

## AN INTEGRATED PLANNING AND RISK MANAGEMENT FRAMEWORK FOR SCALING UP AGRICULTURAL WATER REUSE IN LARGE-SCALE IRRIGATION DISTRICTS UNDER REGULATION (EU) 2020/741

### UN CADRE INTÉGRÉ DE PLANIFICATION ET DE GESTION DES RISQUES POUR LA CROISSANCE DE LA RÉUTILISATION DE L'EAU AGRICOLE DANS LES DISTRICTS D'IRRIGATION À GRANDE ÉCHELLE AU TITRE DU RÈGLEMENT (UE) 2020/741

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#### ABSTRACT

In Mediterranean regions, irrigation demand is increasing while conventional water resources are becoming less reliable due to recurrent droughts, competing uses, and environmental constraints. Treated urban wastewater (TWW) is increasingly recognised as a non-conventional resource that can supplement irrigation water and support climate-change adaptation. Scaling up from isolated pilots to large irrigation basins is complex, as reuse must be integrated into spatially distributed systems serving many fields with heterogeneous crops, irrigation methods, and multiple geographically dispersed wastewater treatment plants (WWTPs) of varying quality. Under Regulation (EU) 2020/741, the key challenge is to integrate TWW alongside conventional irrigation sources within a single allocation and operations framework. This paper presents an EU-aligned methodological package that operationalises the Regulation through three coordinated tools: (i) a basin-scale planning methodology that quantifies and prioritises reuse opportunities across multiple irrigation districts; (ii) Risk Management Plan (RMP) methodology that extends risk assessment beyond the WWTP outlet to the distribution network of a reuse-system; and (iii) a multi-barrier operational methodology that translates crop-irrigation heterogeneity and reclaimed-water quality classes into auditable compliance prescriptions. The package was applied in Northern Italy within the Consorzio della Bonifica Renana (CBR) multi-district irrigation system, in collaboration with the local water utility HERA. The plain basin covers approximately 140,222 ha and is served by approximately 1,572 km of open channels and 307 km of pressurised pipelines. Twenty-five WWTPs were screened for their potential contribution to irrigation supply. Basin-scale prioritisation identified the water reuse system U3 as the highest-priority site; a site-specific RMP was then developed for this system, and a multi-barrier irrigability analysis demonstrated that a treatment upgrade to class C provides the most cost-effective pathway to compliance, rendering virtually all non-root-crop plots irrigable. The application of the package to a real case study demonstrates an operational pathway to enable safe, EU-compliant reuse where hydraulic feasibility, storage, governance capacity, and risk-management measures must be aligned.

**Keywords:** water reuse; Regulation (EU) 2020/741; risk management plan; multi-barrier approach; irrigation district; treated wastewater.

#### RÉSUMÉ

Dans les régions méditerranéennes, la demande en eau d'irrigation augmente, tandis que les ressources en eau conventionnelles deviennent de moins en moins fiables en raison de sécheresses récurrentes, d'utilisations concurrentes et de contraintes environnementales. Les eaux usées urbaines traitées (EUT) sont de plus en plus reconnues comme une ressource non conventionnelle capable de

