

FROM STARS TO REALITY: DEVELOPING A GEOSPATIAL APPLICATION FOR NATIONAL IRRIGATION PLANNING AND MONITORING – A PRACTICAL JOURNEY FROM RWANDA

DES ÉTOILES À LA RÉALITÉ : DÉVELOPPER UNE APPLICATION GÉOSPATIALE POUR LA PLANIFICATION ET LE SUIVI DE L'IRRIGATION NATIONALE – VOYAGE PRATIQUE AU RWANDA

Romain Vidal¹, Jules Wijting², Stéphane Delichère³

ABSTRACT

Rwanda is strongly committed to leveraging digital transformation to accelerate growth and rural development. A “Geospatial Hub” became operational in 2023 to provide centralized geospatial data, infrastructure and services with the ambition to support, among other things, the development of operational geospatial applications that strengthen evidence-based agricultural and water resource management. Within this framework, a Smart Irrigation Solution is being developed by the Rwanda Space Agency with the support of the French Agency for Development and aims of providing reliable and measurable data for irrigation planning and risks monitoring.

The objective is to compute and/or display, at various spatial and temporal scales, arable land suitable for irrigation, land that can be effectively irrigated, net irrigation water requirements, and water availability or water balance in major water bodies. The Solution, designed with the WIMES software toolbox powered by BRLi, integrates satellite observations, meteorological forecasts, hydrological modelling outputs, and agricultural datasets within a geospatial environment to generate near-real-time information on Net Irrigation Water Requirements (NIWR), water availability, and drought risk.

Given the limited availability of in-situ hydrological data, water resource availability is estimated using a coefficient-based – runoff and infiltration - approach derived from WEAP modelling outputs and satellite and field meteorological observations – rainfall, evapotranspiration and soil moisture. The platform produces operational indicators such as water availability and drought risk indicators to support decision makers in monitoring and anticipating critical situations and guiding sectoral decisions. Transforming a conceptual geospatial solution into an operational national system requires navigating various technical and institutional complexities. These include data availability and resolution constraints, crop identification challenges, uncertainties in modelling water basin behaviors and high institutional expectations.

This paper presents the system architecture, methodological approach, and implementation process, that were used, highlighting key challenges and lessons learned. The results demonstrate that robust and scalable irrigation decision-support systems can be developed in data-constrained environments through pragmatic modelling choices, effective data integration, and strong institutional engagement. This process also provides a significant opportunity for collaboration between institutions and disciplines, mobilizing the experiences, tools and capacities of different national stakeholders.

Keywords: spatial and temporal scales; agricultural and water resource management; water availability; meteorological forecasts; drought risk indicators.

¹ BRLi, 1105 avenue Pierre Mendès France, Nîmes, France – romain.vidal@brli.fr

² BRLi, 1105 avenue Pierre Mendès France, Nîmes, France – jules.wijting@brli.fr

³ BRLi, 1105 avenue Pierre Mendès France, Nîmes, France – stephane.delichere@brli.fr

RESUME

Le Rwanda est fermement engagé à tirer parti de la transformation numérique pour accélérer la croissance et le développement rural. Un «Centre Géospatial» est devenu opérationnel en 2023 pour fournir des données géospatiales centralisées, une infrastructure et des services avec l'ambition de soutenir, entre autres, le développement d'applications géospatiales opérationnelles qui renforcent la gestion des ressources agricoles et hydriques fondée sur des preuves.

Dans ce cadre, une solution d'irrigation intelligente est en cours de développement par l'Agence spatiale rwandaise avec le soutien de l'Agence française de développement. Elle vise à fournir des données fiables et mesurables pour la planification de l'irrigation et le suivi des risques. L'objectif est de calculer et/ou d'afficher, à différentes échelles spatiales et temporelles, les terres arables adaptées à l'irrigation, les terres potentiellement irrigables, les besoins nets en eau pour l'irrigation, ainsi que la disponibilité en eau ou le bilan hydrique dans les principaux corps d'eau.

La solution, conçue avec l'aide de la boîte à outils logicielle WIMES alimentée par BRLi, intègre des observations satellitaires, des prévisions météorologiques, des résultats de modélisation hydrologique et des ensembles de données agricoles au sein d'un environnement géospatial afin de générer des informations en temps quasi réel sur les besoins nets en eau d'irrigation. (NIWR), la disponibilité de l'eau et les risques de sécheresse.

