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Snow Water Equivalent Estimation – a new operational Tool for water resources decision-making in the Coquimbo Region (SWEET-Coquimbo)

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1. **Background and scientific and technological content.**

1.1 Problem and opportunity

In Central Chile, precipitation is characterized by episodic events that mostly occur during the winter months, and a large year-to-year variability influenced by El Niño Southern Oscillation (Masiokas et al., 2006; Montecinos et al., 2016). Due to orographic effects over the Andes, precipitation amounts generally increase with elevation (Scaff et al., 2017) and above a certain elevation, it predominantly falls as snow. The resulting seasonal snowpack acts as a temporal buffer by storing water in winter and releasing it during the melt season, which is typically hot and dry. **Melting snow** from high-elevation areas therefore dominates discharge and freshwater supply in semi-arid Chile (Ayala et al., 2020; Cornwell et al., 2016; Masiokas et al., 2010, 2006; Mernild et al., 2016; Ohlanders et al., 2013). Meltwater plays a crucial role in feeding river runoff, but also groundwater aquifers (Ribeiro et al., 2015; Valois et al., 2020) and natural and artificial reservoirs (such as the Puclaro, La Paloma or La Laguna reservoirs). In semiarid regions of Chile, most economic sectors depend on snow melt, including agriculture and mining, but also human and ecosystem consumption.

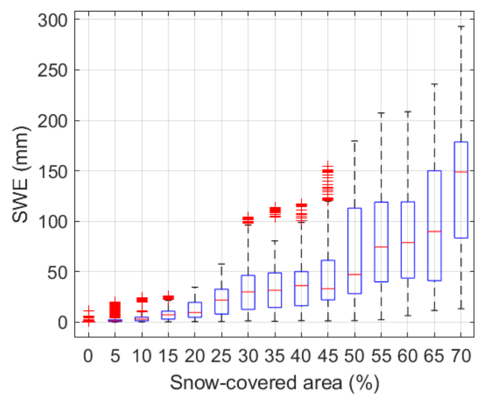

Figure 1 SWE as a function of the snow-covered area (as percentage of the basin area) for the period 1985-2015 in one of the main basins in the Coquimbo Region (Elqui River Basin, measured at El Algarrobal). Data: Extracted from results from Cortés and Margulis (2017).

Due to the critical role of snow in Central Chile, precisely quantifying the snowpack is essential for **water resource management and allocation decisions**. A more efficient and precise water allocation would be made possible by accurately quantifying the spatial distribution of water stored in the seasonal snow, how it changes throughout the winter months, and whether the total water stored is above or below a “normal” year to better prepare for dry summers. While it is relatively simple to estimate the snow-covered area using satellite imagery (e.g. MODIS), this information delivers no information about the actual snow depth and density, and has therefore only limited value as a first-order indicator of available water at high elevations. It is a challenge to covert area to volume of snow on the ground, and the amount of water that would be generated from snow, or **snow water equivalent (SWE),** is only cursorily estimated. Currently, the Chilean Water Directorate (Dirección General de Aguas, DGA) evaluates the annual availability of water resources for the melting season in the main Chilean basins based on manual observations of end-of-winter SWE at only 15 locations along the length of the country, which is insufficient to capture the spatial variability of SWE over the Andes. Current approximations are largely inadequate, and by way of an example, Figure 1 shows how different SWE accumulations can correspond to similar spatial extensions of the snow cover in one of the main basins in the Coquimbo Region (Elqui River Basin). Improving these estimates and generating near-real time assessments of SWE would greatly improve decision-making processes of water managers in this region.

In the recent years, the total water consumption of the Coquimbo region has significantly increased (for instance approximately 15% between only 4 years from 2009 to 2013 in the La Serena-Coquimbo conurbation, Salinas et al., 2016), while precipitation and groundwater levels have decreased (Salinas et al., 2016; Valois et al., 2020). The extraordinarily dry conditions experienced almost continuously since 2010 have led to additional stress of the water system of Central Chile, with important effects on water availability, vegetation and forest fires and also the snowpack (e.g. Garreaud *et al.*, 2020). Also, the role of snow in Central Chile is not only essential today – it will also remain important in the **future years and decades**, especially in view of further decreasing precipitation, more frequent dry conditions and increasing temperatures (IPCC, 2013; Young et al., 2009). Snowmelt-driven watersheds are generally very sensitive to a changing climate because changes in both, precipitation and temperature have important consequences for the snowpack and the hydrological cycle (Barnett et al., 2005). A decrease in precipitation amount or change in timing (IPCC, 2013) would reduce the maximum snow amount accumulated in high-elevation areas during winter. On the other hand, changing temperatures have an impact on the snow-rain transition height which defines the snowline and the contributing catchment area. An increasing temperature also influences snow melt and therefore the timing of the runoff, leading to an earlier runoff during the melt season and leaving less runoff during the already dry summer. Only **long-term monitoring** of SWE provides empirical evidence to understand and predict the evolution of the snow in this region. This is also why the **SWE has also been defined as Essential Climate Variable (ECV) by the World Meteorological Organization** (WMO, 2021). Only by monitoring the current state of snow can we create a solid base of information, which then serves as a foundation for adaptation measures related to snow resources in the future under a changing climate (Sturm et al., 2017).

The major **challenge in estimating SWE** for a region or a catchment comes from its high spatial heterogeneity in mountainous terrain since it is influenced by a range of factors including elevation and orographic effects, slope, aspect, topography and shading, wind redistribution, snow albedo, vegetation and atmospheric circulation (Margulis et al., 2015). The SWE can be estimated based on observations (in-situ or satellite observations) or numerical models. But these methods have important limitations that hamper a robust and accurate estimation of SWE for remote mountainous terrain:

- **In-situ measurements of SWE** are scarce (e.g. four locations in the Coquimbo region by the DGA), which makes a numerical interpolation or extrapolation extremely difficult. It is challenging to determine the areal distribution of water reserves stored in the snow cover of a mountain basin based on in-situ point SWE measurements.
- In general, **precipitation measurements** are not accurate estimates of SWE, since the snowpack is a result of complex deposition, melting, sublimation and redistribution processes. Also, automatic meteorological measurements of snowfall are affected by undercatch, especially in windy conditions (Rasmussen et al., 2012).
- In general, the monitoring of snow with **satellite remote sensing systems** has improved in recent years, but to date no satellite mission dedicated to the estimation of SWE exists (Girotto et al., 2020). Even though there are operational products for SWE, these products

are focused on the Northern Hemisphere, exclude mountainous regions or are only very coarsely resolved (Pulliainen et al., 2020).

- Due to limitations of in-situ and remote sensing observations, **models** are needed to bridge temporal or spatial gaps (to get a gridded estimation at a fine scale). But such model simulations rely on the quality of input forcing datasets, modeling parameterization schemes and land surface characteristics data, with the result being large uncertainties or biases in SWE estimation, which have important consequences for water management.

In summary, despite recent rapid advances in different monitoring and modelling techniques of snow, current products still do not adequately meet operational needs to map SWE in Central Chile, which is a crucial variable to estimate the available water for runoff during the melting season and, hence, water resources planning and decision-making. To bridge this gap there are promising methods to combine remote sensing technologies, in-situ observations, and models via **data assimilation methods** to produce accurate SWE maps with sufficient resolution and near real-time estimates. But until now little work has been completed to combine available data sources through data assimilation methods and to bring it to an operational tool for water resource managers.

Our proposed solution is to develop and implement a new operational tool to quantify SWE at near-real time, based on data assimilation techniques, focusing as a first step on the Coquimbo Region (SWE Estimation Tool for water resources decision-making in the Coquimbo region, **SWEET-Coquimbo**). With this approach, it will be possible to include different types of observations and data, which improves the quality of the SWE estimation for the region, but also for single catchments or locations. The final product will deliver a more robust base of information for different end-users - also in view of adaptation strategies for the next years to decades under a changing climate scenario and related disasters such as droughts. Whilst this project will focus on the Coquimbo Region due to the data available to robustly test the developed model, the approach will be scalable to the length of the country.

The **impact of droughts and water scarcity** on the Coquimbo Region cannot be understated, and with the likelihood of droughts increasing, developing advanced management tools is imperative to not only make better decisions, but also increase the flexibility of data delivery. In the Coquimbo Region agricultural emergencies have been declared due to the catastrophic water scarcity that started in 2009 (Ministerio del Interior y Seguridad Pública, 2020) as a result of increasing water demand and low annual precipitation in the recent years. The emergency has severe consequences for the economy of the region, with important impacts for the population. For example, the Coquimbo Region lost around USD $120M in fruit exports during the 2012/13 season as a result of the drought, equivalent to 30% of regional production (SNA, 2014). Goat producers lost approximately 140,000 goats in the period 2010-2013 (ODEPA, 2018). Likewise, in rural communities the regional government reported a significant increase in the use of water tankers, partly due to decreasing groundwater storage, which has a negative impact on the lives of the inhabitants that only derive 50 liters per day and on the regional economy. In 2011, 33,635 people depended on water tankers with a peak in 2016 of 52,074 people (Guajardo, 2019). It is estimated that this situation will be even more accentuated in the future due to climate change (Vicuña et al., 2011).

Our research directly addresses the **thematic line 3.1** in the Annex (“Adaptación al cambio climático y desastres de origen natural”), research line (a) (Monitoring of climate parameters developing technological innovation to improve decision-making in climate change adaptation).

1.2 State of the art analysis

a. Current research status

There are **different methods to estimate SWE** at various spatial and temporal scales: direct in-situ measurements, remote sensing products or models. Recent advances in snow sciences allow to better understand the role of snow, but there remain fundamental knowledge gaps, and uncertainties in SWE estimates from observations and modeling are still considerable (Girotto et al., 2020). In the following, we will review current methods to estimate SWE and latest advances, as well as limitations of these methods to estimate fine scale SWE in a mountainous environment such as the Central Andes in Chile.

