

INTEGRATED PLANNING OF DESALINATED AND RECYCLED WATER IN ARID WATER SUPPLY SYSTEMS: A CASE STUDY FROM ABU DHABI

PLANIFICATION INTÉGRÉE DE L'EAU DESSALÉE ET RECYCLÉE DANS LES SYSTÈMES D'APPROVISIONNEMENT EN EAU DES ZONES ARIDES : UNE ÉTUDE DE CAS MENEE A ABU DHABI

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ABSTRACT

Abu Dhabi's water supply system is characterized by extreme aridity, negligible natural freshwater resources, and a strong dependence on non-renewable groundwater. At present, approximately 57% of total water use is supplied by groundwater, primarily for agriculture and forestry, with the remainder provided by desalinated seawater and recycled wastewater. Continued groundwater abstraction has led to declining groundwater levels, prompting the Government of Abu Dhabi to set a strategic target of net-zero groundwater abstraction by 2035. Achieving this target requires coordinated expansion of alternative water sources while maintaining security of supply for all users, including agriculture and landscaping.

This paper presents an analysis of the interdependencies between urban water supply, wastewater reuse, and agricultural irrigation demand. Desalinated water supplied to urban areas generates wastewater, which is treated and returned as recycled water for irrigation, creating a feedback loop in which urban demand patterns directly influence recycled water availability, and any shortfall between recycled water production and irrigation demand must be met by additional desalinated water. Quantifying this feedback and its seasonal dynamics is essential for accurate sizing of desalination capacity and for evaluating the benefits of coordinated planning across the two supply systems.

Comparison of independent and integrated planning approaches, using observed daily data, demonstrates that integrated planning, in which full recycled water production is delivered to irrigation and desalinated water provides a flexible top-up for any residual demand, requires materially lower desalination production capacity than an approach in which the two supply systems are planned in isolation.

The findings provide a transferable framework for arid regions seeking to reduce reliance on non-renewable groundwater while safeguarding agricultural productivity, and underscore the need for coordinated planning across desalinated and recycled water supply systems. An integrated water planning model currently under development will operationalise this framework for capacity planning in Abu Dhabi.

Keywords: Natural freshwater resources; groundwater abstraction; Desalinated water; non-renewable groundwater; recycled water production.

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RESUME

Le système d'approvisionnement en eau d'Abou Dhabi se caractérise par une aridité extrême, des ressources naturelles en eau douce négligeables et une forte dépendance à l'égard des eaux souterraines non renouvelables. À l'heure actuelle, environ 57% de la consommation totale d'eau provient des eaux souterraines, principalement pour l'agriculture et la foresterie, le reste étant fourni par l'eau de mer dessalée et les eaux usées recyclées. Le prélèvement continu des eaux souterraines a entraîné une baisse des niveaux d'eau souterraine, ce qui a incité le gouvernement d'Abou Dhabi à fixer un objectif stratégique de prélèvement net zéro d'ici 2035. Pour atteindre cet objectif, il faut développer de manière coordonnée des sources d'eau alternatives tout en maintenant la sécurité d'approvisionnement pour tous les usagers, y compris l'agriculture et l'aménagement paysager.

Cet article présente une analyse des interdépendances entre l'approvisionnement en eau en milieu urbain, la réutilisation des eaux usées et la demande en eau pour l'irrigation agricole. L'eau dessalée fournie aux zones urbaines donne lieu aux eaux usées, qui sont traitées et renvoyées sous forme d'eau recyclée pour but d'irrigation, créant ainsi une boucle de réactions dans laquelle les modèles de demande urbaine influencent directement la disponibilité de l'eau recyclée, et tout écart entre la production d'eau recyclée et la demande en irrigation doit être comblé par apport supplémentaire d'eau dessalée. La quantification de cette réaction et de sa dynamique saisonnière est essentielle pour dimensionner correctement la capacité de dessalement et pour évaluer les avantages d'une planification coordonnée des deux systèmes d'approvisionnement.

La comparaison des approches de planification indépendantes et intégrées, à l'aide de données quotidiennes observées, indique que la planification intégrée, dans laquelle la production totale d'eau recyclée est fournie à l'irrigation et l'eau dessalée offre un complément flexible à toute demande résiduelle, nécessite une capacité de production de dessalement sensiblement inférieure à celle d'une approche dans laquelle les deux systèmes d'approvisionnement sont planifiés de manière isolée.

