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Modelling water resources for planning irrigation development in drought-prone southern Chile

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ABSTRACT
To foster poverty reduction in drought-prone Araucanía, the Chilean Irrigation Commission is planning an important expansion of irrigated areas. Scenarios incorporating climate change (2030–2059) were simulated for a pilot basin using the WEAP water allocation model, showing that larger irrigated areas, coupled with higher temperatures and less precipitation, are likely to cause severe seasonal water scarcity. As decision support for the planning of effective measures to increase drought resilience, we modelled the construction of two upstream reservoirs combined with higher irrigation efficiency. We find that unmet water demand can be reduced by up to 97.7% by these measures.

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Introduction

Water scarcity and droughts are becoming increasingly prevalent throughout the world, deriving from both climate changes and overexploitation of water resources (Bates et al., 2008; UN-Water, 2010). Climate change is expected to increase the intensity and frequency of extreme weather events, such as floods and droughts (Intergovernmental Panel on Climate Change [IPCC], 2014). In particular, this work focuses on hydrological drought, which is defined as the 'deficiency of water reserves in groundwater and surface water bodies', regardless of whether this derives from reductions in precipitation or over-abstraction (Global Water Partnership Central and Eastern Europe, 2015).

An adequate management of hydrological droughts by policy makers requires a good knowledge of adaptation measures and their applicability in the local context. These measures might include optimized water allocation strategies, construction of new infrastructure (grey measures) and nature-based solutions (green measures). Many of the adaptation measures implemented across the globe focus on a systems approach centred on optimizing economic benefits (Brown et al., 2002; Rosegrant et al., 2000), while other studies take meeting food security needs as the primary objective (Wang et al., 2015). Extensions of these methods include the added effects of drought in water allocation models in situations where the demands of all users cannot be met in periods of low water

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Supplemental data for this article can be accessed here.

availability (Giacomelli et al., 2008), quantifying risk management in confronting drought (Merabtene et al., 2002) and multicriteria decision making based on the Driver–Pressure–State–Impact–Response model (Chung & Lee, 2009).

Water allocation models are useful tools for future planning and decision support at the basin and sub-basin scale, because they can capture changes in seasonal patterns or short-term water scarcity events and allow the quantification the combined impacts of multiple adaptation measures planned to cope with such events. In particular, water allocation models allow the quantification of the trade-offs between system supply and demands in multiple scenarios, including improving dam storage capacity, building new storage capacity, changing irrigation coverage and/or efficiency, and reusing treated wastewater (Hussein & Al-Weshah, 2009; Mishra et al., 2017; Souza et al., 2017).

Regarding water management for droughts, the US Army Corps of Engineers (1994) identified three types of measures: strategic (long-term, physical and institutional responses), tactical (responses to short-term deficits) and emergency (ad hoc responses to immediate conditions). More recently, there has been a move towards planning for drought in the context of climate change (Pinson et al., 2015), drought management plans that rely on indicators (Hervás-Gámez & Delgado-Ramos, 2019), demand reduction strategies (Stakhiv et al., 2016), and risk reduction plans that are complemented by drought mitigation or preparedness plans (Wilhite et al., 2014). Rossi and Cancelliere (2013) classify actions to manage drought in three categories: actions that reduce demand, that increase water supply and that minimize impacts.

In the study region of Araucanía in southern Chile, long-term climate projections indicate decreasing precipitation coupled with higher temperatures, greater climate variability, and hydrological drought (Orrego et al., 2016; Prudhomme et al., 2014). The La Niña phenomenon typically reduces precipitation in Chile (Center for Climate and Resilience Research [CR2], 2015; Meza, 2013), and increasing water demands result in critical periods of water scarcity and drought, especially in the low-flow summer months.

To foster poverty reduction in the region, the National Irrigation Commission (CNR, 2017a) has proposed the expansion of the irrigated area in the coming decades. This plan should tackle ongoing reductions in water availability, along with the projected decrease in precipitation coupled with higher temperatures. This article is the first comprehensive water allocation study to address the aforementioned challenges in the study region, and thus provides important decision support information for the identified needs in Araucanía. The Water Evaluation and Planning System, or WEAP (Yates et al., 2005), was selected to predict changes in short-term water resource availability and to analyze the effectiveness of the adaptation measures devised for the region. WEAP has been widely used in studies throughout Chile to model water management scenarios and the effects of climate change on agriculture (CNR, 2017b, 2017c; MAPA, 2019; Vicuña et al., 2012).

The overall objective of this study is to investigate whether the construction and suitable operation of two reservoirs as well as the improvement of irrigation efficiency would be effective strategic adaptation measures to meet future water demand in a data-scarce region in southern Chile, considering an increase of agricultural areas and future climate scenarios. We consider that the scenario analysis is an important input that will serve water planning processes for irrigation development in the region. The specific objectives are to understand the seasonal and interannual variability of water availability and demand in the region; to provide a preliminary assessment of the impact of the lower precipitation and higher temperatures projected for the study region on water availability; and to assess whether building two reservoirs and improving irrigation efficiency will suffice to combat future water scarcity in the study area.

Study area

The Traiguén-Quino catchment is located in the Imperial River basin (DGA code 0900) in the north-eastern area of the Araucanía region of Chile (38.1°S – 38.4°S) and covers an area of 1672 km^2. The study area varies in elevation from 42 to 1693 metres above sea level, and the main rivers (the Traiguén and Quino) flow in a westerly direction towards the catchment outlet. The study area is shown in Figure 1, along with the locations of four discharge stations, 11 precipitation stations and two temperature stations. Currently, there are no dams or reservoirs in the study area. Several small storage locations, called microtranques, exist, but they are considered to have negligible impact at the scale of the study area, and hence are not included in the modelling. The Traiguén-Quino catchment was selected due to the severe water scarcity in the area in the summer, and also after consultation with several key water stakeholders from the region (representatives from the Chilean Water Authority, DGA; CNR; National Emergency Office, ONEMI; and Hydraulic Works Department, DOH). An irrigation canal network extends through the study region, with water diverted at various extraction points, known as *bocatomas* (CNR, 2017a).

Between the latitudes of 35°S and 40°S, the convergence of a northerly jet and baroclinic westerlies typically generates high rainfall in Chile on the western side of the Andes (Garreaud, 2009). The average annual precipitation in the study area over the period 1987–2016 was about 1450 mm, mostly occurring in April through September (DGA, 2016). The average annual precipitation in the upper regions of the study area is almost double the amount in the lower regions. The mean monthly derived precipitation and temperature in this period, along with discharges at the four discharge stations in the basin, are shown in Figure 2.

The Imperial River basin has low precipitation in summer (on average only 20–31% of annual precipitation falls from October to March), lacks water storage infrastructure, and has been subject to long and severe droughts in recent years (DGA, 2016; Mena, 2018; Zambrano-Bigiarini & Baez-Villanueva, 2019; Zamorano, 2016). Historically, there was no need for a comprehensive irrigation network in Araucanía, owing to the humid climate and the principal crop types in the region. Over the last decades, there was a shift away from cultivating cereals towards using the land for exotic plantations, particularly pine and eucalyptus, and to a lesser extent horticulture (Huber & Iroumé, 2006; Jaramillo, 2013). The combined effect of these changing crop preferences, higher temperatures and lower summer streamflow has initiated a steady increase in irrigation requirements, adding extra strain to water resources, particularly in the summer. The CNR (2017a) has developed the Irrigation Plan for Araucanía, which provides a general overview of strategies that aim to extend the irrigation network and meet future water demand.

