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Agricultural water accounting: Complementing a governance monitoring schema with remote sensing calculations at different scales

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ABSTRACT

Water use requires monitoring and quantification at different spatial scales to enhance water security, especially in regions facing water scarcity and threats to food security. Consequently, water metering has been implemented in various countries as part of water governance frameworks. This study aims to evaluate the implementation of a water metering network within the Chilean water governance system, which is based on the commoditisation of water through water rights. Additionally, it assesses the potential of supplementing the water metering network with remote sensing-based estimates of actual evapotranspiration (AET) and discusses the need to integrate these estimates into an appropriate water governance scheme. To conduct this study, publicly available water use reports were obtained from the Water Resources Directorate and subsequently processed to eliminate anomalies in the withdrawal time series. Water withdrawal data was supplemented with information on granted water rights to provide additional insights and contrast water allocations with actual withdrawals. AET estimates from the Mapping EvapoTranspiration at high Resolution with Internalised Calibration (METRIC) model using Landsat scenes were also acquired for the period from 2019 to 2022 to compare withdrawals and water demand in the agricultural sector. It was found that only a small fraction of water rights (~ 2%) is currently being metered. Actual reported withdrawals, on average, amount to approximately one fifth to one fourth of the volumes granted through water rights. However, water extractions vary depending on geographical locations and usage categories. Remote sensing-based AET demonstrates a good correlation with withdrawals, suggesting its potential in auditing water withdrawal records provided by water users and calculating water availability and withdrawals at aggregated scales within an adaptive water governance framework. While different applications were explored within the Chilean context, these have a broader application in global water governance, particularly in regions experiencing similar challenges in water resource management.

1. Introduction

Quantifying water withdrawals in agriculture is a challenging task (Yuan and Shen, 2013; Döll et al., 2014; Wu et al., 2022), but it is crucial for achieving water security and equity (Cook and Bakker, 2012; Lautze and Manthrithilake, 2012; Veettil and Mishra, 2016; Wu et al., 2022), particularly in the face of increasing variability caused by climate change (Döll, 2002; Dinar et al., 2015). Therefore, approaches to quantify water withdrawals used by agriculture are a priority.

Agriculture is the primary water-consuming activity (Scanlon et al., 2017; Wu et al., 2022). While drinking water accounts for approximately 11% and industry for 19% of water consumption, agriculture accounts for about 70% of total water withdrawals globally (Hoekstra and Chapagain, 2007; Davis et al., 2015; Scanlon et al., 2017; FAO, 2020). Moreover, Campbell et al. (2017) identified agriculture as a significant contributor to exceeding Earth system's planetary boundaries.

To achieve sustainability and equity in water availability between different users within a catchment (Falkenmark and Folke, 2002), various water governance schemes exist, consisting of policy structures

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aimed at balancing competing water needs (Rogers and Hall, 2003). However, these schemes can be biased towards specific stakeholders and lack coordinated management efforts (Bakker, 2010). Consequently, integrated catchment management has emerged as the main approach to balance the diverse interests associated with water within a shared drainage area (Wang et al., 2016; Veale and Cooke, 2017). However, in countries where land and water distribution are highly unequal, challenges may arise (Wester and Warner, 2002; Rahaman and Varis, 2005), particularly if water commoditisation and privatisation take precedence over common ownership and the public role of water.

Water management in governance schemes relies strongly on the technical ability to quantify water resources since it helps assessing availability, planning for allocation, and making informed decisions about water management (Foster et al., 2020; Jiménez et al., 2020). As a consequence, a common approach involves the development of water resources monitoring networks, aiding in early detection of issues and assisting with effective water management (Valdés-Pineda et al., 2014; Wutich et al., 2021). If climate conditions impose constraints on water availability, or if water access is essential for the population, countries may complement their monitoring networks by metered water withdrawals (Mudumbe and Abu-Mahfouz, 2015). For instance, Israel, Australia, and South Africa are countries that have implemented water metering in some regions within their water governance approach (Arlosoroff et al., 2002; Holley and Sinclair, 2013; Koech et al., 2018; Pott et al., 2009). However, water metering alone can not address water scarcity issues as it must be an integral part of a water governance scheme.

An often-mentioned study case in terms of water governance that exemplifies the aforementioned global challenges is Chile, in which the commoditisation of water has been deliberately implemented (Bauer, 1997; 2004; Larrain, 2012; Baer, 2014; Prieto et al., 2020; Correa-Parra et al., 2020). The Chilean law guarantees that private water rights can be granted to users (Bauer, 2004). Therefore, water management in the country primarily relies on water users and water user organisations (Donoso, 2014). Moreover, Chilean water rights, granted as maximum exploitation volumes within a defined period, are freely and perpetually granted to owners (Prieto et al., 2022). These factors have led to different deficiencies in terms of water governance and management, some of which have been addressed through successive modifications to the water law, including the implementation of ecological river flow when granting water rights (Aitken et al., 2016), and more recently, through the prioritisation of human water consumption. However, these deficiencies in water management, coupled with dynamic hydroclimatic processes, have caused aridity to extend southwards in the country (Boisier et al., 2017; Araya-Osses et al., 2020). The increasing aridity has led to severe water scarcity affecting some regions in Chile (Aitken et al., 2016; Fuentes et al., 2021a). These issues have been exacerbated by information gaps in terms of water availability and management. One example of this in the Chilean water law is the application of foreseeable use factors that were employed between 1995 and 2010 to account for water use when granting new groundwater rights. This has been recognised as one of the factors explaining groundwater overexploitation (Donoso et al., 2020). Thus, considering Chile as a case study illustrates how these broader governance challenges manifest, emphasising the potential of water metering networks within water governance schemes.

Remote sensing techniques have increasingly been utilised as alternatives to address water quantification at various scales (Long et al., 2015; Zhang et al., 2019; Fuentes et al., 2019; 2021b; 2022; Fuentes et al., 2024). In particular, actual evapotranspiration (AET) has been estimated using a range of techniques, combining data from different satellites with varying spatial and temporal resolutions (Mu et al., 2011; Senay et al., 2013; Zhang et al., 2019). AET plays a crucial role in the water balance, representing the flux of water from soils through plants to the atmosphere, and serves as an indicator of high crop yields resulting from sufficient water availability meeting crop water requirements (Sinclair and Rufty, 2012; Kang et al., 2017).

Given the context of increasing water scarcity and the considerable uncertainty surrounding water availability in different regions, including central North America, South Asia, and Mediterranean regions (Greve et al., 2018), water metering is also expanding. This is also the case in Chile (Aitken et al., 2016; Bozkurt et al., 2018), where the government through the Water Resources Directorate (*Dirección General de Aguas*, DGA) has recently developed a program to monitor and publicly disclose water withdrawals associated with granted water rights (Biblioteca del Congreso Nacional de Chile, 2016). However, this program has thus far only been implemented for a small section of all the water rights. Moreover, since Chilean water rights are privately owned and metering relies on public disclosure by water users, the reported withdrawals may significantly deviate from actual withdrawals, highlighting the need for further investigation. Nevertheless, the data compiled at this stage can provide valuable insights into the relationship between granted water rights and actual withdrawals, contributing to the understanding of water management dynamics. Additionally, water metering in this context may be coupled to remote sensing within a governance and auditing scheme to support water security.

There are very few cases where the effectiveness of agricultural water metering is investigated to address water governance problems (Grantham and Viers, 2014; Sangha and Shortridge, 2023). The objective of this study is to highlight how water metering can be complemented by water use records and remote sensing to improve water governance. As a case study, the implementation of a national metering program in Chile is evaluated, which can highlight solutions and limitations for such programs, in light of the increasing uncertainty in water availability across many regions. Additionally, we seek to examine the relationship between water withdrawals and granted water rights to evaluate the agreement between allocations and actual water extractions. We argue for the integration of this program into a comprehensive water governance framework, highlighting both the strengths and weaknesses of such an approach. In addition, we investigate how declared water withdrawals correspond to remote sensing estimates of water demand derived from AET models which may be linked to water accounting, evaluating two study scales and case studies for different regions and climates. Finally, we discuss the current difficulties in achieving accurate water accounting.

2. Materials and methods

2.1. Withdrawal monitoring program and dataset

The withdrawal monitoring program was initiated based on Article 68 of the Chilean Water Code. Initially, the Water Resources Directorate (DGA) had the authority to require water users to install monitoring devices. In 2013, this provision was expanded to include groundwater rights, making it mandatory to install monitoring devices under certain circumstances where water withdrawals may harm sensitive ecosystems or affect the drinking water supply. These devices would measure groundwater levels, extraction rates, withdrawal volumes, and communicate this information to the DGA.

Subsequently, due to arid conditions in northern regions and worsening water availability, aggravated by a prolonged drought in central regions (Garreaud et al., 2017), the Water Code underwent modifications in 2018. The amendment mandated water communities and users to install monitoring devices for surface water withdrawals and share this information with the DGA. Two laws which were enacted in 2019 and 2020 extending this requirement to groundwater and surface water rights, and established terms and requirements for the water withdrawal monitoring program. As a result, regional laws have progressively been enacted to cover the entire country (Fig. 1 provides information up to the Los Lagos region). The number of recorded withdrawals has consistently increased, particularly after 2020.

Observed water withdrawal data was obtained from the DGA webpage (https://dga.mop.gob.cl/). At the date of data acquisition

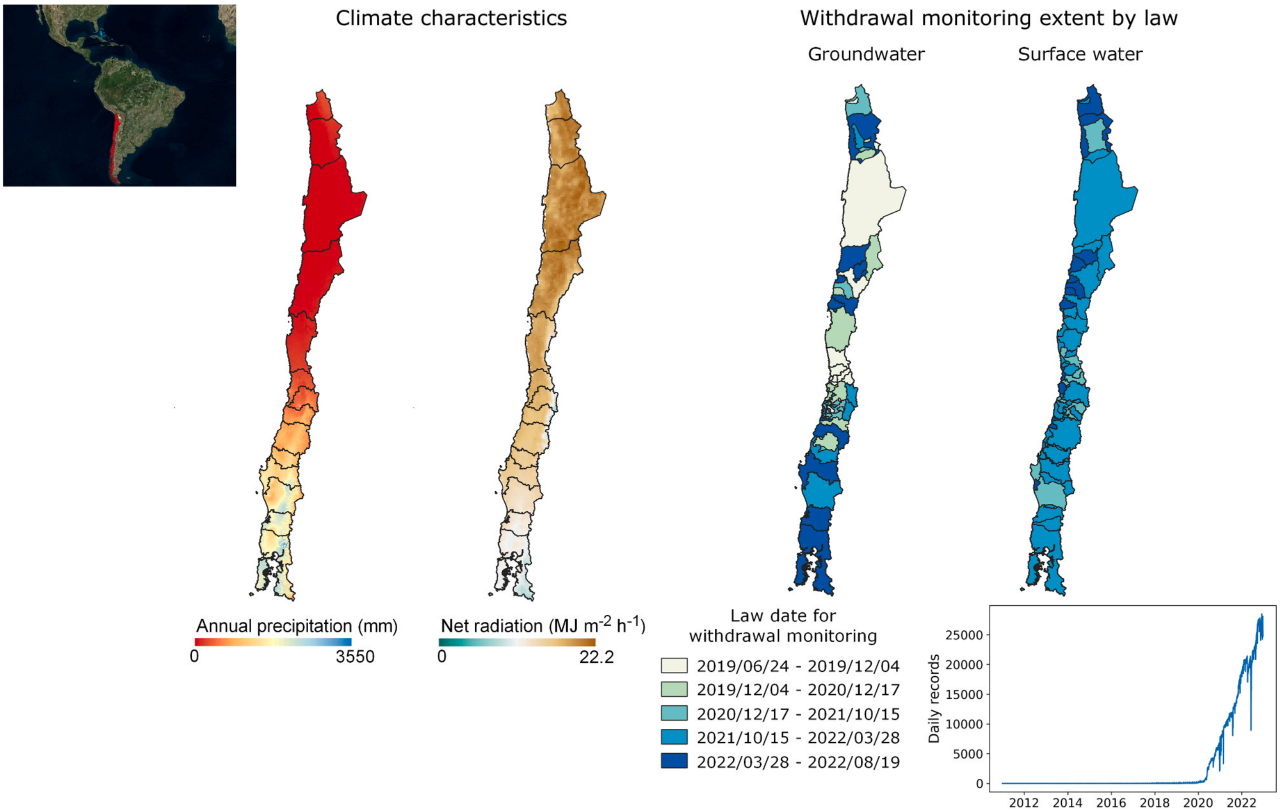

Fig. 1. Climate gradient in terms of rainfall and net solar radiation, and progressive withdrawal monitoring coverage based on several enacted laws. The lower right plot depicts a time series of daily withdrawal records extending up to the Los Lagos region. Drops in the time series result from system maintenance and improvements.

