

WATSIM: AI AND SATELLITE DECISION SUPPORT FOR IRRIGATION

WATSIM : INTELLIGENCE ARTIFICIELLE ET SYSTEME D'AIDE A LA DECISION BASEE SUR LES DONNEES SATELLITAIRES POUR L'IRRIGATION

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ABSTRACT

Climate change is amplifying hydrological variability through rising temperatures, altered rainfall regimes, and more frequent extreme events, which in turn lengthen, intensify, and desynchronise drought episodes. These dynamics undermine the capacity of territories to guarantee water security, sustain economic activities, and preserve aquatic and groundwater-dependent ecosystems. For basin organisations and regulatory agencies, growing uncertainty complicates the allocation of limited water resources among irrigation, drinking-water supply, industry, hydropower generation, and environmental flows, while regulatory pressure and stakeholder expectations for transparency continue to increase. In certain regions, successive dry years and recurring conflicts among users have made these tensions highly visible, with agriculture frequently exposed to early and severe restrictions.

Conventional management approaches, relying on rating curves, static operating rules, and ex-post diagnostics, remain largely reactive and offer limited capacity to explore alternative restriction or allocation strategies before critical thresholds are reached. Proactive management therefore requires decision-support tools capable of projecting future resource availability, simulating contrasted abstraction scenarios, and providing a shared quantitative basis for planning, and drought-management gestion. WatSim responds to these needs with a basin-scale hydrological simulator. Mainly developed by BWI (Blue Water Intelligence), with INRAE's TETIS as scientific partner and co-funded by the Occitanie Region under France 2030 via Bpifrance, the platform is structured around four functions: representing hydrological dynamics at high spatial and temporal resolution under climate stress; explicitly modelling abstractions by use, especially agricultural withdrawals; integrating satellite data to better characterise demand and resource conditions; and providing a scenario-simulation environment to test graduated restrictions, cropping-system adjustments, and structural or operational measures such as reservoir creation or reconfiguration.

WatSim supports more anticipatory, transparent, and adaptive water governance in the face of increasing drought risk, with a specific focus on medium-term projections over a six-month horizon that match the timescale of agricultural decision-making and seasonal water-allocation negotiations.

Keywords: Climate change; frequent extreme events; Proactive management; hydrological dynamics; water governance.

RESUME

Le changement climatique renforce la variabilité hydrologique en raison de la hausse des températures, de la modification des régimes pluviométriques et de la fréquence accrue des événements climatiques extrêmes, ce qui à son tour prolongent, intensifient et désynchronisent les épisodes de sécheresse. Ces dynamiques compromettent la capacité des territoires à garantir la sécurité hydrique, à soutenir les activités économiques et à préserver les écosystèmes aquatiques et ceux qui dépendent des eaux souterraines. Pour les organismes de bassin et les autorités de régulation, l'incertitude croissante complique la répartition des ressources en eau limitées entre l'irrigation, l'approvisionnement en eau

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potable, l'industrie, la production hydroélectrique et les débits environnementaux, tandis que la pression réglementaire et les attentes des parties prenantes concernant la transparence ne cessent de s'accroître. Dans certaines régions, des années de sécheresse successives et des conflits récurrents entre les usagers ont rendu ces tensions très visibles, l'agriculture étant fréquemment soumise à des restrictions précoces et sévères.

Les approches de gestion conventionnelles, qui s'appuient sur des courbes de tarage, des règles d'exploitation statiques et des diagnostics effectifs, restent largement réactives et offrent peu de possibilités d'explorer des stratégies alternatives de restriction ou de répartition avant que des seuils critiques ne soient atteints. Une gestion proactive nécessite donc des outils d'aide à la décision capables de projeter la disponibilité future des ressources, de simuler des scénarios de prélèvement contrastés et de fournir une base quantitative commune pour la planification et la gestion de la sécheresse.