The increase in exotic plantations, especially pine and eucalyptus, is exacerbating the demand for scarce water resources in the study area (Huber & Iroumé, 2006). Water-intensive monoculture plantations can have a detrimental effect on the overall water yield (Scott & Prinsloo, 2008). Little et al. (2009) studied two large watersheds in south-central Chile, where native forest cover was reduced from 52.3% to 14.2% in the first watershed and from 36.1% to 8.1% in the second, while forest plantations, mainly *Pinus radiata*, increased from 12% to 55% in the first watershed and from 4.7% to 42% in the second. The authors determined that the summer runoff reduced by 42.7% and 31.9%, respectively, in the two watersheds.

To manage the water deficit, ONEMI coordinate potable water deliveries to numerous users in the study area. Over the four-year period from 2011 to 2014, approximately 1,120 million Chilean pesos (USD1.4 million) was spent on such water trucks in Araucanía (CR2, 2015). ONEMI indicates that these deliveries are to communities which relied on groundwater abstraction for their potable water, and that these sources have since ceased to yield water. The number of water trucks in operation in Araucanía increased from 15 to 184 from 2009 to 2016, with 11 water trucks operating in the study area in 2017, delivering water six days a week (ONEMI, personal communication, 2017).

Within Araucanía, various stakeholders such as the DGA, DOH, CNR, the regional water utility (Aguas Araucanía) and the Regional Commission for Water Resources play key roles in water rights governance, water supply, and monitoring and managing water-related infrastructure. Although water user organizations are common in Chile, only nine are registered in Araucanía, and none are located in the study area (CRRH, 2017). Chile has a unique system of water rights, which are granted to entities in accordance with the Chilean Water Code of 1981 (Ministry of Justice, 1981). There is no hierarchical prioritization of water uses, e.g. between drinking water and agriculture (Donoso, 2015). CNR (2017a) identified the potential to assist in the development of irrigated areas in Araucanía (e.g. irrigation systems, canals and a potential dam on the Cautín River), but no reports indicate any substantial measures being implemented so far.

Data

Monitoring stations

Table 1 lists the hydro-climatic monitoring stations used to characterize the study area (CR2, 2017; DGA, 2017; DMC, 2017). Four discharge stations, one evaporation station, 11 precipitation stations within 15 km of the extent of the study area and three selected temperature stations were used to characterize climate in the study area, and their locations are presented in Figure 1. Only one temperature station operates in the area (09105002–1); two other stations outside the study area were used to validate lapse rate assumptions and fill data gaps. Humidity, cloud cover and wind speed data are scarce, and values from the station at Temuco were used to represent the entire study area. Discrepancies exist between the exact locations and elevations of monitoring stations according to the differing sources (CR2, 2017; DGA, 2016, 2017; DMC, 2017); we used information about locations and elevations from one source we considered reliable (DGA, 2016).

A 29-year data period from April 1987 to March 2016 was selected to calibrate and verify the water allocation model, which was long enough to include several hydrological drought events and was not subject to the pre-1987 relative data scarcity. The data availability columns in Table 1 refer to the percentage of months from April 1987 to March 2016 with data available for every day (complete), some days (partial) or no days. The monthly precipitation measurements reported by DGA for months with incomplete data are the

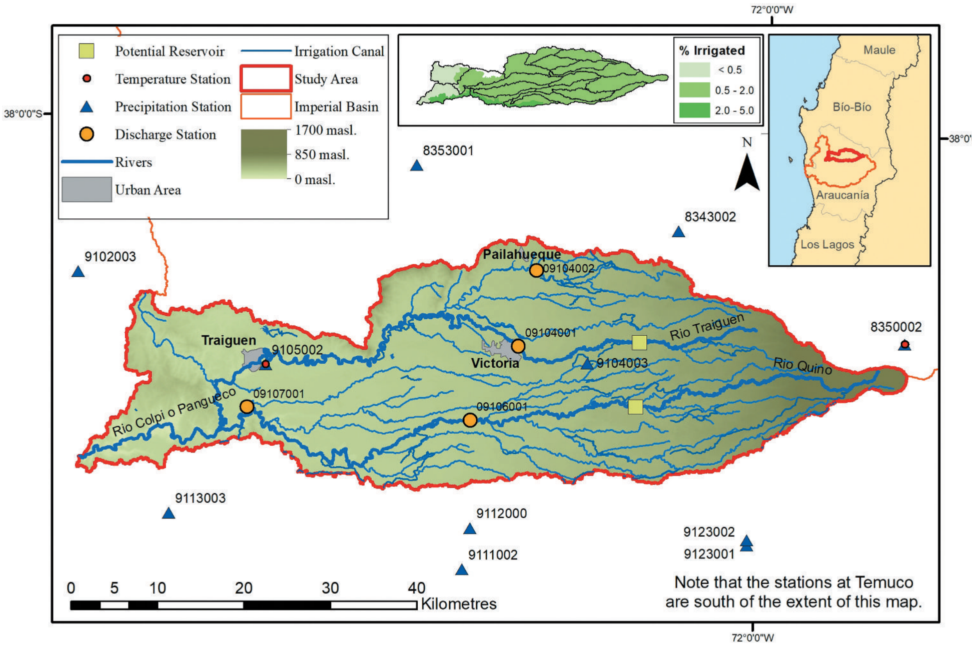

Figure 1. Location of the Imperial basin and the Traiguén-Quino River system (US Geological Survey, 2004; DGA, 2016).

sum of the available days and do not include corrections for missing days. Therefore, only full monthly precipitation data sets were used in model calibration.

Gridded meteorological data

One of the precipitation input data sets was acquired from Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS v2.0), which calibrates quasi-global satellite data from 1981 to near-present against station data to provide a gridded precipitation time series at a resolution of 0.05° (Funk et al., 2015). A comparative research analysis of multiple satellite-based rainfall estimate products concluded that the CHIRPS v2.0 product performed well for the characteristics of the study basin (in the humid south of Chile and in low to mid-elevation zones up to 1000 m above sea level), hence its selection (Zambrano-Bigiarini et al., 2017).

Data from the Catchment Attributes and Meteorology for Large-Sample Studies data set specific to Chile (CAMELS-CL) were used to characterize potential evapotranspiration in the study area (Alvarez-Garreton et al., 2018). The estimates are generated using ground data, remote-sensed products and reanalysis, and the potential evapotranspiration data set used was calculated using the formula from Hargreaves and Samani (1985).

Satellite data from 2000 to 2016 show that snow coverage in the selected sub-basin is minimal throughout the year (National Aeronautics and Space Administration, 2017). Furthermore, there is no significant delay between the peak

Table 1. Hydro-climatic data used.

Station type	Station name and code	Station elevation (m above sea level)	Data availability, April 1987 to March 2016 (%)		
			Complete	Partial [a]	None
Discharge	Río Traiguen en Victoria (09104001–8)	350	98.3	1.1	0.6
	Río Dumo en Santa Ana (09104002–6)	300	96.6	2.3	1.1
	Río Quino en Longitudinal (09106001–9)	450	98.3	1.7	0.0
	Estero Chufquen en Chufquen (09107001–4) [b]	158	72.7	14.4	12.9
Precipitation	Encimar Malleco (08343002–8)	520	92.0	2.6	5.5
	Laguna Malleco (08350002–6)	890	91.1	5.2	3.7
	Ercilla (Vida Nueva) (08353001–4)	250	60.9	0.6	38.5
	Lumaco (09102003–3)	70	100.0	0.0	0.0
	Las Mercedes (Victoria) (09104003–4)	350	98.6	0.6	0.9
	Traiguén (09105002–1)	234	98.6	1.4	0.0
	Quillén (09111002–4)	250	98.0	2.0	0.0
	Perquenco (09112000–3)	290	48.0	0.0	52.0
	Galvarino (09113003–3)	40	98.9	0.9	0.3
	Curacautín (09122001–6)	535	99.1	0.6	0.3
	Rari Ruca (09123002-K)	440	79.0	2.9	18.1
Temperature	Laguna Malleco (08350002–6)	890	50.0	36.5	13.5
	Traiguén (09105002–1)	234	89.4	6.6	4.0
	Maquehue, Temuco AD. (380013)	92	100.0	0.0	0.0
Evaporation	Traiguén (09105002–1)	234	50.9	30.2	19.0
Humidity [c]	Maquehue, Temuco AD. (380013)	92	97.4	0.0	2.6
Cloud cover [c]	Maquehue, Temuco AD. (380013)	92	94.0	0.0	6.0
Wind speed [c]	Maquehue, Temuco AD. (380013)	92	97.7	0.0	2.3

[a]Partial discharge and temperature data sets are taken as the average from available data. These are used in model calibration as they are assumed to be sufficiently representative of the monthly weather variations.
[b]Located on the Quino River.
[c]Average reported monthly values were used to fill data gaps.

measured rainfall and the peak measured discharge. Hence, snowmelt modelling is not considered in this study.

