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INTEGRATED SURFACE WATER AND GROUNDWATER MANAGEMENT IN THE ALGARVE (SOUTHERN PORTUGAL) THE ROLE OF NUMERICAL MODELLING IN REGIONAL WATER RESOURCES PLANNING

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ABSTRACT

The Algarve region, in southern Portugal, is characterized by a Mediterranean climate with pronounced seasonal and interannual variability, where increasing water demand, recurrent droughts, and climate change have intensified pressure on both surface water and groundwater resources. Sustainable management of these resources requires an integrated approach that recognizes the strong hydraulic interactions between reservoirs, river systems, and aquifer systems. This paper presents the Algarve as a representative case study of conjunctive surface water and groundwater management supported by regional numerical modelling. The study reviews the development of a regional groundwater flow model designed as a decision-support tool for water resources planning, enabling the evaluation of groundwater abstraction, reservoir operation, artificial recharge, and the impacts of different management scenarios. Particular attention is given to the contribution of numerical modelling in improving water allocation, protecting coastal aquifers against seawater intrusion, assessing groundwater recharge, and enhancing the resilience of water supply systems under prolonged drought conditions. The paper also discusses the evolution of integrated water resources management over the past two decades, highlighting recent advances in hydrogeological modelling, geographic information systems, remote sensing, climate impact assessment, and decision-support methodologies. The Algarve experience demonstrates that regional numerical models provide an effective scientific framework for optimizing conjunctive use of surface water and groundwater while supporting adaptive management strategies in Mediterranean regions facing increasing water scarcity. The lessons derived from this

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study are applicable to many semi-arid coastal regions worldwide where sustainable water management has become a major environmental and socio-economic challenge.

Keywords: Integrated water resources management; Surface water; Groundwater; Numerical modelling; Conjunctive use; Climate change; Coastal aquifers; Seawater intrusion; Decision support systems; Algarve; Portugal.

INTRODUCTION

Water security in coastal Mediterranean regions can no longer be addressed through the isolated development of dams, aquifers or water-transfer infrastructure. It must instead be understood as a dynamic regional problem in which climatic variability, recurrent drought, seasonal demand, groundwater depletion, declining reservoir reliability, water-quality deterioration and ecosystem vulnerability interact across multiple spatial and temporal scales. Investigations conducted in semi-arid and Mediterranean environments have consistently shown that changes in rainfall distribution and drought persistence directly affect runoff generation, aquifer recharge, reservoir inflows and the long-term availability of water resources (Lazri et al., 2007; Boubakeur, 2018; Bouguerra and Benslimane, 2017; Choukrani et al., 2018; Doumounia et al., 2020; N'Guessan Bi et al., 2020; Kouao et al., 2020; Nakou et al., 2023; Benali Khodja and Ferdjouni, 2024; Koussa, 2025). These pressures are particularly acute in coastal territories, where demographic growth, irrigated agriculture, urban expansion and seasonal tourism concentrate water demand during the driest period of the year, precisely when natural recharge and surface-water availability are at their lowest. The resulting imbalance between supply and demand increases the dependence on strategic reserves and exposes conventional water-management systems to hydrological, economic and environmental failure.

Climate change further intensifies this structural vulnerability by modifying precipitation regimes, increasing evapotranspiration, prolonging dry periods and altering the frequency of extreme events. Its impacts on water resources have been documented in Mediterranean, African and tropical basins, where declining recharge, increasing hydroclimatic variability and growing uncertainty have complicated the planning of both surface-water and groundwater systems (Kouassi et al., 2013; Nichane and Khelil, 2015; El Fellah Idrissi et al., 2017; Assemian et al., 2021; Nassa et al., 2021; Chadee et al., 2023; Ouhamdouch et al., 2016; Oga et al., 2016). Rainfall–runoff modelling studies have also demonstrated that watershed response cannot be inferred from rainfall alone because it depends on catchment structure, drainage-network organization, land use, soil properties and antecedent moisture conditions (Abdeddaim and Benkhaled, 2016; Abdi and Meddi, 2015; Djellouli et al., 2015; Faregh and Benkhaled, 2016; Fernando et al., 2021; Atallah et al., 2024; Mehta and Yadav, 2024; Kherde et al., 2024). Consequently, future water-resource planning must move beyond the assumption of stationary hydrological conditions and explicitly incorporate uncertainty, drought persistence, extreme rainfall and climate-driven changes in recharge and reservoir inflows.

Groundwater occupies a central position in this problem because it provides a naturally stored and spatially distributed reserve that can buffer seasonal and multiannual shortages. However, this buffering capacity is neither unlimited nor automatically sustainable. Excessive abstraction may induce persistent drawdown, reduce spring and river discharge, disturb groundwater-dependent ecosystems and promote the movement of poor-quality water toward pumping areas. These effects have been observed in several semi-arid aquifers affected by overexploitation, anthropogenic pressure and declining recharge (Baiche et al., 2015; Bouchemal and Achour, 2015; Belhadj et al., 2017; Laghezal et al., 2019; Lachache et al., 2023). In coastal aquifers, the consequences may be particularly severe because groundwater-level decline can reverse natural hydraulic gradients and favour seawater intrusion. Studies of coastal groundwater systems have shown that marine intrusion results from the combined influence of pumping, aquifer geometry, recharge variability, freshwater–seawater interactions and land-use pressure (Haouchine et al., 2015; Djabri et al., 2019; Morsli et al., 2017; Ngouala et al., 2016). Hydrochemical, isotopic and geospatial investigations therefore constitute essential tools for identifying recharge sources, defining groundwater flow paths, distinguishing natural salinity from marine intrusion and evaluating the renewability of exploited reserves (Bahir et al., 2015; El Moukhayar et al., 2015; Later and Labadi, 2024; Jaiswal et al., 2023; Deb, 2024).

