

DIGITAL TRANSFORMATION OF ON-FARM IRRIGATION MANAGEMENT: THE RIEGABIEN® APP SUITE AS A SCALABLE MODEL OF PRECISION AGRICULTURE IN CHILE

TRANSFORMATION NUMÉRIQUE DE LA GESTION DE L'IRRIGATION À L'ÉCHELLE DE L'EXPLOITATION: LA SUITE D'APPLICATIONS RIEGABIEN® COMME MODÈLE ÉVOLUTIF D'AGRICULTURE DE PRÉCISION AU CHILI

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ABSTRACT

Chile's agricultural sector is currently facing a structural water scarcity scenario driven by a prolonged megadrought, which has intensified the need for more efficient on-farm irrigation management. Despite this urgency, a persistent technological and knowledge gap remains, as many producers do not incorporate formal irrigation scheduling into their decision-making processes. Instead, irrigation practices are frequently based on empirical criteria or incomplete information, limiting the ability to adequately capture spatial variability in soils, crops, and climate. This gap is particularly critical among small and medium-scale producers. However, this scenario coexists with significant opportunities, including the high penetration of mobile technologies and the advanced development of national agrometeorological networks and satellite-based vegetation indicators, which provide robust, spatially explicit data for estimating crop water requirements.

In response, RiegaBien® was developed as a mobile-based decision-support system aimed at improving irrigation management through the operationalization of scientific methodologies. The platform integrates a soil water balance model based on the FAO-56 approach with real-time reference evapotranspiration data and dynamic crop coefficients derived from NDVI. It also incorporates georeferenced soil properties and user-defined irrigation system parameters to generate site-specific irrigation recommendations. Its modular architecture, structured around climate, crop, soil, and irrigation components, translates complex irrigation models into an accessible and user-oriented interface.

Results from pilot implementations demonstrate that the application improves irrigation decision-making with adaptive scheduling that responds to phenological and environmental variability. The tool is currently recognized within the agricultural sector and has exceeded 2,500 downloads; however, further efforts are required to expand its reach among producers and to consolidate its effective adoption. Overall, RiegaBien® illustrates how the integration of scientific knowledge, existing data infrastructure, and digital technologies can bridge critical gaps and support more efficient and informed water management in agriculture.

Keywords: Digital transformation; Precision agriculture; Irrigation scheduling; Decision-support system; Irrigation models.

RÉSUMÉ

Le secteur agricole chilien est actuellement confronté à une situation structurelle de pénurie d'eau, provoquée par une mégasécheresse prolongée, qui a accentué la nécessité d'une gestion plus

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efficace de l'irrigation à l'échelle de l'exploitation. Malgré cette urgence, un déficit persistant en matière de technologie et de connaissances subsiste, car de nombreux producteurs n'intègrent pas de programmation formelle de l'irrigation à leurs processus décisionnels. Les pratiques d'irrigation reposent souvent sur des critères empiriques ou des informations incomplètes, ce qui limite la capacité à prendre correctement en compte la variabilité spatiale des sols, des cultures et du climat. Ce déficit est particulièrement critique chez les petits et moyens producteurs. Cette situation coexiste néanmoins avec d'importantes possibilités, notamment la forte pénétration des technologies mobiles et le développement avancé des réseaux agrométéorologiques nationaux et des indicateurs de végétation satellitaires, qui fournissent des données robustes et spatialement explicites pour estimer les besoins en eau des cultures.

En réponse, RiegaBien® a été développé comme un système mobile d'aide à la décision visant à améliorer la gestion de l'irrigation en rendant opérationnelles des méthodologies scientifiques. La plateforme intègre un modèle de bilan hydrique du sol fondé sur l'approche FAO-56, des données d'évapotranspiration de référence en temps réel et des coefficients culturels dynamiques dérivés du NDVI. Elle intègre également des propriétés géoréférencées des sols et des paramètres du système d'irrigation définis par l'utilisateur afin de produire des recommandations d'irrigation propres au site. Son architecture modulaire, structurée autour des composantes climat, culture, sol et irrigation, traduit des modèles d'irrigation complexes en une interface accessible et centrée sur l'utilisateur.

Les résultats des mises en œuvre pilotes montrent que l'application améliore la prise de décision en matière d'irrigation grâce à une programmation adaptative qui tient compte de la variabilité phénologique et environnementale. L'outil est actuellement reconnu dans le secteur agricole et a dépassé 2 500 téléchargements ; des efforts supplémentaires sont toutefois nécessaires pour élargir son utilisation parmi les producteurs et consolider son adoption effective. Dans l'ensemble, RiegaBien® illustre comment l'intégration des connaissances scientifiques, des infrastructures de données existantes et des technologies numériques peut combler des lacunes critiques et favoriser une gestion de l'eau agricole plus efficace et mieux informée.