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compléter l'eau d'irrigation et de favoriser l'adaptation au changement climatique. Le passage de projets pilotes isolés à de grands bassins d'irrigation est complexe, car la réutilisation doit être intégrée dans des systèmes répartis dans l'espace desservant de nombreux champs présentant des cultures hétérogènes, des méthodes d'irrigation variées et de multiples stations d'épuration (STEP) géographiquement dispersées et de qualité variable. En vertu du règlement (UE) 2020/741, le principal défi consiste à intégrer les EUT aux sources d'irrigation conventionnelles au sein d'un cadre unique d'allocation et d'exploitation. Cet article présente un ensemble méthodologique conforme aux normes de l'UE qui met en œuvre le règlement grâce à trois outils coordonnés : (i) une méthodologie de planification à l'échelle du bassin qui quantifie et hiérarchise les possibilités de réutilisation dans plusieurs districts d'irrigation ; (ii) une méthodologie de plan de gestion des risques (PGR) qui étend l'évaluation des risques au-delà de la sortie de la STEP jusqu'au réseau de distribution d'un système de réutilisation ; et (iii) une méthodologie opérationnelle à barrières multiples qui traduit l'hétérogénéité des cultures et des modes d'irrigation ainsi que les classes de qualité des eaux réutilisées en directives de conformité vérifiables. Cet ensemble a été appliqué dans le nord de l'Italie au sein du système d'irrigation multi-districts du Consorzio della Bonifica Renana (CBR), en collaboration avec le service public local de l'eau HERA. Le bassin de plaine couvre environ 140 222 ha et est desservi par environ 1 572 km de canaux à ciel ouvert et 307 km de canalisations sous pression. Vingt-cinq stations d'épuration ont été évaluées quant à leur contribution potentielle à l'approvisionnement en eau d'irrigation. Une hiérarchisation à l'échelle du bassin a identifié le système de réutilisation de l'eau U3 comme le site le plus prioritaire ; un plan de gestion de la réutilisation (RMP) spécifique à ce site a ensuite été élaboré, et une analyse de la capacité d'irrigation à barrières multiples a démontré qu'une mise à niveau du traitement vers la classe C constituait la voie la plus rentable vers la conformité, rendant pratiquement toutes les parcelles non destinées aux cultures à racines irrigables. L'application de cet ensemble de mesures à une étude de cas réelle montre une voie opérationnelle permettant une réutilisation sûre et conforme à la réglementation de l'UE, dans laquelle la faisabilité hydraulique, le stockage, la capacité de gouvernance et les mesures de gestion des risques doivent être harmonisés.

**Mots-clés** : Réutilisation de l'eau ; Règlement (UE) 2020/741 ; Plan de gestion des risques ; Approche à barrières multiples ; District d'irrigation ; Eaux usées traitées.

## 1. INTRODUCTION

Agricultural water scarcity is one of the defining challenges of the 21st century, particularly in Mediterranean and sub-Mediterranean regions where climate change is intensifying the frequency and severity of droughts while simultaneously increasing evapotranspiration demand from crops (Huggins et al., 2022). In these contexts, conventional freshwater resources — rivers, reservoirs, and shallow aquifers — are under mounting pressure from irrigation demand, urban consumption, environmental flow requirements, and climate-driven supply variability (European Investment Bank, 2022).

Treated urban wastewater (TWW) is increasingly recognised as one of the most promising non-conventional water sources to supplement agricultural irrigation (Christou et al., 2024). Unlike rainwater harvesting or desalination, TWW is generated continuously throughout the year in proportion to urban population, it is available at the local scale in volumes that often align well with seasonal irrigation demand, and it can be conveyed to agricultural systems through existing or modest new infrastructure. When properly treated and managed, TWW can substitute conventional freshwater withdrawals, reduce discharge loads into receiving water bodies, and supply nutrients that partially offset mineral fertiliser applications (Singh, 2021).

The adoption of Regulation (EU) 2020/741 on minimum requirements for water reuse has provided the first harmonised EU legal framework governing the agricultural application of reclaimed water (Regulation EU 2020/741, 2020). The Regulation defines four reclaimed-water quality classes (A–D) linked to crop use categories, edible-part exposure, and irrigation methods, and mandates the development of site-specific Risk Management Plans (RMPs) for each reuse system (Maffettone and Gawlik, 2022). A cornerstone of the Regulation is the multi-barrier principle, whereby combinations of treatment performance, downstream barriers, and preventive measures are used in an integrated fashion to achieve the required level of health protection (EC 2022/C 298/01). This principle

acknowledges that no single barrier is infallible, and that layered protections — from WWTP operation through conveyance and storage to field application — collectively determine the safety of the reuse system (ISO 16075-2, 2020; Ho et al., 2024).

Existing implementations of agricultural water reuse have predominantly been designed at the scale of a single WWTP connected directly to a limited number of fields, a configuration that simplifies planning, monitoring, and accountability (Paul et al., 2020). Scaling up to a large irrigation basin with a multi-district system introduces a substantially different set of challenges (McLennan et al., 2024): TWW quality varies across contributing WWTPs, seasonal water availability is determined by complex interactions between treatment output, storage capacity, and spatially distributed demand, and compliance must be maintained across extensive fields and networks with multiple exposure points and stakeholders (Maffettone and Gawlik, 2022; Christou et al., 2024). Governance structures in large irrigation authorities — where WWTP operators, irrigation managers, storage operators, and individual farmers all play distinct roles — add further complexity to risk allocation and preventive measure implementation (Ricart et al., 2024).