(December 30, 2022), a total of 6614 water withdrawal points were available. However, some of these points had incomplete or missing data. To ensure data quality, a filter was applied, selecting files that contained at least 12 records. This threshold was established due to the prevalence of several water rights with low extraction rates, which are required to report at least monthly. This requirement ensures a minimum monitoring duration of at least one year. This filtering process reduced the number of observed points to 2779, which are unevenly distributed across the territory (Fig. 3). It is important to note that these 2779 points represent only about 1.9% of the total granted water rights listed in the public water cadastre, representing 143,086 rights. However, it is expected that the number of monitoring water withdrawal points will significantly increase in the coming years as the terms stipulated by the enacting laws come into force.

2.2. Ancillary data and models

The water right cadastre from the DGA was used to complement the information on water withdrawal points (Fig. 2). This was achieved by performing a spatial join using a distance threshold of 20 m. Furthermore, from the water right database an Euclidean distance to water rights raster was developed since the coordinates from granted water rights may differ from their actual withdrawal locations. Additional files containing information on granted water rights were also obtained to overall restrict the location to farms associated with these rights. In addition, a land cover map developed in 2014 using satellite images together with a random forest model trained with ground truth data (Zhao et al., 2016) in conjunction with withdrawal data were used to determine land uses associated with water withdrawal points Fig. 3.

To evaluate evapotranspiration, the Mapping EvapoTranspiration at high Resolution with Internalised Calibration (METRIC) model was used (Allen et al., 2007). The METRIC model utilises satellite and meteorological data to establish an energy balance. This balance is based on the following equation:

$$LE = R_n - G - H \tag{1}$$

where LE represents the latent energy consumed by evapotranspiration, R_n denotes the net radiation, G is the soil heat flux, and H represents the air sensible heat flux. In the METRIC model, the evapotranspiration fraction (ET_rF) is calculated from the instantaneous evapotranspiration at the moment of the satellite data acquisition (ET_{inst}), calculated from LE divided by the latent heat of vaporisation (λ) multiplied by the water density (ρ_w), divided by the reference evapotranspiration (ET_r) computed from meteorological data (Allen et al., 2007).

$$ET_{ins} = 3600\frac{LE}{\lambda\rho_w} \tag{2}$$

$$ET_rF = \frac{ET_{ins}}{ET_r} \tag{3}$$

However, it is important to note that the calibration in the METRIC model is accomplished by selecting anchor pixels, i.e. the selection of hot and cold pixels from land surface temperature rasters. These anchor pixels can potentially be affected by residual clouds or cloud shadows. The METRIC reference evapotranspiration (ET_r) and evapotranspiration fraction (ET_rF) rasters were obtained from the EEFlux platform (https://eeflux-level1.appspot.com) which combines meteorological and Landsat satellite data in the Google Earth Engine platform.

Images from three Landsat tiles (row/column: 001/079; 233/083; 233/084) were used, including scenes from ETM+ , and OLI/TIRS sensors, corresponding to Landsat 7, 8, and 9 (USGS, 2022) from 2019 to 2022. The ET_rF rasters were then masked for clouds using the pixel quality data derived from Landsat images through the application of the CFMASK algorithm (Foga et al., 2017). Subsequently, the ET_r and cloud

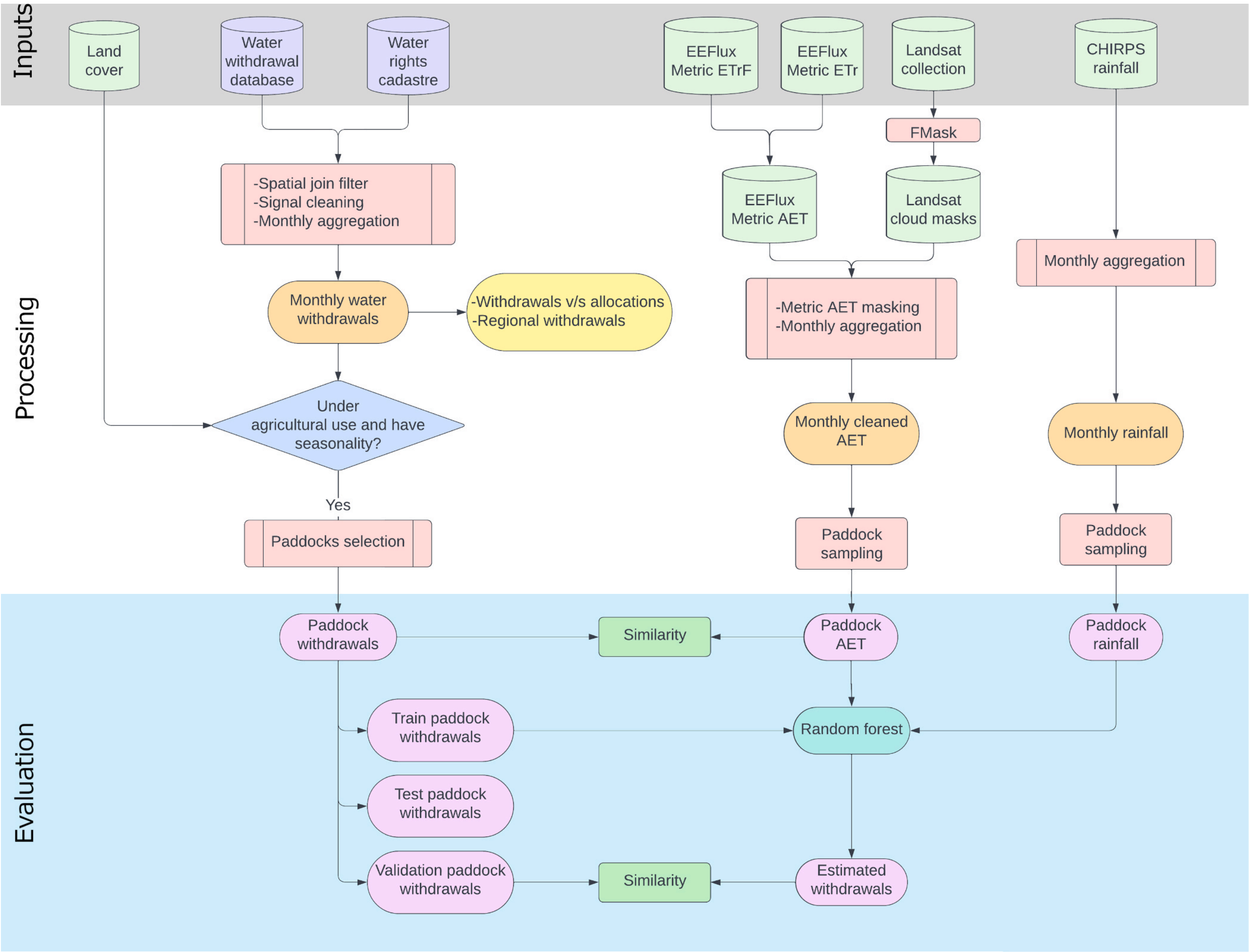

Fig. 2. Study scheme showing inputs, processing and evaluation of results.

masked ET_rF rasters were aggregated to monthly (averaged) values. Actual evapotranspiration (AET) rasters at a spatial resolution of 30 m were obtained by multiplying the aggregated ET_r and ET_rF rasters. This approach was employed rather than using AET directly computed from EEFlux to account for cloudy weather conditions that may impact AET. Additionally, the cumulative annual evapotranspiration for 2021 was estimated.

Lastly, daily rasters of Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) at a spatial resolution of 0.05° (Funk et al., 2015) were aggregated to monthly values by summing the gridded daily precipitation.

2.3. Study site selection

The selection of various study sites for comparing water use with AET was based on the availability of withdrawal data. The time series of withdrawal monitoring points were visually examined, and locations showing a clear seasonal pattern, subsequently confirmed through a Kruskal-Wallis test on monthly aggregated withdrawals (p-value < 0.05; Figure S1 from Supplementary materials), consistent with crop seasonal growth and development, were chosen (Fig. 4).

Furthermore, using the land cover map locations that were not classified as agricultural were filtered out. Sites with sufficient information from the DGA to associate the water right location with a specific paddock were selected. This step is challenging, since the water right allocation does not require the specification of use or the irrigation surface for agricultural purposes. Therefore, relatively isolated paddocks in relation to other irrigation lands were included, resulting in the selection of 27 sites for evaluation. These sites had varying areas ranging from 4.7 to 217.6 ha (Fig. 5A).

At a larger scale, an area of interest (AOI) spanning 98.6 km^2 and characterised by intensive agricultural activity was selected in the III region of Chile. This AOI contained 102 monitoring sites (Fig. 5B). In this area, the withdrawal volumes were aggregated (summed) and compared with AET.

2.4. Data processing and similarity metrics

The withdrawal data underwent several filtering steps to ensure data quality due to common issues related to the metering recording devices. Consequently, peaks and jumps in the withdrawal time series were removed, and consecutive negative meter differences were dropped considering the continuity in withdrawal recordings (Supplementary materials, Figure S2). These errors are assumed to be caused by mechanical faults of water metering devices, storage issues with consecutive readings of the same timestamp, or resets of the meter counter (Khaki and Mortazavi, 2022). Groundwater records with withdrawal rates exceeding 0.5 m^3 s^{-1} and surface withdrawals with rates exceeding 28 m^3 s^{-1} were also eliminated, as these values exceeded common pumping capacities found in characteristic curves from pump catalogues and volumes granted by water rights. Additionally, agricultural records that deviated more than 5 times the standard deviation from the mean