In-situ measurements of snow depth, density and SWE with snow profiles are the most traditional and common method to monitor SWE (Pirazzini et al., 2018). But this manual monitoring technique is labor-intensive, time consuming and it is difficult to undertake in remote and inaccessible mountain sites such as the Chilean Andes and at reasonable temporal frequencies. Automatic point/scale measurements such as snow pillows are large and expensive, difficult to install and maintain and prone to measurement errors (see e.g. Kinar and Pomeroy, 2015). Recently, new monitoring methods have been developed, such as GPS Signal Attenuation (Koch et al., 2019) or gamma/cosmic ray sensors (Schattan et al., 2019) with promising results, especially for dry snow, as expected in a semi-arid environment. Even if recent advances in SWE measurements are promising, one challenge remains: How to interpolate and extrapolate point SWE measurements over complex mountainous terrain. The unknown spatial distribution can lead to large uncertainties of the total SWE over a region or a catchment.

Different **remote sensing methods** exist to monitor snow, with a variety of spatial resolutions and limitations (Girotto et al., 2020; Largeron *et al.*, 2020). Most products estimate snow-covered area with reasonable resolution, but until today, no satellite remote sensing platform resolves local scale SWE variations across all snow-covered environments, and there is no accurate way to estimate seasonal snow changes at sufficiently high temporal and spatial resolutions for the South American continent. Due to these limitations, the current global products for seasonal SWE estimation still does not meet operational needs for water managers in Chile.

Numerical models are an option to estimate the spatial distribution of SWE. Models can generate SWE estimates across large domains, at different spatial resolutions and time steps, offering large ranges between conceptual and physically-based models, and between lumped and fully-distributed. However, models are often limited by the lack of adequate forcing data, particularly high-elevation precipitation and radiative fluxes (Cortés et al., 2016). Additionally, other errors can originate from model parameters that are difficult to measure or calibrate, or the model structure itself, because optimal structure and associated parameterizations might vary from problem to problem.

Data assimilation methods are very promising tools as they bridge local observations and remote sensing products with models. Data assimilation is used in different disciplines to obtain optimized, enhanced estimates of a specific phenomenon of interest. Data assimilation approaches use observed data (e.g. remotely sensed or in-situ) in combination with model data to generate an estimate of the measured phenomenon that takes into account the uncertainty and probabilistic distribution of the underlying variables. Current research has shown that uncertainties, root-mean-square error (RMSE) and biases can be reduced by data assimilation approaches, which is important for the credibility in the operational product for decision makers (e.g. Margulis et al., 2015). There is a wide variety of data assimilation techniques with different degrees of complexity and error treatment. The variety spans from simple direct insertion of observations to the model, to more mathematical methods (such as Kalman filter or particle filter, Girotto et al., 2020; Helmert et al., 2018). Recent research has shown that including a particle filter has some key advantages over other methods (Smyth et al., 2019). Recently, a data assimilation framework has been implemented to obtain high-resolution retrospective SWE estimates over several Andean study basins in Chile with very promising results for the period 1985-2015 (Cortés et al., 2016). Results from the data assimilation framework were robust and showed an improvement upon SWE modelled without data assimilation. Another interesting alternative that has been proven in the Andes are retrospective SWE reconstruction models (Cornwell et al., 2016), but, as they work with a retrospective approach, they are not suitable to generate predictions for the upcoming melt season.

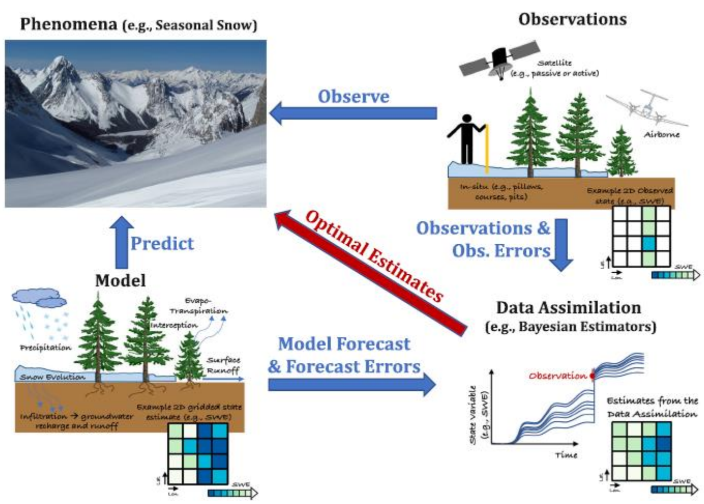

Figure 2 Main concept of a data assimilation method (from Girotto et al., 2020)

From a more hydrological perspective, some efforts have also been made in recent years to improve the **seasonal or monthly forecast for runoff** in the Coquimbo region. But, despite the important role of snow in runoff generation, no seasonal runoff forecast tool including SWE exists to our knowledge. For instance, Delorit et al. (2017) evaluated the potential of SWE as a predictor for runoff, but only based on one station (La Laguna) and they did not retain it as a predictor in their model. Sproles et al. (2016) presented an approach to estimate streamflow one month in advance based on snow covered area observed by MODIS. They use a simplified version of a runoff model, which has shown good results for the period 2003-2015, but it might be limited to estimate the current SWE and therefore streamflow for more than a month in advance.

At the Centro de Estudios Avanzados en Zonas Áridas (**CEAZA)**, there has been intensive research to improve our understanding of the hydrological role of the cryosphere in the semiarid Andes, including glaciological studies (Abermann et al., 2014; MacDonell et al., 2013; Nicholson et al., 2016), the importance of wind effects on snow cover (Gascoin et al., 2013), snow sublimation (Ayala et al., 2017; Réveillet et al., 2020) and runoff contribution from the cryosphere (Gascoin et al., 2011; Schaffer et al., 2019). This current proposal is a natural extension of ongoing research in the area.

b. Background

Recently, several studies have confirmed the great potential of data assimilation frameworks with particle filters for SWE estimations in semi-arid regions (Baba et al., 2018; Cortés et al., 2016). Cortés and colleagues (2016) estimated SWE for 1985 to 2015, with promising results compared to in-situ snow surveys for the Aconcagua River catchment. Their results also indicate a high correlation between SWE and runoff during the melting period in the Elqui River basin at Algarrobal for the period 1985-2015 (Figure 3). This confirms that accurate SWE estimates can improve summer streamflow forecasts, which is crucial for water resource management and adaptation strategies. The importance of SWE for seasonal river flow has also been shown by several other studies (Ayala et al., 2020; Cornwell et al., 2016; Masiokas et al., 2010, 2006; Mernild et al., 2016; Ohlanders et al., 2013; Young et al., 2009).

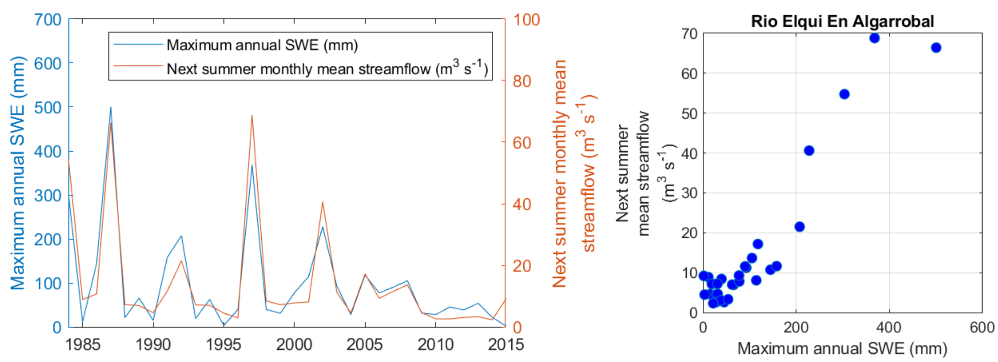

Figure 3 (left) Time series of maximum annual SWE (mm) and next summer monthly mean streamflow; (right) Next summer monthly mean streamflow vs. Maximum annual SWE (mm) for Río Elqui in Algarrobal. Data from Cortés et al. (2016) and DGA

CEAZA is a regional centre for scientific and technological research in the Coquimbo Region. It was founded in 2003, after the second contest for the creation of regional centers for scientific and technological development, thanks to a joint project with the University of La Serena (ULS), the Catholic University of the North (UCN) and the Institute of Agricultural Research (INIA-Intihuasi); financed by CONICYT and the Regional Government of Coquimbo (GORE Coquimbo). In June 2008, it obtained its legal status as a non-profit corporation. Its mission is "to promote the scientific-technological development of the Coquimbo Region, through high-level scientific and technological research aimed at understanding the effects of climatic / oceanographic oscillations on the hydrological cycle and biological productivity in the arid and marine areas of north-central Chile, collaborating in the formation of human capital in science and technology, regional productivity, environmental protection and education, and thereby contribute to progress and quality of life of the inhabitants of the Region of Coquimbo ". The main objective of this regional center is to carry out high-level scientific and technological research, associated with the effects of climatic oscillations in arid and semi-arid areas, which represent an effective contribution to the economic and social development of the region and the country.

The **CEAZA Glaciology Group**, in charge of project execution, has broad experience in working on snow, both in Chile and abroad. This group has carried out several investigations on the contribution of glaciers and snow to the hydrological system, in the basin of the Huasco, Elqui, Choapa, Aconcagua, Maipo, Tinguiririca rivers, among others. The team also has experience in snow energy and mass balance modeling, mainly in arid and semi-arid areas. Its professionals are highly trained for work in high mountain terrain and in extreme conditions. In addition, there are specialist in climatology, climate variability and regional climate that will support the climatological part of the project. In addition, the CEAZA meteorology unit (www.ceazamet.cl), has a network of 58 meteorological stations in the Coquimbo Region, which are connected to an online server for the consultation of users and the general public. Of the total number of stations are connected in real time. CEAZA has a qualified staff for the constant maintenance of the station network and the web platform. It also performs real-time atmospheric modeling of all climatic variables. Therefore, it can be confirmed that CEAZA has the human capital, infrastructure and adequate resources to carry out this project successfully.

c. Analysis of intellectual and industrial property and existing products in the market

To our knowledge, there are no intellectual or industrial property associated with data assimilation methods for the remote monitoring of snow. There are also no specific products in the market. Data assimilation methods are public, and their details are presented in books and scientific publications that are publicly available. This is not the exact case for remote sensing technology or field instruments focusing on snow monitoring, on which several agencies and companies own intellectual and technological property, but this project does not intend to innovate on these areas, and rather focus on data assimilation techniques using publicly available datasets.

d. Regulations

This project considers open access data and methods. Until now, there are no standards, rules and regulations, both national and foreign and international, that are relevant and applicable to the project’s theme.