Geology

The study area is mostly in the central depression between the volcanic Andes mountain range to the east and the coastal mountain range to the west. The central depression consists of Tertiary and Quaternary sediments formed from erosion of the Andes by glacial and fluvial processes, and generally exhibits slight undulations throughout (DGA, 2004, 2016). Superficial soils in large parts of the study area show fine sand with a small clay percentage and abundant small roots (CIREN, 2002; DGA, 2012) while the stratigraphy exhibits interbedded layers of sandy or gravel texture (DGA, 2004).

Groundwater

The central depression is understood to exhibit a higher permeability and water infiltration rate than both the mountain ranges (DGA, 2010). See Table A1 in the online supplemental data for published estimates of groundwater recharge rates in the study area. The dominant groundwater flow direction in the study region is from east to west, consistent with the downward slope of the area (DGA, 1986). Estimated lateral flows

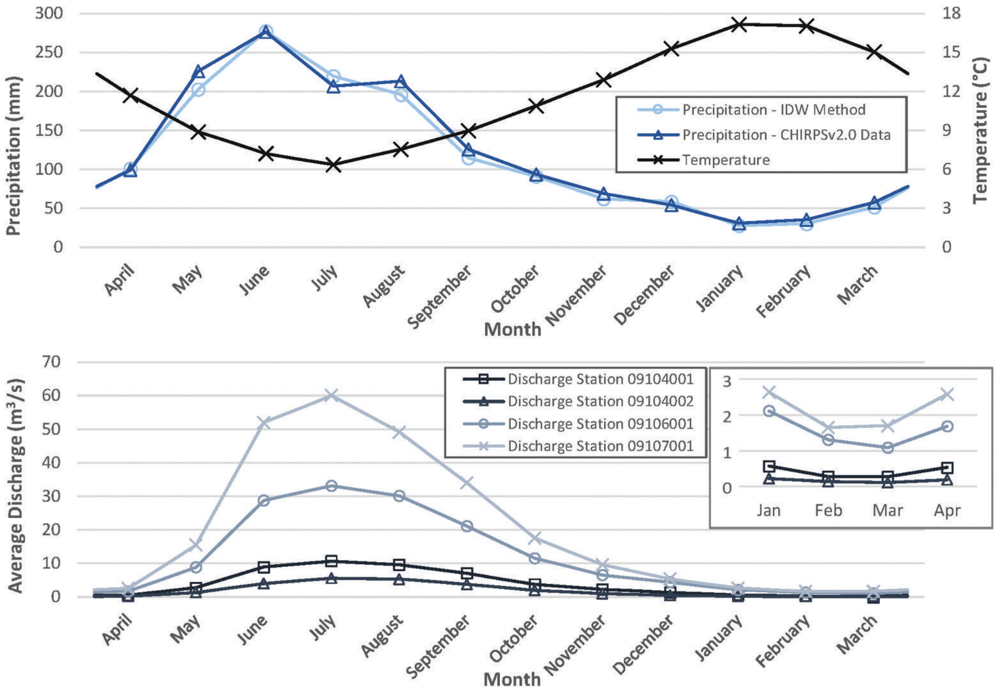

Figure 2. Mean monthly precipitation, temperature and river discharge in the Traiguén-Quino River system.

within the soil structure are also very high, as expected from the moderate permeability derived from pumping tests (DGA, 2016).

Some groundwater modelling has been conducted by DGA (2016), but the steady-state simulations in that study were not deemed to adequately characterize the spatial and temporal variability of groundwater at the aquifer level in Araucanía. Static groundwater levels have been sporadically measured by the DGA from 1986 to present at approximately 100 locations in the study area (DGA, 1986, 2001, 2012, 2016), though these measurements are too sparse both chronologically and spatially to adequately estimate the rate at which groundwater levels change. Information on the necessity of water truck deliveries provides sufficient evidence that the groundwater has been drained faster than the recharge rate over the period analyzed.

Land use

Land use was divided into irrigated and non-irrigated areas, as defined in DGA (2016), where the former refers only to areas where irrigation water is sourced from superficial water. Data sources and methodologies used to derive the historical development of irrigation area, crop water requirements, irrigation efficiencies and forestry areas are presented in Section B of the online supplemental data.

Water demand

Historical water demand both from superficial sources and from the groundwater extraction system were derived from DGA and Ministry of Public Works reports (DGA, 1996, 2001, 2016; MOPW, 2017) with interpolation and extrapolation. To estimate future water demand, trends in coverage of irrigated areas and irrigation efficiency estimates (MOPW, 2017) as well as projections of required potable water from the Regional Water Utility (Araucanía, 2014a, 2014b), were used (see Section B of the online supplemental data).

Because information is scarce regarding the water sources and exact quantities delivered by water trucks, and because the delivered water is assumed to be completely consumed, the water deliveries are not considered in the water balance modelling of the study region.

Climate projections

Climate change models from the IPCC operate at a global scale, with a grid size too large to sufficiently capture the complex topographical effects of the Andes and other geographical features on the weather patterns in Chile. Because of this, downscaled regional analyses were undertaken by the Chilean Meteorological Service (DMC), using the regional Weather Research and Forecasting model (Skamarock et al., 2005) nested in MIROC5 (Watanabe et al., 2010), to model the Representative Concentration Pathway (RCP) 8.5 scenario over the extent of Chile (DMC, 2014).

Methodology

Water management model

The WEAP model is a widely used decision support system, developed by the Stockholm Environment Institute, for Integrated Water Resources Management and policy analysis (Yates et al., 2005), comprising a conceptual, semi-distributed rainfall–runoff hydrology module and options to simulate agricultural water demands and reservoirs, among other features. The WEAP model was selected to analyze the combined impacts of future climate projections (higher temperatures and less precipitation) and increased water demand, which are likely to significantly reduce long-term runoff and water availability, particularly in summer. The model was established for the study area by simplifying its hydrological system into a network, and assigning discrete points from which water can either be added or subtracted. A schematic of the model is presented in Figure 3, with an inset illustrating key components in greater detail. Of the irrigation canals present in the study region, only Cullinco Canal (from Huillinlebu Stream to Salto Stream) was included in the WEAP model during the historical data period, due its tangible impact on the flow system. The schematic shown in Figure 3 is for the future scenarios, and therefore also contains the two modelled reservoirs and required diversions (canals).