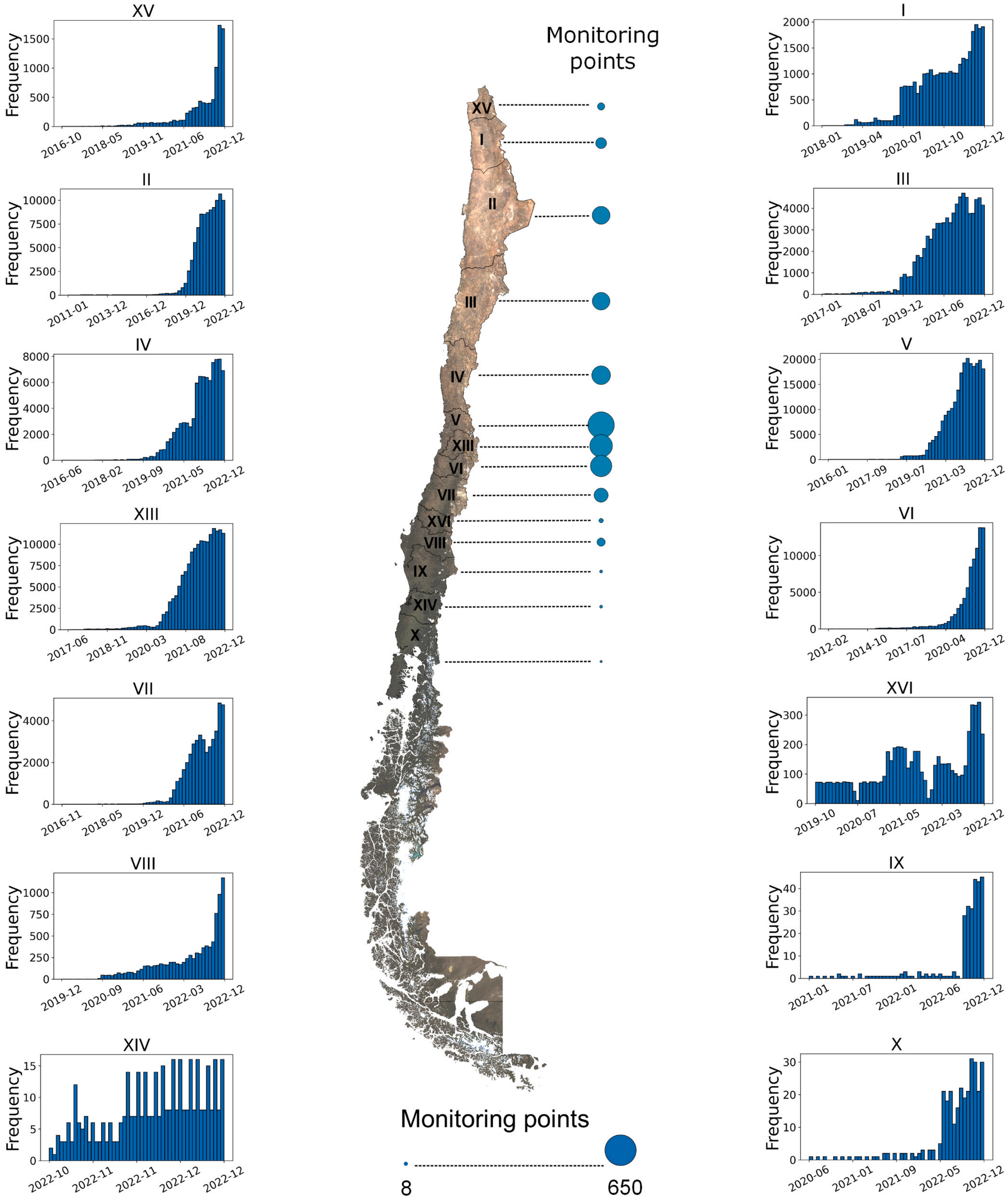

Fig. 3. Withdrawals control points and their spatial distribution. Additionally, the temporal distribution of records are included as histograms for different regions being monitored.

and those with volumes exceeding 10,000 m^3 $month^{-1}$ ha^{-1} were considered recording errors and were dropped.

To assess the relationship between monthly withdrawals and remote sensing evapotranspiration, similarity metrics such as the R^2, root mean square error (RMSE), mean absolute error (MAE), and the Lin's concordance correlation coefficient (CCC) were calculated, covering a measure of agreement and/or measures of absolute bias. Furthermore, rainfall data from CHIRPS monthly rasters were extracted at the study

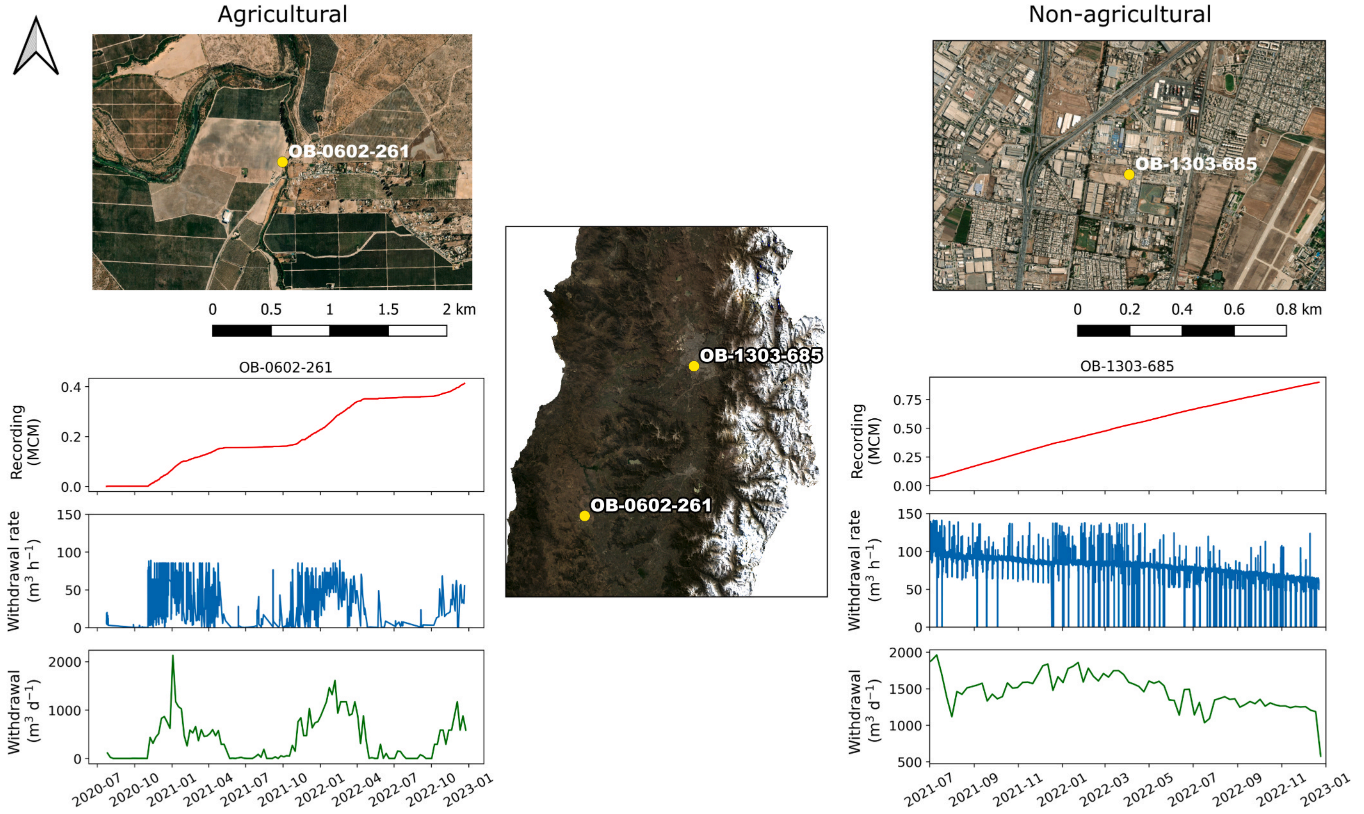

Fig. 4. Differences in seasonal behaviour in abstraction rates for site selection.

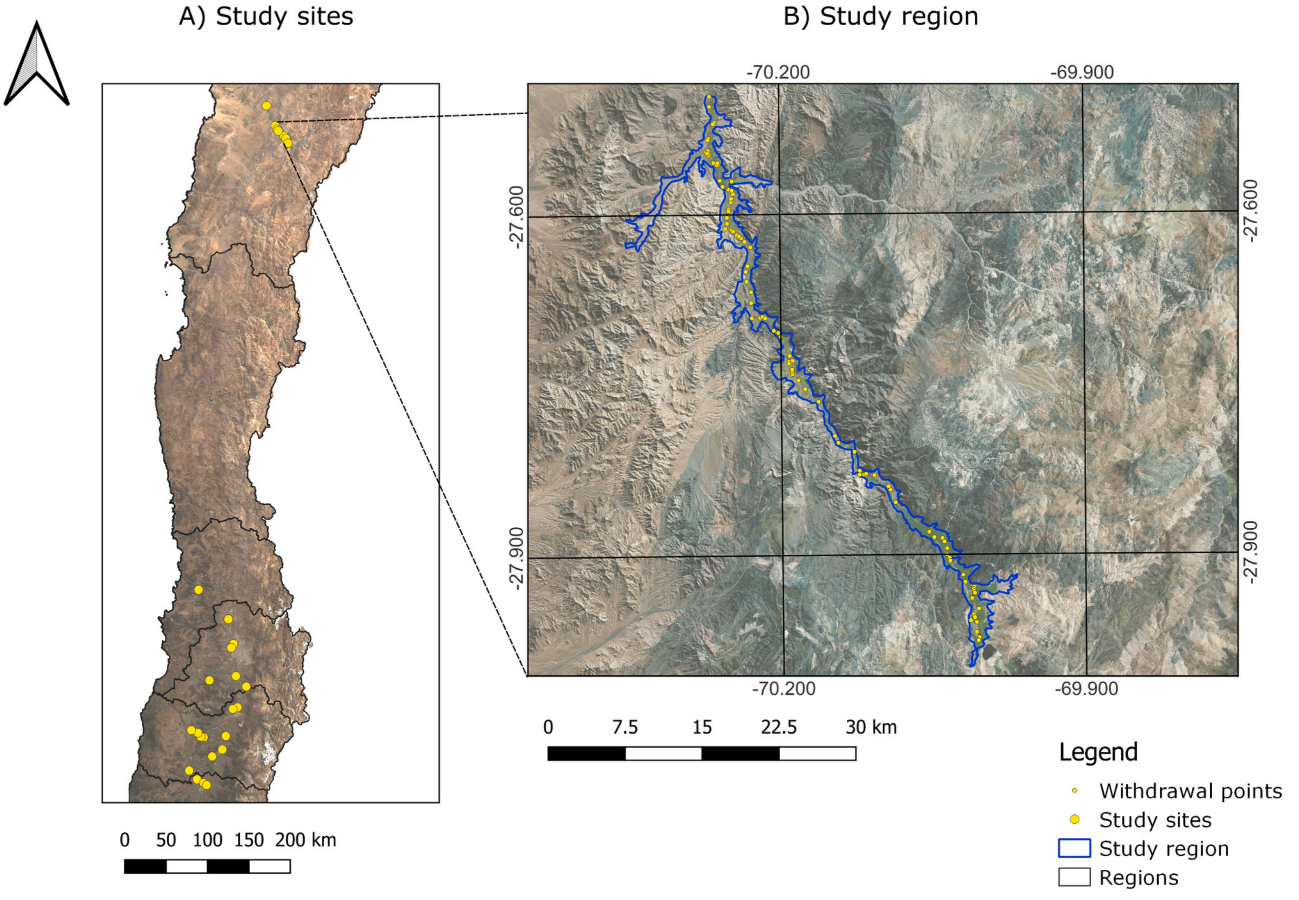

Fig. 5. Study site selection and spatial distribution.

sites and included along with the study site area, and antecedent AET and rainfall data (i.e., from the previous month) to develop a model for predicting withdrawal volumes. The dataset was first randomised and then split into test, training, and validation subsets, with proportions of 10%, 80%, and 10%, respectively (Hastie et al., 2009). Subsequently, a random forest model with 200 trees, a maximum depth of trees of 10, a minimum number of samples per leaf of 1, and a minimum number of samples to split a node of 2 was trained, since these parameters were found by optimising the model using a grid search of parameters.

The model was evaluated using a 10-fold cross validation approach (Fushiki, 2011). Using 10-fold cross validation, a 95% confidence interval was estimated with the random forest model to evaluate the range of predictions. Additionally, assuming the AET and rainfall data were correct, a field application efficiency for irrigation was calculated as the ratio between aggregated net irrigation requirements (AET minus rainfall, assuming all rainfall is stored into the soil) and aggregated withdrawals (Brouwer et al., 1989; Burt et al., 1997; Howell, 2003; Grabow et al., 2013). The trained model was compared to the regression between AET and water withdrawals to evaluate if models lead to better predictions, which may justify their use as auditing tools. Various metrics were assessed, and a Taylor diagram was used to visualise the results across different study sites.