Surface-water reservoirs are equally strategic, but their performance is constrained by hydroclimatic variability, sedimentation, evaporation, leakage, water-quality deterioration and operating rules that may not be adapted to changing demand. Reservoir sedimentation progressively reduces active storage and weakens the ability of dams to regulate droughts and floods, particularly in erosion-prone semi-arid catchments (Larfi and Remini, 2006; Meguenni and Remini, 2008; Meddi, 2015; Benfetta et al., 2016; Bougamouza et al., 2020; Bougamouza et al., 2022). In parallel, high evaporation losses may substantially reduce the effective yield of reservoirs located in dry Mediterranean environments (Boutoutaou et al., 2020), while leakage can compromise storage efficiency and alter exchanges between dams and surrounding aquifers (Benfetta et al., 2017a; Benfetta et al., 2017b). Nevertheless, these exchanges are not always detrimental. Dam releases and reservoir seepage can locally contribute to alluvial-aquifer recharge, demonstrating the potential hydraulic connection between regulated surface water and groundwater reserves (Abaidia and Remini, 2020; Hountondji et al., 2019). Reservoir operation must therefore be analysed within the broader basin water balance rather than as an isolated engineering problem. Optimization methods, decision-support systems and adaptive operating strategies can improve allocation among urban supply, irrigation, environmental requirements and drought storage (Mezenner et al., 2022; Mehta et al., 2023; Argaz, 2018).

These findings converge toward a fundamental principle: the apparent opposition between dams and groundwater is scientifically misleading and operationally counterproductive. Surface water and groundwater are components of the same hydrological system, connected through recharge, infiltration, river–aquifer exchanges, reservoir seepage, pumping-induced gradients and return flows. Their conjunctive use can increase supply reliability by storing water in reservoirs during favourable periods,

preserving aquifers as strategic drought reserves, shifting abstraction between sources according to water quality and availability, and limiting the environmental consequences of excessive dependence on a single resource. Such an approach also creates opportunities for managed aquifer recharge, including the infiltration of surface water or treated wastewater where hydrogeological and sanitary conditions are suitable (Gaaloul, 2015; Bemmoussat et al., 2017; Chibane and Ali-Rahmani, 2015). The need for integration is further reinforced by the interdependence between water quantity and water quality, as nitrate contamination, salinization, leachate infiltration and diffuse anthropogenic pollution may render part of the available groundwater reserve unsuitable for use (Kerboub et al., 2016; Koussa and Berhail, 2021; El Kharmouz et al., 2013; Djabri et al., 2015).

Numerical modelling provides the analytical framework required to translate this integrated vision into operational water-management decisions. Groundwater-flow models can represent aquifer geometry, recharge, hydraulic properties, abstraction, boundary conditions and exchanges with rivers, reservoirs and the sea. Hydrological models can simultaneously estimate rainfall–runoff transformation, reservoir inflows and the response of watersheds to climatic variability. When combined with geographic information systems, monitoring networks, hydrochemical information and scenario analysis, these tools allow managers to test alternative abstraction patterns, drought policies, reservoir releases, managed-recharge schemes and emergency-supply strategies before they are implemented. The increasing use of geostatistical, artificial-intelligence and machine-learning methods also offers new possibilities for predicting groundwater levels, interpolating hydraulic properties and supporting decisions in data-scarce regions (Fatemi and Molavi, 2025; Dendouga et al., 2026; Molavi, 2025; Belouz et al., 2025). However, modelling should not be regarded as a substitute for observation. Its reliability depends on the quality of conceptual models, field measurements, pumping records, piezometric monitoring, recharge estimates and continuous model updating.

For the Algarve, where large seasonal water demand coexists with recurrent drought, coastal aquifers and a regional dam system, the central management challenge is therefore not to determine whether surface water should replace groundwater. It is to define how both resources can be jointly operated without exceeding aquifer renewal, compromising reservoir security or aggravating salinization and ecosystem degradation. The region requires a flexible management framework capable of switching between sources, preserving groundwater during normal years, mobilizing it strategically during droughts, recovering aquifer storage during wetter periods and adapting reservoir operations to changing hydrological conditions. Such a framework must be based on regional numerical models that quantify the consequences of alternative policies and make the physical limits of each resource explicit. The integration of dams, aquifers, monitoring systems and predictive models is thus not merely a technical improvement; it is a necessary condition for achieving long-term water security in a densely used coastal Mediterranean territory.

Water resources are facing unprecedented pressure worldwide as a consequence of rapid population growth, agricultural intensification, urbanization, industrial development and climate variability. In semi-arid and Mediterranean regions, these pressures are

exacerbated by low and irregular precipitation, recurrent droughts, high evapotranspiration rates and increasing seasonal water demand. Under such conditions, ensuring a sustainable and reliable water supply has become one of the major challenges for water managers and policy makers. Consequently, the concept of Integrated Water Resources Management (IWRM) has progressively emerged as the most appropriate framework for coordinating the development and management of surface water and groundwater resources while preserving environmental sustainability and socio-economic development (Wanielista et al., 1997).

Groundwater constitutes one of the most strategic freshwater resources in Mediterranean environments owing to its relatively stable quality, natural protection against evaporation and ability to sustain water supply during prolonged drought periods. Nevertheless, the continuous increase in groundwater abstraction over recent decades has produced significant environmental impacts in many coastal aquifers, including groundwater level decline, seawater intrusion, reduction of spring discharge and deterioration of water quality resulting from agricultural and urban activities (Carreira, 1991; Stigter et al., 1998). These problems are particularly critical in coastal regions where freshwater aquifers are hydraulically connected with the sea and where excessive pumping may irreversibly modify groundwater flow regimes.

In response to these challenges, many Mediterranean countries have invested in the construction of dams and regional water transfer systems in order to reduce dependence on groundwater. However, practical experience has demonstrated that replacing groundwater entirely with surface water does not necessarily guarantee greater water security. Surface reservoirs are themselves vulnerable to prolonged droughts, water quality degradation, eutrophication and operational constraints, whereas groundwater provides a natural strategic reserve capable of compensating seasonal and interannual fluctuations in surface water availability. Consequently, recent water management strategies increasingly advocate the conjunctive use of surface water and groundwater rather than the exclusive reliance on a single resource (Wanielista et al., 1997).