1.3 Proposed solution

In this project, we will develop a platform to generate and deliver accurate and near real-time estimations of SWE for the Coquimbo region.

Our solution consists of an operational tool that uses a data assimilation framework combining numerical modeling, remote sensing and field data, to produce near real time, high-resolution SWE estimates in the Coquimbo Region (SWEET-Coquimbo). For this, we will adapt and further develop an existing methodology that was originally used to reconstruct SWE climatology over large mountain ranges in the U.S. (Margulis et al., 2015) and the Andes (Cortés et al., 2016; Cortés and Margulis, 2017), to work as an operational tool. Our solution will yield four main results: 1) Snow database for the setup and validation of SWEET-Coquimbo, 2) Setup of SWEET-Coquimbo, 3) Web platform and associated services for end users, and 4) scientific publications. Figure 4 shows the workflow of the project, with the four main results and the related objectives (see also Gantt Chart in Section 1.8 for more details).

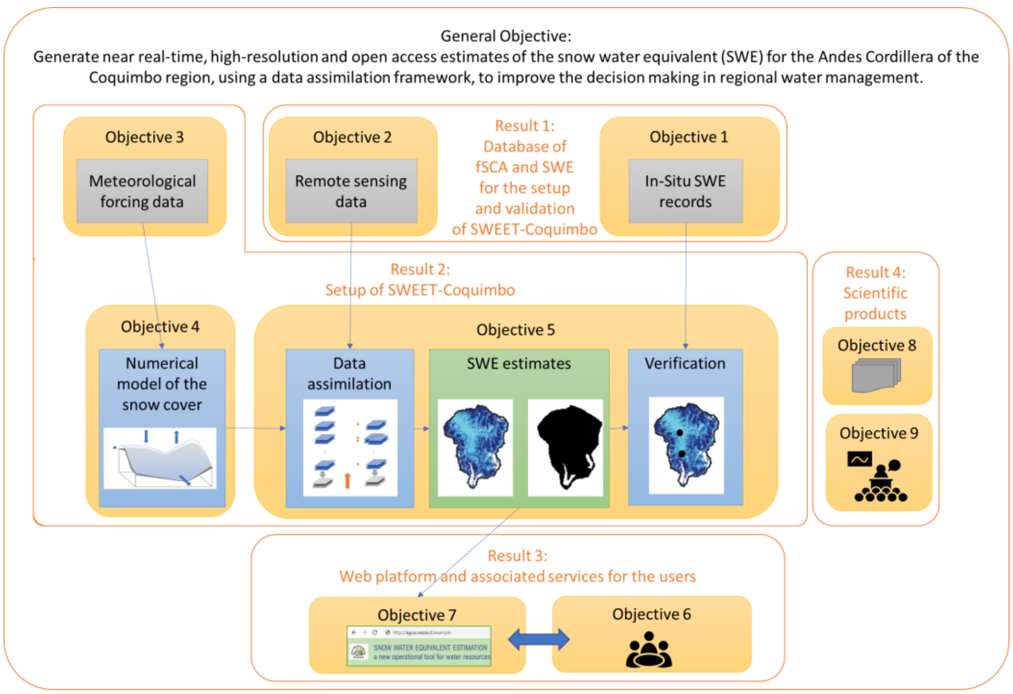

Figure 4 Project workflow with the main results that lead to the implementation of SWEET-Coquimbo in the Coquimbo region. The scientific part (Result 1 and 2 with objectives 1 to 5) is explained in detail in Section 1.6, Figure 6.

Result 1 "Database of fractional snow-covered area (fSCA) and SWE for the setup and validation of SWEET-Coquimbo": addresses the generation of a SWE database of historical and new observations to be collected in several field campaigns for the verification of the SWE estimates (Objective 1), and the development of a tool to automatically download and analyze satellite imagery to be assimilated by SWEET-Coquimbo (Objective 2).

Result 2 "Setup of SWEET-Coquimbo": represents the setup of SWEET-Coquimbo and is divided into three main objectives: the generation of meteorological forcing ensembles (Objective 3), the setup and validation of the snow model (Objective 4) and the development of the data assimilation framework (Objective 4). Results 1 and 2 are described in detail in Section 1.6.

Result 3 "Web platform and associated services for the users": includes the development of a web platform (Objective 7) and associated services for the users (Objective 6). The web platform providing SWE estimates is the final core product of the proposed project. A preliminary draft of the web platform is illustrated in Figure 5. It includes a map of the study region (see Figure 5a), with its main catchments and rivers. At certain points with available runoff measurements, sub catchments are defined to deliver specific products. By selecting the points of interest, the most important information appears such as actual SWE, multiannual mean SWE for the same date, and an estimation of below/above normal. These values will allow the end-users to get a fast overview of the snow situation in the region of interest. In addition, for every (sub)catchment, there will be a more detailed evaluation option to visualize the timeline of SWE and snow cover of the current year and compared to past years (Figure 5 b,c). This will enable the end-user to compare the current situation with past years, or a certain period of interest (e.g. a drought period). The current SWE or snow-covered area can be compared to e.g. multiannual mean, median or percentiles. The SWE estimation will be updated regularly (e.g. every 2-4 weeks, depending on model results and the availability of new satellite images). All the data can be downloaded by end-users. In addition, at the end of each accumulation season, there will be an option to compare the SWE of the current year with the SWE and the corresponding summer runoff volume of past years (see Figure 5d), for basins with runoff data available. This will give an estimation of the total summer runoff that can be expected for the current SWE situation.

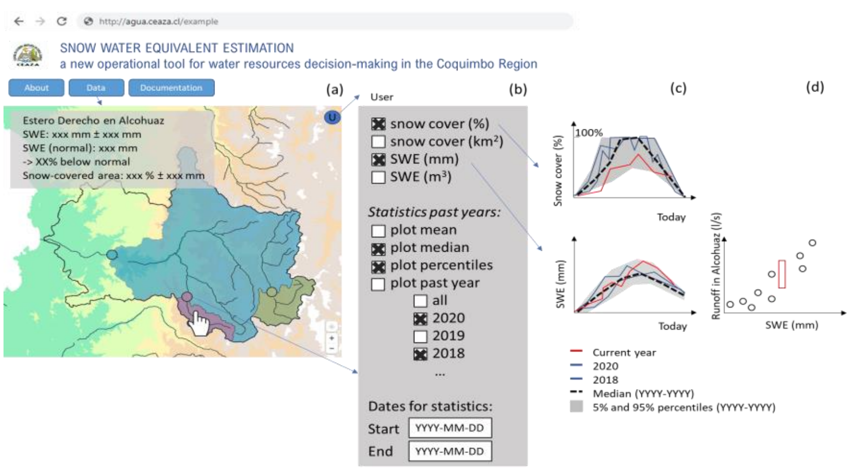

Figure 5 Preliminary draft of the web platform for the SWE estimations of individual catchments, including simple statistics and comparison with past years (a). By clicking on a catchment, more detailed statistics and graphs can be generated, tailored to the end-user's needs (b-d). The draft is based on a similar platform for Colorado, USA, see http://snodas.cdss.state.co.us/app/index.html.

As the final product will be of high interest for different water managers and users, a key element of the project will be the communication with the end-users to adjust the web platform to their needs (Objective 6). We have contacted several local organizations who are in charge of water allocation and managing to act as Associated Institutions in our project. At the start of the project, we will conduct a kick-off meeting and identify user needs (such as subcatchments, relevant variables and statistics). During the project, we will organize two events, hereafter called "working groups", which will be organized to i) present the SWE estimates that we will prepare for the first melt season (2022-23), and ii) to evaluate the results of the first season and identify corrections for the second one (2023-24). By the end of the project, in a final meeting with the Associated Institutions, we will present the SWE estimates for the second melt season (2023-24). An important barrier of the project might be that end users find the results difficult to understand or have low confidence in it. To avoid this, in the final meeting we will also offer a workshop to explain how the results can be accessed and downloaded, as well as carefully explain opportunities, but also limitations of the final product.

Result 4 will focus on scientific publications and presentations at scientific conferences that will present the scientific outputs of our project (Result 4, Objective 8 and 9).

The proposed solution of this project clearly differentiates from existing products/projects in Chile and globally.

- Cortés et al., 2016 estimated SWE for Central Chile, but only retrospective for the time period 1985 – 2015 and it has not been implemented as an operational product.
- The project *Observatorio Satelital de Nieve* (funded by FONDEF) aims at developing a database for snow data and deliver valuable products for end users. To our knowledge, they do focus on snow covered area and cloud cover for the Aconcagua River basin, without estimating the SWE.
- CEAZA publishes a monthly bulletin to describe the actual state of the climate and hydrology. Although the snow cover extent is a valuable information, it is not clearly related to the actual water stored in the snowpack.
- DGA reports on seasonal runoff forecasts: They base their forecasts on few in-situ records of precipitation and SWE, and runoff forecasts are only produced for the largest main basins.
- Different initiatives exist to generate operational or retrospective SWE estimates (GlobSnow, SNODAS, usw.), but these products are only available for the Northern Hemisphere.

The project does not require the use of technologies that are protected by patents. Also, the method will not be protected by patents. The method by Cortés et al. (2016), and data assimilation techniques in general, are described in public scientific publications and can be replicated without any specific authorization. The data (remote sensing, SWE measurements or meteorological station data) that will be used in this study are open access.

The intellectual property that will be generated during this project will be property of the beneficiary institution. It consists of the inputs and outputs of SWEET-Coquimbo, i.e. input variables, model results and field data for verification. The final product (SWE estimates and associated statistical analysis for the Coquimbo region) will be open access and can be freely downloaded from a web page. The methodology and main results will be described in scientific publications.