Finally, we utilised two primary factors to detect unauthorised withdrawals, distinct from instances of over-extraction: the Euclidean distance to water rights and annual evapotranspiration. These factors were classified into five classes (values 1 to 5), considering both water accessibility and vegetation production (Table 1). This classification assumes that unauthorised withdrawals often occur in regions with large evapotranspiration paddocks, typically situated far from water right locations. The water authority enforces a maximum distance of 200 m between withdrawal locations and water rights. As the distance between these sources (water rights) and sinks (like irrigated crops) increases, transportation infrastructure costs for water escalate accordingly. Consequently, greater distances make it less likely for sinks to be irrigated by water rights, thereby increasing the probability of unauthorised withdrawals. By averaging these reclassified values and masking the result to agricultural land uses, we generated an “auditing priority” raster that also ranges from 1 to 5. This raster helps identify areas where governmental auditing priority is very low (class 1) and areas where potential unauthorised withdrawals require evaluation (class 5; very high auditing priority). In essence, this prioritisation attempt aids in efficiently allocating auditing resources where they are needed the most.

3. Results

3.1. Withdrawal control data and granted water rights

Only a small fraction of the filtered withdrawal monitoring dataset corresponds to surface water rights. Out of all the withdrawal points sharing their metering records, only 158 surface water rights were included, accounting for approximately 5.7% of the dataset. This indicates that the majority of water rights that publicly disclose their withdrawals are associated with groundwater (2621 groundwater monitoring devices being metered out). Fig. 6 illustrates the regional distribution of actual and granted withdrawal rates and their ratio for water rights publicly reporting their water extractions for the entire reporting time period.

Table 1
Criteria and classification used for detecting unauthorised water withdrawals.

Criteria	Class	Range	Rating
Distance to water rights (m)	very low	0–250	1
	low	250–500	2
	moderate	500–750	3
	high	750–1000	4
	very high	1000–inf	5
Annual evapotranspiration (mm)	very low	0–250	1
	low	250–500	2
	moderate	500–800	3
	high	800–1200	4
	very high	1200–inf	5

Median granted withdrawal rates generally increase southwards, likely due to an increase in water availability. However, in southern regions, only a few water rights are using meters to measure withdrawals (Fig. 3), which may result in larger data dispersion, particularly in regions XIV and XVI of Chile. In contrast, actual withdrawals show a different behaviour. When evaluating the ratio of actual to granted withdrawals, it generally decreases as we move southwards. The median ratio is significantly lower than the granted volumes, with an average actual-to-granted withdrawal ratio of approximately 0.2. However, locations where actual withdrawal rates exceed the granted withdrawal rates can be observed (actual to granted withdrawal ratio > 1), potentially triggering governmental inspections for compliance with the law.

Water metering and allocations lack user-specific usage details, despite prioritisation on drinking water, prompting the need for DGA record updates. By combining water withdrawal monitoring points with water rights information, it was possible to categorise the monitoring points based on their usage. This resulted in only 734 withdrawal monitoring points with information on water use types. The majority of monitoring points are categorised as “irrigation”, followed by “others” and “drinking” uses (Fig. 7). However, in terms of granted withdrawal rates, “hydropower” generation has the highest values. Other use types show similar granted withdrawal rates, with slightly higher values for “irrigation” (median of $27\ \mathrm{l\ s^{-1}}$) compared to “drinking” (median of $20.3\ \mathrm{l\ s^{-1}}$), “mining” (median of $22\ \mathrm{l\ s^{-1}}$), and “industrial” (median of $25\ \mathrm{l\ s^{-1}}$) uses. The scenario changes significantly when considering actual withdrawals, where values are in general significantly lower (median withdrawals of 6.1, 5.1, 2.6, and $2\ \mathrm{l\ s^{-1}}$ for “mining”, “drinking”, “irrigation”, and “industrial” use categories, respectively). While “hydropower” has the lowest actual to granted withdrawal ratio, this may be influenced by the small number of monitoring points associated with this use type. “Irrigation” and “industrial” use types also show relatively low actual to granted withdrawal ratios, with median actual withdrawals amounting to less than 20% of the granted withdrawals. As expected, “mining” activities result in the highest extraction of granted water withdrawals, followed by the “drinking” use type.

Different seasons also influence withdrawal patterns. Fig. 8 displays the distribution of actual-to-granted withdrawal ratios from monitoring points by season (left panel). The data indicates a generally higher extraction, approximately 25% of the granted withdrawal rates, during summer and spring, while these values drop to about 15% during autumn and winter seasons. Seasonal behaviour based on water use types is also visible in the boxplots of the right panel. “Irrigation” and “others” uses exhibit a similar pattern of higher withdrawals during spring and summer seasons. On the other hand, “mining” shows less seasonality. The prevalence of “irrigation” and “others” use types in the available monitoring points may contribute to the overall similarity among different use types (left panel).

3.2. Withdrawal monitoring applications

3.2.1. Study sites

The relationships between monthly AET and water withdrawals vary across the study sites (Fig. 9). While some sites show a close relationship in terms of seasonal variability and absolute volumes, others indicate significant divergence. In several cases, withdrawals exceed AET volumes, which may be caused by irrigation application efficiencies, but the opposite can also be observed.

The relationship between withdrawals and evapotranspiration (Fig. 10A) yields an R^2 value of 0.33 and a CCC of 0.74. However, the random forest model improves the R^2 to 0.64 and the CCC to 0.79.

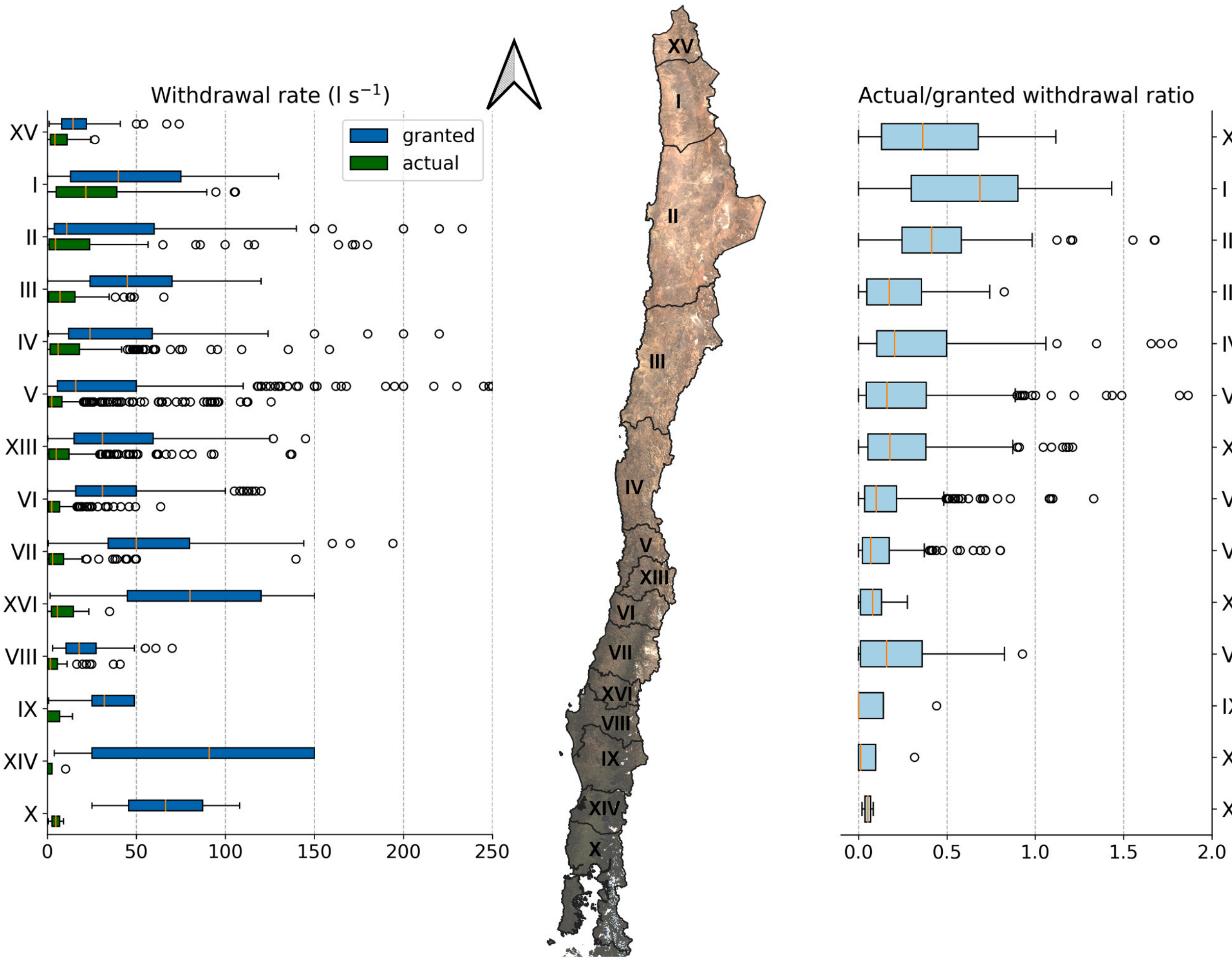

Fig. 6. Actual and granted withdrawals rates (left) and its ratio (right) by region.

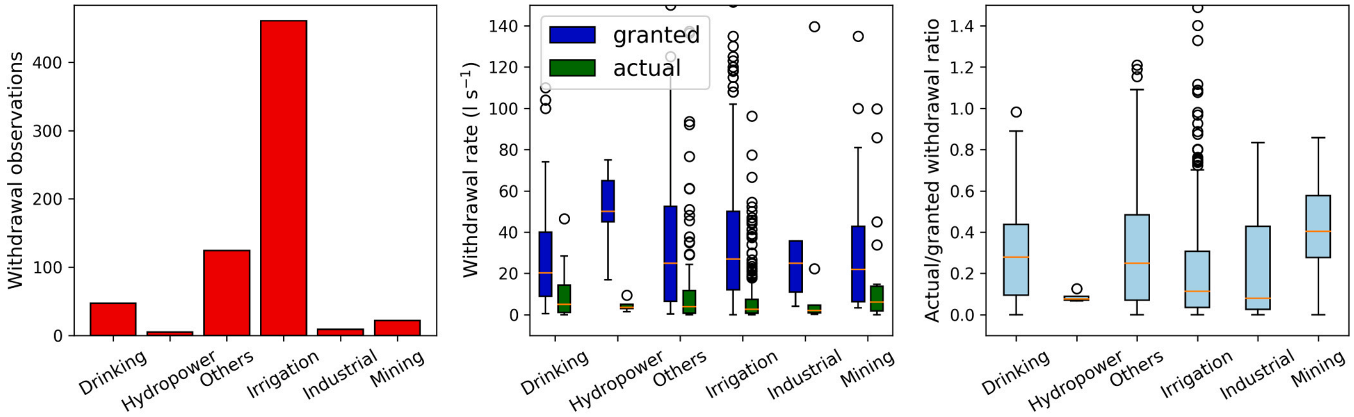

Fig. 7. Number of withdrawal monitoring points filtered by use type (left). Granted and actual withdrawal rate distributions (middle), and actual to granted withdrawal ratio distributions (right) by use type are also depicted.

Despite the improvement in R^2, the errors remain similar (RMSE ~ 0.017 MCM; Fig. 10B). Performance differences among sites are evident between the two approaches (Fig. 10C). The random forest model reduces intra-site errors but also decreases the correlation within study sites, which is compensated when evaluating the R^2 across sites.