Within this context, numerical groundwater modelling has become one of the most effective scientific tools for supporting integrated water resources management. Numerical models enable the simulation of groundwater flow, estimation of recharge and discharge, assessment of groundwater–surface water interactions, prediction of aquifer responses to alternative pumping scenarios and evaluation of management strategies before their implementation. They also facilitate the identification of sustainable abstraction rates, optimization of well fields, assessment of seawater intrusion risks and improvement of regional water allocation policies (De Marsily, 1986). Recent developments in groundwater modelling have further enhanced their capability to integrate climatic variability, geospatial information systems and decision-support methodologies, making them indispensable tools for sustainable water resources planning in complex hydrogeological environments (Akram et al., 2025).

The Algarve, located in southern Portugal, represents one of the most representative Mediterranean coastal regions where these challenges coexist. Covering approximately 5,400 km^2, the region has experienced remarkable socio-economic development during

the last decades, mainly driven by tourism expansion and irrigated agriculture, leading to a substantial increase in annual water demand. Historically, groundwater constituted the principal source of water supply for domestic, agricultural and industrial uses. Thousands of wells and boreholes exploiting carbonate and detrital aquifers ensured regional water supply throughout most of the twentieth century (Trac, 1981). However, the rapid increase in groundwater abstraction progressively generated quantitative and qualitative problems, particularly nitrate contamination associated with agricultural practices and seawater intrusion in several coastal aquifers (Carreira, 1991; Stigter et al., 1998).

To address these problems, the Portuguese authorities initiated an ambitious program involving the construction and operation of major reservoirs, including Bravura, Arade, Beliche, Funcho, Odeleite and, subsequently, Odelouca, with the objective of transferring public water supply from groundwater to surface water. Although this strategy significantly improved regional drinking water management, operational experience demonstrated that the complete abandonment of groundwater was neither technically feasible nor environmentally desirable because each resource exhibits distinct advantages and limitations. This evolution progressively highlighted the necessity of integrated management strategies based on the conjunctive use of reservoirs and aquifer systems, allowing each resource to compensate for the weaknesses of the other under variable hydrological conditions.

Parallel to these developments, hydrogeological investigations considerably improved the understanding of the regional aquifer systems. The identification and characterization of seventeen major aquifer systems in the Algarve provided a comprehensive conceptual framework describing aquifer geometry, hydraulic properties, recharge mechanisms and groundwater flow patterns (Almeida et al., 2000). These advances created the scientific basis required for implementing regional numerical groundwater flow models capable of supporting water resources planning and management. More recent studies have further demonstrated the usefulness of these models for optimizing groundwater abstraction, evaluating managed aquifer recharge schemes and improving regional resilience to drought under changing climatic conditions (Standen et al., 2022; Standen et al., 2023).

The objective of the present study is therefore to demonstrate the contribution of finite-element groundwater flow modelling to integrated water resources management in the Algarve region. Six regional aquifer systems are simulated to analyze groundwater flow behavior, improve groundwater recharge assessment and evaluate the role of numerical modelling as a decision-support tool for the conjunctive management of groundwater and surface water resources. The study also illustrates how regional groundwater models can contribute to improving the sustainability, reliability and resilience of water supply systems in Mediterranean coastal environments.

EVOLUTION OF WATER RESOURCES DEVELOPMENT IN THE ALGARVE

The historical evolution of water resources development in the Algarve reflects the profound transformation of the region during the second half of the twentieth century. Rapid demographic growth, expansion of irrigated agriculture and the remarkable development of tourism progressively increased water demand, requiring major

investments in water infrastructure and a gradual transition from localized groundwater exploitation toward integrated regional water resources management.

Until the 1950s, groundwater represented the only significant source of water supply throughout most of the Algarve. Water was abstracted mainly from shallow hand-dug wells supplying rural communities, small irrigated areas and domestic uses. The relatively low population density and modest agricultural development-maintained groundwater abstraction within the natural recharge capacity of the aquifer systems.

The first major change occurred with the construction of large reservoirs designed to regulate the highly variable Mediterranean streamflow. Fig. 1 illustrates the geographical distribution of the principal reservoirs constructed in the Algarve, namely Arade, Bravura, Funcho, Beliche and Odeleite. These reservoirs are strategically located in the main river basins and provide surface-water storage capable of reducing the seasonal variability of water availability.

The chronological development of these infrastructures is summarized in Table 1, which shows their year of construction, dam height, watershed area, structural type and storage capacity. The table clearly illustrates the progressive increase in reservoir size and storage volume from the 1950s to the 1990s. While the Arade and Bravura dams were originally designed mainly to support irrigation, the later Beliche, Funcho and Odeleite dams were conceived as multipurpose infrastructures supplying both irrigation schemes and regional public water supply. Their combined storage capacity considerably increased the security of water supply throughout southern Portugal.

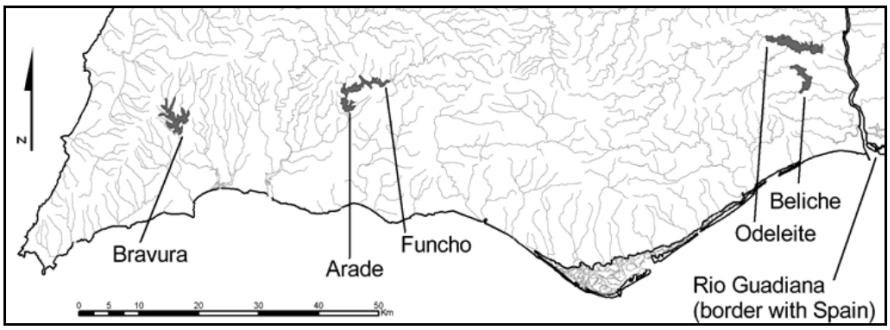

Figure 1: Large dams in the Algarve region

Table 1: Some characteristics of the large dams in the Algarve region

Dam	Year	Height (m)	Watershed (km^2)	Type	Max. storage (10^6 m^3)
Arade	1956	46	224	Embankment	27
Bravura	1958	41	75	Concrete	32
Beliche	1986	54	99	Embankment	48
Funcho	1993	49	211	Concrete	43
Odelcite	1996	65	352	Embankment	117

The technological development of deep-drilling equipment during the 1960s completely changed groundwater exploitation practices. Thousands of drilled boreholes progressively replaced traditional hand-dug wells, allowing abstraction from deeper and more productive aquifers. This technological evolution successfully met the rapidly increasing water demand generated by urban expansion, tourism and agricultural intensification. However, groundwater development occurred largely without regional hydrogeological planning, resulting in numerous independent abstraction systems operated by individual municipalities.