Against this background, the present paper develops and applies an integrated three-tool methodological package that combines basin-scale water balance analysis, site-specific risk management planning, and multi-barrier irrigability assessment. By nesting spatial scales — from the irrigation basin to the individual field — and linking quantitative risk characterisation to practical, auditable barrier prescriptions, the package aims to enable safe and cost-efficient agricultural water reuse within large-scale irrigation districts, providing irrigation managers, water utilities, and regulatory authorities with an actionable pathway from district-level prioritisation to plot-level compliance.

## 2. METHODOLOGY

The package is designed as a spatially nested, three-tool cascade: Tool 1 characterises and ranks irrigation districts at the basin scale, directing attention to the highest-priority reuse site; Tool 2 establishes the human health and environmental risk profile of that site; and Tool 3 converts that risk profile into compliance scenarios at the irrigated field level under the EU multi-barrier framework.

### Tool 1 – Basin-Scale Characterisation, Water Balance, and Area Ranking

In an irrigation basin system serving several districts, the following approach is designed to characterise these districts systematically, rank them by adequacy, and identify the most strategically suitable site for reuse intervention.

For each district under study, a systematic data inventory and a spatial–infrastructural baseline are established to support water balance analysis using a Geographic Information System (GIS). Each district and its surrounding area are examined for the presence of WWTPs, their location regarding the district boundaries, and their connectivity with existing irrigation infrastructures. WWTPs are classified according to the volume of TWW produced and the water quality class defined under Regulation (EU) 2020/741 (A–D), assigned considering monitoring frequency and exceedance analysis as required by the Regulation.

Next, a seasonal irrigation water balance is carried out for each district, accounting for conventional freshwater volumes and gross irrigation water requirements (GIR), comprising net crop water needs and losses connected to irrigation method and conveyance efficiency. This yields the Performance Adequacy (PA) indicator for each district:  $PA = [FW / GIR] \times 100$ , where FW = conventional freshwater volumes and GIR = gross irrigation requirements inclusive of losses. The PA of a district indicates how much of the GIR the available FW can satisfy. The district with the lowest PA and at least one WWTP already discharging within the district water network is selected as the priority site for water reuse and application of Tools 2 and 3.

## Tool 2 – Human Health and Environmental Risk Assessment

Once the priority district is identified by Tool 1, Tool 2 defines the boundaries of the water reuse system and carries out both a human health risk assessment and an environmental risk assessment (Drei et al., 2025). Tool 2 is structured in two phases.

### Phase 1 — Hazard identification and exposure mapping

For each combination of a crop and irrigation method in the water reuse system, the probability that TWW reaches either the body of a field operator (worker pathway) or the edible part of the crop (consumer pathway) is assessed. Worker exposure is characterised by the type and duration of field activity and the associated probability of contact via dermal exposure, aerosol inhalation, or accidental ingestion. Consumer pathway is characterised following Regulation (EU) 2020/741 criteria: crop use category, edible-part height, and irrigation method. Those criteria allow the definition of the minimum TWW quality class required per crop–irrigation–use combination. Environmental hazardous events are identified according to their potential to introduce contaminants into surface water, groundwater, and soil compartments. This characterisation is georeferenced across the water reuse system.

### Phase 2 — Risk assessment and preventive measures

Risk parameters include: Likelihood of Occurrence (LO; 1–5), reflecting probability for pathogen transfer to humans of environmental compartment; Severity (S; 1–5), reflecting potential human health impact; and Environmental Sensitivity (ES; 1–4), capturing site-specific vulnerability of environmental compartments. Human Health Risk (HHR) is calculated as  $HHR = LO \times S$ , while Environmental Risk (ER) as  $ER = LO \times ES \times S$ . A two-tier approach first establishes maximum risk without preventive measures present on site, then computes residual risk after accounting for existing measures. The resulting risk classifications and preventive measures feed directly into Tool 3.

