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Managed Aquifer Recharge: An integrated water resource management solution for the Algarve, Portugal

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I declare that I am the author of this work, which is original and unpublished. Authors and works consulted are duly cited in the text and are included in the list of references included.

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Kathleen Elizabeth Standen

(assinatura)

Publications associated with this research

Peer-reviewed articles:

Standen, K., Monteiro, J. P., & Costa, L. R. (2020). In-channel managed aquifer recharge: A review of current development worldwide and future potential in Europe. *Water (Switzerland)*, *12*(11), 1–28. https://doi.org/10.3390/w12113099

Standen, K., Hugman, R., & Monteiro, J. P. (2022a). Decision-Support Groundwater Modelling of Managed Aquifer Recharge in a Coastal Aquifer in South Portugal. *Frontiers in Earth Science*, *10* (May), 1–14. https://doi.org/10.3389/feart.2022.904271

Standen, K., Costa, L., Hugman, R., & Monteiro, J. P. (2023). Integration of Managed Aquifer Recharge into the Water Supply System in the Algarve Region, Portugal. Water, 15(12), 2286. https://doi.org/10.3390/w15122286

Conference papers:

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Resumo

A Região do Algarve tem sofrido ao longo dos últimos anos períodos severos de escassez de água que se refletem na diminuição da resiliência dos sistemas de abastecimento em períodos de seca. A Gestão da Recarga de Aquíferos (GRA) pode facultar armazenamento temporário de água permitindo compensar estes períodos de escassez com períodos de excesso de disponibilidade, dependendo o sucesso desta estratégia da disponibilidade de água e de capacidade de armazenamento nos aquíferos, que é tanto maior quanto mais sobre explorados estes se encontrem.

O estudo efetuado à escala regional mostra que a GRA pode contribuir com 24 Mm^3/ano, ou seja, 10% do actual volume de procura de água no Algarve recorrendo a água de boa qualidade com origem nos rios temporários, cumprindo as exigências da Diretiva Europeia das Águas Subterrâneas.

As opções mais promissoras para a GRA que foram identificadas correspondem aos perímetros de rega do Sotavento Algarvio e do Mira (parte do qual se encontra no Barlavento Algarvio). Nestes casos a área das bacias hidrográficas geram valores elevados de escoamento anual médio que podem aumentar a resiliência às alterações climáticas. Por sua vez, A GRA no Sistema Aquífero Mexilhoeira Grande – Portimão (M3) poderia ser usada para substituir parte da água obtida a partir da Barragem da Bravura, usada para suprir as necessidades do perímetro de rega do Alvor. No total, a GRA poderá vir a substituir 15 Mm^3/ano de água superficial usados nos perímetros públicos de rega que correspondem a 32%, 28% e 20% dos consumos totais praticados nos perímetros do Alvor do Sotavento e do Mira respetivamente. Constata-se que a disponibilidade de água para GRA excede de forma significativa a procura local na parte do perímetro de rega do Mira que se localiza no Algarve. Por conseguinte, a GRA poderia reforçar o recurso estratégico identificado no Plano de Eficiência Hídrica desenvolvido pela APA a partir de 2020 que consiste na transferência de água no perímetro do Mira do Alentejo para o Algarve, através do Canal do Rogil.

Foram igualmente identificadas condições para criar e gerir recursos estratégicos nos Sistemas Aquíferos de Albufeira – Ribeira de Quarteira (M6) e de Quarteira (M7), através da combinação de GRA com o uso de águas residuais tratadas em rega (com a consequente redução de extração de água subterrânea). Poderia assim obter-se potencialmente um

volume de recursos da ordem dos 9 Mm^3/anos nos aquíferos M6 e M7 para utilização em períodos de seca/ escassez.

Apesar dos impactos de alterações climáticas previstos no escoamento dos cursos de água temporários, de acordo com o cenário RCP4.5 apontarem para um decréscimo na ordem dos 13% para a disponibilidade de GRA no período 2041-2070, este valor poderá ser reduzido através da melhoria das condições técnicas das metodologias empregues. Prevê-se que a recarga natural dos aquíferos do Algarve decresça cerca de 10% no período 2041-2070, apesar de ser expectável que que estas reduções de recarga natural sejam pequenas em comparação com o potencial de GRA no caso dos sistemas deste tipo que se prevê serem viáveis para suporte os perímetros de rega do Sotavento, da Bravura e do Mira. Foram ainda identificadas outras oportunidades para manter o bom estado quantitativo de alguns aquíferos, em particular o Ferragudo-Albufeira (M4), de acordo com as exigências da Diretiva Quadro da Água.

A GRA pode trazer benefícios a uma escala similar aos obtidos com infraestruturas planeadas para o Algarve como a dessalinização ou a captação de água no Guadiana para armazenamento nas barragens de Odeleite e Beliche, com custos menos elevados e vantagens adicionais como a recuperação do mau estado quantitativo dos aquíferos, inversão da ocorrência de intrusão salina, menor consumo energético e menores impactos ambientais, ou mesmo a sua ausência, no caso da produção de grandes volumes de salmoura, resultante da dessalinização para produção de água doce.

Localmente, a GRA pode apresentar algumas limitações, tais como as que foram identificadas no caso de estudo no sector de Vale de Lobo no Sistema Aquífero da Campina de Faro, para o qual um modelo numérico em diferenças finitas foi desenvolvido, para suporte à tomada de decisão, de forma a avaliar a incerteza da eficácia de GRA para prevenir a ocorrência de intrusão salina neste aquífero costeiro. Verificou-se neste caso de estudo que, devido à indisponibilidade de origens de água para GRA, a aplicação desta metodologia apenas poderá contribuir para uma recuperação limitada dos potenciais hidráulicos nesta área. Deste modo, nas atuais circunstâncias, constata-se que apenas uma considerável redução da extração de águas subterrâneas poderá levar a uma recuperação do mau estado quantitativo e consequente redução do risco de salinização do sistema Aquífero da Campina

de Faro que, de outra forma, tudo indica, será inevitável a curto ou médio prazo, se não forem tomadas medidas conducentes à inversão das tendências atualmente observadas.

Em resumo, a GRA constitui uma adaptação de baixo custo para as alterações climáticas. Na Região do Algarve, este tipo de metodologias pode satisfazer potencialmente cerca de 10% da atual procura de água, permitindo a Diretiva Quadro da Água o recurso a estas soluções, bastando para isso que seja agilizado o processo de autorização para o uso destas metodologias. O desafios técnicos e respetivas soluções estão bem estabelecidas num vasto número de casos de estudo na Europa e em muitas outras regiões do mundo nos quais a Gestão da Recarga de Aquíferos é atualmente utilizada.

Palavras chave: Gestão da Recarga de Aquíferos, Aquíferos Costeiros, Modelação de Águas Subterrâneas, Seca, Resiliência do Abastecimento de água, Assimilação de Dados.

Abstract

The Algarve region, Portugal is experiencing severe water scarcity with major concerns that water supplies are insufficient with limited resilience to drought. Managed Aquifer Recharge (MAR) can provide intermediate storage and bridge the gap between water availability and demand. However, success is dependent on water available and the aquifer capacity.

A regional study found that MAR can achieve a water resource benefit of 24 Mm^3/yr, or 10% of the total water demand of the region, using good-quality water from ephemeral rivers that meets the requirements of the Groundwater Directive. MAR can replace 15 Mm^3/yr of surface water used in the public irrigation perimeters, and 9 Mm^3/yr can be used to develop and maintain a strategic groundwater resource in the aquifers of the central Algarve. Although climate change is predicted to result in an 8-13 % decrease in MAR recharge during the period 2041-2070 under the RCP4.5 scenario, this can be addressed by incrementally increasing the MAR design capacity. MAR could bring water resource benefits of a similar scale to planned major infrastructure projects (desalination, River Guadiana abstraction), whilst costs for MAR are lower than almost all the feasible alternatives, with many wider advantages. MAR is thus an important measure to increase water supply security and drought resilience in the region.

Limitations of MAR were identified with a case study of the Vale de Lobo sector of the Campina de Faro aquifer where a numerical model was designed to support decision-making under uncertainty to determine the effectiveness of MAR to prevent sea water intrusion. Due to limited water availability and continued groundwater abstraction at unsustainable rates, only limited improvements in hydraulic heads can be achieved with MAR in this aquifer, indicating a considerable reduction in groundwater abstraction in addition to MAR will be required.

Keywords: Managed Aquifer Recharge, coastal aquifers, groundwater modelling, data assimilation, drought, water supply resilience

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Lists of abbreviations, acronyms and symbols

Glossary

Ag-MAR - An emerging Managed Aquifer Recharge technique that uses agricultural fields as percolation basins to recharge the underlying aquifers usually with flood water.

Bayesian analysis - Methods that implement history-matching according to Bayes equation. These methods support calculation of the posterior probability distribution of one or many random variables from their prior probability distributions and a so-called "likelihood function" – a function that increases with goodness of model-to-measurement fit.

Boundary condition - The conditions within, or at the edge of, a model domain that allow water or solutes to enter or leave a simulated system.

Boundary conductance - The constant of proportionality that governs the rate of water movement across a model boundary in response to a head gradient imposed across it.

Covariance matrix - A matrix is a two-dimensional array of numbers. A covariance matrix is a matrix that specifies the statistical properties of a collection of random variables - that is, the statistical properties of a random vector. The diagonal elements of a covariance matrix record the variances (i.e., squares of standard deviations) of individual variables. Off-diagonal matrix elements record covariances between pairs of variables. The term "covariance" refers to the degree of statistical inter-relatedness between a pair of random variables.

CO_2e – the term CO_2e allows greenhouse gases other than carbon dioxide to be converted, or normalized, to the equivalent amount of CO_2, based on their relative contribution to global warming. This provides for a single, uniform means of measuring emissions reductions for multiple greenhouse gases.

Data assimilation – incorporation of historical measurements of system states and fluxes into a model's structure and parameters to permit uncertainty reduction through history-matching of the modelled output to measured data.

Ensemble - A collection of realisations of random parameters.

EURO-CORDEX data - The climate change projections for Europe based on an ensemble of regional climate model simulations provided by the EURO-CORDEX initiative.

Flood MAR - Managed Aquifer Recharge with floodwater as the water source.

Jacobian matrix - A matrix of partial derivatives (i.e., sensitivities) of model outputs (generally those that are matched with field measurements) with respect to model parameters.

Jessour - an ancient runoff water harvesting technique used widely in the region of the mountains of Matmata, Tunisia. Arranged in the form of a gradoni, the jessour generally occupies inter mountain and hill water courses to intercept runoff and sediments. Jessour is the plural of jessr, which is a hydraulic unit made of three components: the impluvium, the terrace and the dyke (Carletti, 2017).

Iterative Ensemble Smoother – A computationally efficient method of producing a suite of calibration-constrained parameter fields.

MODFLOW - A family of public-domain, finite-difference groundwater models developed by the United States Geological Survey (USGS).

Null space - In the parameter estimation context, this refers to combinations of parameters that have no effect on model outputs that are matched to field observations. These combinations of parameters are thus inestimable through the history-matching process.

Observed historical – The period against which climate models were evaluated, in this case 1971 – 2000.

Objective function - A measure of model-to-measurement misfit whose value is lowered as the fit between model outputs and field measurements improves. In many parameter estimation contexts the objective function is calculated as the sum of squared weighted residuals.

PESTPP - Parameter Estimation suite of tools to undertake non-intrusive, highly parameterized inversion of an environmental model, particularly including the Iterative Ensemble Smoother for production of a suite of calibration-constrained parameter fields.

PEST_HP – Software to undertake highly parameterized inversion of environmental models.

Pilot point - A type of spatial parameterisation device. A modeller, or a model-driver package such as PEST or PEST++, assigns values to a set of points which are distributed in two- or three-dimensional space. A model pre-processor then undertakes spatial interpolation from these points to cells comprising the model grid or mesh. This allows parameter estimation software to ascribe hydraulic property values to a model on a pilot-point-by-pilot-point basis, while a model can accept these values on a model-cell-by-model-cell basis. The number of pilot points used to parameterise a model is generally far fewer than the number of model cells.

Prior probability - The pre-history-matching probability distribution of random variables (model parameters in the present context). Prior probability distributions are informed by expert knowledge, as well as by data gathered during site characterisation.

Poço – A large-diameter (often several meters) hand dug well, intersecting the shallow unconfined aquifer and common in the Algarve.

Posterior probability - The post-history-matching probability distribution of random variables (model parameters in the present context). These probability distributions are informed by expert knowledge, site characterisation studies, and measurements of the historical behaviour of a system.

Quadtree mesh refinement - This term refers to a means of creating fine rectilinear model cells from coarse rectilinear model cells by dividing them into four. Each of the subdivided cells can then be further subdivided into another four cells. However, it is a design specification of a quadtree-refined grid that no cell within the domain of a model be connected to more than two neighbouring cells along any one of its edges.

$\boldsymbol{Q_{MAR}}$ - the design capacity of a MAR scheme, i.e., the maximum daily recharge rate that the recharge infrastructure can accept (m^3/d)

$\boldsymbol{Q_{MIN}}$ - the defined minimum river flow below which the MAR scheme does not operate, i.e., the environmental flow.

$\boldsymbol{Q_R}$ – the MAR recharge achieved based on Q_{MAR}, Q_{MIN}, and the river flow, Q.

R - the correlation, r, measures the linear association between two variables, with values between -1 and 1.

$\mathbf{R^2}$ - the proportion of the variation in the dependent variable that is predictable from the independent variable(s), and is the square of the correlation, R.

Realisation - One random set of parameters.

Recent baseline – The period used for baseline MAR recharge assessment using hydrological years 2000 – 2021.

Recharge efficiency (RE) - Defined as the estimated annual recharge through the structure divided by the dam storage capacity.

Runoff collection efficiency (RCE) - Defined within this thesis as the dam storage capacity divided by the annual captured runoff volume.

Residual - The difference between a model output and a corresponding field measurement.

Singular value decomposition (SVD) - A matrix operation that creates orthogonal sets of vectors that span the input and output spaces of a matrix. When undertaken on a Jacobian matrix, SVD can subdivide parameter space into complementary, orthogonal subspaces; these are often referred to as the solution and null subspaces. Each of these subspaces is spanned by a set of orthogonal vectors. The null space of a Jacobian matrix is composed of combinations of parameters that have no effect on model outputs that are used in its calibration, and hence are inestimable.

Solution space - The orthogonal complement of the null space. This is defined by undertaking singular value decomposition of a Jacobian matrix.

Specific storage - The amount of water that is stored elastically in a cubic metre of porous medium when the head of water in which that medium is immersed rises by 1 metre.

Specific yield - The amount of accessible water that is stored in the pores of a porous medium per volume of that medium.

Stochastic - A stochastic variable is a random variable.

Stress period - The MODFLOW family of models employs this terminology to describe each member of a series of contiguous time intervals that collectively comprise the simulation time of a model.

Tikhonov regularisation - An ill-posed inverse problem achieves uniqueness by finding the set of that departs least from a user-specified parameter condition, often one of parameter equality and hence spatial homogeneity.

WEI+ water scarcity index - Defined as the ratio between the total volume of water abstracted and the renewable water availability, calculated for surface water or groundwater.

Acronymns

Ada	Águas do Algarve
APA	Agência Portuguesa do Ambiente~
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transport and Recovery
BA	Superficial geological unit - Areias, arenitos e cascalheiras do litoral do Baixo Alentejo
CGWB	Central Groundwater Board of India
DDF	Density-dependent flow
E	Potential Evapotranspiration (in GR4J model), alternative acronym PET
EU	European Union
€/m^3/yr	Capital cost per meters cubed of recharge per year
GR4J	Modèle du Génie Rural à 4 paramètres Journalier (4-parameter daily rainfall-runoff model)
IGRAC	International Groundwater Resource Assessment Centre
IRES	Intermittent rivers and ephemeral streams
K_s	Saturated hydraulic conductivity
MAR	Managed aquifer recharge
MCDA	Multi criteria decision analysis
MCL	Maximum concentration level
Mm^3/yr	Million meters cubed per year
MTBE	Methyl tert butyl ether
m^3/d	meters cubed per day
M2	Almádena - Odeáxere aquifer system
M3	Mexilhoeira Grande – Portimão aquifer system
M4	Ferragudo – Albufeira aquifer system
M5	Querença – Silves aquifer system
M6	Albufeira – Ribeira de Quarteira aquifer system
M7	Quarteira aquifer system
M9	Almansil - Medronhal aquifer system
M10	São João da Venda – Quelfes aquifer system
M11	Chão de Cevada – Quinta João de Ourém aquifer system
M12	Campina de Faro aquifer system (now divided into M18 and M19)

M13	Peral – Moncarapacho aquifer system
M14	Malhão aquifer system
M15	Luz-Tavira aquifer system
M18	Campina de Faro – Subsistema Vale de Lobo aquifer
M19	Campina de Faro – Subsitema Faro aquifer
NFM	Natural Flood Management
P	Precipitation (mm)
PEGA	Specific Water Management Plans (Planos Específicos de Gestão das Águas)
PET	Potential Evapotranspiration (mm), equivalent to E
RBMP	River Basin Management Plan
RCP4.5	Representative Concentration Pathway of 4.5 W/m^2 radiative forcing at 2100
RCP8.5	Representative Concentration Pathway of 8.5 W/m^2 radiative forcing at 2100
RH6	River Basin District of Alentejo as defined in the River Basin Management Plan
RH8	Ribeiras do Algarve River Basin District defined in the River Basin Management Plan
RWEP	Regional Water Efficiency Plan
SD	Standard deviation
SMAASA	The multi-municipal water supply system in the Algarve
SWI	Seawater Intrusion
WFD	Water Framework Directive
WTP	Water treatment plant

Chapter 1: Introduction

This thesis investigates the potential for Managed Aquifer Recharge (MAR) in the Algarve region, Portugal, as a solution to water scarcity by identifying how and where MAR can support the existing water supply system and/or meet environmental objectives. The water available for MAR from ephemeral rivers, and the aquifer(s) capacity for MAR are assessed. The thesis also presents a modelling methodology to assess the benefits of MAR in a selected case study (the Vale do Lobo sector of the Campina de Faro aquifer) with a decision-support groundwater model that quantifies and reduces predictive uncertainty.

1.1 Background and motivation

Managed aquifer recharge (MAR) includes a suite of methods to enhance aquifer recharge that are increasingly used to maintain, enhance, and secure groundwater systems under stress (Dillon et al., 2018). MAR schemes can bridge the discrepancy between the timing of water availability during the winter, and peak demand during the summer. MAR can also provide inter-annual storage, improving resilience to droughts and water supply emergencies. In the face of climate change, MAR can be a low-regret climate adaptation measure (Henao Casas et al., 2022).

Despite significant water management challenges, global uptake of MAR is not keeping pace with the increase in groundwater abstraction due regulatory challenges, particularly in Europe (Yuan et al., 2016; Fernández Escalante et al., 2020), the lack of awareness of the costs and benefits of MAR (Arshad et al., 2013) and a fragmented approach to water resource management (Page et al., 2018).

The motivation for this thesis is to determine whether MAR can be a realistic regional water management solution to improve resilience of water supplies and to meet environmental objectives in the Algarve region. The work builds on the pilot MAR trials undertaken by previous EU-funded projects GABARDINE and MARSOL (Diamantino, 2009; MARSOL, 2016), and the hydrogeological characterisation of the Algarve aquifers and hydrogeology undertaken by since the 1980's (Almeida, 1985; Monteiro et al., 2013; Hugman, 2016; Costa, 2022).

1.2 Objectives

The thesis has the following objectives:

1. To identify suitable MAR methods for the Algarve region. In particular to determine whether natural recharge can be augmented in the riverbed by in-channel MAR to deliver water resource benefits at an appropriate scale.
2. To assess the regional potential for MAR, by first identifying local water management objectives where the water demand could be replaced by MAR, and then combining assessments of water available for MAR with the aquifer capacities for MAR. This will allow MAR to be compared to other water resource options currently being considered for the region in terms of water resource benefits, costs, wider benefits and risks.
3. To develop and test a methodology for decision-support numerical modelling in coastal aquifers to allow decision makers to understand the effectiveness of MAR by quantifying and reducing uncertainty through assimilation of data that already exists, such that the benefits of MAR can be assessed without costly and time-consuming further data collection.

The thesis identifies MAR methods and their suitability for the Algarve, quantifies the water available for MAR and estimates future availability under climate change combining rainfall-runoff modelling with MAR operational rules and an assessment of the uncertainty of future river flows. The thesis develops a methodology using numerical modelling to assess the effectiveness of MAR at an aquifer scale, for the Vale do Lobo sector of the Campina de Faro aquifer, that could be replicated to other coastal aquifers where MAR is of interest.

It is hoped this research will contribute to the improvement of water resources management in the region, ultimately by identifying potential MAR schemes, and quantifying their water resource benefit, providing the basis for site-specific investigation and ultimately implementation.

1.3 Thesis structure

The thesis comprises 8 chapters, with a brief description of the remaining chapters outlined below.

Chapter 2 introduces the study area and the water resource system of the Algarve region.

Chapter 3 describes the state of the art relating to MAR focussing on successful operational schemes of relevance to the Algarve region, identifies gaps in the literature, and develops the research questions.

Chapter 4 details a meta-analysis on the effectiveness of in-channel MAR to achieve aquifer-scale benefits based on a global data set from published studies.

Chapter 5 identifies the potential for MAR in the Algarve region, identifying potential objectives, management and regulation of MAR and introducing the potential sources of water for MAR and potentially suitable MAR methods.

Chapter 6 quantifies the MAR potential identified in Chapter 5, with a detailed study of water available for MAR from ephemeral rivers across the region, presenting the results of rainfall-runoff modelling and uncertainty analysis, under recent baseline and climate change scenarios, along with a water quality assessment. The aquifer(s) capacity for MAR and initial MAR design capacity are also assessed to estimate annual average MAR for all potential schemes.

Chapter 7 presents a numerical modelling case study of Vale do Lobo sector of the Campina de Faro aquifer, to determine whether MAR can be a solution to seawater intrusion (SWI) in this area, and presenting a methodology for quantifying and reducing uncertainty in coastal aquifer models where MAR is proposed.

Chapter 8 discusses the results of the previous Chapters in a broader context, making recommendations for further investigation, and presenting the conclusions of the thesis with reference to the overall objectives.

Chapter 2: Water Resources in the Algarve

This Chapter briefly describes the water resources of the Algarve and their use over time, describing the current situation and proposed water resource options for the future.