The spatial distribution of groundwater abstraction points is presented in Fig. 2, together with the regional distribution of the seventeen principal aquifer systems identified in the Algarve. The figure clearly demonstrates the high density of groundwater wells along the coastal zone, where water demand is greatest owing to urban development and tourism. It also highlights the close relationship between borehole concentration and the most productive carbonate and detrital aquifers, emphasizing the strategic importance of these groundwater resources for regional development.

Fig. 2 also reveals that numerous productive boreholes are located outside the boundaries of the main regional aquifer systems. This observation illustrates the hydrogeological complexity of the Algarve and indicates that groundwater resources are not restricted to the major aquifers alone. Consequently, sustainable groundwater management requires a regional hydrogeological approach capable of integrating both the principal aquifer systems and the surrounding fractured and detrital formations (Almeida et al., 2000).

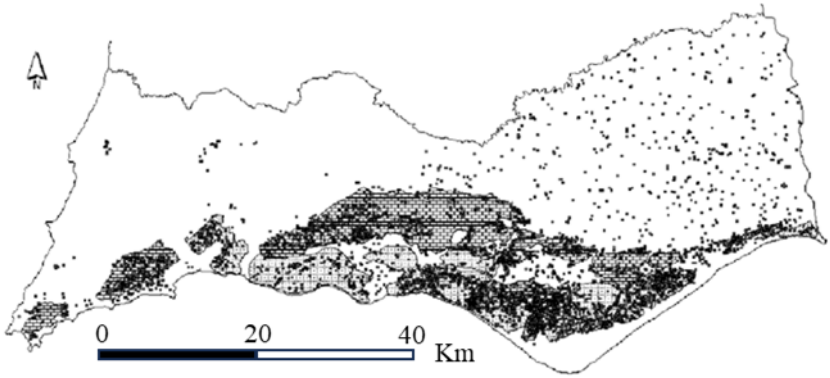

Figure 2: Location of dug wells and boreholes in the Algarve region and geometry of the 17 aquifer systems with regional expression in the Algarve (adapted from the

DRAOT database)

The absence of integrated regional planning during this period contributed to several quantitative and qualitative groundwater problems. Intensive abstraction locally produced declining groundwater levels, while agricultural development increased nitrate

contamination in some aquifers (Stigter et al., 1998). In coastal areas, excessive groundwater withdrawals favored seawater intrusion processes, degrading groundwater quality in several vulnerable aquifer systems (Carreira, 1991). These environmental impacts progressively demonstrated that groundwater resources could no longer be managed independently at the municipal scale.

The response adopted by the Portuguese authorities consisted of developing regional water supply systems based primarily on surface water stored in reservoirs. Although this strategy substantially improved the reliability of public water supply, subsequent experience demonstrated that exclusive dependence on either reservoirs or groundwater could not provide optimal long-term water security under Mediterranean climatic conditions characterized by recurrent droughts and strong hydrological variability.

These developments marked the beginning of a new philosophy of water resources management in the Algarve, based on the complementary use of surface water and groundwater. The historical evolution summarized in Figs 1 and 2, and Table 1 therefore illustrates not only the development of hydraulic infrastructures but also the progressive transition from local water supply systems toward integrated regional water resources management supported by hydrogeological knowledge and scientific planning.

REGIONAL NUMERICAL MODELLING AS A DECISION-SUPPORT TOOL

Governing equation and conceptual hydrogeological model

Integrated management of surface water and groundwater resources requires a quantitative understanding of the hydraulic behavior of regional aquifer systems and their interactions with rivers, reservoirs and the coastal environment. Because these interactions involve complex spatial and temporal processes that cannot be adequately evaluated from field observations alone, numerical groundwater modelling has become an essential scientific tool for analyzing groundwater flow, estimating recharge, predicting aquifer response to pumping, and supporting sustainable water resources planning (De Marsily, 1986; Todd and Mays, 2005).

The Algarve is characterized by a highly heterogeneous hydrogeological setting composed of carbonate, detrital and fractured-rock aquifers exhibiting considerable spatial variability in hydraulic conductivity, storage capacity and recharge conditions. These aquifers are hydraulically interconnected through complex groundwater flow systems influenced by topography, geological structures, surface-water bodies and the Atlantic Ocean. Consequently, understanding groundwater behavior requires a regional conceptual model capable of integrating all major components of the hydrological system rather than analyzing individual aquifers independently.

The conceptual hydrogeological model adopted for the Algarve considers groundwater flow as a continuous process governed by the conservation of mass and Darcy's law. Under transient conditions, groundwater flow may be described by the classical three-dimensional groundwater flow equation (Monteiro and Costa, 2004):

$$div\left(-\left[T\right]\overrightarrow{grad}\,h\right)+Q=0 \tag{1}$$

Where T (transmissivity) is the bi-dimensional conductive parameter [L^2T^{-1}], h is hydraulic head [L], Q (source term) is a volumetric flux per unit volume [L^3T^{-1}], divergence (*div*) is an operation performed in a vector that produces a scalar quantity and the gradient operator (*grad*) performed on a scalar produces a vector. Using this equation the overall water balance equals zero. Therefore, the hydraulic behavior of the flow domain is simulated in a steady state, representing the long-term water balance.

This governing equation expresses the conservation of groundwater mass within a porous medium and constitutes the mathematical basis of virtually all regional groundwater flow models (De Marsily, 1986). The left-hand side represents groundwater inflows and outflows together with external stresses, whereas the right-hand side describes temporal variations in groundwater storage. The equation therefore provides a rigorous quantitative framework for simulating both natural groundwater flow and anthropogenic disturbances resulting from groundwater abstraction or artificial recharge.

Unlike local-scale investigations, regional groundwater modelling requires the integration of all relevant hydrological processes affecting the aquifer system. In the Algarve, groundwater recharge originates primarily from direct infiltration of rainfall, infiltration through ephemeral stream channels, leakage from reservoirs, and lateral inflow from adjacent hydrogeological units. Groundwater discharge occurs through pumping wells, natural springs, river baseflow, evapotranspiration in shallow groundwater areas, and submarine groundwater discharge along the coastline.