Compte tenu de la disponibilité limitée des données hydrologiques in situ, la disponibilité des ressources en eau est estimée grâce à une approche basée sur les coefficients – ruissellement et infiltration - approche dérivée des résultats de modélisation WEAP et des observations météorologiques par satellite et sur le terrain – précipitations, évapotranspiration et humidité du sol. La plateforme produit des indicateurs opérationnels tels que ceux relatifs à la disponibilité de l'eau et aux risques de sécheresse pour aider les preneurs de décision à surveiller et à anticiper les situations critiques et à guider les décisions sectorielles.

La transformation d'une solution géospatiale conceptuelle en un système national opérationnel exige de surmonter diverses complexités techniques et institutionnelles. Il s'agit notamment des contraintes liées à la disponibilité et à la résolution des données, les difficultés d'identification des cultures, les incertitudes liées à la modélisation du comportement des bassins versants et les attentes institutionnelles élevées.

Ce document présente l'architecture du système, l'approche méthodologique et le processus de mise en œuvre qui ont été utilisés, en soulignant les principaux défis et leçons apprises. Les résultats démontrent que des systèmes robustes et évolutifs d'aide à la décision en irrigation peuvent être développés dans des environnements contraints par les données grâce à des choix pragmatiques de modélisation, une intégration efficace des données et un fort engagement institutionnel. Ce processus offre également une occasion importante de collaboration entre les institutions et les disciplines, en mobilisant les expériences, les outils et les capacités des différentes parties prenantes nationales.

Mots-clés : Echelles spatiales et temporelles; Gestion agricole et des ressources en eau; Disponibilité en eau; Prévisions météorologiques; Indicateurs de risque de sécheresse.

INTRODUCTION

Rwanda is ranked the 19th most vulnerable country to climate change in the Notre Dame Global Adaptation Initiative Index. Observations over the past decades have already shown clear changes in the climate. Temperatures have increased significantly, with rises between 1.4 to 2.6°C observed in some regions since the 1970s, especially in the south-west and eastern parts of the country. This trend is expected to continue, with projections indicating an additional increase of between 1.1°C and 3.9°C by the end of the century, together with more frequent and longer heatwaves (The World Bank Group, 2021).

Rainfall is becoming more irregular, even if relatively abundant at the national level with around 1,200 mm per year on average (1991–2020). There is a stronger variability between seasons and regions, with more intense rainfall during wet periods and, at the same time, more frequent deficits, particularly in the eastern regions. Future trends suggest that this variability will continue to increase, with both heavier rainfall events and also longer dry spells. These changes are already leading to more frequent and severe hazards such as floods, droughts, and landslides, affecting agriculture, infrastructure, and rural livelihoods (The World Bank Group, 2021). These challenges are further increased by the country's high population density and the fragmentation of agricultural land.

In this context, improving irrigation has become a key priority for Rwanda in order to stabilize agricultural production, strengthen food security, and increase resilience. However, despite the significant efforts that have been made in recent years, the irrigation sector still faces a number of practical difficulties. The cost of irrigation development, especially in hilly areas, remains very high and is often difficult to sustain over time. Access to finance and the implication of the private sector are both still limited, which slows down the expansion of irrigated areas.

At the same time, many existing irrigation schemes are not performing as expected due to limited technical capacity, weak organization among users, and difficulties in managing water in an efficient and equitable way. Institutional coordination also needs to be improved to ensure fully coordinated approaches and increase the effectiveness of planning and implementation (Republic of Rwanda, 2020). In addition, the lack of reliable and consistent data makes it difficult to properly assess water availability, irrigation needs and inform decision makers.

All these factors make irrigation development more complex. More integrated approaches are needed, combining more accurate, accessible and reliable better data and stronger coordination between stakeholders. This is particularly important in light of the government plans to introduce agrihubs and food basket sites⁴ as part of innovations to drive forward its agriculture sector.