Les résultats fournissent un cadre transmissible aux régions arides qui cherchent à réduire la dépendance aux eaux souterraines non renouvelables tout en préservant la productivité agricole, et soulignent la nécessité d'avoir une planification coordonnée des systèmes d'approvisionnement en eau dessalée et recyclée. Un modèle de planification intégrée de l'eau en cours d'élaboration permettra de rendre opérationnel ce cadre pour la planification des capacités à Abou Dhabi.

Mots-clés : Ressources naturelles en eau douce; Prélèvement d'eau souterraine; Eau dessalée; Eaux souterraines non renouvelables; Production d'eau recyclée.

Introduction

Fresh water scarcity is one of the most pressing resource challenges of the twenty-first century. Arid and hyper-arid regions face a structural deficit between renewable water availability and the demands of growing urban populations, agricultural production, and ecosystem maintenance. In these settings, conventional water supply strategies based on surface water abstraction or reliance on natural groundwater recharge are inadequate, and alternative supply technologies, principally seawater desalination and the reuse of treated wastewater, have become central pillars of long-term water security planning (Elimelech & Phillip, 2011; Qureshi, 2020).

The Emirate of Abu Dhabi exemplifies the challenges faced by hyper-arid regions. Mean annual rainfall is below 100 mm, evapotranspiration rates far exceed precipitation, and there are no perennial surface water bodies. Natural groundwater recharge is negligible, yet groundwater has historically been the dominant source of water for agriculture and forestry. Total groundwater abstraction is estimated at approximately 1,900 million cubic metres per year (Mm³/yr), accounting for roughly 57% of total water consumption in the emirate.

This abstraction occurs almost entirely through private farm wells and is largely unmetered, making precise quantification difficult. The available groundwater is characterised by elevated salinity levels, which compels farmers to apply water at rates substantially exceeding crop requirements in order to leach salts and prevent progressive soil salinisation. As a result, effective irrigation efficiency is low.

Sustained over-abstraction has led to a progressive decline in groundwater levels across Abu Dhabi, threatening the long-term viability of the resource (Dawoud 2020). In response, the Government of Abu Dhabi has established a strategic target of achieving net-zero groundwater abstraction by 2035 within the framework of an Integrated Water Strategy (DOE 2026). Meeting this target requires replacing groundwater with alternative supplies, mainly desalinated seawater and recycled water (wastewater treated to standards suitable for unrestricted irrigation).

At present, a significant portion of the recycled water production is discharged to the sea due to gaps in distribution infrastructure required to convey recycled water to irrigation demand centres. To close this infrastructure gap, twelve project schemes were raised, designed to expand recycled water conveyance capacity and increase utilisation across agricultural and landscaping zones. The projects are scheduled for staged implementation between 2028 and 2031 and represent a major infrastructure commitment supporting the transition away from groundwater abstraction.

Effective planning for this transition cannot be conducted in isolation within a single institutional domain. The water sector in Abu Dhabi is organised across complementary functions: Emirates Water and Electricity Company (EWEC) is responsible for desalination capacity planning and system operation; TAQA Water Solutions manages wastewater collection, treatment, and recycled water production; TAQA Transmission is responsible for the transmission of potable water to the demand centres, and TAQA Distribution oversees the distribution of both potable and recycled water to end users. These functions are deeply interdependent. Desalinated water supplied to urban consumers generates wastewater, which is collected, treated, and reused as recycled water for irrigation. The volume of recycled water available is therefore determined by urban demand patterns and treatment capacity. When recycled water supply falls short of irrigation demand - whether due to seasonal mismatches, peak demand events, or distribution constraints - additional desalinated water is required as a supplementary supply, increasing overall desalination demand. This feedback loop must be explicitly represented in any planning framework.

This paper presents an empirical analysis of the system dynamics governing the interaction between desalinated water supply, recycled water production, and irrigation demand in Abu Dhabi, based on a daily monitoring dataset for a major wastewater catchment. The analysis quantifies the seasonal structure of the feedback loop between urban water consumption, wastewater generation, and recycled water availability, and demonstrates the capacity planning benefits of integrated over independent management of the two supply systems. An integrated water planning model designed to operationalise this framework for system-wide capacity planning across Abu Dhabi's transition to 2035 is also described, with full scenario results to be reported in subsequent work.