2.1 Previous studies

The hydrogeology of this region has been studied since the 1980's, first by the public administration (Serafino, 1985), with the first estimates of surface water and groundwater at the regional scale produced by (Trac, 1981, Silva, 1984; Almeida, 1985; Silva, 1988). After these first studies, contributions to the hydrogeological characterisation of the Algarve region, including the water balance of individual aquifer systems and impact of the respective exploitation were produced, relating to the transition from groundwater being used for municipal urban supply to the current multi-municipal system, which is supplied mainly by surface water dams (Monteiro & Costa, 2004). The development of golf courses as a new group of water users was identified and assessed by Monteiro (2004a, 2004b) leading to revised estimates of the regional water balance at the regional scale (Monteiro, 2006). Improvements in the understanding natural aquifer recharge and, therefore, the water balance at the regional scale were related with the first studies dedicated to the river aquifer interactions (Monteiro et al, 2013) and the understanding of the important role of the allochthonous recharge, resulting from surface runoff generated to the north of the Algarve sedimentary basin to the main karst aquifers (Salvador et al., 2012) and also in hydrogeological contexts in the vicinity of the coastal strip (Standen et al., 2022).

Regarding the actual state of the understanding of the Algarve groundwater resources it is worth mentioning the contributions of Hugman (2016) and Costa (2022), as reference research in the fields of sustainability of exploitation of aquifers and understanding of the main aquifers water balance, groundwater sea water interface, submarine groundwater discharge, transference of inland nutrients towards the sea and saltwater intrusion. Geophysical methods have been applied to the improvement of the knowledge regarding the groundwater resources at the Algarve regional scale by Neves et al. (2016, 2019, 2020), and diversify the assessment methodologies for the characterisation of water resources at the scale of the Algarve region.

2.2 Historical Perspective

The evolution of the water supply system during the second half of the 20th century saw a large increase in water demand in the 1960's, associated with the expansion of irrigated agriculture and tourism, supported by drilling technologies which allowed the construction of thousands of boreholes to meet these demands with groundwater. Until the end of the 20th century, public water supply was independently provided by each of the 16 municipalities, and mostly sourced from groundwater. However, after extensive investment in new surface water reservoirs and rehabilitation of existing ones, along with associated water treatment plants and a regional distribution system (SMAASA), public water supply from surface water increased to 87% of the total by 2002 (Monteiro et al., 2007; Stigter et al., 2007). Whilst this brought benefits in terms of water quality control and distribution, a severe drought in 2004-2005 resulted in almost total depletion of the reservoirs, leading to emergency borehole drilling in Querença-Silves aquifer, and reactivation of former municipal boreholes (increasing the proportion supplied by groundwater to 42%).

Since the drought of 2004-2005, public water supply has continued to be almost entirely from surface water and in 2009, Odelouca was the final reservoir to be commissioned in the Algarve, with a useable storage of 134 Mm^3. Water supplies continue to be augmented by the 'emergency' boreholes drilled at Vale da Vila in the Querença-Silves aquifer. During the recent drought of 2019, the public water supply system was supported by 8 wells at this location, with a combined total abstraction of 6.2 Mm^3/yr. It is worth mentioning that during the drought of 2004-2005, the water wells in the Querença-Silves supported about 15 Mm^3/yr of abstraction without noticeable impacts (Nunes et al., 2006; Monteiro et al, 2007; Cunha et al, 2008).

Groundwater has been important for the expansion of irrigated agriculture in the Algarve, although estimating historical abstraction volumes is difficult. Groundwater levels rose in response to the cessation of abstraction for municipal water supply in the late 1990's, but in the years since then, declining trends have been identified as described in Section 2.3.2.

2.3 Current water supply system

The study area for this thesis is the Algarve region of Portugal, specifically the area defined in the River Basin Management Plans as the RH8 – Ribeiras do Algarve region (APA, 2016), as shown in Figure 2-1 along with the main features of the current water supply system. Total water use across the Algarve region is estimated to be 237 Mm^3/yr. Water use in agriculture has been estimated across the Algarve at 134 Mm^3/yr, water for urban water supply is around 68 Mm^3/yr, whilst the tourism sector uses 28 Mm^3/yr, with industry and other uses forming the remaining 7 Mm^3/yr (APA, 2020). Most of the urban water supply is from the large surface water dams of Odelouca, Odeleite, Beliche, supplemented by water from Bravura, and the Arade-Funcho dams. A multi-municipal system connects the western and eastern parts of the water supply system.

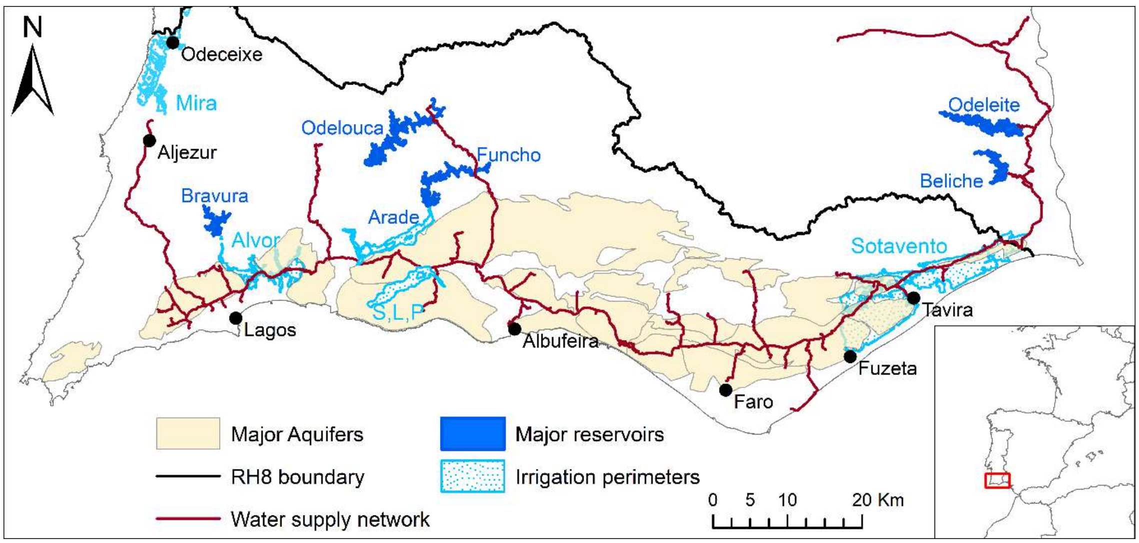


Figure 2-1 Study area and key features of water resource system.

Groundwater is mainly abstracted from the major aquifers shown on Figure 2-1, for irrigated agriculture, although numerous boreholes and wells exist outside the major aquifers, where they still support local water supplies.

2.3.1 Surface Water

The storage provided by the main surface water reservoirs in the Algarve is shown on Table 2-1. It should be noted that the inflow into the Arade dam includes all that enters the Funcho dam as it is located immediately downstream. As shown in Figure 2-1 Odeleite and Beliche are not within RH8, but are part of the Rio Guadiana basin (RH7). There are a few smaller irrigation dams but only one of these, Malhada do Peres (volume 0.46 Mm^3), is located in RH8 (APA, 2020).

Table 2-1 Characteristics of the main reservoirs in the Algarve.

Purpose	Reservoir	Total Volume (Mm^3)	Useable Storage (Mm^3)	Annual average inflow to dam (Mm^3)
Public Supply	Odelouca	157	134	113
Public Supply and Irrigation	Bravura	35	32	18
	Funcho	48	43	53
	Odeleite	130	117	132
	Beliche	48	47.6	19
Irrigation	Arade	28.4	26.7	56.6
	All	**446.4**	**400.3**	**391.6**

In addition to urban use, surface water is also used to supply four irrigation perimeters in the RH8 region as shown on Figure 2-1 with their main characteristics and water sources shown in Table 2-2. Part of the Mira irrigation perimeter is located within RH8, with water use in this part of the perimeter estimated in irrigation association reports (ABM, 2021).

Table 2-2 Key features of main Irrigation Perimeters in RH8

Irrigation Perimeter	Irrigated Area (Ha)	Supply Reservoir(s)	Reservoir useable volume (Mm^3)	Supply for Agriculture 2019 (Mm^3/yr)
Sotavento Algarvio	8,331	Odeleite & Beliche	117.0 + 47.6	**22**
Silves, Lagoa & Portimão	2,300	Arade & Funcho	26.7 + 42.8	**13.8**
Alvor	1,747	Bravura	32.3	**1.5**
Mira	1,855*	Santa Clara	240.3	**1.5**

*Area of Mira irrigation perimeter located in RH8 only

Since the 1950’s the total surface water storage has increased in the Algarve, by augmentation of the Bravura and Arade dams with Funcho and Odeleite and the rehabilitation of Beliche and Bravura during the 1990’s, and finally with the addition of Odelouca in 2009 as shown in Figure 2-2.

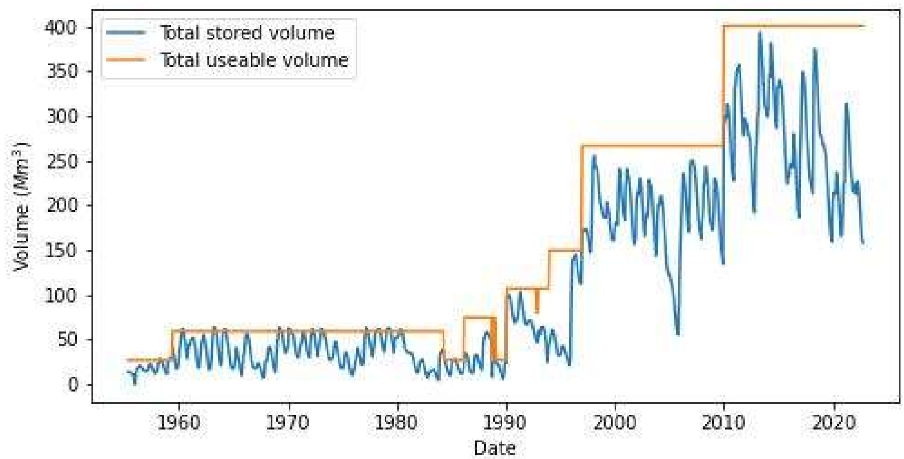


Figure 2-2 Available vs. actual surface water storage in the Algarve 1950's to 2022.

Monthly storage volumes at each of the main dams in the Algarve from 2000 onwards are shown in Figure 2-3. These timeseries show that Odelouca has never filled since construction, and a clear decrease in the water volumes stored has occurred since 2010 particularly at Bravura, Beliche and Odeleite, with only around 160 Mm^3 stored at the end of the 2021-2022 hydrological year. This is compared to an overall yearly surface water demand of approximately 70 Mm^3/yr.

Figure 2-3 shows that by October 2022, the storage in Bravura was approaching the dead storage volume, even with severe water supply restrictions imposed on all users of this reservoir except public water supply.

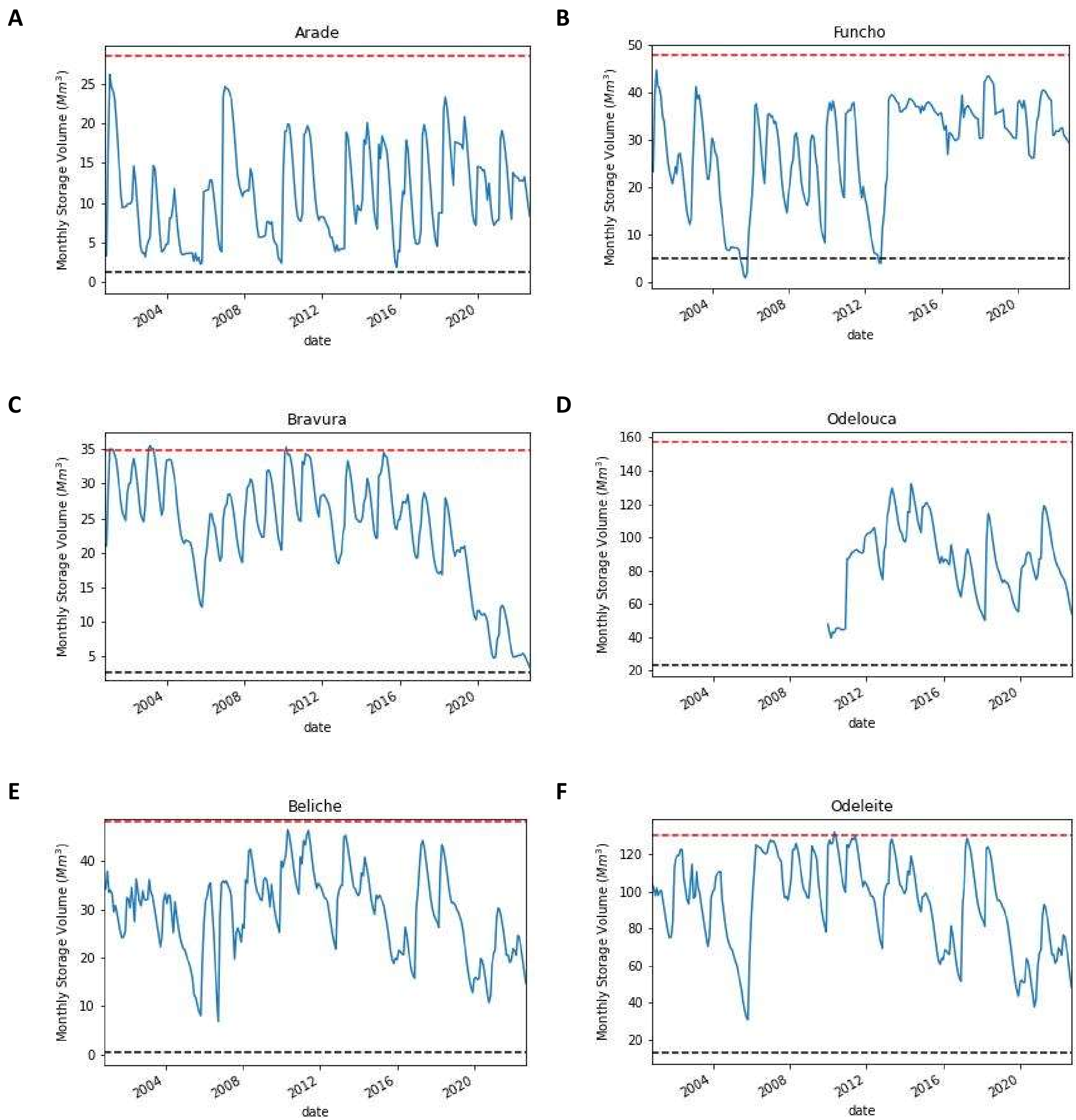


Figure 2-3 Monthly Storage Volumes (blue line) compared to total volume (red dashed line) and dead volume (black dashed line) for each of the main surface water reservoirs in the Algarve.

The WEI+ water scarcity index is defined as the ratio between the total volume of water abstracted and the renewable water availability, calculated through the following expression:

Renewable water availability = Precipitation – Evapotranspiration + External inflows – water requirements + returns

When the WEI+ index is calculated on a long-term average basis for surface water, all regions of the Algarve are in the severe water scarcity (WEI+ 50-70%) class, whilst for 4 regions are classed as having extreme water scarcity (WEI+ >70%) (APA, 2022b), reflecting the high demand and limited supply in the region.

2.3.2 Groundwater

Although difficult to estimate, the major aquifers of the Algarve are estimated to have a long-term average recharge of 168 Mm^3/yr, however during dry years of 2018/2019 and 2004/2005 annual recharge was estimated to be only 82 and 102 Mm^3/yr respectively (APA, 2020).

Groundwater use in agriculture in 2019 has been estimated to be 97 Mm^3/yr, of which 67 Mm^3/yr is from the major aquifers as shown in Figure 2-1 (APA, 2020). The borehole inventory of the Algarve region indicates that there are almost 20,000 boreholes and wells on record, and there is considerable difficulty estimating total groundwater abstraction given that the majority of users are not required to submit abstraction volumes to the regulator.

Águas do Algarve use approximately 12 Mm^3/yr of groundwater, of which 6.2 Mm^3/yr is from the Vale da Vila boreholes for public water supply, and 4.5 Mm^3/yr is for the only public irrigation perimeter fed by groundwater (Benaciate). Urban use of groundwater is limited to around 2 Mm^3/yr, and 'other uses' comprise only 0.5 Mm^3/yr. Irrigation for golf courses is also important in certain aquifers (Campina de Faro and Quarteira particularly), with an estimated total of 9 Mm^3/yr.

The WEI+ for groundwater in the major aquifers of the Algarve is computed at 58% on average (also in the severe water scarcity category (WEI+ 50-70%), based on estimated renewable resources of 160 Mm^3/yr and current abstraction at 97 Mm^3/yr.

2.3.2.1 *Water Framework Directive*

In Europe, the Water Framework Directive (WFD) legislation requires EU member states to achieve "Good" status for all groundwater and surface water bodies by 2027. Where this status is not met, measures must be included in the River Basin Management Plan (RBMP) Program of Measures to achieve these objectives. In Portugal good quantitative status was defined where annual abstraction is <90% average annual recharge for the first and second cycles of the RBMP, whilst the draft RBMP for consultation for the third cycle now defines 'good' status based on abstraction <80% of historical recharge (APA, 2022a).

In the third cycle, it is proposed that of the 25 groundwater bodies, 20 will have 'good' quantitative status and 5 with 'mediocre' status (Querença – Silves (M5), São João da Venda – Quelfes (M10), Chão de Cevada - Quinta João de Ourém (M11), Campina de Faro - Subsystem Vale de Lobo (M18) and Campina de Faro - Subsystem Faro (M19). The pressures leading to this situation are abstraction for agriculture in all these aquifers except Campina de Faro – Subsystem Vale do Lobo (M18), where the main pressure is abstraction for golf course irrigation (APA, 2022a).

The differences in quantitative status between the 2nd and draft 3rd RBMP are shown in Figure 2-4. The draft RBMP also reports that groundwater trend analysis shows that groundwater levels are stable in 13 groundwater bodies, whilst a decreasing trend is found in 11 groundwater bodies, indicating a wider availability vs. groundwater use problem. A total of 8 more groundwater bodies are considered to be at risk of not achieving the environmental objectives, since the volume extracted is close to the available groundwater resource, especially in the bodies of water Várzea de Aljezur (A0Z4RH8), Maciço Antigo Indiferenciado of the Algarve River Basins, Ferragudo-Albufeira (M4) and Quarteira (M7) (APA, 2022a). Therefore, it is clear that a majority of the aquifers of the Algarve are under pressure from current abstraction mainly for irrigated agriculture.

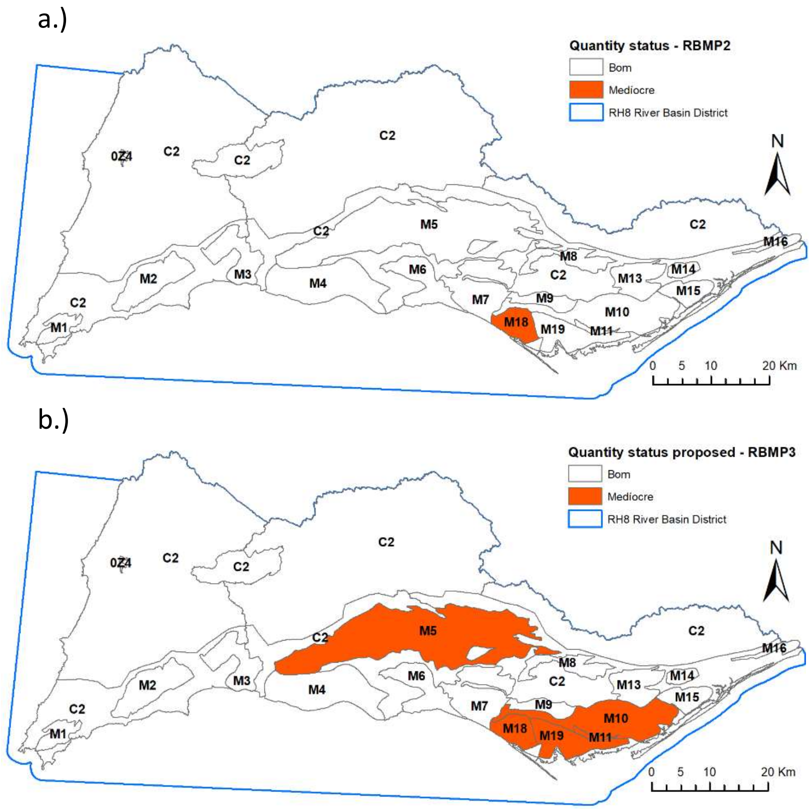


Figure 2-4 Aquifer quantitative status in the 2nd RBMP (a) and proposed status for the 3rd RBMP (b).

Good qualitative status is based on the definition of threshold values at a national level, that may be adjusted locally where there is evidence that natural background values are higher than these. For example, the national threshold value for chloride is 250 mg/l, whilst in the Campina de Faro aquifer, a slightly higher threshold value of 257 mg/l has been applied based on an assessment of background values (APA, 2016).

In the draft RBMP of the third cycle, there are 20 groundwater bodies with 'good' chemical status and 5 with a 'mediocre' chemical status. The parameters leading to mediocre status are desethyl simazine (a selective herbicide for broad leaved weeds and annual grasses) in M9 (Almansil – Medronhal); nitrate in M11 (Chão de Cevada - Quinta João de Ourém) and in M19 (Campina de Faro - Subsystem Faro); chloride in M18 (Campina de Faro – Subsystem Vale de Lobo) and nitrate and total phosphorus in M16 (São Bartolomeu). Of the 20 water bodies that are in 'good' status, a further six are at risk of not achieving the environmental objectives in the future as there are stations whose average value already exceeds the threshold and/or quality standard for nitrate, desethyl simazine, desethyl terbuthylazine and imidacloprid (APA, 2022a).

The difference in qualitative status of the groundwater bodies of RH8 between the 2nd and draft 3rd RBMP are shown on Figure 2-5. M3 now meets good status, whilst M11, M18 and M16 (São Bartolomeu) now fail to meet good status, with M9 and M19 remaining at mediocre status.