Rules and regulations: The project will not be related to rules and regulations. Technology Readiness Level: Until now, the data assimilation framework to estimate SWE has been applied to historical data and proven suitable for the Central Andes (Cortés et al., 2016). As part of this project, we will further develop the method with the aim to generate operational SWE estimates. After the completion of the project, the method will have been operational during a first winter/melting season with a validation for a pilot site and preliminary qualifications, which would correspond to TRL 7 ("System prototype demonstration in operational environment").

1.4 Hypotheses and research component

The hypothesis of this project is that: *Numerical modeling of the snow cover combined with satellite snow covered area and ground data via a data assimilation framework can generate accurate estimates of total SWE in poorly monitored catchments for operational purposes.*

This **hypothesis is mainly supported** by results from Margulis et al. (2015), and for Chile by Cortés et al. (2016) and Cortés and Margulis (2017). In their study, Cortés et al. (2016) verified results from a data assimilation framework with in-situ snow surveys in Central Chile and found significant improvements in the accuracy of the SWE relative to forward model estimates (i.e. the results of a numerical model for snow simulations) without data assimilation. Similar data assimilation approaches have also proved to be useful for different mountainous watersheds in USA (Durand et al., 2008; Girotto et al., 2014b, 2014a; Margulis et al., 2016, 2015) and semi-arid mountainous regions (Baba et al., 2018).

We will **validate** our hypothesis for a study site in the Elqui river basin, by comparing the results of the data assimilation framework with detailed in-situ snow surveys in the study site before implementing the approach across the wider Coquimbo region.

The main scientific research component of the project is:

- The development and application of a **data assimilation framework** for operational SWE estimations is a relatively new research topic. An operational application of this method to a semi-arid environment is therefore of high interest for the scientific community. This method could also be of interest for research in other semi-arid regions around the globe.
- The SWE product, and its meteorological forcing data, generated by this project will be of a high spatial and temporal resolution and open access. It will provide improved input to **hydrological models,** and therefore enhance our understanding of the hydrology in this region. Also, other applications are possible such as hydrological assessments (by DGA) or meteorological forecast (for instance rain-on-snow events).
- It can also be used to improve our understanding of the role of snow in the **climate system**. It could be used as input for Regional Climate Models (RCM) and to assess trends of SWE in the past years, as well as relations with e.g. ENSO.
- In terms of its **utility for operational applications**, we will be able to discuss how SWE estimation might improve the general knowledge of the snowpack compared to snow cover extent, and its potential and added value for decision making actions.

The main challenges of the project:

- The main challenge is that the results might not improve the estimation of the available water compared to snow cover extent, which is much easier to derive and less computationally demanding (see hypothesis). Literature clearly indicates that this should not be the case (see e.g. Cortés et al., 2016; Durand et al., 2008; Girotto et al., 2014b, 2014a; Margulis et al., 2016, 2015)

- Further challenges could be related with the computational need and complexity of the method, that could hamper its applicability after the project. We will design it to derive a robust method that could be run by CEAZA or other interested institutions in the future.

FONDEF area of development:

TECHNOLOGY DEVELOPMENT AREA		FINAL IMPACT AREA	
Agricultural		Agricultural	
Functional Foods		Functional Foods	
Social Sciences and Education		Social Sciences and Education	
Energy and Water	x	Energy and Water	x
Forest		Forest	
Infrastructure		Infrastructure	
Manufacture		Manufacture	
Mining		Mining	
Fisheries and Aquaculture		Fisheries and Aquaculture	
Health		Health	
Information and Communication Technology		Information and Communication Technology	

Final impact:

Climate Sciences		Vulnerability and Adaptation		Mitigation (GHG emission factors, low GHG emission technologies, etc.)	
Atmosphere	x	Water resources	X	Energy efficiency	
Cryosphere	x	Biodiversity		Non-conventional renewable energies (NCRE)	
Oceans		Silvoagricultural	X	Industrial processes	
		Fisheries and Aquaculture		Transport	
		Health		Waste management	
		Infrastructure, energy, housing, transport		Sinks (forests)	
		Social and economic sciences	X	Studies of variables for GHG emission factors	
		Disaster risk	X		
It is not related to climate change					

1.5 Objectives

1.5.1 General Objective

The general objective is to generate near real-time, high-resolution and open access estimates of the snow water equivalent (SWE) for the Andes Cordillera of the Coquimbo region, using a data assimilation framework, to improve the decision making in regional water management.

1.5.2 Specific Objectives

The specific objectives form part of the four main results outlined in section 1.3.

Result 1: Database of fSCA and SWE for the setup and validation of SWEET-Coquimbo

Objective 1. Create a database of historical and new field SWE observations in the Coquimbo Region.

Objective 2. Create a database of historical and current snow cover maps (as fSCA) derived from satellite images.

Result 2: Setup of SWEET-Coquimbo

Objective 3. Generate meteorological forcing data ensembles for snow models and other hydrological applications.

Objective 4. Setup and validate a numerical snow model for the pilot sites and the Coquimbo Region.

Objective 5. Develop and implement a data assimilation framework and verify the project hypothesis.

Result 3: Web platform and associated services for the users

Objective 6. Adjust project results to community needs: Design and conduct capacitation for decision makers and interested end-users.

Objective 7. Create a web platform where the results can be visualized and downloaded.

Result 4: Scientific products

Objective 8. The publication of three scientific articles, presenting i) the generation of the meteorological forcing data ensembles, ii) the application of the numerical snow model for the pilot sites and the region, and iii) SWEET-Coquimbo.

Objective 9. The attendance of one international scientific conference to present model results.

1.6 Research and development methodologies

As outlined in "State of the art analysis" (Section 1.2) and "Proposed solution" (Section 1.3), the project aims at developing and implementing a data assimilation framework to estimate SWE in near real-time.

The following **data** will be used for this project, see also Figure 6 i) to v):

i) Meteorological forcing data are needed to run the model at near real time. For retrospective SWE estimations, models can be forced by atmospheric reanalysis (e.g. MERRA in Cortés et al., 2016 or ERA5). For an operational SWE estimation, atmospheric data are needed. We will evaluate and select the data in the beginning of the project.

ii) Topographic information with a sufficient spatial resolution. Previous experience in the literature suggests a resolution of around 500 m (Cortés et al., 2016)

iii) Remote sensing data (e.g. Landsat, Sentinel-2) to derive fractional snow-covered area (fSCA)

iv) Meteorological station data are available from a local network operated by CEAZA and DGA.

v) In-situ SWE records for validation are available at four locations (Cerro Olivares, Elqui River basin; Quebrada Larga and Cerro Vega Negra, Limarí River basin; El Soldado, Choapa River basin). In addition, we will estimate SWE of a pilot basin with manual in-situ measurements (SWE, snow depth) and with Uncrewed Aerial Vehicles (UAV) or Light Detection and Ranging (LiDAR) measurements.

The main research components for the verification of the hypothesis and the achievement of the product are organized within the Objectives 1 to 5, illustrated in Figure 6.

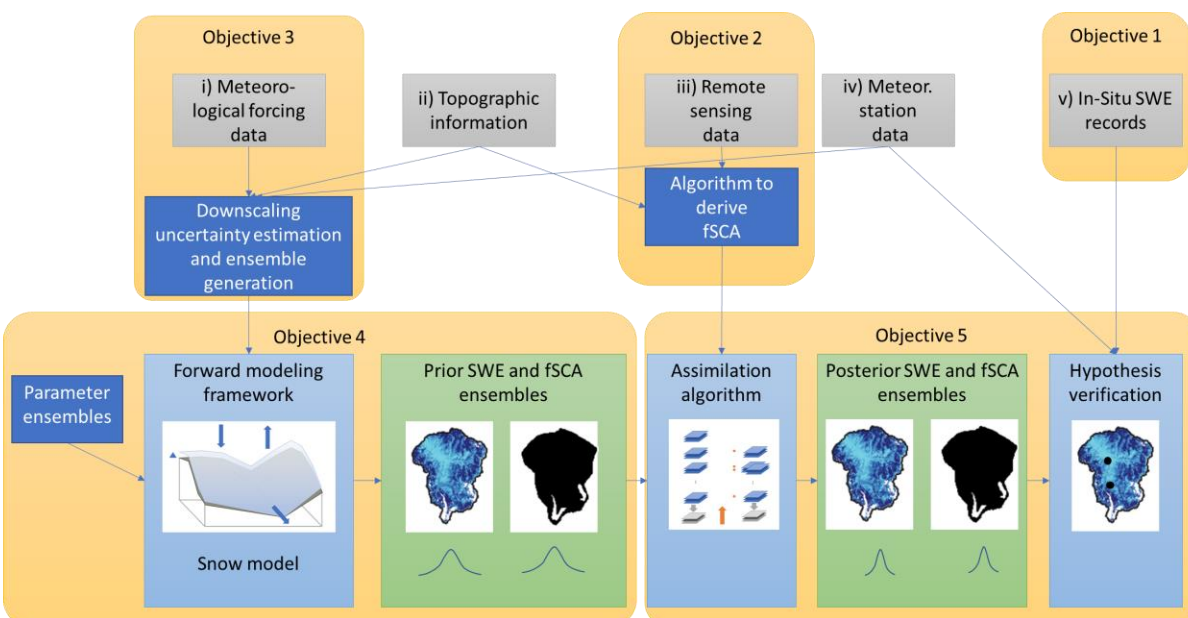

Figure 6: Scheme of the SWE estimation method. Grey: data; Blue: methods; Green: results; Yellow: objectives.

Objective 1: Create a database of historical and new field SWE observations in the Coquimbo Region

For a selected study site, we will compare the model results to in-situ SWE measurements to test the main hypothesis (Section 1.4) before applying the approach to other areas. The study site will be the lower La Laguna catchment area. This area is chosen because i) it is accessible during winter; ii) meteorological station data are available back until 1968; and iii) additional meteorological stations have been installed recently at different elevations, allowing an assessment of temperature gradients. The study site will be monitored with different technologies (see Figure 7). Lidar (Light detection and ranging) and Uncrewed Aerial Vehicle (UAV) flights will deliver the spatial variability of snow depth over a larger area, which could not be done with manual measurements. The land surface will be measured at maximum accumulation (September or October) and during the melting period, as well as for a snow-free situation. The difference between the snow and snow-free surface indicates snow depth. Snow depth will then be converted into SWE using snow density measurements taken at snow pits. These detailed measurements can be complemented by manual snow depth measurements for certain locations or transects.

