just differently distributed from La Paloma and Cogoti. These details show that somehow the associations are performing kind of water transfers, which are not legally based, but maybe in mutual accordance.

2. *Scenario S21* (a,b,c):

After analysing the results of S20, it has been decided to define for the next scenarios a new base scenario with the following target characteristics: for the upper part of the Grande River the real diversion data of the base scenario S1a and for the downstream reservoir catchments the legal water right data which has been used for S20, will be adapted. This has been done since the upper part of the Grande River is differently managed depending on the volume of the reservoirs. In the model just one rule could be implemented, which results to more water use upstream than normally distributed in S20. Therefore the average of the real target has been assumed to reflect the actual management better and is used for further scenarios.

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[46] upper Grande River sub-catchments (Table 4): sum of legal assignation: 130 MCM, mean real target (1990-2010): ~ 93 MCM

[47] Cogoti reservoir (Table 8): sum of legal assignation: 40 MCM, mean real target (1990-2010): 55 MCM

[48] La Paloma reservoir (Table 9): sum of legal assignation: 240 MCM, mean real target (1990-2010): 238 MCM

Simulation of various scenarios: management strategies

With the new base scenario S21, new downstream conditional water rights of the Limarí River were introduces and modelled. These scenarios were modelled with the use of unappropriated flow (UNA[49]) and without, evaluating the impact of the UNA use on the supply of the conditioned WR, which have priority in reality, but since they are conditioned WR they get just junior priorities. Thus permitting the use of UNA flow could curtail these flows. Both management possibilities will be analysed.

One of these conditioned WR was approved only with the requirement of a minimum flow at the downstream site. This requirement was simulated with an instream flow right (IF) and looked at how this influences the supply of the conditioned WR.

a. ***Scenario S21a***:
   Almost the same as S21, for the lower part the UNA flow can be used as calibrated in the downstream part of the Limarí River; in case more water is being depleted for allocation, less water for downstream WR with junior priorities is available. Further, the more recently conditioned WR in the lower part are incorporated, as well as no DI for the Paloma reservoir.
b. ***Scenario S21b:***
   Same as S21a, but incorporating into the analysis not only conditioned WR at the end of the basin (CP-26 and CPEND), but also with this, the minimum flow rights in both control points, which were legally claimed at when approving one of these WR.
   They will be modelled as IF WR, theoretical it is just one right, but due to the change of extraction point of a part of the conditioned WR "Lomas de Talinary" the IF WR is also put in both control point (CP-26 and CPEND) for testing and evaluating the impact on the three conditioned rights.
c. ***Scenario S21c:***
   Finally without the possibility to use UNA flow, the same conditioned WR are being analysed, the minimum flow right which is part of one conditioned right has been set just in CPEND.

The decision to use S21c for further scenario building has been taken, the amount of water available for the conditioned and instream flow water rights are expected to be higher when no extra flow is used and it can be evaluated more correctly how often it complies with the legally designated water.

3. ***Scenario 22***: Further total use of water of the Pama and Combarbala River is been implemented, thus simulating the impact of theoretical reservoirs in these catchments.
4. ***Scenario 23***: All three possible new reservoirs in the upper part of the Cogoti reservoir (La Tranca, and two at the Pama and Combarbala River) have been implemented in the model, with the same management strategy as before in the base scenario.
5. ***Scenario Trans 1:*** Base scenario is S21c; change of extraction point of the WR of CP22 (WRLim2), to the reservoir; total volume is 10 MCM.
6. ***Scenario Trans 2:*** Base scenario is S21c; change of extraction point of the WR of CP24 (WR Lim4) and CP25 (WR Lim5) to the reservoir, total volume is about 10 MCM.

The analysis of the different scenarios in view of the whole basin is presented in the following sections 6.3.1 - 6.3.4, starting with the evaluation of the different target scenarios S1a, S20 and S21; sub-chapter 6.3.2 evaluates the scenarios with the new developments upstream (S21, S22, S23) with respect to the firm yield of the system and supply reliabilities. The impact on the conditioned WR in the downstream part of the Limarí River is discussed in sub-chapter 6.3.3 and finally the results of the new theoretical water transfers from downstream to the reservoir are summarized in sub-chapter 6.3.4.

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[49] UNA: Unappropriated flows associated with a particular control point are the portions of the naturalised streamflows still remaining after the streamflow depletions are made and return flows are returned for all the water rights included in the simulations (WRAP, Reference manual, 2010).

6.3.1 Comparison of the different target scenarios S1a, S20 and S21 with regard to their supply performance

The aggregated metrics for each sub-system were finally calculated out of the indices of each water right as before. The following sub-systems are evaluated:

1. Sub-catchment of the Grande River upstream down to the entrance of the Paloma reservoir
2. Cogoti reservoir downstream to the Paloma reservoir and all its connected water rights
3. Paloma reservoir and the Grande and Limarí River downstream to the outlet of the considered basin, CPEND
4. Recoleta reservoir

The sub-system of the Cogoti River has not been included since it will not or only very marginally change according to the details evaluated before.

Results

Where visualisation is necessary the final aggregated results are presented in diagrams in the text. The first column in the first figure per sub-catchment shows the corresponding target of the scenario and thus the differences between legally and real distributed WRs. Additionally the reservoir curves are presented and discussed.

Grande River upstream

Scenario S20, representing the legal WR assignation, distinguishes also in the upper sub-catchment between permanent WR (P) and conditioned WR (E) in the model. The period reliability decreases from about 83% (S1) to about 76% (S20), similarly the volume reliability (84% to about 78%). The shortage index and maximum consecutive months with shortages are much higher when considering both types of WRs (S 20tot), since the conditioned WR have junior priority. The shortage indices of S20, considering only the permanent rights, are just slightly higher than in S1a. Evaluating the vulnerability and severity of the permanent WRs of S20, they are again slightly higher, but still very low. The maximum shortage does not even reach 2 MCM/month.

Since most of the water which is distributed upstream in the Grande River sub-catchment will not enter the La Paloma reservoir, S20 has a higher impact to the La Paloma reservoir. The annual average regulated flow of CP-12 (just before the La Paloma reservoir) is in average 20 MCM/year less compared to S1a. On the other hand the regulated flow of CP-18 (outlet of the Huatulame River to the La Paloma reservoir) is in average 10 MCM/year higher, thus the water which enters the reservoir in total still is less.

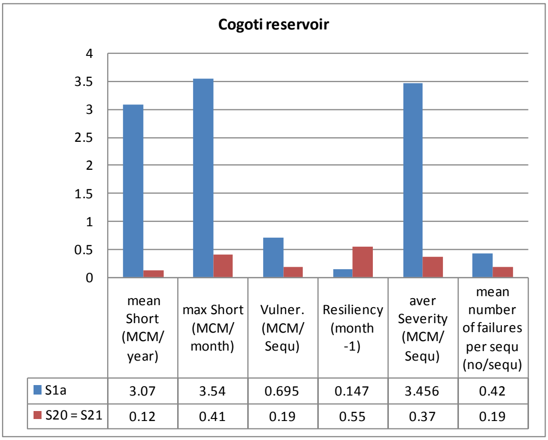
It can be concluded that the resources are available in the upper part to supply more water, since the shortage indices did not increase significantly, but it will have an influences to the lower catchment as presented further down.

Cogoti reservoir

The period reliability increases with S20 from 85% (S1) to about 94% (some shortages are induces by a DI), the volume reliability is almost 100%. The introduced DI Cogoti in S20 reflect the Cogoti-Huatulame River management and thus provokes a slight shortage in some months, to save water in case of longer drought periods, nevertheless the shortage index is almost zero if modelling with the legal assigned volume of 40 MCM for the Cogoti reservoir.

Simulation of various scenarios: management strategies

The indicators of the shortage metrics (Figure 69) show clearly that the legal WR assignation (S20) results in almost zero values; the resiliency is quite good, compared to S1a.



	mean Short (MCM/ year)	max Short (MCM/ month)	Vulner. (MCM/ Sequ)	Resiliency (month -1)	aver Severity (MCM/ Sequ)	mean number of failures per sequ (no/sequ)
🟦 S1a	3.07	3.54	0.695	0.147	3.456	0.42
🟥 S20 = S21	0.12	0.41	0.19	0.55	0.37	0.19

Figure 69: Shortage indicators for the supply of the WR downstream of the Cogoti reservoir, S1a/S21 vs. S20

Paloma reservoir

The target volume of the water rights supplied by the La Paloma reservoir sum up to almost the same amount of about 240 MCM. The reliabilities of supply are all between about 85% - 92% (period reliability) and 89% - 93% (volume reliability), lowest in S20. The mean shortage is about 20 MCM/year, only in the legal scenario it increases to 26 MCM/year.

The comparison of indicators between the current, the legal and the mixed scenarios are resulting in the same pattern as the reliability. They are all very similar and satisfactory, with the exception of the legal scenario, here the indicators resulted to be worse, but still in similar ranges. The reason might be because 27% more water was supplied in the upstream Grande River catchment and therefore less water entered the Paloma reservoir.

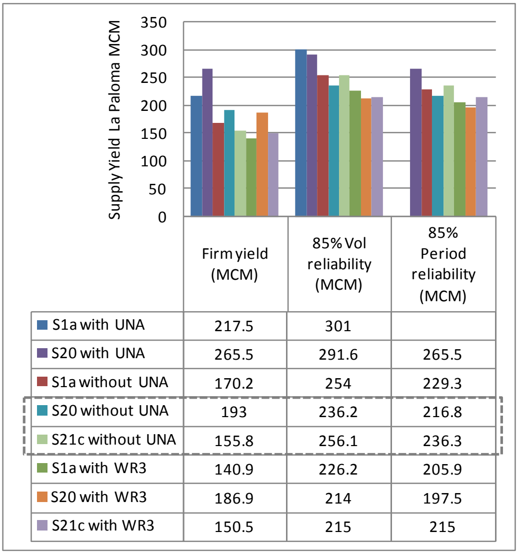
Recoleta reservoir

The difference of targets between the real and legal scenario is just 5%, and does almost not have any influence on the performance as indicated by the reliability metrics. The reliabilities result in all scenarios analysed in about 95%.

Analysing the rest of the indicators, in general S21 gets the best values; the exception is the mean shortage which is slightly higher than S1a. The improvement of the indicators in the mixed scenario is not provoked by a different target, but a DI which has been used here also for the Recoleta reservoir. It is inducing earlier small shortages and results finally into better indicators, since the mean shortage, which has kept the same value, was distributed in a better way reducing the negative impact.

Yields of La Paloma reservoir

To evaluate further the consequences on supply security subject to changes of assignation and water transfers, the yield of all reservoirs in all Scenarios S1a until S23 are calculated. The yields of the La Paloma reservoir are varying within the different scenarios (Figure 70).



	Firm yield (MCM)	85% Vol reliability (MCM)	85% Period reliability (MCM)
■ S1a with UNA	217.5	301	
■ S20 with UNA	265.5	291.6	265.5
■ S1a without UNA	170.2	254	229.3
■ S20 without UNA	193	236.2	216.8
■ S21c without UNA	155.8	256.1	236.3
■ S1a with WR3	140.9	226.2	205.9
■ S20 with WR3	186.9	214	197.5
■ S21c with WR3	150.5	215	215

Figure 70: Yields of the La Paloma reservoir according to different targets scenarios of the actual system (S1a, S20, S21)

The three presented scenarios are calculated with the three following conditions: (i) with and (ii) without the use of unappropriated (UNA) flow downstream and (iii) with WR type 3 for the downstream control points. The modelling with WR type 3 results in a theoretical yield, because streamflow in most of the cases supports the reservoir in water supply.

As expected the highest yields in all scenarios are reached when using additional UNA flow downstream, this probably would curtail WRs with junior priorities (as conditioned WR, or minimum instream flows). Although the calculation with UNA flow does not result in an exact firm yield (this flow is very variable), it results without doubt in an increasing yield.

Without the use of UNA, S20 ("legal" scenario) reaches the highest firm yield ($Y_F \approx 195$ MCM/year); the lowest yield results with S21, ("mixed" scenario"). Analysing the 85% reliabilities the contrary is observed, here the highest values are achieved with the target set up of the "mixed" scenario S21, and the worst is reached with the legal scenario (S20).

Out of the firm yield calculation with WR type 3 it can be concluded that without the additional streamflow of the downstream area the water rights could not been supplied as it is stipulated and required since the highest 85% period reliability is 215 MCM/year (S21).

The firm yield of the whole system (ResPa, ResCo, ResRe) of the current case scenario S1 and the mixed legal/real scenario of S21 is similar with 236 MCM[50] and 222 MCM respectively (both with a DI of La Paloma). The 85% volume and period reliability are in a similar range with about 350 MCM/year and 330 MCM/year. The system is been operated to allocate 320 MCM in years when the resources are available. Thus with the different composition of the legal rights of S21 the system yields almost the same volume, the current scenario results in a bit more, because of the differences in the Cogoti reservoir assignation.

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[50] Firm yields of Cogoti and Recoleta are the same for both scenarios (S1/S21) and the same as in S21c (Figure 71); the 85% reliabilities are taken out of the calculation sheet of Cogoti and Recoleta, the Paloma values are presented in Figure 70.

6.3.2 Firm yield of the system and its supply reliabilities of the different scenarios with further upstream development

The annual firm yield of the La Paloma and Recoleta reservoir is almost not affected by the new reservoirs (Figure 71).

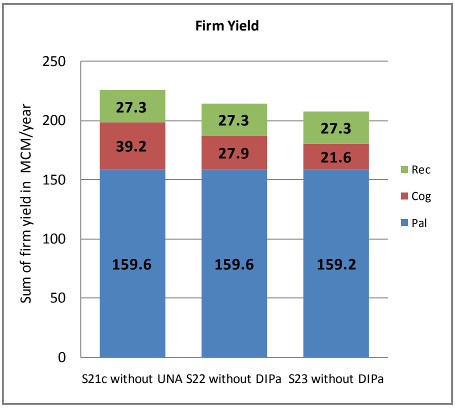


Figure 71: Annual firm yields the La Paloma system in S21c, S22 and S23

The only changes are observed in the Cogoti reservoir as already calculated within S12 and S13 (Figure 66) and reconfirmed with S23 and S22 respectively. In the worst scenario S23 the firm yield reaches only 55% of the firm yield of S21c. Scenario 22 reaches 71% of S21c firm yield. Scenario S21c results in a system firm yield of 226 MCM/year, S22 in 215 MCM/year and S23 in 208 MCM/year.

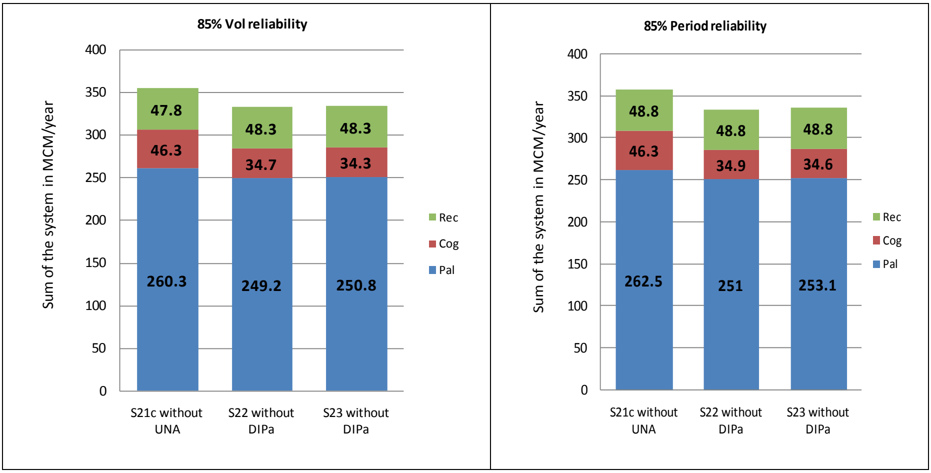


Figure 72: 85% volume and period reliability yields of the whole system S21c, S22 and S23

The 85% yield reliability of Recoleta has in all scenarios the same results; since it is an almost independent sub-catchment. It is not influenced by changes upstream of the Cogoti reservoir, in case no system operational management is introduced. The 85% reliability volumes of La Paloma are almost equal in S22 and S23 (Figure 72).

The yield of the Paloma reservoir drops almost the same amount in volume as the Cogoti reservoir in S22 and S23 (about 10 MCM/year, Figure 72), compared to S21c. For the La Paloma reservoir this is less than 4%, for Cogoti reservoir it drops about 24% to about 35 MCM, which denotes a much higher impact. This implies that not even with the 85% reliability the legal annual target for Cogoti (40 MCM) might be supplied with the future scenario.

The 85% reliability yields of all reservoirs in S22 and S23 sum up to around 335 MCM/year. In S21c it is about 355 MCM/year (Figure 72).

Finally the reliability of supplying the legal assigned volume of 240 MCM from the La Paloma system in the previous scenarios was analysed; it resulted in a range of 88% - 91% (compare Table 27).

Table 27: Reliabilities of supplying 240 MCM from la Paloma in S1a, S21c, S22 and S23

Scenario	Volume reliabilities to supply 240 MCM	Period reliabilities to supply 240 MCM
S1a	89%	90%
S21c	90%	91%
S22	88%	88%
S23	88%	88%

The reliabilities of supplying 240 MCM/year (normal assignation) by the La Paloma reservoirs results best with scenario 21c; period reliability reaches 91%.

Consequently, the Cogoti reservoir is the only reservoir which suffer higher consequences, nevertheless the indices of reliability and shortages are still quite good, since the legally assigned target is reduced by 30% to the current one. Thus the worst reliabilities were still around 84% (S22 and S23). Similar behaviour show the indicators of the shortage metrics, they are quite low, too; S22 results slightly worse than S23.

But as expected the values here are better than in S13, since the assigned target is much lower. The average severity for example is about six times higher in scenario S13 than in S22.

The end-of-month storage line of Cogoti confirms the indices (Figure 73).

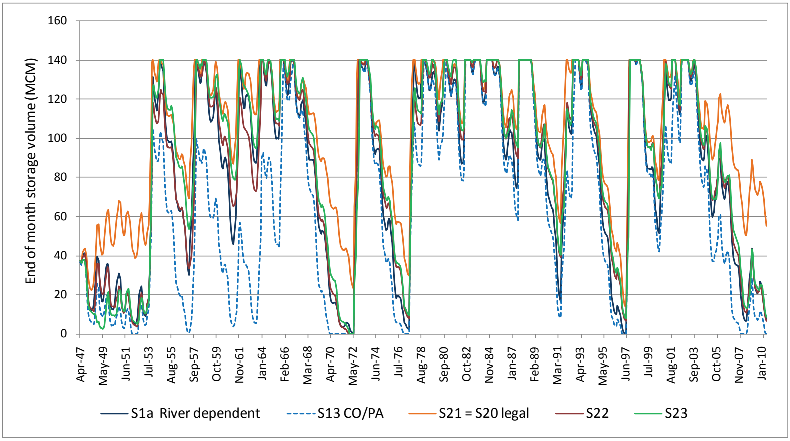


Figure 73: **Cogoti reservoir end-of-month storage curves of S21-S23 compared with real/legal data management**

Simulation of various scenarios: management strategies

The curve of S22 (red) is most of the times lower than of scenarios S23. Additionally the simulated storage curve of S13, is much lower than the corresponding one of scenario S22, thus reassuring the mayor impact to the system when continuing with the higher average water supply from the Cogoti reservoir. The differences of S13 and S22 are alarming.