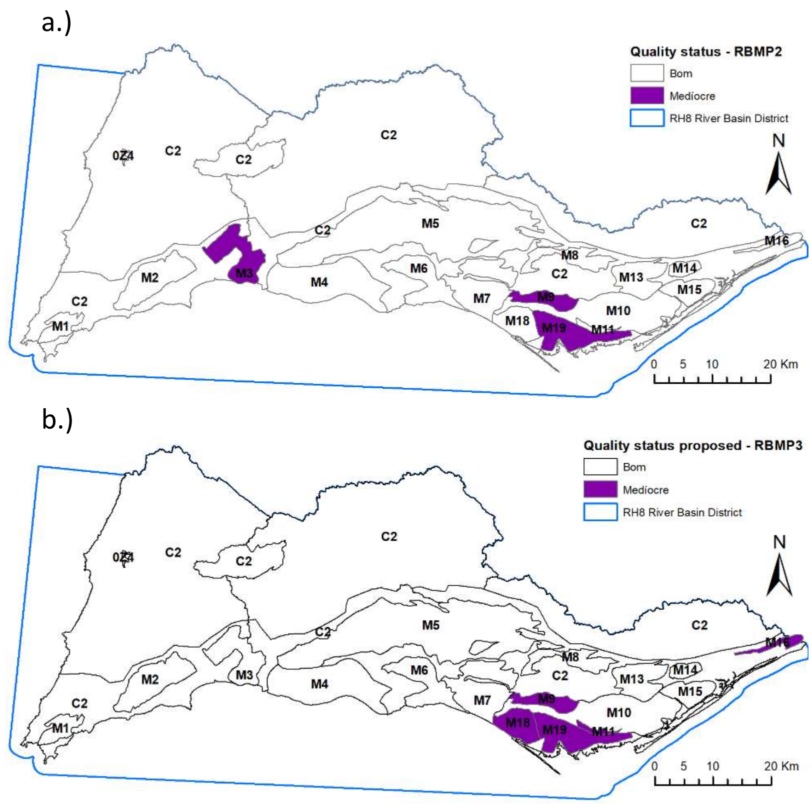


Figure 2-5 Aquifer quality status in the 2nd RBMP (a) and proposed status for the 3rd RBMP (b).

On aggregate, both the quality and quantity status of groundwater bodies have deteriorated between the 2nd and 3rd RBMP, with measures urgently needed to improve the situation by the regulatory deadline of 2027.

2.3.2.2 Groundwater availability

It is challenging to estimate groundwater recharge, which is an extremely non-linear process with considerable variations in both time and space. The APA estimates of long-term annual recharge are presented in Table 2-3, along with current levels of groundwater abstraction, and the estimate future water balance based on the RCP 4.5 climate change scenario, assuming 80% of the annual recharge is available for abstraction, and assuming current levels of groundwater abstraction continue. It should be noted that for the 3rd cycle of assessment, APA now consider that a groundwater body fails to meet "good" quantitative status if annual groundwater abstraction is more than 80% of long-term annual average recharge (a change from the previous 2 cycles, where the value was 90%).

Several aquifers already have negative water balances, where current abstraction is higher than long term average recharge, particularly the Campina de Faro and associated aquifers (M18, M19 and M11), whilst Querença-Silves (M5) is predicted to be in deficit in the future. From this table it appears that several aquifers may have additional water available for licensing, although this was considered and rejected in the Water Efficiency Plan, as during recent years, recharge has been lower than the long-term average, and declining trends in the piezometric levels have been observed (APA, 2020).

Table 2-3 Estimated groundwater recharge, abstraction and future availability under climate change (values in bold indicate abstraction greater than availability)

Groundwater Body	Estimated Average Annual Groundwater Availability (Mm^3/yr)	Proposed groundwater availability 2022-2027 (80%) (Mm^3/yr)	Estimated Current Abstraction (Mm^3/yr) APA, 2020	Estimated remaining water availability (80% recharge - current abstractions) (Mm^3/yr)	Estimated Future Water Balance ((RCP 4.5 Recharge * 80%) - Current Abstraction) (Mm^3/yr)		
					2011-2040	2041-2070	2071-2100
M1	3.46	2.77	0.55	2.22	2.12	1.95	1.89
M2	9.92	7.94	4.06	3.88	3.60	3.15	2.94
M3	6.77	5.42	1.24	4.18	4.03	3.70	3.57
M4	10.73	8.58	7.18	1.40	1.12	0.63	0.39
M5	58.53	46.82	44.29	2.53	0.94	**-1.81**	**-3.15**
M6	7.61	6.09	3.10	2.99	2.79	2.42	2.25
M7	11.09	8.87	5.29	3.59	3.28	2.74	2.47
M8	7.29	5.83	0.46	5.37	5.12	4.76	4.59
M9	4.42	3.54	1.24	2.29	2.14	1.93	1.81
M10	14.77	11.82	8.08	3.74	3.21	2.48	2.07
M11	0.93	0.74	1.03	**-0.29**	**-0.32**	**-0.37**	**-0.40**
M18	2.94	2.35	6.45	**-4.10**	**-4.19**	**-4.33**	**-4.41**
M19	4.96	3.97	5.32	**-1.35**	**-1.53**	**-1.77**	**-1.91**
M13	9.20	7.36	2.22	5.15	4.85	4.40	4.16
M14	2.27	1.82	0.88	0.94	0.87	0.76	0.70
M15	3.58	2.86	1.48	1.38	1.26	1.09	0.99
M16	1.23	0.98	0.34	0.65	0.61	0.55	0.52
A0Z4	0.17	0.14	0.03	0.11	0.11	0.10	0.09

2.3.3 Future Demand

There has been limited assessment of future water demand considering future populations and their water use. There has also been limited assessment of the impact of climate change on both water availability and water use. These two factors are likely to compound one another, resulting in greater water demand at a time where less water is available.

There are major concerns that the water sources currently available to all sectors are insufficient. Supply failures are already occurring in the agricultural sector (e.g., from Bravura dam), and there are major concerns that wider supply failures could occur in future.

Although the scale of the future deficit in the supply-demand balance is unknown, it appears to be significant, with little to no resilience to interannual droughts, or droughts of prolonged duration.

2.4 Future Water Resource Options

Water resource options were identified as part of the Regional Water Efficiency Plan (RWEP) (APA, 2020), and within the decadal plan for the development of public initiative irrigation (EDIA, 2021). The Regional Water Efficiency Plan detailed 57 measures, relating to the administration and management of water resources, along with detailed plans for increasing water efficiency and water supply for the tourism, urban and agricultural sectors, with an estimated cost of 228 M€.

The plan identified water savings in the short and medium term (up to 2026) of 33 Mm^3/yr at a cost of 197 M Euros, on average a cost of 6 €/m^3/yr. The summary table has been reproduced below (Table 2-4), with unit costs added to show the relative costs for each measure per m^3/yr saved / provided. The rehabilitation of the distribution network has by far the highest cost per m^3/year at 47 €/m^3/yr. Other measures such as reuse of treated wastewater (the only supply measure considered) can be achieved at a much lower unit cost (2.62 €/m^3/yr) at least for the first 20 Mm^3/yr, that is unaffected by saline intrusion into the wastewater network. The costs and water resource benefits could not be established for strategic longer term water resource options, given that preliminary studies have not yet been undertaken.

Table 2-4 Potential demand and supply measures and respective costs where the reduction in water consumption could be quantified (summarized and adapted from APA, 2020)

Measure	Type (Demand or Supply)	Water Saving (Mm³/yr)	Estimated Cost (M€)	Unit cost (€/m³/yr)	Timescale
Urb_05_ALG Reduce pressure in supply systems to reduce urban consumption	Demand	1.0	2.55	**2.55**	2021-2022
Urb_06_ALG Rehabilitation of water distribution systems	Demand	2.0	94.00	**47.00**	2020-2025
Urb_07_ALG Monitoring and active control of losses	Demand	3.5	7.82	**2.23**	2020-2025
Urb_10_ALG Reduce irrigated areas or substitution of plants / grasses	Demand	0.26	0.44	**1.69**	2020-2021
Urb_11_ALG Improve infrastructure and irrigation technology in urban green spaces	Demand	0.73	2.56	**3.51**	2020-2026
Tur_02_ALG Water efficiency measures in tourism and other buildings affected by tourist activity	Demand	1.30	6.40	**4.92**	2020-2023
Tur_03_ALG Reduce irrigated areas and/or substitute plants and grasses in the golf courses	Demand	0.5	0.65	**1.30**	2020-2026
Tur_04_ALG Improve irrigation infrastructure and technologies in the golf courses	Demand	0.35	2.15	**6.14**	2020-2026
Agri_02_ALG Rehabilitation and modernisation of the irrigation perimeter of AH Alvor	Demand	1.42	3.50	**2.46**	2020-2026
Agri_06_ALG Rehabilitation and modernisation of the irrigation perimeter of Silves, Lagoa and Portimão	Demand	2.90	11.30	**3.90**	2020-2021
Agri_07_ALG Construction of a new irrigation system in the AH Várzea de Benaciate	Demand	0.14	1.59	**11.36**	2020-2021
Agri_18_ALG Rehabilitation and modernisation public irrigation infrastructure	Demand	3.92	38.00	**9.69**	2022-2026
Agri_19_ALG Promotion of best practice in irrigation on farms	Demand	3.92	3.86	**0.98**	2022-2026
Demand reduction measures (total)	**Demand**	**21.94**	**174.82**	**7.97**	**2020-2026**
Tur_01_ALG Reuse of treated wastewater in the golf courses	Supply	5.62	13.81	**2.46**	2020-2026
Agri_12_ALG Reuse of treated wastewater in agriculture in perennial crops	Supply	1.38	2.05	**1.49**	2020-2026
Urb_03_ALG Reuse of treated wastewater in urban non-potable uses	Supply	1.36	6.03	**4.43**	2020-2026
Supply measures (total)*	**Supply**	**8.36**	**21.89**	**2.62**	**2020-2026**

Urb: urban public water supply measure, Tur: tourism / golf sector measure, Agri: agricultural sector measure. *Desalination was not considered as a short- or medium-term option and was therefore not included in the RWEP.

Subsequently 200 M€ was included in the Plano de Recuperação e Resiliência (Ministério do Planeamento, 2021) to implement water management measures to address the problem of water scarcity in the Algarve region (part of measure C9), with the basis in the Water Efficiency Plan, but also including the following:

- Increase the capacity and resilience of existing reservoirs by reinforcement with new sources of water, including reinforcing the connection between the barlovento and sotavento sectors of the distribution system, reinforcing the inflows to Odeleite by capture in the Guadiana River, and by optimizing the exploitation to utilise the dead storage volume.

- Promote the desalination of seawater with a desalination plant that complements other measures to reinforce the water available and mitigate future risks.

Brief details on some of the measures are described in the remainder of Section 2.4.

2.4.1 Surface water resource options

Preliminary studies included in the RWEP to investigate potential new surface water options for the longer term:

- Medida_Inf_01_ALG – a study to evaluate the possibility of installing an abstraction in the Lower Guadiana near Pomarão, followed by a pipeline to transfer the water to Odeleite reservoir, capturing an annual volume of 30 to 60 Mm^3.
- Medida_Inf_01_ALG - a study to assess the need and possibility of constructing new dams in the Lower Guadiana (RH7) at Foupana, on the Ribeira de Monchique, and the Ribeira de Alportel.
- Medida_Inf_03_ALG – a preliminary study for water harvesting in the Santa Clara reservoir (RH6) and transfer to the Algarve Multi-Municipal water supply system (SMAASA).
- Medida_Inf_04_ALG – a preliminary study for water collection in the Mira canal at Rogil and transfer to SMAASA.

All these options are at the preliminary study stage, and costs are not yet available. New conventional surface water resource options are extremely limited as the main catchments in the Algarve are already dammed for surface water supply. These measures generally focus on smaller catchments for either new dams or direct abstraction, combined with transfer to the existing dams. There are likely to be major constraints associated with all these options, including environmental, social and political issues, as well as concerns of their lack of resilience to climate change.

2.4.2 Augmenting natural recharge

The only measure in the RWEP to consider MAR includes assessing potential locations for the augmentation of natural recharge to the aquifers by retention in the stream bed to facilitate infiltration and increase recharge in the Ribeira do Algibre, Ribeira de Cacela, Ribeira de Quarteira and Ribeira de Bensafrim. This was incorporated at the request of the local APA authorities but was not explicitly funded for further investigation or implementation, however geophysical surveys along the Ribeira da São Lourenço were subsequently undertaken by APA.

2.4.3 Groundwater use during drought periods

The RWEP also identified the importance of considering a reserve of funds for the execution of emergency boreholes for use in drought situations when groundwater availability permits, to meet the most pressing economic or social needs, and indicates the importance of ensuring the maintenance of these boreholes during non-drought periods. This measure considers use from a borehole in Luz-Tavira (M15), and re-use of boreholes from the Portelas bore field close to Lagos (M2).

2.5 Summary

As described by Monteiro and Costa (2004), three periods can be defined in the chronology of public water supply in the Algarve region: (1) a past period in which public water supply was almost entirely supported by groundwater; (2) a present period characterized by large investments in replacing groundwater by surface waters from dams and (3) a future period where the prevailing hydrological conditions and the conflicts between users will force the administration to define an integrated management scheme to guarantee the public water supply at the basin scale.

We have now arrived in this third period, where the Algarve can no longer only rely on existing surface water resources, and the 'emergency' boreholes, and urgently requires integrated water resource options such as reuse of treated wastewater, desalinization of seawater, enhancement of recharge and MAR, to be considered alongside traditional options of increasing surface water and groundwater supplies. These, in combination with demand management and efficiency measures are needed in tandem to provide security of water supplies for all sectors into the future. The next chapters of the thesis evaluate how and where MAR could be employed to provide a water resource benefit in the Algarve, describing the potential objectives that MAR could meet, the water sources available and the suitable methods, before identifying potential MAR schemes for further investigation, and comparing their costs and benefits to those of the water resource options described in this chapter.

Chapter 3: Literature review

This Chapter presents the literature review, presenting evidence of implemented MAR schemes that are achieving aquifer-scale water management or environmental objectives, remediating over-abstraction, or mitigating seawater intrusion (SWI). Existing methods of assessing MAR on a regional and an aquifer-scale are reviewed to identify their limitations. The resulting gaps in the literature are described along with the development of the research questions.

3.1 The need for MAR

The Euro-Mediterranean region has been identified as a "climate change hot spot", with drier summers projected due to the increasing gap between potential evapotranspiration (PET) and precipitation (Giorgi, 2006). Global warming is progressively increasing the frequency, intensity, duration, and extent of droughts, with risk increasing significantly for both 1.5°C and 2°C global warming scenarios. The additional 0.5°C of the 2°C climate scenario leads to significantly higher drought risk (Lehner et al., 2017).

Predicted climate change impacts indicate rainfall is expected to decrease by 10% in the south of Portugal (for the RCP4.5 scenario), with an associated reduction in wet days of 10-20%, which will lead to associated reductions in recharge (Soares et al., 2017). River flows in the Mediterranean region are likely to be even more intermittent in the future due to climate change, with an increasing number of zero flow events (Schneider et al., 2013) whilst there is some evidence that in the south of Portugal that rainfall events at the 95th and 99th percentile will increase under climate change (Soares et al., 2017), making capturing and storing river flows when they occur increasingly important.

Meanwhile, the global demand for food is forecasted to increase by 100–110% from 2005 to 2050, which will lead to extensive land use change across 0.2 to 1 billion ha (Tilman et al., 2011). Agriculture the largest user (80%) of fresh water globally, and the expansion of irrigated land, and associated surface water and groundwater use has been rising drastically (Wada et al., 2011). Further socio-economic and agricultural development in the Algarve region will result in increased water demand for irrigation (Stigter et al., 1998; Hugman et al., 2017).

These compounding factors have already resulted in higher demand at a time when less water is available, therefore climate change is a major driver for adaptation and resilience measures to protect water supplies (Spinoni et al., 2017). Without action, aquifers will face even more severe pressures in the future. The consequences of declining groundwater levels range from local impacts to individual users and failure to meet regulatory requirements (e.g., the WFD), to significant environmental issues such as the loss of groundwater dependent wetlands that is already a reality at Doñana, Spain (Almond et al., 2022), and the risk of large-scale contamination of aquifers by SWI.

A recent study of Portugal and Southern Spain estimated groundwater depletion using the LISFLOOD-EPIC model, and identified that to attain sustainability, irrigation would need to be reduced by up to 70 % in the Algarve region (Gelati et al., 2020), with associated reductions in crop yield of 30% (Gelati et al., 2020).

Defining new sources for drinking water supply and for irrigation is becoming more problematic and expensive, particularly in Southern Europe, where large multi-municipal options, such as reuse of treated wastewater for irrigation, desalinization of seawater, or even direct abstraction in rivers already failing to meet ”Good” status under the WFD are being planned and implemented. MAR is therefore an appealing option to increase water availability, and as a supply-side measure is generally more popular with groundwater users than measures to water demand.

3.2 MAR in the Algarve Region, Portugal

3.2.1 Current regulations in Portugal

The impact of the Water Framework Directive on developing MAR schemes in the EU has been previously identified by the work of Sapiano et al., (2017a, 2017b), and more recently summarised by Monteiro et al., (2023):

“Article 4(1)(b)(i) of the WFD requires Member States to implement the measures necessary to prevent or limit the input of pollutants and to prevent the deterioration of the status of all bodies of groundwater. The Groundwater Directive then introduces the necessary provisions for making the WFD’s ‘prevent or limit’ objectives operational. According to CIS Guidance Document No 17 (2006), under the Groundwater Directive, substances to be PREVENTED from entering groundwater are those substances which have been identified by Member States as

being hazardous. In as much, one may consider that the substances which need to be LIMITED in groundwater such that pollution does not occur are all other pollutants.

In this respect it is noted that the Groundwater Directive (2006/118/EC) recognizes that it is not technically feasible to stop all inputs of hazardous substances, in particular the input of some small inputs of hazardous substances which are environmentally insignificant and thus do not present a risk to groundwater. For such cases the Groundwater Directive, under Article 6(3)(d) introduces a series of exemptions. Artificial recharge is considered under these exemptions. CIS Guidance Document 17 (2006) provides an interpretation of this prevent and limit concept. According to this EU Guidance Document, to PREVENT an input into groundwater therefore means: Taking all measures deemed necessary and reasonable to avoid the entry of hazardous substances into groundwater and to avoid any significant increase in concentration in the groundwater, even at a local scale. It is understood that these measures can include source water quality and flow control mechanisms and upstream treatment of the recharge source water."

The Water Law (Decreto Lei 58/2005) transposes the WFD into Portuguese law. Article 62 of the Water Law establishes that recharge and artificial injection in groundwater require a licence. In national legislation (Decreto-Lei No 77/2006) MAR is recognised as a potential measure to achieve status improvement under the WFD, but it must meet the conditions of the Groundwater Directive (2006/118/EC).

However, there are no Portuguese or EU-wide guidelines or standards on MAR, and no guidance on how a licence under Article 62 can be obtained for MAR to take place. This has effectively prevented MAR from being implemented in Portugal apart from limited pilot trials, discussed in Section 3.2.2. Therefore, MAR has not been considered seriously as a potential water resource option, with MAR only starting to be considered in the recent Regional Water Efficiency Plan (RWEP) (APA, 2020), but limited to augmentation of natural processes to increase recharge through natural streams, indicating a local regulatory preference for these types of MAR schemes.

However, in December 2022, a government resolution (no 86/2022,) was passed encouraging artificial recharge of aquifers to combat drought and water scarcity, providing that environmental impacts can be managed. This indicates that MAR is now considered more favourably and a pathway to implementation may follow.

The WFD requires that ‘good’ status is achieved for all groundwater bodies by 2027, and this assessment includes quantitative and qualitative criteria. In Portugal, good quantitative status is based on a volumetric comparison of recharge vs. groundwater abstraction, where groundwater abstraction may not comprise more than 80% of the long-term average recharge (APA, 2022a), and no further deterioration in groundwater levels is permitted. The groundwater quality status is assigned based on the aquifer-wide comparison of groundwater quality to threshold levels for contaminants. Even if the 80% criteria can be met, groundwater bodies can still have poor status due to historical over-abstraction, that can lead to deterioration in groundwater quality due to SWI.

One possible mechanism for permitting or promoting MAR more widely is detailed under Article 31 of the Water Law, where Specific Water Management Plans (Planos Específicos de Gestão das Águas (PEGA) can be developed for to achieve specific objectives, perhaps for a group of aquifers where MAR can be beneficial.

3.2.2 Pilot MAR investigations in the Algarve

In-channel infiltration basins were developed in the Rio Seco, east of Faro, during the EU funded GABARDINE (Lobo Ferreira and Leitão, 2014) and MARSOL (MARSOL, 2016) projects, to assess at pilot scale whether these schemes could be used to reduce nitrate concentrations to meet WFD objectives. Three infiltration basins with a total surface area of 300 m^2 were excavated to a depth of 6 m, to remove a low permeability clay layer, before being filled with clean gravels. To allow recharge testing, temporary small dam structures were constructed, so water levels could be raised to simulate periods of submergence during river flow.

Repeated testing and long-term monitoring indicate that the infiltration basins’ effectiveness does not appear to have changed over time, and clogging with fine sediments does not appear to be a significant issue (Oliveira et al., 2015b). This appears to be due to the high energy flows at this location, possibly combined with the majority of recharge occurring through the steep sides of the infiltration basin where sediments do not build up. Whilst construction involves significant disruption to the natural riverbed, subsequently there is little interference to natural flows.

During the tests, an average infiltration rate of 1.2 m/day was obtained (MARSOL, 2016) or 360 m^3/day in total. Annual recharge is therefore estimated to be around 18,000 m^3/yr, assuming flow in the Rio Seco available for 60 days/year (MARSOL, 2016), therefore significant scaling up of this design would be needed to have an aquifer-scale impact.

During the MARSOL project, the recharge capacity of traditional large-diameter wells (known as poços) was assessed by recharge tests, finding that for a typically constructed poço (~20m deep, 4.5 m diameter, static water level 10 m below ground level), a recharge rate of 2,500 m^3/d could be achieved for a single well (Costa et al., 2020).

3.3 Achieving water management objectives with MAR

The most common objective for MAR is to increase the available water supply, with a recent trend towards improving water supply reliability during droughts or emergencies (McCurry and Pyne, 2022). Particular objectives relevant to the Algarve include managing aquifer water balancer to recover / maintain 'good' quantitative status under the WFD, balancing seasonal water availability and demand, increasing resilience to drought, and mitigating SWI. Examples of implemented MAR schemes achieving each of these objectives are described in the following Chapters.

3.3.1 Managing aquifer water balance

Controlling aquifer drawdown is stated as a goal at implemented MAR schemes in Finland, USA, Italy and India and Belgium, but only one scheme in Mexico mentions explicitly the recovery of depleted aquifers as a critical goal, but only in the initial phase (Murray et al., 2021).