Rwanda has therefore engaged in an ambitious digital transformation strategy, aiming to use geospatial technologies to support sustainable development. One key component of this strategy is the national Geospatial Hub, which is designed to centralize spatial data and provide integrated decision-making support tools across different sectors, including agriculture, water resources, and environmental management.

As part of this initiative, a Smart Irrigation Solution is being developed to improve irrigation planning and monitoring. The system integrates multiple data sources—including Earth observation products, short-term meteorological forecasts, long-term climate projections, ground-based weather station measurements, and agricultural datasets—within a unified geospatial platform designed to generate operation indicators across different spatial and temporal scales.

Even if the general principles for sustainable irrigation monitoring and development and the potential of remote sensing are well known, applying them through an operational system at national level remains challenging. Data is often incomplete or inconsistent, expectations may differ from one user to another, and the application development requires an allocation of resources that may exceed what was initially planned. The development process showed that given the available data and resources available, methodological choices needed to be adapted to what was practically feasible.

This paper presents the development of the Smart Irrigation Application in Rwanda as an example of the transition from concept to operational tool. It focuses on the system architecture and data integration, the methodological choices for estimating water demand and availability, and the main challenges faced during implementation. On one of the objectives is to share practical lessons that could be useful for similar initiatives in other contexts where the data and resources are limited.

⁴ Agrihubs can be defined as large scale commercial agricultural initiatives for intensive farming and animal husbandry. Food basket sites refer to consolidated farming zones to increase agricultural production with a focus on staple crops.

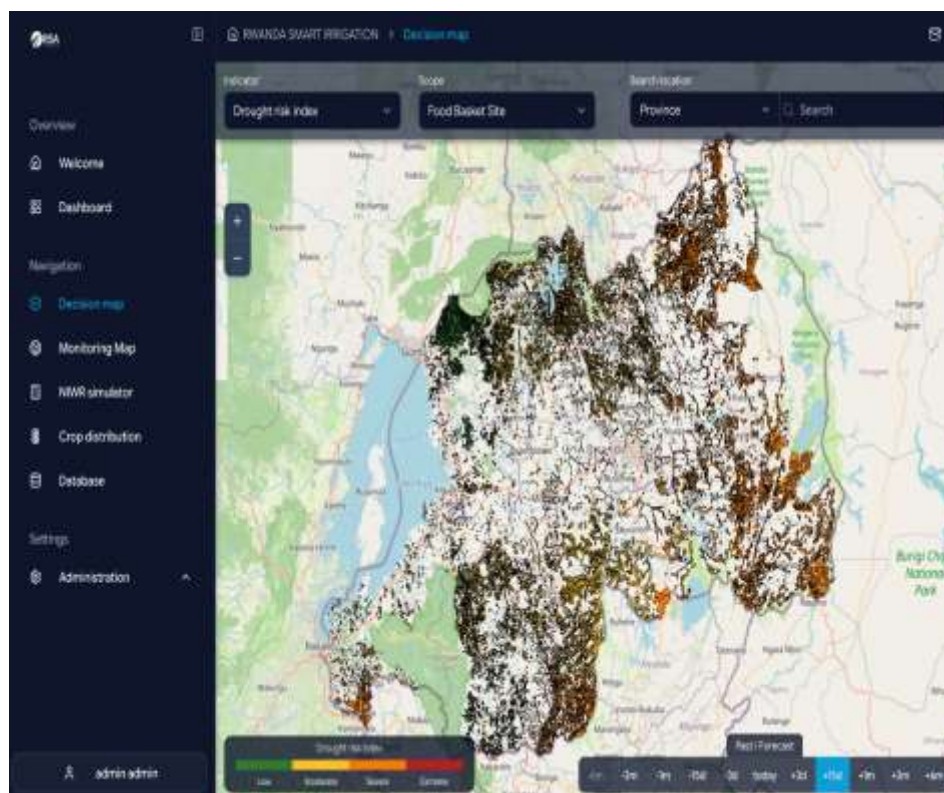
SYSTEM ARCHITECTURE AND DATA INTEGRATION

