

MULTI-SCALE SOIL MOISTURE METROLOGY IN MODELLING TOOLS FOR CLIMATE-RESILIENT AGRICULTURAL WATER MANAGEMENT

MÉTROLOGIE MULTI-ÉCHELLE DE L'HUMIDITÉ DU SOL DANS LES OUTILS DE MODÉLISATION POUR UNE GESTION DE L'EAU AGRICOLE RÉSilIENTE AU CHANGEMENT CLIMATIQUE

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ABSTRACT

The role played by metrology is a blind spot in the decision-making processes that govern agricultural water management at plot, farm and territorial scales, hence covering both the water abstraction and water allocation strategies. Firmly grounded on fundamental arguments, as knowledge of the elementary biophysical processes, thorough understanding of the principles of measurement, and the absence of any commercial statement, the academic world should provide its operational and institutional partners with insights and recommendations on the contextually relevant technologies and practices. The shared, applied and systemic objectives are to evaluate the environmental fluxes and soil-plant water budget dynamics as well as the effects of errors committed on their determination (missing data, large uncertainties, poor representativeness). Those errors propagate in the decision chains in two different ways. In some cases, decisions stem directly from the measures, e.g. the attainment of an irrigation-triggering soil moisture content. In other cases, decisions are taken from the results of models previously fitted against datasets of insufficient quality or containing insufficient information. In all cases, a systemic view is needed, and proposed here, to locate metrology in the comprehensive picture of direct and indirect levers for action in agricultural water management. The latter should rely on a contextual and agreed definition of "water need" depending on the crop, soil, climate, yield target and constrained irrigation strategy applied, informed by metrology or (and) modelling. Ultimately, the reasoning set out here applies primarily to situations of water scarcity, but should also be applicable to situations of occasional abundance and excess, as one of the challenges set by climate change is to perform the joint optimisation of irrigation and control of runoff, erosion and anoxic or hydromorphic conditions.

Keywords : Multi-scale soil moisture metrology; Climate-resilient agriculture; Water management; Water scarcity; Hydromorphic conditions.

RÉSUMÉ

Le rôle de la métrologie constitue un angle mort des processus décisionnels qui régissent la gestion de l'eau agricole à l'échelle de la parcelle, de l'exploitation et du territoire, et qui couvrent donc à la fois les stratégies de prélèvement et de répartition de l'eau. Fort de fondements essentiels — connaissance des processus biophysiques élémentaires, compréhension approfondie des principes de mesure et absence de tout parti pris commercial —, le monde universitaire devrait fournir à ses partenaires opérationnels et institutionnels des éclairages et des recommandations sur les technologies et les pratiques adaptées au contexte. Les objectifs communs, appliqués et systémiques consistent à évaluer les flux environnementaux et la dynamique du bilan hydrique sol-plante, ainsi que les effets des erreurs commises lors de leur détermination (données manquantes, fortes incertitudes, faible représentativité). Ces erreurs se propagent dans les chaînes de décision de deux manières différentes. Dans certains cas, les décisions découlent directement des mesures, par exemple lorsqu'un seuil d'humidité du sol déclenchant l'irrigation est atteint. Dans d'autres, elles sont prises à

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partir des résultats de modèles préalablement ajustés sur des jeux de données de qualité insuffisante ou contenant trop peu d'informations. Dans tous les cas, une vision systémique est nécessaire ; elle est proposée ici afin de situer la métrologie dans le tableau d'ensemble des leviers d'action directs et indirects de la gestion de l'eau agricole. Cette dernière devrait reposer sur une définition contextuelle et convenue du « besoin en eau », qui dépend de la culture, du sol, du climat, de l'objectif de rendement et de la stratégie d'irrigation sous contrainte appliquée, et qui est éclairée par la métrologie et/ou la modélisation. Enfin, le raisonnement exposé ici s'applique principalement aux situations de pénurie d'eau, mais devrait également convenir aux situations d'abondance ou d'excès ponctuels, car l'un des défis posés par le changement climatique consiste à optimiser conjointement l'irrigation et la maîtrise du ruissellement, de l'érosion et des conditions anoxiques ou hydromorphes.