Mots clés : Transformation numérique; Agriculture de précision; Programmation formelle de l'irrigation; Système d'aide à la décision; Modèles d'irrigation.

1. Introduction

Agricultural activities in Mediterranean climates, particularly in Chile, are currently confronting unprecedented environmental stress characterized by a "megadrought" exceeding 15 years in duration (Garreaud et al., 2025). This persistent water deficit has evolved from a temporary climatic fluctuation into a structural constraint for the national agricultural sector, which represents the majority of regional consumptive water use. For researchers and water resource engineers, mitigating this crisis requires more than traditional infrastructure; it necessitates a comprehensive digital transformation of on-farm water management (Urquieta et al., 2022).

Despite the seriousness of this crisis, a paradoxical "quantitative gap" persists in Chilean rural territories. Today, the total irrigated area of Chile represents the 49% of the total cultivated land, and from the irrigated area, a 60% of the area is irrigated with high irrigation technology, such as microirrigation and sprinkler (INE, 2022). However, an exploratory study conducted between 2019 and 2024 among representative fruit growers across central and northern Chile reveal a stark lack of quantitative rigor in daily operations: over 50% of producers admit they do not calculate irrigation time or frequency based on physical data (Gil et al., 2024, unpublished).

Another concerning is that a majority of producers do not provide formal training to their personnel regarding irrigation tasks. This gap is particularly evident in the characterization of soil physical-hydraulic properties; only a small fraction of producers knows the soil water holding capacity of their plots. This lack of foundational data renders many existing technological tools ineffective, leaving the technical operator without the necessary knowledge to manage the system.

Nevertheless, according to data from the Chilean Subsecretariat of Telecommunications (2025), smartphone penetration in Chile, including rural areas has reached 90%. This high level of connectivity suggests a technical readiness for precision agriculture. Additionally, Chile possesses a robust data resources, including automated weather station networks (Ceazamet, RAN, INIA, DMC) and webgis for dynamic crop coefficient estimation like Satellite Agricultural Platform PLAS (INIA).

The objective of this work is to introduce the RiegaBien® App suite as a multidisciplinary tool designed to bridge this quantitative gap through localized, data-driven management.

2. Methodology

The development of RiegaBien® followed a three-stage framework: Regional soil database development, Technological development and digital implementation, and Capacity building and dissemination.

2.1. Stage 1: Regional Soil Database Development

The architectural foundation rests on a georeferenced database integrating the physical–hydraulic characteristics of agricultural zones across five administrative regions (Coquimbo, Valparaíso, Metropolitana, O’Higgins, and Maule). Soil attributes, including texture and effective depth, were synthesized from institutional agrological studies (CIREN 1996, 1997a, 1997b, 2005, 2013) and FAO (2012) datasets.

This matrix enables the estimation of Total Available Water (TAW) and Readily Available Water (RAW) according to Allen et al. (1998). The system utilizes soil polygons to automatically assign site-specific parameters, ensuring context-sensitive management.

2.2 Stage 2: Technological Development and digital implementation

The framework combined participatory design, technical programming, and iterative validation.

- **Service Design:** Grounded in user-centered design (Manzini et al., 2015), sociology-based methodologies guided engagement with producers and consultants through focus groups. This process identified critical functional priorities: simplicity in plot definition and the generation of interpretable weekly schedules.
- **Technical Programming:** The core mathematical engine executes a weekly soil water balance based on the FAO-56 dual crop coefficient approach (Allen et al., 1998). It integrates real-time reference evapotranspiration (ET_o) from the INIA agrometeorological network (INIA, 2026) and crop coefficient (K_c) derived from satellite NDVI imagery provided by PLAS platform (INIA, 2026), to calculate an in situ crop evapotranspiration (ET_c). The system calculates gross irrigation requirements by incorporating effective precipitation, leaching fractions, and system efficiency. Additionally, the system calculates irrigation frequency based on weekly ET_c data and soil water retention capacity, which is determined from the soil matrix generated in Stage 1.
- **Validation:** A beta-testing phase with pilot producers acted as a feedback loop to refine the user interface and computing performance, ensuring that recommendations were actionable for field operators.

2.3. Stage 3: Capacity Building and Dissemination

To address the human factor, this stage involved producing technical manuals, video tutorials, and conducting on-site training. Collaboration with national agencies like the National Irrigation

Commission (CNR) and INDAP facilitated a socio-technical transition from intuitive decision-making to data-driven management.

2.4. Intellectual protection.

Finally, we incorporated intellectual property protection procedures to safeguard the developed technology and support its future transfer and commercialization. Overall, this concluding phase ensured that the application evolved from a functional prototype into a validated, user-centered digital solution, effectively bridging technical modeling with real-world agricultural practice.