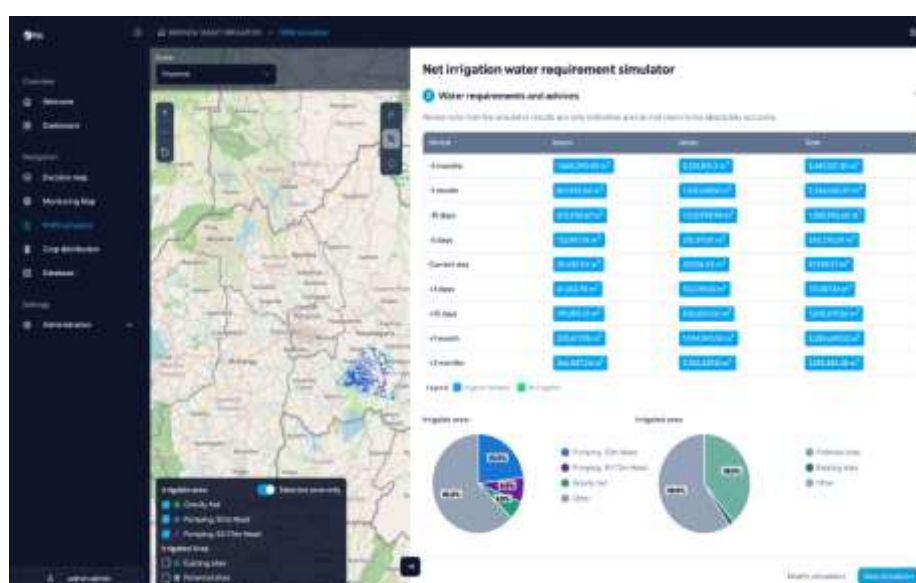
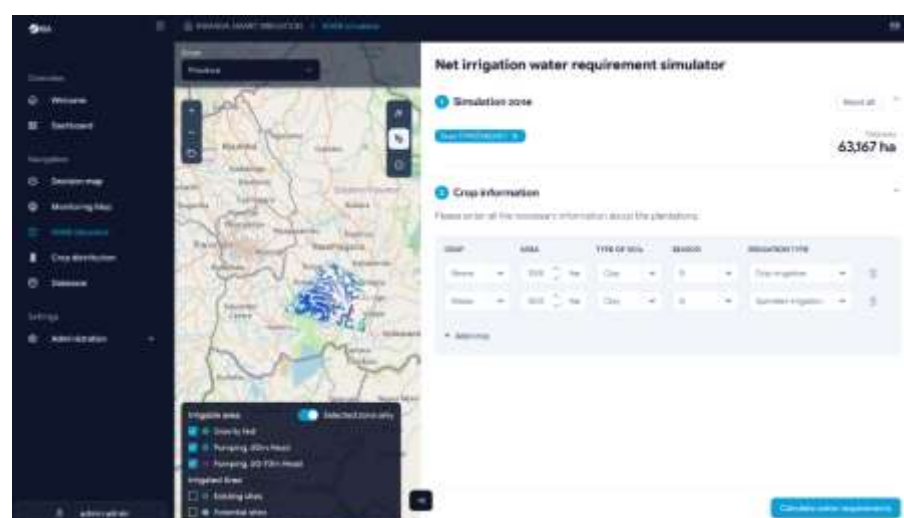
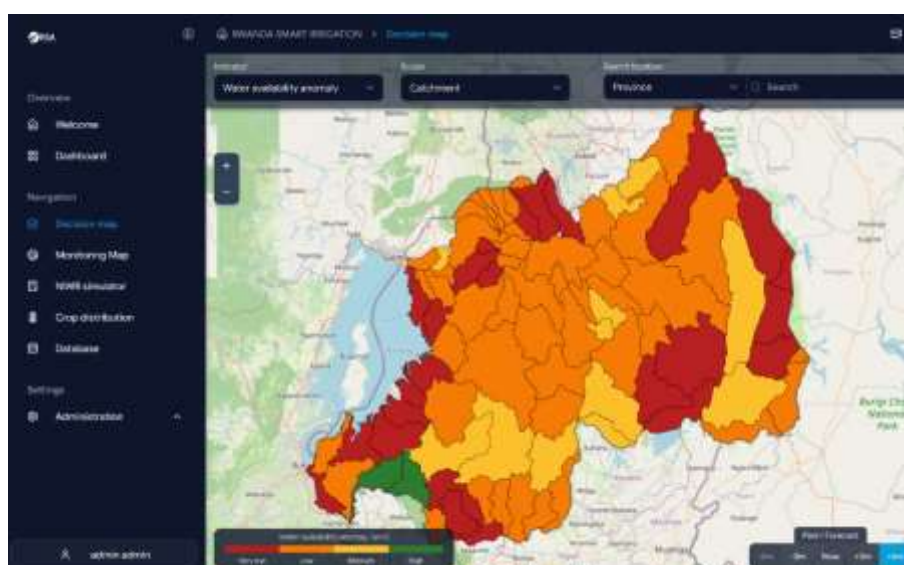
The Rwanda Smart Irrigation Solution is designed as a geospatial platform that will be part of the Rwanda's GeoHub infrastructure. Its architecture reflects the need to combine multiple data sources into a coherent analytical framework while ensuring flexibility for future developments and the integration of additional data sources.