Comparing the current scenario S1a (dark blue line) with the possible future scenarios S22/23, the current scenario is always lower, the last simulated years it gets almost equal to the future scenarios, this is due to the different assigned targets and further discussed in the conclusions.

Just analysing scenario S1a and S20/S21 (dashed orange line), presenting both the current infrastructure, the impact of the different assignation of water to the reservoir curves can be easily noticed. With using just the legal assigned volume the reservoir would still keep water during the worst droughts which happened so far. Especially in the last years the benefit of the legal assigned volume can be observed. In case the periods with years of low precipitation, are getting longer, the legal assigned volume should be respected to save water for another possible low precipitation year.

The evaluation of the Paloma reservoir during the scenarios which include further development in the upstream catchments of the Cogoti reservoir, results in slightly higher shortages than the scenario S21a-c, thus the impact is minor.

Furthermore the reliability of supply drops in the worst case (volume reliability) from 92% to 90%. Shortage indicators are low and the maximum shortage 12.5 MCM/month (5% of the target).

Evaluating further the end-of-month storage curves, both future scenarios again are very similar, nevertheless the S22 storages result sometimes drops below the line of S23 (Figure 74).

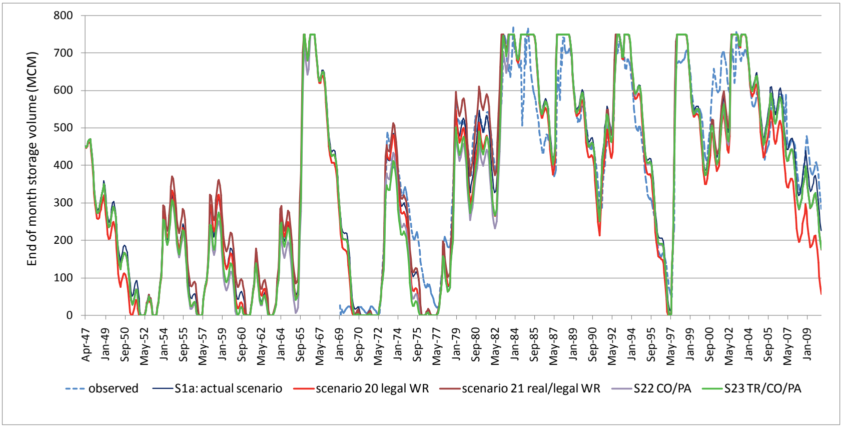


Figure 74: La Paloma reservoir end-of-month storage curves of S21-S23 compared with real/legal data management

Analysing the details between scenario S1a and S20 a difference of the reservoir curves of La Paloma can be observed; the end-of-month storage curve in scenario S20, especially when the drawdown is highest, as well as the last simulated years since 2005 are worst with the legal assignation (in contrast to the Cogoti reservoir). The reason is mainly the different allocation of water from the Grande River upstream.

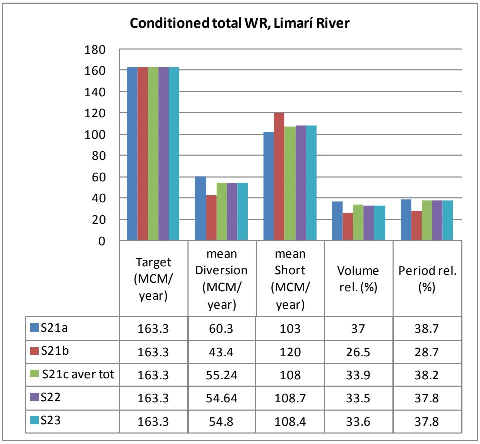
Finally comparing S1a with S21 (actual infrastructure, different targets) in most of the times when refilling occurs, S21 resulted in higher storages. Only in the last years the storage coincides with the storage of S22 and S23.

6.3.3 Evaluation of the conditioned water rights at the downstream end of the Limarí River

Here three water rights were analysed, which together result in the maximum target of 163.3 MCM/year since they got assigned a continuous flow. The last approved conditioned right (thus the most junior WR/least priority) with 4 m^3/sec is the highest (Table 9). A minimum flow right, required by the authority while it was approved, is modelled as instream flow (IF record) in S21b/c, assuming different model conditions. The IF WR here is senior to the conditioned WR.

Scenario S21a does not integrate an instream flow right, but still uses UNA flow and analyses how much water would be supplied for the new junior rights, after serving all the senior permanent rights.

The volume and period reliabilities are in general very low (Figure 75), and are best in Scenario S21a (about 38%), were no minimum flow downstream is considered. The mean annual diversion is about 55 MCM, considering one instream flow downstream of the extraction point (S21c, S22, S23).



	Target (MCM/ year)	mean Diversion (MCM/ year)	mean Short (MCM/ year)	Volume rel. (%)	Period rel. (%)
🟦 S21a	163.3	60.3	103	37	38.7
🟥 S21b	163.3	43.4	120	26.5	28.7
🟩 S21c aver tot	163.3	55.24	108	33.9	38.2
🟪 S22	163.3	54.64	108.7	33.5	37.8
🟦 S23	163.3	54.8	108.4	33.6	37.8

Figure 75: Aggregated reliabilities indicators for the supply of the all conditioned WR, Limarí River: S21a, S21b, S21c, S22 and S23

In the worst case with two instream flows (S21b) the mean annual diversion reaches 43 MCM, since due to the second IF record more water had to pass CP-26. Additionally in S21a and S21b the further use of UNA flow is still permitted. Thus the differences in supply are just provoked by the introduction of the IF-records.

Not considering the last approved conditioned WR, which is the highest, too, in the aggregated value, a highest period reliability of supply is reached also in S21a with 72%, the period reliability of S21c increases to around 60%.

The analysis of the rest of the shortage indicators confirms the previous evaluation. When just calculating the averages of the results of the three lower conditioned WR the results are similar to the results of the permanent WR and in acceptable ranges (e.g. maximum monthly shortage of about 4 MCM), the latest junior right provokes the high values in the aggregated shortage indices (max shortage then: 23 MCM).

With the previous analysis insight is gained, how instream flow simulation and changes in UNA streamflow use have an impact on the supply of the junior rights; however, the obtained results can only be seen as tendencies, not as absolute values. Since they are modelled at the outlet of the catchment and there all the possible errors of the flows and supplies assumed before, are aggregated and even though a lot of effort has been done to get the natural flow in Panamericana as accurate as possible, there are still some uncertainties. Thus it would be risky to handle the following results as absolute ones.

Yearly probability of supply

The low supply reliabilities suggest working out in more detail the reliability of supply of the conditioned WRs. Since the interannual differences in flows are high, here especially the probability, in percentage of years, when diversion is equal or exceeding a certain percentage of targets is studied.

The conditioned rights have in average a 7.9% probability of all years to be served 100%, according to the target (S21c, not counting the last conditioned right approved). In the scenario where two instream flows have been considered (S21b) the first three conditioned WR get an average probability of 5.3% of years, where 90% of the target might be served. In scenario S21c the probability of the years, where 90% of the target is served, gets in average 12.2% (again not considering the last conditioned WR).

Even if the streamflows might be a bit underestimated it can be concluded that the total targets of the conditioned WR will be served just with a very low yearly probability.

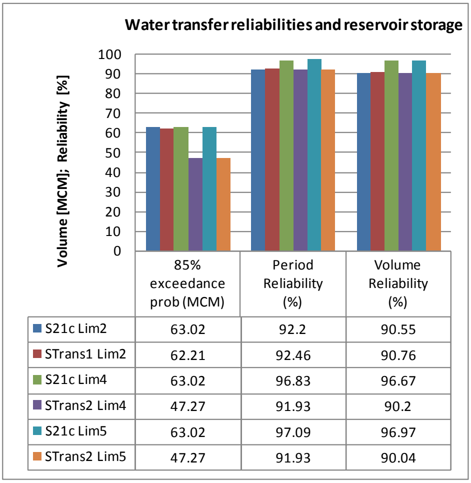
6.3.4 Analysis of transfer of downstream WRs to the La Paloma reservoir

As discussed before the hydrology of the downstream area is a bit particular. Not all control points downstream have the same hydrological conditions; water rights of CP 24, 25, 26 (those which are the most downstream before CPEND, the outlet) count with more available streamflow, caused by different phenomena. These model results are also confirmed by the data of the Limarí River association. A lot of real supply data were analysed with the outcome, that the lower part of the Limarí River gets additional resources, possibly as a result of recharge, ground- and surface-water interaction, and lateral inflow. As already mentioned (chapter 5.1 Assumptions for the model: Limarí River) about 37% (average) to 52% (maximum) of the water assigned to be served by the reservoir for the users along the Limarí River is distributed by the streamflow, generated in the downstream catchment. Furthermore in case UNA streamflow is available, a bit more is supplied. The maximum limits for the model were extracted out of the supply data.

Thus it is expected that not all changes of extractions points from the lower part to the reservoir have the same consequence to supply reliabilities and downstream users.

The transfer of the WRs with S Trans2, thus changing the extraction point from CP24/CP25 to the La Paloma reservoir (Map 2) has the highest impact on the supply reliability of the tested scenarios. Comparing it with the new base scenario S21c it drops from 97% to about 90%, which is still high, nevertheless lower than in the original simulation (Figure 76). Both grouped WR Lim4 (CP24) and Lim5 (CP25) get the same results. To predict the overall average consequences for the reservoir the storage frequencies were calculated.

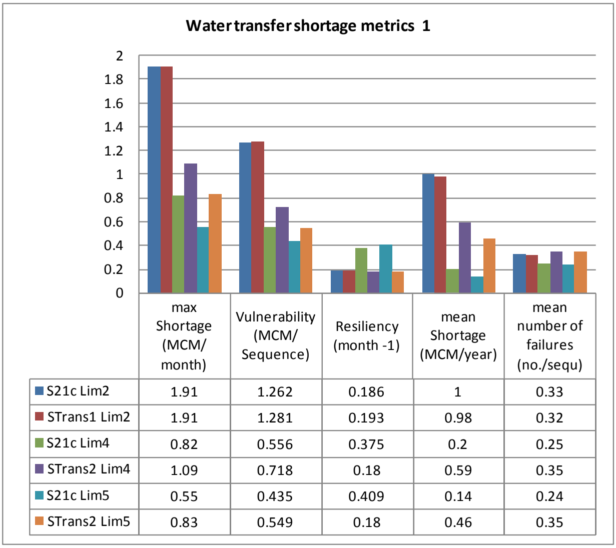
Comparing the 85% storage exceedance probability of the La Paloma reservoir in S Trans2 with S 21c, it decreases by 25% (63 MCM to 47 MCM); in STrans1(change of extraction point of WR Lim2 from CP22 to the reservoir) just by 1% (63.02 MCM to 62.2 MCM), compare Figure 76. The decrease of the 85% storage exceedance probability in S Trans2 will impact finally all WR served by the reservoir.



	85% exceedance prob (MCM)	Period Reliability (%)	Volume Reliability (%)
■ S21c Lim2	63.02	92.2	90.55
■ STrans1 Lim2	62.21	92.46	90.76
■ S21c Lim4	63.02	96.83	96.67
■ STrans2 Lim4	47.27	91.93	90.2
■ S21c Lim5	63.02	97.09	96.97
■ STrans2 Lim5	47.27	91.93	90.04

Figure 76: Reservoir storage in Vol (MCM) of 85% exceedance frequency and supply reliability (%)

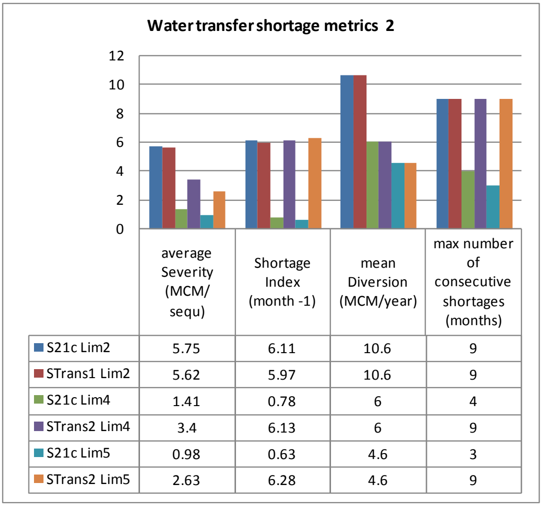
The same pattern can be observed analysing the reliability and shortage metrics of each WR. The details are shown in Figure 77 until Figure 78.



	max Shortage (MCM/ month)	Vulnerability (MCM/ Sequence)	Resiliency (month -1)	mean Shortage (MCM/year)	mean number of failures (no./sequ)
■ S21c Lim2	1.91	1.262	0.186	1	0.33
■ STrans1 Lim2	1.91	1.281	0.193	0.98	0.32
■ S21c Lim4	0.82	0.556	0.375	0.2	0.25
■ STrans2 Lim4	1.09	0.718	0.18	0.59	0.35
■ S21c Lim5	0.55	0.435	0.409	0.14	0.24
■ STrans2 Lim5	0.83	0.549	0.18	0.46	0.35

Figure 77: Shortage indices metrics1 of changed WR in Scenarios S21c, STrans1, STrans2

The only value which keeps the same is the mean annual diversion. Thus the mean diversion from both points (downstream and reservoir) stays the same, but the shortages are increasing.



	average Severity (MCM/ sequ)	Shortage Index (month -1)	mean Diversion (MCM/year)	max number of consecutive shortages (months)
🟦 S21c Lim2	5.75	6.11	10.6	9
🟥 STrans1 Lim2	5.62	5.97	10.6	9
🟩 S21c Lim4	1.41	0.78	6	4
🟪 STrans2 Lim4	3.4	6.13	6	9
🟦 S21c Lim5	0.98	0.63	4.6	3
🟧 STrans2 Lim5	2.63	6.28	4.6	9

Figure 78: Shortage indices metrics2 of changed WR in Scenarios S21c, STrans1, STrans2

Clearly the transfer of the rights from the lower CPs, here CP24, CP25 has a higher impact to the reservoir storage (see Figure 79), as shown with the already calculated storage frequencies. The reservoir storage line of STrans2 (dashed light blue) shows the lowest storage, especially in the last years the difference can be noted.

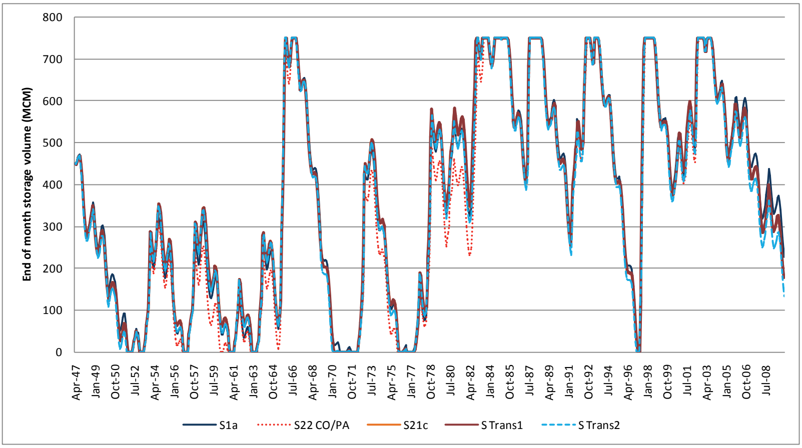


Figure 79: Comparison of the end of month storages of La Paloma: S21c, STrans1, STrans2; further comparison with: S1a, S22

Impact on conditioned rights downstream

Calculating the impact on the conditioned rights for STrans2 and excluding the last conditioned right (WRAleqEven3), the volume reliability increases from around 60% in S21c to 63%, the period from around 60% to 64%, which result in average in more or less 2 MCM/year more water for all conditioned water rights.

The contrary is being observed in STrans1, here the reliabilities of supply of the conditioned rights stay almost the same, in total in the new Scenario STrans1, 0.5 MCM/year are allocated less to the conditioned rights.

Conclusions of 5.3

The following main conclusions of the scenarios with different WR targets, supply to more recently approved conditioned rights with required instream flow, special additional water transfers and its consequences can be summarised as follows:

Comparing S1a, S20, S21 (S21a): current infrastructure

- With the legal scenario S20, 21, the Cogoti reservoir reaches a supply reliability of 100% without DI. The calculation of the 85% supply reliabilities of about 46 MCM (reliability reaches 92%) leads to the conclusion that, when keeping the actual infrastructure, more water could be allocated (best 46 MCM, until probably maximum 50 MCM) to the downstream community. Thus the Cogoti reservoir management took the signal, when diverting more than legally assigned, but according to the model to much for secure supply. Thus the decision here (with the current infrastructure) to allocate more water could be agreed upon in the range mentioned, but only with an adequate drought management.
- The main negative impact (although not high either) on the performance of La Paloma is provoked by using the full legal assignation for the upper Grande River (S20).
- The incorporation of a DI for the Recoleta reservoir in S21 produces better results of the shortage metrics for Recoleta. Thus it is recommended to use a small DI within the Recoleta reservoir management to decrease the negative impact of drought.
- Yield calculations of La Paloma: the 85% period reliability is met best in S21 (almost 240 MCM/year), when not using UNA flow downstream. The legal assignation in normal years is 240 MCM of the La Paloma reservoir, thus, given with the 85% period reliability, the legal scenario (S20) reaches almost 240 MCM/year volume reliability, but only 77% period reliability
- The firm yield of the whole system of the current case scenario and the mixed legal/real scenario of S21 is similar with 236 MCM and 222 MCM respectively (both with DI Pa). The 85% volume and period reliabilities are in a similar range with about 350 MCM/year and 330 MCM/year respectively. Thus with the different composition of the legal rights of S21 the system is almost equal reliable in time as the average real distribution.

Comparing S1a, S20, S21c, S22, S23: current and new infrastructure

- Out of the calculations of the total system yield with an exceedance probability of 85 % (Figure 72) it would be possible to supply the normal diversion target of the system with 320 MCM, also in the future scenarios S22 and S23, but with a **different distribution** from each reservoir. Since the Cogoti reservoir is most affected it has to be balanced with the other two reservoirs, which theoretically is possible since the necessary infrastructure of channels and siphons is existent.
- Keeping the current situation including the targets (scenario S1a) will not result in higher reservoir storages of Cogoti than the future scenarios, keeping the original legal assignation: scenarios S22

and S23 will not result in worse storage volumes of Cogoti than with the current management. Modelling the current average supply data with new infrastructure (S13, as discussed before, Figure 62,Figure 63,Figure 64,Figure 65) results in an alarming difference, compared to the situation with the legal assignation (S22), both presented in Figure 73.

- Evaluation of the La Paloma reservoir leads to the conclusion that S21, the "mixed" target scenario leads in most cases to higher refills, thus the legal assignation downstream of all reservoirs has a positive impact onto the reservoir storage volume of La Paloma.
- Further development upstream has, according to the analysed indicators, no impact on the supply of the conditioned WR in the Limarí River. A higher diversion occurs if just one minimum instream flow downstream of the extraction site is modelled, while also the use of UNA flow in the CPs of the river, upstream of CPEND is prohibited (S21c vs. S21b: about 12 MCM/year more).

Water transfer scenarios:

- The WRLim2 is not subject to changes, when transferring it to the reservoir in STrans1. The reliabilities and shortage metrics stay almost the same
- The period and volume reliability of supply of WRLim4 and WRLim5 in contrast decreases compared to the base scenario S21c, when transferring the extraction point to the reservoir. The contrary probably would have been expected of a user of this WR.
- Both scenarios have just a minor impact on the conditioned WR downstream: STrans1 has a slightly negative impact and STrans2 a more positive impact.

