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Article

Integrated Water Resource Management and Energy Requirements for Water Supply in the Copiapó River Basin, Chile

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Abstract: Population and industry growth in dry climates are fully tied to significant increase in water and energy demands. Because water affects many economic, social and environmental aspects, an interdisciplinary approach is needed to solve current and future water scarcity problems, and to minimize energy requirements in water production. Such a task requires integrated water modeling tools able to couple surface water and groundwater, which allow for managing complex basins where multiple stakeholders and water users face an intense competition for limited freshwater resources. This work develops an integrated water resource management model to investigate the water-energy nexus in reducing water stress in the Copiapó River basin, an arid, highly vulnerable basin in northern Chile. The model was utilized to characterize groundwater and surface water resources, and water demand and uses. Different management scenarios were evaluated to estimate future resource availability, and compared in terms of energy requirements and costs for desalinating seawater to eliminate the corresponding water deficit. Results show a basin facing a very complex future unless measures are adopted. When a 30% uniform reduction of water consumption is achieved, 70 GWh over the next 30 years are required to provide the energy needed to increase the available water through seawater desalination. In arid basins, this energy could be supplied by solar energy, thus addressing water shortage problems through integrated water resource management combined with new technologies of water production driven by renewable energy sources.

Keywords: water-energy nexus; arid region; river basin; groundwater; water supply

1. Introduction

Integrated water resources management (IWRM) is a coordinated process to control the development and use of water assets to maximize the resultant economic and social welfare, by addressing management issues through the application of knowledge from multiple disciplines as well as the insights from diverse stakeholders [1,2]. IWRM has become a paradigm for water resources planning and management. It considers water as a multidimensional resource that must be understood not only from the purely hydrological point of view, but also from socioeconomic, political, administrative, and environmental dimensions [3]. For this reason, a deep interdisciplinary integration is required to solve current and future problems that arise in complex watersheds, where multiple stakeholders and water users compete for valuable and limited resources such as freshwater, food or energy [4–6]. These problems create evermore demanding questions in a complex context of high vulnerability and uncertainty, where exogenous shifts such as climate change, population growth and changing socio-economic boundary conditions are identified [7–9].

To be useful for water planners and decision makers, IWRM requires the development of decision support system (DSS) tools, which must ensure consistency in mass balance among different water cycle components and confirm the fulfillment of socioeconomic, political, administrative and environmental regulations. Thus, DSS tools must combine physically based, integrated surface–subsurface hydrology models [10,11] with other models that can represent several aspects of water resources planning and management, land-use change and environmental vulnerability [12–14]. For instance, Kalbus *et al.* [12] introduced IWRM with DSS tools under different hydrological, climatic and socio-economic conditions aiming to develop specific solutions as a response to water-related problems. Grundmann *et al.* [13] proposed an integrated assessment-prognoses-planning management tool, which couples complex interactions of meteorological, hydrological, agricultural and socio-economic aspects, to ensure optimal sustainable water resources management and long-term planning in arid environments. Leidel *et al.* [14] investigated the concept of capacity development to evaluate social and political circumstances, identify main stakeholders, existing competencies and expected difficulties to implement IWRM.

Many other investigations have focused on developing algorithms to assist decision makers in water resources planning and management [15–17]. Akhbari and Grigg [16] developed a new approach using agent-based models to resolve or mitigate conflicts among competing interests within water management systems. Coelho *et al.* [3] demonstrated the viability of a multicriteria DSS tool for regional delineation in support of IWRM. Razavi-Toosi and Samani [17] ranked water transfer projects using analytic network process in the context of IWRM. Due to these advances, DSS tools are becoming formally supported not only by engineering practitioners but also by governmental institutions to assist river basin authorities in optimal water management [18]. The Jucar river basin, Spain, is one successful example of the use of DSS tools to assist water authorities in IWRM. Andreu *et al.* [19] utilized IWRM for drought planning and management in the Jucar river basin. They used a general DSS tool to integrate long-term planning and short-term management and operation at the basin scale. Relying on the results of DSS to assess risk and efficiency of mitigation measures, the worst drought in the Jucar basin (2005–2008) was successfully endured with relatively low economic and environmental damages.

Although many studies have focused on DSS tools for IWRM, conscious of the inextricable link between water and energy [6,13,15], there is a lack of IWRM investigations that quantify energy requirements for water supply. Curiously, both water and energy managers have applied integrated planning approaches for decades but the broader integration of water and energy is a relatively new area of study [20]. Because the life-cycle to deliver water demands large amounts of energy [4,5,21], the total energy consumed during this cycle becomes an attractive metric when assessing and comparing integrated management policies and/or technologies needed for an IWRM. Albeit many studies have focused solely on the water-energy nexus (e.g., [4,5]), more studies integrating water management and energy requirements are needed to economically quantify future water deficits, and to assess the costs associated with the implementation of strategies to preserve or increase current economic production levels. Moreover, such studies are of particular interest in arid regions where multiple stakeholders and water users face extremely intense competition for limited freshwater resources for municipal, industrial/mining, irrigation and environmental/ecological uses. Many of these regions also have complex hydrological systems and poor data availability [22], posing a challenge for IWRM.

The general aim of this paper is to demonstrate that IWRM and DSS tools can be used to explore the water-energy nexus at the basin scale in an arid location. The specific objectives of this investigation are: (1) to present an IWRM model developed for an arid basin facing water scarcity; (2) to quantify water deficits at the basin scale under different future scenarios; and (3) to compare the energy required to supply the water deficits on each future scenario. We selected the Copiapó River basin, Chile, which represents a true example of an arid basin under tremendous and increasing water stress due to constantly growing demands from the mining industry, crop irrigation, urban water supply and tourism. To achieve the objectives of this paper, we developed a comprehensive model to assess and characterize coupled surface and groundwater resources, as well as the water demands and uses. Subsequently, the model was utilized to compare several water supply and demand scenarios to estimate future water availability in the basin. Finally, these scenarios were evaluated in terms of the energy requirements for desalinating seawater to eliminate the corresponding water deficit.

2. Methods

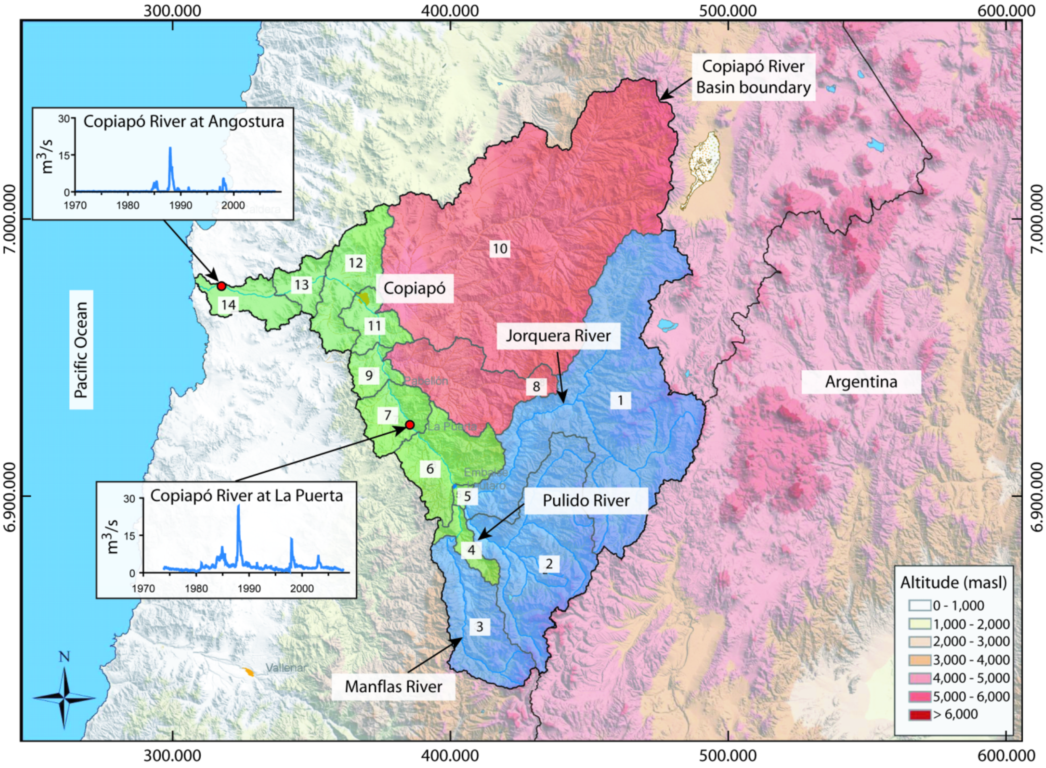
2.1. Study Area

In this section we present the description of the Copiapó River basin and the methods used to gather the data and to perform the basin's hydrogeological characterization, which are relevant for the development of the IWRM model.

2.1.1. The Copiapó River Basin

The Copiapó River Basin (Figure 1) has an area of 18,538 km^2 and is located in the Atacama region of Chile, between the 27° S and 29° S latitudes. The watershed shares its boundaries with the Salado River Basin to the north, the Huasco River Basin to the south, Argentina to the east and the Pacific Ocean to the west, where its outlet is located. Overall, the basin has an arid climate with an average annual precipitation of 28 mm, and an average daily solar radiation of 220 W/m^2 [23]. The average annual temperature in the middle part of the basin is 15.2 °C, whereas the monthly average temperatures range between 11.2 °C and 19.8 °C. Cycles of dry years followed by more humid years are common, most likely due to the El Niño Southern Oscillation phenomenon [24]. The Copiapó River has a mixed hydrologic regime with a monthly average flow ranging between 1.49 and 1.82 m^3/s (measured at the "Río Copiapó en La Puerta" fluvial station). Its three main tributaries are the Manflas River, the Jorquera River and the Pulido River. The Copiapó River is ~162 km long and originates at an elevation of 1230 m at the point in which the last two watercourses converge.