Study Area

Physical Setting and Water Resources

The Emirate of Abu Dhabi occupies approximately 67,340 km² of the southeastern Arabian Peninsula. The climate is classified as a hot desert climate (Köppen BWh; Peel et al., 2007) and meets the UNEP definition of hyper-aridity, with mean annual rainfall below 100 mm and potential evapotranspiration rates exceeding 2,000 mm/yr (UNEP, 1992). There are no perennial rivers or surface water bodies.

Groundwater occurs in shallow alluvial aquifers and deeper sedimentary formations, but natural recharge is negligible and aquifer salinity is generally high, with total dissolved solids (TDS) commonly exceeding 3,000 mg/L in agricultural areas. The combination of climatic aridity, absence of renewable

surface water, and poor groundwater quality renders Abu Dhabi structurally dependent on engineered water supply systems.

Current Water Balance

The total water consumption of Abu Dhabi Emirate is estimated at approximately 3,360 Mm³/yr (2024 data), distributed across three principal sources: desalinated seawater, recycled wastewater, and groundwater.

At present, desalinated seawater contributes approximately 1,100 Mm³/yr to the total water supply of Abu Dhabi, of which around 550 Mm³/yr is directed to irrigation of agriculture, forestry and municipal landscaping. Recycled water contributes a further 360 Mm³/yr, of which 240 Mm³/yr currently reaches irrigation end users. **Table 1** summarises the current water balance by source and end use.

Table 1. Abu Dhabi Emirate's water balance by source and end use (2024 estimates)

Water Source	Total Volume (Mm ³ /yr)	Urban Use (Mm ³ /yr)	Irrigation Use (Mm ³ /yr)	Share of Total (%)
Desalinated Seawater	1,100	560	550	33%
Recycled Water	360	0	240	11%
Groundwater	1,900	0	1,900	57%
Total	3,360	560	2,690	100%

System Dynamics and Implications for Future Water Supply Planning

An area within the Emirate of Abu Dhabi covering the greater Abu Dhabi City area was selected for a quantitative characterisation of the water system dynamics relevant to the integrated planning challenge addressed by this paper. A monitoring data set covering the year 2025 was collected, consisting of the following daily time series:

- Recycled water (RW) production from the main Sewage Treatment Plants (STP) serving the greater Abu Dhabi City area.
- RW consumption served by the outflow of the same STP
- Desalinated water (DW) consumption for agricultural irrigation in the same catchment area
- DW consumption for residential potable use in the same catchment area. This also includes an unquantified volume of irrigation supply to private gardens and municipal landscaping served by the potable network; this fraction could not be disaggregated from available metering data.

The following data analysis examines the interaction between RW production, irrigation demand, and DW supply in the context of the strategic objective of full RW utilisation, defined here as the delivery of all produced RW to irrigation end users, with DW serving as a supplementary top-up supply for any residual irrigation demand not met by RW on a given day.

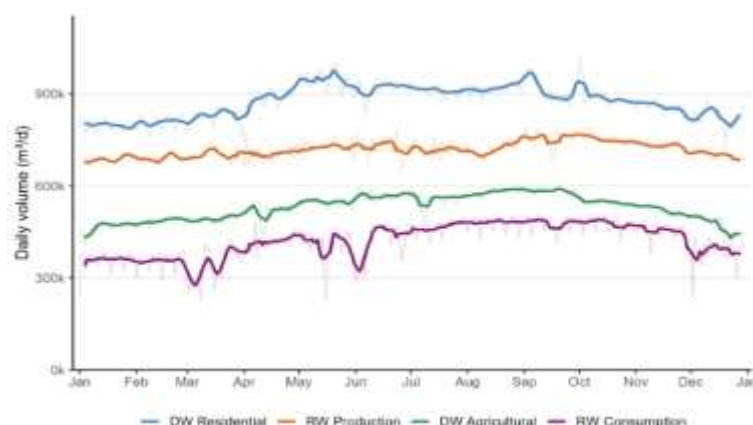


Figure 1. Daily water system variables, 2025. Bold lines = 7-day rolling mean.
Faint lines = daily values. RW = recycled water. DW = desalinated water

RW production at the selected STP in 2025 averaged approximately 720,000 m³/d, exhibiting a relatively narrow seasonal range of 687,000–758,000 m³/d (monthly means, January and September respectively) (**Figure 1**). This corresponds to a variation of only 10% around the annual mean. This stability reflects the continuous and hydraulically buffered nature of STP operation, where inflows from the urban wastewater network are subject to relatively modest seasonal variation compared to outdoor water demands. The wastewater return fraction, defined as the ratio of RW production to residential potable water consumption, averaged approximately 0.82 across the year, falling from approximately 0.86 in winter to 0.79 in summer. This seasonal variation is consistent with higher demand for garden and landscape irrigation during the hot season, which reduces the fraction of potable supply entering the wastewater network. As the residential potable water category includes an unquantified volume of supply to gardens and municipal landscaping, the reported return fraction represents an upper bound on the true domestic wastewater return fraction.