Eighteen subcatchments were defined in the study area, chosen to suitably represent all major river sections. The outflow points of the subcatchments were selected to capture the outflows of each subcatchment and to represent the location of discharge stations, allowing calibration of the model against observed discharges. Because of the small size of the study area and the lack of specific hydrogeological information on aquifer

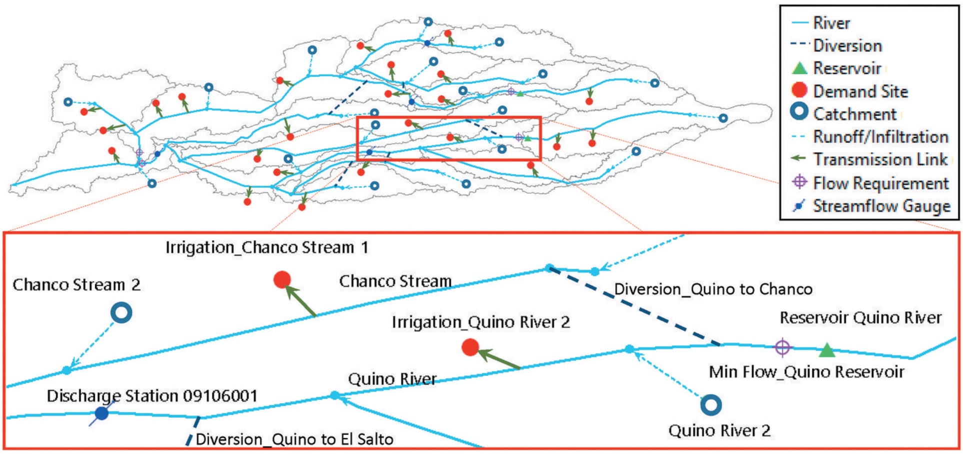

Figure 3. Water Evaluation and Planning System (WEAP) model showing subcatchments and extraction points.

characteristics (and water abstractions), the groundwater component of the WEAP model was simplified to just one aquifer, and all groundwater extractions were modelled from this one aquifer. This aquifer is linked to an external aquifer, used to represent net lateral flow of groundwater out of the study area. The monthly time scale used in this study allows seasonal variations in availability and demand to be comprehensively modelled, both in years of near-average availability and low availability. The principal elements of the WEAP model used and their functions are described in Table 2 (Yates et al., 2005). Refer to Section C of the online supplemental data for a flow chart of the WEAP calculation method for the settings used in study.

WEAP can be operated with numerous calculation settings for the purposes of modelling water flow, soil–water interactions and water consumption. In this study, the rainfall runoff (soil-moisture) method was used, with all subcatchments linked to a groundwater node. The representation of each catchment relies on a two-bucket system: the upper bucket generates streamflow from rainfall and through the soil, while the lower bucket represents the baseflow processes through the deep soil or groundwater. As the runoff sites were linked to a groundwater node, the lower bucket in this study was modelled as one large water mass into which water infiltrates from the upper bucket, returns to the

Table 2. Principal elements in the WEAP model.

WEAP element	Description
Catchment	Models the drainage areas throughout the study area
Runoff/infiltration	Links the runoff and infiltration from the catchments to the rivers and aquifer
River	Models the rivers of the study area
Diversion	Diverts water from one river to another to meet downstream demands
Groundwater	Models an aquifer which is linked to the catchments (infiltration) and also to the rivers to contribute to baseflow
Demand site	Models the water demand at discrete points
Transmission link	Links the extraction point from a river to the demand sites
Reservoir	Models the reservoirs, including evaporation of stored water
Flow requirement	Acts as a proxy to control the reservoir discharges
Streamflow gauge	Compares discharge measurements to the modelled river flows at that point

rivers as baseflow or leaves the study area while staying subterranean. Extraction (demand) locations for both river nodes and the aquifer use monthly time series as inputs, and these points were modelled as completely consumptive, meaning that none of the extracted water flows back into the rivers.

In instances where not all the water demand can be met, a demand priority option is available, which ensures that all the available water is used to first meet the highest-priority demands that are selected by the user. In this model, the same priority was assigned to all extraction points, so in water-scarce months WEAP allocates water to all demand points with equal priority. The placement of minimum flow requirements below the modelled reservoirs acts to simulate reservoir operations to release enough water to meet demand requirements and minimum flows for ecosystems, with these points assigned a secondary priority.

Model inputs

Two methods were investigated to estimate the precipitation in each subcatchment defined in the study area. The first method used monthly precipitation data from the 11 precipitation stations and an inverse distance weighting (IDW) calculation method. The two-dimensional IDW method generates a grid of cells in the study area and calculates an IDW factor for all precipitation stations for which data exist in a given month, without accounting for the influence of elevation. The second method used the CHIRPS v2.0 precipitation estimates. A comparison of the two data sets is presented in Section D of the online supplemental data.

Temperature estimates were based on measurements recorded at Traiguén (the only station in the study region), using a derived lapse rate (–0.50 °C per 100 m, see Section E of the online supplemental data) to calculate values for each subcatchment. Missing data points were filled using a linear correlation with the temperature station at Maquehue, Temuco AD, using data from 1970 onwards (DGA, 2016).

Potential evapotranspiration data, used to estimate water demand for irrigation, were taken from the CAMELS-CL data set (Alvarez-Garreton et al., 2018). Monthly average humidity, wind speed and cloudiness readings are available from DMC (2017) at Temuco, and these values were directly adopted in the model. Although the climate station is outside the study area, it is still within the central depression, and no more detailed data are available.

Monthly differences between precipitation and evaporation are required to determine changes in reservoir storage. Using data from the station Traiguén (09105002–1), the following correlation between temperature and evaporation was calculated (DGA, 2016):

$$E = 0.75T^2 - 3.20T - 6.07 \tag{1}$$

where E is monthly evaporation in mm and T is average monthly temperature in °C. In the scenarios with reservoirs, evaporation rates were calculated using the projected temperature and Equation (1).

The precipitation time series, development of irrigated land, crop coefficients, irrigation efficiency (see Section B of the online supplemental data) and potential evapotranspiration were used to derive historical time series of crop water requirements over the data period using both precipitation inputs.

Model calibration

The 29-year period from April 1987 to March 2016 was divided into a 22-year model calibration period and a seven-year validation period.

The model was calibrated using the measured discharges at the four stations in the study area, with an emphasis on minimizing the following errors:

- Discharges in the low-flow months (defined as November to May);
- Discharges at the stations further downstream;
- Differences in total observed and modelled flow volumes over the data period; and
- Discharges at the stations on the Quino and Traiguén, the two rivers on which reservoirs are modelled.

As the specific aims of this work require emphasis on these mentioned points, a heuristic analysis was undertaken to minimize these errors, while ensuring that the calibration variables remained within reasonable bounds. Only months with discharge data available at the relevant station were included in these analyses. The Nash-Sutcliffe efficiency (NSE) coefficient, used to assess model efficiency, is defined as (Nash & Sutcliffe, 1970):

$$E = 1 - \frac{\sum_{t=1}^{T} \left(Q_m^t - Q_o^t\right)^2}{\sum_{t=1}^{T} \left(Q_o^t - \bar{Q}_o\right)^2} \tag{2}$$

where

E is the NSE coefficient,

Q_m^t is the modelled discharge at time t (m^3/s),

Q_o^t is the observed discharge at time t (m^3/s), and

$\bar{Q}_o$ is the mean observed discharge over the data period (m^3/s).

The NSE coefficients were calculated at all four discharge stations using all monthly data from the calibration period; only data from the low-flow months in the calibration period; and log values of all monthly data.

Soil and crop parameters

Given the relatively small study area and the similar soil types and land use throughout, the same values for each variable optimized in the calibration process were adopted in each sub-catchment. The following variables were optimized in this process (see Table 3), either with monthly variation or fixed values for the entire year:

Table 3. Monthly calibrated soil and crop parameters.

Variable	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
K_C	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Runoff resistance factor	3.50	3.50	4.00	5.50	5.50	3.50	1.25	1.25	1.25	2.00	3.00	3.50
Root zone conductivity (mm per month)	115	115	115	115	115	100	95	95	95	95	110	115
Preferred flow direction	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Soil water capacity (mm)	465	465	465	465	465	465	465	465	465	465	465	465

- K_C – represents an average crop coefficient (not accounting for the forest areas).
- Runoff resistance factor – controls the surface runoff response and is affected by factors such as leaf area and slope; defined as a number between 0 (lowest resistance) and 1000 (highest resistance).
- Root zone conductivity – the conductivity rate of the defined top bucket at full saturation (mm per month).
- Preferred flow direction – separates flow out of the top bucket into interflow and flow to the aquifer; defined in the range from 0 (only to the aquifer) to 1 (only interflow).
- Soil water capacity – the effective water-holding capacity of the modelled top bucket of soil.