Figure 1. The Copiapó River basin: its drainage network and sub-basins, and water flow time-series at selected locations.



The city of Copiapó, Tierra Amarilla and Los Loros, which are the main urban centers in the basin, support a population larger than 200,000. This population is likely to grow rapidly in the next decades due to the main economic activities in the basin, *i.e.*, agriculture and mining [25]. Fruit exportation, viniculture and vegetable production are the main agricultural activities, accounting for ~71% of the total water demand in the basin. On the other hand, 22% of the available water within the basin is used to mine copper, iron, gold and silver. These economic activities have brought the river basin to a highly strategic position within northern Chile.

Although agriculture and mining efficiently manage water resources in the basin, the excessive stress induced to the aquifer by water consumers combined with the arid climate has resulted in a state of acute water scarcity [24]. Groundwater storage is being depleted, resulting in lower table levels, poorer water quality and larger amounts of energy required for pumping. Thus, the cost of treating groundwater for potable use is increasing. Given the current uncertainty in the water supply, some mining companies are reducing their reliance on groundwater by developing seawater desalination projects. This additional water production is essential to estimate cumulative cost of future water deficit and to maintain current economic and production levels.

2.1.2. Data Collection

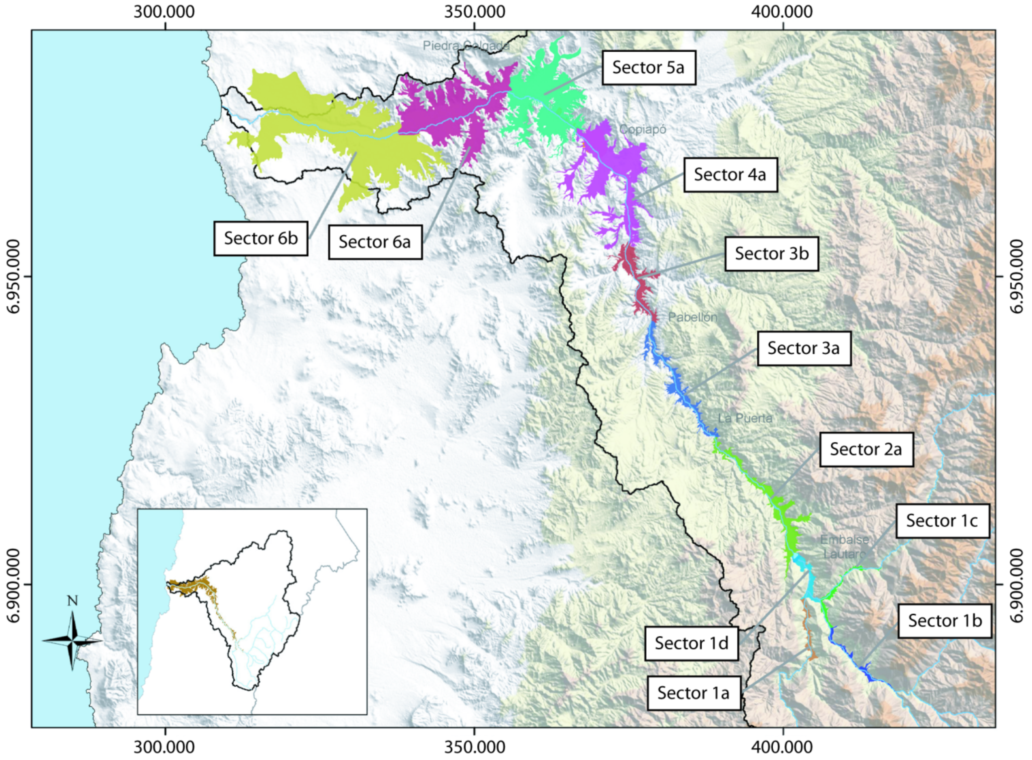
Data for this study were gathered from different sources, including hydro-meteorological records, cadasters and cartographic information, field campaigns and 28 previous studies carried out by both governmental and private institutions, containing information about hydrology, groundwater, geology, agriculture, mining, and legal issues. Data were analyzed considering the six administrative sectors of the aquifer defined by the Chilean National Water Agency (DGA) for the basin (Figure 2). The delineation of these sectors was based on considerations such as inhabitants' distribution, groundwater allocation and water use, among others. Hydro-meteorological data were aggregated on a monthly basis, and include mean, minimum and maximum streamflow, precipitation, evaporation, and mean air temperatures. Cadasters available from the DGA, state institutions, judicial courts and the agricultural and livestock service provided significant information about wells, intakes, distribution systems, channels, land use and water rights. Overall, data were extensively available for the upstream locations of the Manflas, Pulido, and Jorquera Rivers (Figure 1), but less available for the area between La Puerta and the mouth of the Copiapó River at the Pacific Ocean. Thus, a field campaign was carried out between August and December 2008 to complete this information. The information collected from this field campaign included water rights granted to each owner, water sources (surface or groundwater), surfaces irrigated by well or channels, location of intakes, types of crop, irrigation systems, and period of irrigation.

2.1.3. Hydrogeological Characterization

The sub-catchment delimitation and the drainage network extraction of the river basin (Figure 1) were performed using ArcGIS (ESRI, Redlands, CA, USA) and a 90 m Digital Elevation Model [26]. The spatial and temporal distribution of the precipitations was characterized using the DGA meteorological stations that had more than 10 years of data (Table 1). Precipitation is positively correlated with altitude and strongly seasonal, with 80% of the rainfall occurring between May and

August. In terms of stream flows, the Pulido and Jorquera rivers are the main contributors to the Copiapó River, while discharge in the Manflas River is approximately half of that in the Jorquera River. The mean annual evaporation is ~1500 mm/year at 350 m of altitude, and increases at a rate of 2000 mm/km approximately. More details on the hydrological characterization are presented by DICTUC [23].

Figure 2. Administrative sectors (1 through 6) in the aquifer of the Copiapó River basin. The subsectors were defined to run the decision support system tool to evaluate different scenarios of water resource management.



A hydrogeological characterization was carried out to determine the main properties of the geological units in terms of water transmission and storage. Geological, geophysical and geomorphological information allowed determining aquifer thicknesses and regional distribution of the geological deposits [23]. Water levels in wells and pump tests permitted the estimation of aquifer storage volume, hydraulic conductivity and transmissivity [27]. Previous studies have shown that the aquifer can be divided into 14 zones for hydrological modeling purposes [23]. In this work, these 14 zones were grouped into the six administrative sectors defined by the DGA (Figure 2), and results are presented accordingly.

Historical recharge in the Copiapó Valley was estimated using the collected hydrologic data. This estimation was performed at a monthly basis using stream flow rates in the Copiapó River and water levels in the wells within the basin. This analysis focused on the area between La Puerta and Angostura (Figure 1), in which long-term data are available, and where the subsurface water balance of the basin is hydrologically closed [23]. Thus, the stream flows measured at La Puerta and at Angostura are appropriate estimates of the water inputs and outputs, and the water supply can be then estimated as the difference between the flow rates at these locations.

Table 1. Hydrometeorological data at selected stations.

Meteorological stations		**Monthly mean precipitation (mm)**												**Annual values**		
Name	**Altitude (m)**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Precip. (mm)**	**Mean temp. (°C)**	**Evaporation (mm)**
Caldera	15	0.0	0.0	0.8	0.4	1.3	5.3	4.9	5.1	0.5	0.0	0.0	0.0	18.3	N/A	N/A
Canto de Agua	330	0.2	0.0	0.4	1.2	3.1	9.7	8.8	6.6	0.4	0.4	0.0	0.2	31.0	16.9	1494.7
Conay Albaricoque	1600	0.1	1.8	2.6	3.1	8.5	26.1	19.8	14.0	0.5	0.0	0.8	1.0	78.3	17.2	3126.5
Copiapó	385	0.0	0.0	1.1	0.2	1.4	6.0	4.3	3.8	0.2	0.0	0.0	0.1	17.1	16.7	1680.2
El Totoral	150	0.2	0.0	0.7	0.9	3.0	10.1	7.6	5.0	0.3	0.3	0.0	0.0	28.1	N/A	N/A
Elibor Campanento	750	0.0	0.0	1.0	0.6	2.6	9.1	7.5	5.9	0.4	0.1	0.0	0.0	27.2	N/A	N/A
Hacienda Manflas	1410	0.2	0.2	1.9	2.9	4.8	13.3	10.2	10.3	1.0	0.6	0.0	0.1	45.5	N/A	N/A
Iglesia Colorada	1550	0.2	0.2	1.5	4.0	6.0	12.2	10.9	9.5	1.4	0.8	0.0	0.3	47.0	18.6	3961.6
Jorquera en la Guardia	2000	0.2	1.4	3.2	3.5	6.4	13.3	7.3	7.6	2.8	1.3	0.1	0.3	47.4	N/A	N/A
Las Vegas	2250	0.0	1.0	2.9	0.8	5.7	6.6	26.4	4.5	0.8	0.2	0.0	0.0	48.9	N/A	N/A
Lautaro embalse	1110	0.3	0.4	2.7	2.4	4.2	8.9	8.1	8.8	1.5	0.3	0.2	0.2	38.0	19.6	2873.3
Los Loros	940	0.0	0.0	1.2	1.4	2.8	10.5	9.3	8.1	0.9	0.1	0.0	0.1	34.4	18.1	2908.7
Pastos Grandes	2260	0.0	1.6	3.2	1.8	3.4	8.9	9.8	4.8	2.3	0.7	0.0	0.2	36.7	N/A	N/A

Notes: N/A: data not available; Precip.: precipitation; temp.: temperature.