Mots clés : Métrologie multi-échelle de l'humidité du sol; Agriculture résiliente au changement climatique ; Gestion d'eau; Pénurie d'eau; Conditions hydromorphes.

INTRODUCTION

Agriculture remains the largest global consumer of freshwater, placing agricultural water management at the centre of climate-resilient biomass production (Lakhiar et al., 2024; Pereira et al., 2026). Increasing water scarcity, rising energy costs, environmental impacts of irrigation, and growing climate variability strengthen the need for improved management of soil–plant water dynamics (Derardja et al., 2024; Lakhiar et al., 2024; Mortazavizadeh et al., 2025). Reliable information on soil water status across spatial and temporal scales is therefore essential, both for operational irrigation decisions at the plot and farm levels and for strategic planning at larger territorial scales (Liu et al., 2025; Singh et al., 2023).

Despite significant progress in monitoring technologies, important limitations persist (Liu et al., 2025; Loconsole et al., 2025). *In situ* sensors provide accurate point-scale measurements and support irrigation scheduling, but their deployment at sufficient density is costly, operationally fragile, and difficult to maintain over time (Loconsole et al., 2025). More importantly, point measurements remain difficult to upscale to larger spatial domains, where understanding integrated hydrological responses is required (Liu et al., 2025). Conversely, proximal and remote sensing approaches offer broader spatial coverage but introduce challenges related to interpretation, validation, and uncertainty (Derardja et al., 2024; Lakhiar et al., 2024). As a result, no single measurement technique can fully meet the requirements of multi-scale agricultural water management (Mortazavizadeh et al., 2025; Singh et al., 2023), but is able to suffice at least partially.

These limitations reveal a more fundamental issue: the fragility of the data–model link. Metrology is expected to anchor models in observable reality, while models extend measurements to unobserved or hypothetical situations, particularly in prospective studies exploring future scenarios (Kivi et al., 2023). However, this relationship is often weakened by three major risks: insufficient or unreliable data, modelling frameworks that are not sufficiently generic, and inadequate testing of their combined performance under uncertainty (Auer et al., 2024; Panchanathan et al., 2024). Addressing these risks is essential to ensure the robustness of model-based analyses used to support water management decisions.

Within this context, the notion of crop water need emerges as a central yet insufficiently defined concept (Pereira et al., 2026). At the plot and farm scale, water management consists of allocating water in space and time to meet production objectives under operational and economic constraints. Here, water need is implicitly associated with achieving a target yield. At the territorial scale, the perspective shifts toward managing a shared resource, where the focus lies on handling deficits and restrictions during periods of scarcity. These differing viewpoints result in multiple interpretations of water need, often left implicit or treated as self-evident, thereby limiting its usefulness as an operational and scientific variable.

To overcome this ambiguity, water need must be perceived and represented as a context-dependent quantity, emerging from the interaction of multiple determinants rather than as a fixed value. This calls

for a framework capable of combining measurements and modelling to quantify water need in a consistent and interpretable manner. A useful perspective is provided by the production function, linking water inputs, such as rainfall, irrigation, and initial soil reserves, to crop yield. In practice, this relationship is not unique but forms a dispersion envelope shaped by climate conditions, soil properties, crop characteristics, and management strategies (Liu et al., 2025). Irrigation strategies, defined through decision rules based on soil water status, represent a key interface where measurements and model outputs are directly mobilised.

This plot- and farm-scale perspective constitutes a first entry point to assess the robustness of the data–model link, by examining whether available data are sufficient, whether modelling approaches are appropriate, and how uncertainties influence outcomes. However, agricultural water management cannot be fully understood at these scales alone. Local determinants of water need are influenced by external drivers, including agricultural policies, technological innovations, and climate conditions, while local practices generate feedbacks that affect water availability at larger scales.