3. Results and discussion

The RiegaBien® project has successfully evolved from a research-based prototype into an operational suite of regionally adapted applications, achieving a notable level of adoption within the Chilean agricultural sector. This transition highlights not only the technical robustness of the platform but also its capacity to address real-world constraints in irrigation management, particularly in contexts characterized by heterogeneous agroecological conditions and limited formal training among users.

To date, the RiegaBien® suite has exceeded 2,500 downloads across multiple platforms, reflecting a growing interest among producers and technical advisors. The development strategy has been explicitly oriented toward regional specialization, allowing the application to capture local variability in crop types, soil and climatic conditions, and irrigation practices.

Currently released versions include the versions for Coquimbo, Metropolitana, O'Higgins, Maule and Valparaíso regions, each tailored to specific productive systems (Figure 1). For instance, the Coquimbo and Valparaíso version emphasizes arid (Coquimbo) and semiarid-zone (Valparaíso) production (e.g., vegetables, flowers, table grapes, mandarins, avocado), whereas the Metropolitana version addresses more diversified systems including vegetable, walnut, peach, and lemon production. Similarly, the O'Higgins and Maule versions focus on intensive fruit systems such as cherries, apples, and table grapes, and other important annual crops such as maize production.

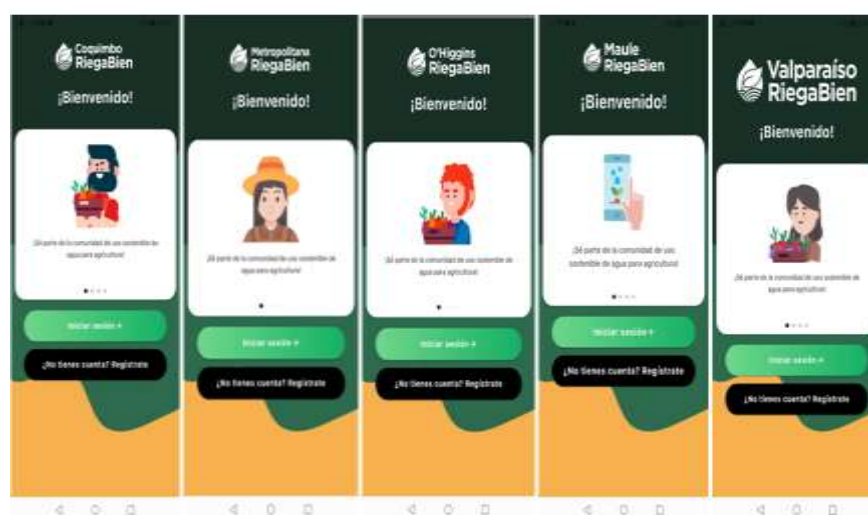


Figure 1. Welcome screen for current available versions of the RiegaBien® app.

The regional diversification demonstrates a key strength of the platform, as it enables contextual adaptation rather than relying on generalized irrigation recommendations, which are often a limitation of global decision-support tools.

From a functional perspective, the application consists of four main modules: Climate, Crop, Soil, and Irrigation. This modular architecture enhances both computational efficiency and user comprehension, facilitating interaction with complex datasets.

A critical feature is the automated management of soil, climate and crop data (Kc). Users define their farm units and irrigation sectors using GPS-based delineation. For example, the system automatically assigns soil parameters such as field capacity, permanent wilting point, stone content and electrical conductivity from the georeferenced database, as well as ETo and Kc data from agrometeorological platforms. This automation addresses a critical limitation previously identified among users, namely the underutilization of soil water-holding capacity in irrigation decision-making.

In addition, the application incorporates system-specific configuration algorithms, enabling precise adaptation to different irrigation methods. For drip irrigation, user-defined parameters (e.g., emitter spacing, number of laterals per row, row spacing, and flow rate) are translated into calculated precipitation rates (mm h^{-1}) and irrigation times (e.g., 9 hours to meet a weekly demand of 24 mm). Equivalent logic is applied to furrow and center pivot systems, incorporating assumptions such as non-erosive flow rates or efficiency values. Overall, the programming phase ensured that the prototype effectively integrated complex agronomic and hydrological models into a functional decision-support tool. The resulting system not only generates accurate irrigation recommendations but also operationalizes these outputs in a format directly applicable to farm management, thereby bridging the gap between scientific modeling and practical implementation (Figure 2).