2.2. Water Resources Management Model

In this work, the SIMGES model [28] was utilized to simulate different water resources management scenarios. SIMGES is a module of the DSS shell AQUATOOL for the modeling and analysis of the integrated management of water resources systems. AQUATOOL was developed for complex river basins containing surface and underground elements for water storage and regulation, transport, intake, consumption, and artificial recharge. This software has been successfully used in complex systems similar to the Copiapó River basin to characterize water resources in regions with water deficit. In particular, it has been used as a DSS to manage drought risks and vulnerability in many arid and non-arid regions, such as the Juca River and the Duero River basins [28–31], and to represent interactions between groundwater and surface waters in the Segura River basin [32]. For further details the reader is referred to the work of Andreu *et al.* [28].

The IWRM model of the basin, constructed and implemented in AQUATOOL, considers the hydrological and hydrogeological data, as well as the different water users within the basin. Different elements and connections available in the model were used to couple the hydrologic units of the watershed, which was divided into 14 sub-basins (Figure 1), whereas the six administrative sectors defined for the basin were subdivided in 11 sectors, as shown in Figure 2. These 11 sectors were defined to report the results of the hydrological modeling using a more physical division instead of an administrative division. The model was manually calibrated using the historical water demand between the years 1971 and 2007. Calibration criteria considered fitting the model to monthly streamflow series observed in selected DGA's streamflow gauges (Table 2) and monthly observed aquifer volumes for the 11 more relevant sectors. These volumes were calculated using a digital model of the bedrock and measured water levels at different wells. The calibration was carried out by adjusting model parameters in different sub-basins, beginning from the upper part of the basin and then moving to the sub-basins located downstream. Model parameters that were adjusted represent interactions between surface waters, groundwater and its uses. The most relevant parameters that were calibrated are: infiltration losses from irrigation channels, streams, lakes and reservoirs that result in aquifer recharge; the drainage coefficient of an aquifer, which is a parameter that relates the volume stored in the aquifer with the groundwater discharge into streams; and water demands for irrigation. Further details regarding the hydrological processes represented in the model are presented elsewhere [23,28–32]. The Nash-Sutcliffe coefficient of efficiency (E) [33,34] was used to evaluate the IWRM model goodness-of-fit.

2.3. Integrated Water Resource Management Scenarios

The calibrated AQUATOOL model, used to study different IWRM scenarios, was designed to visualize new conditions to achieve efficient water use in the basin, maximizing the welfare of all users. Five scenarios were studied, each of which consisted of one or more simulations of varying water demands, water resource management decisions, and water demand translocation between aquifer zones. Even when climate projections and a downscaling methodology could be used to simulate the future [35], the meteorological conditions observed during the calibration period

(1971–2007) were repeated during the prediction time-period (2008–2043). Table 3 describes all the scenarios and simulations considered in the analysis.

Table 2. Mean annual water flows in the basin and main statistics.

Fluvial stations	**Mean annual water flow (m^3/s)**					
Name	**Mean**	**Min**	**Max**	**N**	**σ**	**γ**
Río Copiapó en Angostura	0.44	0.10	5.29	41	0.98	3.99
Río Copiapó en Mal Paso aguas arriba Canal	1.06	0.23	4.88	37	0.88	2.78
Río Copiapó en Mal Paso aguas abajo Canal	0.99	0.69	1.28	2	0.42	-
Río Copiapó en ciudad de Copiapó	1.93	0.33	7.19	11	2.09	1.92
Río Copiapó en Lautaro	1.29	0.37	4.53	53	0.96	2.01
Río Copiapó en Pastillo	1.79	0.72	4.83	35	0.94	1.41
Río Copiapó en La Puerta	2.41	0.79	9.92	52	1.60	2.75
Río Copiapó en San Antonio	1.50	0.33	5.99	17	1.44	2.18
Río Jorquera en Vertedero	0.72	0.17	2.96	41	0.51	2.57
Canal Mal Paso después de Bocatoma	0.72	0.19	1.33	17	0.28	0.16
Río Manflas en Vertedero	0.46	0.09	2.58	33	0.49	2.98
Río Pulido	1.43	0.42	3.76	41	0.88	1.33

Notes: N: years of data; σ: standard deviation; γ: skewness.

Table 3. Scenarios considered for the integrated water resources management (IWRM) analysis.

Scenario	**Simulation**	**Simulation description**
1. Current status.	1.1	Water demand maintained in the future.
2. Uniform reduction of water demand.	2.1	20% reduction in water demand.
	2.2	30% reduction in water demand.
	2.3	50% reduction in water demand.
3. Segmented reduction of water demand.	3.1	Reduction in agricultural irrigation, mining industry and potable water demand. 20% reduction in Sectors 1 and 2; 35% reduction in Sector 3; 50% reduction in Sector 4.
	3.2	Reduction in agricultural irrigation and mining industry. 20% reduction in Sectors 1 and 2; 35% reduction in Sector 3; 50% reduction in Sector 4.
4. Water resource management with uniform reduction of water demand and translocation of water between aquifer zones.	4.1	30% reduction in all water uses except for potable water. 50% of potable water demand is transferred from aquifer Sector 4a to 5a.
	4.2	30% reduction in all water uses except for potable water. 50% of potable water demand is transferred from aquifer Sector 4a to 6a.
	4.3	30% reduction in all water uses except potable water. 30% of potable water demand is transferred from aquifer Sector 4a to 5a, and 20% of potable water demand is transferred from aquifer Sector 4a to 6a.
5. Water resource management with segmented reduction of water demand and translocation of water between aquifer zones.	5.1	Segmented reduction in all water uses except potable water: 20% reduction in Sectors 1 and 2; 35% reduction in Sector 3; 50% reduction in Sector 4a; 50% reduction in Sector 5a. 50% of potable water is transferred from aquifer Sector 4a to 5a.
	5.2	Segmented reduction in all water uses except potable water: 20% reduction in Sectors 1 and 2; 35% reduction in Sector 3; 50% reduction in Sector 4a; 50% reduction in Sector 5a. 50% of potable water is transferred from aquifer Sector 4a to 6a.
	5.3	Segmented reduction in all water uses except potable water: 20% reduction in Sectors 1 and 2; 35% reduction in Sector 3; 50% reduction in Sector 4a; 50% reduction in Sector 5a. 30% of potable water is transferred from aquifer Sector 4a to 5a, and 20% of potable water is transferred from aquifer Sector 4a to 6a.

Scenario 1 represents a baseline where the water demand is maintained constant in the future. In Scenario 2, different uniform reductions of water demand were studied; while in Scenario 3 a segmented reduction of water demand was studied. Two cases were considered in this scenario: first, a water reduction in agricultural irrigation and in the mining industry; and second, an additional water reduction in the potable water demand. Scenario 4 consisted in a water resource management with uniform reduction of water demand and translocation of water between different aquifer sectors. Finally, Scenario 5 studied water resource management options with segmented reduction of water demand and translocation of water between different aquifer sectors. All these scenarios were defined in conjunction with the Water Agency as a first approach to analyze adapting actions taken by the water users to face the future resource availability. The scenarios were thought to support policy makers for future policy developments by analyzing sectorial, spatial and temporal changes in water demand. Note that even when the percentages of water demand reductions are arbitrary and not necessarily optimized (Table 3); these are values that can be easily understood by decision-makers and are considered test cases that might later be fine-tuned once the general management scheme has been decided.

2.4. Impacts of Water Resource Management on Energy Requirements for Water Supply

Assuming that maintaining current production levels intimately tied to water use would be economically and socially desirable, the first goal of a sustainable water management will be to eliminate the water deficit. This water deficit reduction will be associated with additional costs and energy requirements. The objective of this section is to have a first-order approximation of the energy required to reduce the water deficit in the basin. This estimation is based on the same assumptions used in the IWRM scenarios studied before.

Under the objective of deficit neutrality, the mining industry and the water utility company (to a lesser degree) have begun to produce additional water through seawater reverse osmosis (SWRO). To estimate the energy and cost required for water supply within the basin, we will assume that SWRO can be used to create additional sources of freshwater and to eliminate the water deficit. This assumption implies that an estimation of the energetic requirements most likely will overestimate the real requirements because not all the water deficit needs to have the same quality as that obtained by SWRO (e.g., water quality for agricultural use and human consumption does not need to be the same). Nonetheless, this calculation allows for comparing the different IWRM scenarios, which is one of the objectives of this work.

Water production through SWRO requires 3–7 kWh/m^3 [36–38]. Assuming that future technologies will maximize efficiency, we adopted an average value of 3.8 kWh/m^3 for our estimates of energetic requirements [38]. The energy required to pump freshwater from the ocean to the different sectors of the basin was also included in this analysis. The energy required to circulate freshwater through the distribution system was estimated by assuming that frictional losses are the main resistance to flow and using an equivalent hydraulic pipe system. Under these assumptions, the cumulative costs and energetic requirements for the IWRM scenarios were estimated.

3. Results and Discussion

3.1. Data Collection–Water Use

The collected data were used as an input for the IWRM model. These data were aggregated in terms of water use and organized according to the sectors defined by the DGA. Table 4 summarizes the number of groundwater rights granted in each sector. Rights are granted predominantly for irrigation and mining, with Sector 1 being that in which the lowest rate (719 L/s) has been granted.