6.4 Assessment of the impact on the different calculated minimum flows Qeco

Furthermore the consequences of the different allocation management and reservoir operations with respect to environmental needs, here expressed by the legal minimum ecological flows and instream flow rights, will be analysed and evaluated.

The map shows again the points of interest which were calculated and furthermore in the diagram the used scenarios and corresponding analysis are summarized. The system is assumed to not operate with a common system operational rule (DI 0).

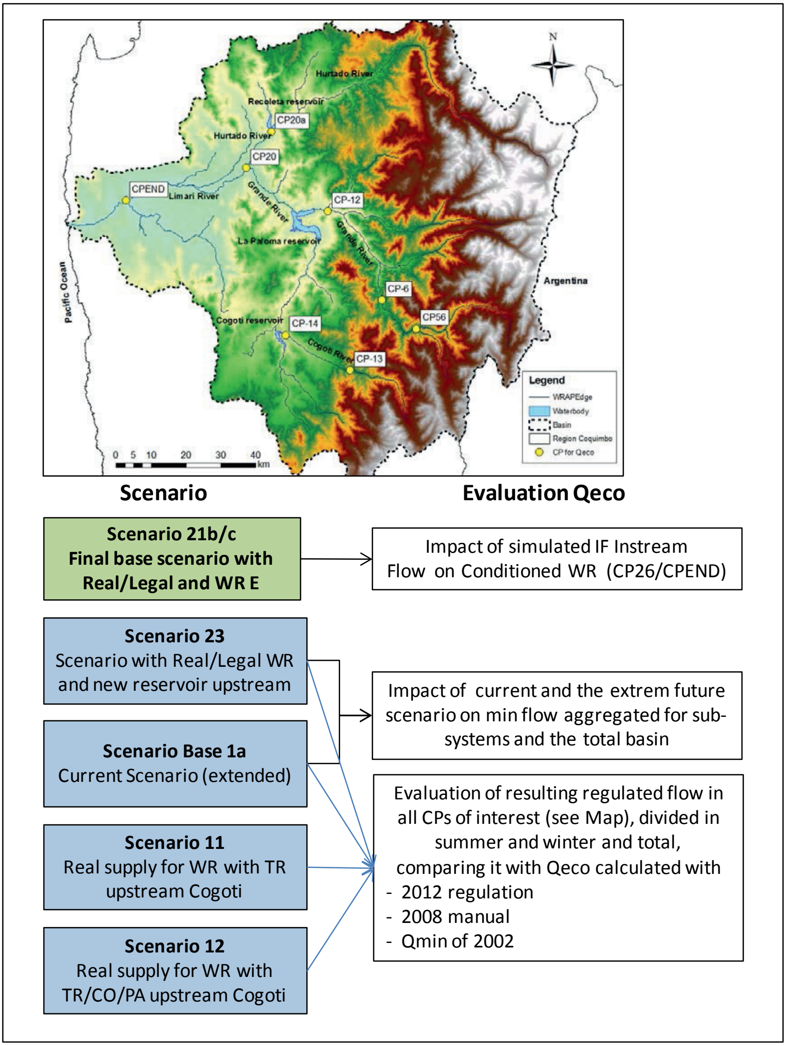


Figure 80: Diagram of the scenarios used for the evaluation of Qeco

6.4.1 Qeco evaluation with instream Flow (IF) in S21b/21c

As presented in upper diagram (Figure 80), the evaluation of Qeco is done in two different ways. The first evaluation has been performed by simulating the required minimum flow as instream flow with an IF-record of the model. In chapter 6.3.3 the consequences of the required IF on water supply to WRs with less priorities was tested; here the impact of the general water supply on the IF is evaluated. The priorities were assigned as before: 1. highest priorities, thus senior to all permanent rights, 2. instream flow right (minimum flow) and 3. Conditioned water right: The target of the IF is set to the requirement which was connected with the approval of a specific conditioned WR: 1m3/sec, resulting in a volume of 31.56 MCM/year or 2.63 MCM/month.

Two scenarios, S21b and S21c are analysed. The different shortages can be observed in Figure 81, which shows the annual target and annual shortages of the different scenarios and IF-WR during the whole hydrological sequence. In the most of the years the IF in CP-26 (TaliIF) of S21b results with fewer shortages. The shortages in CPEND (TaliIF2) are almost equal in both scenarios, nevertheless slightly lower in the majority of the simulated years in S21c, when just one IF was considered.

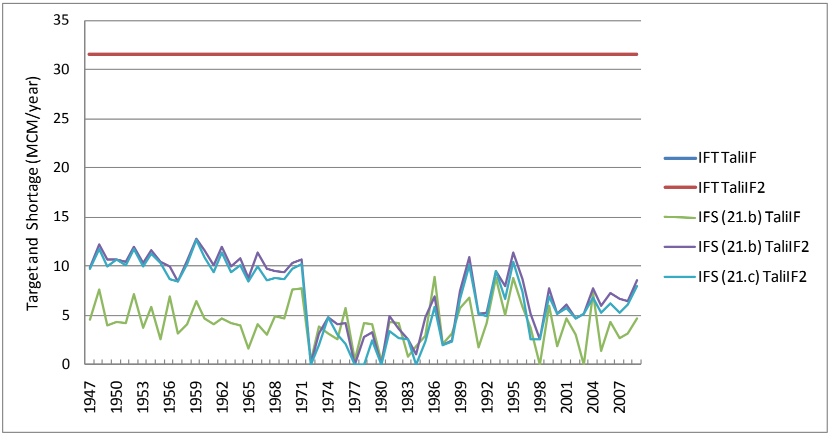


Figure 81: Yearly target (IFT) and shortage (IFS) in MCM of the IF records in the Limarí River

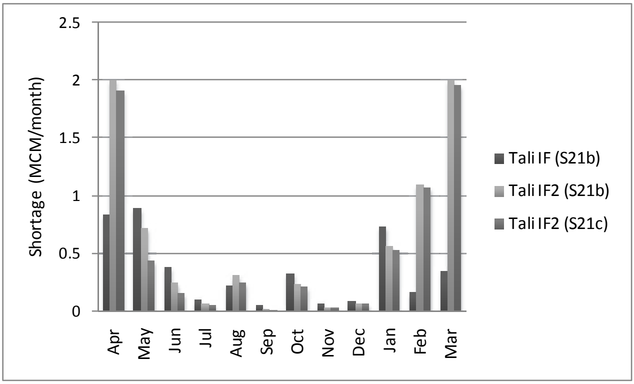


Figure 82: Mean monthly shortages of the IF: CP-26/CPEnd (S21b) and CP-26 (S21c)

The main shortages (monthly means) occur at the end and beginning of the hydrological season and less in month with precipitation and more water use downstream (Figure 82), and thus more water release of the reservoir and possible more return flow, too. Both scenarios show similar pattern, but especially in February, March and April the IF-WR: Tali IF, of CP-26 has much less shortage as the second IF-WR (Tali IF2) in CPEND. Furthermore when just considering the IF in CPEND (Tali IF2, S21c), the shortage is less than in S21b.

6.4.2 Qeco evaluation with regulated flow (REG) in different scenarios

Four scenarios of the total simulated scenarios have been chosen to estimate the impact of the system in operation and possible future developments on the theoretical legal minimum ecological flow requirements (CP compare Map in Figure 80/Map 5). The following scenarios have been selected for evaluations, including different target definitions (real vs. legal) as well:

i. S1a: Base scenario (extended), present system structure, average real supply
ii. S11: Including the possible new reservoir La Tranca, average real supply
iii. S12: As S11, but with further total water use of Pama and Combarbala sub-catchment
iv. S23: As S12 regarding the possible future changes in the upper parts of the Cogoti reservoir, "mixed" targets: Real/Legal, IF and conditioned WR downstream Limarí

All scenarios are considered without a system drought index (DI), assuming that no artificial shortages are induced and water used as needed in case available.

The analysis was done comparing the modelled monthly streamflow[51] of each month of the whole sequence with the monthly requirements of minimum ecological flow calculated in chapter 4.4.1 (here all different regulation/legislation of 2002, 2008 and 2012 are considered). The analysis is performed for each selected CP and scenario.

Thus here, other as in the previous approach, the theoretical minimum flows were not put as a requirement into the model. This reflects the reality, since legally the minimum flows cannot be claimed here, because the rights were approved before these regulations has been implemented, but the impact on them has to be studied and evaluated.

The results are expressed as monthly failure in percentage of the total months considered. A failure F is defined as follows:

F = 1, if: $Q_{mreg(sim)} < Q_{meco(cal)}$

F = 0, if: $Q_{mreg(sim)} \geq Q_{meco(cal)}$

With: $Q_{mreg(sim)}$: Mean monthly regulated flow resulting from the simulation

$Q_{meco(cal)}$: Monthly minimum ecological flow, calculated according to Chilean legislation

For some CPs two stretches had to be looked at and therefore also two results were obtained:

1. CP20: until CP20 (confluence of Grande River and Hurtado River) the flow is higher (regulated flow + flow diversion), after CP20 just the regulated flow is left.
2. CP-13 (Fragüita): in scenario 11, 12 and 23 evaluated two times: (i) one at the entrance of the reservoir and (ii) at the outlet and in the base scenario S1, (i) before diversion of CP-13 and (ii) after diversion.

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[51] Modelled streamflow: most of the times the simulation results of the regulated flows are the modelled monthly streamflow, to be compared with the legal minimum flow; nevertheless in some CPs the diversion had to be added too, resulting from simplifications or allocation calculations; not all CP could be treated in the same way.

Simulation of various scenarios: minimum flow Qeco

Since all sub-catchments are different concerning the natural flow and further regulations and water use, the first objective is to evaluate the average percentage of failure per CP (F_{CP}) for each sub-catchment, with:

$$F_{CP}\ [\%] = \frac{\sum_{m=i} N(F=1)}{\sum total\ month\ m} * 100$$

F_{CP}[%] = Failure in % of CP under consideration

N = number of failures (F=1)

First the current scenario (S1a) and secondly the "final" future scenario (S23) are analysed. The percentage of failure per sub-catchment is the average percentage of failure of all CP considered in one sub-catchment.

The resulting failures of S1, aggregated per sub-catchment and for each of the different regulations (y axis) are presented in Figure 83. As expected the maximum failures result from the most recent legislation of 2012, since the requirements are the highest, too. The failures reach 38% in the basin, as average of all sub-basins, compared with just 18.3% failure, taking into account the legislation of 2002. The legislation of 2008, which, as explained before, might be a good indicator for a hydrological based ecological minimum streamflow (Qeco) in the region and thus in the basin, has an average failure of 31% in total, similar to 2012.

The downstream basin, here represented through CP-20 and CPEND shows the maximum percentage of failure with the regulations of 2012 and 2008; this could be expected, since the downstream part, with the two reservoirs (La Paloma and Recoleta) is highly intervened. The smallest failures occur in the sub-catchment of the Grande River with 11% considering the regulation of 2008 and 14% with Qeco calculated according to the 2012 regulations.

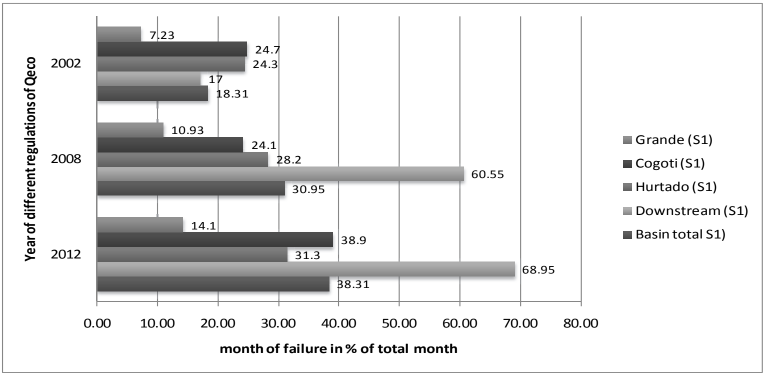

Figure 83: Percentage of monthly failures per sub-catchment/basin with the different legal requirements (S1)

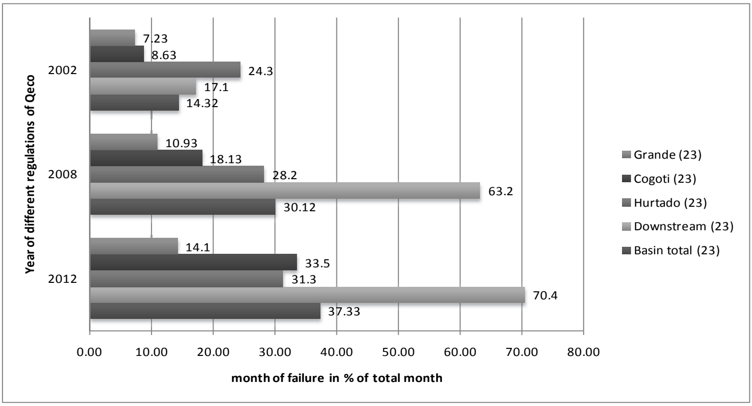

Figure 84: Percentage of monthly failures per sub-catchment/basin with the different legal requirements (S23)

Comparing the current scenario S1 (Figure 83) with S23 (Figure 84), where all new possible upstream uses of Cogoti are considered, the Cogoti sub-catchment displays fewer failures with all different regulations. With the 2002 legislation the percentage of failures decreases 16% reaching about 9% of failures. Considering the regulations of 2008 and 2012 failures are decreasing in each about 6%, resulting in 18% of failure considering the regulations of 2008 and 34% of failures with the newest regulation of 2012. The downstream part gets similar results as in S1, decreasing in both last legislations only about 2% (Figure 84). Thus the new possible reservoir has a positive influence on Qeco in Cogoti and almost no further impact on the rest of the basin.

The second objective is to evaluate each selected CP for the selected scenarios comparing all regulations. Since the flows are quite different in most of the CPs during summer (S: Nov-Mar) and winter (W: Apr-Sep), the month of failures are calculated separately per season and also annually (tot).

Comparison of the simulation results with Qeco calculated according to the legal regulation of 2012

The diagram Figure 85 shows only those CPs, which experienced changes subject to the different scenarios studied. Thus all CPs and their results of the base scenario S1 are presented and evaluated, furthermore the CPs of the sub-catchment of Cogoti (CP-13 and CP-14) are analysed from all considered scenarios, as well CPEND, because of the different required IF and Qeco flows. The results are listed in an ascending order, starting with Scenario 1 and CP56, which is the highest upstream CP in the Grande River and ending with CPEND (S23-S21c).

Simulation of various scenarios: minimum flow Qeco

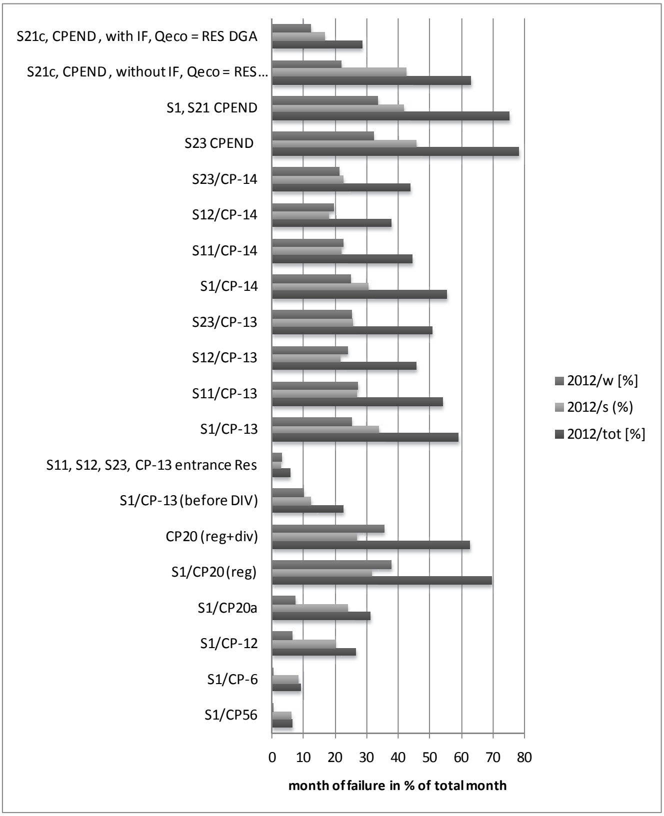

Figure 85: Percentage of monthly failures of not complying with Qeco of 2012 analysing different scenarios and CP

It can be observed that the failures increase from CP56 until CP20 in S1. Until CP20a, and thus upstream of the reservoirs the main failures occurred in the summer months. In CP-20 this changes, since this CP is located in the regulated part of the basin and thus the failures are more equally distributed between summer and winter and even slightly higher in winter, since then less water is released from the reservoir. When considering the river stretch upstream of CP-20, and thus the sum of the regulated flow of CP-20 and diversion in CP-20 (reg+div), the total failure decreases from 70% to 63%, still quite high.

CP-20 obtains the second highest percentage of monthly failures in the basin, after CPEND. This might be due to the fact that it constitutes the confluence of the Hurtado and Grande River and hence is also negatively influenced from the Recoleta reservoir This does not release any water to the Hurtado River in normal years, just in case the reservoir spills.

Analysing in detail the Cogoti sub-catchment the amount of failures in CP-13 varies subject to the different scenarios which consider a new reservoir and changes of extraction points upstream of CP-13. In the best case the river stretch before CP-13 result in 6% failures. This occurs when the extraction points from upstream are moved to the reservoir. The current scenario resulted in the maximum amount of failures, compared to S11 S12, S13, after the diversion.

The failures of CP-14 have the same pattern as in CP-13, but all values are slightly smaller than in CP-13. The lowest percentage of failures is obtained from S12, with 38%.

The outlet of the considered basin in CPEND suffers the main failures in S23 (but similar to S21/S1), almost 80% of all months simulated. This scenario also include an IF record in CPEND. The resulting regulated flow of CPEND is then compared with the Qeco calculated.

For comparison the results of the regulated flow of S21c has been analysed, too. Here first without and the second with IF record, the regulated flows were compared with the minimum ecological flow which was required by the DGA resolution, not Qeco calculated. Here the influences of the IF record is obvious, cutting the failures in more than half. But even in the scenario with the IF-record, the failures reach still almost 30%.

Comparison of the simulation results with Qeco calculated according to the legal regulation of 2008

Comparing the resulting failures shown in Figure 86 with the ones recently discussed, the same pattern are detected; nevertheless all CPs in all scenarios show a lower percentage of failures than before; the best result in about 30% of the failure of 2012 until reaching 96% of the previous failures, thus almost the same as with the regulations of 2012.

The fewest failures are the following: In S1 the upper CPs suffers less failures: CP56 and CP-6 of the Grande River result in 51% and 41% of the previous failures respectively; the stretch before CP-13 gets only 30% of the previous failure; CP-12 keeps almost the same with 96% of the previous failures.

Evaluating the regulated flows with *Qeco 2008* in CP-13 at the entrance of the possible new reservoir no failures occurred in S11, S12 and S23. At the outlet of CP-13 in these scenarios about 55% of the previous failures were reached and CP-14 resulted in between 58% and 68% of the previous failures. The worst are as before are obtained in CPEND, all scenarios reached more than 90% of the previous failures.

The difference between the maximum requirement of 2008/2012 and the requirement of 2002 is around 2.5 m^3/sec. Therefore the decrease of failure between 2008 and 2002 requirements is very high and the percentage of failure of the requirements considering the regulations of 2002 very low with an average of all presented CPs and scenarios of 16.6%. The objective was to present the differences and changes in legislation and impact over the last decades. But since the first regulation of 2002 is obsolete considering all the new knowledge about minimum ecological flows, no further detailed discussion about the outcomes is done.