This leads to the need for a systemic, multi-scale perspective, where metrology and modelling are considered as integral components of a broader set of interacting processes (Mortazavizadeh et al., 2025). Within such a framework, it becomes possible to compare the relative importance of different levers for action, such as improving measurement accuracy, modifying agricultural practices, or investing in infrastructure, and to evaluate their combined effects under uncertainty.

METHODOLOGY

This study adopts a conceptual and integrative approach to analyse the links between soil water metrology and modelling in agricultural water management. Rather than relying on a single dataset or case study, the methodology is designed to structure and evaluate how measurements and models interact across spatial and temporal scales, with particular emphasis on their use in prospective analyses. The underlying premise is that the robustness of agricultural water management studies depends on the strength of the data–model link, understood as the capacity of measurements to inform models and of models to extend measurements to unobserved or hypothetical conditions. To examine this relationship, the analysis is organised as a progressive framework that follows the same logic as the paper: first addressing the data–model link itself, then focusing on the concept of water need at plot and farm scales, and finally extending to a systemic, multi-scale perspective.

The first step consists in analysing the data–model link through the identification of three interrelated risks that commonly arise in agricultural water management studies. The first risk concerns the adequacy of measurement data, questioning whether available observations are sufficiently reliable, representative, and complete to constrain modelling approaches. The second risk addresses the relevance and generality of conceptual and modelling frameworks, examining their capacity to represent diverse conditions and to remain valid when extrapolated beyond observed situations. The third risk relates to uncertainty, considering whether the combined data–model system has been sufficiently tested against measurement errors, parameter variability, and scenario assumptions. These three dimensions should not be considered separately but as interacting factors that jointly determine the robustness of model-based analyses, especially in prospective contexts where both data and models are subject to extrapolation.

The second step focuses on the quantification of crop water need using a so-called generalized or generic production-function perspective as an organising framework. In this approach, the relationship between water inputs, such as rainfall, irrigation, and initial soil water reserves, and crop yield is deemed strongly influenced by several interacting determinants. These include crop type and variety, soil properties, climatic conditions, yield targets, and management strategies. Instead of assuming a single deterministic relationship, the production function is shown as a dispersion envelope within which different combinations of these factors lead to varying outcomes. Water need therefore emerges as a context-dependent quantity, rather than a fixed, predetermined value – which *de facto* pleads for adaptable management strategies. Particular attention is given to irrigation strategies, which serve as a interface between metrology and modelling. These strategies are defined through decision rules,

often expressed as threshold values of soil water indicators that may be either measured in the field or simulated by models. This framework provides an opportunity to assess, at plot and farm scales, whether measurement systems deliver sufficient information, whether modelling approaches capture system variability adequately, and how uncertainties influence both the estimation of water need and resulting management decisions.

The third step extends the analysis to a systemic and multi-scale framework, allowing the integration of local processes within a broader set of interacting drivers. Agricultural water management is thus considered as a system where local determinants of water need are influenced by external factors such as climate variability, technological developments, and agricultural policies, while local practices generate feedbacks that affect water availability at regional scales. The methodology consists in structuring these interactions and identifying the direct and indirect levers for action that operate across scales. Emphasis is placed on understanding how metrology contributes to this system, not only through the production of measurements but also through its role in informing modelling, supporting decision-making and influencing broader management strategies. In this context, measurement systems are evaluated both in terms of their intrinsic properties, the accuracy, representativeness, and repeatability, and their functional role within the data–model continuum.

Across these three steps, the analysis is guided by a set of common evaluation principles aimed at assessing the robustness and usability of the combined metrology–modelling framework. These include the reliability and representativeness of measurements, the consistency and interoperability of datasets, the adaptability and generality of modelling approaches, and the explicit consideration of uncertainties throughout the process. The focus is given to how uncertainties propagate from measurements to model outputs and how they affect the interpretation and use of results in decision-making contexts. The methodology ultimately leads to a synthetic assessment of the data–model link, identifying limitations, complementarities, and opportunities for improving the integration of measurements and models in agricultural water management.