Two example cases illustrate the potential use of combining water metering with remote sensing for water auditing (Fig. 11). Example A shows the calculation of application efficiency, dividing the net irrigation requirement (AET minus rainfall) by the withdrawal volumes at different locations. The median application efficiency is approximately 80%. However, variations across sites are clear, which might be attributed to differences in irrigation practices (Brouwer et al., 1989). Application efficiencies exceeding 100% may warrant investigation by a decision maker or government agency, as they indicate lack of closure of the water balance. Furthermore, investigating field application efficiency can help target financial support for irrigation technologies for

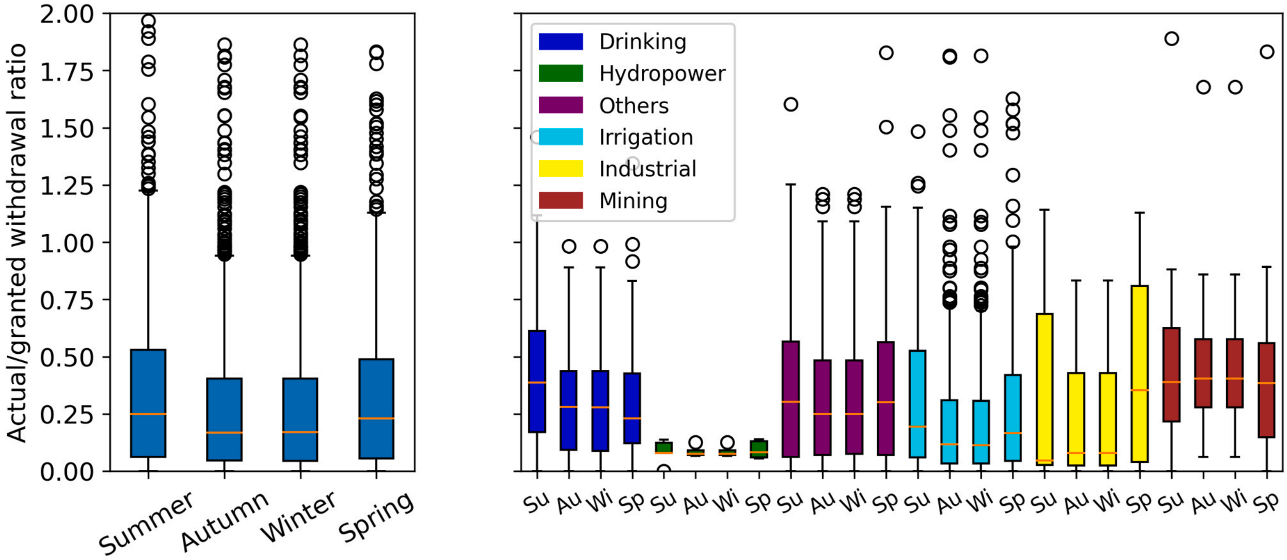

Fig. 8. Seasonal use distributions as actual - granted withdrawal ratios for all withdrawal points (left) and filtered by use type (right). Su, Au, Wi, and Sp are abbreviations for Summer, Autumn, Winter, and Spring seasons, respectively.

specific users or regions.

Example B in Fig. 11 illustrates the potential for auditing paddocks where withdrawal records consistently exceed the confidence interval of predictions derived from the trained model. This analysis can be extended to all study sites (refer to Figure S3 from Supplementary materials). In this study, with the exception of the site linked to the third plot in the middle column panel of Figure S3, which may be worth inspecting, no sites consistently and significantly exceeded the model's predictions.

3.2.2. Aggregated scale

In the Supplementary materials (Figure S4), two zoomed-in areas within the selected AOI can be observed, showcasing the spatial distribution of AET. The seasonal pattern of AET is clearly observed, primarily influenced by crops and vegetation present in the area. The spatial variation in AET is primarily attributed to the presence or absence of vegetation, with areas lacking vegetation indicating very low AET values due to the sparse vegetation cover and limited available water for evaporation from the soils given the arid climate conditions from the AOI.

The comparison between lumped (summed) AET and recorded withdrawal volumes can be found in the Supplementary materials (Figure S5), while the monthly distribution of AET pixels and withdrawals within the AOI are in Figure S6. The seasonal pattern of AET is once again confirmed, with a peak of about 7 MCM month^{-1} during summer and a minimum below 1 MCM month^{-1} during winter. Withdrawals indicate a similar seasonal pattern but show an increasing trend and increasing variability. The decreasing divergence between AET and withdrawals may be explained by the inclusion of monitored withdrawal points over time (Figure S5 left). However, this appears to stabilise between 2020 and 2021, suggesting that withdrawal volumes are approaching lumped AET values. In fact, it is possible that withdrawals might even exceed AET in the future, considering that the AOI contains other uses than irrigation.

3.2.3. Unauthorised withdrawals

Two zoomed-in areas with water auditing priority classes and different factors reclassified are in Fig. 12. Small areas with very high auditing priority can be observed in both regions characterised by agricultural land uses with a large distance to water rights and a high annual evapotranspiration.

Additionally, Table 2 displays the distribution of various auditing priority classes within the agricultural lands of the study area. A very small portion of the evaluated land falls under the category of "very high auditing priority", with no occurrences in the northern region (Landsat row/column tile: 001/079). However, agricultural lands identified with a high auditing priority constitute a notable 30% of the evaluated agricultural lands.

This simple approach may help targeting areas where water demand may accuse unauthorised water withdrawals. However, water right information needs to be updated since a non-negligible fraction of them contain known physical references but not geographical coordinates, which may obscure the results.

4. Discussion

Water governance should rest on information gathered through water monitoring programs that may enhance our comprehension of water availability to achieve sustainability (UN Water, 2016). Having specific quantifiable knowledge about water withdrawals is essential for effective allocation of resources to balance different needs (Figure S7 from Supplementary materials), and may be further supported by water resources modelling, which plays a vital role in facilitating effective monitoring and decision making (Beven and Alcock, 2012). While water metering has been implemented as a key strategy in different countries (Arlosoroff et al., 2002; Holley and Sinclair, 2013; Koech et al., 2018; Pott et al., 2009), regulations may vary among them (Bjornlund and McKay, 2002), resulting in differences in potential applications. However, few studies have explored the potentials of water metering beyond billing purposes. One study highlighted the potential of water metering as an important aspect of integrated water management and conservation in Australia (Koech et al., 2018), albeit it constitutes a review. To the best of our knowledge, this is the first study that leverages information from a national metering network to identify real-world applications that can enhance our understanding of water and serve as tools for water governance. It is commonly observed across countries that different actors are responsible for metering water, depending on its intended use. For instance, in Israel, where water is owned by the state, water metering is carried out by various stakeholders, including the Water Authority, Mekorot (a national water company), local water corporations, municipalities, and water users themselves (Becker, 2015). In Chile, where water rights have been granted to users, drinking water in urban areas is primarily metered by sanitation companies and municipalities (Ferro and Mercadier, 2016), while other water uses are

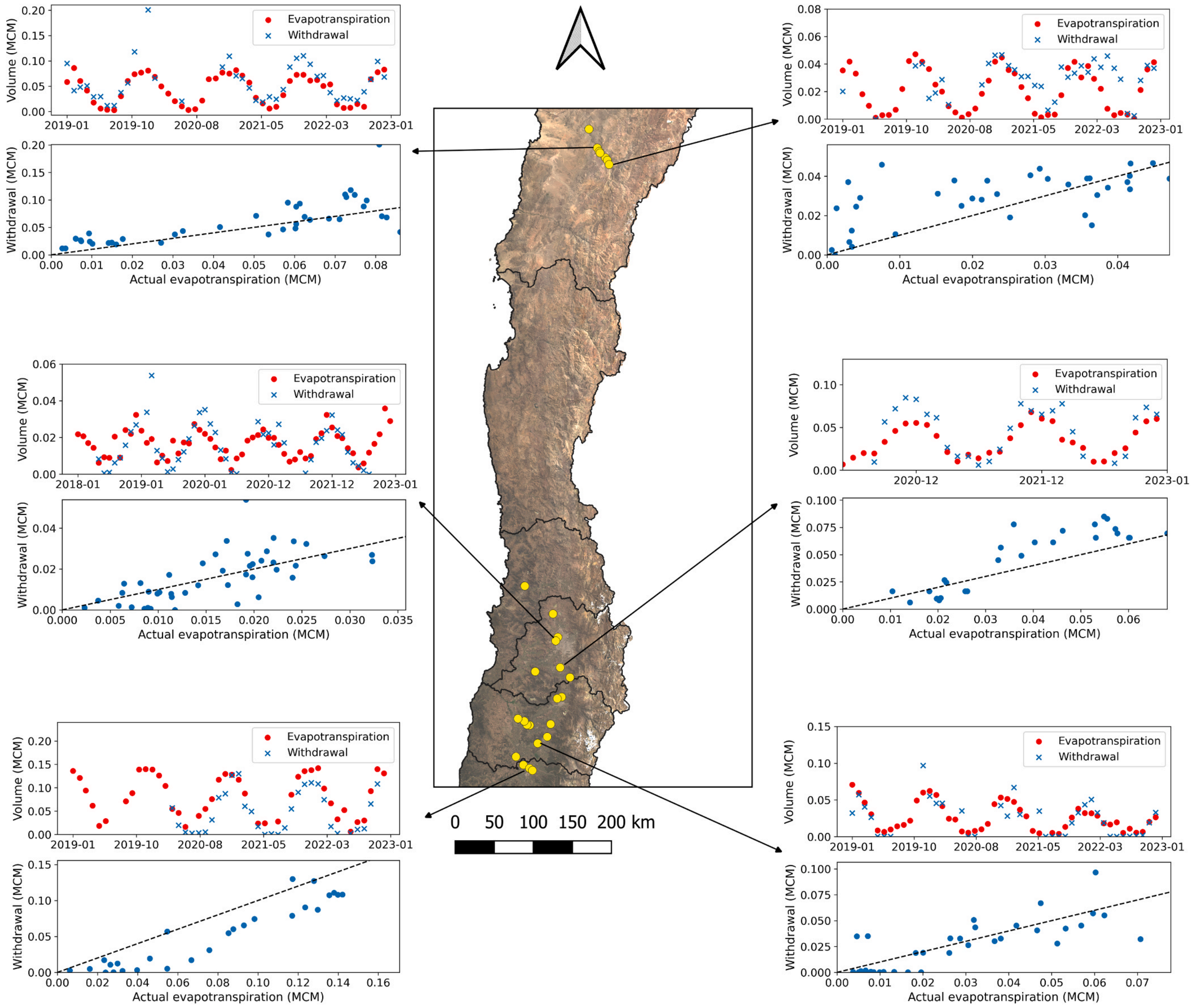

Fig. 9. Examples of study site withdrawals and their relationship with AET.

now required to be metered by the actual users. This may demonstrate how effective water governance involves the collaboration of different parties.

Some studies have reported over-granting of water resources in catchments in Chile, while others have highlighted a strong decrease in water availability (Novoa et al., 2019; Fuentes et al., 2021a). Additionally, there are concerns about the current water allocations being unsustainable (Alvarez-Garreton et al., 2023). Similarly, water over-allocation has been reported in other regions across the world (Syme and Nancarrow, 2006; Bates et al., 2010; Grantham and Viers, 2014; Challies et al., 2022). Interestingly, the available information on water use in Chile thus far indicates that withdrawals are significantly lower than allocations for most water rights. Some cases of overuse might currently be penalised, but there is also uncertainty regarding the accuracy of disclosed extractions versus actual extractions. Differences in water withdrawals can be observed based on geographic locations and use categories. Given that only a small fraction of water rights are currently being metered, the question of how much water from allocations is actually being extracted remains unanswered. In our analysis, we found that between one-fifth to one-fourth of the granted withdrawal rates are utilised according to the reported withdrawals, yet extrapolating this to the entire set of granted water rights introduces a significant degree of uncertainty. However, these findings align with those reported at the state level in California (United States) by Grantham and Viers (2014), revealing that allocations for surface waters are five times larger than withdrawals, although in specific counties, withdrawals may exceed allocations. These preliminary results underscore the need to investigate unauthorised water withdrawals in order to comprehend current trends in water resources. Consistent with this finding, Sangha and Shortridge (2023) highlighted unreported withdrawals in Virginia (United States), estimating that unreported withdrawals averaged 13% and 110% of reported withdrawals for small and large farms, respectively. Furthermore, this study shows that using remote sensing AET and water rights data may help in prioritising the auditing of paddocks for potential unauthorised withdrawal evaluation.