WatSim répond à ces besoins grâce à un simulateur hydrologique à l'échelle du bassin versant. Développée principalement par BWI (Blue Water Intelligence), avec le projet TETIS de l'INRAE comme partenaire scientifique et cofinancée par la région Occitanie dans le cadre du programme France 2030 via Bpifrance, la plateforme s'articule autour de quatre fonctions : la représentation des dynamiques hydrologiques à haute résolution spatiale et temporelle en situation de stress climatique; la modélisation explicite des prélèvements par usage, en particulier les prélèvements agricoles; la mise à disposition d'un environnement de simulation de scénarios permettant de tester des restrictions progressives, l'intégration des données satellitaires pour mieux caractériser la demande et l'état des ressources; et des ajustements des systèmes agricoles, ainsi que des mesures structurelles ou opérationnelles telles que la création ou la redéfinition de réservoirs.

WatSim favorise une gouvernance d'anticipation de l'eau plus transparente et évolutive face au risque croissant de sécheresse, en mettant particulièrement l'accent sur des projections à moyen terme sur un horizon de six mois, qui correspondent à l'échelle temporelle de la prise de décision agricole et des négociations saisonnières sur la répartition de l'eau.

Mots-clés : Changement climatique; Événements climatiques extrêmes; Gestion proactive; Dynamique hydrologique; Gouvernance de l'eau.

1. NECESSITY TO RESPOND TO THE INCREASING DIFFICULTY OF HYDROLOGICAL FORECAST MANAGEMENT

1.1 *The challenge of anticipatory water management before seasonal conditions become visible*

In the Upper Atbara dam in Sudan, seasonal forecasts revealed that earlier drought management and water-allocation decisions could have avoided US\$16 million in losses in one year, showing the cost of allocating water too late or without sufficient medium-term visibility². This example reflects a broader reality in many basins, where agricultural water management still unfolds under partial visibility and high uncertainty, while decisions often have to frame an entire irrigation season. Cropping patterns, sowing dates, irrigation investments, and water-sharing arrangements are usually fixed several months before peak water demand, at a moment when future river flows, rainfall, and aggregate demand remain highly uncertain. This temporal mismatch constitutes a structural feature of irrigated basins, particularly where summer low flows play a central role and where multiple uses compete for limited resources.

In such contexts, irrigators, basin managers, and public authorities frequently rely on a combination of local experience, historical records, and near-real-time hydrological monitoring to guide decisions that would in principle require a much longer planning horizon. Historical analogies and expert judgement retain operational relevance, but climate variability, drought intensification, and the changing frequency of low-flow episodes reduce confidence in the idea that future seasons will behave like past ones. As a

² Portele, T., Lorenz, C., Dibrani, B., Laux, P., Bliefernicht, J., & Kunstmann, H. (2021). Seasonal forecasts offer economic benefit for hydrological decision making in semi-arid regions. *Scientific Reports*, 11(1).

result, many stakeholders are forced to manage water distribution in real time, with limited ability to test how different early choices could influence both resource availability and agricultural production later in the season.

Seasonal and subseasonal hydrological prediction has emerged as a research field precisely because of this gap between the timing of decisions and the visibility of seasonal conditions³. Forecast skill at these horizons depends on both initial hydrological conditions and the quality of seasonal climate information, which creates a strong link between hydrology, climatology, and operational water management. For all stakeholders, the central question is not only the technical accuracy of forecasts, but also the ability of medium-term information to support appropriate decisions under uncertainty.

1.2 Insufficient forecast horizon for agricultural planning

Existing operational tools in many basins remain concentrated on short-term monitoring and early warning, rather than on the seasonal perspective required for agricultural planning. Hydrological dashboards, gauging-station portals, and regulatory threshold systems provide essential information on observed flows, current alert levels, and ongoing restrictions; such tools are indispensable for compliance monitoring, flood warning, and low-flow management on time scales of days to weeks. However, the emphasis of these systems remains strongly oriented towards present or past states, with limited capability to represent plausible seasonal trajectories of discharge and demand in a way that speaks directly to cropping decisions.

Agricultural decision tools, for their part, commonly focus on agronomic performance, input management, or economic optimisation at farm level, often with little direct connection to basin-scale resource constraints. Crop calendars, fertilisation advice, and irrigation scheduling guidelines may implicitly assume a certain level of water availability, but rarely integrate explicit projections of basin-scale hydrology under climate stress. The result is a fragmented information environment, in which resource monitoring and agricultural decision-making proceed largely in parallel rather than through a shared analytical frame.