RESULTS

Data-model link in prospective agricultural water management studies

Put simply, metrology vows to anchor models in tangible, observable reality while models aim to extend measurements to non-observed, unrealised situations, including the hypothetical and often "extrapolated" conditions of prospective studies known to question the robustness of the data-model link. Two major risks exist, that "not enough reliable information is present in the dataset" or "the conceptual approach or the modelling framework is not generic enough", they combine when "the data-model link has not been tested against significant uncertainties". By following this line of thought, these three broad, unresolved questions can be rephrased in more specific terms for the agricultural water management issue tackled here. The proposed way to proceed is to first indicate what is meant by "agricultural water management" here, what is covered, encompassed, and expected, then to consider the above three angles as separate entry points, via measurements only, via conceptual representations only, or trying to jointly operate them.

At plot and farm scale, from the irrigator's point of view, water management consists in finding the most appropriate strategy of spatial and temporal water allocation, having to rule water amounts between plots and in time on all plots. Seeking improvements certainly appeals to "scenarios of scenarios" which combine crop rotation scenarios with irrigation scenarios. Then what is meant by "the most appropriate strategy" is certainly decision rules able to meet the production, economic and environmental objectives assigned to irrigation, most likely under personal, operational and regulatory constraints. However, the main concern remains to which extent crop water needs will be satisfied. At territorial scales, from the water manager's point of view, the main concern is rather to which extent crop water needs will not be satisfied, as the result of necessary restrictions, leading to deficit irrigation, during periods of tension on the shared resource.

In summary, the concept of water need is central but quite loosely defined, or defined differently between actors of the same territory, depending on their goals, perception and sensibilities. This concept is sometimes even deliberately left undefined, as if it was self-evident, or maybe to short-circuit any discussion, analysis or formal examination - which in turn should be conducted in scientific terms. The challenge is to quantify water need, at least by providing correct orders of magnitude, to undermine principled stance and facilitate consultation leaning on scientific approaches: metrology, modelling or both in combination.

Despite these developments, significant limitations persist in both measurement and modelling approaches. *In situ* sensor networks remain difficult to deploy at sufficient density, and their outputs are not easily extrapolated to larger spatial domains where emergent hydrological processes must be captured. At the same time, modelling frameworks used to simulate soil–plant–atmosphere interactions often rely on simplified assumptions or insufficiently constrained parameters, limiting their robustness under changing or hypothetical conditions.

This dual limitation highlights a fundamental issue: the weakness of the data–model link in agricultural water management. On the one hand, datasets may lack sufficient reliability, representativeness, or completeness. On the other hand, conceptual representations and modelling frameworks may fail to adequately capture system complexity or remain insufficiently generic across contexts. These shortcomings become particularly critical in prospective studies, where models are used to explore scenarios beyond observed conditions.

Addressing this challenge requires moving beyond isolated measurement or modelling efforts toward integrated frameworks, where metrology and modelling are explicitly connected, evaluated, and jointly improved. In this perspective, metrology anchors models in observable reality, while models extend measurements to unobserved, extrapolated, or future situations. Ensuring the robustness of this relationship is therefore a key scientific and operational objective.

Metrology and modelling to document water needs in the production function

Assuming no absolute definition of crop water needs exists, only contextual evaluations should be conducted, which suggests the co-existence of several determinants for a context-specific water need value, as illustrated in Fig.1. This figure can be interpreted in two different yet complementary ways, as follows.

First, as a generalised production function whose dispersion envelope indicates that several factors intervene in the complex link between water in the system (initial water reserve, total rainfall, total irrigation) and the irrigated yield obtained. For example, different climatic characteristics (here, different rain chronicles) will result in different “rainfed” yields, while different irrigation strategies will add dispersion too. The envelope becomes even larger when considering different crops or varieties, as well as possible actions on soil properties. Finally, the target zone indicated in light blue is the domain to reach, playing on metrology- or model-informed irrigation strategies and other possible levers for action, when combining the mentioned constraints and expectations.