## Tool 3 – Multi-Barrier Applicability Assessment

Building on the HHR and ER established by the Tool 2, and on the accredited barrier portfolio defined in Regulation (EU) 2020/741, Commission Notice EC 2022/C 298/01, Commission Delegated Regulation (EU) 2024/1765, and ISO 16075-2 (2020), an irrigability framework is developed for the defined water reuse system. The TWW quality class at the point of compliance (from Tool 1) and the required class for each irrigated field (from Tool 2) are compared, resulting in the number of accredited barrier equivalents ( $N = 1-3$ ) needed to close any quality gap. Each irrigated field is assigned one of three possible outcomes: directly irrigable (no additional barriers required), conditionally irrigable (accredited barriers required), or not irrigable.

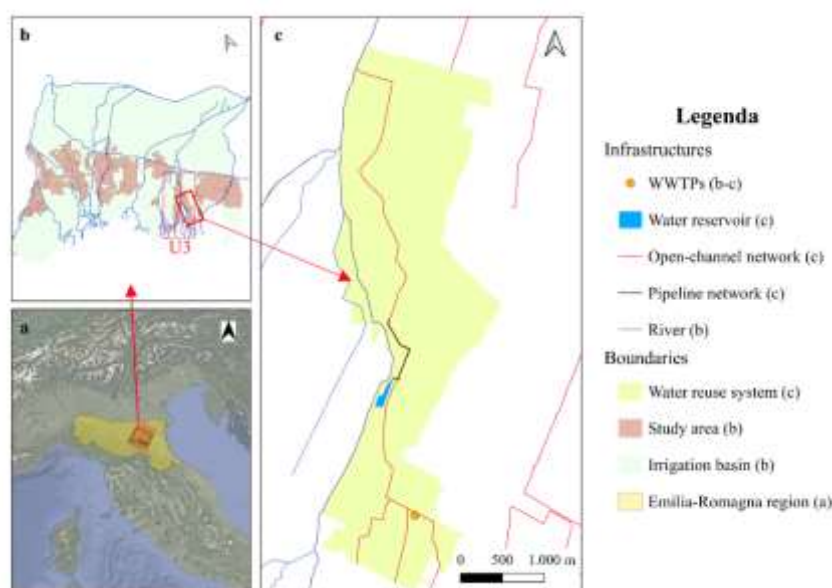
The irrigability framework is applied for the selected irrigation season. Per-plot outcomes are aggregated to produce two district-level indicators: the TWW volume that could be used for irrigation before ( $N = 0$ , reflecting current conditions) and after barrier application ( $N \geq 1$ , reflecting the potential unlocked by the multi-barrier approach). The difference between these two volumes quantifies the operational gain from deploying the accredited barriers.

## 3. RESULTS

### Case study: the plain basin district of the CBR system

The study area is located within the irrigation basin of the Consorzio della Bonifica Renana (CBR), a large-scale irrigation authority operating in the Po Valley of the Emilia-Romagna region, Northern Italy (Figure 1a,b). The basin-scale analysis (Tool 1) focused on the irrigation districts (Figure 1b) where the CBR water manager identified greater drought risk. This area is divided into 17 irrigation districts, covering approximately 36,514 ha, being served by the irrigation infrastructure of approximately 330 km of open channels and 213 km of pressurised pipelines. Within the study area, 25 WWTPs managed by

the water facility (HERA) were initially screened for their potential contribution to irrigation supply (Figure 1b).



**Figure 1.** Case study framework: (a) location of the CBR irrigation basin within the Northern Italian region of Emilia-Romagna; (b) irrigation districts screened for TWW supply potential; (c) detail of the water reuse system U3.

### Tool 1 results: Basin-scale water balance and district prioritisation

Tool 1 was applied for the year 2023 as a demonstration exercise for package validation. Within the irrigation basin, 17 irrigation districts were characterised in detail, combining infrastructure mapping, surface characterisation, and WWTP association. For each district, a seasonal irrigation water balance was computed by aggregating three components across the March–October irrigation season: GIR, FW, and TWW potentially available. From the results, the district U3 (Figure 1c) emerged as the one with the lowest PA, having at least one WWTP discharging within the district irrigation network.