The model estimates are then compared to the measured SWE and evaluated using certain verification metrics that compare prior and posterior ensembles to in-situ measurements (see also Cortés et al., 2016).

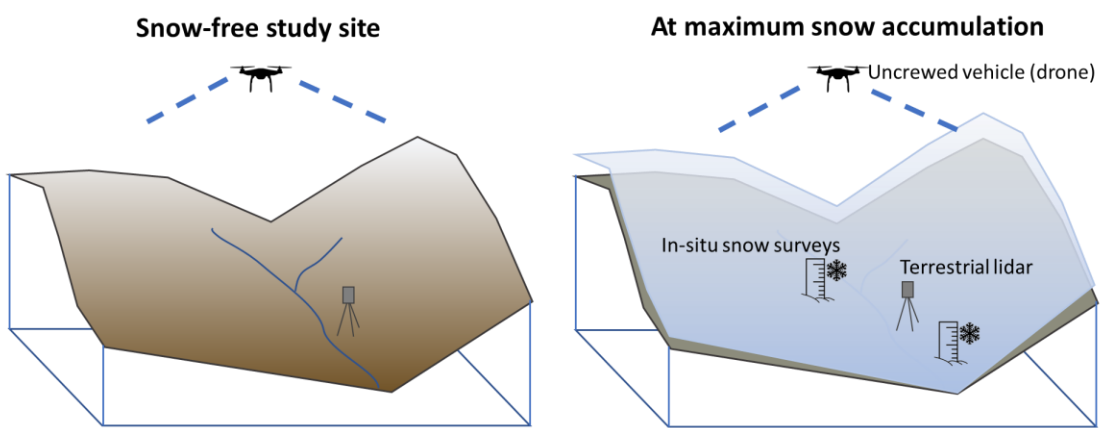

Figure 7 Scheme of the measurements in the pilot site, including UAV, terrestrial lidar and manual measurements of snow depth, SWE and density.

Objective 2: Create a database of historical and current snow cover maps derived from satellite images

For the assimilation procedure, fSCA estimates from remote sensing (e.g. Landsat and Sentinel-2) are needed. We will develop a tool to automatically download satellite imagery and estimate fSCA, to create a data base of historical and current snow cover maps. The fSCA is retrieved using specific algorithms that have been tested in previous studies (Cortés et al., 2014; Painter et al., 2003).

Objective 3: Generate meteorological forcing data ensembles

The model is forced by ensemble meteorological fields at 1-hour to 3-hour time steps. We will use data that are available for the past decades and near real-time (for instance ERA5 with its preliminary dataset available to users within 5 days). A variety of variables is required, including air temperature, shortwave and longwave radiation, precipitation, wind speed, humidity and air pressure. These variables need to be downscaled to the spatial resolution of the snow model. The uncertainty of the input variables will be characterized using ground meteorological stations from the network by CEAZA (Figure 8) or DGA, as well as results from previous research. Based on these uncertainties, ensembles of downscaled input fields will be generated. Note that the meteorological forcings are probabilisitic (ensemble) prior estimates that are updated during the data assimilation.

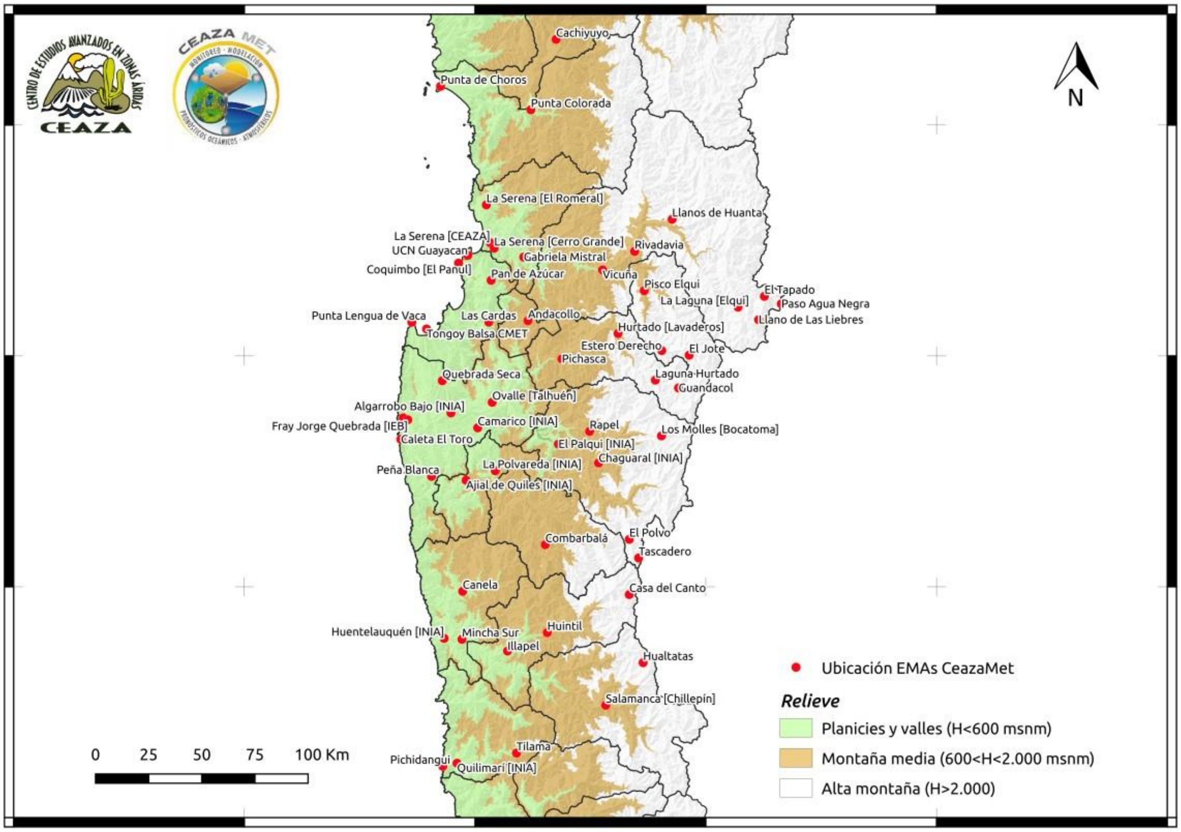

Figure 8: Map of the Coquimbo region with CEAZA stations

Objective 4: Setup and validate the snow model

The core of the SWE estimation consists in a forward modeling framework based on a numerical model for the simulation of the seasonal snow cover, which we have referred to simply as "snow model". Preliminary, we propose the use of the Coupled Snow and Ice surface energy and mass balance model in Python (COSIPY) (Sauter et al., 2020). COSIPY is an open-source physically-based snow and glacier model with a flexible and modular structure. The snow model uses the meteorological forcing data to calculate the energy and mass balance of the snow based on a set of equations that represents the main physical processes that control the dynamics of the snow cover. The model outputs are prior (forward modeling) SWE and fSCA evolution estimates for every model grid at a certain time step. Note that ensembles of SWE and fSCA are produced, based on the input and parameter ensembles from the former steps.

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Uncertainty that needs to be addressed comes from the parameters of the snow model. There are several parameters that need to be estimated, such as snow density, surface roughness, liquid water content, etc. The uncertainty associated with these parameters is the base to generate ensembles of the snow model results, and it will be calculated based on the differences between the results of the snow model for the pilot sites and a set of historical and new field data. These parameter ensembles are used to generate the prior ensembles.

Objective 5: Develop and implement a data assimilation framework and verify the hypothesis

This objective focuses on the setup of the data assimilation framework. We will use the Particle Batch Smoother (PBS) data assimilation algorithm, that was proposed by Margulis et al., (2015) and implemented by Cortés et al. (2016) in the Andes. In this framework, prior SWE and fSCA estimates are updated, resulting in the posterior, which is probabilistically conditioned. In the PBS framework, the prior and posterior state replicates are the same with an equiprobable distribution assumed for the prior (see Figure 9). The weights of each of the ensemble replicates are updated based on the assimilated observations of snow cover extent. The algorithm assigns higher weights to those replicates that show model predictions closer to the observations. The weight of those with higher differences are reduced. These weights are then used to calculate prior and posterior ensemble metrics such as the mean, median and interquartile range of SWE. When correctly implemented, data assimilation algorithms result in a reduction of the uncertainty and bias of the prior SWE estimation.

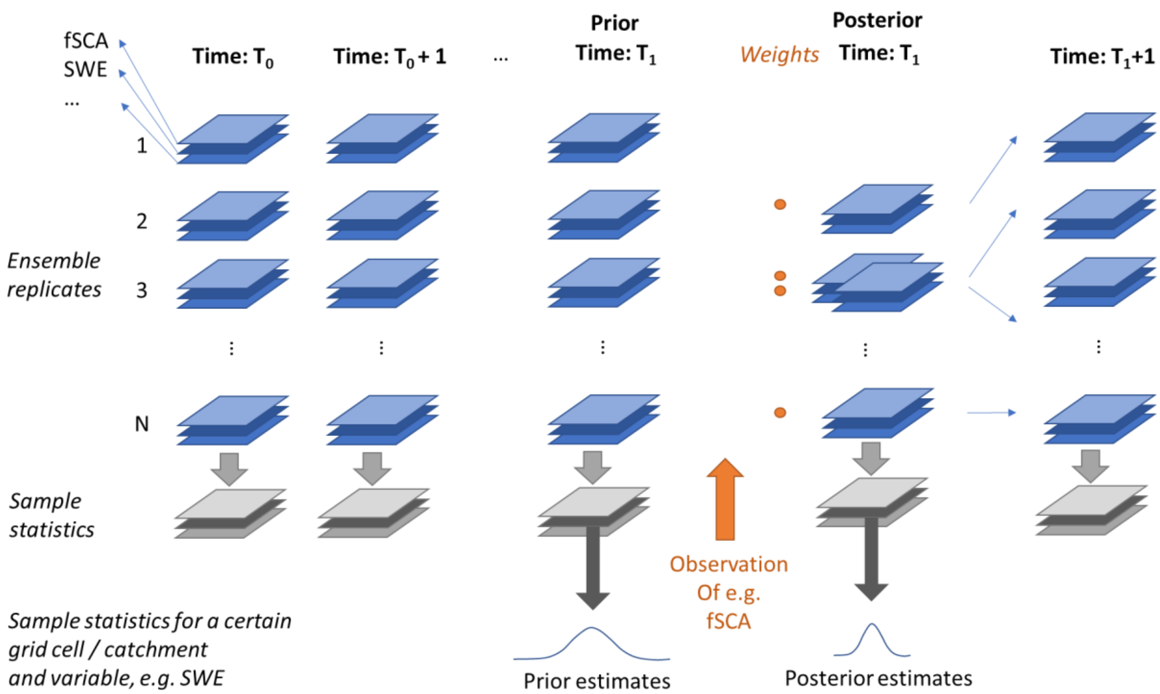

Figure 9 Particle Batch Smoother data assimilation algorithm scheme.