It should be kept in mind that conversely, the traditional and conservative version of the production function only depicts the link between cumulative irrigation amounts and yield increase, disregarding all other effects, thereby precluding broader adaptations and perspectives.

Second, the same representation allows identifying the interplay between multiple determinants of the contextual water need, jointly controlled by crop or varietal selection, local soil properties, yield target with associated constraints and expectations, and irrigation strategies opted for. The latter forcefully appeal to irrigation-triggering criteria expressed in terms of threshold values of soil water reserve, soil volumetric water content or soil matric potential, either measured in some locations or (and) modelled over the domains of interest.

This representation rather pertains to the plot and the farm scale. This is the first occasion to apply the proposed procedure, to check if "enough reliable information is present in the dataset", then verify that "the conceptual approach or the modelling framework is generic enough", and finally test "the data-model link against significant uncertainties".

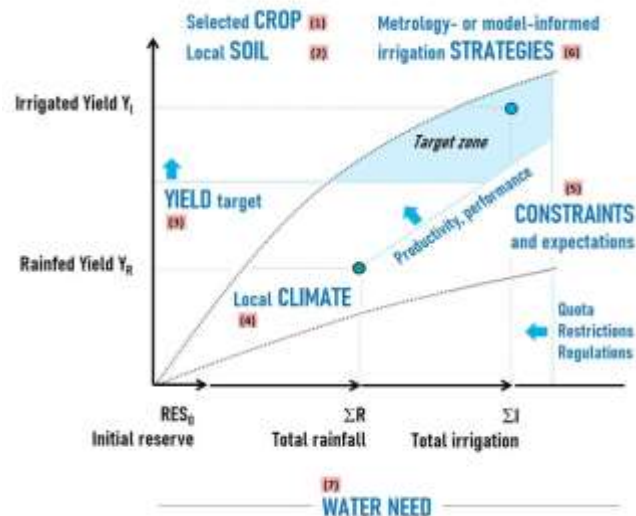


Figure 1. Production function showing the combined, contextual and systemic determinants of water need (7), jointly controlled by the selected crop and variety (1), the local soil properties (2), the assigned yield target (3) for the "irrigated yield" (Y_I), the local climate (4) as total rainfall and rain chronicle result in the reference rainfed yield (Y_R), and various constraints and expectations (5) associated to the explored irrigation strategies and decision rules (6), the latter either informed by modelling or directly drawn from field measurements.

DISCUSSION

The position of metrology and modelling in a systemic view

Larger spatial and temporal scales are addressed when importing the previous analysis in a broader picture, gathering most of the direct and indirect levers for action in agricultural water management, aiming to organize them in a systemic view (Fig.2).

Such a representation clearly indicates that all previously mentioned determinants of crop water need, at local scales, may be influenced by external effects, that is effects issued from larger scales. For example, crop properties will differ whether varietal selection is used or not, or if maize is replaced by sorghum. In the same logic, soil properties are expected to differ between no-tillage conservation agriculture and conventional systems, some of those evolutions being encouraged by dedicated funds.

In other words, national agricultural models and public policies result in local effects in soil and crop properties, with subsequent influence on local water needs, but also soil and water quality. Recent comprehensive modelling efforts Europe wide have shown combinations of land management and hydro morphological measures optimally placed withing small agricultural catchments better perform compared to a set of individual measures (Praprotnik Kastelic et al, 2025), however the policy instruments for spatially coordinated implementation of combinations of measures are still inadequate to explore this potential of optimally retaining water and nutrients at a catchment scale (Nesheim et al., 2026).

Several feedback loops also exist from the smallest spatial and temporal scales to the largest ones, as for example the influence exerted by local short-term water use strategies on the medium-term availability of the regional-scale resource, as possibly described by coupled agronomic and hydrological approaches. Another example is the possibility for relevant practices and technologies in

metrology to be recognised then recommended within public policies, then encouraged via economic incentives or derogatory water rights, thus alleviating the use constraints bearing on irrigation strategies.