Simulation of various scenarios: minimum flow Qeco

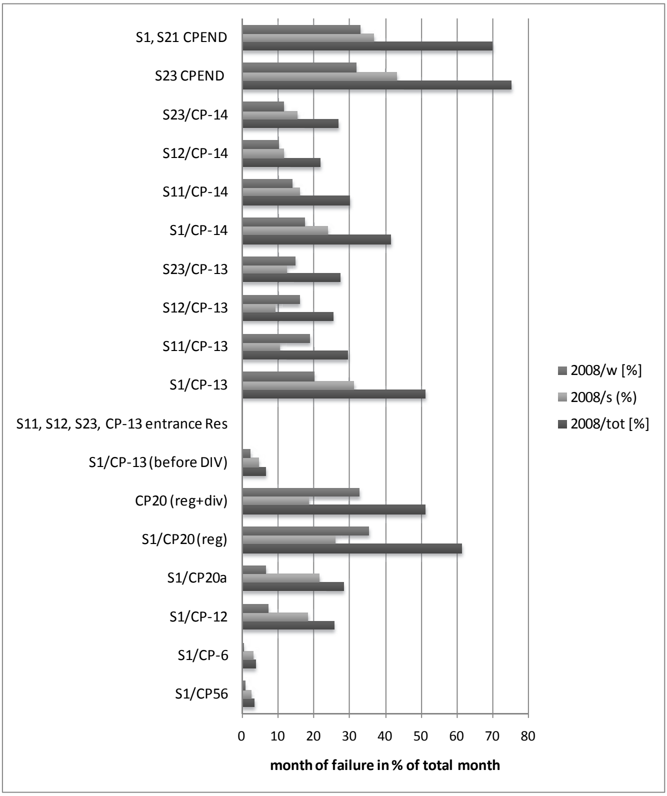

Figure 86: Percentage of monthly failures of not complying with Qeco of 2008 analysing different scenarios and CP

Conclusions

- The results of evaluating the instream flow IF confirm again that scenario S21.b, leads to the best compliance with an annual mean shortage of 4.16 MCM. The total required IF is not available in most of the years.
- None of the historic and more recent legal requirements for the minimum ecological flow (Qeco) can be satisfied in total, neither in the current nor in the future scenarios. The results with the requirement of 2008 are better than with the more recent regulation of 2012. Forcing the fulfilment of Qeco in the evaluated CP, would consequently result in very high shortages in the supply of the WR.
- One has to be aware that the CP aggregates a sum of water rights, which are assumed to be supplied together. This is a simplification of all the extraction points along the rivers and thus might result in some cases in worse outcomes as occurring in reality. Nevertheless the differences are not expected to be significant, knowing the amount of failures of the previous calculations

6.5 Modelling and performance analysis of each reservoir using different operational system rules in different scenarios

The following flow chart shows the three scenarios which were simulated each with three different operational rules, defined below.

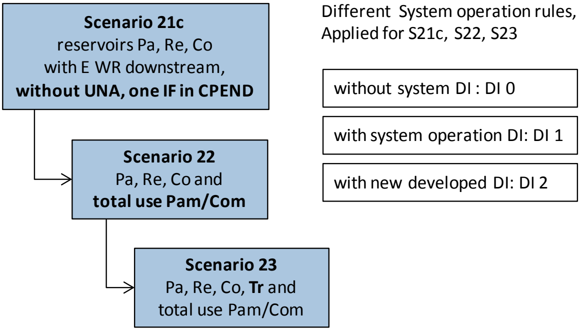

Figure 87: Diagram of scenarios used for DI System evaluation

Each of the final scenarios S21c, S22 and S23 has been simulated three times, with different system management strategies (implemented with the drought index, DI) and evaluated:

1. DI 0: without a DI (drought index) system record, thus as much water as available can be distributed from the three reservoirs depending just on the target and use factor of the WR
2. DI 1: with the current DI system record (prevailing operational rule of the La Paloma System). The system rule had to be translated in model logic and resulted in the following drought index record (as used in the model:

DI[52]	1	3	ResPa	ResCo	ResRe				
IS[53]	7	0	200	300	400	499	500	1000	[$10^6 m^3$]
IP[54]		20	30	46	61	77	100	100	[%]

The model is evaluating each month the sum of the current volume of the reservoirs and depending on the result a certain percentage of the target is supplied.
The DI record can be translated to the following target supplies:

IF $\sum ResPa + ResCo + ResRe \geq 500\ MCM$ => 100% * T_{max}
IF $400 \leq \sum ResPa + ResCo + ResRe < 500\ MCM$ => 61% - 77% * T_{max}
IF $300 \leq \sum ResPa + ResCo + ResRe < 400\ MCM$ => 46% - 61% * T_{max}
IF $200 \leq \sum ResPa + ResCo + ResRe < 300\ MCM$ => 20% - 46% * T_{max}
With T_{max} = 320 MCM
The last 20 % have to be assigned, since also the incoming streamflow is going to be used for supply. To guarantee its use, a certain percentage has to be defined although the reservoir might be empty.

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[52] DI (Drought Index reservoir): here three reservoirs, which are going to be evaluated together (Paloma, Cogoti, Recoleta)
[53] IS (Index Storage): Sum of the volume of the reservoir in 10^6 m^3
[54] IP (Index Percentage table): percentage of target to be supplied when defined storage is reached

3. DI 2: Finally after various different test simulations the following new DI system record will be presented, which gets intermediate results to the before described. Here the percentage of the target to be supplied is increased.

DI	1	3	ResPa	ResCo	ResRe				
IS	7	0	200	300	400	499	500	1000	[$10^6 m^3$]
IP		20	45	65	75	99	100	100	[%]

The DI record can be translated as before, just the target supplies are higher.

IF $\sum ResPa + ResCo + ResRe \geq 500\ MCM$ => 100% * T_{max}
IF $400 \leq \sum ResPa + ResCo + ResRe < 500\ MCM$ => 75% - 99% * T_{max}
IF $300 \leq \sum ResPa + ResCo + ResRe < 400\ MCM$ => 65% - 75% * T_{max}
IF $200 \leq \sum ResPa + ResCo + ResRe < 300\ MCM$ => 20% - 65% * T_{max}
With T_{max} = 320 MCM

The objective is to evaluate which management might be preferable. Therefore the supplies of each reservoir are analysed in detail. The results are manifold and after a first assessment the decision has been made to use the following indicators for evaluation:

- *Storage frequencies and characteristics:*
  85% storage reliability, Spills (counts of the years with spill), average spill of all years, Evaporation (MCM/annual)
- *Reliabilities metrics Shortage metrics indices:* as before

Where necessary the detailed results of the single WR had been aggregated to evaluate the performance of the reservoir supply.

In the following the resulting diagrams are presented for better analysis and discussion were necessary; the results are organised per reservoir, scenario and system DI.

6.5.1 Cogoti reservoir

Scenario 21c

The main indicators of storage and volume reliability are almost equal with all system DI rules. Looking at the shortages with the introduction of the DIs they increase clearly and as expected, the result of the period reliability decreases from about 95% to 65%. Furthermore with both DI the amount of spill also increases, until 3 MCM/year with the system operational DI (DI 1).

Evaluating furthermore the shortage almost all are worse with the introduction of the system DI, but all are still very low, since in this scenario the target is lower and shortages are only induced by the DI. The highest shortage index reaches 2.2 month^{-1}.

This can be confirmed with the storage line presented in Figure 88. Not many changes can be observed and the reservoir keeps more water than necessary assuming that the historical hydrological sequences are also repeated in the future. This might be the reason why often more water was released and the common operational rule (DI 1) not always followed by the ACECogoti (compare sub-chapter 6.3).

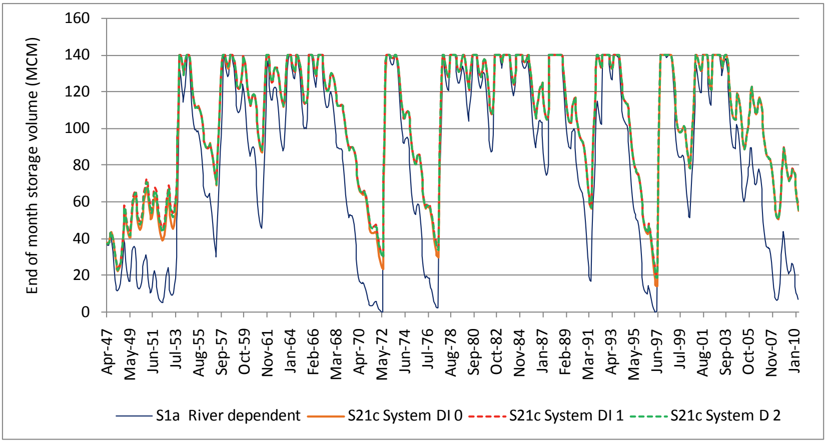


Figure 88: End-of month storages (MCM) of Cogoti, scenario 21: all possible future set ups and DI simulations

Conclusion: Clearly in these scenarios the operation of the reservoirs should be independent and no common system DI implemented; but an individual, independent DI for the Cogoti reservoirs is recommended, to take the drought years into account.

=> Cogoti in **S21c** is best managed **without a system DI (DI 0)**

Scenario S22

In S22 the results are similar with all system DI, but the 85% storage reliability drop ssignificantly from about 60 MCM in S21 to about 25 MCM in S22. The spill and 85% storage reliability is slightly higher with the use of the DI 1; the maximum number of month with shortage is the same in all system DI simulations, thus no extra shortages are induced by the DI 1 and DI 2. Period reliability again shows the highest differences, better with DI 2 (70.5%) as with DI 1 (61.5%), best in DI 0 (84.4%). Most of the shortage indices, with a maximum average shortage of 2.5 MCM/year, are equal or better with the system DI 2.

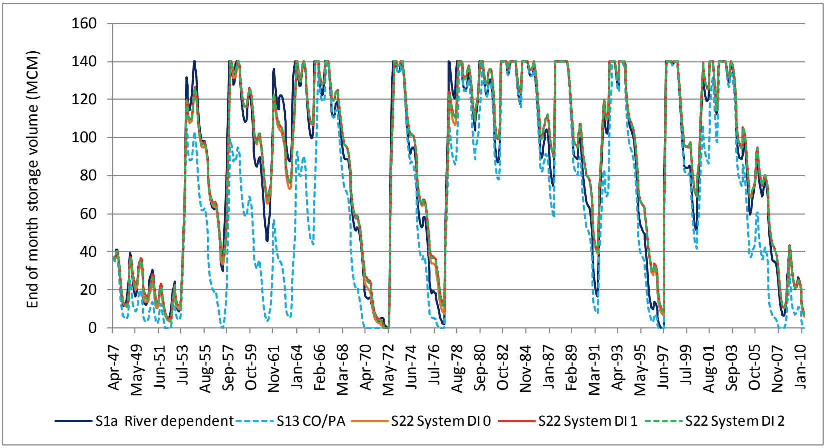


Figure 89: End-of month storages (MCM) of Cogoti, scenario 22: all possible future set ups and DI simulations

Simulation of various scenarios: operational rules

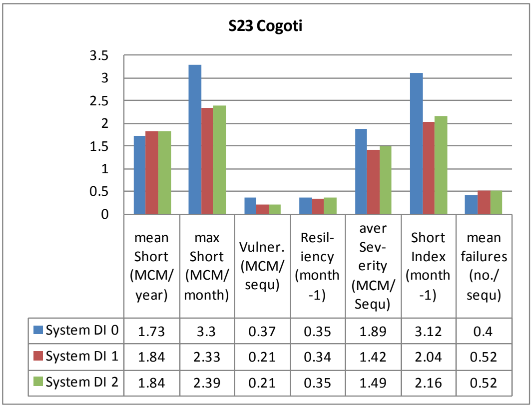
The reservoir curves are all almost the same and follow the curve of the current scenario S1a.

=> This leads to the conclusion that **S22** gets better results with the **final system DI (DI 2)**, but still the differences are not that huge.

Scenario S23

Reservoir indices and reliabilities show similar patterns and almost equal values as scenario S22. Only the period reliability decreases further with DI 2 (to 61%), in S22 it reached 70.5% .

In contrast to the indices evaluated before, the shortage indices show different patterns compared to S22 and result in higher differences between the system DI. Nevertheless the values are still quite low (Figure 90). For the first time some indices are higher without the system DI (DI 0); mainly the maximum shortage, the vulnerability, the average severity and the shortage index. Here simulation with a system DI results in a better reservoir operation.



	mean Short (MCM/ year)	max Short (MCM/ month)	Vulner. (MCM/ sequ)	Resil-iency (month -1)	aver Sev-erity (MCM/ Sequ)	Short Index (month -1)	mean failures (no./ sequ)
🟦 System DI 0	1.73	3.3	0.37	0.35	1.89	3.12	0.4
🟥 System DI 1	1.84	2.33	0.21	0.34	1.42	2.04	0.52
🟩 System DI 2	1.84	2.39	0.21	0.35	1.49	2.16	0.52

Figure 90: Scenario 23, Cogoti shortage indices

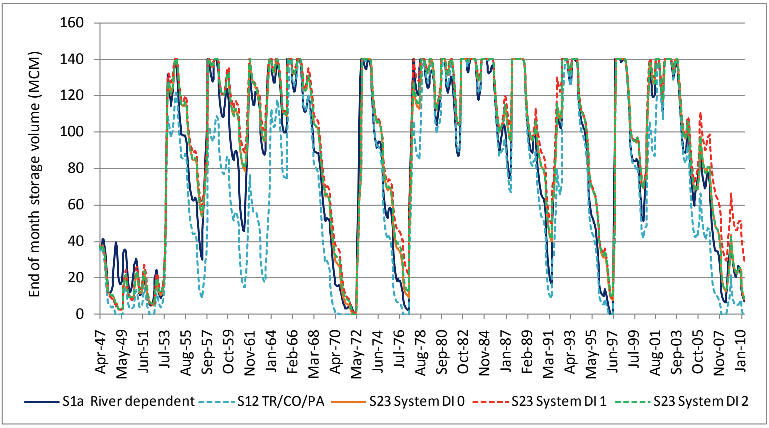


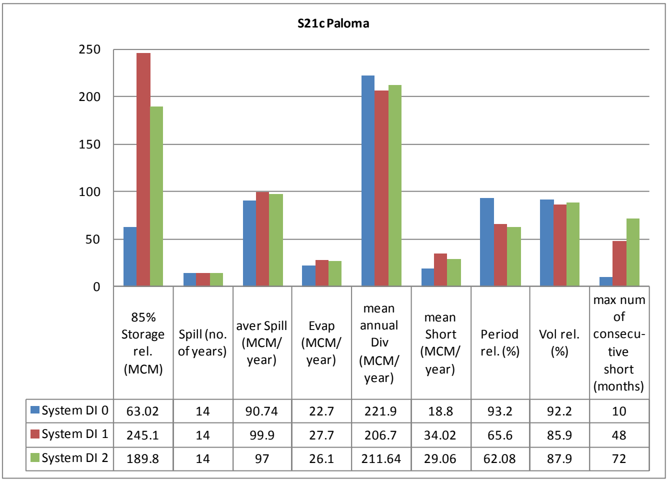
Figure 91: End-of month storages (MCM) of Cogoti, scenario 23: all possible future set up and DI simulations

=> The comparison of the reservoir curves (Figure 91) confirms that for **S23** the **Cogoti reservoir** is best operated with **the DI operational rule (DI 1)**.

6.5.2 La Paloma reservoir

Scenario S21c

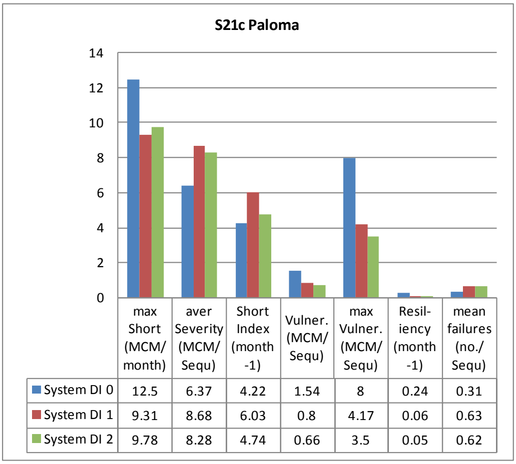
The pattern of the indices in Figure 92 are very similar to the indices of the Cogoti reservoir with the main difference in the 85% storage exceedance probability, which It is just about 8% of the capacity in the scenario without DI; the highest is observed using system DI 1, it reaches a volume of 33% of the capacity and with system DI 2 about 25%.



	85% Storage rel. (MCM)	Spill (no. of years)	aver Spill (MCM/ year)	Evap (MCM/ year)	mean annual Div (MCM/ year)	mean Short (MCM/ year)	Period rel. (%)	Vol rel. (%)	max num of consecu-tive short (months)
🟦 System DI 0	63.02	14	90.74	22.7	221.9	18.8	93.2	92.2	10
🟥 System DI 1	245.1	14	99.9	27.7	206.7	34.02	65.6	85.9	48
🟩 System DI 2	189.8	14	97	26.1	211.64	29.06	62.08	87.9	72

Figure 92: Scenario 21c, La Paloma reliability and shortage indices, part 1

As before due to the introduction of the system DI, shortages are induced, which result in higher number of shortages and less period reliability (precaution has to be taken while interpreting the diagram: different units, as detailed denoted in the columns are presented).



	max Short (MCM/ month)	aver Severity (MCM/ Sequ)	Short Index (month -1)	Vulner. (MCM/ Sequ)	max Vulner. (MCM/ Sequ)	Resil-iency (month -1)	mean failures (no./ Sequ)
🟦 System DI 0	12.5	6.37	4.22	1.54	8	0.24	0.31
🟥 System DI 1	9.31	8.68	6.03	0.8	4.17	0.06	0.63
🟩 System DI 2	9.78	8.28	4.74	0.66	3.5	0.05	0.62

Figure 93: Scenario 21c, La Paloma shortage indices, part 2

The pattern of the shortage indices are unlike the pattern of the Cogoti reservoir in the same scenario. The average severity and shortage index are best without a system DI. The second best is reached with system DI 2, which results furthermore in the lowest vulnerability and lower maximum shortage compared to the simulation without system DI (DI 0).

=> The analysis of all indices leads to the conclusion that the best alternative to use is the **system DI 2.** The evaluation of the first shortage indices is not explicit, but the 85% exceedance probability of the storage with 25% of the maximum storage is a sufficient volume to assure some elasticity for the system. This is also confirmed with the reservoir storage curves, here referred to by the green line (Figure 94).