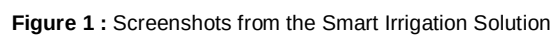
From the user perspective, the Solution provides several complementary interfaces:

- A dashboard allowing users to visualize all the data available for a specific zone and time period.
- A “decision” map displaying computed indicators at different temporal horizons and across multiple spatial levels: national, provincial, district, sector, food basket sites and also catchment and agroecological zones.
- A monitoring map that displays collected data and allows the user to navigate through several datasets.
- A net irrigation simulator that allows users to define crops scenarios and estimate irrigation needs for a given area based on observations and forecast conditions.
- A database centralizing the data required by the systems and data relevant to the irrigation sector.

At this stage, the system integrates four main categories of data: meteorological data, hydrological data, agricultural datasets, and socio-economic and land-use information. Each of these data categories presents specific challenges in terms of spatial resolution, temporal frequency, reliability and use perspectives.







Reference evapotranspiration and root soil moisture measurements are obtained from WaPOR satellite products for observations, offering high spatial resolution (~300 m) which is particularly suitable for irrigation analysis. For forecast horizons, ETP and root soil moisture measurements are derived from ICON and CFSv2 temperature forecasts using the Oudin formula, which provides a simple and

consistent method suited to data-limited contexts. The agricultural dataset includes crop calendars, crop coefficients (K_c) and spatial crop distribution information for 10 crops: maize, beans, cassava, soy bean, rice, wheat, Irish potato, eggplant, tomato and onion. Crop calendars and crop coefficients are based on information provided by national institutions and FAO reference values. These calendars are translated into structured configuration files used directly by the system.

At this stage, spatial crop distribution is derived from agricultural survey statistics provided by the Ministry of Agriculture, complemented by preparatory work undertaken in parallel under the Smart Agriculture application. Given current limitations, the resulting crop distribution layers represent aggregated patterns rather than actual plot-level realities. They are considered transitional and are expected to be progressively replaced by more detailed products derived from remote sensing. Land-use information, particularly the extent of cropland, is derived from national land cover datasets and used to estimate cultivated areas and potential exposure to water stress. Socio economic information is taken from national statistics.

Data harmonization and technical implementation

Integrating these heterogeneous datasets requires a robust harmonization process. This process involves spatial resampling to a common grid, temporal aggregation to consistent time steps (e.g., daily or dekadal), and quality control procedures to address missing or inconsistent data. From a technical perspective, the application is implemented using a containerized architecture based on Docker. Data processing, storage and visualization components are deployed as separate services, allowing them to evolve independently. Geospatial and time-series data are stored using PostgreSQL/PostGIS and TimescaleDB, ensuring efficient handling of both spatial and temporal information.

This modular architecture improves system robustness and scalability, while facilitating maintenance and future upgrades, as individual components can be modified or replaced without affecting the entire system.