This representation also allow comparing the weights of virtually any effects shown in the diagram, provided the corresponding connections may be documented. For example, to compare the effects of large size water storage infrastructure with those of positive effects of conservation agriculture on soil storage capacity, in a given context. The same logic holds when focusing on metrology as such, or how it feeds agronomic modelling. For example, reducing uncertainties on the identification of soil properties will help meeting the irrigation targets more precisely thus reduce water needs to do so, and in turn preserve the shared resource.

To which extent is it more efficient, comparable to, or compatible with efforts in the transition from conventional to agroecological systems? Indeed, current evaluations suggest that European Common Agricultural Policy (CAP) funds are more likely to promote greater rather than more efficient water use (European Court of Auditors, 2021). Furthermore, at a global level, half of the irrigation expansion in the twenty-first century has occurred in already water-stressed regions (Mehta et al., 2024), highlighting the disconnect between technical potential and policy implementation.

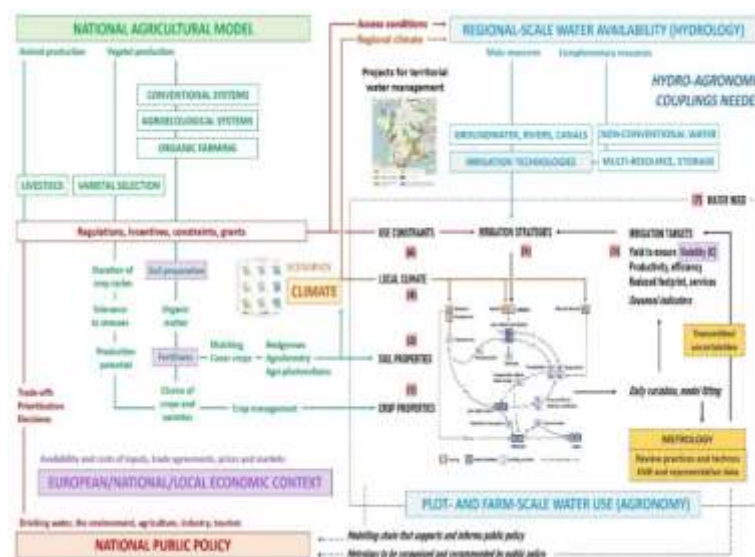


Figure 2. Systemic view of the direct and indirect levers for action in the multi-scale, multi-purpose agricultural water management issue, in the face of climate change. Emphasis is placed on the position and role played by metrology in supporting irrigation decisions, either straight from field measurements or via crop and irrigation models. The merits, drawbacks, performance and uncertainties of different practices and technologies in metrology may (and should) be reviewed in this framework to assess their influence and weight in the whole process.

Reframing metrology and modelling as a coupled system

The systemic representation proposed in this study (Fig. 2) allows reframing metrology and modelling not as independent technical components, but as a coupled system governing the quality of agricultural water management decisions across scales. This shift is essential because the effectiveness of irrigation strategies and resource allocation policies ultimately depends not only on the availability of data or the sophistication of models, but on the consistency and robustness of their interaction.

At plot and farm scales, metrology directly informs decisions through measurable thresholds, such as soil water content triggering irrigation. At the same time, it indirectly supports decision-making through model calibration and validation. However, as shown in the results, weaknesses in measurement

representativeness or uncertainties in parameter estimation may lead to structurally biased models, whose outputs are then used in prospective analyses. This introduces a critical but often overlooked issue: errors originating in metrology can become amplified when propagated through modelling frameworks, especially when extrapolating beyond observed conditions. Once accounted for, could those multi-scale interactions lead to redefine and better evaluate water need?

The systemic perspective further advocates that crop water need cannot be understood independently of the multi-scale processes that shape agricultural systems. Local determinants, such as soil properties or crop selection, are influenced by broader drivers including climate change adaptation strategies, technological development, and policy incentives, including payments for environmental services, decided at the regional, national or European levels. Conversely, local irrigation decisions and water use strategies collectively influence regional resource availability and long-term system resilience.