These hydraulic processes are summarized in the conceptual hydrogeological model presented in Fig. 3.

Fig 3 illustrates the principal components of the regional groundwater flow system and the hydraulic interactions between surface water and groundwater. Recharge occurs predominantly in elevated carbonate formations where fractured limestones favor rapid infiltration, whereas groundwater flows toward lower topographic areas before discharging naturally through springs, rivers or directly into the Atlantic Ocean. The figure also highlights the influence of reservoirs and pumping wells on regional groundwater circulation, illustrating the need to analyze these hydraulic components as a single integrated system rather than as independent water resources.

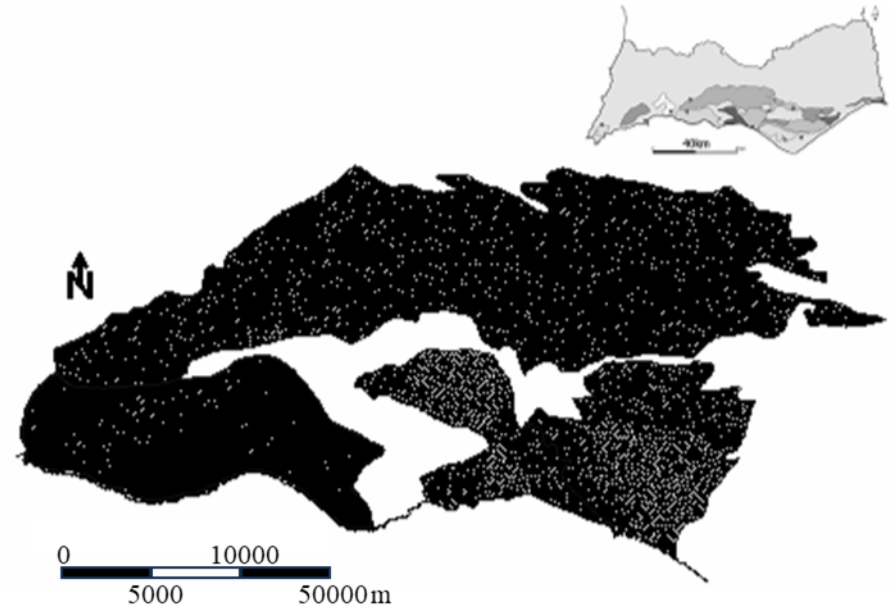

Figure 3: Finite element meshes built for the of Querença-Silves, Ferragudo Albufeira, Albufeira-Ribeira de Quarteira and Quarteira aquifer systems. The position of these aquifers is showed in the map above, adapted from Almeida et al. (2000).

The conceptual model further recognizes that groundwater abstraction modifies the natural hydraulic gradients by creating cones of depression around pumping wells. Under intensive pumping conditions, these perturbations may alter groundwater flow directions, reduce spring discharge and increase the risk of seawater intrusion in coastal aquifers. Conversely, reservoir leakage and managed aquifer recharge may locally increase groundwater storage and partially compensate groundwater withdrawals. The quantitative assessment of these competing processes requires numerical simulation under different management scenarios.

An important feature of the Algarve conceptual model is the explicit consideration of groundwater–surface water interactions. Rivers, reservoirs and aquifers exchange water continuously depending on hydraulic gradients, seasonal recharge conditions and operational management of hydraulic infrastructures. During wet years, increased reservoir storage and river infiltration contribute to groundwater recharge, whereas during prolonged droughts groundwater provides essential support to river baseflow and public water supply. Such bidirectional exchanges constitute one of the fundamental principles of conjunctive water resources management.

The regional conceptual model therefore provides the scientific basis for transforming complex hydrogeological information into a mathematical representation suitable for numerical computation. By integrating geological structure, hydraulic properties, recharge mechanisms, abstraction systems and hydraulic boundary conditions within a unified framework, the conceptual model becomes the essential intermediate step between field investigations and numerical simulation.

The development of this conceptual framework represented a major advance in regional water resources planning in southern Portugal. It enabled groundwater management to evolve from empirical local practices toward quantitative decision-support methodologies capable of evaluating alternative development strategies, assessing long-term sustainability and supporting integrated management of surface water and groundwater resources under increasing climatic uncertainty.

Development of the regional finite-element groundwater models

The transition from the conceptual hydrogeological model to a numerical representation constitutes a fundamental step in the quantitative analysis of regional groundwater systems. While the conceptual model defines the geometry of the aquifers, the hydraulic boundaries, the recharge mechanisms and the principal groundwater flow paths, the numerical model transforms this qualitative representation into a mathematical tool capable of simulating groundwater flow under both natural and anthropogenic conditions.

The numerical models developed for the Algarve were implemented using the finite-element method because of its ability to represent groundwater flow within hydrogeological systems characterized by complex geometry, irregular boundaries and heterogeneous hydraulic properties. Compared with regular finite-difference grids, the finite-element approach allows the computational mesh to conform accurately to geological contacts, river valleys, coastlines and aquifer boundaries, thereby improving both the realism and numerical stability of groundwater simulations (De Marsily, 1986).

The regional modelling strategy was progressively developed over more than two decades through the integration of geological, hydrogeological, hydrological and climatological information obtained from numerous field investigations. Particular attention was given to the six principal aquifer systems for which sufficient hydrogeological information was available: Almádena-Odeáxere, Querença-Silves, Ferragudo-Albufeira, Albufeira-Ribeira de Quarteira, Quarteira and Luz de Tavira. These aquifers represent the largest groundwater reserves of the Algarve and play a strategic role in regional water supply.

Model construction required the compilation and harmonization of a large amount of hydrogeological information, including geological maps, borehole logs, pumping-test interpretations, groundwater-level measurements, spring inventories, recharge estimates and groundwater abstraction records. These datasets were incorporated into a common spatial database from which the numerical models were generated.

A major innovation of the Algarve modelling program consisted in the development of an integrated platform linking the numerical groundwater model with a Geographic Information System (GIS). This interface allowed the automatic generation of model geometry, spatial attribution of hydrogeological parameters, management of monitoring data, and visualization of simulation results. The GIS also considerably simplified the preparation of input data and facilitated the continuous updating of the models as new hydrogeological information became available (Monteiro et al., 2002a).