METHODOLOGICAL FRAMEWORK

Estimation of Net Irrigation Water Requirement

The estimation of Net Irrigation Water Requirement (NIWR) is central to the Smart Irrigation Application and its inclusion was a specific request from several public stakeholders. This theoretical approach is well known through the FAO-56 methodology (Allen and al., 1998), which provides a standardized framework for estimating crop water requirements, however its implementation required several adaptations. One of the main challenges was the limited availability of spatially explicit crop distribution data. Crop identification through remote sensing requires significant resources and agricultural systems in Rwanda are characterized by small and fragmented plots, often with multiple crops grown simultaneously. This complexity makes it difficult to assign a single crop type to a given spatial unit. To address this issue, the system incorporates two complementary approaches. For large-scale analyses, generalized crop scenarios are used based on available agricultural statistics and data from the smart agriculture application. For localized analyses, a simulation tool allows users to define crop types and areas manually, enabling a more accurate estimation of water requirements at the plot level. Effective rainfall is another critical component of NIWR estimation. This represents the proportion of total rainfall that is actually available for crop use. In the absence of detailed soil and infiltration data, effective rainfall is estimated using simplified empirical relationships, which provide a reasonable approximation under operational constraints.

Assessment of Water Availability

The estimation of water availability presents significant challenges due to the limitations in hydrological data usability. While Rwanda's hydrometric network includes numerous stations measuring water levels, only 13 rating curves are currently available to convert these observations into discharge estimates. Furthermore, delays in data transmission and validation constrain their integration into a near-real-time

operation system. Consequently, streamflow information remains incomplete and insufficient for fully observation-based monitoring approaches.

To partially compensate for the absence of an explicit representation of storage processes, the methodology integrates satellite-derived soil moisture observations with a one-month temporal lag to dynamically modulate the WEAP-derived coefficients. This adjustment aims to indirectly account for delayed hydrological responses linked to previous moisture conditions and catchment storage effects. Given these constraints, the project adopted a simplified approach based on WEAP model simulations provided by the Rwanda Water Board. For each of the 88 catchments, a coefficient-based approach was developed using runoff and infiltration coefficients derived from long-term WEAP simulations to estimate the proportion of rainfall contributing to surface and groundwater resources.

This approach capitalizes on the significant hydrological work carried out in previous years, which had not yet been operationally mobilized, and ensures a reliable framework for deriving water resources availability from rainfall observations and forecasts.

The main limitation of the selected approach remains the simplified representation of hydrological storage processes. Reservoir dynamics, groundwater storage, and flow regulation effects are therefore only partially captured at this stage. This limitation is clearly identified by the project team and is expected to be progressively reduced through the development of additional rating curves, further hydrological investigations, and the strengthening of the technical capacity of the teams responsible for operating the Solution. As monitoring networks improve and operational experience grows, the system should progressively evolve towards a more complete and robust representation of water availability.

Development of Decision-Support Indicators

To translate model outputs into useable information, the system generates a set of indicators designed to capture key aspects of water availability and demand. Three different indicators have been selected to be computed across different spatial and temporal scales:

- Water availability index: this indicator compares available water resources to irrigation demand based on rainfall, ETP and agricultural datasets.
- Drought risk index, which measures the extent to which precipitation meets evapotranspiration requirements. It is computed based on the ratio between precipitation and evapotranspiration, providing a simple yet effective measure of climatic conditions.
- Water anomaly: it allows the identification of anomalies and extreme events by comparing weather conditions to historical baselines (1995-2059).

These indicators are presented through interactive dashboards and maps, enabling users to visualize spatial and temporal patterns and to identify the priority geographical areas for intervention.

IMPLEMENTATION CHALLENGES

The development and deployment of the Smart Irrigation Solution revealed several interconnected challenges that influenced both the methodological choices and the system design. Firstly, finalizing the objectives and functions of the Solution required nearly weekly exchanges over a period of about ten months. As data availability constraints and practical development issues gradually emerged, the scope and specifications of the Solution had to be regularly adjusted, resulting in frequent updates throughout the process.

Data-related challenges were significant. Achieving better accuracy and consistency in the results and indicators would have required “better” and easily accessible datasets. In practice, the spatial resolution of available datasets varies widely, from approximately 300 meters for evapotranspiration data to more than 25 kilometers for some forecast products. The coexistence of multiple crops within small plots,

combined with variations in soil properties and management practices, makes it difficult to represent water demand accurately. The lack of data related to hydraulic infrastructures hindered the capacity of the Solution to effectively translate the water resources derived from precipitation and runoff into effective water availability. This would have required human and development resources that were not compatible with the framework envisaged initially. Simplified assumptions were therefore needed to bridge the gap until future improvements are added to create a more permanent Solution. The Solution has been designed to allow these additions.