The sole WWTP serving District U3 (called WWTP-U3) has an effluent classified as class D for *E. coli* — the lowest quality tier under Regulation (EU) 2020/741 — based on 2023 analytical data (BOD5: class B; TSS: class A). This class means that direct reuse without WWTP upgrade or application of barrier measures, would be incompatible with the requirements for most irrigated crop types. On the basis of these results, the analysis proceeded to Tool 2, applying the RMP methodology to the water reuse system U3.

### Tool 2 results: Risk management plan for the water reuse system U3

The RMP was developed for the water reuse system U3, which comprises four main components: (i) WWTP-U3 (secondary biological treatment with peracetic acid disinfection); (ii) a water reservoir managed by the CBR for seasonal buffering; and (iii) an open-channel irrigation network serving a total irrigated area of 77.7 ha in 2023. Three principal stakeholders were identified in the role-allocation phase: WWTP-U3 as WWTP operator and sewer manager (HERA), CBR as distribution and storage infrastructure operator, and individual farm operators as final users.

The crop characterisation for 2023 showed a heterogeneous agricultural landscape across the 20 irrigated fields. The dominant crops were sugar beet for seed and other seed crops (collectively constituting the largest share, requiring class D quality or higher), followed by maize (biomass and grain), tomato, mixed vegetables, spring onion, vine, and alfalfa. Irrigation methods comprised

approximately equal shares of sprinkler and drip irrigation, with no surface-flow irrigation recorded. This heterogeneity is critical for risk assessment because it generates a wide range of minimum quality requirements at the field level, with significant portions of the system requiring water class B or higher in the absence of additional barriers.

The risk assessment was performed together with the main stakeholder in the area, due to their operational knowledge of the water reuse system. The HHR assessment identified 34 hazardous events across the two sub-systems (treatment plant and distribution network). The preliminary risk matrix (not considering preventive measures) classified 8 events as high or very high risk at the WWTP level and 9 events as high or very high risk within the distribution network. Following characterisation of the existing preventive measures — including the automated telecontrol system, the peracetic acid disinfection unit, the emergency storm-water buffer tank, and CBR operational protocols — a residual risk assessment was conducted. The final classification for the HHR yielded 14 low-risk events, 11 medium-risk, 6 high-risk, and 3 very-high-risk events, confirming that existing controls are insufficient to reduce all identified risks. For the Environmental Risk (ER) assessment, the preliminary risk matrix classified 49 events as low risk, 17 as medium, and 6 as high risk. Following characterisation of the existing preventive measures — including a real-time monitoring and alert system — the residual risk assessment yielded 51 low-risk events, 15 medium-risk, and 6 high-risk events, with no very-high-risk events identified.

The most critical residual risks for consumer health were associated with microbiological non-compliance at the WWTP-U3 outlet. To address these risks, the following recommendation measures were identified: installation of online turbidity and suspended-solids sensors at the WWTP outlet; formalisation of a multi-party communication protocol for emergency suspension of irrigation; and reinforcement of the disinfection regime under high-loading conditions.

### **Tool 3 results: Multi-barrier irrigability scenarios for 2023**

Building on the crop-irrigation characterisation of the 20 irrigated fields established in the RMP (Tool 2), the multi-barrier approach was applied to the 2023 season under three effluent quality configurations at the point of compliance: class D (current status), class C, and class B (after a potential WWTP upgrade) at the point of compliance. For each field, the analysis — based on crop type, irrigation method and effluent quality class — determined whether irrigation was feasible without additional barriers, feasible only with specified accredited barriers, or not feasible under any combination of barriers, thereby identifying the portions of crop water demand coverable through direct reuse, coverable with barriers, or requiring supply from other water sources.

Table 1 presents, as a percentage, the volumes of TWW that could be used in 2023 under each scenario to cover total crop water needs of approximately 218,391 m<sup>3</sup>. Under the current class D conditions, 36.25% of the crop water needs could not be covered by TWW, owing to the presence of crops — primarily spring and autumn onion destined for raw consumption — for which class D water is explicitly excluded under the Regulation. An additional 21.15% could be covered by TWW with the adoption of at least one accredited barrier equivalent, while the remaining 42.6% could be covered by TWW without additional barriers, corresponding to industrial and seed crops irrigated by techniques without direct contact with the edible part.