The initial soil saturation values were taken as the average values at the start of April over the last 15 years of the calibration period. Regardless of the initial values chosen, the soil saturation in different iterations tends towards the same value, therefore an average of these values provides a reasonable estimate.

Aquifer volume and outflows

Two of the important conditions to be met for baseflow to exist in the dry months are outlined by Smakhtin (2001): the draining aquifer must be recharged seasonally; and a sufficiently shallow phreatic surface must intersect the stream channel. Flow was recorded in all months throughout the calibration period, even when little or no precipitation was recorded, suggesting that a baseflow exists, despite evidence that the phreatic surface has lowered over the calibration period (ONEMI, unpublished data, 2017).

Subterranean water occupies most of the study area (DGA, 2004), and due to the lack of detailed available data, the entire study region was modelled as containing just one aquifer body, with an adjoining aquifer modelled to account for water leaving the study area but remaining sub-surface. An exponential aquifer storage–discharge relationship was used to model flow from the aquifer into the rivers in the study area and lateral flow into aquifers outside the study area.

Future scenarios

The time period for future scenarios must be long enough to model several drought cycles, far enough in the future that the proposed infrastructure could reasonably be built and operational, and starting far enough in the future to include observable climate change impacts. The period of 2030 to 2059, for which regional climate projections were available, was deemed to satisfy these criteria. Twenty-four scenarios were defined (Table 4), ranging from an optimistic best-case (no climate change effects, small increase in irrigated areas) to a business-as-usual, worst-case scenario (highest-emissions climate change scenario, large increase in irrigated areas), to provide suitable uncertainty bounds for the proposed adaptation measures.

Climate projections

Two scenarios were modelled to bound the future climate conditions between a best-case and a worst-case scenario. The worst-case scenario is based on the RCP8.5 greenhouse concentration trajectory, providing an upper bound to the predicted long-term climate variability by

Table 4. Scenarios modelled.

Period	Climate scenario	Irrigation area	Irrigation efficiency	Scenario name	
				Without reservoirs	With reservoirs
April 2030 – March 2059	Base Case	Lower bound	Lower bound	B_A1-L_N	B_A1-L_R
			Estimated	B_A1-E_N	B_A1-E_R
			Upper bound	B_A1-U_N	B_A1-U_R
		Upper bound	Lower bound	B_A2-L_N	B_A2-L_R
			Estimated	B_A2-E_N	B_A2-E_R
			Upper bound	B_A2-U_N	B_A2-U_R
	RCP8.5	Lower bound	Lower bound	R_A1-L_N	R_A1-L_R
			Estimated	R_A1-E_N	R_A1-E_R
			Upper bound	R_A1-U_N	R_A1-U_R
		Upper bound	Lower bound	R_A2-L_N	R_A2-L_R
			Estimated	R_A2-E_N	R_A2-E_R
			Upper bound	R_A2-U_N	R_A2-U_R

considering the worst-case emissions projections (IPCC, 2014). Data from DMC (2014) for the RCP8.5 scenario were analyzed to ascertain trends in precipitation and temperature compared to the hindcasting period, and the derived scaling factors were applied to the historical data for the study region (Section F of the online supplemental data).

A best-case scenario defined by the IPCC (RCP2.6) should capture the best-case scenario; however, downscaled projections were not available at the regional level. The historical data from 1987 to 2016 were therefore replicated for the 'base case' scenarios described in Table 4. As even the optimistic emissions scenario (RCP2.6) is not expected to see either falling temperatures or increasing precipitation compared to the historical data, this provides a reasonable lower bound for the modelled scenarios.

Irrigation demand

CNR (2017a) indicate that irrigated areas will continue to increase throughout the state, owing to agricultural needs and forestry. Two cases were selected to bound the expected increase: the lower bound considers the continued rate of increase estimated by MOPW (2017); and the upper bound assumes that this estimate is very conservative given the planned increases in irrigation (CNR, 2017a) and therefore uses five times that rate (Section B of the online supplemental data). Correlations between historical temperature and evapotranspiration data were used to derive potential evapotranspiration estimates based on the projected temperature increases, and these values were used to determine irrigation demands under the RCP8.5 scenario.

The irrigation efficiency conditions are lower-bound efficiency of 45%, based on estimates by CNR (2014); estimated future efficiency of 71% (MOPW, 2017); and upper-bound efficiency (88% to 90%) estimated by MOPW (2017).

Reservoir construction and operation

Two locations on the two major rivers in the study region (the Quino and Traiguén) were selected as potential reservoir locations and these are displayed on Figure 1. It is important to note that the locations chosen for this study are purely hypothetical and are not based on the land ownership or land use in the area. Their locations were selected as a trade-off between being too far downstream, so that not enough area (including areas served by hypothetical or existing canals) could benefit from a guaranteed water supply throughout the year, and being too far upstream from the headwaters, so that the reservoirs are not sufficiently recharged in the winter months. In the first year (2030) of the scenarios period, we assumed that construction of the reservoirs would have just been completed, hence they are modelled to be empty at the start of this period.

Four physical variables are required in WEAP for the modelling of the reservoirs. They were determined as follows:

- *Storage capacity*: derived after running the model and sized to ensure that demand could be met in most months under the R_A2-E_R scenario while avoiding excessive unused storage capacity.
- *Volume elevation curve*: used to calculate the surface area of water at a particular storage volume and hence convert the net evaporation into a change in storage volume. Consistent with the topography of the region, a slope of 5% was modelled for the potential reservoirs.
- *Net evaporation*: the difference between the calculated evaporation and the modelled precipitation was used to calculate a direct change in water elevation in the reservoir.
- *Groundwater interaction*: The loss to or gain from groundwater is dependent on many factors, including soil type, water table depth and soil permeability. As these data are unknown, zero net loss to groundwater was modelled.

Setting minimum flow requirements in WEAP acts as a proxy to model reservoir operations. Minimum flows should not be set too low, as effects such as degraded water quality due to the inability of certain effluents to be completely dissolved can affect the aquatic ecosystem (US Army Corps of Engineers, 1994). Minimum hydrological flows were set following the guidelines specified by DGA (2008) for watercourses designated with a minimum ecological flow of 10% of Q_{ma} (mean annual flow). These specifications use monthly calculations of 50% of the discharge levels that have a 95% probability of exceedance (Q_{95}). The monthly specifications for minimum ecological flow (Q_{min}) are:

- If 10% of Q_{ma} > 50% of Q_{95}, then Q_{min} = 10% of Q_{ma}.
- If 20% of Q_{ma} < 50% of Q_{95}, then Q_{min} = 20% of Q_{ma}.
- For all other cases, Q_{min} = 50% of Q_{95}.

Two points on both the Quino River and the Traiguén River were assigned these minimum flow requirements. The points were selected immediately downstream from the reservoir (to ensure a minimum flow at this point) and at the most downstream point before the rivers flowed into the Colpi o Pangueco River (to ensure the minimum flow after all downstream abstraction points).

Results

Model calibration

Table 5 lists the NSE coefficients and percentage differences in overall observed and modelled discharges calculated over the calibration period (April 1987 to March 2009) and validation period (April 2009 to March 2016) using the calibration constants described in

Table 5. Model efficiency coefficients: calibration and validation.