3.2. Hydrogeological Characterization

The geologic units of the Copiapó river basin can be grouped into unconsolidated deposits and undifferentiated bedrock. The unconsolidated deposits have hydrogeological potential to store and transmit important volumes of groundwater, as well as to facilitate the recharge of the aquifer. The aquifer's mean hydraulic conductivity is 22 m/day with a minimum of 2 m/day and a maximum of 470 m/day. Estimated transmissivities are 868, 100 and 12,200 m^2/day for the mean, minimum and maximum respectively, and the storage coefficient ranges between 0.1 and 0.2 [23]. The undifferentiated bedrock is made up of impermeable rocks with no water storage capacity. For further details on the hydrogeological characterization the reader is referred to the work performed by DICTUC [23].

Table 4. Distribution of the groundwater rights granted in the aquifer of the Copiapó River basin.

Number of ground water rights granted in the aquifer of the Copiapó River Basin

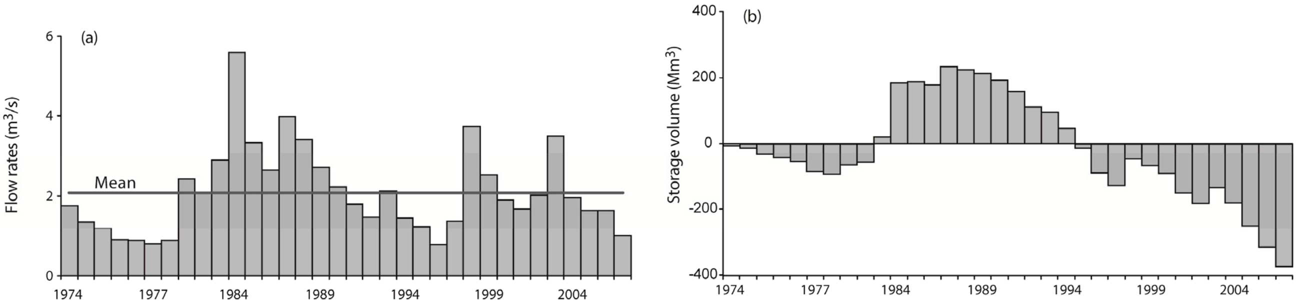
Sector	Irrigation	No.	Human consumption	No.	Mining	No.	Other uses	No.	Total	No.
1	3%	9	0%	0	0%	0	1%	1	2%	10
2	18%	56	7%	2	7%	5	6%	5	14%	68
3	14%	43	0%	0	7%	5	17%	14	13%	62
4	6%	19	69%	20	46%	31	10%	8	16%	78
5	30%	91	17%	5	27%	18	35%	29	30%	143
6	28%	86	7%	2	12%	8	31%	26	25%	122
Total	100%	304	100%	29	100%	67	100%	83	100%	483

Water flow granted (ground water) in the aquifer of the Copiapó River Basin

Sector	Irrigation	L/s	Human consumption	L/s	Mining	L/s	Other uses	L/s	Total	L/s
1	6%	619	0%	0	0%	0	3%	100	4%	719
2	25%	2,482	2%	38	13%	399	14%	447	19%	3,366
3	23%	2,276	0%	0	5%	159	25%	777	18%	3,211
4	4%	393	79%	1,234	66%	2,002	11%	342	22%	3,971
5	22%	2,172	16%	256	14%	418	33%	1,022	22%	3,868
6	21%	2,066	2%	32	2%	69	14%	453	15%	2,620
Total	100%	10,008	100%	1,560	100%	3,047	100%	3,141	100%	17,756

Historical recharge in the Copiapó River basin was estimated using the collected hydrologic data on a monthly basis, and allowed calculation of the water supply in the Copiapó River basin. Figure 3a shows that the mean water supply of ~2 m^3/s is exceeded only in 13 out of 34 years. In addition, the temporal evolution of the aquifer storage volume since January 1974 (*i.e.*, the reference year with zero volume) can be estimated from records of water level in different wells (Figure 3b). An important reduction in the stored volume starting from 1995 is observed, which is explained by the combined effect of drought and increasing water use by the different consumers.

Figure 3. Estimated water balance in the Copiapó River basin. (**a**) Water supply; (**b**) Annual fluctuations in the aquifer's storage volume. The reference (null) volume corresponds to 1974.



3.3. Water Resources Management Model Calibration

Figure 4a–d compares measured and calibrated streamflow rates in some of the selected DGA's streamflow gages located in the Copiapó River. In general, simulated values and observations have a good agreement, particularly at "Río Copiapó en Pastillo" and at "Río Copiapó en La Puerta" (Figures 4a–b and Table 5). In these fluvial stations, both the mean observed and simulated water flows are well represented, as well as their standard deviation and their cumulative flows, with Nash-Sutcliffe [32] coefficient of efficiencies (E) of 0.905 and 0.493 for "Río Copiapó en Pastillo" and "Río Copiapó en La Puerta", respectively. Downstream these stations is located the "Río Copiapó en ciudad de Copiapó" stream gauge (Figure 4c). Albeit the simulated streamflows in this station do not perfectly match the observed flows (Table 5), the trends between simulated and measured streamflows are similar, with an E = 0.568. As shown in Table 5, observed streamflows in the gauge nearest the outlet to the ocean, *i.e.*, "Río Copiapó en Angostura" (Figure 4d)—where there are practically no water users–were the ones with a worse representation in the IWRM model (E = 0.071), even when the simulations represented well the timing of the observed peaks. Despite this issue, the calibration of the aquifer volume time-series (Figure 4e) shows good agreement between the modeled and estimated cumulative water volumes in the aquifer (Table 5), with E = 0.436. The model simulated the decreasing trend starting in 1976 and subsequent slight recovery between 1980 and 1988. Sustained declines have been observed and modeled ever since. Note that Figure 4e shows variations in cumulative groundwater storage using the volume of the year 1974 as a reference volume, which allows observation of periods of water abundance or scarcity. For instance, the periods 1976–1984 and 1996–present correspond to seasons of water scarcity. It is worth to remark that what is seen as a substantial underestimation in groundwater storage for the period 2000–2008 (Figure 4e), is actually less than 2.5% in terms of the stored volume (the observed storage is ~8900 Mm^3 and the storage estimated by the model is ~8700 Mm^3) and is within the uncertainty of the estimations based on the observed data.

Figure 4. Results from the calibration process in the Copiapó River basin. (**a**)–(**d**) Stream flows at selected fluvial stations; (**e**) Cumulative fluctuations in the aquifer's storage volume. The reference (null) volume corresponds to 1974.

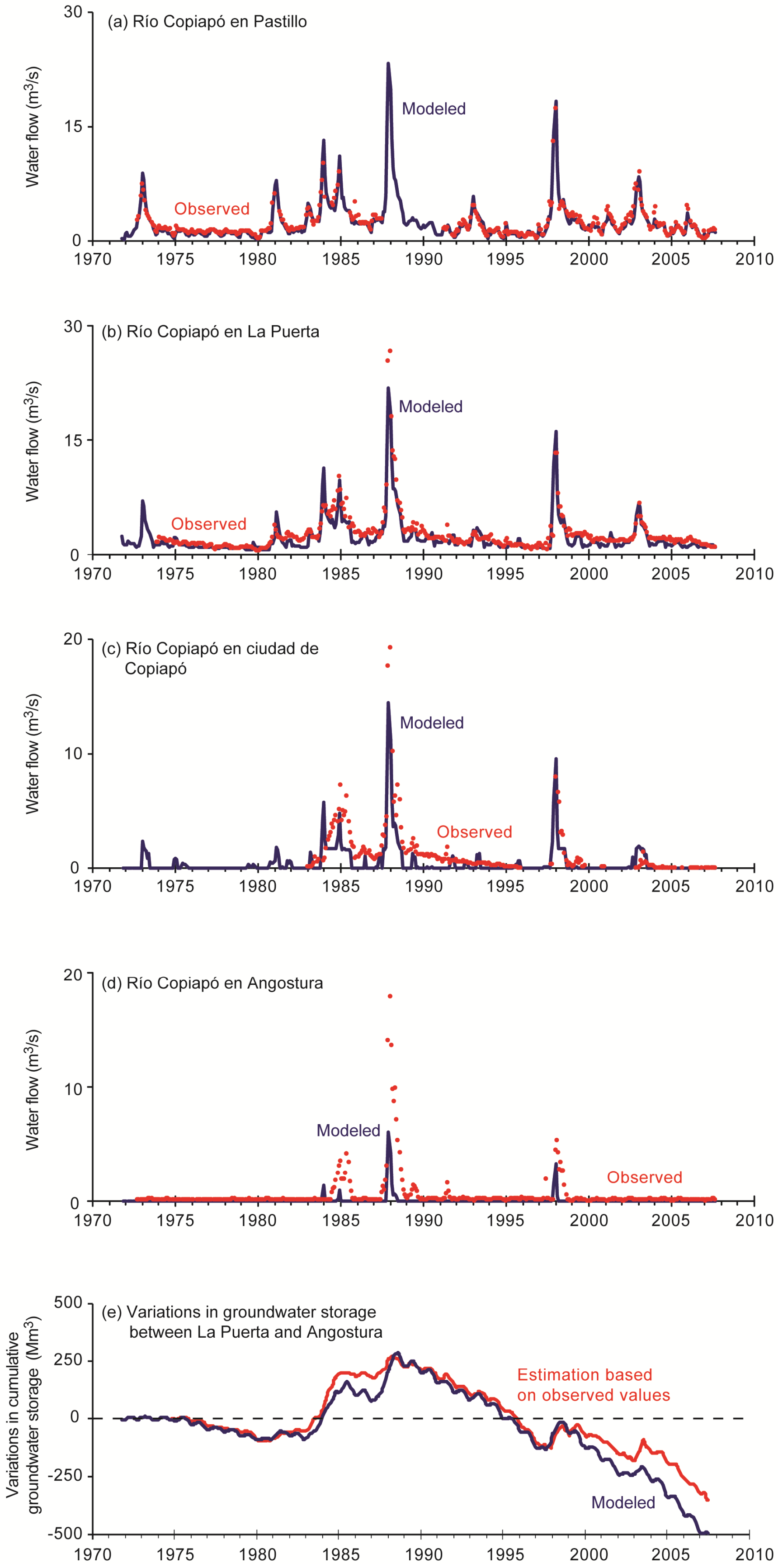


Table 5. Observed and simulated data obtained during the entire calibration period.