This fragmentation weakens the critical link between projected hydrological conditions and spatially distributed crop water demand. That link plays a central role in modern allocation problems, because the balance between availability and demand determines where tensions will emerge, which uses remain compatible with projected conditions, and how changes in cropping patterns affect river hydrology and environmental flows. Short-range forecasts over a few days or weeks, such as the 10-day prevision provided by Blue Water Intelligence deliver high value for immediate operations, but rarely support major adjustments in crop choice, sowing schedules, or allocation agreements.

1.3 Need for anticipatory management under climate and demographic pressure

Climate change and demographic trends are increasing pressure on water resources and making allocation choices more sensitive⁴. Rising temperatures, changing rainfall patterns, and more frequent extreme events are lengthening drought periods, while population growth and expanding irrigated areas are reinforcing demand for water, especially in regions where agriculture accounts for a large share of With drawals. At the global level, projections also point to a major increase in irrigation demand by 2050, which highlights the need to anticipate water stress rather than react to it once it has already intensified. In this context, purely reactive management narrows the range of possible responses and tends to push allocation negotiations into crisis mode.

When decisions are taken only after critical thresholds have been crossed, room for adjustment becomes very limited, and trade-offs are often made under pressure, with a higher risk of conflict between users. By contrast, anticipatory approaches based on medium-term projections, structured

³ WMO Guidelines on Seasonal Hydrological Prediction (WMO-No. 1274); Tang et al. (2016).

⁴ OECD. (2023). Water resources allocation: Sharing risks and opportunities. OECD Publishing.

scenario analysis, and an explicit representation of both supply and demand make it possible to prepare restriction plans, crop adjustments, and infrastructure measures in advance.

These approaches also respond to growing expectations around transparency and accountability in water governance⁵. Regulators, users, and the public increasingly expect allocation, restriction, and prioritization decisions to be clearly and quantitatively justified. Decision-support tools that can anticipate, can therefore contribute to stronger and more legitimate governance frameworks.

2. CONTRIBUTION OF WATSIM TO DECISION-MAKING

The **Wat Sim** project, led and funded in majority by Blue Water Intelligence (BWI) with INRAE's UMR TETIS as an scientific partner, and Région Occitanie as a minority funding partner through the France2030 program processed by Bpifrance, seeks to address these needs by developing an advanced hydrological simulator. As a freshwater abstraction simulator, WatSim is designed to quantify the impact of water withdrawals and releases on river hydrology and to connect those impacts with agricultural water demand in predominantly agricultural watersheds.

The methodological foundation combines process-based hydrological models with AI-powered dynamic calibration, based on historical meteorological data, numerical weather-prediction outputs, discharge and water-level time series, and digital terrain models.

2.1 *Six-month horizon for anticipating water availability*

A central design choice in WatSim concerns the temporal horizon of hydrological projections, which extends up to six months. This medium-term window aligns with key agricultural decisions such as crop selection, sowing dates, seasonal irrigation investments, and the negotiation of allocation rules between user groups. Decisive choices for a given irrigation season are often made several months before the most water-demanding phases of crop cycles; a six-month projection therefore offers stakeholders enough time to adjust strategies while remaining close enough to current conditions to retain practical value.

Projections rely on a constructed analogs method that identifies historical meteorological patterns similar to recent atmospheric conditions and recombines those patterns into plausible future trajectories for variables such as precipitation and temperature. Analog-based approaches have a long tradition in seasonal forecasting and water-supply planning, especially when the objective consists of exploring plausible seasonal states rather than predicting single deterministic outcomes. Meteorological projections generated in this way then feed the hydrological model, which delivers projected discharge and water-level series for each virtual station along the river network over the six-month window.

The six-month horizon represents a compromise between reliability and usefulness. Shorter horizons of a few weeks generally do not allow major adjustments in cropping systems or sowing schedules, while longer horizons of one year or more become too uncertain to support concrete operational decisions on irrigation or allocation. In temperate basins such as those of southwestern France, a six-month window typically covers the core spring–summer irrigation season, which often coincides with the period of greatest tension on water resources.