Total irrigation demand (combined volume of RW consumed and DW delivered to the agricultural network under current operations) exhibits a pronounced seasonal cycle, ranging from approximately 823,000 m³/d in January to approximately 1,065,000 m³/d in September, a seasonal amplitude of approximately 29%. This demand is driven primarily by evapotranspiration, which is substantially higher during the hot and humid summer months than in the cooler winter period.

Total irrigation demand in the study catchment exceeds RW production on virtually every day of the monitoring year. Under a full-utilisation scenario in which all RW production is directed to irrigation, DW top-up is nevertheless required to guarantee security of supply. The volume of DW top-up required varies substantially across the year, with direct implications for capacity planning. In winter months (January–March), lower irrigation demand combined with stable RW production limits the required DW top-up to approximately 130,000–155,000 m³/d on average. As irrigation demand increases through spring and into summer, the DW top-up requirement grows markedly, reaching a monthly mean of approximately 340,000 m³/d in August and a peak single-day value of approximately 401,000 m³/d in September 2025 (**Figure 2**). This pattern arises because irrigation demand responds strongly to summer evapotranspiration while RW production, which is constrained by the relatively stable residential wastewater inflow, grows only modestly. The peak desalination capacity required to guarantee irrigation supply security is therefore determined by the summer season, even though RW production is also at its annual maximum during this period.



Figure 2. Daily DW top-up required under a full RW utilization scenario.

Figure 2 illustrates the full temporal structure of the daily top-up requirement across 2025. The stepped monthly mean line makes the seasonal ramp from winter minima to the summer peak clearly visible, while the individual daily bars show the short-term variability around this trend arising from weekly irrigation rhythms and episodic operational fluctuations. The average of the peak week is used for capacity planning purposes, as it ensures that residual irrigation demand is fully met on all but the most extreme days of the year, while avoiding the cost of over-sizing infrastructure to accommodate rare peak events.

The analysis reveals an important asymmetry in the seasonal relationship between RW supply and irrigation demand. RW satisfies a larger fraction of irrigation demand in winter (approximately 82–85% of daily demand in January through March) than in summer, where the RW share falls to approximately 68–73% in July through September. The residual dependence on DW top-up is therefore greatest during the season of peak overall water demand, when the consequences of supply shortfalls are most severe. Capacity planning must therefore ensure that DW supply capacity is sufficient to meet peak summer top-up requirements.

Value of integrated planning

Scenario Definitions

To quantify the benefit of integrated water supply planning, two contrasting planning approaches are compared using the 2025 monitoring dataset. Both scenarios take observed daily irrigation demand as fixed and consider how DW production capacity would be sized under different planning approaches.

Under **Scenario A (independent planning)**, RW and DW supply are planned in isolation. Some areas are served by RW exclusively; to guarantee security of supply without a DW backup, the RW allocation to these zones must be sized to the minimum reliable daily output. The guaranteed RW allocation is here sized to the 10th percentile of observed daily RW production (equivalent to a 90% exceedance probability) representing the volume reliably deliverable on all but approximately 36 days per year under normal operating conditions. This is consistent with standard firm capacity criteria used in water supply planning. Any production above this guaranteed floor cannot be reliably absorbed by the RW-served zones and is discharged. Areas not served by RW receive DW exclusively. DW production capacity is

therefore sized to cover the peak demand of these DW-served zones without any contribution from the RW system.

Under **Scenario B (integrated planning)**, the full volume of daily RW production is delivered to irrigation, and DW production provides a flexible top-up to cover any shortfall between RW production and total irrigation demand on a given day. DW production capacity is therefore sized only to the peak top-up requirement rather than to the full residual demand. This approach requires a feedback mechanism whereby a daily deficit in RW production is automatically translated into an additional DW production requirement.

Both scenarios require RW distribution infrastructure, though the sizing and operational flexibility requirements of that infrastructure may differ between scenarios; quantification of these differences is outside the scope of this analysis.