Surface waters				
Fluvial stations	**Obs. Flow (m^3/s) ***	**Sim. Flow (m^3/s) ***	***E* (-) ****	**Sim./obs. cumulative flow (m^3/s)**
Río Copiapó en Pastillo	2.29 ± 1.85	2.46 ± 2.64	0.905	0.932
Río Copiapó en La Puerta	2.63 ± 2.66	2.19 ± 2.28	0.493	0.832
Río Copiapó en ciudad de Copiapó	1.47 ± 2.68	0.48 ± 1.34	0.568	0.509
Río Copiapó en Angostura	0.53 ± 1.69	0.06 ± 0.43	0.071	0.114
Groundwater				
Sector	**Obs. Volume (Mm^3) ***	**Sim. Volume (Mm^3) ***	**Maximum Volume (Mm^3)**	**Sim./obs. Cumulative Volume (Mm^3)**
Sector 1a	24 ± 3	16 ± 9	34	0.728
Sector 1b	39 ± 2	44 ± 7	48	1.125
Sector 1c	38 ± 5	38 ± 6	66	1.104
Sector 1d	142 ± 9	123 ± 29	163	0.923
Sector 2a	545 ± 3	538 ± 20	588	0.994
Sector 3a	187 ± 20	176 ± 20	257	0.941
Sector 3b	189 ± 18	190 ± 23	256	1.012
Sector 4a	1036 ± 35	1027 ± 55	1024	0.993
Sector 5a	2378 ± 56	2395 ± 47	2583	1.009
Sector 6a	1603 ± 22	1607 ± 18	1663	1.005
Sector 6b	3131 ± 5	3130 ± 6	3262	1.002
Total			9944	

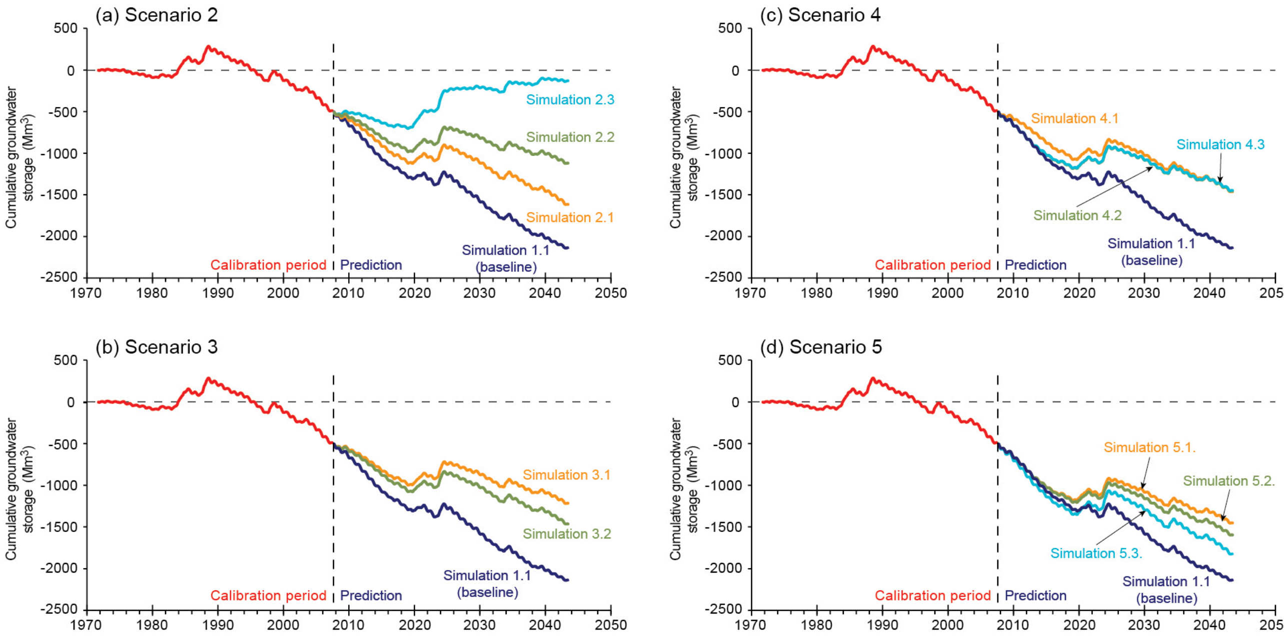
Notes: * Mean values ± standard deviation; ** *E*: Nash-Sutcliffe coefficient of efficiency [33,34]; Obs.: Observed; Sim.: Simulated.

3.4. Integrated Water Resource Management Scenarios

The uses and water demands in Scenario 1 (or baseline scenario) correspond to the basins' current situation, calculated as the monthly average of the net water consumption over the last few years of the calibration period. These monthly series of water demand were repeated for each year during the simulation period. Figure 5 presents the predicted stored volume in the entire aquifer of the Copiapó River basin. The baseline scenario (Simulation 1.1) shown in Figure 5 suggests that if no water management actions are taken, a sustained and significant decline of the water stored in the aquifer will be observed throughout the watershed. Moreover, the largest decrease in the stored volume occurs for the baseline scenario (~2200 × 10^6 m^3 by the end of the simulation period—equivalent to a 21.2% decrease of the initial aquifer's volume). Thus, actions are urgently needed to assuage the water scarcity expected for the basin.

Figure 6 shows the fluctuations in monthly cumulative volume (%) in the administrative sectors for the different scenarios. In the baseline case, the stored volume decreases in all the aquifer sectors. At the end of the simulation, the largest reductions occur in Sectors 3 and 4 (*i.e.*, around 50% of the initial volume), while no significant fluctuations are predicted for Sector 6, most likely due to a high degree of disconnection from the rest of the aquifer [23]. The main water demands in the most vulnerable zones of the watershed are agricultural irrigation (Sector 3), and mining industry and human consumption (Sector 4). Therefore, policy makers must work closely with these water users to develop new policies that can reduce the risk of water shortage while maintaining their production levels. The decrease in stored volume is also relevant in Sector 2, in which water is mainly used for agricultural irrigation. Sector 5, which uses most of its waters for agricultural purposes, has a reduction in stored volume that is approximately half that observed in Sector 4. Major fluctuations are simulated in Sector 1, which are explained by the sensitivity of this Sector to meteorological conditions. For instance, the conditions observed between years 2030 and 2033 correspond to a hydrological drought, which results in a decrease in the water volume stored in the aquifer. In Sector 1, there is only a small amount of groundwater flow granted (~0.72 m^3/s, as shown in Table 1). Thus, variations in this sector due to anthropogenic causes are not expected.

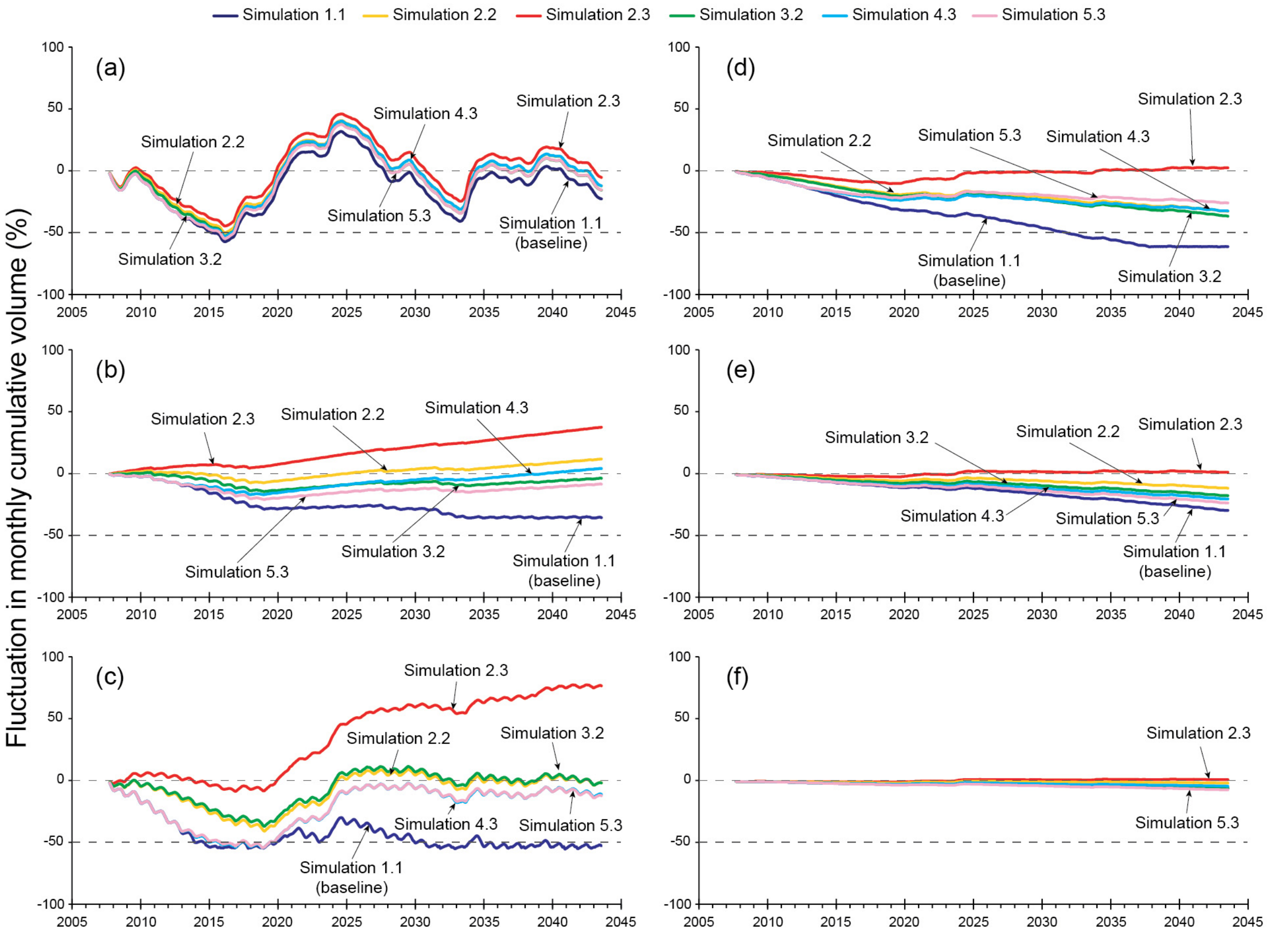
Figure 5. Cumulative aquifer storage volume for different scenarios. The reference (null) volume corresponds to 1974. (**a**) Scenario 2; (**b**) Scenario 3; (**c**) Scenario 4; (**d**) Scenario 5.