Medium-term projections therefore support several levels of planning: before the season, hydrological conditions help farmers and advisory services assess whether high-water-demand crops remain compatible with expected availability; during the season, updated projections provide early signals of worsening drought risk, enabling basin authorities to design graduated restriction plans ahead of time.

⁵ OECD. (2023). Water resources allocation: Sharing risks and opportunities. OECD Publishing.

2.2 Simulation of abstraction and water-sharing scenarios

Beyond projection, WatSim incorporates a dedicated abstraction simulator that represents withdrawals and releases explicitly and supports comparison of alternative water-sharing arrangements at basin scale. Scenario construction takes place through map-based interfaces and menus such as the **Virtual Station**, **Map Layer**, **Scenario Draft**, and **Scenario Archive components**. These interfaces allow users to select river reaches or virtual stations, define abstraction or release points, and specify parameters such as withdrawal magnitude, temporal pattern (continuous or seasonal), and activation period.

Parameterised scenarios can be stored in draft form, revised through consultation processes, and submitted to the modelling engine for full hydrological runs. Once executed, scenarios become accessible through the Scenario Archive module, which links each scenario to a specific model run and exposes projected natural discharge, projected discharge under abstraction, and associated indicators at relevant stations. Dashboards allow export of results in tabular form, making further analysis and integration into external reporting tools straightforward.

From an operational perspective, this architecture turns WatSim into a scenario laboratory for basin-scale allocation questions. Stakeholders can examine, for example, how combinations of irrigation withdrawals, environmental flow targets, and drinking-water abstractions affect key control sections during low-flow periods. Scenario analysis also supports the design of graduated restriction plans, by illustrating how successive reductions in agricultural or industrial uses influence compliance with alert and crisis thresholds along the network. Spatially explicit outputs anchored in basin cartography help discussions focus on concrete control sections rather than on abstract volume allocations, thereby making upstream–downstream dependencies and distributional effects more visible.

2.3 Linking projections with crop water requirements

A major innovation of WatSim lies in the explicit integration of crop water requirements into a framework that previously concentrated mainly on hydrological supply. Earlier tools in the BWI ecosystem focused on river flows, while the new configuration introduces a detailed characterisation of agricultural water demand at parcel scale. The demand-side component relies on a combination of land-cover mapping, evapotranspiration modelling, and coupling between demand projections and hydrological outputs.

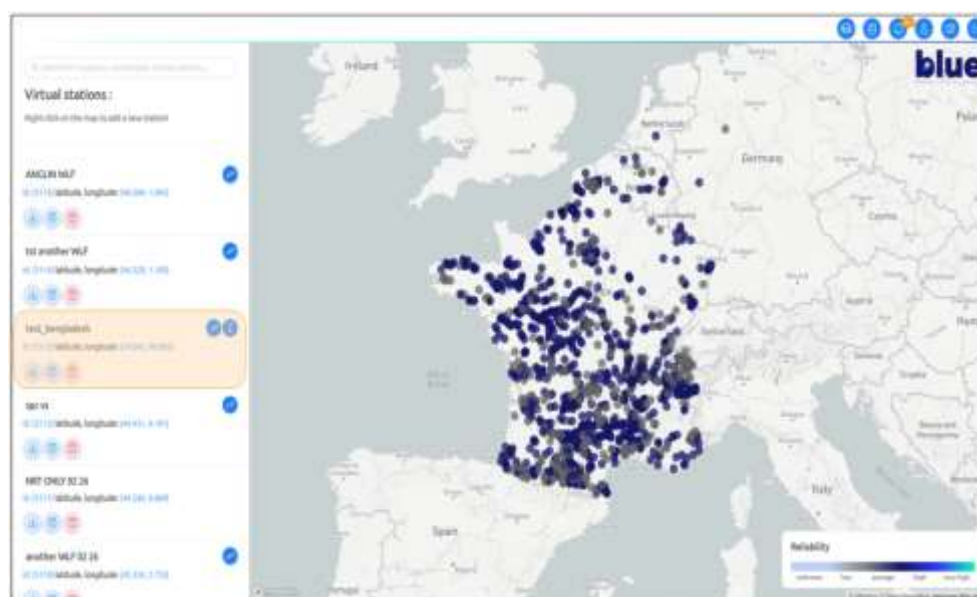


Figure 1. Interactive map interface for placing BWI virtual stations



Figure 2. Virtual station discharge data interface

Satellite-derived land-cover and crop-type maps, based on Sentinel-1 and Sentinel-2 image time series and INRAE classification methods, identify crop types and irrigated parcels, while the *Registre Parcellaire Graphique* provides parcel boundaries used as work units. A seasonal mask distinguishes spring–summer cultivation from winter crops, reflecting differences in irrigation demand during the critical low-flow period. Such mapping aligns with recent developments in crop-type classification using multi-temporal Sentinel imagery and machine-learning approaches.