Annual Water Balance Comparison

Figure 3 shows the monthly mean irrigation supply composition under each scenario. Under Scenario A, the guaranteed RW allocation of 681,000 m³/d is delivered to irrigation consistently throughout the year, while RW production above this floor is discharged. DW covers the residual irrigation demand in all months, averaging 246,000 m³/d in winter and rising to 380,000–384,000 m³/d during the summer peak months of August and September. Under Scenario B, the full daily RW production volume is delivered to irrigation, eliminating discharge almost entirely. The DW top-up is lower in every month, ranging from 130,000 m³/d in March to 340,000 m³/d in August.



Figure 3. Monthly mean irrigation supply composition under independent and integrated planning.

Desalination Production Capacity Requirements

A significant planning implication of integration concerns the DW production capacity required to guarantee security of supply for irrigation.

Under Scenario A, DW production must be capable of meeting the full residual irrigation demand on peak days, regardless of actual RW production on those days. The peak week average of this residual demand amounts to 393,000 m³/d, which determines the required production capacity under independent planning.

Under Scenario B, DW production only needs to cover the daily top-up (gap between actual RW production and total irrigation demand). Because RW production is consistently higher relative to its guaranteed floor, the integrated approach captures most available RW production on most days, leaving

a substantially smaller residual for DW to cover. The peak week average top-up amounts to 361,000 m³/d, which is a reduction of 32,000 m³/d, or 8%, in required DW production capacity relative to Scenario A.

This capacity saving is the primary planning benefit of integration. DW production capacity is capital-intensive to construct and commission, and facilities are typically sized to the peak demand they must reliably meet. A reduction in required capacity translates directly into avoided capital investment over the planning horizon. An independent planning approach that does not account for the interaction between RW production variability and irrigation demand would oversize DW production capacity, incurring unnecessary expenditure.

The Integrated Water Planning Model

Modelling platform and overall structure

An integrated water planning model was developed to plan the required DW production capacity and infrastructure for the transition of all groundwater users to alternative sources, consisting mainly of RW and DW. The model was developed in GoldSim (GoldSim Technology Group, 2024), a professional continuous simulation platform designed for dynamic modelling of complex systems subject to uncertainty and stochastic variability. GoldSim represents system behaviour through a network of interconnected elements that evolve continuously through time, making it well suited to water supply systems in which flows, storage states, and demand patterns interact dynamically across multiple timescales. The platform's native support for probabilistic simulation via Monte Carlo analysis provides a direct pathway from deterministic water balance modelling to risk-based reliability assessment within a single integrated framework.

The model is structured around two coupled modules: a DW supply module and a RW supply module, linked by an explicit feedback mechanism that represents the dependence of irrigation demand on RW availability. The model operates at a daily timestep, with provision for sub-daily (hourly) resolution as higher-frequency demand and operational data become available. This temporal resolution is sufficient to capture the intra-week variability in irrigation demand and RW offtake documented in the previous section, and to represent the delays inherent in wastewater collection, treatment, and distribution that are central to the system's dynamic behaviour.

Desalinated Water Supply Module

The DW supply module represents the production, transmission, storage, and distribution of potable DW to end users. Supply is sourced from a portfolio of desalination plants, with bulk water conveyed through a transmission network comprising large-diameter mains, pumping stations, and balancing storage reservoirs before distribution to end users.

Recycled Water Production Module

RW production is modelled through a sequential chain of processes that explicitly represents the link between urban potable water consumption and treated effluent available for irrigation reuse.

For each delineated wastewater catchment in the model domain, the volume of wastewater generated is calculated by applying a wastewater return fraction to the potable water demand served within that catchment. This fraction accounts for the proportion of supplied water that enters the sewage collection network, with the remainder assumed to be consumed through garden or landscape irrigation, or other non-returned uses. As noted previously, this fraction varies seasonally. In the study catchment, it averages approximately 0.82 across the year but declining to approximately 0.79 in summer months when outdoor irrigation losses are highest. The resulting wastewater inflow to the sewage collection network is modelled with a time delay representing the combined effect of in-pipe storage and hydraulic

travel time from points of consumption to the STP inlet. This delay ensures that temporal fluctuations in potable demand are propagated to STP inflows with an appropriate lag rather than instantaneously.