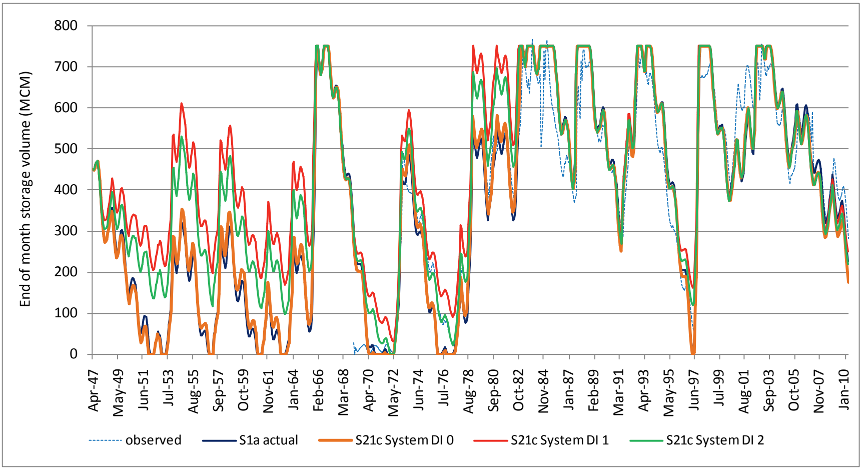


Figure 94: End-of month storages (MCM) of La Paloma reservoir, scenario 21c: all possible future set ups and DI simulations

Scenario S22

As expected S22 results in the same pattern as the scenario before, but with even less volume for the 85% exceedance storage probability for all system DI (between 3.6% until 31%), all shortage indicators are just slightly worse.

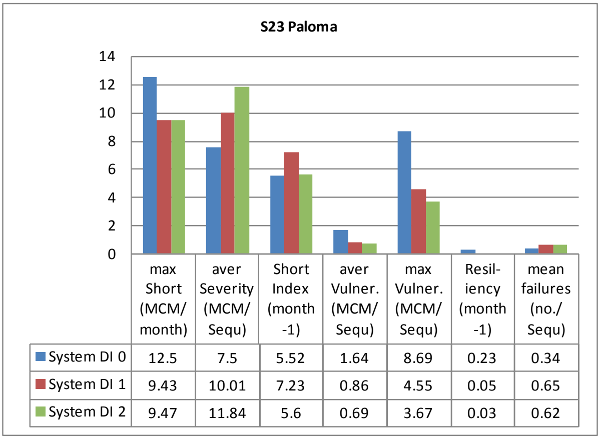
This is confirmed by the reservoir curves, which are in water scarce years slightly lower as in the previous scenarios.

=> Finally the **system DI 2** is recommended for S22, too, although it could be that a new system DI, which simulates the targets in between system DI 1 and system DI 2, could even perform better.

Scenario S23

The La Paloma reservoir performs in scenario S23 as before in S21c and S22; again almost all indices have the same pattern and are similar to the values of S22. The amount of spill decreases slightly between S21c and S23. One exception is the average severity, which is increasing from DI 0 to DI 2 and is higher as before (Figure 95). Although again the values are not very different, now the worst value results from the system DI 2.

=> Nevertheless, also here, **system DI 2**; or another which could be between DI 1 and DI 2 is recommended (see S22).



	max Short (MCM/ month)	aver Severity (MCM/ Sequ)	Short Index (month -1)	aver Vulner. (MCM/ Sequ)	max Vulner. (MCM/ Sequ)	Resil- iency (month -1)	mean failures (no./ Sequ)
🟦 System DI 0	12.5	7.5	5.52	1.64	8.69	0.23	0.34
🟥 System DI 1	9.43	10.01	7.23	0.86	4.55	0.05	0.65
🟩 System DI 2	9.47	11.84	5.6	0.69	3.67	0.03	0.62

Figure 95: Scenario 23, La Paloma shortage indices, part 1

The recommendation is strengthened by a further analysis of the storage statistics (Figure 96). The Standard Deviation (Std. Dev.) is higher in the scenarios without DI, the mean is about 350 MCM and the Std. Dev. 250 MCM, the 85% volume probability just 30 MCM.

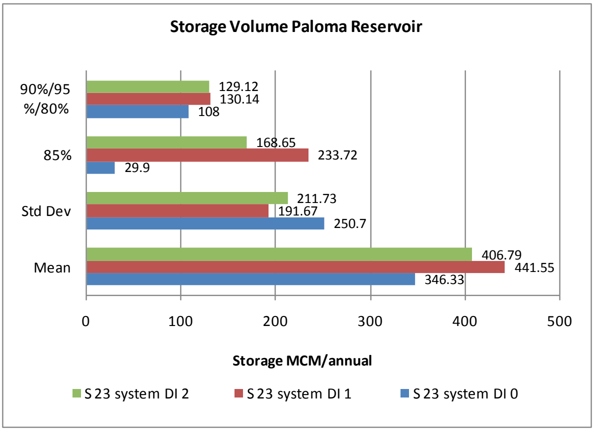


Figure 96: Details of storage volume of La Paloma with S21c, S22, S23

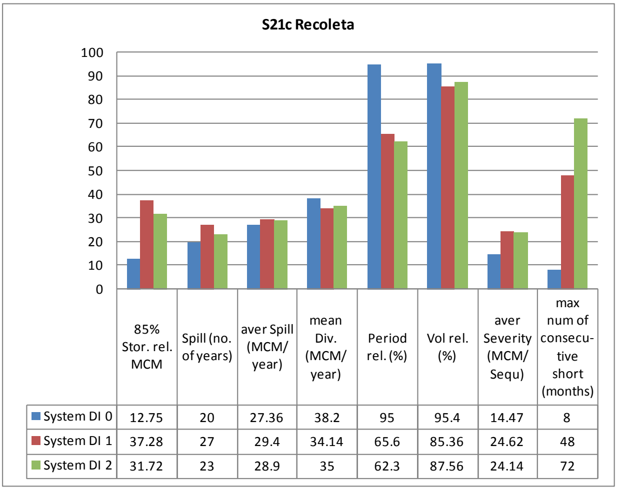
With the system DI 2, the Std. Dev. decreases to about 200 MCM, the mean is 400 MCM and the 85% results in 170 MCM, thus the probability is higher that water can be served with a certain percentage of reliability, also in water scarce years. With the system DI 1 the mean storage is about 40 MCM in average higher and the 85% storage exceedance probability about 60 MCM, which is probably not necessary.

Almost no difference between S22 and S23 can be observed analysing the reservoir curves and thus not presented here.

6.5.3 Recoleta reservoir

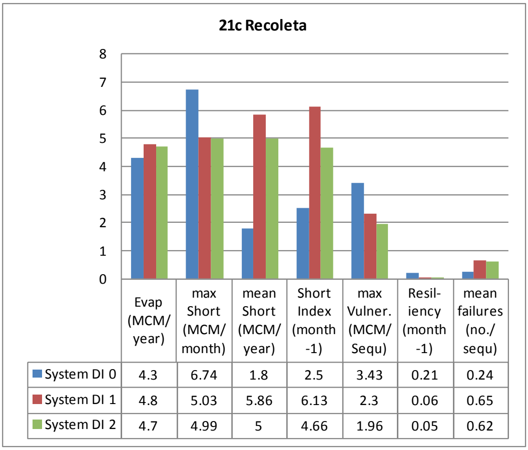
Scenario S21c

In general the Recoleta reservoir is more independent of changes happening in the other sub-systems, since it is not directly connected to the other reservoirs. Analysing the results of the different scenarios and evaluating just the simulation without any system operation rule (System DI 0) this can be confirmed. All indices get the same results (example Figure 97). Thus the changes in the sub-system of Cogoti do not have any influence on the Recoleta reservoir system. When introducing a system DI the results change, since then the target of Recoleta is dependent on the volumes of the other reservoirs.



	85% Stor. rel. MCM	Spill (no. of years)	aver Spill (MCM/ year)	mean Div. (MCM/ year)	Period rel. (%)	Vol rel. (%)	aver Severity (MCM/ Sequ)	max num of consecu-tive short (months)
🟦 System DI 0	12.75	20	27.36	38.2	95	95.4	14.47	8
🟥 System DI 1	37.28	27	29.4	34.14	65.6	85.36	24.62	48
🟩 System DI 2	31.72	23	28.9	35	62.3	87.56	24.14	72

Figure 97: Scenario 21c, Recoleta reliability and shortage indices, part 1



	Evap (MCM/ year)	max Short (MCM/ month)	mean Short (MCM/ year)	Short Index (month -1)	max Vulner. (MCM/ Sequ)	Resil-iency (month -1)	mean failures (no./ sequ)
🟦 System DI 0	4.3	6.74	1.8	2.5	3.43	0.21	0.24
🟥 System DI 1	4.8	5.03	5.86	6.13	2.3	0.06	0.65
🟩 System DI 2	4.7	4.99	5	4.66	1.96	0.05	0.62

Figure 98: Scenario 21c, Recoleta shortage indices, part 2

The difference of volume reliability between the different system operational rules is higher than before. The number of spills gets more and also the amount of spill (Figure 97).

Looking at the shortage indices (Figure 98), most are lower in the scenarios without the system DI (DI 0), exception are the maximum shortage and the maximum vulnerability. Evaporation is slightly higher in the DI scenarios, too, since less water is used.

Analysing the storage reservoir curves, the indices are confirmed (Figure 99). Water is not used optimal when forcing the system rules also to be applied for the Recoleta reservoir.

On the other hand the maximum shortage and vulnerability are highest in the simulation without a system DI, which leads to the conclusion that here another approach should be implemented. This will further be discussed in the conclusions.

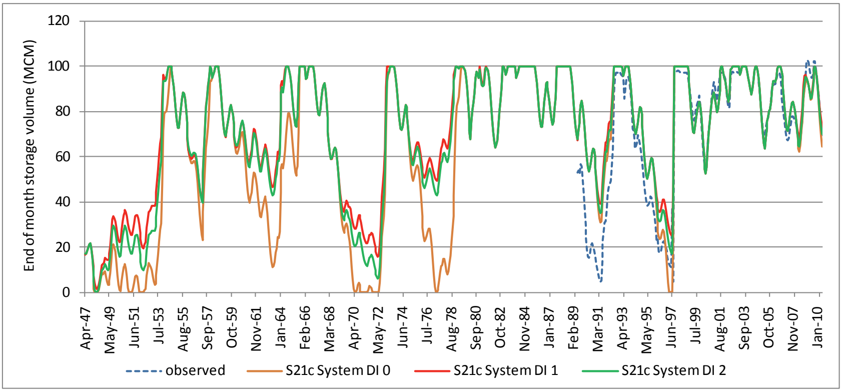


Figure 99: End-of month storages (MCM) Recoleta reservoir, scenario 21c, and DI simulations

Scenario S22

The results of the analysis are similar for all scenarios. The indices of part 1 in S22 have almost the same pattern as in S21c, but worse values in period reliability, mean diversion and the 85% storage reliability gets even higher. Comparing the indices of part 2, they follow exactly the same pattern and are slightly worse, too. Just one exception can be observed: the maximum shortage resulting out of the simulation without DI (DI 0) is higher than before.

Again the reservoir curves show almost the same results as S21c, even a bit higher with the system DI 1 and 2, since with the DIs less water is supplied and more shortages are induced.

Scenario S23

The results are almost identically with S22; just the maximum shortage in system DI 0 is lower again.

=> The following conclusion can be drawn out of the discussed results of the Recoleta reservoir: a system DI as simulated does not improve the situation for Recoleta; on the contrary, it worsens the impact of shortages. Nevertheless shortages are witnessed during the simulation without a DI, thus for this sub-system it will be a good alternative to introduce **a Recoleta DI**, which is just dependent on the storage volume of the Recoleta reservoir and thus manages this system independently from the rest. In a previous scenario one test has been done, using an individual DI for Recoleta, which resulted in less shortages (S21, chapter 6.3.1, results of Recoleta reservoir).

Simulation of various scenarios: operational rules

Summarized the following final recommendations for the use of the system DI for each reservoir in each scenario is obtained:

Table 28: Recommended system DIs for the different scenarios and reservoirs

Scenario	Cogoti	Paloma	Recoleta
S21c	**System DI 0**	**System DI 2**	**New Recoleta DI**
S22	**System DI 2**	**System DI 2**	**New Recoleta DI**
S23	**System DI 1**	**System DI 2**	**New Recoleta DI**

Conclusions

- In general Table 28 shows that the three reservoirs do not react all in the same manner to changes in the catchment, thus it is not recommended to implement a common system DI
- Only in scenario S22 the Cogoti and Paloma reservoir are managed together with the same rule to get the best results. The system rule is always looking at the sum of all reservoirs which can be kept as it is, or also changed only to the sum of Cogoti and Paloma reservoir. The difference will not be huge, but should be simulated, before changes are made in the DI rules.
- For the La Paloma reservoir and its downstream users, the system DI 2 resulted in the most recommendable for all scenarios. A suggestion had been given to probably refine the system DI 2 further (for S22 and S23). This should be done, including the other recommended individual DIs for Cogoti and Recoleta.
- The Cogoti reservoir varies with each scenario. Without any upstream changes the sub-system Cogoti gets better results without a system rule (DI 0), and just the Cogoti management rules. The changes in S22 lead to better results with the "System DI 2" and further S23, with all upstream reservoirs installed is forcing the "System DI 1" to be used, since this is more conservative and thus keeps more water in water scarce years for the coming season, inducing slightly more shortages.
- The Recoleta reservoir is performing best when not included in a system operation rule. With system operation rules, unnecessary shortages are induced and more water is lost through evaporation and spill. Here the recommendation is to developed a new Recoleta DI for further supply improvement, with an individual rule for the sub-system of the Recoleta reservoir
- In addition a further analysis had been done with more detailed reservoir frequency statistics. The storage frequency gives an estimate of how conservative the operational strategies are, the higher the volumes the more conservative and secure, but with induced shortages, depending on the operational rule.

7 Final conclusions and recommendations

The detailed conclusion of each model section has been already presented, here only the main outcomes are summarized. After the development of the model including all input records, simulation and analysis of the results it can be stated that the WRAP modelling system is applicable for the Chilean water management framework and further suitable for this basin. Flexibility is provided for adaption of a broad range of modelling approaches. A huge variety of management records can be combined in many different ways to be able to model any application. Ingenuity is asked from the modeller to achieve the incorporation of sometimes quite complex allocation rules, apply different target options, demands, administrate a variety of users and include new developments within a multiple and multipurpose reservoir-river management system. Although some simplification of the independent sub-catchments had been decided on and simplification (aggregation) of extraction points and thus less control points were considered, the achieved results show that with the model the consequences of allocation decisions, including water transfer and future development are simulated very satisfactory and thus are much better understood. The model system is adequate to serve as a basis for decision making in the basin.

Since simulation time is fast, any change and its result can be assessed more or less quickly, in case the modeller once got all the necessary knowledge about the model functions.

Although the legal water rights are the base for allocation, the real water supply data of the two decades which were used for testing and calibrating the base model, deviated from the legal assigned maximum volumes in some sub-catchments significantly. This shows that the human decisions, not always coinciding with the operation model, are also part of the model and could even be explained in some cases with the obtained results. Here especially it could be confirmed with the model, that the Cogoti reservoir could supply more water per year as previously assigned, which actually has been done in the history, even though sometimes more than the system could support.

In the natural water course sections, here especially the Grande River and Limarí River where supply data are available, the concept of tolerant use of the users in time and volume could be witnessed and has been integrated in the scenarios. Downstream for example the normal supply of the reservoir is fixed, the rest (here the maximum volume calculated with the continuous unappropriated UNA flow) can be supplied by additional streamflow (mixed assignation); but rarely the users can or want to get the maximum allowed volume according to the water rights. Here it depends on demand, availability of water and maximum capacity of the channels. This phenomenon could be well transferred in the model, a maximum limit for supply with streamflow was assigned according to the real data and thus conditioned rights in the lower part could be served, too, or less shortage occurred in other sub-catchments.

This shows that all operational rules and different allocation concepts based on the legal Chilean framework can be incorporated in the WRAP modelling system. The system which is priority based gives without any problems answers for example how new permanent and conditioned water rights might be supplied including their impact on downstream or upstream users (depending which priority they hold).

Furthermore it is also suited for simulating water transfers arising from the water market and thus providing a necessary, reliable and transparent decision basis for the involved stakeholders, which in the most of the times in Chile so far is missing.

Modelling constraints

The model system WRAP holds, as all models, its proper constraints. Since the presented problems and organisations exclusively use surface water, the model is quite appropriate; the strength of the modelling system is surface water allocation analysis. In case the hydrological and operational conditions require more or mainly groundwater, this allocation model cannot be recommended to be used. However some groundwater issues can be incorporated as simple inputs, when modelled before with a groundwater model.

Another restriction might be the available information. The incorporation of the energy generation of the small hydroelectric power plant of the La Paloma reservoir for example had to be disregarded finally, since the attempt to obtain the necessary characteristics of the plant was not successful. The operator of the plant is a private entity and this problem shows that in a system where a lot of private entities are taking part, difficulties occur to get sufficient information for simulating the system with all its specifications.

The model assumption that the historical naturalized streamflows and net evaporation rates are assumed to be statistically representative for future river basin hydrology, presents a constraint or uncertainty. Hydrological variables such as river flows are highly variable, stochastic and uncertain. Positive is that here more than sixty years of naturalized flows could be used after previous naturalization for the simulations. The model and resulting reliabilities are thus typically based on the premise that historical hydrology is statistically representative for the climatic and hydrologic characteristics of the river basin to be expected in the future. Uncertainties are inherent in modelling water management and usage practices. Return flow for example had been estimated based mainly on information about conveyance structures and observations of the organisation.

Recommendations

A further refinement of the system should be modelled, incorporating more control points in the model, especially when water transfers are simulated. Additionally more streamflow data in the upper part of the Pama and Combarbala River are necessary to model in more detail a possible reservoir operation in the independent Combarbala and Pama sub-catchments. This data could be obtained for example by applying a rainfall - runoff model. For this study it would not have changed the worst case scenarios of the total upper use, thus it was not necessary to improve the hydrology of these catchments further in the model.

Another enhancement in time resolution by analysing different operational rules in the CRM-Conditional reliability mode (thus shorter time periods, with chosen starting reservoir volumes) can be simulated with the WRAP system. This can be used to support decision making during drought periods.

Finally looking again on the main results of the different scenarios of the case study considering the further upstream development, it can be stated that according to the model, the basin as a common system holds sufficient resources to deal with these changes. Nevertheless, this would imply that the distribution between the organisations has to be reviewed and adapted to the new conditions. Here mainly the users of the Cogoti reservoir in the downstream catchment could receive a higher share by the Paloma reservoir (the necessary infrastructure is existent). To not curtail only the user of the Limarí River, the association of the channels of the Recoleta reservoir could use more water per year of their reservoir and less from the La Paloma reservoir. Thus the reliabilities of supply decrease for all slightly, but the consequences are shared.

Although it has been confirmed during this investigation that in some cases the organisations use already different assignations (as originally agreed upon) during some years, a redistribution of the volumes in the necessary amount is not very likely to occur. In general it is almost not possible to take an already given benefit officially from one organisation to give it to another. But the model and its result show the possibilities and consequences and thus serve as a good discussion and decision basis. The pressure of the scarce water resources is getting higher for all actors in the basin, thus it might be the time for rethinking. Having shown that the model is very suitable for Chilean basins with predominant surface water use, the model is recommended to be applied in catchments with similar conditions as presented.

8 References

Ainsa Alvaro (2009): Caracterización del potencial hídrico xilemático en vid de mesa (vitis vinifera L.) cultivar Thompson Seedless, bajo diferentes niveles de reposición hídrica en la Provincia de Limarí, Chile, Universidad de La Serena, Facultad de Ciencias, Escuela de Agronomías

Alvarez P., Kretschmer N., Oyarzun R. (2006): Water management for irrigation in Chile: causes and consequences: Kongress der Wasser Berlin 2006: Integrated water resources management in Africa, Asia and Latinamerica}

Alfaro C., Honores C. (2001): Análisis de la disponibilidad del recurso hídrico superficial en causes controlados de las cuencas de los rios Elqui, Limari y Choapa, Thesis de la Universidad de la Serena, Facultad de Ingenieria, Departamento Obras Civiles

Allen R., Pereira L., Raes D., Smith M. (1998): FAO Irrigation and Drainage Paper, No. 56: Crop Evapotranspiration, Guidelines for computing crop water requirements, FAO -Food and Agriculture Organizations of the United Nations Rome 1998 (http://www.fao.org/docrep/x0490e/x0490e00.htm), with corrections of 2006 (http://www.kimberly.uidaho.edu/water/fao56/fao56.pdf)

Barrios , A. G., Urrubarri L. A. (2010): Aplicación del modelo SWAT en los Andes Venezulanos: Cuenca alta del río Chama, Revista Geográfica Venezolana, Vol. 51(1) 2010, 11-29.