In Windhoek, Namibia, MAR has been occurring since 2004 into a fractured and mostly confined, hard-rock quartzite aquifer with surface water and reclaimed wastewater recharged and recovered by dedicated boreholes. Since 1950's abstraction had led to a 40 m decline in groundwater levels, which was largely recovered within a decade of the start of MAR. Natural recharge is estimated to be 1.73 Mm^3/yr, compared to a currently installed injection capacity of 3.75 Mm^3/yr, and abstraction capacity of 11 Mm^3/yr (Murray et al., 2021). Losses extremely low (3%) due to the hydrogeological setting in a graben. A major benefit of the scheme is the downsizing or deferment of future water supply infrastructure with a far greater cost involving long distance (700 km) water transfer, or desalination plus long distance (350 km) transfer (Murray et al., 2021).

The Santa Ana River recharge scheme in Orange County, California (Hutchinson and Woodside, 2021) is one of the largest MAR schemes in the world. In the early 1900s, it was recognized that the Orange County Groundwater Basin (Basin) was being over-exploited. By the early 1920s, sea water intrusion was occurring and flows of the Santa Ana River (SAR) were declining. MAR started in 1936 using the Santa Ana River flow with both in-channel and off-line infiltration basins, which now cover an area of 4.5 km^2. The average recharge through the Santa Ana River flow is estimated to be 148 Mm^3/yr.

The El Carracillo MAR scheme recharges the Los Arenales in Castille y Leon region of Spain seasonally using water from the Cega River and recharged by 16 infiltration ponds, 17 km of MAR canals (infiltration trenches), 2 spreading basins, and 3 artificial wetlands, with recovery by existing abstraction boreholes for irrigation purposes. An average of 2.4 Mm^3/yr (2002-2015) was recharged increasing water levels by 2.3 m and comprising 25% of the irrigation demand of 3,500 Ha (Fernández-Escalante and Sauto, 2021). The scheme was locally promoted and implemented by an irrigation association who proposed the plan to the river basin authorities.

In San Luis Río Colorado City, Mexico, average rainfall is only 55 mm/yr, and the aquifer is depleted at a rate of 7.6 Mm^3/yr. A MAR scheme infiltrates 10.75 Mm^3/yr of treated wastewater through 12 infiltration ponds, with a total area of 145,200 m^2, and due to the high permeability, only a few cm of water level rise occurs. The water is re-abstracted for use in agriculture, and the annual recharge volumes have successfully reversed the deficit in the water balance (Chávez et al., 2021).

Schemes of the size of Santa Ana River would be extremely expensive to install today, with the 2019 equivalent capital cost is estimated to be 239 million USD (Hutchinson and Woodside, 2021). Whilst this scheme provides a very good example of recovery from SWI and sustainable management of groundwater, it is extremely unlikely that such a scheme could be newly developed today, due to the considerable increase in land costs, which would make a scheme of this size prohibitively expensive. However, the other schemes are of a more realistic scale for the Algarve, and achieve recharge rates in the range of 2 – 11 Mm^3/yr.

These schemes clearly highlight the success of MAR in improving aquifer water balance, with groundwater recovery clearly evidenced at Los Arenales, and in San Luis Río Colorado City, Mexico, indicating that a positive water balance can be recovered using MAR, giving hope that 'good' quantitative status can be achieved or maintained by implementing MAR.

Recovery of a large cone of depression was achieved at Windhoek, where the low storage aquifer probably contributed to the success of the scheme, making recovery within a decade achievable. However, MAR schemes exhibiting such significant aquifer recovery from over-abstraction appear to be rare.

3.3.2 Drought resilience

MAR can develop or maintain strategic drought water supplies, such as those developed in London (Jones et al., 2021) and Horton Kirby (Shipley, 2016) by Thames Water in the UK, and in Madrid (Sánchez & Gutiérrez, 2019), for drinking water supplies. In some places, such as Arizona, California and Western Australia, MAR schemes use water banking as an important strategy for improving the security of groundwater supplies and helping to buffer future drought (Murray et al., 2021).

The North London Artificial Recharge Scheme (NLARS) is a strategic water resource for use during drought periods or other emergencies to maintain London's water supply. Water is stored in the confined Chalk aquifer and abstracted by a network of 48 boreholes with 30 equipped for aquifer recharge, up to 130 m deep (Jones et al., 2021). The current peak abstraction can be >200,000 m^3/d, with an annual licensed capability of 66 Mm^3, and the recharge to the aquifer can occur at rates up to 60,000 m^3/d. Recharge uses potable quality water, taken from the same network used for public supply, with no significant impact on the stored water or its treatability (i.e., no issues with disinfection by-products have been found). The scheme has been used in practice to recharge only where natural recharge is likely to be insufficient for the groundwater levels to recover following an abstraction phase (Jones et al., 2021). A similar scheme is being developed at Horton Kirby in the UK, where storage in the Lower Greensand aquifer will be used to develop a 5,000 m^3/d drought source to be used during a 1 in 5 or 1 in 10-year drought (Shipley, 2016). These are good examples of MAR being used to create and maintain a strategic resource for emergency or drought use.

In Arizona, in return for MAR infrastructure on their land, landowners receive rebates on their water bills in line with the amount of recharge achieved. The Arizona Water Banking Authority (AWBA) was established in 1996 to store the unused portion of Arizona's annual Colorado River entitlement in Central and Southern Arizona. The AWBA stores water in underground aquifers to earn long-term storage credits. These credits can be recovered (pumped) during a shortage to provide back-up water supplies (known as "firming") for Arizona water users. There is an enormous range in scale of current MAR infrastructure within the scheme from a 0.6 Mm^3/year vadose zone well project in Chandler, Arizona, to the 185 Mm^3/year, fully automated Tonopah Desert project west of Phoenix, where spreading basins achieve infiltration rates >1 m/d. The largest projects use spreading basins that cover tens of hectares of land (Megdal et al., 2014).

The storage credit system distinguishes between water stored for recovery in the same calendar year and that left in storage for future recovery. Colorado River water left in storage beyond the calendar year in which the water was stored at a recharge facility is typically subject to a one-time five percent "cut-to-the aquifer", which is stored water that cannot be recovered. This is a small but important contribution to aquifer storage (Megdal et al., 2014).

Under Arizona state law, the recharge program offers additional flexibility by allowing the withdrawal of stored water to take place in a different area than where the water was recharged. In this respect, Arizona's regulatory system relies on a mass-balance approach; the extensive recharge permitting and monitoring determines the volume of water contributing to the regional aquifer system, and the regulatory accounting then authorizes an equivalent amount of pumping to occur. The "recovered" water may be hydrologically distinct from the recharge activity, but it retains the legal characteristic of the source water that was stored.

3.3.3 Mitigating seawater intrusion

SWI is the landward movement of seawater in coastal aquifers, the most common causes being groundwater abstraction and / or sea-level rise (Ferguson and Gleeson, 2012; Lu et al., 2013). SWI is a global issue exacerbated by increasing dependence on coastal groundwater resources, sea level rise and climate change. Most severe cases of salinization occur where groundwater levels fall below mean sea level and the groundwater flow direction turns landward (Werner, 2017).

In Southern Europe, SWI already affects many coastal aquifers to some degree, particularly those in Spain, Italy, and Turkey as shown in Figure 3-1 (EEA, 2009). SWI is also extensive in some coastal aquifers in Greece (Petalas and Lambrakis, 2006; Kazakis et al., 2016).

Corrective measures for aquifers already impacted by, or at risk of, SWI essentially comprise two options: reducing abstraction rates, or artificially increasing recharge (Abarca et al., 2006). Engineering measures to artificially increase recharge include subsurface dams, recharge dams, hydraulic barriers, or saline water pumping.

Figure 3-1 Main seawater intrusion sites along the Mediterranean coast (EEA, 2009).

MAR schemes have been implemented for coastal salinity control in several countries. Brief details of selected schemes are provided below.

A scheme to recharge treated wastewater (after advanced water treatment) into a sand dune coastal aquifer in Torreele, Belgium has enabled groundwater levels to stabilise and SWI to be halted, protecting drinking water abstraction. The infiltration rate has stabilised at 1.8 Mm^3/yr into an infiltration basin of 18,200 m^2 surface area (Houtte and Verbauwhede, 2012). In Atlantis, South Africa, MAR has been occurring since the 1970’s with indirect reuse of treated wastewater and storm water for the town water supply, where 30% of the supply is derived from recycling, and 70% from natural groundwater. More saline industrial effluent is discharged into coastal recharge basins as a measure to prevent SWI. Two main infiltration basins upgradient of the main well field (total area 450,000 m^2) achieve a recharge between 3.6 and 8.0 Mm^3/yr, supporting wellfields that abstract in total around 16 Mm^3/yr (Bugan et al., 2016). Whilst the scheme has faced many challenges including clogging of the abstraction wells, and a lack of on-going monitoring to understand MAR performance, it continues to support water supply for the town.

In Oman, several dams were constructed along major coastal wadies to replenish the aquifers and control SWI. By 2012, a total of 34 dams were constructed of which 21 are aligned along the coast to control advancing SWI. The dams vary in height (5–25 m), storage capacity (0.04–11.4 Mm^3) and length (100–9,000 m). Geophysical surveys identified an annual recession rate of 120 m of the interface, attributed to the recharge dam of Wadi Al Hawasinah, constructed in 1995 (Abdalla et al., 2010). After the AlKhod dam construction, the 0 m water table contour line has been pushed back, almost reaching the coast (Abdalla and Al-Rawahi, 2013). The effectiveness of these dams is partly attributed to the controlled release of water from the dams which optimizes infiltration downstream of the dams into the unconfined aquifer (Abdalla and Al-Rawahi, 2013).

In Shandong, China, a total of 6 groundwater reservoirs have been created by subsurface dams to augment irrigation supply, and to protect the shallow aquifer from SWI. The cost of construction per m^3 of water stored is only US$0.10, or 1/2 to 1/3 of that for a surface water reservoir (Wang et al., 2021). The success of these schemes is attributed to the shallow aquifer having very limited thickness (typically less than 5 m thick), making a physical barrier to SWI cost effective. Other authors have suggested constructing physical barriers only at the base of an aquifer to prevent migration of the interface toe inland (Hussain et al., 2019), however these are likely to be very difficult to construct, and prohibitively expensive, for deeper aquifers.

Schemes where the stated objective is to mitigate SWI are not usually implemented solely for that purpose; usually they are designed to protect significant groundwater abstractions from SWI. The schemes employing infiltration basins or recharge boreholes have greater relevance to the Algarve, although in some cases the sizes of infiltration basins required to generate significant recharge (e.g., Atlantis) may be prohibitive in terms of land availability and cost in the Algarve. The wadi-recharge dams and subsurface dams require very specific hydrological and hydrogeological settings that do not occur in the Algarve.

3.3.4 Summary

A common difficulty in assessing the achievement of water management objectives by MAR is that very often the MAR objectives are not sufficiently quantified, and the performance of MAR schemes are rarely compared to the original objectives. In part this could be explained due to the need for long-term data on MAR recharge rates to make this assessment, particularly where there is high inter-annual variation in availability of water for MAR. However, this section has clearly demonstrated that MAR schemes have been implemented successfully to manage aquifer water balance and water levels, to provide drought resilience and to mitigate SWI.

3.4 Assessment of MAR

3.4.1 Assessment of regional MAR potential

Regional suitability for MAR is typically assessed spatially using Multi-Criteria Decision Analysis (MCDA) methods, of which 63 such studies were reviewed by Sallwey et al., (2019) such as Rahman et al. (2012), who demonstrated this technique in the Querença-Silves aquifer of the Algarve. These studies focus on constraint and suitability mapping and provide a reasonable method of comparing potential sites at an aquifer scale, but they are typically poor in addressing uncertainty and risk (Bailey et al., 2005), and without a specific purpose or applicant in mind, these maps are often published with best intentions but perish thereafter (Sallwey et al., 2019).

MCDA methods lack quantitative assessments of recharge (injection of infiltration) capacity, and thus cannot inform MAR design. Quantitative assessments can be based on the Theis equation applied spatially (Gibson et al., 2018; Shandilya et al., 2022) to estimate groundwater level rise at an injection borehole site, or the Glover method to estimate groundwater level rise beneath an infiltration basin (Smith and Pollock, 2012), but they typically suffer from lack of aquifer property information leading to interpolation over large areas. Site specific methods to confirm MAR suitability and determine the fate of the recharge water usually require numerical modelling e.g., Abarca et al. (2006); Scherberg et al. (2014).

Hydrological studies are usually required to estimate the water available for MAR from natural streams / rivers, based on rainfall-runoff modelling and flow routing. Published works on the subject include studies in the USA (Kocis and Dahlke, 2017; Hanak et al., 2018; Yang and Scanlon, 2019; He et al., 2021), of which only He et al. (2021) considers climate scenarios when estimating water available for MAR (WAFM) for Flood-MAR.

Neither of these quantitative approaches link the WAFM with the aquifer capacity for MAR, whilst also considering the water demand and the potential MAR objectives; such studies are usually site-specific. All these aspects are important when assessing the potential for MAR on a regional scale.

3.4.2 Assessment and modelling of Coastal MAR Schemes

MAR is expensive, particularly for SWI barriers, or where deep recharge boreholes are needed (Vanderzalm et al., 2022). Further pre-treatment of water prior to discharge is often necessary, particularly where urban wastewater or storm water is used leading to high operational and maintenance costs (Dillon et al., 2019). Given the costs associated with MAR, identifying the appropriate course of action is difficult. It is hard to demonstrate to stakeholders why, and when, action is necessary. However, decision-making under uncertainty is the norm for most decisions of consequence in groundwater management (Caers, 2011). Notwithstanding, decision-makers need to be informed of the risks surrounding their decisions. This requires quantifying the uncertainty of decision outcomes. Modelling supports decision making by providing the means to consolidate available data and information to both quantify, and reduce, the uncertainty surrounding outcomes of a management action (Doherty and Moore, 2021).

The subsurface is complex, and data on aquifer properties and boundary conditions are typically very limited. Expressing their uncertainty requires the use of many parameters to allow spatial variability to emerge through history-matching of the model to the historical behaviour of the system. The methods employed by industry standard tools for history-matching, PEST (Doherty, 2020) and PESTPP (White et al., 2020) software suites, need to run models many times to calculate parameter sensitivities. Therefore, incorporating existing information on system properties and past system behaviour into a model that is capable of quantifying and reducing uncertainty, requires a model that is fast and stable. To accomplish this, model development and deployment must be purposefully designed to achieve these two goals (Caers, 2011; Doherty and Moore, 2021).

Modelling coastal aquifers is particularly challenging as the need to account for variable density on flow introduces several complications. There are three commonly used approaches to handling density differences when modelling coastal aquifers: (1) ignoring it, (2) sharp-interface models or (3) density-coupled flow and transport models. The latter requires solving the coupled, non-linear groundwater flow and advective-dispersive solute transport equations. The advective-dispersive transport equation is numerically more difficult to solve, and to ensure stability of the solution fine grids and time-discretisation are required. Thus, the simulation of large-scale three-dimensional coastal aquifer systems can be computationally very expensive (Dausman et al., 2010). As a result, model-based data assimilation and uncertainty quantification become difficult, if not impossible (Carrera et al., 2010). This is perhaps one of the main reasons that the quantification of predictive uncertainty in real-world coastal aquifers remains scarce (Werner et al., 2013).

Sharp-interface codes, such as the SWI package for MODFLOW (Bakker and Schaars, 2013), offer an attractive alternative. These models neglect mixing processes and simulate a sharp boundary at the interface between fresh and saltwater. As they do not solve the transport equation, run-times are significantly reduced. This makes them more suitable for highly parameterized calibration and uncertainty analysis, with several publications on the subject over the last few years e.g., Llopis-Albert et al. (2016); Coulon et al. (2021). However, simulated outcomes can be quite sensitive to initial conditions, definition of the coastal boundary condition and model layering. This becomes particularly problematic for a confined or semi-confined system, in which the position of the interface and the extent of the discharge face are unknown and may be kilometres offshore. Accommodating this uncertainty may require extending a model grid for 10s of kilometres offshore (substantially increasing the number of model cells and increasing the run time), as well as requiring a long “wind-up” time to obtain pre-development initial conditions.

Constant-density flow models, which ignore density differences, reduce the computational cost but introduce their own set of complications. They are not applicable if the modelling purpose requires the prediction of salinities (although neither are sharp-interface models), and where the interface affects simulated hydrodynamics of the system, bias will be introduced. However, if the horizontal extent of an aquifer is significantly larger than the vertical extent, constant-density models can offer reasonable representations of the system (Abarca et al., 2006).

An appropriate modelling approach is needed where predictive uncertainty can be quantified and reduced through assimilation of existing data, in a model that addresses the coastal boundary appropriately, allowing preliminary estimation of the effectiveness of MAR schemes.

3.5 Gaps in the literature

There is considerable evidence that MAR can be used to meet water management objectives, yet MAR does not appear to often be applied with a goal of recovering depleted aquifers (UNESCO, 2021) except for the Windhoek case study, in fact has been stated it is unreasonable to expect that MAR can achieve that aim (Dillon et al., 2019). The first gap in the literature has two aspects:

a) There is limited evidence that MAR can achieve recovery of depleted aquifers and therefore meet ‘good’ status under the WFD, as meeting this status requires ‘no further deterioration’, which cannot be guaranteed where there is potential for SWI, unless sea-ward flow is regained.
b) A lack of evidence that in-channel MAR methods can achieve significant water resource benefits. Nature-based solutions are becoming very popular and have been implemented widely for a range of purposes, but there is now a growing body of evidence that details their lack of effectiveness except at the local scale.

The second gap in the literature is a regional assessment methodology that bridges the gap between academic studies on MAR, based on GIS – MCDA techniques and site-specific investigations once a location has been selected. Regional assessments need to consider and quantify both the aquifer capacity for MAR, and the water availability for MAR, whilst also considering the existing water supply system and potential MAR objectives.

The third gap in the literature is an appropriate modelling approach is needed where predictive uncertainty can be quantified and reduced through assimilation of existing data, in a model that addresses the coastal boundary appropriately, allowing preliminary estimation of the effectiveness of MAR schemes, and providing support to decision-makers. Only a limited number of case reports where these techniques have been employed exist (e.g., Gallagher and Doherty, 2020), with fewer still in coastal aquifers.

3.6 Research questions

Based on the identified gaps in the existing literature, the main research questions for this thesis are defined as:

1. Can an aquifer-scale benefit be achieved by using in-channel MAR methods, and if not, what are the alternatives?
2. Can a regional assessment methodology be developed to quantify the potential for MAR in the Algarve, and to what extent can MAR support the current water resource system?
3. Can numerical models support decision-making for MAR in coastal aquifers, and what adjustments need to be made to these models to quantify and reduce their predictive uncertainty to allow the benefits of MAR to be determined?

The first research question is addressed by a detailed literature review and meta-analysis of existing in-channel MAR schemes worldwide, which is presented in Chapter 4.

The second question is addressed by Chapters 5 which identifies potential objectives for MAR in the Algarve, potential management of MAR, water sources and suitable MAR methods, which are then quantified to determine the regional water resource benefit of MAR in Chapter 6.

The third research question is addressed by a case study which develops a decision-support groundwater model to determine if MAR with locally available sources of water can mitigate SWI in a small coastal aquifer, the Vale do Lobo subsystem of the Campina de Faro aquifer in the Algarve. This is presented in Chapter 7.

Chapter 4: In-channel MAR meta-analysis

This chapter is based on the published paper:

Standen, K., Monteiro, J. P., & Costa, L. R. (2020). In-channel managed aquifer recharge: A review of current development worldwide and future potential in Europe. Water (Switzerland), 12(11), 1–28. https://doi.org/10.3390/w12113099

The motivation for this meta-analysis of in-channel MAR is that there appears to be little evidence that significant water resource benefits can result from such schemes. In the Algarve, the local regulators have a preference for in-channel methods that augment natural processes of recharge, as included in the RWEP (APA, 2020). Therefore, as these types of methods may be more likely to meet regulatory approval, and thus be implemented, there is clear practical relevance for this study.

4.1 Introduction

Whilst several previous reviews collate information on a global or regional scale, none examine in-channel MAR in detail (Bonilla Valverde et al., 2018; Dillon et al., 2018; Stefan and Ansems, 2018). This review and meta-analysis collates and analyses information on these schemes, identifying their characteristics, hydrogeology, water balance, and recharge effectiveness, identifying opportunities for wider applicability.

This review uses the definitions for in-channel modifications for MAR, as defined by the MAR portal (IGRAC, 2007), and further refined to identify different types of recharge dams:

1. Sand storage dams are constructed above ground in intermittent streams, trapping sediment behind the dam, so that future runoff infiltrates, creating an artificial aquifer upstream of the dam. They are usually of earthen, stone, or concrete construction, and are common in parts of Africa and China.
2. Recharge/check dams, including:
    a. Wadi-recharge dams to intercept runoff during flash floods in wadi environments, typically with controlled release downstream where most of the recharge occurs.

    b. Rubber dams across relatively large rivers. These flexible elliptical structures are made of rubberized material and attached to a concrete base, inflated by air/water, and deflated as necessary to flush out sediments and prevent damage during extreme floods. For MAR, these appear to be mainly used in China and California.

c. Recharge dams across small streams, often of earthen, concrete, or gabion construction, are particularly common in India where they are also known as check dams, nalah bunds, anicuts, or johads.

d. Erosion/sediment control dams, generally in mountainous areas with large catchment slopes, which may also enhance recharge. Once full of sediment, these could be considered sand storage dams.

e. Debris or leaky dams, which form either naturally or by the natural activities of beavers or are constructed as part of Natural Flood Management (NFM) measures, or river restoration activities that slow river flow and enhance recharge.

3. Channel spreading techniques, which increase the wetted area and infiltration rate of the streambed by widening, leveling, scarifying, dredging, and the use of L-shaped levees.

Figure 4-1a shows a typical recharge dam where recharge occurs through the base of the pond, and downwards to the underlying aquifer. Ideally the groundwater levels will be below the base of the pond at all times of year such that the recharge occurs vertically downwards to the groundwater table, where it forms a mound. The most effective recharge dams have silt removal mechanisms to allow release of silt to maintain the infiltration rate. Wadi-recharge dams are shown in Figure 4-1b, with the only difference from Figure 4-1a being that water is stored in the dam and released over several days/weeks so it can gradually infiltrate through the riverbed downstream.