Upgrading the treatment to class C would reduce the non-usable TWW fraction from 36.2% to 25.4%, simultaneously expanding the share of directly usable TWW to 63.8%. In this case, TWW could not be used only for the irrigation of root vegetables consumed raw, for which no multi-barrier pathway is considered. The class B scenario, on the other hand, allows the use of all TWW produced, with 79.2% of TWW usable without barriers, yielding a further gain in usable TWW volume relative to class C. Collectively, the scenarios demonstrate that the multi-barrier approach alone, applied at class D, can unlock only a marginal expansion of TWW volume applicable for reuse (from 42.6 to 63.8 %), whereas upgrading treatment to class C provides probably the most cost-effective threshold improvement. Full crop coverage requires class B quality, confirming that an integrated strategy combining targeted treatment upgrading with structured barrier prescriptions is necessary to maximise reuse within the district.

**Table 1.** Multi-barrier scenarios for the water reuse system U3 for year 2023. Three scenarios were considered - class D (current), class C, and class B at the point of compliance.

| TWW category                                 | Class D – current (%) | Class C scenario (%) | Class B scenario (%) |
|----------------------------------------------|-----------------------|----------------------|----------------------|
| Not usable                                   | 36.2                  | 25.4                 | 0.0                  |
| Usable with barriers                         | 21.2                  | 10.8                 | 20.8                 |
| Usable without barriers                      | 42.6                  | 63.8                 | 79.2                 |
| <b>Total crop water need (m<sup>3</sup>)</b> | <b>218,391</b>        |                      |                      |

#### 4. CONCLUSIONS

The integrated three-tool package presented in this paper demonstrates a practical and EU-compatible pathway for planning and implementing agricultural water reuse in large-scale irrigation districts. The basin-scale analysis (Tool 1) successfully identified the highest-priority irrigation district for water reuse application within the study area, directing subsequent detailed analysis to the water reuse system U3 — a site with a current class D effluent quality that would constrain irrigability across 28% of the district irrigated area.

The risk management plan (Tool 2) provided a structured characterisation of hazardous events across both the WWTP outlet and the distribution network, confirming that existing controls alone were insufficient to reduce all consumer health risks to acceptable levels and identifying specific recommendation measures to address residual high-risk events. Among these, the most critical aspect was the absence of real-time monitoring beyond the reservoir intake, underscoring the importance of extending the risk management perimeter beyond the WWTP boundary — an aspect that the proposed methodology explicitly addresses.

The multi-barrier scenarios (Tool 3) demonstrated that the accredited barrier framework under Regulation (EU) 2020/741 can serve as a valuable operational tool to expand the use of TWW to cover crop water needs. However, the results clearly show that barriers alone, applied at the current class D quality, yield only a marginal expansion in volumes that could be used. The most significant gain is achieved through a combination of treatment upgrade to class C and barrier deployment, which renders virtually all non-root-crop plots compliant and that could probably be considered as the best option taking into account the costs needed for the WWTP treatment investment. Full use of produced TWW requires class B quality, confirming that the multi-barrier approach and treatment upgrading are rather complementary than alternative strategies.

It should be noted that the package presented in this paper constitutes its first operational test in a real large-scale irrigation setting. In order to expand water reuse practices, it is necessary to cover the whole reuse chain, therefore enabling transition from basin-scale prioritisation to field-level compliance in a single methodology approach. This operational test demonstrates that the integration of hydraulic planning, risk assessment, and regulatory compliance tools is both technically feasible and practically actionable within existing management structures. It also shows that the stakeholder input is critical for its practical application. Nonetheless, the package application identified several aspects that should be further developed.

Future work should consider seasonal presence of TWW, and take into consideration a possible storage of this resource during the winter months in order to increase water availability. Moreover, real-time effluent quality monitoring could be integrated into the irrigability decision framework. This monitoring

might also include contaminants of emerging concern to provide safer application of water reuse. Finally, the economic dimension — specifically the cost–benefit analysis of treatment upgrade and the consequent increase in TWW reuse — also warrants dedicated investigation to support practical decision-making by water utilities and irrigation authorities seeking to maximise the safe and cost-efficient use of reclaimed water at large scale.

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