The following scenarios (2–5) were defined to study different strategies that may help to alleviate this water crisis. These scenarios were defined in conjunction with the Water Agency to analyze the choices that stakeholders and water managers have to reduce risk of water shortage and to adapt to face the future water resource availability.

Scenario 2 was defined to analyze the effect of reducing uniformly all the water demands within the basin in 20%, 30% and 50%. Figure 5(a) shows that larger reductions in the water demand yield larger volumes stored in the aquifer. For instance, a 50% uniform reduction of water demands (Simulation 2.3) results in a stored volume similar to that of the initial aquifer volume. In addition, Simulation 2.3 shows that there could be more water available in the different aquifer sectors within the basin (Figure 6). In particular, stored water in Sectors 2 and 3 significantly exceed the baseline scenario volumes. Note however that a 50% reduction in water demand throughout the entire basin is very unlikely given increasing economic activities and population growth. A more reasonable 30% reduction of the present water demand (Simulation 2.2) does not decrease the current aquifer's volume stored in Sectors 1, 2, 3, and 6 (Figure 6), while the volume of Sectors 4 and 5 declines without recovery (being Sector 4 the most vulnerable).

Figure 6. Fluctuations in monthly cumulative volume (%) in the administrative aquifer sectors for different simulations. (**a**) Aquifer Sector 1; (**b**) Aquifer Sector 2; (**c**) Aquifer Sector 3; (**d**) Aquifer Sector 4; (**e**) Aquifer Sector 5; (**f**) Aquifer Sector 6. The reference (null) volume corresponds to 1974.



In Scenario 3, a segmented reduction in agricultural, mining and industry, and potable water use was studied. The details of this reduction are presented in Table 3. Note that no action was taken in Sector 6 since the baseline scenario showed no significant change in its water volume during the simulation period. Figure 5b shows that Simulation 3.1 yields larger water volumes stored in the aquifer compared to the baseline scenario. The watershed stored volume, however, still decreases by ~1250 × 10^6 m^3. Simulation 3.2 has a segmented reduction of water demand similar to that of Simulation 3.1, but assumes that water for human consumption cannot be reduced in the future. This situation still delivers better results than the baseline scenario in terms of water stored in the entire aquifer. In terms of stored water in the different sectors (Figure 6), Simulation 3.2 ranks between Scenarios 1 and 2 for effectiveness in scarcity mitigation, greatly improving upon the baseline situation observed in Sectors 2, 3 and 4. Nevertheless, volumes stored in aquifer Sectors 4 and 5 decrease without recovery.

Scenario 4 studied uniform reduction of water demand and translocation of water between different aquifer sectors. In this scenario and for all its simulations (described in Table 3), it is assumed that a water management action takes five years to be implemented. Therefore, the current water demand is kept constant through the fifth year of simulation and starting from the sixth year the water demand is reduced by 30% for all uses except for potable water, which is maintained constant. In all of the Scenario 4 simulations, a similar volume of water is observed in the aquifer at the end of the simulation period (Figure 5c). This suggests that water translocation between sub-catchments may not be the best IWRM choice for this watershed. Even when the results show that groundwater storage of Scenario 4 is higher than that observed in the baseline case, Scenario 2 still is the case that achieves the highest aquifer storage.

Scenario 5 studied IWRM options with segmented reduction of water demand and translocation of water between different aquifer sectors (the description of each simulation is presented in Table 3). This scenario also considers that water management actions take five years to be implemented. Thus, starting from the sixth year, a segmented reduction in all water uses except potable water is analyzed. As shown in Figure 5d, Simulation 5.1 results in the largest water volume in the aquifer but still show a decreasing trend. In terms of water stored in the different aquifer sectors (Figure 6), Scenario 5 ranks between Scenarios 1 and 2, greatly improving upon the baseline situation observed in Sectors 2, 3 and 4. The volume in Sectors 4 and 5, however, declines without recovery throughout the simulation.

The simulated mean water balance in the entire aquifer shows a recharge of ~4 m^3/s and a discharge of ~1.4 m^3/s. The difference between recharge and discharge (~2.6 m^3/s) constitutes the maximum amount of groundwater that can be sustainably exploited in the valley. Moreover, the average pumping rate is ~2 m^3/s for Simulation 2.3, and varies between 3.2 and 4.0 m^3/s for the other simulations. Hence, only Simulation 2.3 implies an increase in the average volume stored in the aquifer, and is the only option environmentally sustainable in the long-term.

It is important to recall that the conditions utilized for the simulations assumed stationary historical biophysical conditions, without accounting for the effects of climate change, which is expected to exacerbate current stresses on water resources. For instance, a 10%–30% decrease in runoff is projected over some dry regions at mid-latitudes due to decreases in rainfall and higher rates of evapotranspiration [39–41]. Therefore, climate change should have negative impacts on water supply, agriculture, energy production, health, and on other aspects. In the study zone, an increase in the radiative forcing should reduce the availability of water and increase the water demand for irrigation of crops–worsening the results obtained from the IWRM model. Thereby, social and economic development in the region must consider an adaptive capacity to reduce the risk of water shortage. Examples of planned adaptation in the water sector include improvements in [41]: water storage and conservation techniques, water reuse, desalination, and water-use and irrigation efficiency. These adaptation capacities should be framed within a national water-policy framework, which has to be supported by more advanced IWRM models that consider the effects of climate change more appropriately than the model presented in this work. IWRM will also help to define key constraints (e.g., financial, technological or physical barriers) and opportunities (e.g., synergies with other sectors) of implementing these adaptation capacities.

3.5. Impacts of Water Resource Management on Energy Requirements for Water Supply

To address the water-energy nexus at the basin scale, we utilized the results obtained from the IWRM model to investigate how much additional energy is required to eliminate the water deficit. The cumulative costs and energetic requirements for the IWRM scenarios are shown in Figure 7. It was found that the baseline case (Simulation 1.1) requires a significant input of both energy (which is also associated with an important investment capital) to eliminate the water deficit when compared with any of the water resource management scenarios. In this scenario, almost 60% of the energetic requirements are used to circulate freshwater through the distribution system. Although the total cumulative cost for Scenarios 2–5 rises along with the base scenario until the year 2017 (a drought period), the deficit and thus total cost of not making a management decision (Simulation 1.1) greatly exceeds those of any water management scenario. Figure 7 also shows that between the years 2010 and 2020 all the water resource management scenarios experience water stress, which results in additional cost and energy requirements. After the year 2035, however, what is seen as a relatively insignificant deficit for water resource management Scenarios 2–5 results in a drastic rise in cost for Simulation 1.1. This drastic increase in cost most likely occurs because the aquifer has reached a critical state from which it cannot recover and that none of the other scenarios reach. The existence of this critical level was also found by DICTUC [23], and represents a very complex situation in which minor deficits in the potable water wells of the city of Copiapó are significant. Because of the critical state of the aquifer in the baseline scenario of inaction, the aquifer will nearly have been pumped dry and any demand unable to be satisfied by surface water will directly result in a deficit, a quite common situation in the Copiapó river basin. The managed scenarios, however, will have groundwater reserves to mitigate this deficit.

Figure 7. Costs and energetic requirements associated with an increase in the water supply by reverse osmosis.