		Calibration period (04/1987 – 03/2009)				Validation period (04/2009 – 03/2016)			
		NSE		Log-NSE		NSE		Log-NSE	
Discharge station	Precipitation input	All months	Nov.–May	Difference in overall discharge (%) [a]	All months	All months	Nov.–May	All months	Difference in overall discharge (%) [a]
09104001–8	IDW	0.85	0.84	0.90	−12.8	0.84	0.65	0.81	−10.0
	CHIRPS v2.0	0.79	0.75	0.86	−12.2	0.78	0.55	0.81	−13.5
09104002–6	IDW	0.84	0.82	0.87	1.4	0.82	0.60	0.87	−1.9
	CHIRPS v2.0	0.78	0.73	0.83	−3.7	0.79	0.50	0.86	−12.7
09106001–9	IDW	0.88	0.87	0.91	−9.2	0.75	0.73	0.90	−25.4
	CHIRPS v2.0	0.82	0.77	0.87	−2.2	0.68	0.69	0.90	−24.1
09107001–4	IDW	0.89	0.92	0.90	7.8	0.94	0.76	0.90	5.3
	CHIRPS v2.0	0.80	0.76	0.84	17.9	0.90	0.58	0.90	7.6

[a]Positive values signify that the modelled discharge is greater than the observed discharge.

Table 3. The three calculation methods of NSE coefficients were selected because all provide different insights into separate aspects of the model efficiency, by focusing on distinct aspects:

- *NSE, all months*: the standard measure provides a summary of overall model reliability.
- *NSE*, *November to May only*: due to the importance of low-flow months in the context of hydrological drought, model efficiencies were calculated considering values only from these months.
- *Logarithmic-NSE, all months*: an efficiency coefficient calculated from log values of the discharge data removes the bias associated with values that vary greatly from the average flow (the peaks in this system), thus placing a greater emphasis on the low-flow months (Krause et al., 2005).

Figure 4(a-d) show scatter plots comparing the observed and modelled (IDW) discharges calculated in the WEAP model at the four discharge stations, on a logarithmic scale. For the most downstream discharge station (09107001–4), Figure 4(e) plots the hydrographs, comparing the observed measurements against those calculated in the WEAP model using both the CHIRPS v2.0 and IDW data sets. As is evident in Table 5, the NSEs for the IDW precipitation input are consistently higher than those derived using the CHIRPSv2.0 input. For this reason, the precipitation inputs for future scenarios are based on the scaled IDW historical data, and Figure 4(a-d) plots only the data comparison for the IDW data set.

Future water demand and availability

The mean temperature increases from the hindcasting data (1970–1999) to the RCP8.5 scenario (2030–2059) in the study region were calculated as 0.92 °C and 0.28 °C for the defined dry months and wet months, respectively. The results also show a decrease in mean precipitation of 20.8% and 20.9% in the dry months and wet months, respectively. The standard deviation of seasonal precipitation also increases. Under the lower-bound irrigation area scenarios (and without reservoirs or changed efficiency), application of the RCP8.5 scenario resulted in an average reduction in total streamflow (B_A1-E_N compared

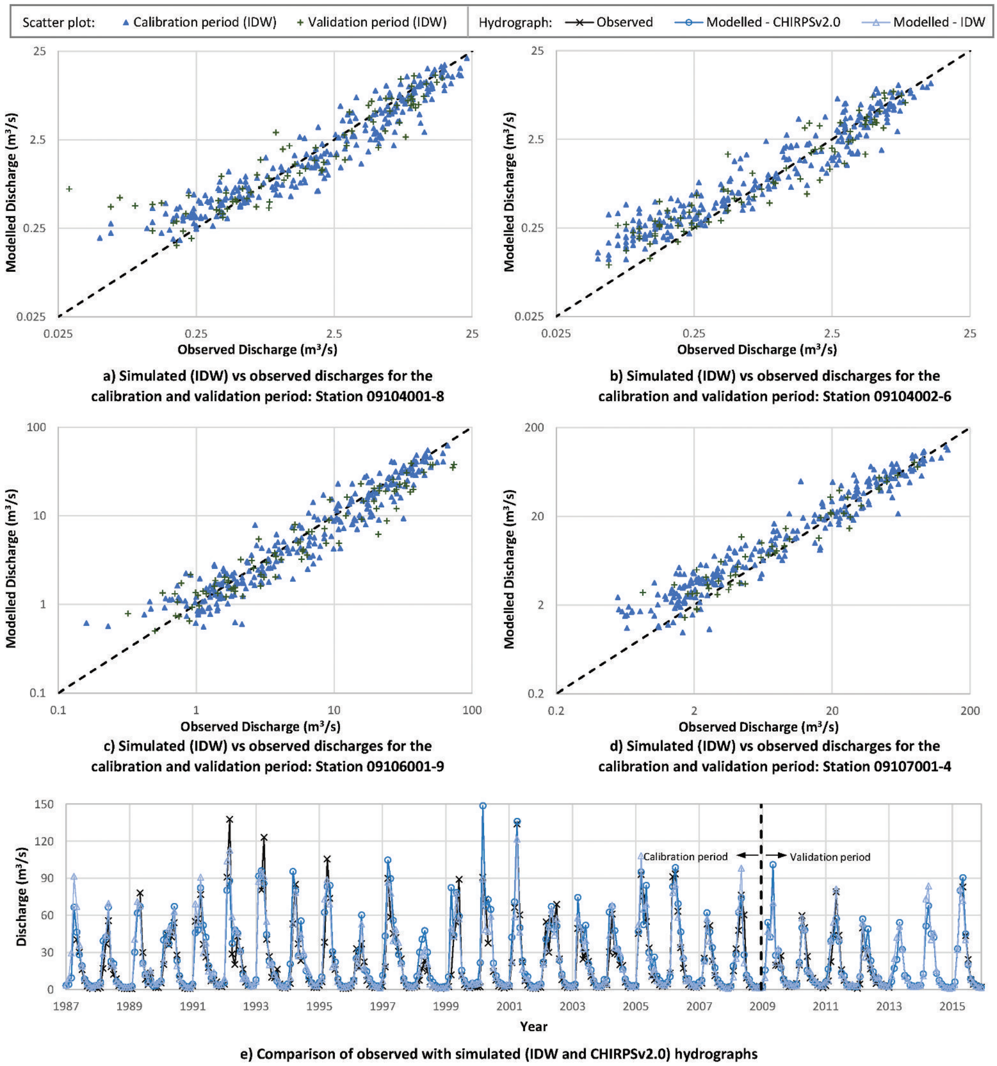

Figure 4. Calibration and validation results: (a–d) scatter plots and (e) hydrographs.

to R_A1-E_N) of 30.3% at the outlet of the study area. Based on satisfying irrigation demands in almost all months under the R_A2-E_R scenario, the required storage capacities calculated for the Quino and Traiguén Reservoirs were 20×10^6 m^3 and 15×10^6 m^3, respectively. These calculated capacities were used to model all reservoir construction scenarios.

Table 6 lists the total unmet demand for all modelled scenarios, calculated for all downstream (surface water) demand nodes that would be served by the potential reservoirs, either on the rivers with the reservoirs or hypothetically linked by irrigation canals (Section C of the online supplemental data). To present comparable results, the same selection of nodes is used to calculate unmet demand for cases where no reservoir is modelled.

Table 6. Simulated total unmet demand below potential reservoir locations (2030–2059).

Scenario	Total unmet demand (10^6 m^3)	
	Without reservoirs (_N)	With reservoirs (_R)
B_A1-L	2.2	0
B_A1-E	0.01	0
B_A1-U	0	0
B_A2-L	107.5	25.2
B_A2-E	14.9	0
B_A2-U	3.3	0
R_A1-L	14.3	2.0
R_A1-E	0.3	0
R_A1-U	0.03	0
R_A2-L	238.7	89.5
R_A2-E	49.6	9.5
R_A2-U	16.4	1.2

The key results for the estimated irrigation efficiency (71%) are:

- When only changes in climatic projections are considered with the lower-bound irrigation area (B_A1-E_N compared to R_A1-E_N), the increase in total unmet demand is relatively small (0.01×10^6 m^3 to 0.29×10^6 m^3).
- The unmet demand under the upper bound irrigation area scenario rises from 0.01×10^6 m^3 to 14.9×10^6 m^3 from the B_A1-E_N to the B_A2-E_N case.
- The cumulative effect of the addition of climate change effects and increased irrigation needs (R_A2-E_N) increases the unmet demand to 49.6×10^6 m^3.
- Building the reservoirs (sized at 20×10^6 m^3 and 15×10^6 m^3) is estimated to reduce downstream unmet demand by 80.9% under the R_A2-E scenario and eliminate unmet demand under all other scenarios.