The numerical representation incorporated all the principal components governing groundwater flow at the regional scale. Aquifer geometry was defined from geological mapping and drilling information, whereas hydraulic parameters were assigned according to lithological characteristics and pumping-test results. Recharge resulting from precipitation infiltration was spatially distributed according to land cover, soil characteristics and geological formations. Groundwater abstractions were represented using the location and pumping rates of the principal production wells, while rivers, springs and the Atlantic coastline were introduced as hydraulic boundary conditions according to their hydrogeological behavior.

An important aspect of model implementation concerned the estimation of groundwater recharge. Previous hydrogeological investigations indicated that recharge rates vary considerably according to lithology, ranging from relatively low infiltration percentages in unconsolidated Quaternary deposits to much higher values within fractured and karstified carbonate formations (Almeida et al., 2000). Because recharge constitutes one of the most sensitive parameters controlling groundwater availability, particular effort was devoted to its spatial representation within the numerical models. The GIS environment facilitated this task by allowing the automatic assignment of recharge values to each computational element according to geological and climatic information.

Following model construction, calibration was undertaken through an iterative process aimed at minimizing the discrepancies between observed and simulated groundwater heads. Calibration involved the adjustment of hydraulic conductivity, recharge rates and storage coefficients while maintaining consistency with the available field measurements and hydrogeological knowledge. Rather than seeking a purely mathematical optimization, calibration emphasized the physical realism of the simulated groundwater flow system and the preservation of the conceptual hydrogeological interpretation.

Model validation was subsequently performed by comparing simulated hydraulic heads, groundwater flow directions and regional water balances with independent hydrogeological observations. The satisfactory agreement obtained between measured and simulated groundwater levels demonstrated that the adopted conceptual model adequately reproduced the dominant groundwater circulation patterns within the principal aquifer systems of the Algarve. These results provided confidence in the predictive capability of the numerical models and justified their application as decision-support tools for regional water resources planning.

The integration of numerical groundwater models with a GIS environment also represented an important advance for operational water management. Beyond facilitating model construction and calibration, this integrated platform enabled rapid visualization of simulation results, comparison of alternative management scenarios and continuous incorporation of new hydrogeological information. Consequently, the models evolved from purely research-oriented tools into operational instruments capable of supporting groundwater management, infrastructure planning and environmental decision-making at the regional scale.

The methodology adopted in the Algarve demonstrated that the reliability of regional groundwater simulations depends not only on the numerical solution technique but also on the quality of the conceptual hydrogeological model, the availability of field observations and the consistency of the spatial database used during model construction. Numerical modelling should therefore be regarded as a continuous process integrating field investigations, monitoring programs and scientific interpretation rather than as an isolated computational exercise.

Application of regional numerical models to integrated water resources management

The ultimate objective of regional groundwater modelling is not merely to reproduce groundwater flow patterns but to provide a scientific basis for water resources planning and operational decision-making. Once calibrated and validated, numerical models become powerful predictive tools capable of evaluating alternative management strategies before they are implemented in the field. In regions such as the Algarve, where water resources are limited and climatic variability is high, numerical modelling represents one of the most effective approaches for integrating scientific knowledge into water management policies.

The regional finite-element models developed for the Algarve were therefore designed as decision-support systems, enabling water managers to evaluate the consequences of different groundwater abstraction policies, reservoir operation strategies and groundwater recharge conditions. Instead of relying exclusively on empirical observations, management alternatives can be assessed quantitatively through numerical simulation, reducing uncertainty and improving the sustainability of water allocation decisions. This role of groundwater models as decision-support tools has been reinforced by subsequent work on managed aquifer recharge and integrated planning in southern Portugal.

One of the first applications consisted of analyzing the regional distribution of hydraulic heads and groundwater flow directions. These simulations provide a comprehensive representation of groundwater circulation throughout the aquifer systems and allow identification of recharge areas, discharge zones and preferential groundwater flow paths.

As shown in Fig. 4, the simulated equipotential surfaces reproduce the regional hydraulic gradients expected from geological and topographic conditions. Groundwater flow vectors indicate that recharge occurs mainly within elevated carbonate formations before groundwater migrates toward springs, river valleys and finally the Atlantic coastline. The

close correspondence between simulated groundwater flow directions and the observed hydrogeological behaviour demonstrates the reliability of the conceptual model and confirms the adequacy of the finite-element methodology for representing regional groundwater circulation. Furthermore, the simulations allow visualization of hydraulic perturbations generated by intensive pumping, thereby providing valuable information for evaluating the long-term sustainability of groundwater exploitation.

A second major application concerns the quantitative estimation of groundwater recharge. Recharge constitutes one of the most influential variables controlling groundwater availability because it determines the renewable component of groundwater resources. Earlier regional water balances were generally based on simplified precipitation maps and empirical infiltration coefficients. The integration of Geographic Information Systems with finite-element models enabled the incorporation of improved spatial precipitation datasets and refined infiltration maps, resulting in more reliable recharge estimates.

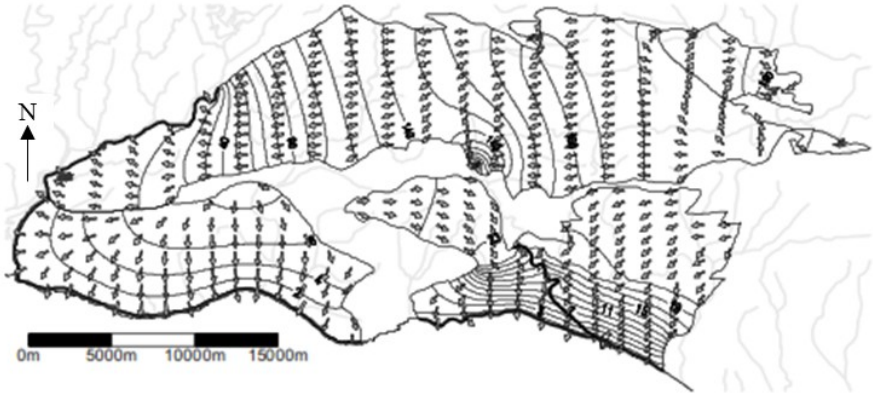

Figure 4: Example of finite element simulations performed for a variant of the models implemented for the Querença-Silves, Ferragudo-Albufeira, Albufeira-Ribeira de Quarteira and Quarteira aquifer systems.