This last step focuses on verifying the hypothesis (Section 1.4) for the pilot site. The posterior SWE estimates are compared to the in-situ SWE estimates from Objective 1 and evaluated with statistical scores.

The data assimilation framework will also allow retrospective SWE estimates, for instance from 1979 onward. This will be important for the comparison of the current snow situation with past years to decades. It will be excellent data base for research and deliver valuable information for different research areas (such as hydrology, glaciology, natural risks). These data will be made available for further studies.

Here, we declare if our proposal must have any of these certifications or special permits:

CERTIFICATE	
Ethics	
Bioethics	
biosafety	
Archeological site	
Wild area	
Protected species introduction	
Databases with sensitive information	
Other (indicate which)	
No need special certifications or permits	x

1.7 Committed results

1.7.1 Production result and milestones

Production result and milestones	Brief description
RESULT 1: **Database of fSCA and SWE for the setup and validation of SWEET-Coquimbo**	SWEET-Coquimbo will be evaluated against extensive field data over a pilot site. Field data consists of distributed snow depth from UAV flights, terrestrial LiDAR, and manual measurements (of snow depth and density) over two melt seasons.
Milestone 1 - fSCA and SWE database	This milestone will be achieved in parts, at four different times of the project. The fSCA database consists of the results from the tool that automatically downloads satellite images and calculates fSCA. Date of achievement: Month 12. The SWE database corresponds to the historical period and for melt seasons 2021-22, Date of achievement: Month 6. The latter will be updated for melt season 2022-23 (Month 18) and at end-of-winter of 2023 (Month 24).
RESULT 2: **Setup of SWEET-Coquimbo**	The Snow Water Equivalent Estimation Tool for the Coquimbo Region (SWEET-Coquimbo) combines in-situ meteorological information, global climate reanalysis, satellite images and numerical modelling of the seasonal snow cover in a data assimilation framework to produce near real-time SWE estimates over the Coquimbo Region.
Milestone 2 - Meteorological forcing data ensembles for year 2022 (and adjustments for the next season)	Input data for the snow model. This milestone will be achieved in two steps: Historical and melt season 2022-23 (Month 12), and for the melt season 2023-24 (Month 24)
Milestone 3 - Snow model ready for year 2022 (and adjustments for the next season)	Snow model ready for the data assimilation framework (Month 10), and possible adjustments for the next season (Month 22).

Milestone 4 - SWE estimates for melt season 2022	SWE estimates from SWEET-Coquimbo for the melt season 2022-23 ready to be communicated to the Associated Institutions (Month 12)
Milestone 5 - SWE estimates for melt season 2023	SWE estimates from SWEET-Coquimbo for the melt season 2023-24 ready to be communicated to the Associated Institutions (Month 24)
RESULT 3: **Web platform and associated services for the users**	The platform and products delivered to the Associated Institution and the public.
Milestone 6 - Delivering SWE estimates for melt season 2022-23	Working group in which the SWE estimated will be communicated to the Associated Institutions
Milestone 7 - Delivering SWE estimates for melt season 2023-24	Working group in which the SWE estimated will be communicated to the Associated Institutions
Milestone 8 - Webpage launching	Launching of the webpage using social networks from the Beneficiary Institution (CEAZA)

1.7.2 Other results

Results	Brief description
Scientific output: Article 1	- Presenting the generation of meteorological ensembles. - Led by Dr. Simone Schauwecker
Scientific output: Article 2	- Presenting the snow simulations at pilot site(s) - Led by Dr. Álvaro Ayala
Scientific output: Article 3	- Presenting SWEET-Coquimbo - Led by Dr. Gonzalo Cortés
Scientific output: International conference	- Scientific team (project directors, postdocs and professional) attending.

	- Options are AGU 2022, EGU 2023 or AGU 2022. It will be decided depending on the results.

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1.8 Activity planning (Gantt chart)

Assuming October 2021 as starting month of the project. Possible changes might be implemented depending on the exact starting date of the project.

ACTIVITY PERIOD

RESULT	OBJECTIVES	ACTIVITY	ACTIVITY MANAGER	MILESTONE	START (month)	ACTIVITY PERIOD (months)	MILESTONE ACHIEVEMENT (month)	MONTHS 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
1. Database of fSCA and SWE for the setup and validation of SWEET-Coquimbo				Milestone 1 - fSCA and SWE database (achieved in 4 steps, months 6, 12, 18 and 24, see on the right)				
	Objective 1.- SWE database of historical and new observations	1.- Organization of existing data from regional and national sources	Snow monitorig professional		1	2		
		2.- Field data collection for melt season 2021-22	Snow monitorig professional		1	6	6	
		3.- Field data collection for melt season 2022-23	Snow monitorig professional		13	6	18	
		4.- Field data collection for the end-of-winter 2023	Snow monitorig professional		24	1	24	
	Objective 2.- fSCA from satellite images	5. Automatic tool for downloading satellite images	Snow monitorig professional		1	9		
		6. Automatic tool for deriving fSCA from satellite images	Snow monitorig professional		4	9	12	

ACTIVITY PERIOD

RESULT	OBJECTIVES	ACTIVITY	ACTIVITY MANAGER	MILESTONE	START (month)	ACTIVITY PERIOD (months)	MILESTONE ACHIEVEMENT (month)	MONTHS 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
2. Setup of SWEET-Coquimbo	Objective 3.- Generation of meteorological forcing data ensembles	1.- Downscaling of meteorological forcing data from atmospheric reanalyses	Simone Schauwecker		1	12		
		2.- Generation of meteorological forcing data ensembles	Simone Schauwecker	Milestone 2 - Meteorological forcing data ensembles for year 2022 (and adjustments for 2023)	7	18	12, 24	
	Objective 4.- Setup and validation of the snow model	3.- Model testing at pilot sites	Álvaro Ayala		7	6		
		4.- Model setup for the Coquimbo region	Álvaro Ayala	Milestone 3 - Snow model ready for year 2022 (and adjustments for 2023)	7	18	10, 22	
	Objective 5.- Data assimilation framework	5.- Integration of products and models into the data-assimilation framework	Gonzalo Cortés		1	24		
		6.- SWE estimates for melt season 2022-23	Gonzalo Cortés	Milestone 4 - SWE estimates for melt season 2022	7	6	12	
		7.- SWE estimates for melt season 2023-24	Gonzalo Cortés	Milestone 5 - SWE estimates for melt season 2023	19	6	24	
3. Web platform and associated services for the users	Objective 6.- Adjust project results to community needs	1.- Kick-off meeting (identifying user needs)	Project coordinator		1	1		
		2.- Work table 1 (SWE estimates for melt season 2022-23)	Project coordinator	Milestone 6 - Delivering SWE estimates for melt season 2022-23	13	1	12	
		3.- Work table 2 (identifying corrections)	Project coordinator		19	1		
		4.- Final meeting (SWE estimates for melt season 2023-24 and workshop)	Project coordinator	Milestone 7 - Delivering SWE estimates for melt season 2023-24	24	1	24	
	Objective 7.- Web platform	5.- Tool definitions and design (server, language, software, etc.)	Web designer		13	3		
		6.- Online tests	Web designer	Milestone 8 - Webpage launching	16	9	24	

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2. Potential Social Economic Impact

2.1 Description of the final product, process or service.

The final product is a near real-time SWE estimation for different sites or catchments of the Coquimbo region. This information will be available through an open access web platform with the following information:

- Regional map including SWE and snow cover estimates for different sites or (sub)catchment of interest

- Statistical metrics for the current SWE and snow-covered area of (sub)catchments such as ensemble median, mean, percentiles

- A comparison of the current situation with past years

- An estimation of the melting season runoff that could be expected with the current SWE for selected catchments, including the uncertainty range.

The product will be a public good and the results will be freely accessible. It will be of interest for water resources managers, state agencies, private companies, scientists and the wider community. The information can be accessed and downloaded via the web platform but needs to be cited. The web platform will be run by CEAZA.

2.2 Competitive advantage

Until now, there is no product for near real-time SWE estimates available for the Coquimbo region.

Water managers base their decisions mainly on the following information (main competitors to our solution):

- **Precipitation measurements** in the region (by e.g. CEAZA or DGA): The precipitation recorded during winter can give an indication on the available water in the snowpack. But precipitation records are not accurate to estimate SWE. Firstly, precipitation is recorded at only a few high elevation locations (see Figure 8), which might not be representative for the entire region or unmonitored catchments. Secondly, precipitation records do not directly represent the amount of water that is stored in the snow, since there are complex snow redistribution, sublimation and melting processes.
- **SWE measurements** in the region: There are only four locations with SWE measurements (Cerro Olivares, Elqui River basin; Quebrada Larga and Cerro Vega Negra, Limarí River basin; El Soldado, Choapa River basin) published in the reports on seasonal forecasts by the DGA.

Even if in-situ SWE measurements are extremely valuable to understand the snow properties, such records cannot be easily extrapolated to other sites.