Bauer, C. (2004) Siren Song: Chilean Water Law as a Model for International Reform, Washington DC: Resources for the Future Press, 173 pages.

Bauer C., Schlager E.(2011): 1.02 - Governing Water: Institutions, Property Rights, and Sustainability, In Treatise on Water Science, edited by Peter Wilderer, Elsevier, Oxford, 2011, Pages 23-33, ISBN 9780444531995, http://dx.doi.org/10.1016/B978-0-444-53199-5.00003-8.

Brown Fernández Ernesto, Ferrer Artigas Patricio (1976): Estudio hidrológico y operacional del sistema paloma, Ministerio de obras públicas, Dirección de Riego, Chile

Cazalac (2012): Project data base: Modelo integrado para la gestión hídrica sustentable del valle del Huasco: Caudal ambiental y valoración de servicios, accessed with Sr. Leoncio Francisco Martínez Barrera

Chaube U.C, Suryavanshi S., Nurzaman L., Pandey A. (2011): Synthesis Of Flow Series Of Tributaries In Upper Betwa Basin, International Journal of Environmental Sciences, Vol.1 No.7, 2011

Cristi (2001): Mercado de Agua para Irrigación: Una Aplicación al sistema Paloma de la Cuenca de Limarí, Chile; Informe Final: World Bank-Netherliangs Water Partnership Programm (BNWPP), Julio 2001

CIREN (1997): Eto values, published by CNR (Comisión Nacional de Riego): estudio "*Cálculo y Cartografía de la Evapotranspiración en Chile*", realizado por la CNR, in digital format on CD, distributed though CIREN: Centro de Informacíon de Recursos Naturales

Código de Agua (2005): Ley 20017, Art. 1º Nº 16, Titulo X: De La Protección De Las Aguas Y Cauces Ley 20017; D.O. 16.06.2005

Código de Aguas (2005): Código de Aguas, 13. Augusto de 1981, ultima modificación: Ley 20017. 16.06.2005, Biblioteca de Congreso Nacional.

Código de Aguas, 1981: the last versión accessed the 15.10.2013 (http://www.leychile.cl/Navegar?idNorma=5605), assessed 26.01.2010

References

CONAMA (Comisión Nacional del Medio Ambiente) (2006) Estudio de la variabilidad climática en Chile para el siglo XXI. Comisión Nacional del Medio Ambiente, Santiago

CONAMA Política para la Conservación y Protección de Glaciares. Comisión Nacional del Medio Ambiente, Santiago, Chile (2009). Available at http://www.conama.cl/portal/1301/articles-45467_PoliticaGlaciales.pdf
(Accessed: December 2009)

CONAMA, 2004. Guía CONAMA para el Establecimiento de las Normas Secundarias de Calidad Ambiental para Aguas Continentales Superficiales y Marinas, Comisión Nacional del Medio Ambiente, Santiago, Chile (2004).

CONAMA, 2007: Estrategia nacional de Gestión Integrada de cuencas hidrográficas, Santiago de Chile 2007, Propuesta de 25. Julio 2007

CONAMA. Estrategia Nacional de Gestión Integrada de Cuencas Hidrográficas, Comisión Nacional del Medio Ambiente, Santiago, Chile (2007).

DGA (2002): Manual de Normas y Procedimientos para la Administración de Recursos Hídricos, Dirección General de Recursos Hídricos, Departamento de Administración de Recursos Hídricos, Ministerio de Obras Publicas, República de Chile, Santiago 31. Mayo 2002

DGA (2005): MAGIC v1.3: Modelación Analitica, Genérica y Integrada de Cuencas, Manual de Referencia Técnica Versión 1.1., Agosto 2005, SIT 107, Gobierno de Chile, MOP, DGA

DGA (2008): Manual de Normas y Procedimientos para la Administración de Recursos Hídricos, S.I.T. N^o 156; Dirección General de Recursos Hídricos, Ministerio de Obras Publicas, Republica de Chile, Santiago 17. Diciembre 2008

DGA (2014): Evolución e Implicancias en la Aplicación del Caudal Ecológico para la Constitución de Derechos de Aprovechamiento, Dirección General de Aguas, Ministerio de Obras Públicas, Valparaíso, 23. April 2014, access Internet: 4.07.2014: http://www.camara.cl/pdf.aspx?prmID=15907&prmTIPO=DOCUMENTOCOMISION

DGA, 2004: Model MQM win v.1.0 Simulación de Caudales Medios Mensuales DGA, Direccion General de Agua, Departamento de Estudios y Planificación

DGA, 2007. Mesas Regionales del Agua. Informe Técnico Nº 7. Dirección General de Aguas, Santiago, Chile (2007).

FAO AquaCrop (2013): software http://www.fao.org/nr/water/infores_databases_aquacrop.html

FAO AquaCrop: Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change: AquaCrop, United Nation Framework Convention on Climatic Change:
http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5403.php; consulted July 2015

FAO (web page): Irrigation Water Management: Irrigation Scheduling, Annex I: Irrigation efficiencies http://www.fao.org/docrep/T7202E/t7202e08.htm

FAO Blaney, Criddle (2012): http://www.fao.org/docrep/S2022E/s2022e07.htm#3.1.3 blaney criddle method; consulted January 2012, verified December 2015

Ferreyra E.Raúl, Sellés V. Gabriel, Sellés M. Iván (2001): Riego deficitario controlado en nogales. Estrategias de Riego para enfrentar situaciones de escasez de agua en frutales, Santiago, Chile. Instituto de Investigaciones Agropecuarias. Boletin INIA N° 58. 36p.

Francke (2003): La Situación del manejo Integral de Cuencas Hidrográficas en Chile, Corporación Nacional Forestal, Ministerio Agricultura – Chile, Santiago de Chile, Noviembre 2003

Galleguillos (2008): Personal conversation with the director of the DGA

Gopalan, Hema (2003): WRAPHydro Data Model: Finding Input Parameters for the Water Rights Analysis Package, Thesis: Presented to the Faculty of the Graduate School of The University of Texas at Austin in Partial Fulfilment of the Requirements for the Degree of Master of Science in Engineering, The University of Texas at Austin, May 2003; http://www.crwr.utexas.edu/gis/gishydro03/WRAPhydro/Thesis.doc

Gupta,H.V., Sorooshian S., Yapo P.O. (1999): Status of automatic calibration for hydrological models: Comparison with multilevel expert calibration. J. Hydrologic Eng. 4(2): 135-143.

Hadjigeorgalis, Ereney (2000): Private Water Markets in Agriculture and effects of Risk, Uncertainty and Institutional Constraints; Dissertation, University of California, unpublished

Hadjigeorgalis, Ereney (2004): Comerciando con incertidumbre: los mercados de agua en la agricultura chilena, Cuadernos de Economía, Vol. 41 (Abril), pp. 3-34, 2004

Hadjigeorgalis, Ereney and Lillywhite, Jay (2004): The impact of institutional constraints on the Limarí River Valley water market; Water Resources Research, Vol. 40, W05501, doi:10 1029/2003WR002701, 2004

Handbook of Hydrology, of David R. Maidment, McGraw-Hill, 1993

Harris, Guillermo Donoso (2003): Water Markets: Case Study of Chile’s 1981 Water Code, Global water Partnership, Pontificia Universidad Católica de Chile, Faculty of Agricultural Economics.

Hashimoto Tsuyoshi, Stedinger Jery R., Loucks Daniel P. (1982): Reliability, Resiliency, and Vulnerability Criteria For Water Resource System Performance Evaluation, WATER RESOURCES RESEARCH, VOL. 18, NO. 1, PAGES 14-20, FEBRUARY 1982

Hearne Robert and William Easter K. (1995): Technical Paper Number 315: Water allocation and water markets, An Analysis of gains from trade in Chile by Robert R. Hearne and K. William Easter, World Bank

I-CET Sistema de Consulta Estadístico Territorial ODEPA, Ministerio de Agricultura, VII Censo Agropercuario 2007, data at district level; http://icet.odepa.cl/ assessed 13.04.2011

Indengesa, 1992: Mejoramiento Sistema Paloma IV Region, Estudio Hidrológico, Informe Final; Consultaria OME-04; Ministerio de Obras Publicas, Dirección de Riego, Abril 1992

INE (2007). Instituto nacional de estadística, Censo Agropecuario. Assessed in: www.censoagropecuario.cl, but just at commune level, since 9.April 2009

INSTITUTO NACIONAL DE ESTADÍSTICAS, INE (2007). Censo Agropecuario. Assessed in www.censoagropecuario.cl, but just at commune level, since 9.April 2009

John Briscoe, Pablo Anguita Salas, Humberto Pefia T. (1998): Managing Water as an Economic Resource: Reflections on the Chilean Experience; Environmental Department Papers, Paper no. 62, April 1998

Kretschmer N., Corso S., Alvarez P. (2008): Water allocation strategies and their implications – A Drought in the Limarí Watershed, Chile; Conference proceeding: The International Water Resource Association XIIIth World Water Congress in Montpellier, France, September 2008

Kretschmer Nicole, Wendt Anja (2011): Report about the WSI Limari, CEAZA (Unpublished)

Kretschmer Nicole, Wendt Anja, Oyarzun Ricardo, Henrique Chaves (2011): El índice de Sostenibilidad de Cuencas en la cuenca del Río Limarí en Chile, Memorias del Segundo Simposio Internacional: Constryuendo Caminos de Conociemiento para un Futuro con Sostenibilidad Hïdrica (p.318-325), Programa Hidrológico Internacional, Hidrología para el Ambiente, la Vida y las Politicas –HELP, Panamá 21-24 noviembre 2011

Kretschmer Nicole, Wendt Anja, Oyarzun Ricardo, Henrique Chaves (2011): The Watershed Sustainability Index in the Limarí River Basin, Chile, Journal of Hydrological Environment, UNESCO IHP HELP Programme; Special Edition, Vol. 7, No.1, December 2011.

Kretschmer Nicole, Wendt Anja, Oyarzún Ricardo (2012): Watershed management: Its scope, a general analysis of its situation in Chile, and one approach to deal with it integrating environmental, political and social issues; in: Chile: Environmental, Political and Social Issues, page 69 -90, e-book, Novapublisher, INC 2012

La Paloma (2008): En histórico acto regantes de Limarí firmaron convenio que les entrega la administración del embalse La Paloma para riego más grande de Chile y el segundo de América del Sur.

Legates, D.R. and McCabe G.J. (1999): Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model valitations. Water Resources Res. 35(1):233-241

Ley 20017, 2005: here the changes which are made to the Código de Agua due to the law: (http://www.leychile.cl/Navegar?idNorma=239221&idParte=8131089&idVersion=2005-06-16)

Ley 20417, 2010: here the changes which are made to the Código de Agua due to the law: (http://www.leychile.cl/Navegar?idNorma=1010459&idParte=8848210&idVersion=2010-01-26)

Lostarnau C., Oyarzún J.,Maturana H, Soto G., Señoret M., Soto M., Rotting T., Amézaga J., Oyarzún R.:Stakeholders participation within the public environmental system in Chile: Major gaps between theory and practice. Journal of Environmental Management, 92(10): 2470-2478 (DOI 10.1016/j.jenvman.2011.05.008) (2011).

McMahon T.A. (1993): Hydrologic design for water use; Chapter 27 of

McPhee James and Yeh William W-G. (2007): Multiobjective analysis for sustainability –conjuctive use planning of groundwater and surface water; Chapter 6 of “Water Resources Sustainability”, Larry W. May, Editor in Chief, McGraw-Hill, New York, 2007.

Merlet, H. y Santibañez, 1989: Agroclimatologia y Zonificacoin de la Region Vitricicola Chilena: Bases para la denominación de origen de los vinos

Ministerio de Obras Publicas, Dirección General de Aguas, Departamento de Hidrología (date?): Análisis estadística de caudales en los ríos de Chile, Descripción general de los Trabajos realizadas, biblioteca digital de la DGA: http://documentos.dga.cl/FLU434_v2.pdf

MMA, Ministerio del Medio Ambiente (2012): Reglamento para la Determinación del Caudal Ecológico Mínimo, Decreto N^{o} 014, Santiago 22. Mayo 2012

MN Ingenieros LTDA. (2008)a.: Estudio de Factibilidad construcción embalse Murales Viejas, Región de Coquimbo, Contrato ES-EMV-01, Informe Etapa 1, Doc.No: FMV-IE1-ING-A, Gobierno de Chile, Ministerio de Obras Publicas, Dirección de Obras Hidráulicas

MN Ingenieros Ltda. (2008)b.: Estudio de Factibilidad construcción embalse La Tranca en rio Cogoti, Región de Coquimbo, Informe Etapa 1, Rev. B, N^{o} FLT-IE1-ING-B, Gobierno de Chile, Ministerio de Obras Publicas, Dirección de Obras Hidráulicas

Moriasi, D. N. , Arnold, J. G., Van Liew, M. W., Bingner R. L., Harmel R. D., Veith T. L. (2007): Model Evaluation Guidelines For Systematic Quantification Of Accuracy In Watershed Simulations, ASABE, Soil & Water Division, Vol. 50 (3): 885-900, March 2007

Moy Wai-See, Cohon Jared L. , Revelle Charles S. (1986): A Programming Model for Analysis of the Reliability, Resilience, and Vulnerability of a Water Supply Reservoir, WATER RESOURCES RESEARCH, VOL. 22, NO. 4, PAGES 489-498, APRIL 1986

Mutarello, Darwin (2009): Caracterización del estado hídrico, desarrollo y producción de vid de mesa (Vitis vinifera) cultivar Thomson seedless, durante una segunda temporada bajo diferentes niveles de reposición hídrica, en la localidad de Camarico, Provincia del Limarí, Chile, Universidad de La Serena, Facultad de Ciencias, Escuela de Agronomías

Oyarzún R, P. Alvarez ,N. Kretschmer, M. Muñoz F. Meza, G. Soto, M. Soto, J. Núñez, (2011): Monografia Limarí (unpublished, prepared in the context of a thematic network: Aquiferural (Metodologías de análisis y aplicación de tecnologías para el manejo sostenible de acuíferos en zonas rurales)

Oyarzún R., Jofré E., Morales P., Maturana H., Oyarzún J., Kretschmer N., Aguirre E., Gallardo P., Toro L., Muñoz J., Aravena R. (2015): A hydrogeochemistry and isotopic approach for the assessment of surface water - groundwater dynamics in an arid basin: The Limarí watershed, North-Central Chil; Environmental Earth Sciences, Vol. 73, Issue 1, pp.39-55 (Online since June 2014)

Pizarro Cruz, Veronica Rossana (2001): Efect de Riego Deficitario Controlado (RDC) sobre el Rendimiento y Calidad de la materia prima para Pisco proveniente de la uva Moscatel de Alejandria, Provincia de Limarí, IV Region, Tesis….

PTI, 2005: Levantamiento de Situación base para el programa territorial integrado cuenca Limarí, IV Region de Comquimbo, Informe Final Ano 2005; Proyecto Tecnológico Integral de la Cuenca Limarí

Raes Dirk, Steduto Pasquale, Hsiao Theodore, Fereres Elias (2012): Reference Manual, AquaCrop Version 4.0, FAO Land and Water Division Rome, Italy

Renault Daniel, Vehmeyer Paulwillem (1999): On reliability in irrigation service preliminary concepts and application, Irrigation and Drainage Systems 13: 75–103, 1999.

Rendel, Palmer y Tritton (1967): Informe sobre el proyecto de regadio y desarrollo de La Paloma, Volumen I, Informe, Rendel, Palmer y Tritton, Ingenieros Consultores, Westminster, London, S.w.1., Informe No. R/1018, para Republica de Chile, Ministro de Obras Publicas, Direccion de Riego

Reo, Orlando (1979): Una Interpretación Económica de la Seguridad de Riego ,Cuadernos de Economía, Vol. 16, N° 47, pp. 35-62, 1979. http://www.economia.puc.cl/docs/047reosa.pdf

Rhodos (2006): Aplicación de Metodologías para determinar la eficiencia de Uso del Agua; estudio de Caso de la Región de Coquimbo, elaborado por CAZALAC, Diciembre 2006. 540 p

Riestra Miranda Francisco (2011): “Aspectos Relevantes En La Implementación Caudales Ambientales En Chile”, Jefe de Fiscalización, Dirección General de Aguas, Ministerio de Obras Públicas (Presentation during a workshop for the Project: “Modelo para la Gestión Hídrica Sustentable del Valle de Huasco; Mediante la Evaluación de Caudales Ambientales y la Valorización Económica – Social de los Servicios Hidrológicos” of CAZALAC, Chile)

Rivera Ortíz, Ricardo (2009): Estimación de los coeficientes de cultivo y comportamiento productivo aji, cultivar UF 555, Bajo tres tasas de riego, Provincia de Limarí, Región de Coquimbo, Chile, Universidad de La Serena, Facultad de Ciencias, Escuela de Agronomías

Romano Donato, Leporati Michel (1997): The distributive Impact of the Water Market in Chile: A Case Study in the Limarí Province, 1981 – 1997; http://www.dga.cl/otros/publicacioneslinea/archivos/6.pdf

Santibañez y Juan Caldentey (1987), origen es de Caldentey & Pizarro (1980): CD: Mapa de Evapotranspiración Potencial de Chile, Versión 1.0, 2000; desarrollado por Smartsys S.A., especialmente para l comisión nacional de riego, República de Chile

Sieber J., Purkey, D (2007): WEAP, Water Evaluation and Planning System, User Guide for WEAP 21, Stockholm Environmental Institute, U.S. Center, USA

Simmers I (2003) Hydrological processes and water resources management. In: Simmers I (ed) Understanding water in a dry environment. Hydrological processes in arid and semi-arid zones. International Association of Hydrogeologists. A.A. Balkema, Rotterdam, pp 1–14

Singh, J., Knapp, H.V., Demissie M. (2004) Hydrologic modeling of the Ironquois River watershed usind HSPF and SWAT.

Solanes, Miguel (1996): Mercados de Derechos de Agua: Componentes Institucionales. Revista de CEPAL 59: 83 – 96.