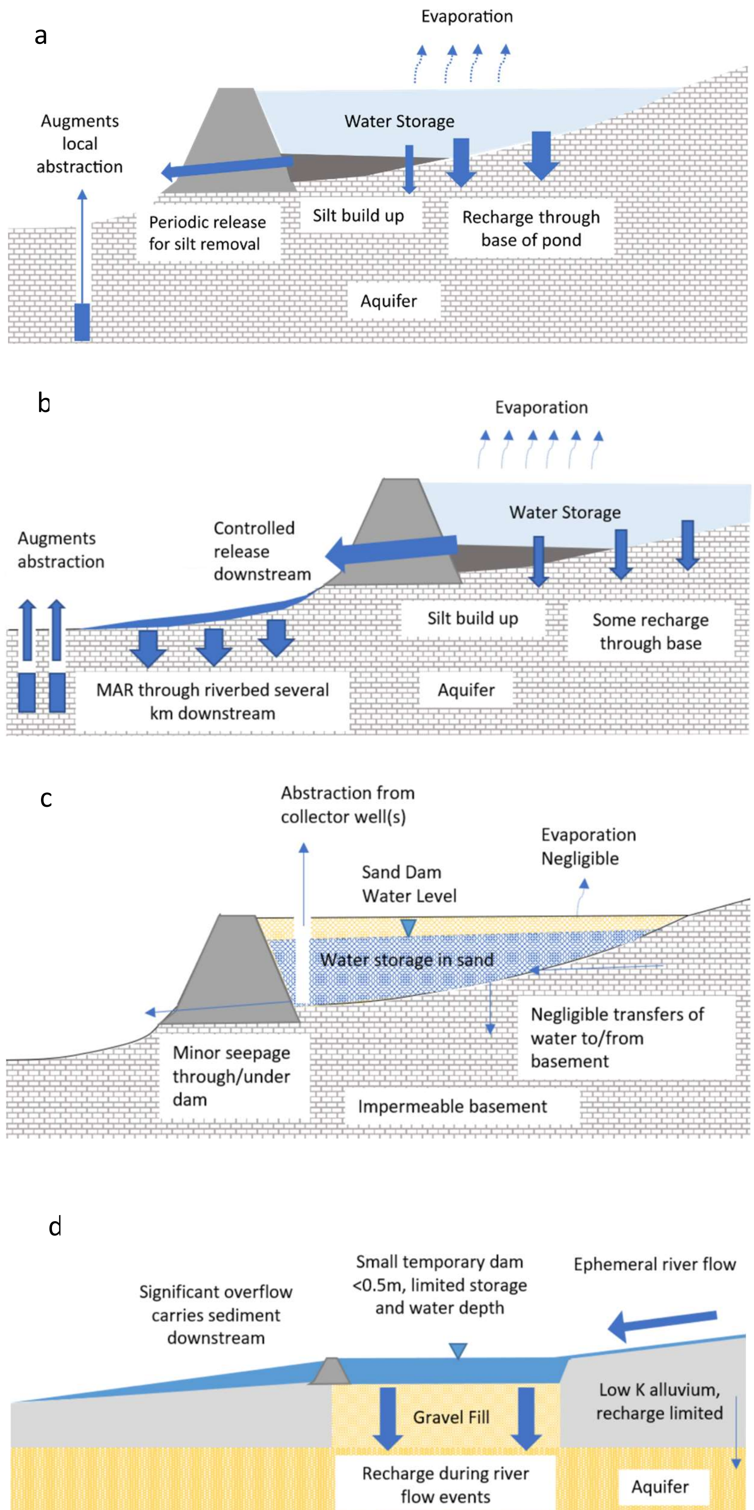


Figure 4-1 Types of in-channel modification for managed aquifer recharge (MAR): (a) a recharge dam, (b) a wadi-recharge dam, (c) a sand storage dam, and (d) a riverbed modification to enhance recharge by removal of alluvial sediments and replacement with gravel fill.

Figure 4-1c shows a sand storage dam, where recharge occurs either by direct rainfall onto the accumulated sediment, or by infiltration of runoff that flows over/into the sediments. Figure 4-1d shows a type of in-channel infiltration basin, where low permeability riverbed sediments have been removed and replaced with gravel infill, which provides a pathway for recharge to occur from the river into the underlying permeable aquifer, as installed in the Rio Seco and described in Section 2.2.2.

In other MAR schemes where river water is the source for MAR, e.g., spreading methods/infiltration basins, it is usually necessary to route the water to the MAR scheme, particularly where these are gravity fed, and small dams are often needed at the abstraction site. Here, recharge through this structure can be a side-benefit, as occurred at the El Carracillo in-channel MAR structure (Fernández Escalante, et al., 2015).

4.2 Methodology

Case studies were collected from academic papers, theses, conference proceedings and internal reports published in English, Spanish, or Portuguese. A major source of information was the IGRAC MAR portal, where the Global MAR Inventory Working Group consolidated information on 1,200 MAR projects (Stefan and Ansems, 2018), along with papers based on reviews of this information, e.g., Bonilla Valverde et al. (2018); Ebrahim et al. (2020).

A search for the topic "Check Dam" in the Web of Science database found 1,365 hits, whilst "Recharge Dam" found 591 hits, indicating a relative scarcity of published literature on these MAR structures. The search term "Check Dam" included many papers where the focus was sediment and erosion control rather than MAR structures. The top 10 countries publishing on this topic were China (335), USA (170), India (162), Spain (121), Italy (96), Japan (68), Iran (61), France (60), Taiwan (48), and England (42) (Web of Science, 2020).

Data were collated from 16 papers, relating to the characteristics of 79 recharge dams, mainly located in India (52), Spain (13), Jordan (6) China (4), Saudi Arabia (2), Cyprus (1), and Oman (1) (Ai-muttair et al., 1994; Kulkarni et al., 2005; Gale et al., 2006; Sharda et al., 2006; Martín-Rosales et al., 2007; Glendenning and Vervoort, 2010; Chen et al., 2012; de Laat and Nonner, 2012; Abdalla and Al-Rawahi, 2013; Parimalarenganayaki and Elango, 2015; Xanke et al., 2015; Farooqi et al., 2016; Djuma et al., 2017; Dashora et al., 2018; Salameh et al., 2019). The analysis included recharge dams, check dams for sediment control, wadi-recharge dams, and rubber dams, but not sand storage dams as recharge to the underlying aquifer is not the objective in these cases. The inclusion criteria were that information from individual recharge dams was available (not combined for several structures), and as a minimum, values for dam storage capacity and estimated annual recharge were available, as the dam storage capacity is one of the main factors controlling the recharge volumes. Data on other factors controlling the recharge were captured, including annual rainfall, runoff and flow duration, infiltration rates, and geological setting, where available. Only constructed MAR schemes were included.

4.3 Results

4.3.1 Occurrence

The approximate numbers of recharge dams by each country/region are summarized in Figure 4-2, based on data from Sharda et al., (2006), Martín-Rosales et al., (2007), Stonestrom and Constantz, (2008), Chen et al., (2012), CGWB, (2013), Parimalarenganayaki and Elango, (2015), Stefan and Ansems, (2018), Salameh et al., (2019), and Ebrahim et al., (2020). It is likely that these numbers are significantly underestimated, as these small structures are not frequently studied or reported in scientific literature. The MAR Portal is not reflective of the large total numbers shown in Figure 4-2, as the inclusion criteria for the MAR portal required a specific location for each structure (Stefan and Ansems, 2018).

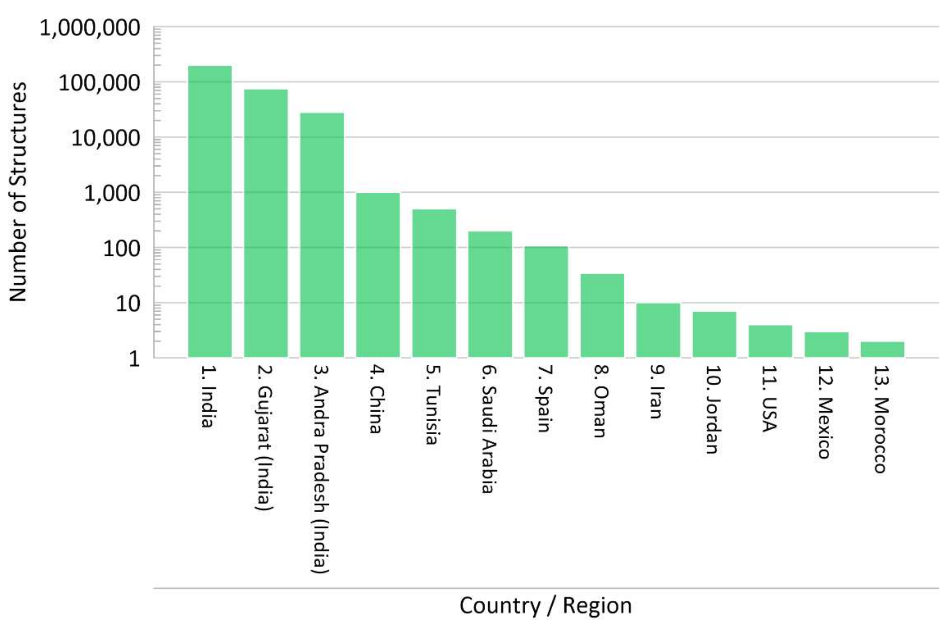


Figure 4-2 Recharge dam occurrence identified through the literature review.

A diverse range of dam sizes and types are encountered. They are most frequent in India, where more than 200,000 recharge dams have been constructed. In Tunisia, small earthen reservoirs for both irrigation and artificial recharge were constructed by the government (Montoroi et al., 2002), including a large water harvesting project in the province of Médenine, (wadi Oum Zessar), which comprised the construction of jessour, tabias, contour stone ridges and also 177 groundwater recharge gabion check dams, 21 flood spreading gabion check dams and 8 recharge wells were installed (Carletti, 2017). In Oman, large wadi-recharge dams were designed to mitigate saline intrusion (Abdalla and Al-Rawahi, 2013). Finally, in China, rubber dams are often built to manage monsoon flood runoff and to maintain river flows during the dry season for recreational or aesthetic purposes, but they have also been constructed specifically for groundwater recharge to mitigate saline intrusion or remediate groundwater deficits, often in cascades of several dams (Sun et al., 2005; Parimala Renganayaki and Elango, 2013).

Small recharge dams are ubiquitous in India to enhance groundwater recharge to sustain irrigation water supplies. Significant further construction of recharge dams is envisaged by the 2013 Master Plan, where 11 million artificial recharge structures were proposed (CGWB, 2013).

4.3.2 Site Selection

For location and design of a recharge dam, it is important to consider the physiography, geology, hydrology, hydrogeology, hydrochemistry, sediment load, and infiltration capacity on a site-specific basis (Kalantari et al., 2010). During this review, the following broad criteria were identified:

- The recharge dam needs to be upstream/upgradient from where the recharged water is required, and close enough to this location that the additional recharge can be captured/used.
- Groundwater levels need to be sufficiently below the base of the stream at the time of year when recharge occurs, and more regionally, sufficient unsaturated zone thickness is needed to accept the additional recharge without causing unacceptable groundwater level rise and consequent flooding of land or damage to structures.

- The underlying strata should have sufficient permeability, such that the water held in the dam can be recharged at a sufficient rate (before the water is evaporated); i.e., low permeability alluvial deposits should not be present or should be removed during construction.
- The storage volume and retention time of the structure needs to be matched to the catchment inflow, such that sufficient volumes are recharged, balanced by the cost of providing increased storage due to increased dam size. Typically, the storage is small in comparison to peak flows, so only a small proportion of flow is captured during these events.

The most comprehensive and specific guidance on the design and construction of recharge dams (including gully plugs, nalah bunds, and check dams) for MAR is from India, indicating that a catchment of 40 to 100 ha area should be selected, with rainfall <1,000 mm/year, the width of stream bed 5–15 m, the depth of stream bed >1 m, the dam height normally less than 2 m, with the land downstream of check dam/nalah bund under well irrigation (CGWB, 2007). To harness the maximum runoff along a stream, a series or cascade of structures is required for recharge to be effective on a regional scale (CGWB, 2007). These criteria were developed based on significant country specific experience, but do not necessarily translate to other areas or situations and may not be suitable in wadi regions.

River water quality and sediment load need to be considered in the selection of suitable locations, i.e., avoiding areas with industrial discharges to rivers, and considering how the sediment input into the dam can be managed to avoid reductions in infiltration rates. Social considerations such as assessing where water is needed, and the cost–benefit of any proposed structure are also important (CGWB, 2007).

4.3.3 Hydrogeology and Water Balance

Methods for estimating the recharge occurring beneath a recharge dam include:

1. Water balance method by measuring inputs and outputs from the dam and inferring recharge (Dashora et al., 2018; Parimalarenganayaki and Elango, 2018);
2. Water table fluctuation (WTF) method using nearby groundwater level measurements (Sharda et al., 2006; Glendenning and Vervoort, 2010; Parimalarenganayaki and Elango, 2018);

3. Stable isotopes to identify different water qualities between native groundwater and water recharged by the MAR structure to infer proportions and hence recharge volumes (Stonestrom and Constantz, 2008; Bel Hadj Salem et al., 2012; Xanke et al., 2015);
4. Chloride mass balance to estimate recharge where there is a significant difference in chloride concentrations between native groundwater and recharge water (Sukhija et al., 1997; Sharda et al., 2006);
5. Direct site investigation methods to estimate infiltration rates, e.g., the Haefeli method or double-ring infiltrometer tests (Martín-Rosales et al., 2007) or tension infiltrometers (Al-Saqri et al., 2016); and
6. Indirect methods, using vertical profiles of temperature time series measurements to estimate river flow duration and infiltration (Hatch et al., 2006).

When methods are compared, for a recharge structure near Hyderabad, India, the recharge using a chloride mass balance approach, was 30–35% of the dam volume compared to 50% when estimated with the water balance method (Sukhija et al., 1997), whilst there was good agreement between recharge estimated with the WTF method and the chloride mass balance method (7.3–9.7% vs. 7.5% of annual rainfall) for a check dam in Gujarat, India (Sharda et al., 2006).

There will be differences in recharge estimates depending on the methods used and a combination of methods may identify a range of recharge estimates. One important limitation was identified in that measuring water loss from the dam (even after accounting for evaporation) does not necessarily equal the recharge reaching groundwater, especially when the unsaturated zone has a large thickness (Missimer et al., 2015). For example, at the Sidi Saad dam in Tunisia (capacity 154 Mm^3, annual release for infiltration 0–163 Mm^3/year) it was shown that most of the released water was lost to evaporation or nonbeneficial vegetation growth rather than to aquifer recharge through the riverbed (Bel Hadj Salem et al., 2012). This is often the case for recharge through ephemeral streams where transmission losses are usually much higher than recharge (Shanafield and Cook, 2014).

The water balance method requires estimates of inflow, overflow, dam storage, and evaporation loss over time to estimate the recharge. Where river gauging is not available, estimating surface water inflow to a recharge dam can be achieved with one of several rainfall–runoff models ranging from simple to more complex, all of which transform catchment rainfall data to an estimate of runoff into the recharge dam, for example, the Australian Water Balance Model (AWBM) (Boughton, 2004), the Surface Water Management Model (SWMM) (Rossman, 2015), or the Soil Water Accounting Tool model (SWAT) (Arnold, 1998).

4.3.4 Recharge Dam Characteristics

Recharge dams can be constructed of many different materials (stone, earth, concrete, gabions) and can even be demountable (inflatable rubber dams). Dam heights are usually between 3 and 5 m, and dam storage capacities span almost five orders of magnitude, from hundreds of m^3 to greater than 10 Mm^3, whereas the recharge/check dams' storage capacity are usually between 1,000 and 100,000 m^3 in size. Wadi recharge dams can be considerably larger, and the rubber dams in China, even larger still. The relationship between dam storage capacity and estimated annual recharge occurring due to the dam is shown in a double log plot (Figure 4-3). A positive relationship is obtained (using data from all types of recharge dams) with an $R^2 = 0.64$ and $R = 0.80$ based on a linear fit. As expected, dam storage capacity alone cannot account for all the variability in recharge rate, hence the low R^2 value. Most recharge dams recharge an annual volume greater than their storage capacity, particularly where storage is between 1,000 and 10,000 m^3, where many recharge dams are able to recharge 10,000 - 100,000 m^3/year. However, as dam capacity gets larger, the annual recharge is likely to be closer to the capacity, or slightly below this figure. It is expected this could be a function of the event for which the dams are designed. For example, although the hydrology of wadi environments varies considerably, wadi recharge dams are often designed for both flood control and aquifer recharge, and therefore capture a high-intensity, higher return period event (e.g., dams spilling during a 1-in-2-year to 1-in-5-year return period event (de Laat and Nonner, 2012)) compared to the smaller check dams of India, which fill three or four times a year (Farooqi et al., 2016). Therefore, the storage volume will be larger, but will fill less frequently, resulting in a lower ratio between storage capacity and recharge.

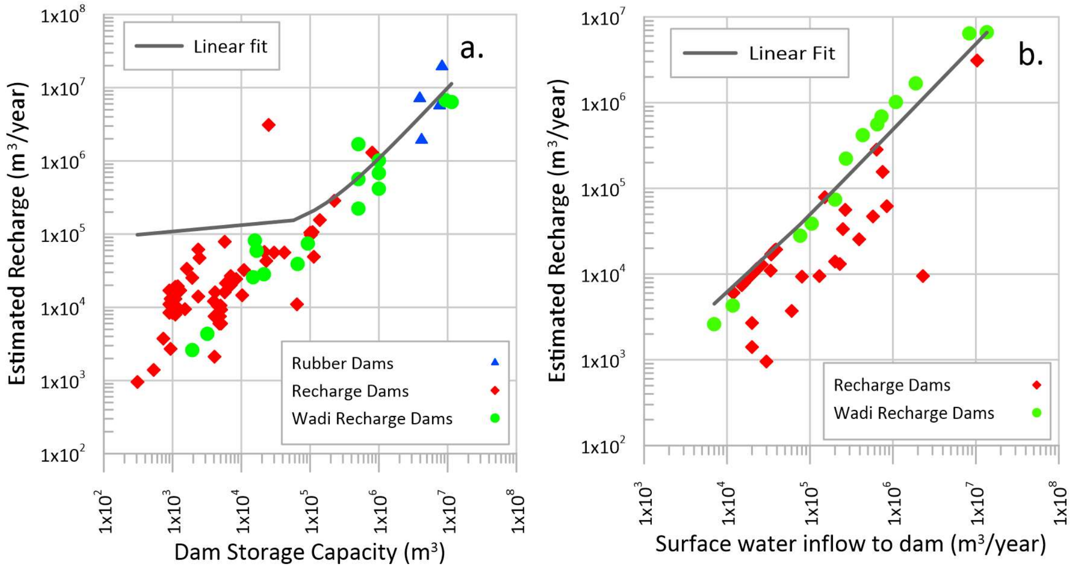


Figure 4-3 (a) Dam storage capacity (m³) vs. estimated annual recharge (m³). (b) Estimated annual runoff vs. estimated groundwater recharge for recharge dams and wadi-recharge dams (no equivalent data for rubber dams).

For the check dams in Almería, it was possible to define two clear linear relationships between storage capacity and induced recharge for two geologies with very different permeabilities (limestone and calcoschist) (Martín-Rosales et al., 2007), with the slope of the line in this case being related only to the hydraulic conductivity, as the data were based on the same design rainfall event. For the majority of the recharge dams reported here, the recharge was estimated annually, with the exception of the check dams in Almería, where recharge was estimated based on a 1-in-5-year return period 6-hr storm event rather than an annual total (Martín-Rosales et al., 2007).

Annual surface water inflow is plotted against estimated annual recharge in Figure 4-3 (b) (no data on annual runoff available for the rubber dams). Visually, the figure shows that for the same annual runoff, wadi dams appear to have a greater annual recharge than other recharge dams. An overall line of best fit was calculated (with a coefficient of determination, $R^2 = 0.87$, and correlation, $R = 0.93$) for all types of recharge dams. As for dam storage capacity, annual surface water inflow alone cannot account for the variability in recharge rate, due to the importance of saturated and unsaturated zone flow processes beneath the recharge dams, and their dependence on head gradients and vertical hydraulic conductivity.

Table 4-1 presents statistics for the recharge dams analysed. Annual average rainfall ranges from 115 to 1,860 mm/year, even though there is some guidance (CGWB, 2007) that suggests additional recharge should not be necessary in situations where rainfall is greater than 1,000 mm/year. Interestingly, the case study with the highest rainfall (1,860 mm/year) was in the Kolwan valley (India). There, it was found that two of the three check dams were gaining water from groundwater rather than replenishing the aquifer, and although the third did recharge groundwater, the recharged water would emerge in the river channel further downstream (Kulkarni et al., 2005; Gale et al., 2006), indicating the importance of appropriate site selection. This also occurred where recharge dams were located on second order streams in the Dharta watershed (India), where during years of higher rainfall, recharge was reduced as groundwater levels rose and became hydraulically connected to the recharge dams (Dashora et al., 2019). When designing recharge dams, it should be noted that although the 75th percentile height is only 5.0 m, higher dam heights of 19–25 m in Pakistan have been reported (Ashraf et al., 2007).

Table 4-1 Recharge dam statistics

Statistic	Annual Average Rainfall (mm)	Catchment Area (km^2)	Dam Capacity (m^3)	Dam Height (m)	Volume Recharged (m^3/year)	Annual Runoff to Check Dam (m^3)	Annual Runoff (m^3/km^2)
Minimum	115	0.07	308	1.5	960	7,018	5,076
25th Percentile	359	0.88	1543	3.0	10,250	20,000	23,864
Median	387	1.53	7000	3.5	20,200	39,000	24,615
75th Percentile	673	7.45	76,250	5.0	80,375	390,000	59,656
Maximum	1860	1770.00	11,400,000	11.0	19,340,000	13,600,000	2,951,278
Mean	481	59.20	603,552	4.5	737,337	853,625	117,770
Count	62	78	86	25	79	53	47

4.3.5 Recharge Effectiveness

Two measures were considered to measure the effectiveness of recharge dams:

1. Recharge efficiency (RE), defined and used by (Martín-Rosales et al., 2007; Glendenning and Vervoort, 2010; Dashora et al., 2019) as the estimated annual recharge through the structure divided by the dam storage capacity, and
2. Runoff collection efficiency (RCE), defined herein as the dam storage capacity divided by the annual captured runoff volume.