Bin Fig. 4, oundary conditions correspond to imposed hydraulic heads (represented by bold lines) in the limits of the aquifers (coast line and rivers in hydraulic connection with aquifers). There are also imposed heads in springs controlling the regional flow pattern in the Querença-Silves's system. The equipotentials and gradient vectors show the direction of groundwater flow. The stream network is also represented in order to illustrate the coincidence of the predominant patterns of groundwater and surface water flows.

Table 2 demonstrates that the recalculated recharge values differ significantly from earlier estimates for several aquifer systems. Depending on the hydrogeological characteristics of each aquifer, differences range from approximately 8% to more than 30%, reflecting the influence of improved precipitation mapping and more realistic spatial representation of infiltration processes. These results illustrate that groundwater recharge should not be considered a fixed parameter but rather a dynamic variable that evolves as new climatic,

geological and hydrogeological information becomes available. Consequently, periodic updating of regional groundwater models is essential to maintain the reliability of water resources assessments.

Table 2: Recharge values proposed in ALMEIDA et. al (2000) and computed with the implemented models.

Aquifer system	Area (Km^2)	Recharge (m^3/yr) Referenced values	Recharge (m^3/yr) Models	Deviation (%)
Querença-Silves	324.24	7.00E+07	9.33E+07	133.26
Almádena-Odiáxere	63.49	2.00E+07	1.67E+07	83.41
Luz de Tavira	27.90	4.00E+06	4.77E+06	119.36
Ferragudo-Albufeira	118.26	8.00E+06	1.00E+07	124.98
Albufeira e Rib. Quart.	140.97	2.37E+07	2.56E+07	108.05

The improved recharge estimates have important implications for regional water management. Recharge directly controls the renewable groundwater resource and therefore determines sustainable abstraction limits. Underestimation of recharge may lead to unnecessary restrictions on groundwater development, whereas overestimation increases the risk of long-term groundwater depletion, declining groundwater levels and seawater intrusion in coastal aquifers. Numerical modelling therefore provides a rational basis for defining abstraction policies consistent with the natural replenishment capacity of each aquifer system.

Beyond water balance calculations, regional groundwater models also permit simulation of alternative management scenarios. Pumping rates may be increased or reduced, new production wells introduced, artificial recharge schemes evaluated and drought conditions reproduced numerically before management decisions are implemented. Such predictive analyses considerably reduce the uncertainty associated with infrastructure planning and improve the efficiency of regional investment strategies.

Fig. 5 illustrates one of the practical applications of the regional numerical models to groundwater resources management. Unlike Figure 4, which represents the calibrated groundwater flow regime under reference conditions, Figure 5 presents the response of the aquifer system to a management scenario involving modified groundwater abstraction patterns. The simulation demonstrates the capacity of the numerical model to predict changes in hydraulic heads and groundwater flow resulting from alternative water-use strategies.

N
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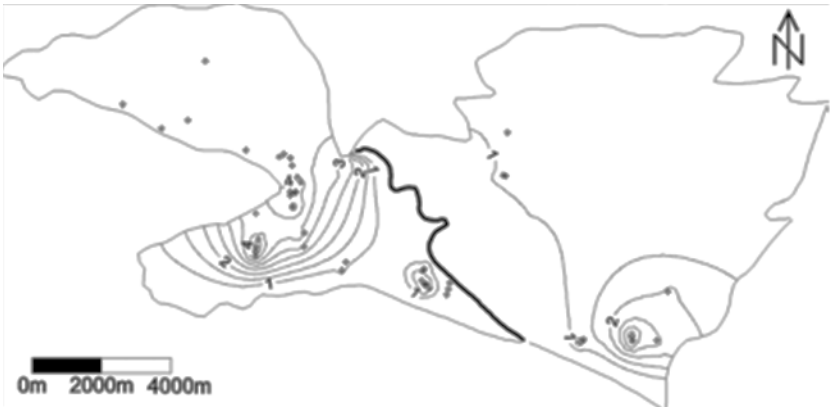

Figure 5: Equipotentials (meter) generated from a simulation.

When drwing Fig. 5, it has been taking into account only the recharge-discharge balance of the aquifer in natural conditions (top left), and from a simulation where the withdrawals of the pumping wells used for urban supply is superimposed to the natural conditions (top right). At the bottom a residual map shows the difference between these two simulations

The results indicate that groundwater responses are spatially heterogeneous and strongly dependent on local hydrogeological conditions. Areas subjected to increased pumping exhibit noticeable drawdowns and local modifications of groundwater flow directions, whereas sectors located farther from abstraction centres remain only marginally affected. Such simulations enable the identification of zones where groundwater exploitation may become critical and where corrective measures should be considered before adverse impacts occur.

From a management perspective, Fig. 5 demonstrates the value of numerical modelling as a predictive decision-support tool. By comparing alternative abstraction scenarios, water managers can assess the consequences of future developments, optimize the conjunctive use of surface water and groundwater, and minimize the risks associated with aquifer overexploitation. This capability is particularly important in the Algarve, where groundwater constitutes a strategic resource during prolonged droughts and where coastal aquifers remain vulnerable to seawater intrusion.

The scenario analysis also illustrates the flexibility of regional numerical models. Once calibrated, the same modelling framework can be applied to evaluate drought conditions, emergency water-supply strategies, artificial recharge programs, reservoir operation policies and long-term climate-change adaptation measures. Consequently, numerical modelling becomes an essential component of integrated regional water resources planning rather than merely a scientific exercise.

On the other hand, the flexibility of numerical modelling also facilitates evaluation of climate change impacts. Regional climate projections indicate increasing temperatures, reduced average precipitation and greater interannual variability across southern Portugal. These trends are expected to reduce natural groundwater recharge while simultaneously

increasing water demand. Numerical models provide an effective framework for analyzing these combined pressures by simulating future groundwater levels, changes in storage, spring discharge and groundwater-surface water interactions under alternative climate scenarios. Similar modelling approaches continue to support groundwater management in the Algarve, particularly for coastal aquifers threatened by seawater intrusion and for the assessment of managed aquifer recharge strategies.