Remotely sensed estimates of AET should be considered as a reference for contrasting water withdrawals, but not as ground truth observations. Several studies have evaluated the performance of remote sensing AET models and found that they can differ significantly from actual water fluxes (Elnashar et al., 2021; Fuentes et al., 2024; Salazar-Martínez et al., 2022). However, METRIC AET has been reported to perform well for agriculture (Madugundu et al., 2017; Ortega-Salazar et al., 2021). Furthermore, different studies have attempted to estimate water withdrawals using remote sensing data, some using AET

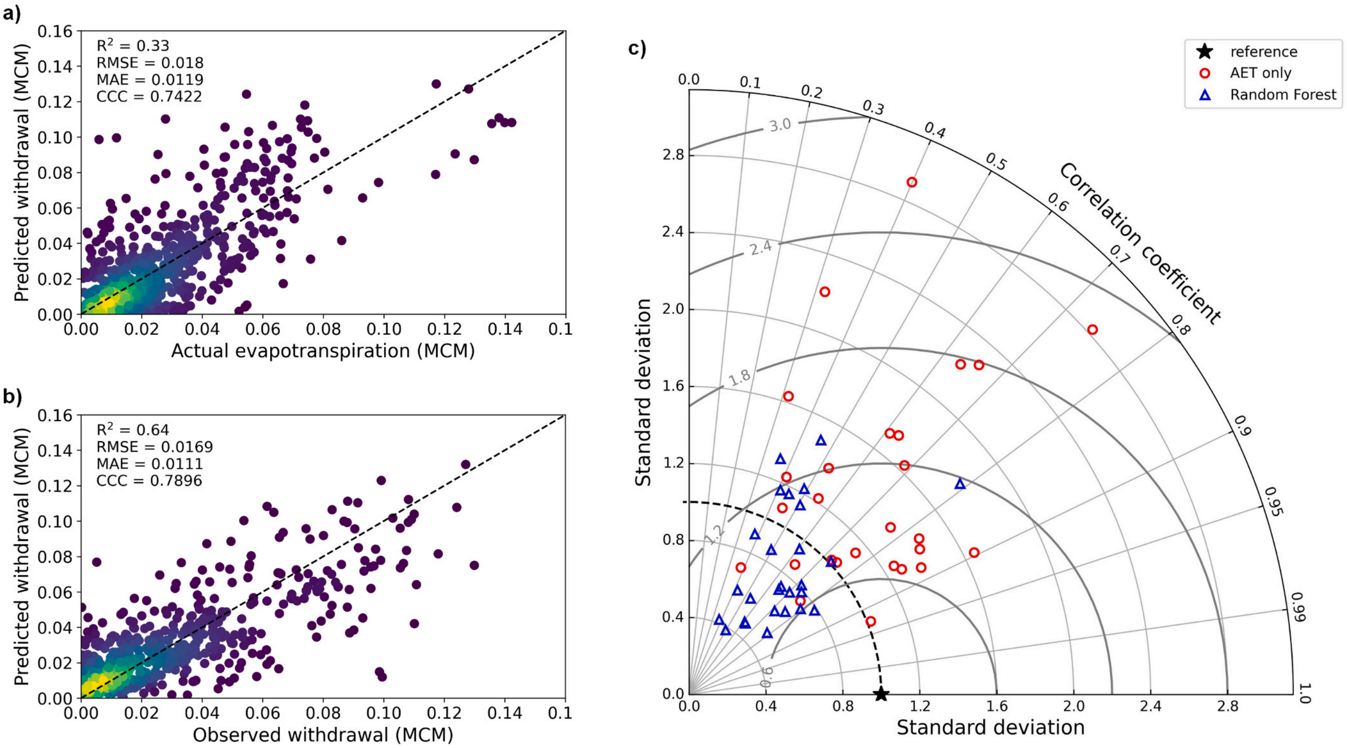

Fig. 10. Density scatterplots depicting the relationship between evapotranspiration and withdrawals (a) and the performance of a random forest model trained for withdrawal prediction (b) in all study sites. A Taylor diagram showing the differences in performance between study sites is also shown for both approaches (c). RMSE and MAE are calculated in MCM.

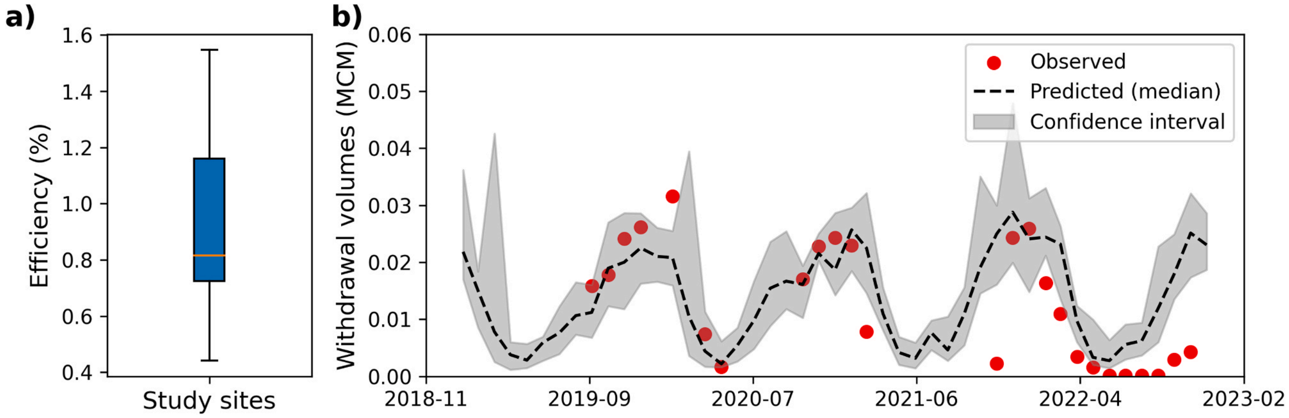

Fig. 11. Boxplot of water application efficiencies across study sites (a) and time series with a 95% confidence interval of the random forest model for a particular study site (b).

estimations (Toureiro et al., 2017; Droogers et al., 2010), and others utilising soil moisture estimates (Jalilvand et al., 2019; Dari et al., 2020), with varying levels of accuracy. In our study, we demonstrate that remote sensing AET and rainfall can be used as predictors to calculate withdrawals, but prediction uncertainties must be considered. This approach is based on an R^2 of approximately 0.6, with non-negligible errors (RMSE ranging between 163 and 1320 m^3 ha^{-1} $month^{-1}$, with a median RMSE of 372 m^3 ha^{-1} $month^{-1}$ across the study sites). This indicates that factors other than meteorological variables, such as water management and irrigation techniques, strongly influence water withdrawals and irrigation efficiency (Brouwer et al., 1989). Consequently, the current estimates must be interpreted with caution, and uncertainty ranges should be considered for any real-life applications. In this regard, this study aligns with the findings of Foster et al. (2020) who reported significant uncertainties when comparing water use estimates derived from remote sensing AET with in-situ irrigation data at different scales. Such uncertainties could have adverse effects on the economy and policies. However, increasing the number of monitoring points and improving the delineation of property boundaries may help capture a wide range of variability and enhance the predictive ability of models.

While this study explored potential applications related to improved water metering based on the Chilean context, its methodology and findings hold broader implications for global water governance, particularly in regions experiencing similar challenges in water resource management. These applications could be replicated in other regions where water rights or licences, along with metering data, are available. One notable example is the United States, where water stresses in multiple states are shifting the water balance focus towards the demand side (Tidwell et al., 2014; Marston et al., 2022). Additionally, in regions

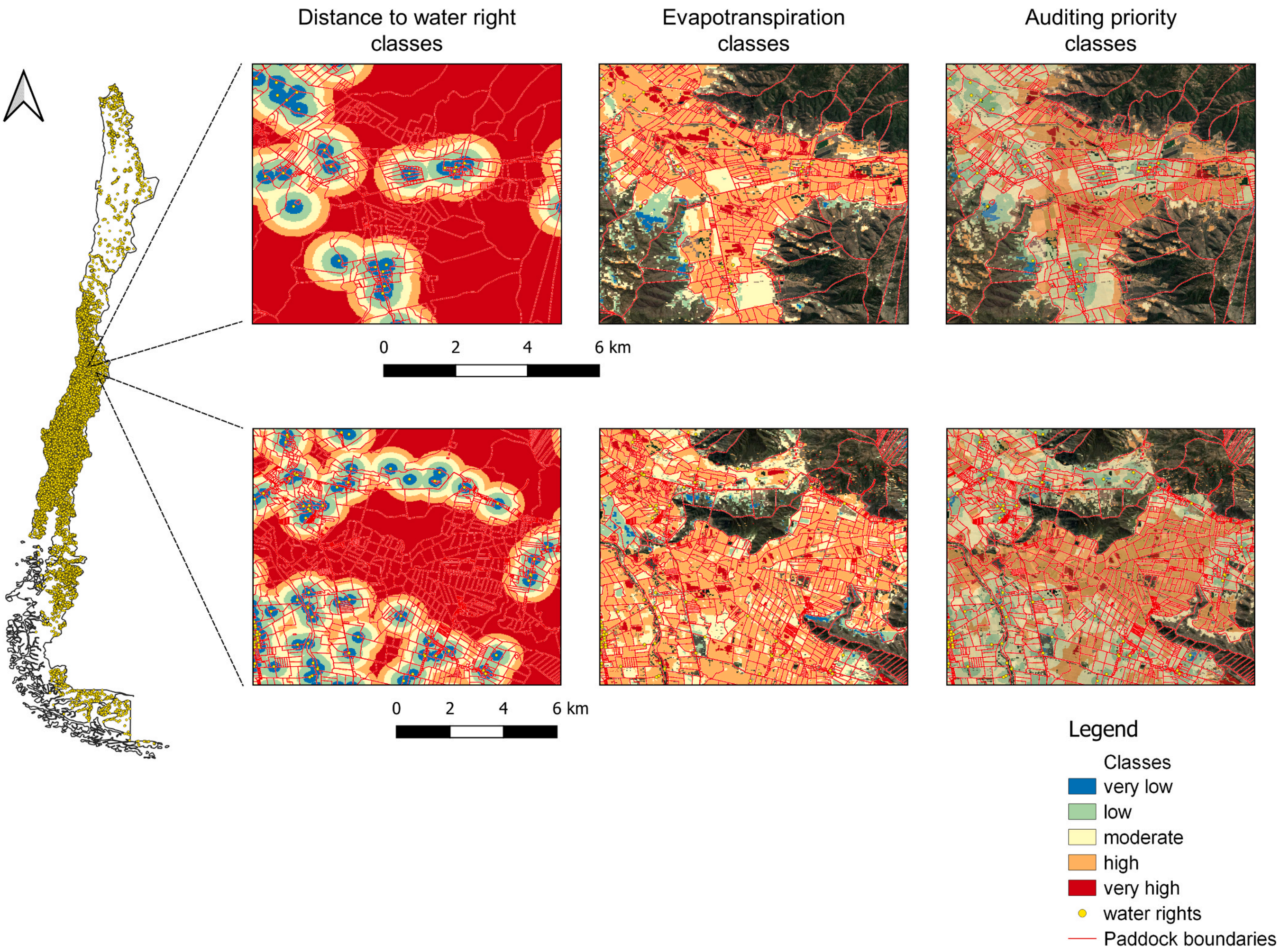

Fig. 12. Zoomed-in regions of reclassified factors (distance to water rights and evapotranspiration) used for mapping water auditing priority classes.