RE is a measure of how effective the structure is and allows identification of recharge dams that are more effective per m^3 of storage. Values of RE were calculated for all recharge dams in the literature where storage capacity and a recharge estimate were available and are presented in

Table 4-2. Some of the small dams have extremely high effectiveness, with small capacity dams being responsible for recharge of up to 125 times the storage capacity. In Almería, the check dams overlying highly permeable strata (limestones and dolomites) had RE values range from two to four. Meanwhile, for the check dams overlying lower hydraulic conductivity strata (calco-schists), the RE is almost one (Martín-Rosales et al., 2007).

Table 4-2 Recharge Efficiency (RE) and Runoff Collection Efficiency (RCE) of recharge dams

Statistic	Recharge Efficiency	Runoff Collection Efficiency
Minimum	0.17	0.0007
25th Percentile	1.27	0.0289
Median	2.82	0.0556
75th Percentile	8.75	0.4000
Maximum	124.88	3.0732
Mean	6.69	0.3468
Count	79	53

Runoff collection efficiency (RCE) does not appear to have been previously defined in the literature reviewed but is a useful measure to describe the proportion of runoff collected. Where the runoff collection efficiency is less than one, the dam storage capacity is less than the annual runoff. This is usually the case, except for some wadi recharge dams where the interannual rainfall variability is substantial and the dams are often designed for an event that does not occur every year. For example, most of the dams at Wadi Madoneh were designed to capture the 1-in-2-year rainfall event without spilling, with one dam designed for the 1-in-5-year rainfall event (de Laat and Nonner, 2012). For smaller dams, a value higher than one may indicate an inappropriately large dam for the runoff available, although interannual runoff is typically variable in ephemeral catchments, and therefore RE and RCE may vary considerably each year.

RE is plotted against RCE in Figure 4-4 where both measures could be calculated. Both RE and RCE are dependent on the provided estimates of recharge presented in the literature, and it should be noted that recharge can be calculated using several different methods (see Section 4.3.3), which introduces additional uncertainty to this analysis. Wadi dams generally have a higher RCE than other recharge dams, but their RE values are the same as many check dams and nalah bunds, and lower than some check dams. The higher RCE is a reflection of hydrological situation with fewer, higher intensity rainfall events, and the comparatively larger storage capacities can intercept a greater proportion of the runoff. The low frequency of these events is thought to result in the low RE values. In Jordan, four check dams in the Wadi Madoneh were constructed with capacities from 2000 to 66,400 m^3, and three of these were designed to capture flows up to the 1-in-2-year event, with one dam capturing up to the 1-in-5-year event. In conclusion, Figure 4-4 shows that collecting a higher proportion of runoff (higher RCE) does not necessarily increase the recharge effectiveness (RE value), and therefore where MAR is the main aim, then smaller, less expensive structures that capture a lower proportion of the runoff may be more effective per m^3 of storage provided.

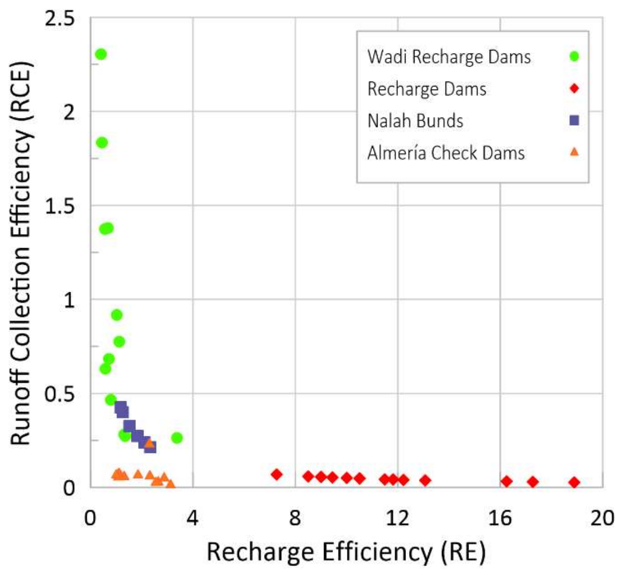


Figure 4-4 Runoff collection efficiency vs. recharge efficiency by type of recharge dam.

Even within the smaller structures, there appears to be a difference between nalah bunds and check dams, probably relating to their position in the catchments, with nalah bunds having higher RCE values, indicating they capture a larger proportion of the annual runoff, and are often located higher up the catchment on streams of lower order than check dams.

Interestingly for each type of structure, there appears to be a negative correlation between RCE and RE. The amount of recharge through a recharge dam is affected by several factors, but one of the most important appears to be the percentage of time that the structure holds water, as these are all located on ephemeral watercourses. Structures that have higher RE may tend to experience longer periods of time where the dam is full, allowing recharge to occur over a longer period, but these will tend to collect a lower proportion of the annual runoff, as once the structure is full, any further runoff will be lost downstream.

One of the main controlling factors of recharge through check dams is the hydraulic conductivity of the underlying aquifer, and any deposited sediments. However, the infiltration rates or saturated hydraulic conductivity (K_s) values are rarely reported. A number of sites in India report infiltration rates in the range of 12–78 mm/day (Gale et al., 2006; Glendenning and Vervoort, 2010; Dashora et al., 2018), which is relatively low, reflecting the hard rock terrain, and limited weathered zone aquifers that these check dams intersect, with the recharge rates owing to the length of time that water is stored in the dams (often around 5 months (Gale et al., 2006)). Infiltration rates beneath some wadi dams, and certainly downstream of the dams are likely to be higher, based on the saturated hydraulic conductivity measurements from Al Khod dam (K_s up to 8 m/day) (Al-Saqri et al., 2016). A review of MAR sites in Africa identified that they were much more likely to be situated in sedimentary rocks, with schemes located in Egypt, Ethiopia, Morocco, South Africa, and Tunisia (Ebrahim et al., 2020).

In Almería, of the 107 check dam structures, only 64 were considered to promote infiltration of water retained, as these were located on permeable strata (limestones, dolomites and calcoschists compared to impermeable phyllites) (Martín-Rosales et al., 2007).

4.3.6 Sediment Control/Siltation

Siltation is regularly described as one of the main challenges to the recharge efficiency of check dams at wadi-recharge dams (Salameh et al., 2019) and in other locations, e.g.,(Martin, 2013). However, from the literature reviewed, sedimentation does not seem to be a particular problem, with multiple studies indicating that although siltation occurred to some extent, the dams are still functioning as intended. This may reflect a positive bias in that recharge dams that are failing are less studied and reported in the literature, or reflect that as siltation problems are well understood, dams are now designed with mechanisms to reduce siltation, typically by allowing flood water from extreme floods to pass through the dams to remove the built-up sediment.

4.4 Other In-channel MAR

4.4.1 Sand Storage Dams

Sand storage dams are usually constructed for local water supply. They are generally located on mountainous streams that are confined on both sides where bedrock is close to the surface and relatively impermeable . The sediment load carried by the river is deposited behind the dam forming a semi-artificial aquifer in an area with otherwise limited groundwater resources. The water storage of a sand storage dam is lower than that of a recharge dam as it is limited to the drainable porosity of the stored sediments, but evaporation from a sand dam is lower than a recharge dam (Baurne, 1984). An example of a sand storage dams pre-and post-construction is shown in Figure 4-5 (Ertsen and Hut, 2009).

(**a**)

(**b**)

Figure 4-5 Typical sand storage dams: (a) filled sand dam and (b) sand dam prior to filling. Photographs reproduced with permission from Ertsen and Hut, Physics and Chemistry of the Earth Parts A/B/C, published by Elsevier (2009).

Sand storage dams are known to have existed since Roman times in Sardinia and in ancient civilizations in North Africa (Nilsson 1988, in (Hut et al., 2008)) and now there are more than 3,000 in sub-Saharan Africa, mainly in Kenya (Lasage et al., 2008). They provide an additional water supply source for a village, enabling reduced travel time to obtain water and additional water for crop irrigation (Excellent Foundation, 2019).

Check dams that become completely filled with sediment essentially become sand storage dams, and these have been constructed for more than 400 years on the Loess Plateau of China, with more than 110,000 check dams having been constructed in the last 50 years (Wang et al., 2011; Jin et al., 2012).

Local site-specific conditions govern successful location of sand storage dams, hence regional site selection studies are limited ((Gijsbertsen, 2007; Forzieri et al., 2008). Developed criteria identify the importance of local communities in determining the need for, and location of, a sand storage dam. Factors to consider include how much time and physical labour the community is willing to invest, the proximity of the site to the end users, and any land access/legal constraints (Maddrell and Neal, 2013).

Sand storage dams have very specific applicability in hard rock areas where increased seasonal storage of water is required. As they create an artificial aquifer, they rely on an impermeable base, and high energy river flows to deposit sediments with suitable grain size to form an aquifer behind the dam. They are therefore unlikely to be suitable in the Algarve.

4.4.2 Riverbed Modification

The MAR pilot trials in the Rio Seco described in Section 2.3.2 are an example of riverbed modifications to increase recharge. A much larger scheme has been constructed on the Huangshuihe River, China where the river bed was originally of low permeability, which was artificially enhanced by in-channel modifications, including 2518 infiltration wells, 448 trenches, and 773 basins excavated in the riverbed, and the six rubber dams augmented by a 6 km long subsurface dam 27 m in depth. Since implementation in 1995, the infiltration capacity of the riverbed has been reduced by half, and maintenance by removal of sediment has been onerous and expensive (Sun et al., 2005). This appears to be an issue with the sediment load carried by the river and low flow velocity in the MAR location. Therefore, selecting a suitable location for this type of MAR is extremely important.

4.4.3 Natural Flood Management (NFM)

In the UK, more than 230 implemented projects or feasibility studies have been carried out for NFM measures and recorded on a web portal (JBA Trust, 2016). The aim of these measures is to increase infiltration and reduce runoff, e.g., cover crops, reducing stocking levels, land use change from arable to pasture, as well as in-channel or off-channel measures to store water (slowing the flow and allowing more infiltration) (Barlow et al., 2014). NFM measures are noted to be more effective in permeable catchments, where recharge to the aquifer from temporary flood storage occurs (Hankin et al., 2017). In permeable catchments, these features have the potential to enhance natural recharge by methods similar to recharge dams, by raising the water level and water storage behind the dam, allowing greater infiltration and recharge.

As more significant flooding problems usually occur in impermeable catchments, the majority of research has focused on these, where, for example, in upland peat catchments in the UK, restoration measures have been used with the aim to reduce the flood peak and increase the time to peak. Methods include gully blocking, for example, on the Kinder plateau where 0.5 m high stone dams composed of millstone grit cobbles (75–200 mm diameter) were installed across the width of the gully, approximately 6–7 m apart. Timber dams are also being used in smaller tributary gullies constructed with a 38 mm-deep ”V-notch” cut into the top board to promote flow over the centre (Shuttleworth et al., 2019), and restoration of natural vegetation (sphagnum moss), lost from moorland due to historical industrial air pollution (Shuttleworth et al., 2019). On a field scale/small catchment scale, these appear to reduce the flood peaks and increase the lag time (time to peak). Notwithstanding, there is doubt as to whether any additional groundwater recharge occurs in the long term, as the observed water table rise was only small (0.03 m) and no significant changes in flood volume were found (Shuttleworth et al., 2019). Therefore, these may be only temporary storage rather than any significant recharge. In conclusion, NFM measures have been proven to work on a small field site or very small catchment scale, but further work is necessary to determine whether they can be effective over a larger catchment scale and for extreme flood events (Wentworth & Zu Ermgassen, 2020).

4.5 Regional Impacts

One of the main research questions is whether small in-channel modifications can have a regional impact on an overexploited aquifer, and if construction of MAR structures at such a scale is feasible. Regional benefits include the ability of MAR to prevent saline intrusion on an aquifer scale, improve regional groundwater quality, or raise groundwater levels and provide additional water resources on an aquifer scale.

Regional benefits were seen at the following schemes:

- Souss–Massa, Morocco, which recharges 100 Mm^3/year by capturing flood water in the dams of combined capacity 115 Mm^3. The majority of infiltration occurs downstream of these during regulated releases (Ebrahim et al., 2020), and the scheme comprises 3% of Morocco’s total groundwater use.
- Sidi Saad Dam, Tunisia (capacity 154 Mm^3), recharge also occurs in the riverbed downstream by release of water from the dam. Here up to 5.25 m groundwater

level rise was seen up to 8 km downstream, with water taking four months to reach the water table (Bel Hadj Salem et al., 2012).

- Louhe River (Louyang City, China) recharge scheme comprises five stepped rubber dams, between 3.5 and 4.5 m in height, with a combined storage capacity of 19 Mm^3 (Sun et al., 2005) This rubber dam cascade almost completely alleviated the groundwater overdraft, with groundwater level rise of up to 30 m occurring within four years of the first dam being constructed.
- At Huangshuihe, a MAR scheme similar in scale to Louhe but also including a subsurface dam, since implementation in 1995 the groundwater resource has increased by 11 to 60 Mm^3/year, and saline intrusion has been prevented (Sun et al., 2005)
- At Peristerona River, Cyprus, 7 recharge dams were installed. The most upstream check dam (named Orounda check dam) with a storage capacity of 25,000 m^3, recharged the aquifer with an average of 3.1 Mm^3 of the 10.4 Mm^3/year of streamflow (30%), compared to a natural upstream reach of 11 km in length that recharged 1.5 Mm^3/year over the same period (Djuma et al., 2017). This dam has the highest RE value of all analysed in this paper (RE = 125), apparently due to a relatively high runoff (close to the maximum reported) and although not reported, a high infiltration rate is probable due to the small size of the storage.

In conclusion, regional benefits are usually achieved by a very large storage capacity, and hence recharge volume at a single dam, or by a cascade of several large recharge dams. In some cases, these are constructed along with a subsurface dam. However, the achievement of regional benefits depends on the size of the aquifer unit and its characteristics. In the majority of these cases, the aquifers are of high permeability, including Quaternary sands and gravels in China, and high permeability alluvial/colluvial deposits in Cyprus.

The example from Cyprus is important as it shows that even small check dams can have a significant, potentially regional impact where aquifer properties and runoff volumes/durations are favourable, however it appears to be an isolated exception.

4.6 Implications for MAR in the Algarve

In the Algarve, the length of the rivers where they flow across permeable aquifers is limited by the extent of the meso-Cenozoic sedimentary basin, which often results in a limited width of the aquifer (and river) between the coast to the south, and the basin limit to the north, often 10 km or less. This is further limited as the aquifer units dip towards the sea, resulting in narrow bands of permeable outcrop area. The rivers also tend to be located at the boundaries of these coastal aquifer systems, often aligned along known faults, the permeability of which is unknown. There is a considerable risk that placing in-channel modifications along these rivers would enhance recharge that is then rapidly transmitted to the sea, along permeable faults.

The meta-analysis has shown that an approximate 1:1 relationship between dam storage capacity and annual average recharge exists for the dams analysed. Therefore, if check dams were installed in the Algarve, the expected annual recharge could be expected to be equivalent to the installed dam capacity. The Algarve rivers are usually narrow and often in deeply incised channels, with relatively high slopes, limiting the potential dam capacities. Therefore, as a dam of 10,000 m^3 may only achieve the same annual recharge, and river length is limited for multiple structures, hence achieving an aquifer scale benefit is not possible with this type of MAR.

The rivers are also underlain by variable thicknesses of low permeability alluvium, which limit natural infiltration rates. Although the infiltration basins at the Rio Seco are very successful in terms of maintaining high infiltration rates since construction (Oliveira et al., 2015b), they required significant excavation of low permeability clays (6 m thickness), and replacement with clean gravel. Therefore, there is limited potential for scaling up of this design, given the environmental and carbon impacts of the excavation of large volumes of material.

Therefore, for the reasons described above, alternative MAR methods are more suitable. MAR methods are assessed on an aquifer-specific basis in Chapter 6, whilst the following Chapter examines the broad potential of MAR in the Algarve.

Chapter 5: Potential for MAR in the Algarve

This Chapter identifies objectives for MAR within the RH8 region, to augment the existing water resources of the Algarve. Initial estimates of water available for MAR from all sources are determined along with details of MAR methods suitable for use in the Algarve, considering alternative methods to in-channel MAR due to the conclusions in the previous Chapter. Costs are identified based on schemes implemented in other countries, and potential options for managing water quality risks during MAR are outlined.

5.1 MAR Objectives

Prior to developing MAR schemes, the project objectives should be clearly defined at the outset. The most common objective is to increase the available water supply, with a recent trend towards improving water supply reliability during droughts or emergencies (McCurry and Pyne, 2022). Typically, 3 to 5 objectives are identified and ranked by importance, to guide subsequent planning and implementation of the scheme. Potential objectives for MAR are described in Table 5-1, modified from McCurry & Pyne (2022) to consider whether these objectives are relevant for the RH8 region.

Table 5-1 Example objectives for MAR projects and their applicability for the RH8 Region

Example Objectives for MAR Projects	Type	Applicability in RH8 region*	Comments
Provide seasonal to long term storage	Water Supply	A	Priority objective
Improve reliability of supplies	Water Supply	A	Priority objective
Improve wellfield production	Water Supply	A	In limited situations
Defer expansion of water facilities	Water Supply	A	Priority objective
Maintain pressures in distribution systems	Water Supply	B	
Maintain flows in distribution systems	Water Supply	B	
Offset out-of-priority stream depletion	Water Supply	N/A	
Sustain economic activity	Water Supply	A	Agriculture & Tourism
Improve groundwater quality	Water Quality	A	WFD objective
Reduce disinfection by-products of treated recharge water	Water Quality	N/A	See Section 5.3, treated water not considered
Provide additional water treatment	Water Quality	B	Not main purpose of MAR given water sources (Section 5.3)
Restore groundwater levels	Aquifer Restoration	A	WFD objective
Reduce subsidence	Aquifer Restoration	N/A	Not a known issue in RH8
Manage sea-water intrusion	Aquifer Restoration	A	In limited situations, helps attain WFD objectives

Example Objectives for MAR Projects	Type	Applicability in RH8 region*	Comments
Increase baseflow to streams	Environmental Protection	B	
Maintain wetlands	Environmental Protection	B	
Enhance riparian habitat	Environmental Protection	B	
Stabilise surface water temperature	Environmental Protection	B	
Control aquifer contamination	Environmental Protection	A	WFD Objective
Protect human health	Environmental Protection	A	Fundamental to success of all water supply projects

*Applicability A: Potential main objective, B: Potential secondary benefit, N/A: Not applicable in RH8

More specific MAR objectives for RH8, considering the current status of the water resource system, and the regulatory objectives of the WFD have been defined as:

1) **Improve aquifer quantitative status:**
    a) Improve water balance, potentially reverse deficits
    b) Support current levels of groundwater-fed irrigation
    c) Support recovery of groundwater levels / storage if former municipal boreholes are used for emergency supply
    d) Support status in longer term (climate change, increased irrigation)
2) **Improve aquifer quality status:**
    a) Improve water quality, particularly where impacted by nitrate contamination
    b) Prevent further deterioration (i.e., by SWI)
3) **Reduce pressure on surface water system, by providing a water resources benefit, and thus:**
    a) Delay, reduce or avoid the need for alternative water sources
    b) Reduce risk of supply failures, and associated impacts
    c) Increase drought resilience of public water supplies

Environmental benefits should be considered during the development of MAR projects, as MAR may also help to support achievement and maintenance of surface water objectives under the WFD, by increasing baseflow to rivers, maintaining wetlands, enhancing riparian habitats, and stabilising surface water temperatures. These benefits should not only be considered as ‘losses’ from MAR systems, as they can provide important ecosystem services and wider benefits.

5.2 Management of MAR

Portugal does not yet have guidelines on the management and operation of MAR facilities; however, a wealth of regulations and guidance documents have been produced in countries where MAR schemes have been operational for up to 60 years. Countries such as Australia, the USA, and India have well developed guidelines that are in their second phase, having had the chance to implement guidance, determine which aspects are successful, and revise where necessary in the second version. A summary of MAR guidance documents is provided in the MARSoluT project deliverable D2.2 (Monteiro et al., 2023).

There are many management aspects that will need to be considered relating to development, operation, maintenance of MAR facilities, but these are outside the scope of this thesis. Only water quality aspects are discussed in more detail below, given that a preliminary water quality assessment is required to determine suitable sources of water for MAR.

5.2.1 Water Quality

There are several options for management of water quality in MAR:

- Qualitative management takes a catchment risk identification and management approach, by identifying potentially hazardous activities within the catchment that could negatively affect water quality, i.e., a water safety plan approach. Providing no significant potential sources of contamination are identified, water quality analyses of the source water are not necessary. This option is better suited to low-risk MAR projects recharging natural waters in unconfined aquifers for use in irrigated agriculture (Dillon et al., 2022).
- Prescriptive management usually stipulates a suite of specific parameters for which water quality standards (maximum contaminant levels; MCLs) must be met prior to recharge and/or on recovery and stipulates the frequency of sampling. This is intended to be a receptor-based approach and MCLs commonly address public health protection (e.g., in drinking water supply), but can also accommodate environmental protection targets where relevant (e.g., in irrigation water supply). In the European Union, the Water Framework Directive precludes the entry of contaminants to the saturated zone. This one-size-fits-all approach can mean that

low-risk projects are over-managed and high-risk projects are under-managed (Dillon et al., 2022).

- Risk-based management promotes integrated risk-management from catchment to consumer and recognizes the role of the aquifer and unsaturated zone in providing water quality improvements, where appropriate. Combining natural and engineered treatment processes can improve the economic viability of MAR schemes by reducing the requirements to treat the source water prior to recharge (Dillon et al., 2022). This type of management has been implemented by both the Californian and Australian MAR guidelines.

Whilst protecting human health is paramount, overly prescriptive requirements for MAR that preclude the use of generally good quality water can be counterproductive. In particular, the comparison between natural recharge, or irrigation return becoming recharge, and the standards for irrigation water should be considered in comparison to the water quality requirements for MAR schemes, particularly in the light that treated wastewater is already permitted for direct irrigation in agriculture in Portugal, subject to an assessment of the risks. Meanwhile, meeting the Groundwater Directive effectively means that treated wastewater cannot be used for MAR, without tertiary treatment that usually renders such a scheme prohibitively expensive. It is recommended that any licensing process takes into account both the water quality of the water source, and whether it is being recharged directly to the saturated zone or unsaturated zone. In this way, degradation and attenuation within the unsaturated zone can be considered.