At the STP, a retention time is applied to the influent flow, representing the hydraulic residence time of wastewater within the treatment process. This introduces a further temporal offset between the pattern of wastewater generation and the timing of RW production and is of particular relevance for planning purposes: a sustained increase in urban water demand will not translate into increased RW availability for some time. The model therefore captures the temporal mismatch between demand-side signals and supply-side responses that is characteristic of water reuse systems and is not represented in conventional static water balance frameworks.

The treated effluent leaving the STP is partitioned between two fractions: an internal use and process loss fraction, representing water consumed within the treatment facility itself, and a releasable fraction that is made available for distribution to irrigation end users. The releasable RW volume is then compared against the irrigation demand allocated to the RW network for that catchment and timestep. If RW production exceeds demand, the surplus is discharged. If demand exceeds production, the shortfall is passed as an additional demand increment to the DW supply module. This feedback mechanism is the key coupling between the two modules and is the principal mechanism through which the integrated model differs from treating DW and RW as independent supply options.

Risk-based component

The module incorporates a risk-based component that evaluates supply reliability under conditions of asset failure and demand variability. Failure behaviour is represented for four asset classes: desalination plants, transmission mains, pumping stations, and storage facilities, each characterised by failure and repair statistics drawn from operational records. Uncertainty in supply reliability is evaluated through Monte Carlo simulation across thousands of independent realisations, from which probability distributions of supply shortfall frequency, duration, and magnitude are derived to assess infrastructure adequacy and identify system vulnerabilities. Extending this probabilistic framework to the recycled water module represents a planned development step.

Model limitations and ongoing development

Catchment delineation at the interface between DW supply zones and wastewater collection areas represents a current model limitation, as mismatches between these boundaries can result in over- or under-estimation of STP inflows at individual sites. Resolving this requires reconciliation of spatial catchment boundaries across the two supply systems, which is ongoing. This limitation does not affect the system-level water balance results presented in this paper, which are based on aggregated data, but will be addressed prior to site-specific capacity planning applications.

Summary and Conclusions

This paper has presented an analysis of integrated water supply planning for irrigation in Abu Dhabi, motivated by the Government's strategic commitment to achieve net-zero groundwater abstraction by 2035. Replacing the emirate's current groundwater dependence with desalinated seawater and recycled wastewater within a decade requires coordinated expansion of both supply sources and the distribution infrastructure connecting them to demand centres. This paper has argued that such coordination cannot be achieved effectively through independent planning of the two supply systems and has presented empirical and analytical evidence to quantify the benefit of an integrated approach.

Analysis of a daily monitoring dataset for a selected wastewater catchment for 2025 reveals that RW production is relatively stable throughout the year, varying by only 10% around the annual mean, while irrigation demand exhibits a pronounced seasonal cycle with an amplitude of approximately 29%. Under current operations, only 58% of RW production reaches irrigation end users, with the remainder discharged to the sea due to insufficient distribution infrastructure. Completing this infrastructure is

identified as an important near-term lever for reducing DW demand. In support of this objective, TAQA Distribution has initiated twelve RW distribution expansion schemes scheduled for delivery between 2028 and 2031. These schemes will substantially increase RW conveyance capacity, reduce RW discharge to the sea, and enable a larger share of irrigation demand to be met through RW.

Nevertheless, under full RW utilisation, DW top-up is required on virtually every day of the year, varying from approximately 130,000 m³/d in winter to 340,000 m³/d in summer, with a peak week average of 361,000 m³/d that determines the required firm DW production capacity.

The central quantitative result concerns the comparison between independent and integrated planning. Under independent planning, RW zones are served by a guaranteed allocation sized to the volume reliably deliverable without a DW backup, with any production above this floor discharged. DW must then cover the full residual irrigation demand. Under integrated planning, full daily RW production is delivered to irrigation, and DW covers only the residual top-up, reducing required DW production capacity. These savings are achievable without any increase in treatment capacity, through coordinated operational and capacity planning of the two supply systems.

The findings demonstrate that integrated planning of DW and RW supply delivers measurable benefits in both resource utilisation and infrastructure efficiency.

An integrated planning model is currently under development. Full scenario runs across the planning horizon to 2035, incorporating demand growth, infrastructure commissioning timelines, and asset reliability for both supply systems, will be reported in subsequent work.

The approach presented is transferable to other arid regions facing analogous challenges, and highlights the importance of institutional coordination across desalination planning, wastewater treatment, and water distribution in enabling the transition away from non-renewable groundwater.

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