The effects of the irrigation efficiency are:

- Under the R_A2_N scenario, the total unmet demand is heavily influenced by irrigation efficiency, with values of 238.7×10^6 m^3, 49.6×10^6 m^3 and 16.4×10^6 m^3 for lower-bound, estimated, and upper-bound efficiency, respectively.
- Total unmet demand is considerably lower considering the upper-bound efficiency, yet under the B_A2 and R_A2 scenarios, reservoirs would still be useful to alleviate water scarcity in drought years.

Figure 5 plots the downstream river discharges, reservoir storages and cumulative unmet water demand on the Quino and Traiguén Rivers for the bounding scenarios with the estimated irrigation efficiency (the B_A1-E and R_A2-E cases). Figure 5(a) and (d) plot water availability and demand. Figure 5(b) and (e) show zoomed-in sections of Figure 5(a) and (d), respectively, focusing on selected critical water supply years resulting from climatic variables, and Figure 5(c) and (f) plot the cumulative unmet demands for only R_A2-E_N and R_A2-E_R, because the unmet demand in B_A1-E_N and B_A1-E_R is zero or negligible. The results of the four other scenarios with the estimated irrigation efficiency are presented in Section G of the online supplemental data.

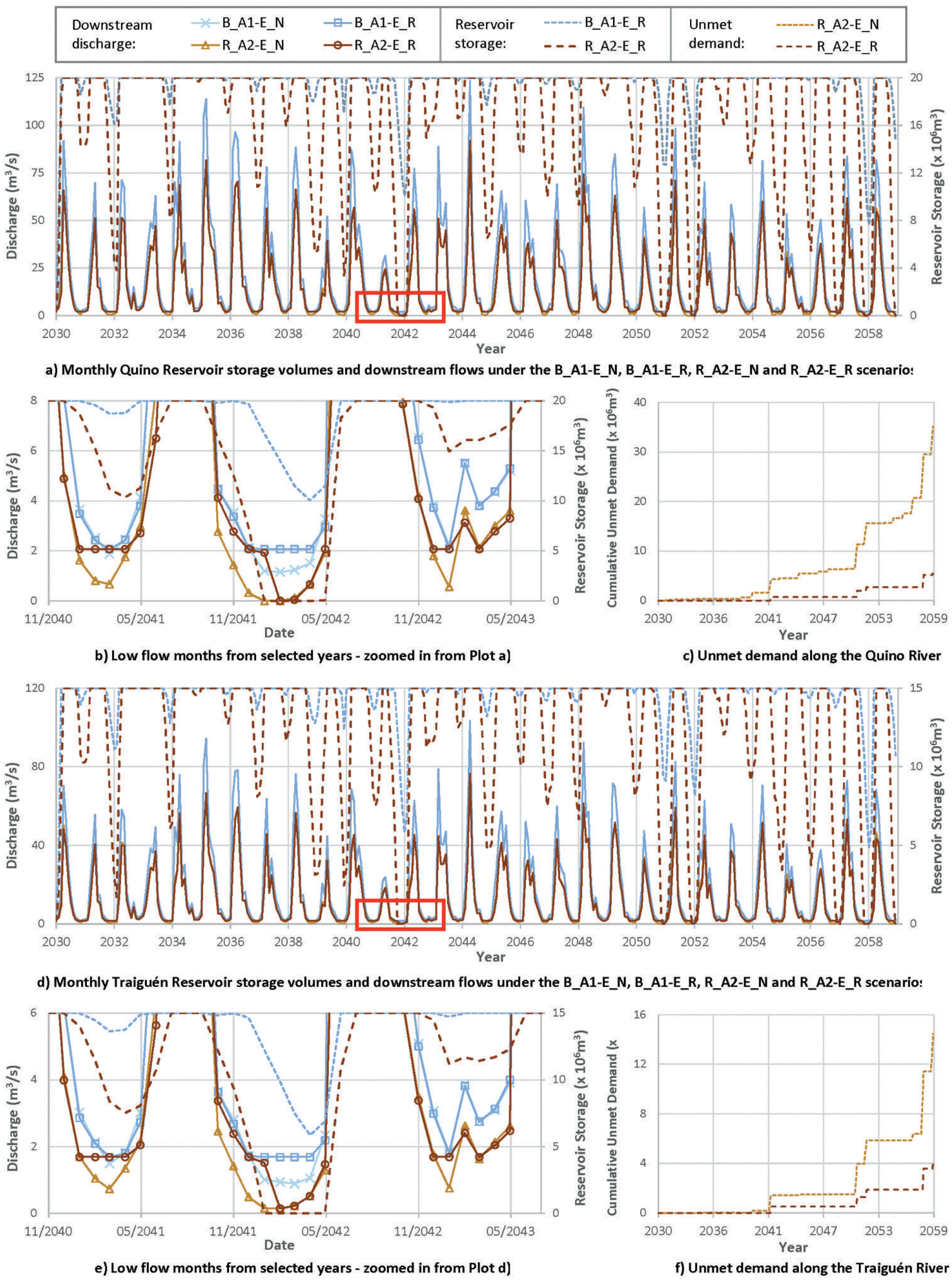

Figure 5. Simulated hydrographs and reservoir storages (a, b, d and e) as well as unmet irrigation demand (c and f) for the modelled scenarios based on different climate projections, irrigation demands and reservoir construction.

Discussion

WEAP as a water allocation model was an effective mechanism for simulating both historical data and future scenarios designed to bound the climate and irrigation best-case and worst-case scenarios, including the effect of modelling reservoirs and improving irrigation efficiency to meet increasing water demands. The published article, along with the implemented water allocation model, will be delivered to local irrigation authorities to be used in planning for water management under future irrigation scenarios. The discussion is subdivided into three sections, based on the three study objectives identified in the introduction.

Calibration of the WEAP model

The WEAP model accurately captured the hydrological balance of the study area, as evidenced by the NSEs varying from 0.78 to 0.89 in the calibration period and from 0.68 to 0.94 in the validation period. Calibrating the model for the low-flow months provided a challenge because a significant percentage of the streamflow in summer months comes from baseflow, meaning that accurate modelling of the aquifer–river interactions is of extreme importance. The high log-NSEs and NSEs for low-flow months suggest that these low-flow months have been captured to a reasonable level of accuracy (Krause et al., 2005). Despite this, a key limitation in the calibration and validation of the model was the lack of groundwater data for the study area, meaning that the model could only be calibrated against superficial water flow measurements.

At all four discharge stations, the model performed better using the precipitation data from the ground-based climate stations (interpolated using the IDW method) than using the CHIRPS v2.0 satellite-based data. The better performance of the IDW method is probably due to the spatial and elevation-based variations in precipitation being captured by the rain gauges, which are well distributed over most of the study region. A study of a high-elevation adjacent watershed without climate stations at higher elevations showed contradictory results, with the CHIRPS v2.0 data outperforming that of the IDW method (H. Hann, 'Combining satellite-based rainfall data with rainfall-runoff modelling to simulate low flows in a Southern Andean catchment', submitted to *Journal of Natural Resources and Development*, ITT, Cologne, Germany).