The requirement to meet the Groundwater Directive ultimately means that it is likely prescriptive management will form part of any MAR scheme, and it seems that the source water will probably be required to meet the water quality standards included in the RBMP[1]. These are reproduced in Table 5-2. This would be a relatively conservative approach, as it does account for attenuation and degradation in the unsaturated zone. Assessment of surface water quality by this method has been undertaken for potential water sources for MAR in the Algarve and is presented in Chapter 6.

[1] https://apambiente.pt/sites/default/files/_SNIAMB_Agua/DRH/PlaneamentoOrdenamento/PGRH/2016-2021/PTRH8/PGRH_2_RH8_Parte2_Anexos.pdf

Table 5-2 National threshold values and quality standards

Parameter (Portuguese)	Parameter (English)	CAS Number	Threshold Values (Limiares)	Quality standards (Norma de qualidade)
Azoto Amoniacal (mg/L)	Ammoniacal Nitrogen (mg/L)	CAS_7664-41-7	0.5	-
Condutividade (µS/cm)	Conductivity (µS/cm)	EEA_3142-01-6	2500	
pH	pH	EEA_3152-01-0	5, 5-9	
Arsénio (mg/L)	Arsenic (mg/L)	CAS_7440-38-2	0.01	-
Cádmio (mg/L)	Cadmium (mg/L)	CAS_7440-43-9	0.005	-
Chumbo (mg/L)	Lead (mg/L)	CAS_7439-92-1	0.01	-
Mercúrio (mg/L)	Mercury (mg/L)	CAS_7439-97-6	0.001	-
Cloreto (mg/L)	Chloride (mg/L)	CAS_16887-00-6	250	-
Sulfato (mg/L)	Sulphate (mg/L)	CAS_151-21-3	250	-
Tricloroetileno (µg/L)	Trichloroethene (µg/L)	CAS_79-01-6	Σ =10	-
Tetracloroetileno (µg/L)	Tetrachloroethene (µg/L)	CAS_127-18-4		-
Nitrato (mg/L)	Nitrate (mg/L)	CAS_14797-55-8	-	50
Pesticidas (substância individual) (µg/L)	Pesticides (individual substances) (µg/L)	EEA_34-01-5	-	0.1
Pesticidas (total)[1] (µg/L)	Pesticides (total)] (µg/L)	EEA_32-02-0	-	0.5
Naftaleno (µg/L)	Naphthalene (µg/L)	CAS_91-20-3	2.4	-
Acenafteno (µg/L)	Acenapthene (µg/L)	CAS_83-32-9	0.0065	-
Acenaftileno (µg/L)	Acenapthalene (µg/L)	CAS_208-96-8	0.013	-
Antraceno (µg/L)	Anthracene (µg/L)	CAS_120-12-7	0.1	-
Fenantreno (µg/L)	Phenanthrene (µg/L)	CAS_85-01-8	0.0065	-
Fluoreno (µg/L)	Fluorene (µg/L)	CAS_86-73-7	0.0065	-
Pireno (µg/L)	Pyrene (µg/L)	CAS_129-00-0	0.0065	-
Fluoranteno (µg/L)	Fluoranthene (µg/L)	CAS_206-44-0	0.1	-
Benzo[a]antraceno (µg/L)	Benzo[a]anthracene (µg/L)	CAS_56-55-3	0.0065	-
Criseno (µg/L)	Crysene (µg/L)	CAS_218-01-9	0.0065	-
Benzo[a]pireno (µg/L)	Benzo[a]pyrene (µg/L)	CAS_50-32-8	0.01	-
Benzo[b]fluoranteno (µg/L)	Benzo[b]fluoranthene (µg/L)	CAS_205-99-2	Σ=0.1	-
Benzo[k]fluoranteno (µg/L)	Benzo[k]fluoranthene (µg/L)	CAS_207-08-9		-
Benzo[g,h,i]perileno (µg/L)	Benzo[g,h,i]perylene (µg/L)	CAS_191-24-2		-
Indeno[1,2,3-cd]pireno (µg/L)	Indeno[1,2,3-cd]pyrene (µg/L)	CAS_193-39-5		-
Dibenzo[a,h]antraceno (µg/L)	Dibenzo[a,h]anthracene (µg/L)	CAS_53-70-3	0.0065	-
Benzeno (µg/L)	Benzene (µg/L)	CAS_71-43-2	1.0	-
Etilbenzeno (µg/L)	Ethylbenzene (µg/L)	CAS_100-41-4	1.3	-
Tolueno (µg/L)	Toluene (µg/L)	CAS_108-88-3	1.3	-
Xileno (µg/L)	Xylene (µg/L)	CAS_1330-20-7	1.3	-
MTBE (µg/L)	MTBE (µg/L)	CAS_1634-04-4	0.65	-

1. "Total" means the sum of all individual pesticides detected and quantified during the monitoring process, including their metabolites and degradation and reaction products.

5.3 Water sources for MAR

5.3.1 Ephemeral rivers during wet season

The locations and flow characteristics of the gauged catchments in RH8 are shown in Figure 5-1 and Table 5-3. Of these 4 have annual average flows greater than 10 Mm^3/yr, whilst the rest have flows under 5 Mm^3/yr. The two catchments with the highest flow per unit area ($m^3/yr/km^2$) are 31K/03H and 30L_02H, the easternmost catchments located on impermeable schists and greywackes, whilst the river that drains the western part of the karstic limestone Querença-Silves aquifer (30G/08H) has a unit flow almost an order of magnitude lower.

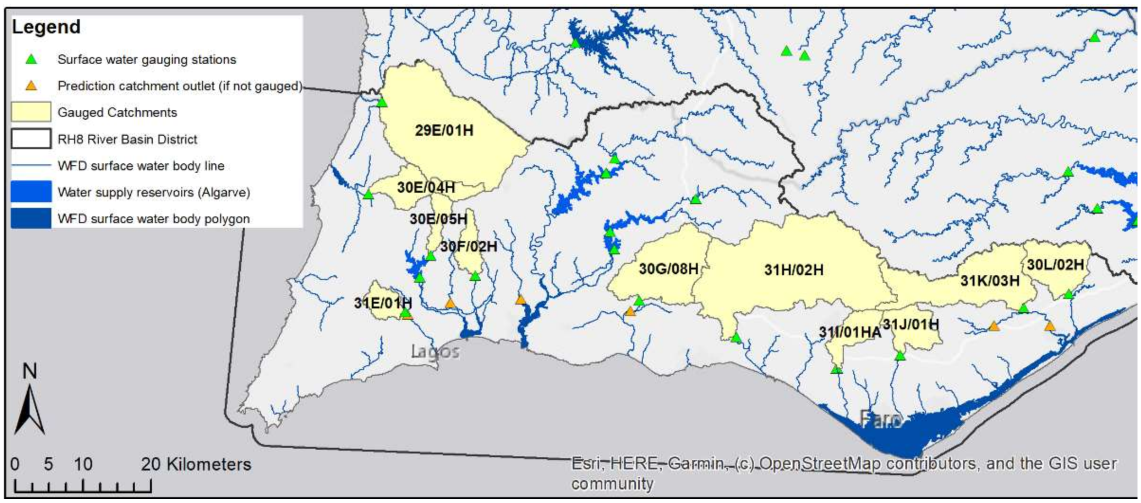


Figure 5-1 Location of gauging stations and associated catchments in the Algarve.

Table 5-3 Catchment areas and flow characteristics for gauged catchments with potential for MAR

Gauging Station	Catchment area (km^2)	Annual average flow (Mm^3/yr)	Annual average unit flow ($m^3/yr/km^2$)	Average number of days where flow greater than zero (days)	Number of years analysed (where data availability >90%)
29E/01H	249.50	**34.20**	137,064	351	2
30E/04H	50.58	**4.64**	91,630	170	5
30F/02H	23.99	**3.79**	157,998	210	54
30G/08H	111.52	**2.57**	23,014	81	12
30L/02H	61.37	**11.36**	185,051	119	27
31E/01H	21.62	**1.73**	80,166	153	2
31H/02H	323.90	**34.31**	105,916	224	27
31J/01H	40.00	**4.41**	110,296	130	18
31K/03H	132.56	**27.59**	208,154	139	20

Not all these gauged catchments are of interest as water sources for MAR, as in some cases their flows are already captured by the surface water dams shown on Figure 5-1.

Due to the highly variable streamflow and the limited number of days when the rivers are flowing each year, the MAR scheme design will need to include the number of days flow / year when considering the planned recharge rate, to achieve annual recharge objectives..

5.3.2 Capturing overflow from dams

During the MARSOL project, it was considered that during wet years, water discharged to the Arade estuary from the Odelouca, Funcho and Arade dams when these dams are close to reaching their capacities, could be captured and used for MAR within the Querença-Silves aquifer. The source of water could also take advantage of the tunnel connection between Odelouca to Funcho, and from Funcho to the Alcantirilha WTP. During the project it was estimated that 70 Mm^3 could be available during wet years (Oliveira et al., 2015a).

Considering the evolution of water storages over time in these three dams (Arade and Funcho are operated together), it can be shown that storage volumes have never approached their maximum capacity at any of these 3 dams in the last 20 years (Figure 2-3) and it is highly unlikely these volumes would be available for MAR in the future. Furthermore, the infrastructure and engineering requirements to transmit such large volumes of water long distances, only during extreme events, is likely to be prohibitively expensive, and may not be technically feasible.

5.3.3 Treated Wastewater

In 2020, almost 37 Mm^3 wastewater was produced from 23 wastewater treatment works (WTP) in the Algarve. Wastewater treatment in the Algarve is usually considered to be more stringent than secondary, as defined by the Urban Wastewater Treatment Directive (2018), as primary and secondary treatment is usually followed by UV disinfection, given the proximity to the sea and bathing waters. Only two WTP have enhanced nitrogen and phosphorus removal (Albufeira Poente and Quinta do Lago), whilst all except Companheira have ultraviolet treatment prior to discharge.

Recently the importance of reusing treated wastewater has been recognised in Portugal and in August 2019 a new policy was approved (Law decree n.º 119/2019, 08/21) that identifies the production of water for reuse from several sources (urban, domestic, industrial, agriculture overflow and runoff) for use in multiple non-potable purposes such as agriculture irrigation, urban uses (landscape, flushing, fire-fighting, street cleaning, recreational uses) or for ecosystem support (Rebelo et al., 2020). The policy focuses on a site-specific risk management framework and in quality standards defined according to a fit-for-purpose approach based on ISO standard 16075, to meet the needs of the end users (Rebelo et al., 2020).

Saline intrusion into the wastewater network, either through the pipe network or at the WTP's, results in approximately half of the available volume (20 Mm^3) being currently unsuitable for re-use due to salinity, without further investment to control sewer infiltration (APA, 2020). The wastewater unaffected by saline intrusion, and therefore the first priority for reuse is located along the coast from the WTPs of Faro-Noroeste, Vila Moura, Albufeira, Lagos and Vila Real de Santo Antonio.

A recent effluent reuse trial in the Algarve, using wastewater from the Faro-Noroeste WTP to irrigate a citrus orchard (Moreira et al., 2022), as a replacement for groundwater from the Campina de Faro aquifer concluding that reuse for citrus irrigation was technologically feasible with several environmental advantages, including avoiding abstraction from the Campina de Faro aquifer, preventing eutrophication of aquatic ecosystems (by not discharging the treated wastewater to the Ria Formosa), improving the soil characteristics, and decreasing carbon emissions associated with orange production. It was estimated that the orchard sequestered 87.5% of the CO_2e emitted by the WTP in the effluent treatment, converted to orange biomass (Moreira et al., 2022).

For MAR with treated wastewater to be possible, further treatment is likely to be necessary prior to recharge, either conventional treatment, or within the MAR scheme / unsaturated zone, to meet the current EU Groundwater Directive regulations, mainly due to ammonium ion concentrations of 3.92 ± 1.59 mg/l (reported in Moreira et al. (2022) for Faro Noroeste) significantly in excess of the threshold value of 0.5 mg/l shown in Table 5-2). In future there may be further opportunities for MAR due to a mismatch between irrigation demand and wastewater production, particularly in the winter period, and this could provide opportunities for MAR to store wastewater seasonally for reuse during the peak summer demand, if water quality challenges can be overcome.

However, presently the most appropriate use of treated wastewater in the Algarve is likely to be as a direct replacement for groundwater-fed irrigation of crops, green spaces and golf courses, particularly in the areas of few water supply alternatives (e.g., Campina de Faro).

5.3.4 Greenhouse Runoff

A recent study identified the potential water available for recharge from intercepting greenhouse roof runoff and recharging the Campina de Faro aquifer (Costa et al., 2020) for the purpose of reducing groundwater nitrate concentrations by dilution. The study identified greenhouses located within 150 m of an existing large diameter well (to recharge the aquifer), concluding that 1.51 Mm^3/year of rainwater could be harvested from a total greenhouse surface of 2.21 km^2 and recharged by existing wells.

The effect of injecting this volume in the aquifer was estimated using a numerical groundwater flow and transport model. Results show improvement in nitrate concentrations in the study area, in certain locations decreasing up to 70 mg/l by 2027. The model results (of Costa et al., 2020) predict a decrease in the number of nitrate threshold exceedances in observation points, from 33 to 30 by 2027 and 14 to 9 by 2040, but the measure on its own is insufficient to enable good qualitative status to be met.

A re-analysis of the data indicated the estimated capture of greenhouse runoff for the other aquifers as shown in Table 5-4. This shows that the water availability is only significant as an aquifer scale resource in and surrounding the Campina de Faro, including M10 and M11 where 2.87 Mm^3 could be available on average.

Table 5-4 Number of greenhouses (in use and abandoned) and their total area by aquifer

Aquifer	Code	Greenhouse Area (m^2) (in-use and abandoned)	Number	Estimated Intercepted Rainfall (Mm^3/yr)
Campina de Faro	**M18+M19**	**2,919,838**	**147**	**1.737**
S. João da Venda - Quelfes	**M10**	**1,451,453**	**131**	**0.863**
Querença-Silves	M5	442,865	41	0.263
Almancil - Medronhal	M9	423,201	26	0.252
Chão de Cevada - Quinta João de Ourém	**M11**	**382,002**	**28**	**0.227**
Quarteira	M7	359,924	12	0.214
Mexilhoeira Grande - Portimão	M3	169,674	2	0.101
Almádena - Odeáxere	M2	144,939	8	0.086
Luz - Tavira	M15	130,463	29	0.078
Ferragudo - Albufeira	M4	68,694	8	0.041

Aquifer	Code	Greenhouse Area (m^2) (in-use and abandoned)	Number	Estimated Intercepted Rainfall (Mm^3/yr)
S. Bartolomeu	M16	40,264	3	0.024
S. Brás de Alportel	M8	31,882	2	0.019
Peral-Moncarapacho	M13	26,402	7	0.016
Albufeira - Ribeira de Quarteira	M6	25,826	7	0.015
Malhão	M14	1,077	1	0.001

To achieve the water resource benefit, widespread participation in such schemes would be needed. This would involve significant effort in terms of stakeholder engagement, grants or incentives for participation, and perhaps a water-banking initiative where users pay less for their groundwater by offsetting the amount of rainfall recharged on a similar, but smaller scale to that implemented in Arizona (Megdal et al., 2014).

There is no regional information on rainwater quality, or on the water quality of runoff from greenhouse roofs. The water quality of the runoff is dependent on many factors, including roof material and physical condition, inclination, exposure and location of the roof, rainfall intensity and water quality and chemical properties of the parameter (Meera and Mansoor Ahammed, 2006). Generally, it is expected that water quality will be suitable, although it is sometimes necessary to capture and discharge the first-flush, usually the first 2 and 6 mm of rain during the wet season (Meera and Mansoor Ahammed, 2006).

5.3.5 Summary

The characteristics of the potential water sources for MAR can be summarised in Table 5-5. The sources of water have very different characteristics in terms of their availability. Wastewater is available year-round, with a slight peak in summer due to increased water use, whilst river flow and rainfall harvesting are available seasonally during the winter. Dam overflow appears unlikely to be available and may only occur less than once every 20 years.

Total quantities likely to be available for capture for MAR are highest for the ephemeral rivers, where if only 10 to 20% of the annual average flow was captured, 13 – 26 Mm^3/yr could be recharged, whilst for greenhouse runoff, assuming only 50% of the available volume could be recharged, would only result in 1.4 Mm^3/yr. Availability of wastewater is higher (18.5 Mm^3/yr), but a preferable alternative use exists (direct reuse for irrigation).

Table 5-5 Summary of main characteristics of the potential water sources for MAR

Source of water	Further treatment requirements	Availability (days per year)	Total quantities (% available for MAR) (Mm^3/yr)	Locations	Selected for further consideration?
River flow	Pre-settlement	60 – 150	128 (10-20%)	12 locations distributed across Algarve	Yes
Dam overflow	Pre-settlement	< once every 20 years	70	M5, downstream of Odelouca, Arade and Funcho dams	No, water availability unlikely and significant cost and engineering challenges to overcome.
Treated wastewater	Yes, tertiary treatment	365	37 (50%)	7 main locations close to centres of population	No, irrigation with wastewater is the more sensible use of this water to meet the same objectives
Greenhouse Runoff	Pre-settlement	60 - 150	2.9 (50%)	M10 / M18	Yes, given lack of alternative sources of water for these aquifers

Based on considerations of the timing and duration of water availability, quantity, and quality, and consideration whether MAR would be the most appropriate use of the water, only ephemeral river flow and greenhouse runoff are considered to be suitable for MAR in the Algarve at this stage.

If MAR with these water sources was found to be successful, but limited by water availability, a second stage could be considered, using treated wastewater, perhaps where generated during the winter (and not needed for direct irrigation). However, this would be difficult to achieve without expensive tertiary treatment, or significant changes to the implementation of the WFD regulations.

5.4 Suitable MAR Methods

Selection of appropriate MAR technique requires detailed consideration of the local hydrology, hydrogeology, aquifer type, topography, soil zone and unsaturated thickness, land use, native groundwater quality and intended use of recovered water.

5.4.1 Geology and hydrogeology of the coastal Algarve aquifers

The hydrogeology of this region has been studied systematically since the 1980's as described in Section 2.1. A summary of the relevant findings to selection of appropriate MAR methods is provided here.

The coastal aquifers are comprised of Mesozoic and Cenozoic rocks of two superimposed sedimentary basins, and are shown on Figure 5-2. Mesozoic rocks date from Upper Triassic to Lower Cretaceous and were deposited in a basin developed in a trans-tensional regime related to the opening of the Tethys Sea and the Central Atlantic Ocean (Terrinha, 1998). The Cenozoic basin was formed by flexural processes associated with the collision of Africa and Iberia and involved deposition of sediments of Miocene age and younger (Terrinha, 1998). The northern part of the Algarve is comprised of Palaeozoic basement rocks, flysch sequences of slates and greywackes that were folded and faulted during the Variscan orogeny and are not considered to be major aquifers (soco paleozóico on Figure 5-2).

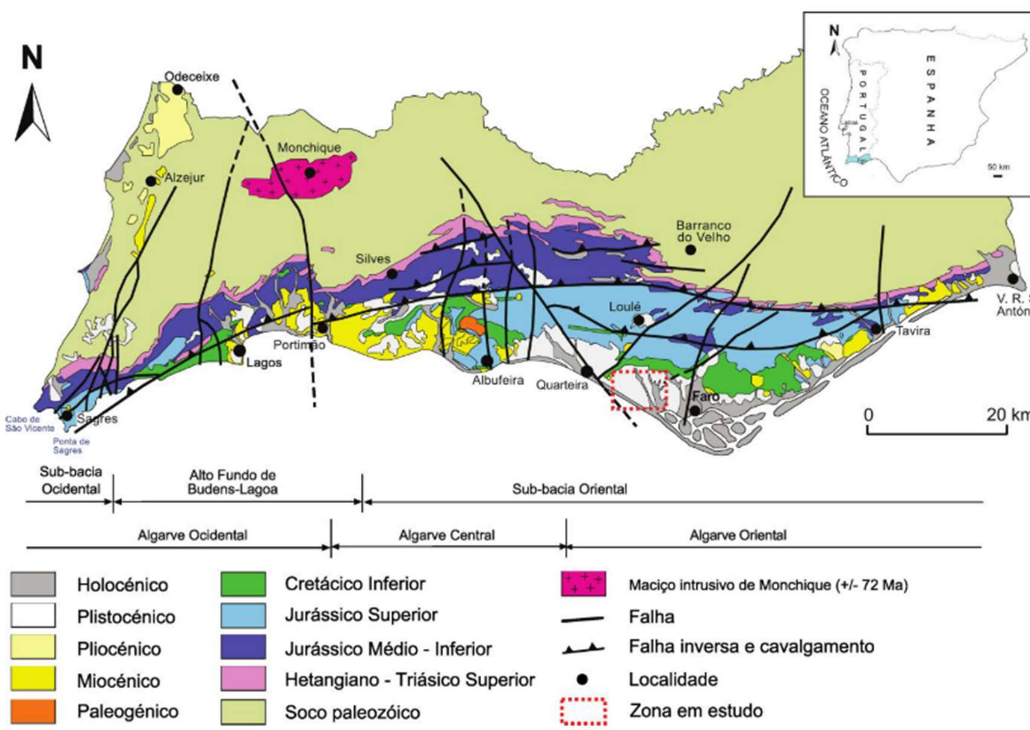


Figure 5-2 Simplified geology of the Algarve region, showing location of case study area (Chapter 7) adapted from Manuppella et al, 1988; Oliveira et al, 1992; Terrinha, 1998; and Lopes, 2006.