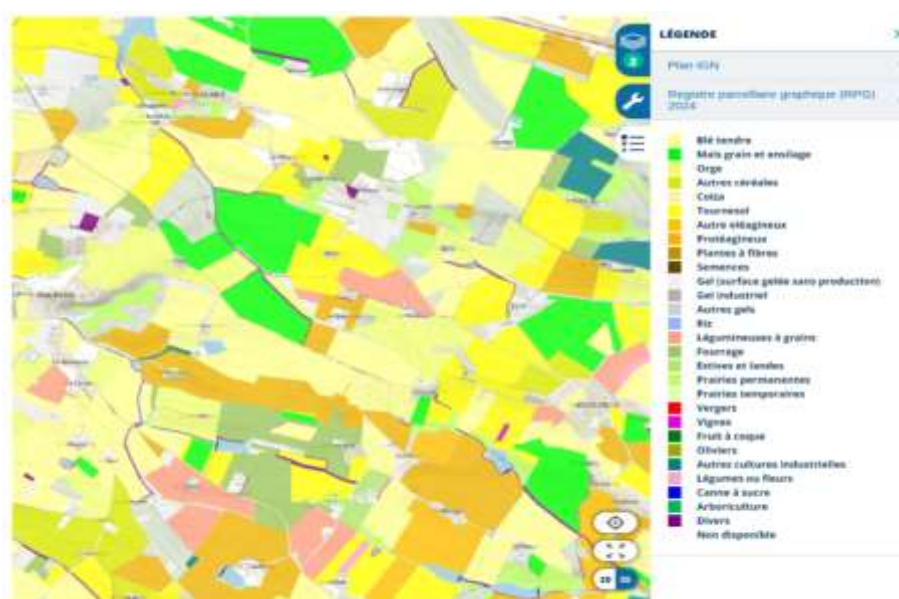


Figure 3. INRAE mapping and classification methods

Medium-term meteorological projections then feed a Penman–Monteith evapotranspiration module consistent, generating reference and crop-specific evapotranspiration over the six-month horizon. Crop-specific parameters such as coefficients, phenological stages, rooting depth, and sensitivity to water stress are associated with each parcel, based on agronomic knowledge derived from INRAE and related research. The difference between potential evapotranspiration under non-limiting supply and effective evapotranspiration under constrained irrigation yields estimates of unmet crop water requirements.

Coupling between crop-demand projections and hydrological projections enables computation of synthetic indicators that remain operationally meaningful. For each virtual station or management unit, the platform can estimate, for example, the percentage of irrigation demand that can be satisfied given projected resources and a chosen abstraction strategy. Conversely, deficit hotspots where unmet demand systematically emerges under certain climate scenarios, cropping systems, or restriction plans become visible, providing insight into the spatial distribution of vulnerability within the basin. Such indicators are essential for evaluations of trade-offs between production objectives and ecological or regulatory constraints.

2.4 Decision-support environment for basin organisations and IWRM

The combination of six-month projections, scenario-based abstraction modelling, and parcel-scale demand estimation transforms WatSim into a decision-support environment rather than a purely academic modelling exercise. Virtual stations act as spatially explicit decision points along the river network, where projected discharges, historical series, anomalies, and scenario results can be visualised through dashboards and exported for further analysis. Additional analytical layers such as historical-data windows, anomaly-trend views, and monthly comparative summaries organise hydrological information into formats suited to day-to-day operations.