- The DGA publishes **forecasts of runoff volume** for current melting seasons in comparison with past years for individual basins and based on precipitation records and SWE records. The report is published in September to estimate the hydrologic situation that could be expected during September – March[1], complemented with monthly bulletins on the hydrological situation. However, for the large region comprising Atacama to Bio-bio, there are only nine SWE measurements and the runoff forecast is realized for 19 large basins which might not meet the needs of local water resources managers. For the Coquimbo Region, the following four basins are included in the annual report: Elqui in Algarrobal, Hurtado en San Agustín, Grande en las Ramadas, Choapa en Cuncumén and four SWE estimates are included.
- **Snow covered area** is published monthly in the CEAZA bulletin. They estimate the current snow cover extent and compared with the climatology (2002 onward). But the area of snow is not directly related to the SWE (see Figure 1 and Figure 10). For instance, Figure 10 indicates a “normal” snow cover extent by end of July, but clearly drier precipitation records than normal. Even if this information is valuable and important, it might be difficult to interpret for decision makers, especially if they need to estimate the available water for melt for a certain location or subcatchment.

There are other products in Chile or globally that do not meet the need of water managers in the Coquimbo region:

- The project “Observatorio Satelital de Nieve” focuses on generating snow data for the Acongagua River basin or the bulletin by CEAZA), but the SWE is not included in these products.
- SWE estimates exist for the region, but these data were generated retrospectively (1985-2015) and not operationally (Cortés et al., 2016).
- Several international initiatives exist to generate SWE estimates, but only for the Northern hemisphere. GlobSnow from the European Space Agency (ESA) provides SWE estimates at a coarse resolution (~25 km) and only for the Northern hemisphere (Luojus et al., 2013). The GlobSnow SWE record utilizes a data-assimilation based approach combining space-borne passive radiometer data with data from ground-based synoptic weather stations. SWE maps are produced daily, but mountains and the Southern Hemisphere are excluded. SNODAS from the National Oceanic and Atmospheric Administration (NOAA) is available since 2003 and at a 1 km resolution, but only for continental USA (Barret et al., 2003). It is a modeling and data assimilation system, to integrate snow data from satellite and airborne platforms, and ground stations with model estimates of snow cover, to provide daily SWE estimates. Also, the Canadian Meteorological Center (CMC) Daily Snow depth Analysis product, available since 1998 and at ~25 km resolution, is only focusing on the Northern hemisphere (Brown and Brasnett, 2010). There are additional recent international

[1] https://dga.mop.gob.cl/productosyservicios/informacionhidrologica/Paginas/default.aspx

campaigns combining remote sensing and in-situ measurements such as NASA's SnowEx (NASA, 2021) and the Nordic Snow Radar Experiment (NoSREx, Lemmetyinen et al., 2011) with the aim to address the most important gaps in snow remote sensing knowledge. But these initiatives are also focusing on the Northern Hemisphere.

In conclusion, our solution shows clear differences to the existing products. It will be an accurate and near real-time estimation of SWE with a high spatial resolution. As seen by the diversity of project partners, it is of high interest for different end-users.

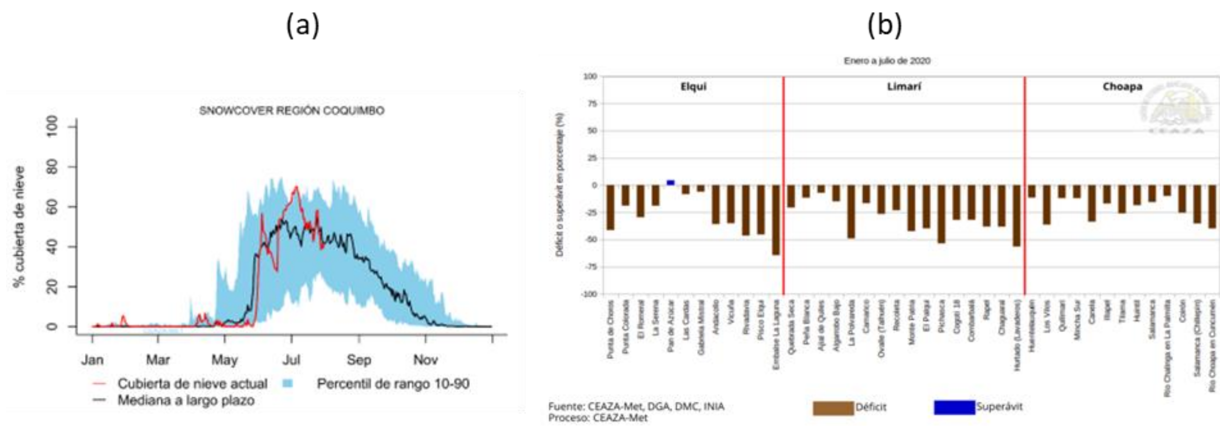

Figure 10 (a) Time series of regional snow covered area, based on MODIS satellite data, the red line shows the snow covered area during 2020 until end of July, the black line the median snow covered area (since 2002) (b) Percent of accumulated precipitation until July 2020, compared to the climatology (1981-2010). Figures from CEAZA bulletin from August 2020. Note that the snow covered area of July 2020 lies approximately 14% above the multiannual mean, while precipitation records clearly indicate drier conditions than normal.

2.3 Identification of future stages and estimated time for commercialization.

When the project ends, the web platform with near real-time SWE estimates and related statistics will be running and can be used by the end-users for decision making processes. The results will have been validated for the study site. The platform will be developed in the second year of the project. We will be in contact with end-users and their feedback will be used for adjustments until near the end of the project. The dissemination of the platform and its associated products will be carried out during the entire duration of the project.

The methodology and web platform will be ready to be transferred to other parts of Chile, but additional funding would be needed for this and 1-2 additional years. There might be components of the methodology that need adjustment if applied to regions with for instance more cloud cover and therefore reduced satellite information, different topography or hydrological processes.

The aim of this project is to develop a method and routine to estimate the SWE almost automatically. But after the duration of the project, additional funding will be needed to continue validating the result, update the scripts (due to e.g. changes in the satellite imagery or atmospheric forcing data), adjust the web platform according to the end-users needs that might change in the future. These additional efforts in the future would be minor in comparison to the development of the methodology itself during the project, as the most important components (snow model, data assimilation framework) will have been tested and implemented.

2.4 Potential market or target population

The potential market or target population can be grouped into the following categories: general public, public and private organizations, as well as agriculture. The project targets at different direct or indirect end-users. Since the product will be freely accessible, there are no barriers for interested users.

From the public sector, the direct beneficiaries are the DGA and the Government of the Coquimbo region. Indirect beneficiaries are various municipalities in the Coquimbo region, such as Vicuña, Paihuano, Río Hurtado, Monte Patria, Illapel and Salamanca. An accurate estimation of the available water could improve their water management planning and policies.

From the private sector, the organizations that directly benefit are the *Juntas de Vigilancia* in the region, especially the ones involved in the project. A skillful SWE estimation may allow more efficient water allocation and predictable trade-offs between flows for different sectors such as energy, irrigation, municipalities and environmental services. Such information is particularly important for below-normal precipitation years, such as those since 2010, when allocation has had to be reduced.

A high percentage of water rights are held by farmers (for instance >90% in the Elqui Valley, Delorit et al. 2017), thus this product will be of special interest for this sector. Agriculture is highly relevant for regional activity. According to the 2007 Agricultural Census, there are 15,121 farms in the region and a total of 75,818.5 ha of irrigated area. The Province of Limarí contains the highest percentage of farms (51%), followed by the Province of Choapa (33%) and the Province of Elqui (17%). Regarding the area designated for agriculture, Elqui holds the largest area (41%), followed by the Province of Limarí (33%) and the Province of Choapa (25%). Tax information reveals that the PIB of agriculture in the Coquimbo regions is approximately USD $372 M in 2015 and in 2017, 47,914 workers in the agriculture sector were reported, which corresponds to 13.5% of the regional total (ODEPA, 2018). Therefore, it is the second most important labor force, only surpassed by the construction sector, which represents 19.3% of the regional total, which denotes its importance in the region's economy.

In the last decade with below-average annual precipitation, the interest in hydroclimatic information for decision making processes has increased. In the future, such information will be increasingly important for water resources allocation decision making. A model framework to estimate SWE could therefore also be of interest of water managers in other regions in Chile.

2.5 Relevance Associated Entities

The Water User Associations, in Spanish: ***Juntas de Vigilancia*** are key partners for this project. The Juntas de Vigilancia are defined by the Chilean Water Law as organizations of water users in charge of the administration and allocation of the water resource among their members, and other duties such as ensuring the interests of the associates against the State or private organizations, providing control, coordination, surveillance and representation services for a sustainable management of water resources. In our project, four *Juntas de Vigilancia* in the Coquimbo Region will be main users of our results. We will coordinate with them, during at least four working groups, the format of the project results and define the main products for the general public. It is worth noting that all four

Juntas de Vigilancia were involved in previous projects with the CEAZA glaciology group, including the installation of snow fences in these areas. Therefore, we have a well-tested model for two-way communication that includes informal and formal pathways.

The participation of the *Juntas de Vigilancia* (JV) in the project is crucial since their main functions relate to the aim of this project. The role of the JV in the project will be to define their needs in view of SWE estimates, give feedback to the web platform, evaluate its setup and functioning, and to disseminate and apply the results, and to use the platform. With the four associated Juntas de Vigilancia, we will have partners in all three provinces of the Coquimbo Region:

- JV del Río Elqui y sus Afluentes, Elqui Province
- JV del Río Hurtado y sus Afluentes, Limarí Province
- JV del Río Grande y Limarí y sus Afluentes, Limarí Province
- JV del Río Illapel y su Afluentes, Choapa Province

The ***Dirección General de Aguas* (DGA)** is the state agency in charge of promoting the management and administration of water resources in a framework of sustainability, public interest, and efficient allocation, as well as providing and disseminating the information generated by its hydrometric network and that contained in the public water register (Catastro Público de Aguas) in order to contribute to the competitiveness of the country and improve people's quality of life. Their participation in the project is indispensable since the outcome of this project is connected with their main functions. They will be end-users of the product, since they need hydrometeorological information to plan the development of the water resource in natural sources, to formulate recommendations for its use. The role of the DGA in the project will be to provide hydrometeorological data, advice on the SWE measurements, define end-user's needs, and spread the use of the platform, as well as provide reviews for the project reports and evaluate the inclusion of the project results in their own products. We have a history of working together with the Glaciology and Snow unit of the DGA on projects in the Elqui River Basin, in particular understanding cryosphere change and water availability, and have built a relationship of interaction at various levels.