Technical challenges were also closely linked to geospatial processing performance. One of the main difficulties was the reprojection and aggregation of large Earth observation and forecast grids into decision-relevant spatial units such as food basket sites.

The continuous processing of high-resolution raster datasets generated substantial computational and storage requirements, particularly for near-real-time workflows. Optimizing data pipelines, spatial processing routines, and storage architecture therefore became essential to ensure both analytical robustness and operational responsiveness.

Institutional challenges also played a critical role. The project was led by the Rwanda Space Agency but required coordination with multiple stakeholders, including, the Rwanda Agriculture Board, and the Rwanda Water Board. Each stakeholder had different views about the Solution and ensuring the convergence of multiple perspectives was challenging. Differences in data formats, standards, and accessibility also required the establishment of data-sharing protocols and governance mechanisms, facilitated by the national data sharing policy adopted in 2025.

In addition, capacity building was necessary to ensure that local stakeholders could both effectively use and maintain the Solution, and also develop it further.

DISCUSSION

The experience of developing the Smart Irrigation Solution highlights the importance of balancing scientific rigor with operational feasibility and practical realities. While advanced modelling approaches can provide detailed insights, they often require data that is not available in many contexts. In such cases, simplified approaches based on global datasets and empirical relationships can provide a practical alternative and can be as consistent from a scientific perspective as a more advanced approach based on multiple assumptions or datasets of limited reliability.

The use of remote sensing data is often perceived as a panacea in such contexts, as it provides consistent and spatially comprehensive information, but experience shows that it only partially addresses the transition from observations to effective water availability and management. Taking into account the human factor and physical capacity to actually use water for irrigation or other purposes is something more complex. It involves significant developmental efforts and a shift in mindset, as it requires accepting uncertainty and approaching indicators in a more pragmatic way, seeing them not as an end in themselves but as snapshots at a given moment, imperfect by definition yet designed to support the monitoring of the sector and irrigation planning. Although the indicators are not highly precise, they are useful for identifying trends, comparing regions, and detecting emerging risks.

Another key lesson is the importance of user-centered design. The inclusion of visualization tools and simulation capabilities enhances the usability of the system, strengthens user capacity to make a smart use of the Solution, subtly reflecting the uncertainty of the indicators computed by the Solution and the monitoring role through a set of indicators and observations. This facilitates its adoption by different user groups.

Institutional factors such as data governance, stakeholder engagement, and capacity building are also critical for ensuring long-term sustainability and development.

CONCLUSION

The Smart Irrigation Solution developed in Rwanda demonstrates that it is possible to design and implement an irrigation decision-support system in a data and resources-constrained environment. By integrating satellite data, simplified modelling approaches, and user-orientated tools, the system provides valuable insights into water demand and availability.

This type of Solution provides an opportunity for centralizing and visualizing multiple datasets and fostering relationships among public stakeholders. It also allows for linking very specific tools such as WEAP models, often only used by a small number of stakeholders to more global solutions. Through that and its benefits for sectorial planning and monitoring, it highlights and recognizes the work of researchers and engineers. The project highlights the importance of alignment between objectives and resources dedicated to development, clear and practical methodologies, data integration, and strong institutional support. While challenges remain, particularly in terms of data quality and indicator accuracy, the Solution development is the first essential step in paving the way for future improvements. This project highlights the importance of considering the development of such a solution as a journey across multiple disciplines and institutions, and of embracing the uncertainties that inevitably come with integrated approaches. It also offers a clear opportunity to foster a broader culture of informed governance, as it requires both developers and users to share data and practices, and to make the effort to understand each other's constraints and perspectives. Co-construction and co-production are key in effectively designing such a tool. Thinking about the solution with a longer-term perspective and anticipating the functionalities that could be developed in the future and the related data that would be required, also provides public authorities with a practical pathway for steering sectoral development.

The lessons learned from this experience are relevant for other countries seeking to leverage geospatial technologies for irrigation sector development. They emphasize the need for flexibility, adaptability, and collaboration in the development of operational systems. Finally, they highlight the importance of a robust and effective institutional framework, which is a sine qua non for the implementation of such solutions.

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