Basin organisations, irrigation operators, and regulatory agencies gain access to a shared quantitative frame of reference, which supports ex-ante assessment of allocation rules, graduated restriction plans, and structural measures such as reservoir operation or channel modifications. By grounding discussions in hydrological and agronomic evidence, the platform contributes to more anticipatory, transparent, and negotiated water governance at basin scale. The same environment also offers opportunities for training and communication, since graphical interfaces and scenario narratives help stakeholders grasp the consequences of different strategies and the rationale behind regulatory decisions.

3. CURRENT AND FUTURE CAPABILITIES OF WATSIM

3.1 Partial coverage of water-management contexts

The current configuration of WatSim focuses exclusively on basins with a strong agricultural component. The model design and hydrological scenario logic have been adapted to irrigated landscapes, cropping choices, and river-flow constraints typical of this type of context. Urban water systems, for example, are not covered.

This choice reflects both the platform's origins in agricultural case studies and the broader fact that agriculture accounts for 69% of global freshwater withdrawals⁶. In particular, this matters in regions where climate stress is already threatening low-flow regimes. Bwi has built experience in hydrological forecasting through several international projects in India, Senegal, Nepal, and Bangladesh, where agricultural uses and flood risks are central. This experience naturally oriented WatSim's initial development toward agricultural basins, while leaving open the possibility of future extension to more complex multisectoral contexts.

3.2 Scope for stronger scenarios, data, and sectoral coverage

Several avenues could strengthen WatSim in terms of scenarios, data, and sectoral coverage, building on recent work in agro-hydrological modelling and seasonal forecasting⁷. On the scenario side, more systematic libraries of restriction plans, crop variants, and reservoir-management strategies would make it easier to compare options and reduce the time needed to co-build scenarios with stakeholders

⁶ Food and Agriculture Organization of the United Nations. Agriculture's use of water. AQUASTAT.

⁷ Cammalleri, C., et al. (2020). Assessing groundwater irrigation sustainability in the Euro-Mediterranean region with an integrated agro-hydrologic model.

Standard drought scenarios, such as gradual cuts in irrigation quotas or explicit prioritisation rules between uses, could also be preconfigured.

On the data side, adding information on groundwater, soil moisture, and higher-resolution weather inputs would improve the representation of storage and local variability. Recent work also highlights the value of combining modelling and remote sensing, while noting that mapping irrigated areas and estimating applied water volumes are still far from perfect⁸. Finally, sectoral coverage could be expanded to industry, urban demand, and environmental flows, while keeping the same hydrological backbone but adding dedicated modules.

3.3 Future support for climate adaptation and water governance

Medium-term hydrological projections, abstraction scenarios, and crop water-demand indicators already help stakeholders move beyond crisis response toward a more structured assessment of future options in agricultural basins⁹. Over time, the same architecture could also support broader climate adaptation strategies and water-governance reforms, especially in territories where recurring droughts and allocation conflicts make transparent, evidence-based negotiation increasingly necessary¹⁰.

Built around virtual stations and parcel-scale demand mapping, these simulation environments can help define adaptation pathways that combine changes in cropping systems, infrastructure investments, and regulatory tools, rather than considering each measure separately. Comparative analysis of scenarios focused on drought-tolerant crops, reduced irrigated areas, increased storage capacity, or revised environmental flow targets can reveal not only the relative effectiveness of each option, but also their consequences for different water uses¹¹.

By relying on hydrological and agronomic evidence, WatSim could therefore support more robust planning under uncertainty and more readable governance of scarce water resources in a changing climate. At the same time, interfaces that make model assumptions, data sources, and scenario logic more visible can help build a culture of transparency and learning, which is essential when stakeholders are asked to accept difficult trade-offs during periods of water stress¹².

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⁸ Taghvaeian, S., Neale, C. M. U., et al. (2011). Water balance of irrigated areas: A remote sensing approach.

⁹ World Meteorological Organization. (2020). Guidelines on seasonal hydrological prediction (WMO-No. 1274).

¹⁰ INRAE. (2022). L'agriculture va-t-elle manquer d'eau ?

¹¹ Kitlaster, W., Morway, E. D., Niswonger, R. G., Gardner, M., White, J. T., Triana, E., & Selkowitz, D. J. (2021). Integrated hydrology and operations modeling to evaluate climate change impacts in an agricultural valley irrigated with snowmelt runoff. Water Resources Research.

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