Table 2
Surface distribution (%) associated with auditing priority classes in agricultural lands.

Auditing priority Class	Surface (%)
very low	3.5
low	25.5
moderate	40.1
high	29.8
very high	1.1

like certain states in Australia, where water metering is being encouraged, these applications may shed light on discrepancies between actual and expected river flows, influencing policy decisions (Williams and Grafton, 2019). At the field scale, coupling water use reports with remotely sensed AET estimates can support water withdrawal reports. Combined with modelling, this could serve as a potential accounting tool (Vervoort et al., 2022). Calculating field application efficiencies could enable governments to compare water withdrawal reports and allocate resources more effectively. Additionally, supplementing these efficiencies with water balance calculations could significantly enhance the current limited understanding of distribution efficiencies in rural areas. Other user applications could involve monitoring water demand to schedule irrigation, ensuring a timely meeting of water requirements, thereby enhancing water use efficiency and management practices. However, achieving this would require field monitoring devices for calibration and more frequent image acquisition, which could be facilitated by harmonising Sentinel and Landsat surface reflectance data (Claverie et al., 2018). At a larger scale, water withdrawals could be used to close the water balance and quantify different components, enabling a balanced consideration of societal needs and prioritisation of uses.

Several deficiencies in the Chilean water withdrawal monitoring program need to be addressed. The most obvious one is the need to expand the metering network and providing policy instruments that may encourage water users to comply with regulations (Figureau et al., 2015). Gathering additional information on water withdrawals, including use categories and irrigation extents, could enhance the program's applicability and enable auditing of water withdrawal reports. Furthermore, data quality issues must be addressed. Considering the existing deficiencies in the current water governance, the water metering program should be integrated with the water monitoring network of government institutions and its compliance might be fostered either by punitive actions or through incentives to stakeholders (Valdés-Pineda et al., 2014).

One of the challenges of water governance is related to institutional and financial gaps that may lead to inequities in water access among users and impairing environmental functioning (World Health Organization, 2014; Muñoz et al., 2020; Aitken et al., 2016). Addressing these gaps requires prior knowledge of water availability and withdrawals (UN Water, 2016). In this regard, the implementation of metering networks represent a step forward in establishing appropriate frameworks where different needs can be democratically agreed upon through governmental institutions and society organisations. However, further research is needed to evaluate the current implementation of the water metering program in Chile, as it is still in its early stages and undergoing progress.

5. Conclusions

Effective water governance requires the quantification of water resources availability and withdrawals to enable informed decision-making by stakeholders. Consequently, water monitoring and metering networks are being implemented as part of water governance schemes in different regions. In line with this, a water withdrawal monitoring program is currently being implemented in Chile, where water users are required to disclose their withdrawals. Here, we reveal significant disparities between water withdrawals and allocated water rights. Reported withdrawals represent one fifth to one fourth of water allocations, with variations across different regions and water use types. Additionally, the potential of combining remote sensing data and agricultural withdrawal reports as an auditing tool is underscored through the comparison of reported withdrawals with modeling at the field scale. While remote sensing actual evapotranspiration correlates moderately with agricultural withdrawals, stochastic models incorporating other meteorological variables may improve predictive accuracy. Furthermore, at a larger scale, withdrawals can aid in calculating the different components of the water balance. Integrating water metering networks with remote sensing estimates and incorporating them into governance schemes may be applied in different regions experiencing water scarcity risk across the world, and lead to various applications that may enhance water security and sustainability. However, these applications necessitate the quantification of uncertainty associated with model predictions, particularly when addressing water accounting for auditing purposes.

Code availability

Code associated with this project will be available in the following repository: https://github.com/IFuentesSR/water_accounting.

CRediT authorship contribution statement

Fuentes Ignacio: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Vervoort R.Willem:** Methodology, Supervision, Writing – review & editing. **McPhee James:** Investigation, Methodology, Supervision, Writing – review & editing. **Reyes Rojas Luis A:** Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ignacio Fuentes reports financial support was provided by National Agency for Research and Development. Ignacio Fuentes reports a relationship with National Agency for Research and Development that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data is publically available, and datasources have been identified in the manuscript.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108676.

References

Aitken, D., Rivera, D., Godoy-Faúndez, A., Holzapfel, E., 2016. Water scarcity and the impact of the mining and agricultural sectors in chile. Sustainability 8 (2), 128.

Allen, R.G., Tasumi, M., Trezza, R., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (metric)—model. J. Irrig. Drain. Eng. 133 (4), 380–394.

Alvarez-Garreton, C., Boisier, J.P., Billi, M., Lefort, I., Marinao, R., Barría, P., 2023. Protecting environmental flows to achieve long-term water security. J. Environ. Manag. 328, 116914.

Araya-Osses, D., Casanueva, A., Román-Figueroa, C., Uribe, J.M., Paneque, M., 2020. Climate Change projections of temperature and precipitation in chile based on statistical downscaling. Clim. Dyn. 54, 4309–4330.

Arlosoroff, S. et al. (2002). Integrated approach for efficient water use case study: Israel. In: World Food Prize Symposium: "From the Middle East to the Middle West": Managing Freshwater Shortages and Regional Water Security, 24–25.

Baer, M., 2014. Private water, public good: water privatization and state capacity in chile. Stud. Comp. Int. Dev. 49, 141–167.

Bakker, K., 2010. Privatizing water: governance failure and the world's urban water crisis. Cornell University Press.

Bates, B.C., Walker, K., Beare, S., Page, S., 2010. Incorporating Climate Change in water allocation planning. Water Rep. Ser. 28, 196–198.

Bauer, C.J., 1997. Bringing water markets down to earth: the political economy of water rights in chile, 1976–1995. World Dev. 25 (5), 639–656.

Bauer, C.J., 2004. Results of chilean water markets: empirical research since 1990. Water Resour. Res. 40, 9.

Becker, N., 2015. Water pricing in israel: various waters, various neighbors. Water Pricing Exp. Innov. 181–199.

Beven, K.J., Alcock, R.E., 2012. Modelling everything everywhere: a new approach to decision-making for water management under uncertainty. Freshw. Biol. 57, 124–132.

Biblioteca del Congreso Nacional de Chile (2016). Ley no21.064: Control de extracciones de derechos de aprovechamiento de aguas.⟨https://www.leychile.cl/Navegar?idNorma=1108083⟩.

Bjornlund, H., McKay, J., 2002. Aspects of water markets for developing countries: experiences from australia, chile, and the us. Environ. Dev. Econ. 7 (4), 769–795.

Boisier, J.P., Rondanelli, R., Garreaud, R.D., Muñoz, F., 2017. Anthropogenic and natural contributions to the southeast pacific precipitation decline and recent megadrought in central chile. Clim. Dyn. 49 (1-2), 103–122.

Bozkurt, D., Rojas, M., Boisier, J.P., Valdivieso, J., 2018. Projected hydroclimate changes over andean basins in central chile from downscaled cmip5 models under the low and high emission scenarios. Clim. Change 150, 131–147.

Brouwer, C., Prins, K., and Heibloem, M. (1989). Irrigation water management: irrigation scheduling, fao.Water Resources, Development and Management Service Land and Water Development Division.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. 123 (6), 423–442.

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the earth system exceeding planetary boundaries. Ecol. Soc. 22, 4.

Challies, E., Fragaszy, S., and Rouillard, J. (2022). Water allocation in aotearoa new zealand: societal values and ecological bottom lines.

Claverie, M., Ju, J., Masek, J.G., Dungan, J.L., Vermote, E.F., Roger, J.-C., Skakun, S.V., Justice, C., 2018. The harmonized landsat and sentinel-2 surface reflectance data set. Remote Sens. Environ. 219, 145–161.

Cook, C., Bakker, K., 2012. Water security: Debating an emerging paradigm. Glob. Environ. Change 22 (1), 94–102.

Correa-Parra, J., Vergara-Perucich, J.F., Aguirre-Nuñez, C., 2020. Water privatization and inequality: Gini coefficient for water resources in chile. Water 12 (12), 3369.

Dari, J., Brocca, L., Quintana-Seguí, P., Escorihuela, M.J., Stefan, V., Morbidelli, R., 2020. Exploiting high-resolution remote sensing soil moisture to estimate irrigation water amounts over a mediterranean region. Remote Sens. 12 (16), 2593.

Davis, J., O'Grady, A.P., Dale, A., Arthington, A.H., Gell, P.A., Driver, P.D., Bond, N., Casanova, M., Finlayson, M., Watts, R.J., et al., 2015. When trends intersect: the challenge of protecting freshwater ecosystems under multiple land use and hydrological intensification scenarios. Sci. Total Environ. 534, 65–78.

Dinar, S., Katz, D., De Stefano, L., Blankespoor, B., 2015. Climate Change, conflict, and cooperation: global analysis of the effectiveness of international river treaties in addressing water variability. Political Geogr. 45, 55–66.

Döll, P., 2002. Impact of climate change and variability on irrigation requirements: a global perspective. Clim. Change 54 (3), 269–293.

Döll, P., Fritsche, M., Eicker, A., MüllerSchmied, H., 2014. Seasonal water storage variations as impacted by water abstractions: comparing the output of a global hydrological model with grace and gps observations. Surv. Geophys. 35, 1311–1331.

Donoso, G. (2014). Integrated water management in chile.Integrated water resources management in the 21st century: revisiting the paradigm, 217–233.

Donoso, G., Lictevout, E., and Rinaudo, J.-D. (2020). Groundwater management lessons from chile.Sustainable groundwater management: a comparative analysis of French and Australian policies and implications to other countries, 481–509.

Droogers, P., Immerzeel, W., Lorite, I., 2010. Estimating actual irrigation application by remotely sensed evapotranspiration observations. Agric. Water Manag. 97 (9), 1351–1359.

Elnashar, A., Wang, L., Wu, B., Zhu, W., Zeng, H., 2021. Synthesis of global actual evapotranspiration from 1982 to 2019. Earth Syst. Sci. Data 13 (2), 447–480.

Falkenmark, M., Folke, C., 2002. The ethics of socio-ecohydrological catchment management: towards hydrosolidarity. Hydrol. Earth Syst. Sci. 6 (1), 1–10.

FAO (2020). Aquastat: FAO's global information system on water and agriculture.

Ferro, G., Mercadier, A.C., 2016. Technical efficiency in chile's water and sanitation providers. Uti. Policy 43, 97–106.

Figureau, A.-G., Montginoul, M., Rinaudo, J.-D., 2015. Policy instruments for decentralized management of agricultural groundwater abstraction: a participatory evaluation. Ecol. Econ. 119, 147–157.

Foga, S., Scaramuzza, P., Guo, S., Zhu, Z., Dilley Jr, R.D., Beckmann, T., Schmidt, G., Dwyer, J., Hughes, M., Laue, B., 2017. Cloud detection algorithm comparison and validation for operational landsat data products. In: Remote Sensing of Environment, 194, pp. 379–390.

Foster, T., Mieno, T., Brozović, N., 2020. Satellite-based monitoring of irrigation water use: Assessing measurement errors and their implications for agricultural water management policy. Water Resour. Res. 56 (11), e2020WR028378.

Fuentes, I., Padarian, J., Van Ogtrop, F., Vervoort, R.W., 2019. Spatiotemporal evaluation of inundated areas using modis imagery at a catchment scale. J. Hydrol. 573, 952–963.

Fuentes, I., Fuster, R., Avilés, D., Vervoort, W., 2021a. Water scarcity in central chile: the effect of climate and land cover changes on hydrologic resources. Hydrol. Sci. J. 66 (6), 1028–1044.