The **Centro del Agua para Zonas Áridas y Semiáridas de América Latina y el Caribe (CAZALAC)** is an entity sponsored by UNESCO, and it is the only international center in Latin America and the Caribbean dedicated to studies on the water management of arid and semiarid zones. As such, CAZALAC generates several products and services, such as maps of arid and semiarid zones in Latin America and the Caribbean, studies on water efficiency, methodologies and information on droughts, training courses, and others. CAZALAC will contribute with their expertise to the communication with the Juntas de Vigilancia and the spread and dissemination of project results. In the past the CEAZA glaciology group worked together with CAZALAC on the monitoring of glacial resources in the Elqui catchment, and in recent years have participated in several panels to develop public policy around cryosphere processes.

The University of La Serena (Universidad de La Serena, ULS) is a regional university, founded in 1981. Its objectives have been to create, promote and divulge the region's scientific, technological, cultural and artistical advancements. The ULS offers different training programs for professionals and postgraduates. The collaborators from ULS will participate in the working groups, collaborate and advice on snow water equivalent measurements, review the progress and reports of the project and disseminate the product through different media that are part of the University. The ULS is a founding member of CEAZA, and has ongoing collaborations. It should be noted that the CEAZA glaciology group has worked together with PROMMRA on several projects, that CEAZA and PROMMRA currently work together to produce a monthly climate bulletin, and members of the glaciology group also contribute to postgraduate programs within the ULS, enabling constant communication between the members of the groups.

2.6 Development and business strategy or massification

The web platform will be hosted and maintained by CEAZA, similarly to the meteorological and forecast web page by the same center (www.ceazamet.cl). The access to the data will be open, which is an important factor for the massification of the product since all interested users can access and benefit.

The massification of the web platform will be guaranteed via diverse publications and presentations, such as scientific publications, theses, conference presentations, general outreach (including public talks, social media and mailing lists), or reports (see Figure 11). With this strategy, every focus group (international, national, and regional public) would be reached by at least three of these types of publications/presentations, which guarantees a broad massification.

Through theses and scientific publications, CEAZA and ULS will present the methodology to a broad national and international public. In addition, the project team will present main outcomes at national and international conferences to a broad scientific public interested in water resources management and hydrology. CEAZA has broad experience in public dissemination of scientific results. We will publish relevant outcomes of this project using social networks and contact local radio stations and newspapers with the help of its internal team of journalists. This will help to disseminate the project's products at the local level, but also nationally and internationally. The associated *Juntas de Vigilancia* and CAZALAC will be responsible for the dissemination of the web platform and outreach activities. The SWE estimates can be used in reports such as the monthly CEAZA bulletin or the seasonal runoff forecast by DGA. If published in these reports, the product will achieve a high visibility among potential end-users in Chile.

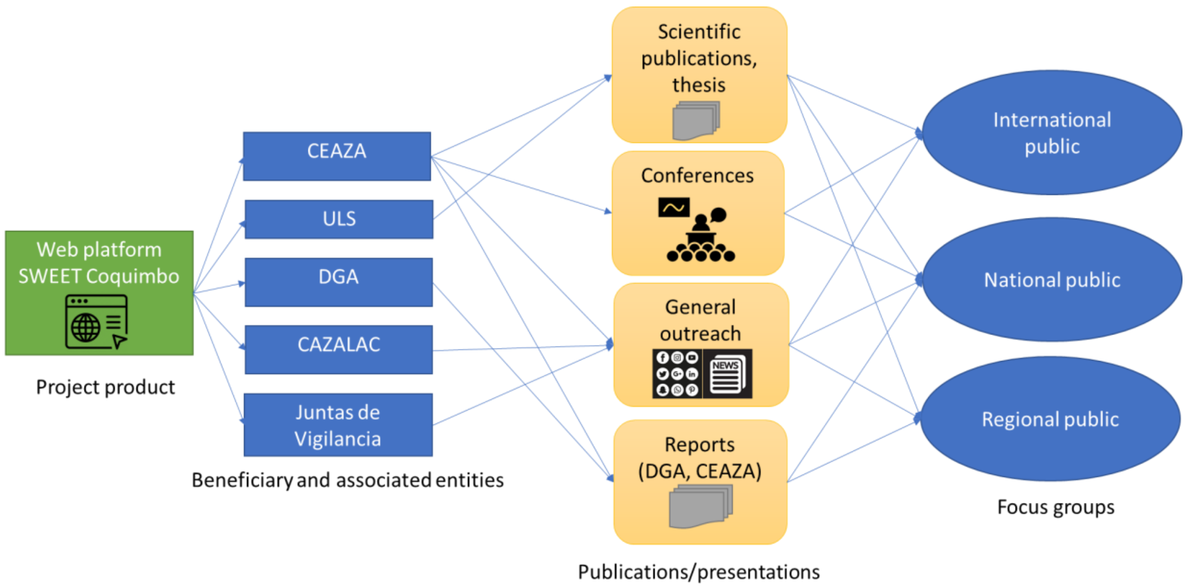

Figure 11 Diagram showing the massification strategy of the project.

3. Capabilities and Management

3.1 Detailed definition of positions and functions.

The project team includes the right combination of specialized scientists and professionals of CEAZA, together with the project partners from the associated entities. The interdisciplinary collaboration brings together researchers with diverse and extensive experience in climatology, hydrology, and cryosphere (snow and glaciers) in high mountain regions and semi-arid environments. The expertise and skills perfectly combine and cover the need of this project. In the project team there is a high degree of experience in basic and applied research in different research fields and skills such as outreach, communication, project management, cost planning, leadership or field work. There will be a weekly meeting to coordinate and track the activities of the project.

Scientific and Technological Research

Name / RUT	Institution	Position in the project	Role and critical capacities that it contributes to the project	Dedication HH/Month	$/HH	Activities *
Shelley MacDonell 23.061.076-2	CEAZA	Director	Researcher in glaciology with experience in the interactions between the climate, cryosphere and hydrology. Experience managing scientific projects on these fields. She will supervise and coordinate the project.	48	14425	1.1-1.6 2.3-2.7 3.1-3.4 4.1-4.4
Katerina Goubanova 25.758.058-K	CEAZA	Deputy Director	Researcher in climate variability at regional scales. She will supervise the generation of the meteorological forcing data.	24	14425	2.1, 2.2 4.1-4.4
Simone Schauwecker 14.760.797-0	CEAZA	Postdoctoral Researcher	Postdoctoral researcher with experience in climate-cryosphere interactions. She will develop the methods for the generation of the meteorological forcing data.	160	11400	2.1, 2.2 4.1-4.4

Álvaro Ayala 16.013.876-9	CEAZA	Postdoctoral Researcher	Postdoctoral researcher with experience in numerical models of the cryosphere with a focus on runoff generation. He will work on the snow model. He starts on month 7 after the first season of snow field campaigns.	160	11400	2.3-2.4 4.1-4.4
Gonzalo Cortés 16.354.360-5	CEAZA	Postdoctoral Researcher	Postdoctoral researcher with experience in data assimilation framework to estimate SWE in the Andes. He will work on the data assimilation framework.	80	11400	2.5-2.7 4.1-4.4
NN	CEAZA	Snow monitoring professional	Professional with experience in the monitoring of snow using remote sensing and field methods. This person will be in charge of generating the fSCA and SWE database.	160	7500	1.1-1.6
NN	XXX	Web designer	Professional with experience in webpage design. This person will in charge of the web page.	80	7500	1.1-1.2
Administrative Support						
NN	CEAZA	Project coordinator	Professional with experience in project management and outreach. This person will be in charge of the administrative tasks and the interactions with the Associated Institutions	80	7500	3.1-3.4

* Activities to develop in the project are individualized in the Gantt chart

3.2 Contribution to the formation of human capital

The project is conducted in a regional research center and directed towards finding solutions for water management in the Coquimbo region, which helps the development and the formation of human capital.

There will be working groups to train the different water managers in the region. They will be able to improve their knowledge on the importance of snow for water resources and on how to include such information in their decision-making processes.

The project considers the inclusion of three postdoctoral researchers, two of them are young researchers: Dr. Schauwecker and Dr. Ayala have gained their doctoral degree less than five years ago. This project offers a good opportunity to publish scientific results. They will not only improve their scientific profiles, but also gain skills such as project management, outreach and communication of scientific results.

The project will include two thesis students working closely with the postdoctoral researchers. This will not only foster the formation of new professionals, but also improve the supervising skills of the postdoctoral researchers. The formation of new professionals in the fields of climatology, hydrology and water resources is fundamentally important for the development of the Coquimbo region and Chile. Since experienced researchers are traditionally underrepresented in this discipline in Chile, it has been often undertaken by foreigners. It is vitally important to fill this gap with well-trained Chilean researchers.

The project will generate a unique set of meteorological and hydrological data for the Coquimbo region, which will be available for further studies and theses through the web platform, having a large positive impact on the formation of future professionals in the fields of hydrology and water management. The new methodology will be described in publications and can be applied in other regions, having an impact also on the formation of human capital in other regions.

In addition, this project has to female directors (2 from 2) and also 1 postdoctoral position (1 from 3) is covered by a female researcher. We will also try to maintain the gender equality during the project by carefully selecting professionals and students.

3.3 Statement of holdings engaged in other projects

Name	2021	2022	2023	2024
1. Shelley MacDonell	128/month	80/month	80/month	64/month
2. Katerina Goubanova	136/month	136/month	88/month	88/month
3. Simone Schauwecker	160/month (until September)	0	0	0
4. Álvaro Ayala	160/month	160/month (until March)	0	0
5. Gonzalo Cortés	64/month	64/month	0	0

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