In this context, water need emerges as a negotiated and context-dependent variable, rather than a purely biophysical quantity. Its interpretation depends on the scale of analysis, the objectives of different actors, and the constraints imposed by the system. The production-function framework provides an operational entry point, but its meaningful application relies on the ability of metrology and modelling to consistently characterise the underlying processes and uncertainties.

Improvements in agricultural water management should be evaluated not only within domains (e.g. better sensors or better models), but across competing and complementary levers for action. The framework proposed enables comparison between investments in measurement accuracy, changes in agronomic practices (e.g. conservation agriculture), and infrastructure development (e.g. storage systems). Improving metrology can lead to immediate gains in the precision of irrigation decisions and reductions in unnecessary water use. However, its relative effectiveness depends on how measurement improvements propagate through models and decision chains compared to structural changes in farming systems. This raises an important research and policy question: to what extent should efforts prioritise better quantification of existing systems versus transformation of those systems?

The technical robustness we seek is essential for the effective implementation of emerging policy frameworks. For instance, the proposed 2028–2034 CAP and the EU Water Resilience Strategy aim for "simpler, more targeted" interventions, and catchment-scale nature-based solutions. However, the success of these initiatives depends on moving away from generic administrative rules toward mapped, site-specific interventions. Here, the metrology-modelling framework proposed in this study should aim to provide the necessary bridge between environmental monitoring and contractual compliance. By using traceable indicators and optimal spatial targeting, administrations can better align CAP eco-schemes and agri-environment-climate interventions with local hydrology. Ultimately, coupling these policy instruments with a rigorous, model-supported data continuum allows for the shift toward the "water-smart" agricultural economy envisioned by current EU strategies, ensuring that investments in resilience are backed by verifiable, evidence-based performance metrics.

CONCLUSIONS

This study highlights the central role of metrology in strengthening agricultural water management through its interaction with modelling frameworks. By explicitly addressing the data–model link, it shows that the robustness of both operational decisions and prospective analyses depends on the availability of reliable, representative, and well-characterised measurements, as well as on the capacity of models to generalise beyond observed conditions while accounting for uncertainty.

The analysis demonstrates that crop water need cannot be treated as a fixed quantity, but must be understood as a context-dependent outcome resulting from the interaction of soil, crop, climate, and management factors. The production-function perspective provides a useful framework to formalise this concept and to connect measurements and modelling at plot and farm scales. Extending this approach to a systemic, multi-scale perspective further reveals the importance of feedbacks and

external drivers, positioning metrology and modelling within a broader set of interacting levers for action.

Ultimately, improving agricultural water management under climate variability requires integrated frameworks that combine multi-scale measurements, robust modelling approaches, and explicit consideration of uncertainties. Strengthening this integration will enhance decision-making across scales, support more efficient use of water resources, and contribute to the long-term resilience of agricultural systems.