Souvignet M, Gaesse H, Ribbe L, Kretschmer N, Oyarzún R (2010) Statistical downscaling of precipitation and temperature in north-central Chile: an assessment of possible climate change impacts in an arid Andean watershed. Hydrolog Sci J 55(1):41–57

Startz, Richard (2007): EViews Illustrated for Version 6, Quantitative Micro Software, LLC, University of Washington; Palmer Publishing Services

Tapia Araya, A. (2014): Analysis multitemporal de imagines satelitales para la Identificación de suelos regados en las áreas baja del Sistema Paloma, Chile; Universidad de La Serena, Facultad de Ciencias, Escuela de Agronomías

Tongongar, B., Kan Chun-E, Chen Jin Hwua (2008): Can Efficiency offset reliability in Irrigation System?, American – Eurasian J. Agric.& Environ.Sci. 3(2): 269-278, 2008, ISSN 1818-6769

World Bank (2011): Chile - Diagnostico de la gestión de los recursos hídricos. Documento del Departamento de Medio Ambiente y Desarrollo Sostenible Región para América Latina y el Caribe; Publication number 63392 ,World Bank, 31. Marzo, 2011

Wurbs R.A. (1993): Reservoir-System Simulation and Optimization Models, J. Water Resour. Plann. Manage. 1993, 119:455-472

Wurbs R.A. (2005): Comparative Evaluation of Generalized River/Reservoir System Models, TR-282, e FOrt Worth District of the U.S. Army Corps of Engineers, for tTexas Water Resources Institute, College Station, Texas; April 2005

Wurbs, R.A. (2005), "Modeling River/Reservoir System Management, Water Allocation, and Supply Reliability, " Journal of Hydrology, Elsevier, Vol. 300, 2005.

Wurbs, R.A. and Walls (1989): Water Rights Modelling and Analysis, J. Water Resour. Plann. Manage., vol 115, no.4, pp. 416-430, 1989.

Wurbs, R.A: (2006): Methods for Developing Naturalized Monthly Flows at Gauged and Ungauged sites, Journal of Hydrologic Engineering, Vol.11, No.1 , 1.January 2006

Wurbs, R.A., (2010.1) *Water Rights Analysis Package (WRAP) Modeling System Reference Manual*, Technical Report 255, Texas Water Resources Institute, First Edition August 2003, Last Edition 2010.

Wurbs, R.A., Hoffpauir R.J., Olmos H.E., Salazar A., Kim T.J., Schnier S.T.(2010.3) Conditional Reliability, Sub-Monthly Time Step, and Flood Control Features of WRAP, Technical Report 284, Texas Water Resources Institute, March 2010 Draft.

Wurbs, R.A., Jin Kim, Tae (2011): River Flows for Alternative Conditions of Water Resources Development, Journal of Hydrologic Engineering, ASCE, February 2011, Vol.16: 148-156

Wurbs, R.A. (2011): Generalized Models of River System Development and Management, Current Issues of Water Management, Dr. Uli Uhlig (Ed.), ISBN: 978-953-307-413-9, InTech, Available from: http://www.intechopen.com/books/current-issues-of-water-management/generalized-models-of-river-system-development-and-management

Zegarra Eduardo (2002): Water Market and Coordination failures: The Case of the Limarí Valley in Chile, a dissertation at the University of Wisconsin-Madison

9 Annex

Table-A 1: WR Grande River upstream of the La Paloma reservoir and their theoretical target, as well as real diversion

Control Point ID	Water right ID P = permanent E = eventual	Priority	Return Flow CP	Number of WR (acciones)	Theoretical Diversion Target max.MCM/ year/month	New Calc Target (UC) MCM/ year	Real diversion (S1 and more)
CP3	WRCarriP	1000	CP03	159	5.014/0.419	3.566	5.5
CP3	WRCarriE	2000	CP03	1.18	0.037/0.003	0.026	
CP3	WRCP3totP	1000	CP03	255	8.042/0.672	5.721	
CP3	WRCP3totE	2000	CP03	56.32	1.776/0.148	1.264	
CP03	WRTurbioRestP	1000		152	4.793/0.401	3.413	8.0
CP03	WRTurbioRestE	2000		11.45	0.361/0.030	0.360	
CP04	WR1CanalSauceP	1000		100	3.154/0.264	2.244	3.88
CP04	WR1bRestP	1000		92	2.901/0.242	2.063	
CP04	WR04CCharacas	1000		29	0.912/0.076	0.649	
CP04	WR1E	2000		20	0.631/0.053	0.450	
CP4	WRGra1hastaTasscP	1000		107	3.374/0.282	2.398	2.18
CP4	WRGra1hastaTasscE	2000		95	2.996/0.250	2.132	
CP2	WRTascP	1000	CP56	479	15.11/1.262	15.11	5
CP56	WREndofsec1P	1000		77	2.428/0.203	1.728	1.38
CP05	WRTorcaInfer2P	1000	CP-6	210.51	6.639/0.554	4.722	6.876
CP05	WRTorcaInfer2E	2000	CP-6	40	1.261/0.105	0.897	
CP-6	WR612bP	1000		270.49	8.530/0.712	6.070	1.768
CP-6	WR622bE	2000		12	0.378/0.031	0.270	
CP-6	WR622RestP	1000		140	4.415/0.369	3.139	
CP-6	WR622RestE	2000		20	0.631/0.053	0.450	
CP06	WRChanP	1000	CP07	199.54	6.293/0.526	4.492	4.1
CP06	WREndofsec2P	1000	CP07	206	6.496/0.543	4.622	4.145
CP06	WREndofsec2E	2000	CP07	15	0.473/0.040	0.335	3.65
CP07	WR3aPCapPera	1000	CP08	167.3	5.276/0.441	4.510	4.5
CP08	WR3aPPalqui	1000	CP08a	361+*714 (benefit)*	11.38+ 22.517	22.517	16.38
CP08	WR3bP	1000	CP08a	401.58	12.66/1.058	9.01	8.101
CP08a	WR3cP	1000	CP09	641.92	20.24/1.691	14.40	9.5
CP08a	WR3cE	2000	CP09	15	0.473/0.04	0.335	
CP09	WR3dEndofsec3P	1000	CP09b	87.5	2.759/0.231	1.964	1.6
CP09	WR3dEndofsec3E	2000	CP09b	15	0.473/0.04	0.335	
CP9b	WR4P	1000	CP-12	312.5	9.855/0.824	7.011	5.5
CP-12	WR5	1000	CP019	172.79	5.449/0.455	3.875	1.3
CP-12 CP019	*WRPaRefE, conditioned WR, least priority WR owner: National Irrigation Association, Commission de riego*			*38051.75 Refilling rights, this doesn't influence the model*			
Sum				P =4621.1 Palqui : *+714* E =300.95	Tot: 177.727 E =9.49	**Tot: 130.07** **E =7.02**	**Tot: 93.36**

Table-A 2: WR of the Mostazal River upstream of the La Paloma reservoir and their theoretical maximum targets

Control Point ID	Water right ID	Priority	Return Flow Location	WR type	Number of rights (acciones)	Diversion Target (max. MCM/year)
CP7a	WRMost1	1000	CP7	1	940	29.64
CP7b	WRMiguel	1000	CP7	1	390	12.29
CP7	WRMost2	1000	CP7c	1	1040	32.79
CP7c	WRMost3	1000	CP-8	1	1119.875	35.32
CP-8	WRTulahue				180.125	5.68
Sum					**3670**	**115.74**
In the model assumed to be supplied all in the outlet of the sub-catchment						
CP-8	**WRMostot**	**1000**	**CP-8**	**1**	**3670**	**115.74**

Table-A 3: Water rights of the Rapel River upstream of the La Paloma reservoir and their theoretical maximum targets

Control Point ID	Water right ID	Priority	Return Flow Location	WR type	Number of rights (acciones)	Diversion Target (max. MCM/year)
CP9x	WRMolles1P	1000	CP9a	5	114	3.595
CP9x	WRMolles1E	2000	CP10a	5	50	1.577
CP9a	WRMolles2	1000	CP10a	5	588	18.543
CP10a	WRRapel1	1000	CP10b	1	1161	36.613
CP10b	WRRapel2	1000	CP-11	1	1759	55.472
Sum					**3672**	**115.8**
CP-11	**WRRaptot**	**1000**	**CP-11**	**1**	**3672**	**115.8**

Table-A 4: Water rights Combarbala River and their theoretical target, calculated with 1l/sec/WR

Control Point ID	Water right ID	Priority	Return Flow Location	WR type	Number of WR rights (acciones)	Diversion Target (max. MCM/year)
CP15a	WRCombar1P	1000	CP-15	1	781.5	24.64
CP-15	WRCombar2P	1000	CP15b	1	568.5	17.93
CP-15	WRCombarPot	1000	CP15b	1	195.5	6.165
CP15b	WRCombar3P	1000	CP-17	1	2060.5	64.98
Sum					**3606**	**107.55(+6.165)**

Table-A 5: WR and diversion target of the Cogoti reservoir (Huatulame association and Canalistas Cogoti)

Control Point ID	Water right ID	Return Flow Location	WR type	Owner/Water management organization	Number of WR rights (acciones)	Diversion Target (max. MCM/year)	Real diversion (S1 and more)
CP018	WRCoguntilIn	CP18a	1	Canalistas Cogoti (Zone 1	637.3921	4.2724 (6702.94 m3/WR/year)	3.57
CP018	WRHuauntilIn	CP18a	1	JVRHuatulame	86.75	0.8128 (9368.94 m3/WR/year)	5.35
CP018	WRHuauntilIn	CP18a	1	JVRHuatulame	329.59	3.0879 (9368.94 m3/WR/year)	
CP018a	WRCogIntake		2	Canalistas Cogoti (until 48 km channel Matriz)	1884	12.628 (6702.94 m3/WR/year)	33.30
CP018a (CP-12)	WRCogIntake fuente Cogoti or Grande River (indirect: La Paloma)		2	Canalistas Cogoti (zone 4: downstream ResPa) Can be served also by ResPa	1117.8604	7.4929 (6702.94 m3/WR/year served by Cogoti) (9.002) (8053.52 m3/WR/year served by La Paloma)	
CP018a	WRHuaIntake	CP-18	2	JVRHuatulame (channel Aray)	47	0.4403 (9368.94 m3/WR/year)	7.65
CP018a	WRHuaIntake	CP-18	2	JVRHuatulame (again pumped without losses)	547.66	5.1310 (9368.94 m3/WR/year)	
CP18a	WRCauIntake	CP019	2	Canalistas Cogoti (channel Palqui – Cauchil)	915.89	6.1392 (6702.94 m3/WR/year)	5.13
Sum	**Cogoti reservoir**				**5566.1425**	**40.00**	**55.00**

Table-A 6: Water rights Pama River and their theoretical target, calculated with 1l/sec/WR

Control Point ID	Water right ID	Priority	Return Flow Location	WR type	Number of WR rights (acciones)	Diversion Target (max. MCM/year)
CP16a	WRPama1P	1000	CP16b	1	384	12.110
CP16b	WRPama2P	1000	CP-17	1	1069	33.712
CP16b	WRPamaE	1000	CP-17	1	581.6	18.341
Sum					**2034.6**	**64.163**

Table-A 7: WR and diversion targets of the La Paloma reservoir to the different association

Control Point ID	Water right ID	Return Flow Location	WR type	Owner/ Water management organization	Number of WR (acciones)	Diversion Target (max. MCM/year)	Real diversion (S1 and more)
CP019	WRdirectpump (Rights have been displaced to ResPa)		1	JVRGyRL	102.54	0.615 Normally this right has 6,000m3/WR/ year, due to displacement they can lose a part	0.615
CP019	WRPunitPaP		1	Canalistas Punitaqui	803.5	8.544 (due to the % of the La Paloma sytem)	10.00
CP019	WRTamelcP		1	JVRGyRL	627.25	6.2725 (10,000m3/WR /year)	6.6
CP019	WRCaRePaP		1	Canalistas Camarico	3000 Inside the association there are 5499.37 rights	25.28	37.00
CP019	WRCMCg1PaP		1	Canalistas Cogoti	7444.8574	68.9552 (9,262.12 m3/WR/year)	54.00
CP019	WRCamCanal		1	JVRGyRL	255	2.55 (10,000m3/WR /year)	10.6
CP019	WRCamCanal		1	JVRGyRL	31	0.183 (6,000m3/WR/	

						year)	
CP019	WRCamCanal		1	JVRGyRL	790.554	7.906 (10,000m3/WR /year)	
	Sum **WRCamCanal**					**10.64**	
CP019	WRRioGran2 through Canal Matriz		1	JVRGyRL	127 + 20	0.882 (6,000m3/WR/ year)	0.762
CP019	WRRecPa	CP25	1	Canalistas Recoleta	13.714.26	69.4547 (served by La Paloma, canal Matriz)	60.455
CP019	WRRecPa	CP25	1	Canalistas Recoleta	830.54	4.2062 (served by La Paloma: Canal Matriz)	
CP19a	WRRioGran1	CP20	2	JVRGyRL	1160	6.96 (6,000m3/WR/ year)	7.08
CP20	WRRomeral	CP21	2	JVRGyRL	678	4.068	7.3
CP20	WRAguaPot	CP21	2	Agua delValle	300l/sec	(9.46)	(9.46)
CP20	WRLimari (until Potrerillo Bajo)	CP21	2	JVRGyRL	660	3.96	3.96
CP21	WRLim1 (until Vecinario Grande)	CP22	2	JVRGyRL	376	2.256	5.8
CP22	WRLim2 (until Manzanito)	CP23	2	JVRGyRL	1770.71	10.624	14.0
CP23	WRLim3 (until Carajal)	CP24	2	JVRGyRL	440	2.64	5.0
CP24	WRLim4 (until Algarrobo)	CP25	2	JVRGyRL	1008	6.048	6.048
CP25	WRLim5 (until La Huerta)	CP26	2	JVRGyRL	769	4.614	4.614
CP26	WRLim6 (until Panam.)	CPEND	2	JVRGyRL	655	3.93	3.93
Sum	***Permanent WR***			**La Paloma system**	**21.401.95**	**240 MCM (+9.46)**	**237.76 MCM (+9.46)**

Eventual rights (simulated just in the last scenarios, since until now there haven't been used much)							
CP26	WRTal1Even1 Agricola Lomas de Talinary Ltda, conditioned WR	CPEND Priority: 2100	2	JVRGyRL	Just a part: 630 l/sec (tot: 980l/sec)	19.86 (continuous, just from streamflow...)	-
CPEND	WRTal1Even2 Agricola Lomas de Talinary Ltda, conditioned WR	Priority: 2100	2	JVRGyRL	350 l/sec (tot: 980l/sec)	11.037 (continuous, just from streamflow...)	-
CPEND	WRTalIF2 Alternative 2 IF records, the same WRTalIF1 in CP26	Priority: 1001	IF	IF of WR Tal1Eventot	1 m^3/sec	31.539 (continuous, just from streamflow...)	-
CP26	WRSaliEven2 El Satire	CPEND Priority: 2200	2	JVRGyRL	200 l/sec	6.307 (continuous, just from streamflow...)	-
CP26	WRAleEven3 Inversiones Alequin LImitada	CPEND Priority: 2300	2	JVRGyRL	4 m^3/sec	126.14	-
Hydroelectric Power Plant, private Hydropower Company							
CP19	WRHydroL	Non-consumptive	6	private	water which is supplied for irrigation	630.72	-
CP19	WRHydroT		6	private		315.36	-

Table-A 8: WR and diversions for the Recoleta association (by the La Paloma and Recoleta reservoir)

Control Point ID	Water right ID	Return Flow Location	WR type	Owner/Water management organisation	Number of rights (acciones)	Diversion Target (max. MCM/year)	Real diversion (S1 and more)
CP20a	WRRecVilla In Model: **WR20aRec**	CP24	1	Canalistas Recoleta	1027.91	5.206 Just Recoleta, Datacion normal: 5064.4m3/WR/year	38.00
CP20a	WRRecMatriz In Model: **WR20aRec**	CP24	1	Canalistas Recoleta	6855.79	34.7205 Just Recoleta, Datacion normal 5064.4m3/WR/year	
CP20a	WRRecother In Model: **WR20aRec**	CP24	1	Canalistas Recoleta	160.5	0.8128 Just Recoleta, Datacion normal 5064.4m3/WR/year	
CP019	WRRecPa	CP25	1	Canalistas Recoleta	13.714.26	69.4547 served by La Paloma, canal Matriz and Recoeta: Canal Villalon/Canal Matriz Recoleta	60.455
CP019	WRRecPa	CP25	1	Canalistas Recoleta	830.54	4.2062 served by La Paloma: Canal Matriz	
Sum					**22589**	**114.400**	**98.46**

Table-A 9: Sub-catchments with their respective districts as aggregated to calculated the irrigated area according to the Census 2007.

County	District	Sub-catchment	Irrigated area
Combarbala	Valle Hermoso	Rio Pama	67.90
	Pama		116.30
	Soruco		51.60
	Quilitapia		182.02
Total			417.60
Combarbala	Ramadilla	Rio Combarbala	163.70
	Ciudad Oriente		146.80
	Ciudad Poniente		279.70
Total			588.00
Combarbala	Chépica	Rio Cogoti	148.00
	Cogotí		861.63
	La Ligua		30.10
	El Maiten		6.40
Total			1,046.13
Monte Patria	Las Ramadas	Upstream Rio Grande until Rio Mostazal	247.13
	Tulahuén		216.70
	Carén		303.92
Total			767.52
Monte Patria	El Maqui	Rio Mostazal	263.10
	Pedregal		303.10
	Colliguay		154.80
Total			721.00
Monte Patria	Semita	Rio Grande (Between Rio Mostazal and Rio Rapel)	344.62
	Mialqui		391.43
	Chilecito		122.80
	Carén		230.98
	Juntas		394.98
Total			1,484.81
Monte Patria	Las Mollacas	Rio Rapel: Juntas (Final Rio Rapel, until the monitoring station San Juan, Confluence with Rio Ponio)	253.50
	Rapel		848.90
	Cerrillos		270.90
	Juntas		789.96
Total			2,163.26
Monte Patria	Monte Patria	La Paloma	252.90
Combarbala	San Marco	Rio Huatulame until La Paloma	105.32
Monte Patria	San Lorenzo		21.10
	Chañaral Alto		1335.91
	Los Morales		482.65
	Guatulame		236.68
	Palqui		2181.20
	Guanillas		1027.40
Total			5,390.26
Río Hurtado	Las Breas	Rio Hurtado until the Monitoingstation Hurtado en Angostura	556.40
	Chañar		137.30
	Hurtado		159.90
	Serón		184.00
	Fundina		136.30
	El Romeral		13.70
	Pichasca		130.40
	Samo Alto		148.91
	Cachacos		28.00
Total			1,494.91
County	**District**	**Sub-catchment**	**Irrig. Area**
	Tabaqueros	Between Monitoring station and Recoleta	178.39
	El Cobre		6.80
Total			185.19
Ovalle	La Paloma	Rio Grande, de Paloma hasta Rio Hurtado	273.62
	Guallillinga		543.15
	Sotaqui		779.42
Total			1,596.20
Ovalle	Algarrobo	Rio Hurtado hasta Confluencia con Rio Limari	106.00
	Samo Bajo		310.30
	Guamalata		581.74
Total			998.04
Ovalle	Angostura	Creek El Ingenio until Rio Limari	618.36
	Lagunillas		128.80
	El Ingenio		1153.80
	Mirador		25.70
	Limarí		2694.14
Total			4,620.80
Ovalle	Ferrocarril	Limari until El Ingenio	126.65
	Plaza de Armas		109.65
	La Chimba		4080.24
Total			4,316.54
Ovalle	Talhuén	Quebrada	1477.40
	La Torre		916.30
Total			2,393.70
Ovalle	Camarico	Rest of Ovalle until the monitoirng station	2215.43
	Barraza		2785.89
	Cerrillos		4112.39
	Las Sossas		230.99
	Oruro		1218.79
Total			10,563.50
Punitaqui	Llano de La Laja	Punitaqui arriba de Camarico y Chalinga	63.31
	El Altar		38.01
	San Pedro de Quiles		62.01
	Parral		81.71
	Punitaqui		803.12
	Camarico Viejo		1557.31
Combarbala	Huilmo		208.50
Total			2,813.97
Ovalle	Los Canelos	Monitoring station until mouth	148.28
	Socos		67.20
	Fray Jorge		264.62
Total			480.10
			42294.43