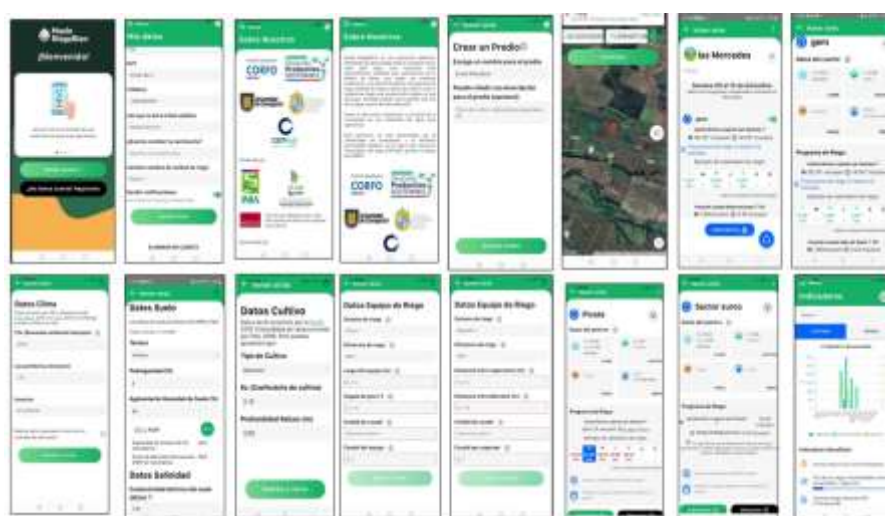


Figure 2: Main screens for Maule RiegaBien®

The application further enhances usability through a dashboard that visualizes irrigation schedules and integrates sustainability indicators. Among these, the blue water footprint ($\text{m}^3 \text{ton}^{-1}$) provides an informative metric for evaluating water use efficiency. Additionally, comparative visualizations of applied versus recommended water volumes highlight operational gaps.

Data obtained from pilot cases demonstrates the dynamic capabilities of the RiegaBien® engine. For example, in a monitored apple orchard (Fundo Manzanares, Maule, Chile), irrigation subunit (Sector 1) during the development growth stage (second week of October 2025) had a weekly cumulative reference evapotranspiration (ETo) and crop coefficient (Kc) of 20 mm and 0.54 respectively, corresponding to a weekly water demand of 12 mm. By the full-canopy stage (second week of January 2026), the corresponding values increased to 36 mm and 0.66, as well as the weekly water demand (27 mm). By integrating NDVI data from the PLAS platform and ETo data from the agrometeorological networks, the application captures both crop phenological development and weather variability, updating irrigation requirements accordingly. This dynamic approach contrasts with conventional fixed

irrigation schedules, in which water applications remain constant despite changes in crop water demand and environmental conditions.

The results so far indicate that this adaptive capacity can significantly reduce over-irrigation, particularly during late-summer periods characterized by declining evaporative demand. In monitored cases, this led to measurable reductions in both water use and associated energy consumption for pumping. These findings highlight the importance of integrating remote sensing and real-time data streams into irrigation decision-support tools to enhance resource efficiency.

In an international context, RiegaBien® aligns with existing decision-support systems such as the SmartIrrigation applications developed by the University of Florida (Migliaccio et al., 2016). However, the RiegaBien® system introduces several distinctive features that enhance its applicability in the Chilean context. First, the platform utilizes soil data structured based on previously generated polygons derived from the Natural Resources Information Center (CIREN), enabling more precise parameterization compared to international models that often rely on simplified or generalized soil classes. Second, the system operates as a “closed-loop” platform, integrating data acquisition, processing, and decision output within a single environment.

Finally, and perhaps most importantly, RiegaBien® incorporates a socio-technical dimension explicitly designed to address the significant training gap identified in Chile (approximately 92% of producers lacking formal technical training in irrigation management). This integration of service design principles with technical modeling represents a key innovation, positioning the platform not only as a computational tool but also as a mechanism for capacity building and digital transformation in agriculture.

Collectively, the results demonstrate that RiegaBien® effectively bridges the gap between advanced scientific modeling and practical irrigation management. Its regional adaptability, modular design, real-time data integration, and user-centered development approach contribute to both its technical validity and practical relevance. Moreover, the observed improvements in water and energy efficiency highlight its potential as a scalable solution for addressing water scarcity challenges in Mediterranean and semi-arid agricultural systems. However, despite its demonstrated potential, further efforts are required to expand its penetration among producers, quantitatively assess its level of adoption, and define a sustainable business model that ensures the tool remains freely accessible and widely available for mass use.

Acknowledgments

The authors gratefully acknowledge the contributions of all the collaborating institutions involved in this development. In particular, we thank CORFO and the Regional Government of Coquimbo for their financial support. We also acknowledge CEAZAMET, the Dirección Meteorológica de Chile (DMC), and Agrometeorología-INIA for providing access to their agrometeorological networks, as well as CIREN and FAO for supplying essential soil databases. We are further grateful to the National Irrigation Commission (CNR) and the Agricultural Development Institute (INDAP) for their support in organizing dissemination and training activities. Special recognition is extended to the pilot producers whose valuable feedback was instrumental in refining the tool. Finally, we thank the farmers, professionals, technicians, and undergraduate students who participated in the development and training activities, as well as the undergraduate collaborators involved in the application's development and field validation.

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