REFERENCES

- Auer, A., Gauch, M., Kratzert, F., Nearing, G., Hochreiter, S., Klotz, D., 2024. A data-centric perspective on the information needed for hydrological uncertainty predictions. *Hydrol. Earth Syst. Sci.* 28, 4099–4126. <https://doi.org/10.5194/hess-28-4099-2024>
- Derardja, B., Khadra, R., Abdelmoneim, A.A.A., El-Shirbeny, M.A., Valsamidis, T., De Pasquale, V., Deflorio, A.M., Volden, E., 2024. Advancements in Remote Sensing for Evapotranspiration Estimation: A Comprehensive Review of Temperature-Based Models. *Remote Sens.* 16. <https://doi.org/10.3390/rs16111927>
- European Court of Auditors, 2021. Sustainable water use in agriculture: CAP funds more likely to promote greater rather than more efficient water use. European Union. 55p.
- Kivi, M., Vergopolan, N., Dokoohaki, H., 2023. A comprehensive assessment of in situ and remote sensing soil moisture data assimilation in the APSIM model for improving agricultural forecasting across the US Midwest. *Hydrol. Earth Syst. Sci.* 27, 1173–1199. <https://doi.org/10.5194/hess-27-1173-2023>
- Lakhari, I.A., Yan, H., Zhang, C., Zhang, J., Wang, G., Deng, S., Syed, T.N., Wang, B., Zhou, R., 2024. A review of evapotranspiration estimation methods for climate-smart agriculture tools under a changing climate: vulnerabilities, consequences, and implications. *J. Water Clim. Change* 16, 249–288. <https://doi.org/10.2166/wcc.2024.048>
- Liu, R., Chang, C., Zhong, R., Lu, S., 2025. Soil Moisture Monitoring Method and Data Products: Current Research Status and Future Development Trends. *Remote Sens.* 17. <https://doi.org/10.3390/rs17243945>
- Loconsole, D., Elia, M., Conversa, G., De Lucia, B., Cristiano, G., Elia, A., 2025. Soil Moisture Sensing Technologies: Principles, Applications, and Challenges in Agriculture. *Agronomy* 15. <https://doi.org/10.3390/agronomy15122788>
- Mehta, P., Siebert, S., Kumm, M., Deng, Q., Ali, T., Marston, L., Xie, W., Davis, K.F., 2024. Half of twenty-first century global irrigation expansion has been in water-stressed regions. *Nat. Water* 2, 254–261. <https://doi.org/10.1038/s44221-024-00206-9>
- Mortazavizadeh, F., Bolonio, D., Mirzaei, M., Ng, J.L., Mortazavizadeh, S.V., Dehghani, A., Mortezaei, S., Ghadirzadeh, H., 2025. Advances in machine learning for agricultural water management: a review of techniques and applications. *J. Hydroinformatics* 27, 474–492. <https://doi.org/10.2166/hydro.2025.258>
- Nesheim, I., Szulecka, J., Monaco, F. and R. Cvejić, 2026. Development of incentives for the promotion of water and nutrient management techniques in agricultural catchments based on the Sustainable Development Goals. Deliverable D6.4. EU Horizon 2020 OPTAIN Project, Grant agreement No. 862756
- Panchanathan, A., Ahrari, A., Ghag, K.S., Mustafa, S., Haghighi, A.T., Kløve, B., Oussalah, M., 2024. An overview of approaches for reducing uncertainties in hydrological forecasting: Progress and challenges. *Earth-Sci. Rev.* 258, 104956. <https://doi.org/https://doi.org/10.1016/j.earscirev.2024.104956>
- Pereira, L.S., Salman, M., Paredes, P., López-Urrea, R., Allen, R.G., 2026. Innovations in the Revised FAO56 Guidelines for Computing Crop Water Requirements: Data, Calculation Methods, Irrigation, and Climate Change Challenges. *Water* 18. <https://doi.org/10.3390/w18070793>
- Praprotnik Kastelic, J., Banovec, P., Cilenšek, A., Cvejić, R., Farkas, C., Krzeminska, D., Nesheim, I., Strauch, M., Szulecka, J., Škerjanec, M., Volk, M., Witing, F., Glavan, M. 2025. Guidelines for optimal implementation of NSWRM and their combinations in the specific European biogeographical region of interest (Pannonian, Continental, Boreal) across various agroecosystems, terrain, soil, climatic conditions. Deliverable D6.3 EU Horizon 2020 OPTAIN Project, Grant agreement No. 862756
- Singh, A., Gaurav, K., Sonkar, G.K., Lee, C.-C., 2023. Strategies to Measure Soil Moisture Using Traditional Methods, Automated Sensors, Remote Sensing, and Machine Learning Techniques: Review, Bibliometric Analysis, Applications, Research Findings, and Future Directions. *IEEE Access* 11, 13605–13635. <https://doi.org/10.1109/ACCESS.2023.3243635>