Table-A 10: Sub-catchments with the area of each cultivation sub-group and its irrigation efficiency, part 1

Sub-catchment	***Pama Valley***			***Combarbala Valley***			***Cogoti Valley***			***Grande River (Las Ramadas)***			***Grande River (middle part)***		
Surface area irrigated (ha)	417.60			588.00			1046.13			246.90			520.62		
	ha	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*
Vineyard	5.00	1.20%	85%	0.00	0.00%	85%	47.00	4.49%	85%	4.00	1.62%	85%	7.72	1.48%	85%
Pisco grapes	13.00	3.11%	85%	8.00	1.36%	85%	15.22	1.45%	85%	4.00	1.62%	85%	221.90	42.62%	47%
Table grapes	6.80	1.63%	45%	239.00	40.65%	70%	263.80	25.22%	45%	2.30	0.93%	45%	129.30	24.84%	45%
Fruit trees	307.90	73.73%	57%	245.80	41.80%	85%	468.11	44.75%	85%	86.50	35.03%	51%	81.00	15.56%	45%
Legumes..	9.60	2.30%	45%	27.10	4.61%	45%	13.00	1.24%	45%	5.50	2.23%	45%	8.80	1.69%	45%
Vegetables..	3.10	0.74%	45%	21.80	3.71%	45%	15.60	1.49%	45%	2.90	1.17%	45%	6.90	1.33%	45%
Forages	28.30	6.78%	45%	33.60	5.71%	45%	169.70	16.22%	45%	130.00	52.65%	45%	45.40	8.72%	45%
Allotments	43.90	10.51%	45%	12.70	2.16%	45%	53.70	5.13%	45%	11.70	4.74%	45%	19.60	3.76%	45%

Sub-catchment	***Mostazal Valley***			***Grande River (lower part until Rapel)***			***Rapel Valley***			***Puntilla San Juan***			***Huatulme Valley***		
Surface area irrigated (ha)	721.00			1484.81			2163.26			252.90			5390.26		
	ha	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*
Vineyard	50.70	7.03%	85%	3.10	0.36%	85%	96.10	4.44%	85%	0.00	0.00%	85%	0.00	0.00%	85%
Pisco grapes	186.70	25.89%	85%	146.00	17.00%	85%	438.80	20.28%	85%	22.40	8.86%	85%	3.00	0.06%	85%
Table grapes	149.40	20.72%	45%	319.70	37.22%	60%	703.60	32.52%	45%	127.90	50.57%	79%	3,535.36	65.59%	85%
Fruit trees	255.30	35.41%	45%	376.95	43.89%	85%	740.06	34.21%	85%	46.60	18.43%	85%	1,601.20	29.71%	85%
Legumes..	13.20	1.83%	45%	2.30	0.27%	45%	17.70	0.82%	45%	2.00	0.79%	45%	7.30	0.14%	45%
Vegetables..	5.60	0.78%	45%	2.30	0.27%	45%	45.80	2.12%	45%	47.70	18.86%	45%	214.10	3.97%	45%
Forages	34.20	4.74%	45%	0.20	0.02%	45%	87.30	4.04%	45%	2.80	1.11%	45%	4.10	0.08%	45%
Allotments	25.90	3.59%	45%	8.30	0.97%	45%	33.90	1.57%	45%	3.50	1.38%	45%	25.20	0.47%	45%

Table-A 11: Sub-catchments with the area of each cultivation sub-group and its irrigation efficiency, part 2

Sub-catchment	***Hurtado Valley***			***HurtadoRiver (before the reservoir)***			***Lower Part of GrandeRiver until Hurtado River***			***Between Recoleta-Limari River***			***El Ingenio***		
Surface area irrigated (ha)	1494.90			185.10			1596.20			998.04			4620.80		
	ha	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*
Vineyard	37.20	2.49%	85%	0.00	0.00%	85%	18.80	1.18%	85%	38.40	3.85%	85%	142.10	3.08%	85%
Pisco grapes	292.90	19.59%	85%	16.70	9.02%	85%	360.30	22.57%	85%	405.00	40.58%	85%	1,104.20	23.90%	85%
Table grapes	9.30	0.62%	45%	26.20	14.15%	45%	188.20	11.79%	45%	112.40	11.26%	45%	418.10	9.05%	50%
Fruit trees	286.40	19.16%	54%	82.10	44.35%	85%	861.50	53.97%	85%	316.84	31.75%	56%	1,528.40	33.08%	85%
Legumes..	30.50	2.04%	45%	13.60	7.35%	45%	4.90	0.31%	45%	25.00	2.50%	45%	444.80	9.63%	45%
Vegetables..	12.10	0.81%	45%	36.30	19.61%	45%	70.40	4.41%	85%	47.20	4.73%	45%	776.20	16.80%	45%
Forages	754.80	50.49%	45%	4.40	2.38%	45%	89.50	5.61%	45%	38.50	3.86%	45%	203.70	4.41%	45%
Allotments	71.70	4.80%	45%	5.80	3.13%	45%	2.60	0.16%	45%	14.70	1.47%	45%	3.30	0.07%	45%

Sub-catchment	***Limari River until Ingenio***			***Quebrada: Upstream Ingenio***			***Limari River until Panamericana***			***Upper Part of Punitaqui***			***Panamericana station until mouth***		
Surface area irrigated (ha)	4,316.54			2393.70			10563.50			2813.97			480.10		
	ha	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*	*ha*	*%*	*Irr.Effi.*
Vineyard	92.10	2.13%	85%	25.20	1.05%	85%	781.30	7.40%	85%	59.00	2.10%	85%	43.00	8.96%	85%
Pisco grapes	967.70	22.42%	85%	470.90	19.67%	85%	1,323.20	12.53%	85%	892.30	31.71%	85%	0.00	0.00%	85%
Table grapes	485.60	11.25%	59%	0.00	0.00%	45%	600.70	5.69%	45%	378.20	13.44%	45%	0.00	0.00%	45%
Fruit trees	1,104.8	25.60%	85%	1,451.6	60.64%	73%	3,388.00	32.07%	85%	953.97	33.90%	85%	181.70	37.85%	52%
Legumes..	296.00	6.86%	45%	35.00	1.46%	45%	1,081.80	10.24%	45%	87.20	3.10%	45%	11.30	2.35%	45%
Vegetables..	982.10	22.75%	45%	243.60	10.18%	45%	2,422.40	22.93%	45%	88.20	3.13%	45%	46.40	9.66%	45%
Forages	378.70	8.77%	45%	166.00	6.93%	45%	956.40	9.05%	45%	275.30	9.78%	45%	180.10	37.51%	45%
Allotments	9.50	0.22%	45%	1.40	0.06%	45%	9.70	0.09%	45%	79.80	2.84%	45%	17.60	3.67%	45%

Table-A 12: Calculated mean temperatures of eight stations in the basin, out of daily temperature data (data DGA)

Station	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Las Ramadas	17.0	14.8	13.0	12.2	13.2	14.1	16.2	18.2	19.4	19.9	20.0	19.2
Caren	18.0	15.5	13.8	13.2	14.3	15.7	17.6	19.2	20.8	21.4	21.2	19.9
Puntilla San Juan	16.7	14.6	12.3	12.0	13.0	14.5	16.7	18.7	20.5	21.6	21.0	19.3
La Paloma	17.2	14.9	13.0	12.3	13.4	14.9	16.9	18.5	20.3	21.4	21.2	19.7
Cogoti en Embalse	17.3	15.0	12.8	12.0	13.1	14.5	16.7	18.4	20.1	21.0	20.9	19.6
El Tome	17.7	15.0	12.5	12.1	13.6	15.3	17.7	19.8	21.8	22.8	22.4	20.7
Hurtado	17.3	15.2	13.6	12.9	14.1	14.7	16.7	18.3	19.7	20.3	20.5	19.6
Recoleta Embalse	16.7	14.6	13.3	12.4	13.2	14.6	15.7	17.6	19.4	20.4	20.1	19.1

Table-A 13: Eto (mm/mes), calculated with the simple Blaney-Criddle equation

Station	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
Las Ramadas	123	110	96	101	109	117	139	152	168	165	155	146	1582
Caren	127	113	99	105	113	123	145	156	174	172	160	149	1636
Puntilla San Juan	122	110	94	100	108	119	141	154	173	172	159	147	1600
La Paloma	124	110	96	102	110	120	142	154	172	171	160	148	1610
Cogoti en Embalse	124	111	96	101	109	119	141	153	171	170	158	148	1600
El Tome	126	111	95	101	110	122	145	159	179	178	165	152	1642
Hurtado	124	112	98	104	112	120	141	153	169	167	157	148	1604
Recoleta Embalse	122	110	98	102	109	119	137	150	168	167	155	146	1582

Table-A 14: Eto (mm/month) due to CIREN: Calculated based one the values of the CD for each area under consideration

Sub-catchment	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
Pama	86	60	44	48	67	89	123	146	176	174	144	124	1280
Combarbala	87	61	45	49	69	91	126	150	180	178	147	127	1308
Cogoti	96	67	49	54	75	100	138	164	197	195	161	139	1430
Rio Grande (Las Ramadas)	80	56	41	45	63	83	115	137	165	163	135	116	1199
Rio Grande (parte medio)	90	63	46	51	70	93	129	154	185	183	151	130	1341
Mostazal Valley	91	64	46	51	72	95	131	156	187	185	153	133	1362
Rio Grande (lower part until Rapel)	109	76	55	61	85	113	156	186	223	221	183	158	1625
Rapel Valley	104	73	53	58	81	108	149	178	213	211	174	151	1550
Puntilla San Juan	120	84	61	68	94	125	173	206	248	245	203	175	1802
Huatulme Valley	121	85	62	69	95	126	174	208	250	247	204	176	1815
Hurtado Valley	106	74	54	59	83	110	152	180	217	215	177	153	1576
Hurtado (before the reservoir)	117	82	60	66	92	122	168	200	240	238	197	170	1749
Lower Part: Grande - Hurtado	104	72	53	59	81	108	149	177	213	211	174	151	1550
Recoleta-Limari	96	67	49	54	75	99	138	163	196	195	161	139	1428
El Ingenio	88	61	45	50	69	91	126	150	180	178	148	127	1311
Limari - Ingenio	86	60	44	49	68	89	124	147	177	175	145	125	1285
Quebrada del Ingenio	84	59	43	47	66	88	121	144	173	171	142	122	1260
Limari - Panamericana	84	59	43	47	66	87	120	143	172	170	141	121	1253
Upper Part of Punitaqui	86	60	44	48	67	89	124	147	176	175	144	125	1282
Panamericana - pacific	78	54	40	44	60	80	111	133	163	165	136	115	1175

AI between the natural flow of Grande en Cuyano, Rapel in Juntas, Mostazal in Carén y Puntilla San Juan

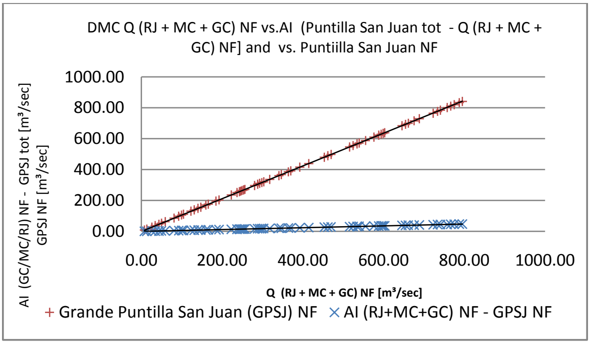


Figure-A 1: DMCs of the natural flow of the entrance of the adjacent catchment of Puntilla San Juan vs. discharge of the AI (of RJ, MC, GC) (blue) and v. the natural fow at the station of Puntilla San Juan (red)

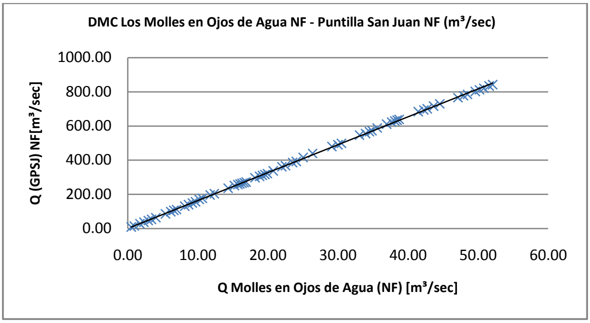


Figure-A 2: DMC of the flow in Los Molles en Ojos de Agua and the natural flow of Puntilla San Juan.

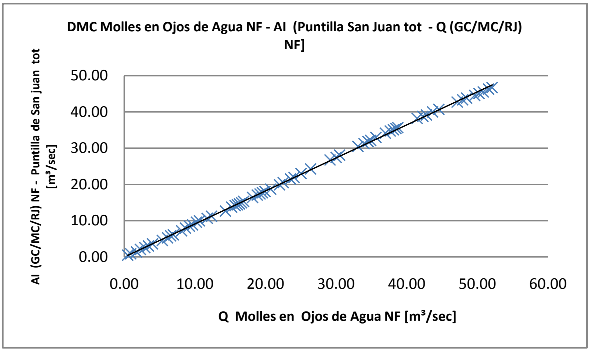


Figure-A 3: DMC of the flow in Los Molles en Ojos de Agua and the adjacent area until Puntilla San Juan.

Natural flow of El Ingenio and Punitaqui Creek

Table-A 15: Final parameter set for MQM win v. 1.0

Catchment	Year No.	Area	Si	Ezi	Cisy	Cevap	P min	Hmax	K	FC	α	Smin	Scrit	Scc
Ingenio	67	118.03	0.01	0.01	1.383	1.00	0.15	600	120	8	30	0.23	0.805	0.974
Punitaqui	67	303.43	0.01	0.01	1.574	1.00	0.025	600	120	8	30	0.23	0.805	0.974

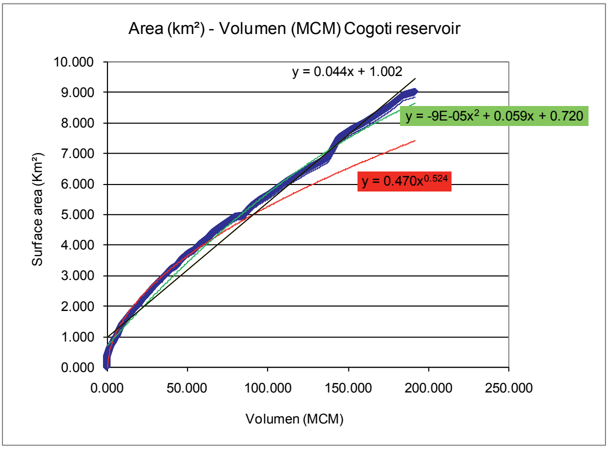
Most of the parameters are in the range of the two former calibrated set of parameters, the change was made in Cisy (A)(looking at the sensibility analysis) and in “α”, with α = 30, the best results are obtained, all other trials of parameter calibration resulted in worst final results.

Developed watershed parameters to use in the model

Table-A 16: Watershed parameters for WRAP model: Accumulated drainage area and average precipitation for all CPs

CP	*Drainage area*	*Average Precip*
CP56	985.8	376
CP-6	1280.4	343
CP2	240.5	277
CP3	121.3	348
CP03	132.3	346
CP04	524.8	435
CP4	701.9	415
CP05	1010.1	373
CP06	1300.4	341
CP07	1371.7	335
CP7a	217.8	403
CP7b	121.8	449
CP-7	260	397
CP7c	424.7	405
CP-8	639.2	376
CP08	2035.6	346
CP08a	2135.7	338
CP09	2185.2	334
CP9x	158.7	346
CP9a	228.6	345
CP10a	511.7	312
CP10b	640.8	299
CP-11	823	275
CP9b	3019.7	317
CP-12	3530.1	297
CP13a	149.9	235
CP13b	303.6	234
CP-13	481.9	224
CP13c	531	221
CP-14	753	211
CP15a	153	214
CP15b	224.1	213
CP16a	159.3	215
CP-17	801.6	210
CP018	1601.3	210
CP18a	2008.7	205
CP-18	2464	199
CP019	6302.7	251
CP-3	2544.4	160
CP-3a	2644.5	159
CP19	6302.6	251
CP19a	6411.2	250
CP30a	6698.4	244
CP20	9343	220
CP21	9377.7	220
CP22	9388.9	220
CP23	9407.8	219
CP24	9718.4	216
CP25	9997.4	213
CP26	10040	213
CPEND	10090.5	212

Reservoir: Developed relationships of volume and surface area for all reservoir



V [MCM]	0.002	1.610	4.264	7.983	13.278	20.011	25.481	31.815	39.053	47.234	56.439	66.699	78.104	90.418	103.996	118.835	134.891	152.945
A [km^2]	0.011	0.586	0.835	1.215	1.619	2.016	2.353	2.709	3.094	3.503	3.873	4.359	4.767	5.193	5.670	6.185	6.657	7.671

Figure-A 4: Cogoti reservoir relationship between surface area and storage volume (finally the table was used for the model)

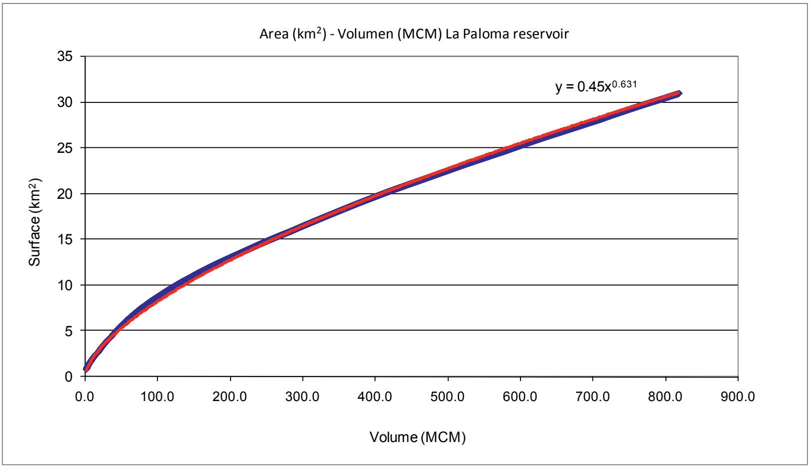


Figure-A 5: La Paloma reservoir relationship between surface area and storage volume, equation used in the model

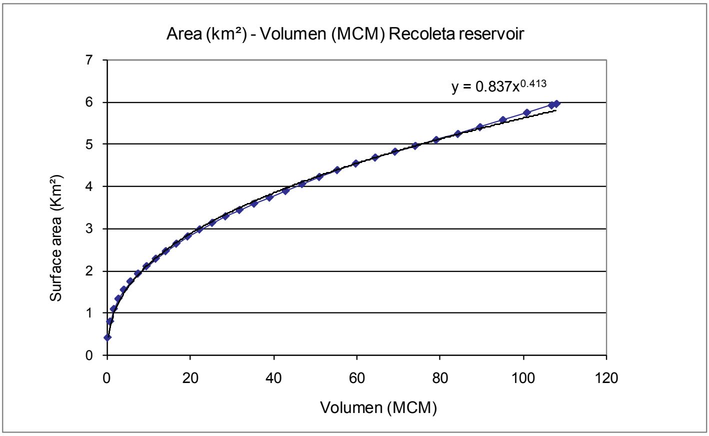


Figure-A 6: Recoleta reservoir relationship between surface area and storage volume, equation used in the model

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