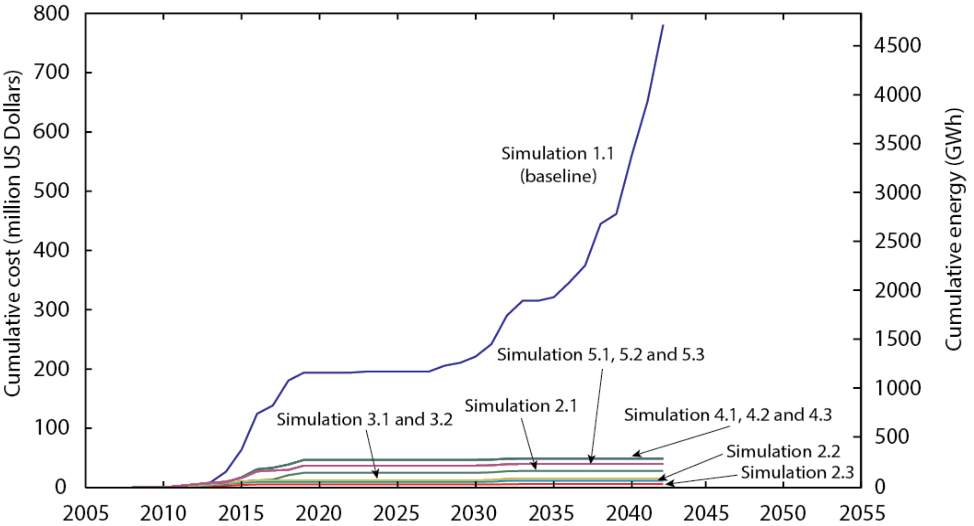


Table 6 present the energetic requirements and their associated costs estimated at the end of the simulations. These costs are estimated by the Centro de Despacho Económico de Carga (CDEC, The system operator in charge of the coordinating grid operation in Chile) to be ~US$0.166/kWh [42], and correspond to the marginal production costs of the Termopacífico thermoelectric power plant, the power plant nearest Copiapó. Between the years 2008 and 2042, the baseline scenario has an estimated cost of $781 million US Dollars with energetic requirements on the order of 4702 GWh when 3.8 kWh/m^3 are assumed to be required to drive SWRO. The previous cost results in a volumetric marginal cost of ~$1.48/m^3 that includes both the energy required to pump the fluids and to drive

SWRO. A sensitivity analysis considering rates of 3 and 7 kWh/m^3 for SWRO desalination lead to energetic requirements of 4280 GWh and 6391 GWh, respectively; and associated fuel costs of US$710 million ($1.35/m^3) and US$1,061 million ($2.01/m^3), respectively. The estimated range of the total water cost is within the range of reported SWRO desalination plants [38,43]. On the other hand, the water resource management scenarios significantly reduce these costs and energetic needs. Cost reductions of more than 90% are observed in all water resource scenarios. Overall, any of the water resource management scenarios studied here are significantly more economic than the option of inaction (Simulation 1.1). Note that we are only comparing the relative cost of covering water deficits associated with different management actions, but we are not comparing the costs of implementing these actions, which may be higher due to investment and social costs.

Table 6. Energetic requirements and corresponding costs for each IWRM scenario.

Scenario	Simulation	Energy for SWRO (GWh) *	Total Energy Required (GWh) *	Cost ($ Million US Dollars) **
1. Current status.	1.1	2006 (1584–3695)	4702 (4280–6391)	781 (710–1061)
2. Uniform reduction of water demand.	2.1	122 (97–225)	168 (143–271)	28 (24–45)
	2.2	52 (41–95)	70 (59–114)	12 (10–19)
	2.3	26 (20–48)	35 (30–57)	6 (5–9)
3. Segmented reduction of water demand.	3.1	67 (53–123)	91 (77–147)	15 (13–24)
	3.2	67 (53–123)	91 (77–147)	15 (13–24)
4. Water resource management with uniform reduction of water demand and translocation of water between aquifer zones.	4.1	207 (163–381)	294 (250–468)	49 (42–78)
	4.2	207 (164–382)	294 (250–468)	49 (42–78)
	4.3	207 (163–381)	294 (250–468)	49 (42–78)
5. Water resource management with segmented reduction of water demand and translocation of water between aquifer zones.	5.1	171 (135–316)	241 (205–385)	40 (34–64)
	5.2	171 (135–316)	241 (205–385)	40 (34–64)
	5.3	171 (135–316)	241 (205–385)	40 (34–64)

Notes: * Energy that is required to eliminate the water deficit within the basin using SWRO. Values in parentheses show the expected range when assuming SWRO energetic requirements of 3 and 7 kWh/m^3; ** Estimated cost based on SWRO energetic requirements [36–38], frictional losses, and 2013 prices of fossil fuels. Additional costs incurred by water users in the scenarios under analysis or by infrastructure are not included. Values in parentheses show the expected range when assuming SWRO energetic requirements of 3 and 7 kWh/m^3.

To integrate the energy and water cycles it is also important to quantify the water footprint of energy production and conversion, defined as the amount of water consumed to produce a unit of energy [44]. This footprint has to be measured both in terms of water quantity, water quality, and considering other social, environmental and ecological aspects. Because the influence of energy production and conversion is much more difficult to assess in the latter aspects [45], here we only provide estimates in terms of water quantity. Lazarova *et al.* [44] and Olsson [45] provide a summary of water footprint of energy production and conversion for different energy sources. When considering conventional coal combustion, the water footprint values range from ~1 to 3 L/kWh. Using this range and the previous energetic requirements at the end of the simulations, we estimated that the water footprint should range from 0.1×10^6 to 1.4×10^6 m^3. Smaller water requirements were related to

Scenario 2, and larger water needs were required for Scenarios 4 and 5, which also are associated with translocation of water between aquifer zones. In Scenarios 4 and 5, the water footprint is on the order of 5% of the water deficit in the basin.

Based purely upon environmental sustainability, reducing water demand by 50% (Simulation 2.3) is the best management case as the aquifer is actually recharged rather than being depleted. Simulation 2.3 is the most economic option when considering the amount of energy input necessary to neutralize the water deficit; however, it is also likely the most costly option in social terms as it would require drastic measures of water reduction by all users. Although this scenario would merely reduce production capacity of the mining sector, reducing half of the water available for irrigation most likely will cause the withering of crops and completely eliminate the agricultural economy. A much more likely possibility would be reducing water demand by 20% or 30% (Simulations 2.1 or 2.2), values seen in practice through technological advancement in water reuse and recycling [37]. Hence, future studies should explicitly address the feasibility of water reuse and recycling to achieve more sustainable levels of water demand.

Conventional fossil fuel combustion, however, should not be the only energy source considered to reduce the water deficit within the basin. If an IWRM scheme is to be sustainable, it must use renewable energy sources to increase the amount of available water. Being that Copiapó is located in one of the driest deserts on Earth at near-tropic latitude, with solar radiation levels on the order of 2350 kWh/m^2 per year [46], solar energy is a promising renewable energy source that could be used to reduce the water deficit in the basin. Using the average yearly radiation, assuming typical photovoltaic solar panel efficiencies to generate electricity [46], and considering the energy required to increase the amount of available water in the basin, we estimated the required area of solar panels to provide the energy necessary to completely eliminate the water deficit. The base scenario (Simulation 1.1) would require on the order of 200 ha of solar panels whereas the IWRM scenarios would require less than ~10 ha. In terms of water footprint, a photovoltaic power plant requires on the order of 0.1 L/kWh for array washing and potable water needs [47]. This water footprint is much smaller than that estimated for conventional coal combustion, which is on the order of 1–3 L/kWh [44,45]. Although a more detailed economic and scientific analysis would be required before the feasibility of a project of this scale may be assessed, an order-of-magnitude estimate of renewable energy sources coupled with sustainable management decisions offers reason to believe in the benefits of water recycling and supply powered by solar energy, and calls for further exploration. The implementation of this type of projects has to be framed within national water and energy policies, which have to encourage use of new technologies and of alternative energy sources supported by an IWRM. These policies will allow following a more sustainable approach for water and energy use in basins where multiple users face intense competition for limited freshwater resources for socio-economical activities.

4. Conclusions

An IWRM model was developed to investigate the relationship between water and energy to reduce water stress in the arid, highly vulnerable Copiapó river basin. The model was used to evaluate and characterize groundwater and surface water resources, as well as water demand and uses. Our results showed that no more than ~2.6 m^3/s can be sustainably pumped from the aquifer. To estimate the future availability of water within the basin, different IWRM scenarios were studied. The scenarios were defined in conjunction with the Water Agency to visualize the choices that stakeholders and water managers have to reduce the risk of water shortage and to adapt to future water resource availability. These scenarios considered different magnitudes of both uniform and segmented reductions of water demands, as well as translocation of water between aquifer sectors, and were thought to support policy makers for future policy developments. Model results suggested that the basin is facing a very complex situation and that decisions must be made to guarantee the water supply and sustainable development of the basin. Since the model assumes stationary biophysical conditions, it is expected a more severe situation than that predicted by the IWRM model.

The results of this investigation suggest that any of the water resource management scenarios are significantly more economic than the option of inaction. Therefore, policy and decision-makers must act quickly to lessen the water crisis in this basin. One solution to reduce this crisis is to use SWRO to eliminate the water deficit. Four thousand seven hundred and two (4702) GWh are needed to eliminate the water deficit under the baseline scenario using SWRO powered by fossil fuel, with associated operational costs of ~US$781 million. These estimates are first-order approximations that only include energy required to drive desalination and to circulate fluids through the distribution systems. In the best-case scenario—50% reduction in the water demand—the energy required to suppress the water deficit is ~35 GWh (US$6 million). This scenario, however, is likely the most expensive in terms of social, capital and economic production, as it would require drastic measures of water reduction by all users. If a more feasible 30% reduction in the water demand is adopted, ~70 GWh are needed over the next 30 years to meet the energy requirements to increase the available water through SWRO. Given that Copiapó is located in one of the driest deserts on Earth, these energetic requirements could be supplied by solar energy.

This study highlights the importance of a broader integration between water and sustainable energy in which water recycling and reuse, combined with IWRM, could provide a solution for the water shortages observed in highly vulnerable basins located in arid environments. This broader integration will help decision makers and water and energy managers to delineate future policies and adapting capacities that must be adopted to overcome the unsustainable water use, which is intimately linked to the energy required to supply more freshwater to the basin's water users.