Fuentes, I., Scalzo, R., Vervoort, R.W., 2021b. Volume and uncertainty estimates of on-farm reservoirs using surface reflectance and lidar data. Environ. Model. Softw. 143, 105095.

Fuentes, I., Padarian, J., Vervoort, R.W., 2022. Towards near real-time national-scale soil water content monitoring using data fusion as a downscaling alternative. J. Hydrol. 609, 127705.

Fuentes, I., Vervoort, R.W., McPhee, J., 2024. Global evapotranspiration models and their performance at different spatial scales: contrasting a latitudinal gradient against global catchments. J. Hydrol. 628, 130477.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., et al., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. data 2 (1), 1–21.

Fushiki, T., 2011. Estimation of prediction error by using k-fold cross-validation. Stat. Comput. 21, 137–146.

Garreaud, R.D., Alvarez-Garreton, C., Barichivich, J., Boisier, J.P., Christie, D., Galleguillos, M., LeQuesne, C., McPhee, J., Zambrano-Bigiarini, M., 2017. The 2010–2015 megadrought in central chile: Impacts on regional hydroclimate and vegetation. Hydrol. earth Syst. Sci. 21 (12), 6307–6327.

Grabow, G., Ghali, I., Huffman, R., Miller, G., Bowman, D., Vasanth, A., 2013. Water application efficiency and adequacy of et-based and soil moisture–based irrigation controllers for turfgrass irrigation. J. Irrig. Drain. Eng. 139 (2), 113–123.

Grantham, T.E., Viers, J.H., 2014. 100 years of california's water rights system: patterns, trends and uncertainty. Environ. Res. Lett. 9 (8), 084012.

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S., et al., 2018. Global assessment of water challenges under uncertainty in water scarcity projections. Nat. Sustain. 1 (9), 486–494.

Hastie, T., Tibshirani, R., Friedman, J.H., Friedman, J.H., 2009. The elements of statistical learning: data mining, inference, and prediction. volume 2. Springer.

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour. Manag. 21, 35–48.

Holley, C., Sinclair, D., 2013. Non-urban water metering policy: Water users' views on metering and metering upgrades in new south wales, australia. Australas. J. Nat. Resour. Law Policy 16 (2), 101–131.

Howell, T.A., 2003. Irrigation efficiency. Encycl. Water Sci. 467, 500.

Jalilvand, E., Tajrishy, M., Hashemi, S.A.G.Z., Brocca, L., 2019. Quantification of irrigation water using remote sensing of soil moisture in a semi-arid region. Remote Sens. Environ. 231, 111226.

Jiménez, A., Saikia, P., Giné, R., Avello, P., Leten, J., LissLymer, B., Schneider, K., Ward, R., 2020. Unpacking water governance: a framework for practitioners. Water 12 (3), 827.

Kang, S., Hao, X., Du, T., Tong, L., Su, X., Lu, H., Li, X., Huo, Z., Li, S., Ding, R., 2017. Improving agricultural water productivity to ensure food security in china under changing environment: from research to practice. Agric. Water Manag. 179, 5–17.

Khaki, M. and Mortazavi, N. (2022). Water consumption demand pattern analysis using uncertain smart water meter data.

Koech, R., Gyasi-Agyei, Y., Randall, T., 2018. The evolution of urban water metering and conservation in australia. Flow. Meas. Instrum. 62, 19–26.

Larrain, S., 2012. Human rights and market rules in chile's water conflicts: a call for structural changes in water policy. Environ. Justice 5 (2), 82–88.

Lautze, J., Manthrithilake, H., 2012. Water security: old concepts, new package, what value? volume 36 Natural resources forum. Wiley Online Library, pp. 76–87. volume 36.

Long, D., Longuevergne, L., Scanlon, B.R., 2015. Global analysis of approaches for deriving total water storage changes from grace satellites. Water Resour. Res. 51 (4), 2574–2594.

Madugundu, R., Al-Gaadi, K.A., Tola, E., Hassaballa, A.A., Patil, V.C., 2017. Performance of the metric model in estimating evapotranspiration fluxes over an irrigated field in saudi arabia using landsat-8 images. Hydrol. Earth Syst. Sci. 21 (12), 6135–6151.

Marston, L.T., Abdallah, A.M., Bagstad, K.J., Dickson, K., Glynn, P., Larsen, S.G., Melton, F.S., Onda, K., Painter, J.A., Prairie, J., et al., 2022. Water-use data in the united states: Challenges and future directions. JAWRA J. Am. Water Resour. Assoc. 58 (4), 485–495.

Mu, Q., Zhao, M., Running, S.W., 2011. Improvements to a modis global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115 (8), 1781–1800.

Mudumbe, M.J. and Abu-Mahfouz, A.M. (2015). Smart water meter system for user-centric consumption measurement.In: 2015 IEEE 13th international conference on industrial informatics (INDIN), 993–998.IEEE.

Muñoz, A.A., Klock-Barría, K., Alvarez-Garreton, C., Aguilera-Betti, I., González-Reyes, Á., Lastra, J.A., Chávez, R.O., Barría, P., Christie, D., Rojas-Badilla, M., et al., 2020. Water crisis in petorca basin, chile: The combined effects of a mega-drought and water management. Water 12 (3), 648.

Novoa, V., Ahumada-Rudolph, R., Rojas, O., Munizaga, J., Sáez, K., Arumí, J.L., 2019. Sustainability assessment of the agricultural water footprint in the cachapoal river basin, chile. Ecol. Indic. 98, 19–28.

Ortega-Salazar, S., Ortega-Farías, S., Kilic, A., Allen, R., 2021. Performance of the metric model for mapping energy balance components and actual evapotranspiration over a superintensive drip-irrigated olive orchard. Agric. Water Manag. 251, 106861.

Pott, A., Hallowes, J., Backeberg, G., Döckel, M., 2009. The challenge of water conservation and water demand management for irrigated agriculture in south africa. Water Int. 34 (3), 313–324.

Prieto, M., Fragkou, M.C., Calderón, M., 2020. Water policy and management in chile. Encyclopedia of water: science, technology, and society. Wiley-Blackwell, Hoboken, pp. 2–589.

Prieto, M., Calderón-Seguel, M., Fragkou, M.C., Fuster, R., 2022. The (not-so-free) chilean water model. the case of the antofagasta region, atacama desert, chile. Extr. Ind. Soc. 11, 101081.

Rahaman, M.M., Varis, O., 2005. Integrated water resources management: evolution, prospects and future challenges. Sustain.: Sci., Pract. Policy 1 (1), 15–21.

Rogers, P., Hall, A.W., 2003. Effective water governance. volume 7. Global water partnership Stockholm.

Salazar-Martínez, D., Holwerda, F., Holmes, T.R., Yépez, E.A., Hain, C.R., Alvarado-Barrientos, S., Ángeles-Pérez, G., Arredondo-Moreno, T., Delgado-Balbuena, J., Figueroa-Espinoza, B., et al., 2022. Evaluation of remote sensing-based evapotranspiration products at low-latitude eddy covariance sites. J. Hydrol. 610, 127786.

Sangha, L., Shortridge, J., 2023. Quantification of unreported water use for supplemental crop irrigation in humid climates using publicly available agricultural data. Agric. Water Manag. 287, 108402.

Scanlon, B.R., Ruddell, B.L., Reed, P.M., Hook, R.I., Zheng, C., Tidwell, V.C., Siebert, S., 2017. The food-energy-water nexus: Transforming science for society. Water Resour. Res. 53 (5), 3550–3556.

Senay, G.B., Bohms, S., Singh, R.K., Gowda, P.H., Velpuri, N.M., Alemu, H., Verdin, J.P., 2013. Operational evapotranspiration mapping using remote sensing and weather datasets: a new parameterization for the sseb approach. JAWRA J. Am. Water Resour. Assoc. 49 (3), 577–591.

Sinclair, T.R., Rufty, T.W., 2012. Nitrogen and water resources commonly limit crop yield increases, not necessarily plant genetics. Glob. Food Secur. 1 (2), 94–98.

Syme, G.J., Nancarrow, B.E., 2006. Achieving sustainability and fairness in water reform: a western australian case study. Water Int. 31 (1), 23–30.

Tidwell, V.C., Moreland, B.D., Zemlick, K.M., Roberts, B.L., Passell, H.D., Jensen, D., Forsgren, C., Sehlke, G., Cook, M.A., King, C.W., et al., 2014. Mapping water availability, projected use and cost in the western united states. Environ. Res. Lett. 9 (6), 064009.

Toureiro, C., Serralheiro, R., Shahidian, S., Sousa, A., 2017. Irrigation management with remote sensing: evaluating irrigation requirement for maize under mediterranean climate condition. Agric. Water Manag. 184, 211–220.

UN Water (2016). Monitoring water and sanitation in the 2030 agenda for sustainable development: An introduction.

USGS (2022). Landsat 8–9 collection 2 (c2), level 2 science product (l2sp) guide.

Valdés-Pineda, R., Pizarro, R., García-Chevesich, P., Valdés, J.B., Olivares, C., Vera, M., Balocchi, F., Pérez, F., Vallejos, C., Fuentes, R., et al., 2014. Water governance in chile: Availability, management and climate change. J. Hydrol. 519, 2538–2567.

Veale, B., Cooke, S., 2017. Implementing integrated water management: illustrations from the grand river watershed. Int. J. Water Resour. Dev. 33 (3), 375–392.

Veettil, A.V., Mishra, A.K., 2016. Water security assessment using blue and green water footprint concepts. J. Hydrol. 542, 589–602.

Vervoort, R.W., Fuentes, I., Brombacher, J., Degen, J., Chambel-Leitão, P., Santos, F., 2022. Progress in developing scale-able approaches to field-scale water accounting based on remote sensing. Sustainability 14 (5), 2732.

Wang, G., Mang, S., Cai, H., Liu, S., Zhang, Z., Wang, L., Innes, J.L., 2016. Integrated watershed management: evolution, development and emerging trends. J. For. Res. 27, 967–994.

Wester, P., Warner, J., 2002. River basin management reconsidered. Hydropolitics Dev. World.: A South. Afr. Perspect. 61–71.

Williams, J., Grafton, R.Q., 2019. Missing in action: Possible effects of water recovery on stream and river flows in the murray-darling basin, australia. Australas. J. Water Resour. 23 (2), 78–87.

, 2014World Health Organization (2014). Un-water global analysis and assessment of sanitation and drinking-water (glaas) 2014 report: investing in water and sanitation: increasing access, reducing inequalities.

Wu, B., Tian, F., Zhang, M., Piao, S., Zeng, H., Zhu, W., Liu, J., Elnashar, A., Lu, Y., 2022. Quantifying global agricultural water appropriation with data derived from earth observations. J. Clean. Prod. 358, 131891.

Wutich, A., Jepson, W.E., Stoler, J., Thomson, P., Kooy, M., Brewis, A., Staddon, C., Meehan, K., 2021. A global agenda for household water security: measurement, monitoring, and management. JAWRA J. Am. Water Resour. Assoc. 57 (4), 530–538.

Yuan, Z., Shen, Y., 2013. Estimation of agricultural water consumption from meteorological and yield data: a case study of hebei, north china. PloS One 8 (3), e58685.

Zhang, Y., Kong, D., Gan, R., Chiew, F.H., McVicar, T.R., Zhang, Q., Yang, Y., 2019. Coupled estimation of 500 m and 8-day resolution global evapotranspiration and gross primary production in 2002–2017. Remote Sens. Environ. 222, 165–182.

Zhao, Y., Feng, D., Yu, L., Wang, X., Chen, Y., Bai, Y., Hernández, H.J., Galleguillos, M., Estades, C., Biging, G.S., et al., 2016. Detailed dynamic land cover mapping of Chile: accuracy improvement by integrating multi-temporal data. Remote Sens. Environ. 183, 170–185.