The experience acquired in the Algarve also demonstrates that regional groundwater models evolve continuously as new information becomes available. Hydrogeological monitoring, improved geological characterization, updated abstraction records and advances in numerical methods progressively reduce model uncertainty and increase predictive capability. Consequently, numerical models should not be regarded as static products but as dynamic scientific tools that accompany the continuous evolution of regional water resources management.

The conceptual framework proposed by Monteiro and Costa (2004) anticipated many principles that are now widely adopted within Integrated Water Resources Management (IWRM), including conjunctive use of surface water and groundwater, adaptive management, scenario analysis and evidence-based decision-making. More recent developments, such as the integration of managed aquifer recharge, uncertainty analysis and enhanced monitoring networks, have confirmed the relevance of this approach for Mediterranean coastal aquifers (Vieira and Monteiro, 2003).

Overall, the Algarve case study clearly demonstrates that regional numerical groundwater models constitute far more than computational simulation tools. They provide an integrated scientific platform capable of combining geological, hydrological, climatic and operational information into a coherent decision-support system. Their application considerably improves the capacity of water managers to evaluate future scenarios, optimize conjunctive use of surface water and groundwater, protect coastal aquifers against overexploitation and seawater intrusion, and enhance the resilience of regional water supply systems under increasing climatic uncertainty.

CONCLUSIONS AND PERSPECTIVES

The Algarve constitutes one of the most water-stressed regions of southern Europe, where the combined effects of climatic variability, seasonal tourism, agricultural irrigation and population growth exert increasing pressure on both surface water and groundwater resources. These constraints require integrated management strategies capable of ensuring a reliable water supply while preserving the long-term sustainability of the region's aquifer systems.

This study has demonstrated that regional groundwater flow modelling provides an effective scientific framework for supporting integrated water resources management. The finite-element models developed for the principal Algarve aquifer systems successfully reproduce the regional groundwater flow regime and provide quantitative estimates of recharge, hydraulic heads and groundwater flow directions. The integration

of these models within a Geographic Information System considerably enhances the management of spatial data, facilitates model updating and improves the interpretation of simulation results.

The numerical simulations presented in this study confirm that groundwater cannot be considered independently from surface water resources. Rivers, reservoirs, aquifers and coastal discharge zones constitute interconnected components of a single hydrological system whose behavior can only be properly understood through integrated analysis. Consequently, regional planning should be based on the conjunctive management of all available water resources rather than on the exclusive use of a single source. This conclusion remains fully consistent with the principles of Integrated Water Resources Management (IWRM), which advocate coordinated development and management of water, land and related resources to maximize economic and social welfare without compromising ecosystem sustainability (GWP, 2000).

The results also demonstrate the importance of periodically updating groundwater recharge estimates. The recalculated recharge values obtained using improved precipitation maps and distributed spatial analysis differ substantially from previous regional estimates, confirming that groundwater recharge should be regarded as a dynamic variable reflecting advances in climatic information, hydrogeological knowledge and numerical modelling techniques. Regular updating of regional groundwater models is therefore essential for maintaining reliable assessments of groundwater availability and sustainable abstraction limits.

One of the principal contributions of this work lies in demonstrating that numerical groundwater models extend far beyond their traditional role as research tools. Once calibrated and validated, they become operational decision-support systems capable of evaluating alternative groundwater abstraction strategies, reservoir operation policies, artificial recharge projects and emergency drought management plans before their implementation. Such predictive capability considerably reduces technical uncertainty and contributes to more efficient planning of regional water infrastructures.

The Algarve experience also illustrates the advantages of conjunctive use of surface water and groundwater. Surface reservoirs generally provide large storage capacity but remain vulnerable to prolonged droughts and seasonal deterioration of water quality. Groundwater resources, on the other hand, offer greater natural protection against short-term climatic fluctuations but may become susceptible to overexploitation and seawater intrusion if abstraction exceeds natural recharge. The complementary use of both resources therefore increases the reliability, flexibility and resilience of regional water supply systems. Similar conclusions have been reported by Wanielista et al. (1997), who emphasized that variations in the quantity and quality of surface water rarely coincide with those observed in groundwater resources, allowing one resource to compensate for temporary deficiencies of the other.

Future water management in the Algarve should increasingly incorporate adaptive strategies capable of responding to climate change. Regional climate projections consistently indicate decreasing precipitation, increasing temperatures and more frequent

drought events throughout southern Portugal. These trends are expected to reduce groundwater recharge while simultaneously increasing urban, agricultural and environmental water demands. Under such conditions, numerical groundwater models become indispensable tools for evaluating future management scenarios and identifying sustainable adaptation measures.

The progressive development of managed aquifer recharge, optimization of groundwater abstraction schedules, protection of strategic recharge areas and continuous expansion of hydrogeological monitoring networks represent promising approaches for strengthening regional water security. Advances in remote sensing, Geographic Information Systems, automatic monitoring and numerical modelling now provide unprecedented opportunities for improving groundwater management at both regional and local scales.

The methodology developed for the Algarve also possesses broader scientific relevance. Many Mediterranean coastal regions experience hydrological conditions similar to those of southern Portugal, including irregular precipitation, highly variable recharge, intensive seasonal water demand and vulnerability to seawater intrusion. The integrated modelling framework presented in this study may therefore serve as a reference for other semi-arid coastal regions seeking to improve the sustainable management of conjunctive surface water and groundwater resources.

Finally, this work confirms that effective water resources management depends not only on engineering infrastructure but also on the continuous integration of scientific knowledge into planning and decision-making. Numerical modelling, supported by comprehensive hydrogeological investigations and high-quality monitoring data, constitutes one of the most powerful tools currently available for achieving sustainable and resilient water management under increasing environmental uncertainty. The Algarve experience clearly demonstrates that integrated management based on scientific evidence offers the most appropriate strategy for ensuring long-term water security in Mediterranean regions.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could influence the work reported in this article.

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