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Author Contributions

The manuscript was primarily written by Francisco Suárez, Jorge Gironás and Christian K. Hunter, but all the authors contributed to its preparation and review. The IWRM model was developed under the guidance of José F. Muñoz and Bonifacio Fernández. Jean-Marc Dorsaz and Christian K. Hunter improved the IWRM model and performed model runs. Data analysis and discussion of results was carried out by Jorge Gironás, Francisco Suárez, Christian K. Hunter, José F. Muñoz, and Bonifacio Fernández.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Global Water Partnership. *Towards Water Security: A Framework for Action*; Global Water Partnership: Stockholm, Sweden, 2000.
2. Gallego-Ayala, J.; Juízo, D. Integrating stakeholders' preferences into water resources management planning in the incomati river basin. *Water Resour. Manag.* **2014**, *28*, 527–540.
3. Coelho, A.C.; Labadie, J.W.; Fontane, D.G. Multicriteria decision support system for regionalization of integrated water resources management. *Water Resour. Manag.* **2012**, *26*, 1325–1346.
4. Malik, R.P.S. Water-energy nexus in resource-poor economies: The Indian experience. *Int. J. Water Resour. D* **2002**, *18*, 47–58.
5. Sima, L.C.; Kelner-Levine, E.; Eckelman, M.J.; McCarty, K.M.; Elimelech, M. Water flows, energy demand, and market analysis of the informal water sector in Kisumu, Kenya. *Ecol. Econ.* **2013**, *87*, 137–144.
6. Bindra, S.P.; Hamid, A.; Salem, H.; Hamuda, K.; Abulifa, S. Sustainable integrated water resources management for energy production and food security in Libya. *Procedia Technol.* **2014**, *12*, 747–752.
7. Vörösmarty, C.J.; Green, P.; Salisbury, J.; Lammers, R.B. Global water resources: Vulnerability from climate change and population growth. *Science* **2000**, *289*, 284–288.
8. Arnell, N.W. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Glob. Environ. Chang.* **2004**, *14*, 31–52.
9. Pahl-Wostl, C. Transitions towards adaptive management of water facing climate and global change. *Water Resour. Manag.* **2007**, *21*, 49–62.
10. Kalbacher, T.; Delfs, J.; Shao, H.; Wang, W.; Walther, M.; Samaniego, L.; Schneider, C.; Kumar, R.; Musolff, A.; Centler, F.; *et al.* The IWAS-ToolBox: Software coupling for an integrated water resources management. *Environ. Earth Sci.* **2012**, *65*, 1367–1380.
11. Hadded, R.; Nouiri, I.; Alshihabi, O.; Maßmann, J.; Huber, M.; Laghouane, A.; Yahiaoui, H.; Tarhouni, J. A decision support system to manage the groundwater of the Zeuss Koutine aquifer using the WEAP-MODFLOW framework. *Water Resour. Manag.* **2013**, *27*, 1981–2000.
12. Kalbus, E.; Kalbacher, T.; Kolditz, O.; Krüger, E.; Seegert, J.; Röstel, G.; Teutsch, G.; Borchardt, D.; Krebs, P. Integrated water resources management under different hydrological, climatic and socio-economic conditions. *Environ. Earth Sci.* **2012**, *65*, 1363–1366.
13. Grundmann, J.; Schütze, N.; Gerd H. Schmitz, G.; Al-Shaqsi, S. Towards an integrated arid zone water management using simulation-based optimization. *Environ. Earth Sci.* **2012**, *65*, 1381–1394.

14. Leidel, M.; Niemann, S.; Hagemann, N. Capacity development as a key factor for integrated water resources management (IWRM): Improving water management in the Western Bug River Basin, Ukraine. *Environ. Earth Sci.* **2012**, *65*, 1415–1426.
15. Moharram, S.H.; Gad, M.I.; Saafan, T.A.; Khalaf-Allah, S. Optimal groundwater management using genetic algorithm in El-Farafra Oasis, Western Desert, Egypt. *Water Resour. Manag.* **2012**, *26*, 927–948.
16. Akhbari, M.; Grigg, N.S. A framework for an agent-based model to manage water resources conflicts. *Water Resour. Manag.* **2013**, *27*, 4039–4052.
17. Razavi-Toosi, S.L.; Samani, J.M.V. Evaluating water transfer projects using analytic network process (ANP). *Water Resour. Manag.* **2012**, *26*, 1999–2014.
18. European Commission. *EU Water Framework Directive* (Directive 2000/60/EC); European Parliament and Commission: Brussels, Belgium, 22 December 2000.
19. Andreu, J.; Ferrer-Polo, J.; Pérez, M.A.; Solera, A. Decision support system for drought planning and management in the Jucar river basin, Spain. In Proceedings of the 18th World IMACS/MODSIM Congress, Cairns, Australia, 13–17 July 2009.
20. Wilkinson, R. Integrating water and energy resource management: Progress and opportunities. In Proceedings of the World Environmental and Water Resources Congress, Tampa, FL, USA, 15–19 May 2007.
21. Mo, W.; Nasiri, F.; Eckelman, M.J.; Zhang, Q.; Zimmerman, J.B. Measuring the embodied energy in drinking water supply systems: A case study in the Great Lakes Region. *Environ. Sci. Technol.* **2010**, *44*, 9516–9521.
22. Buytaert, W.; Friesen, J.; Liebe, J.; Ludwig, R. Assessment and management of water resources in developing, semi-arid and arid regions. *Water Resour. Manag.* **2012**, *26*, 927–948.
23. División de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile (DICTUC). *Análisis Integrado de Gestión en Cuenca del río Copiapó*; DICTUC: Santiago, Chile, 2010.
24. Oyarzún, J.; Oyarzún, R. Sustainable development threats, inter-sector conflicts and environmental policy requirements in the arid, mining rich, Northern Chile territory. *Sustain. Dev.* **2011**, *19*, 263–274.
25. Instituto Nacional de Estadísticas (INE). *CHILE: Proyecciones y Estimaciones de Población 1950–2050*; INE: Santiago, Chile, 2005.
26. The National Map Viewer and Download Platform. Available online: http://nationalmap.gov/viewer.html (accessed on 1 August 2014).
27. Fetter, C.W. *Applied Hydrogeology*, 4th ed.; Prentice Hall, Inc.: Upper Saddle River, NJ, USA, 2001.
28. Andreu, J.; Capilla, J.; Sanchis, E. AQUATOOL: A generalized decision support-system for water-resources planning and operational management. *J. Hydrol.* **1996**, *177*, 269–291.
29. Ochoa-Rivera, J.C.; Andreu, J.; García-Bartual, R. Influence of inflows modeling on management simulation of water resources system. *J. Water Res. Pl. ASCE* **2007**, *133*, 106–116.
30. Paredes-Arquiola, J.; Andreu, J.; Martín-Monerris, M.; Solera, A. Water quantity and quality models applied to the Jucar River basin, Spain. *Water Resour. Manag.* **2010**, *24*, 2759–2779.

31. Paredes-Arquiola, J.; Martínez-Capel, F.; Solera, A.; Aguilella, V. Implementing environmental flows in complex water resources systems—Case study: The Duero River basin, Spain. *River Res. Appl.* **2011**, *29*, 451–468.
32. Pulido-Velázquez, M.; Sahuquillo, A.; Andreu, J. An efficient conceptual model to simulate surface water body-aquifer interaction in conjunctive use management models. *Water Resour. Res.* **2007**, *43*, doi:10.1029/2006WR005064.
33. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models part I–A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290.
34. Legates, D.R.; McCabe, G.J., Jr. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resour. Res.* **1999**, *35*, 233–241.
35. Fowler, H.J.; Blenkinsop, S.; Tebaldi, C. Linking climate change modelling to impacts studies: Recent advances in downscaling techniques for hydrological modelling. *Int. J. Climatol.* **2007**, *27*, 1547–1578.
36. Mahmoudi, H.; Ouagued, A.; Ghaffour, N. Capacity building strategies and policy for desalination using renewable energies in Algeria. *Renew. Sust. Energ. Rev.* **2009**, *13*, 921–926.
37. Shaffer, D.L.; Yip, N.Y.; Gilron, J.; Elimelech, M. Seawater desalination for agriculture by integrated forward and reverse osmosis: Improved product water quality for potentially less energy. *J. Membr. Sci.* **2012**, *415–416*, 1–8.
38. Ghaffour, N.; Missimer, T.M.; Amy, G.L. Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination* **2013**, *309*, 197–207.
39. Terink, W.; Immerzeel, W.W.; Droogers, P. Climate change projections of precipitation and reference evapotranspiration for the Middle East and Northen Africa until 2050. *Int. J. Climatol.* **2013**, *33*, 3055–3072.
40. Earman, S.; Dettinger, M. Potential impacts of climate change on groundwater resources—A global review. *J. Water Clim. Chang.* **2011**, *2*, 213–229.
41. IPCC. Summary for Policymakers. In *Climate Change 2013: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2013.
42. Centro de Despacho Económico de Carga–Estadísticas e informes. Available online: https://www.cdec-sic.cl/est_opera_privada.php (accessed on 2 May 2014).
43. Karagiannis, I.C.; Soldatos, P.G. Water desalination cost literature: Review and assessment. *Desalination* **2008**, *223*, 448–456.
44. Lazarova, V.; Choo, K.; Cornel, P. *Water-Energy Interactions in Water Reuse*; IWA Publishing: London, UK, 2012.
45. Olsson, G. *Water and Energy. Threads and Opportunities*; IWA Publishing: London, UK, 2012.
46. Duffie, J.A.; Beckham, W.A. *Solar Engineering of Thermal Processes*, 3rd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2006.
47. Gleick, P.H. Water and energy. *Annu. Rev. Energy Environ.* **1994**, *19*, 267–299.