Despite the good performance of the WEAP model in the study area, we note some limitations: semi-distributed models do not capture the full spatial complexity of a watershed; irrigation requirements are based on crop types and climate variables, so they assume that watering procedures were optimized based on weather for the specific month; and the model vastly simplifies interactions between surface water and groundwater.

Scenario development: regional climate projections and future water demand

The integration of climate change projections in hydrological models enables better planning for water management policies, especially when they consider interannual variability in precipitation, as demonstrated by García-Vera (2013). The projected temperature and precipitation values under the RCP8.5 scenario were compared with the historical observed data specific to the study region. The increases in mean temperature (more pronounced over the dry months) and reduced precipitation are consistent with the results of Orrego et al. (2016), who used a downscaled climate projection model over the Araucanía region to investigate long-term precipitation trends. Furthermore, the projected increase in the standard deviation of seasonal precipitation values suggests that more extreme weather events are likely in the future, which is in line with predictions by the IPCC (2014).

A key limitation in the creation of climate projections for this study was that no downscaled raster data were available from the DMC for the best-case (RCP2.6) scenario. As the low-resolution projections from the IPCC are inadequate to capture the complex weather patterns in the study area, the historical data were replicated to model the base-case climate scenario. The base-case scenario therefore includes extra conservatism, as the models of the RCP2.6 scenario suggest that Araucanía will still have higher mean temperatures and less precipitation (IPCC, 2014).

Uncertainty in future changes in water demand, more specifically the large differences between the assumed lower-bound and upper-bound irrigated area scenarios, leads to vastly different upper and lower bounds on water demand in the modelled scenarios. Furthermore, the question remains as to whether the irrigation efficiencies listed in MOPW (2017) are unrealistically high, as the estimate of 45% obtained in the region by CNR (2014) is significantly lower. In the Irrigation Plan for Araucanía, the National Irrigation Commission investigated where to develop irrigation infrastructure and reservoirs and identified suitable crop types for different regions in the state (CNR, 2017a). Approximately 13% of the granted water rights for irrigation are currently used in Araucanía (CNR, 2017a), and a reallocation of water rights is of key importance for the future development and optimization of water available for irrigation.

The reduction in total streamflow of 30.3% at the outlet of the study area in the B_A1-E_N scenario compared to the R_A1-E_N scenario quantifies the effects of climate change on water availability, yet the total unmet demand remains small (0.29×10^6 m^3) in the latter scenario. This suggests that despite very low flows in the dry summer months, water retention infrastructure is not of high priority if irrigation needs do not increase significantly; however, plans are already underway to considerably enlarge the irrigated area (CNR, 2017a; Intendencia, 2017). The scenario results for greater irrigation area with neither reservoirs nor an increase in irrigation efficiency (total unmet demands of 14.9×10^6 m^3 in B_A2-E_N and 49.6×10^6 m^3 in R_A2-E_N) emphasize the need to improve water allocation in the study area.

Modelling the effects of building reservoirs and increasing irrigation efficiency to combat future water-scarcity situations

The scenario results demonstrate the effective role that reservoirs can play as an infrastructure solution to cope with drought, water scarcity and greater irrigation needs, as well as the importance of maximizing irrigation efficiency. The role of reservoirs is not only confined to meeting user demands but also helps maintain minimum ecological flows in times of drought. Results showed that reservoirs construction under the B_A2-E scenario would leave no unmet demand in the subcatchments modelled to be fed by the Quino and Traiguén reservoirs, while under the R_A2-E scenario, unmet demand would be reduced by 80.9%. The results also demonstrate the importance of maximizing irrigation efficiency (reducing unmet demand by 66.9% in R_A2-E_N relative to R_A2-U_N), as well as the potential benefits of combining reservoir construction and improving irrigation efficiency (reduction of 97.7% from R_A2-E_N to R_A2-U_R).

The sizing of reservoirs requires significant planning. In this study, the reservoirs were sized to provide water in most low-flow months, for a balance between being a practical size and serving downstream needs. The minimum flow requirements for ecological purposes had a considerable effect on the calculation of required reservoir storage capacities. Two key assumptions for the modelling of the reservoirs were that the irrigation canal network would be updated to connect downstream subcatchments to the reservoirs and that minimum ecological flow requirements are satisfied by reservoir operational procedures.

Reservoir operations must well planned and executed to meet irrigation demands and ecological flow requirements, and these optimized operations formed an underlying assumption of the WEAP model. Such operations can be based purely on operating objectives or can also include forecasting to inform operations (Turner et al., 2017). Long-term (e.g. seasonal) forecasting could improve reservoir management, but dealing with forecast uncertainties remains a key challenge (Butts et al., 2017; Peng et al., 2018).

Regarding water policy in Chile, Donoso (2015) notes that the water market in Chile, which derives from the Chilean Water Code of 1981, manages to resolve neither inefficiency in the sectors nor the maintenance of minimum environmental flows. Our study demonstrates that the combined effects of climate change and the increase in irrigation area will increase the pressure on water resources in the study area, suggesting that a fundamental rethink of the policy for water rights allocation is needed. The National Irrigation Commission has developed plans to help farmers in the region adapt to the effects of climate change, advocating the improvement of irrigation efficiency and managing crops through water-scarcity events (CNR, 2018). Polpanich et al. (2017) implemented a WEAP model to quantify climate change impacts on agricultural development and demonstrated how effective the outputs can be to convey results to relevant parties and to facilitate acceptance of subsequent policy changes. This highlights the usefulness of this study in facilitating water resources planning in the region.

The modelling of reservoirs and changes to irrigation efficiency in this study are an important first step in understanding the benefits these measures could have in coping with drought and water scarcity and meeting downstream water demands in the study region. The process followed in this study can be transferred to other basins in the region or upscaled to cover a greater area. This study is a first step in water resources planning in this drought-prone region; further analysis is required to fully understand the positive and negative economic, social and environmental impacts of such infrastructure in the region, as well as further research to reduce the bounds of uncertainty in future climate projections and water demand.

Conclusions

Increasing drought frequency and water scarcity throughout Chile have led to responses such as irrigation expansion plans to reduce reliance on rainfed agriculture. In this study, we developed a methodology to assess the risk of drought and water scarcity in a rural and data-scarce catchment in the Imperial River basin (southern Chile), considering both climate change (lower precipitation and higher temperatures) and anthropogenic aspects (increasing water demand). *In situ* and satellite-based climate data were used to simulate the water balance of the study region using the WEAP planning software. The calibrated model showed a strong agreement between the measured and simulated discharges, including in the low-flow months, which are of highest importance to drought management. Twenty-four scenarios from 2030 to 2059 were created based on the combinations of four key variables: climate (base case against RCP8.5 projections); lower- and upper-bound increases in irrigation area; three degrees of irrigation efficiency; and whether two upstream reservoirs are built as strategic adaptation measures. The water allocation model showed that seasonal water scarcity is likely from vastly increasing the irrigated area or due to the higher temperatures and reduced precipitation under the RCP8.5 scenario, and the combination of these is likely to bring severe water scarcity. Under this scenario, the unmet water demand decreases significantly with the construction of upstream reservoirs (80.9%), an increase in irrigation efficiency (66.9%), or by the combination of these two measures (97.7%).

The results provide a robust basis for designing future water planning strategies in response to climate change and increasing water scarcity in the region and provide planners with vital information to improve water resources management for the region. It is strongly recommended to transfer and apply this method to assess similar regions of Chile where plans exist to expand irrigation systems. We conclude that the methodological framework developed here, consisting of innovative data sets and the application of a widely used water allocation model, is extremely valuable to provide a preliminary assessment of the usefulness of strategic adaptation measures to cope with drought and water scarcity under climate change and growing water demand.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

Some data used during the study were provided by a third party. Direct requests for these materials may be made to the providers indicated in the Acknowledgments. All other data, models and code generated or used during the study are available from the corresponding author by request.

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