From oldest to youngest, the aquifers of the Algarve are formed by the following sediments:

- Lower to Upper Jurassic sediments (Lias and Dogger formations) include dolomites, limestones and marls of variable permeability and karstification, forming many of the Algarve aquifers (M2, M5, M8, M9, M13, M14), and part of M3, M6, M7, M13 aquifer units. They have favourable hydraulic properties and are at outcrop over a large extent. In part, their porosity and permeability characteristics are due to are due to secondary dolomitization processes that have affected a large part of these formations (Almeida et al., 2000).
- Cretaceous formations produce lower flows than Jurassic limestone and dolomite formations, although they are of some importance especially when they are thicker and more extensive, i.e., where they form the M10 aquifer, and parts of the M15, M18 and M19 aquifers at depth. Some limestone and dolomite layers of the lower Cretaceous (Lagoa) and upper Cretaceous (crystalline limestones of the Pão Branco and Chão de Cevada dolomites) can produce large flows, similar to those produced by Jurassic limestones, although their outcrop extent is much smaller (Almeida et al., 2000).
- The Miocene formations comprise sandy limestones / biocalcarenites and are also of importance to water supply, particularly the Lagoa-Portimão formation which forms the M4 aquifer and part of the M3, M6, M7, M15, M18 and M19 aquifers. This unit is important at depth, where it is overlain by Plio-Quaternary deposits particularly in the Campina de Faro aquifers (M18 & M19).
- Plio-Quaternary deposits may be up to 70 m thick in places (Ludo-Montenegro), but are typically much thinner, form a superficial / phreatic aquifer in places. These deposits cover the irregular karst surface, and are often affected by subsidence or sudden collapse (Carvalho *et al.*, 2012). In general, the Ludo Formation consists of sandy sediments at the base with feldspars, mostly white, medium to coarse grained, and well sorted, especially at the base. They pass to metric benches of fine sand with overlapping of overlapping clays by dark red clay countertops. The dark red clay at the surface tend to limit direct recharge through these sediments. They form minor aquifers, which are locally important in the Campina de Faro (M18 and M19 aquifer units).

A further potential aquifer has been identified, hosted in Pliocene sediments, the Areias, arenitos e cascalheiras do litoral do Baixo Alentejo (sands and gravels of the littoral region), located to the south of Odeceixe. These sediments overlie basement rocks in a shallow basin setting, and are expected to form an aquifer, similar to those found further north (Soares Lima, 2020).

Holocene alluvial deposits are also found along and surrounding the riverbeds, and during investigations of the Rio Seco during the MARSOL project, were found to be ~7 m thick (MARSOL, 2016).

The extensional basin setting means that aquifer units generally increase in thickness towards the coast, often reaching several hundred meters in thickness, as shown in the conceptual cross section Figure 5-3.

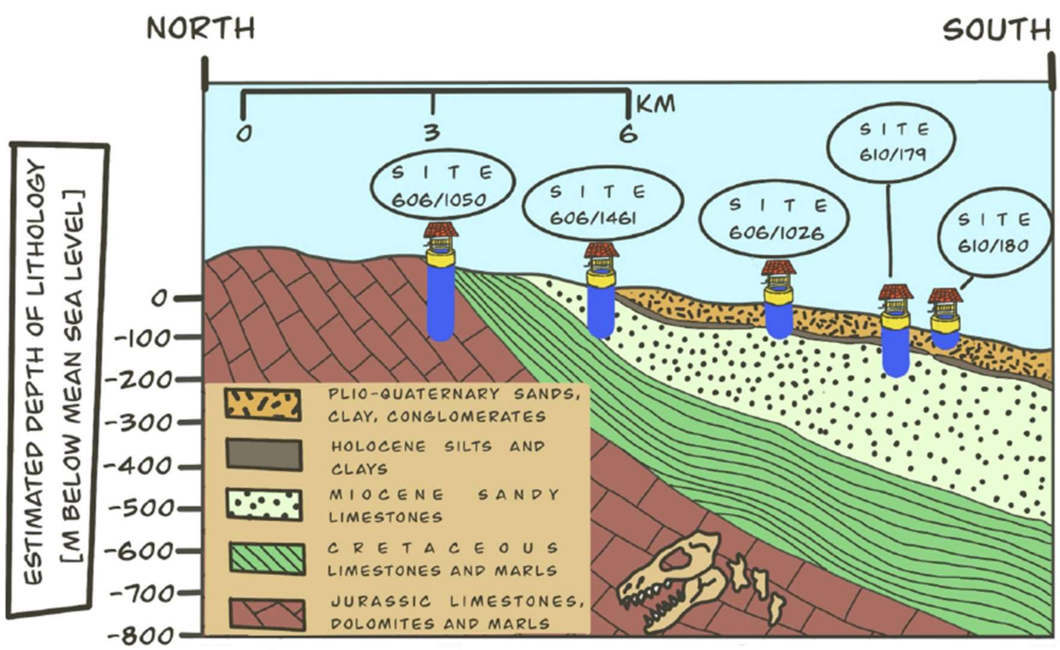


Figure 5-3 Conceptual cross section of the M19 aquifer (Juchem, 2021).

The presence and thickness of these units has been confirmed in offshore boreholes, where 20 km offshore at the Ruivo borehole, approximately 750 m of Pliocene and Miocene sands and limestones were encountered (Lopes et al., 2006). These were underlain by 150 m of Oligocene limestones (not found onshore), before a hiatus until the Lower Cretaceous units, with a thickness of approximately 200 m. Beneath these, over 1,000 m of Jurassic limestones are encountered to the base of the well. The Plio-Quaternary sediments also appear to extend offshore with over 300 m of Pliocene through to Quaternary sediments at the Corvina borehole (15 km southeast of Faro), but the onshore deposits (Ludo Formation) only form the upper part of this (Lopes et al., 2006).

Where the coastal aquifers of the Algarve are covered by PQ deposits, they are often recharged at depth from permeable aquifers of Jurassic age further north, and prior to exploitation for water supply, hydraulic heads were artesian in some places along the coast (e.g., Quarteira). Historically, the shallow aquifer hosted in PQ deposits was exploited by large-diameter shallow wells, which as demand increased, became dry, and were frequently over-drilled by rotary methods through the aquitard into the underlying Miocene aquifer.

There are several important faults and structural features, often forming boundaries between the aquifer units, including:

1. The Carcavai fault zone, a NE–SW trending outcropping structure extending between S. Brás de Alportel (North) and Quarteira (south), with a total length of about 20 km, presenting left-lateral strike-slip fault geometry with reverse component, and separating the Campina de Faro aquifer from the M7 (Quarteira) aquifer to the west, and M8 (Almansil-Medronhal) to the north (Carvalho et al., 2012).
2. The São Marcos-Quarteira fault, which separates the M6 aquifer to the west from the M7 (Quarteira aquifer) to the east, and is aligned with the course of the Ribeira de Quarteira (Carvalho et al., 2012).

The estimated unsaturated zone thickness across the coastal aquifers of the Algarve is shown in Figure 5-4, based on average groundwater levels measured between September and November 2020 at the monitoring locations also shown on Figure 5-4. Given the importance of geological structure, interpolation between aquifers may not be accurate, and where water level measurements are from deeper aquifers, these values may represent the difference between ground level and the hydraulic head, where the aquifers are confined.

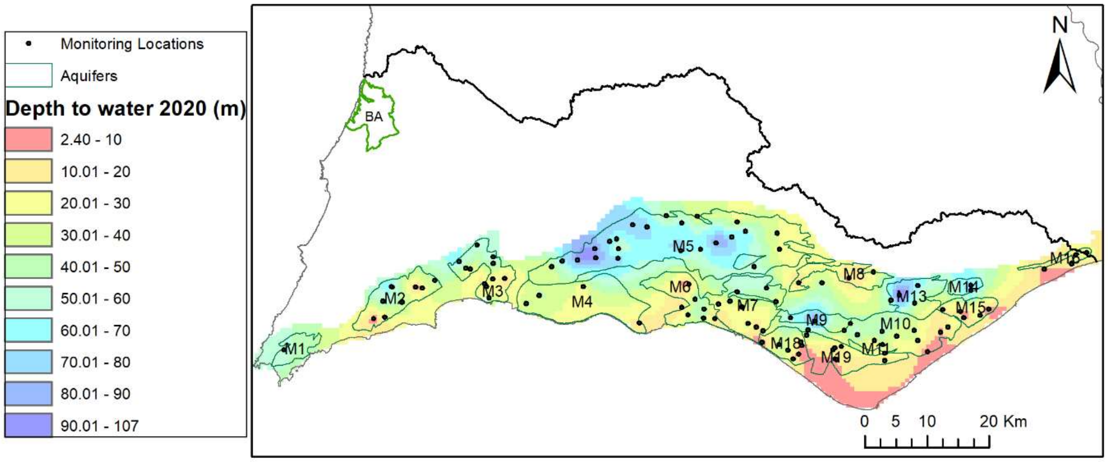


Figure 5-4 Unsaturated zone thickness based on October 2020 groundwater levels, compared to the aquifers considered for MAR described in Chapter 6.

Despite these limitations, Figure 5-4 indicates that large unsaturated zone thicknesses exist, regularly exceeding 60 m in the karstic limestone aquifers (M5, M9, M13, M14 and M5). The unsaturated zone is rarely less than 10 m except in small parts of M18, M18, M15 and in the area to the east of Tavira. The coastal aquifers formed (or partly formed) from Miocene sandy limestones typically have unsaturated zone thicknesses of 10 – 40 m). No groundwater monitoring data is available for the area south of Odeceixe, but this superficial aquifer of sands and gravels is likely to have limited unsaturated zone thickness.

5.4.2 Implications for MAR methods

As described in Section 5.4.1, the geology and hydrogeology is complex, giving rise to a range of aquifer types. Except for the PQ and Pleistocene sediments, all the aquifers of the Algarve are known to have significant secondary permeability, often with Karst features. The aquifers formed only of Jurassic-age carbonates (M2, M5, M8, M9, M13, and M14) may be expected to be unconfined aquifers, although the presence of lower permeability layers within these units may result in the need for MAR recharge to target specific horizons.

Where the aquifer units are formed by Miocene and/or Cretaceous units, overlain by PQ sediments, these are known to give rise to semi-confined aquifers, as the weathered clays at the top of the Miocene can result in limited hydraulic connection with the overlying PQ. This includes the aquifer units M3, M4, M6, M7, M15, M18 and M19 aquifers. The majority of abstraction is now from the Miocene and/or Cretaceous units of these aquifers, therefore MAR recharge would be needed at depth.

The potential for surface infiltration methods is limited to areas where recharge is required to shallow aquifers, where water levels are close to the surface, such as the area east of Tavira (Miocene / PQ sediments at surface) and the shallow sedimentary deposits of the Baixo Alentejo area, south of Odeceixe (Figure 5-4).

5.4.3 Selected MAR methods

Therefore, based on the information presented in Section 5.4.1 and 5.4.2, an initial assessment of the suitability of MAR methods for the Algarve region is presented in Table 5-6.

Table 5-6 Types of MAR methods (IGRAC, 2007) and preliminary assessment of their suitability in the Algarve Region

Type of MAR method	Specific MAR methods	Preliminary assessment of suitability in the Algarve Region
Spreading methods	Infiltration Ponds	Yes*
	Flooding	Very limited potential as main crops cannot tolerate roots being submerged
	Ditches and furrows	Yes*
	Excess irrigation	Already unintentionally occurring in Luz-Tavira aquifer
Induced bank filtration	River/lake/bank filtration	No, usually used to improve quality of river water for potable use, not a MAR objective here
	Dune filtration	
Well, shaft and borehole recharge	Aquifer storage and recovery (ASR)	Yes*
	Aquifer storage, transport and recovery (ASTR)	Yes*
	Shallow wells / shaft / pit infiltration	Yes*
In-channel modifications	Recharge dams	Yes*
	Subsurface dams	No, aquifer thickness too large for this to be technically feasible
	Sand storage dams	No, specific high energy river environment needed, usually situated on impermeable strata
	Channel spreading	Yes*
Runoff harvesting	Rooftop rainwater harvesting	Yes*
	Barriers and bunds	Yes*
	Trenches	Yes*

*Yes, subject to site-specific assessment of technique suitability and assessment and management of risks

Recharge wells or boreholes are often used for MAR, particularly in multi-layered systems to allow recharge to specific aquifer units at depth, or where sediments have low permeability at the surface. Whilst they avoid losses due to re-wetting of the unsaturated zone, they also provide a direct pathway for the recharge to reach groundwater. This is an advantage providing that the source water quality is appropriate. Recharge boreholes are often used in Aquifer Storage and Recovery (ASR) or Aquifer Storage, Transport and Recovery (ASTR) schemes, where recovery efficiencies (the percentage of recharged water that can be recovered with acceptable water quality) often reach 90%. ASR is often used to develop a bubble of good-quality water in an aquifer of poorer water quality, by managing the recharge and recovery to maintain acceptable water quality on re-abstraction. Often these schemes are developed in deep confined aquifers, that are not usually used for other purposes, and recharge may occur for several years before the water is used during a severe drought period (e.g., North London and Horton Kirby (UK) described in Section 3.3.2).

Recharge boreholes / well have broad applicability, given their relative ease of construction and their relatively small land requirements compared with spreading methods, although land for pre-settlement is still required to avoid borehole clogging. Gas clogging also needs to be mitigated against by avoiding free falling water into the borehole, and recharge via a dedicated recharge pipe installed to below the water level in the borehole. Although MAR infrastructure is usually designed and constructed specifically for this purpose, the Los Arenales scheme also makes use of existing boreholes and wells that have been abandoned to reduce infrastructure costs. This is likely to be possible in the Algarve, as shallow aquifers were historically (and currently) exploited using large-diameter wells (known as poços), of which hundreds are documented in the inventory. For a typically constructed poço (~20m deep, 4.5 m diameter, static water level 10 m below ground level), pumping tests indicate a recharge rate of 2,500 m^3/d could be achieved for a single well (Costa et al., 2020). Recharge by these existing wells could reduce the land required for infiltration basins significantly.

Some of the largest MAR schemes in the world use spreading methods, such as infiltration basins, such as Santa Ana River (Hutchinson and Woodside, 2021), and Menashe, Israel (Kurtzman and Guttman, 2021), whilst Los Arenales uses both infiltration basins and trenches / canals for recharge (Fernández-Escalante and Sauto, 2021). Infiltration trenches filled with porous material and buried beneath the surface were used successfully in the Walla Walla basin in Washington state, USA, where surface water was used as the recharge source from canals, achieving recharge rates as high as 3974 m^3/d with a 100 m^2 gallery (Bower, 2011, in Godwin et al (2022)).

Where these schemes use a river source, they typically require an abstraction from the river, and transmission either by gravity or by pumping firstly to a pre-settlement basin to remove the sediment load, before flowing into an infiltration basin. At the abstraction point on the river, a small dam may be required to maintain suitable water depth for the pumps / transfer pipework to operate.

Spreading methods are not limited to engineered basins. Purposeful excess irrigation is now referred to as Ag-MAR or Flood-MAR. Ag-MAR is an emerging MAR technique using agricultural fields as infiltration basins to recharge the underlying aquifers (Ganot and Dahlke, 2021), and is a specific technique for MAR rather than an unintended consequence of excess irrigation. Ag-MAR flooding is preferable during fallow or dormant periods, when crop damage is potentially minimal, so agricultural lands can serve as spreading basins for groundwater recharge. However, this technique is unsuitable for crops such as citrus, avocado, almond, kiwi, papaya and plum as they have almost no tolerance (0 to 48 hours) to their roots being under water (Ganot and Dahlke, 2021). Ag-MAR does pose several risks, in addition to crop tolerance to flooding, including soil aeration and changes in texture, biogeochemical transformations and leaching of pesticides and fertilizers to groundwater (Ganot and Dahlke, 2021). However, it appears that these challenges can be overcome by appropriate site selection, and Ag-MAR is currently being implemented in California (Faunt et al., 2016, Harter et al, 2015). Recent research has emerged from geophysical characterization coupled with unsaturated and saturated zone modelling of Flood-MAR of an almond plantation found that after 2 years of recharge, 37% of the water recharged was held in the unsaturated zone, and not available to plants or to abstraction wells (Perzan et al., 2022). This has important consequences for the success of Ag-MAR or Flood-MAR schemes, and for the success of infiltration basins where the unsaturated zone is relatively thick (10-40 m).

Based on the results of the literature review (Chapter 2) and the meta-analysis of in-channel MAR in Chapter 3, the following recharge methods are the most appropriate for the Algarve and will be considered in the identification of potential MAR schemes in the Chapter 6:

- Spreading methods e.g., off-line infiltration basins or trenches
- Boreholes
- Re-using existing large-diameter wells (poços)

5.5 MAR scheme costs

Costs for MAR can be assessed using the net present value methodology for assessing the economic feasibility of MAR systems as described by Maliva et al. (2014), who identified that for drinking water supplies, typical MAR costs are about half that of brackish water desalination. The benefits of MAR can be assessed based on benefit cost ratios (BCR) where benefits can be considered based on the costs of the next best alternative source of water or water treatment process, and the value of production using MAR water (Ross, 2021).

Schemes using infiltration and spreading basins using untreated water are cheaper in comparison to those employing recharge wells / boreholes. Where additional advanced water treatment is required, significant extra costs are incurred (Ross and Hasnain, 2018). A study of 21 MAR schemes from 5 countries found levelized cost to be the most appropriate measure for comparison, as it amortises capital costs and operating costs over the volume supplied through the life of the scheme. A summary of the costs by MAR scheme type and water source based on costs from a range of sources is shown in Table 5-7.

Table 5-7 MAR Scheme Capital, Operational, Maintenance and Levelised Costs from existing case studies

MAR scheme type / water source	Capital cost / m³ recharged	Operational and maintenance cost / m³ recharged	Levelised cost (US$ / m³ recharged	Source
Recharged wells / recycled water (N=4)	$ 8.07	$ 0.53	$1.16	Ross & Hasnain (2018)
Infiltration basins / recycled water (N=3)	$ 11.41	$ 0.84	$ 1.89	Ross & Hasnain (2018)
Recharge wells / natural water (N=5)	$ 3.29	$ 0.19	$ 0.45	Ross & Hasnain (2018)
Infiltration basins / natural water (N=8)	$ 0.77	$ 0.13	$ 0.19	Ross & Hasnain (2018)
Natural water wells and infiltration basins (N=11)	-	-	$0.16 (average) $ 0.06 (stdev)	Ross (2021)
Los Arenales infiltration basin & canals with river water	€ 2.19 /m³/yr	-	$ 0.21	Fernández-Escalante & San Sebastian Sauto (2021)
Borehole resilience / drought schemes (N=3)	$ 2.06 /m³/yr	-	-	Ross (2021)

Costs for MAR schemes (using river/storm water) recharging by infiltration and spreading basins are cheaper in comparison to those using recharge wells / boreholes (Ross and Hasnain, 2018). MAR schemes using natural water sources and recharge wells were found to have average levelized costs of $ 0.45/m^3 based on 5 schemes, compared to an average of

$0.19/m^3 for infiltration basins, based on 8 schemes (Ross and Hasnain, 2018). The Los Arenales MAR scheme in Castille y Leon, Spain, is probably the most similar in terms of location and MAR type to those proposed in the Algarve (Fernández-Escalante and San Sebastian Sauto, 2021). The estimated levelized cost of this scheme is $0.21/m^3.

Levelised costs for the demand and supply measures of the RWEP described in Section 2.4 are not available. Therefore, cost comparison will be based on capital costs divided by the average water resource benefit in €/m^3/yr. The most suitable scheme to base the estimated MAR costs on is that of Los Arenales, which recharges on average 2.4 Mm^3/yr for a capital cost of 5.27 M€, i.e., a cost of **2.2 €/m^3/yr**. The size of the scheme is similar to those identified for the Algarve, it is expected that land purchase costs would be considerably higher, whilst the length of the transfer from the river to the recharge locations is expected to be much shorter. Nevertheless, this provides a good indication of the expected costs for the schemes involving infiltration basins. Those schemes requiring recharge by borehole are expected to be slightly more costly, but in many cases, these could be reduced by re-using existing boreholes / wells, therefore the same costs were assumed.

Although at a preliminary stage of estimation and not the main focus of this thesis, MAR costs (2.2 €/m^3/yr) compare favourably to those in the RWEP, where the 57 short-medium term measures of the RWEP to generate / save 33 Mm^3/yr cost on average 6 €/m^3/yr, reuse of treated wastewater directly for non-potable uses has an estimated cost of 2.6 €/m^3/yr, and rehabilitation of irrigation networks is estimated to cost 4 €/m^3/yr. Costs for desalination are understood to be significantly higher still.

5.6 Summary

It is assumed that water quality must meet the requirements of the Groundwater Directive (Table 5-2) therefore only ephemeral river flow and greenhouse runoff are suitable for MAR in the Algarve without significant further treatment and associated increases in cost. MAR with these sources has a lower unit cost than almost all the alternative water supply or demand saving measures. The quantities of water for greenhouse runoff are well documented by Costa et al., (2020), however ephemeral river flow is highly uncertain and estimation of these flows and quantities available for MAR is one of the key foci of this thesis. The suitability of MAR methods is highly site-specific, and in the Algarve the most suitable methods are considered to be infiltration basins / trenches, recharge boreholes and re-use of existing poços.

In the following Chapter (Chapter 6), individual schemes are developed using ephemeral river flow as the source of water for MAR, and the water available and aquifer capacity are estimated to quantify the regional water resource benefit of MAR.

Chapter 6: Quantifying MAR Potential in the Algarve

This Chapter presents a regional study that quantifies water available for recharge from ephemeral rivers under recent baseline conditions and climate change scenarios and assesses the capacity of the adjacent aquifer(s) to accept and store this water. Potential MAR objectives were identified based on the current water resource system, developing individual MAR options in sufficient detail to allow their comparison with the measures proposed in the RWEP in terms of their water resource benefits and preliminary costs.

This chapter is based on the published manuscript:

Standen, K., Costa, L., Hugman, R., & Monteiro, J. P. (2023). Integration of Managed Aquifer Recharge into the Water Supply System in the Algarve Region, Portugal. Water, 15(12), 2286. https://doi.org/10.3390/w15122286

And the technical report:

Standen, Kath., Monteiro, José Paulo., Costa, Luís R.D. Deliverable 4.2: Opportunities for MAR to improve the River Basin Management Plan of the Algarve Region, Portugal. MARSoluT ITN Project, submitted February 2023.

6.1 Introduction and objectives

The objective of this Chapter is to quantify the regional potential for MAR in the Algarve region, respecting the current legislation. Four main aspects are included:

- Quantifying the water available for MAR under recent baseline conditions and future climate change;
- Assessing the source water quality against the groundwater threshold values;
- Identifying objectives and need for MAR; and
- Estimating the aquifer capacity for MAR

The results of these tasks were combined to produce preliminary designs of MAR schemes, to quantify the potential regional water resources benefit of MAR. Finally, the MAR options were compared to water resources options already documented, or under consideration, in terms of costs and benefits.

6.2 Study Area

The Algarve water resources are discussed in detail in Chapter 2, where the key features of the water resources system within the study area were outlined. Of particular relevance are the four public irrigation perimeters supplied by surface water from Bravura (Alvor), Arade (Silves, Lagoa e Portimão), Odeleite-Beliche (Sotavento) and the Santa Clara dam in Alentejo (Mira in RH8) are shown in Figure 6-1.

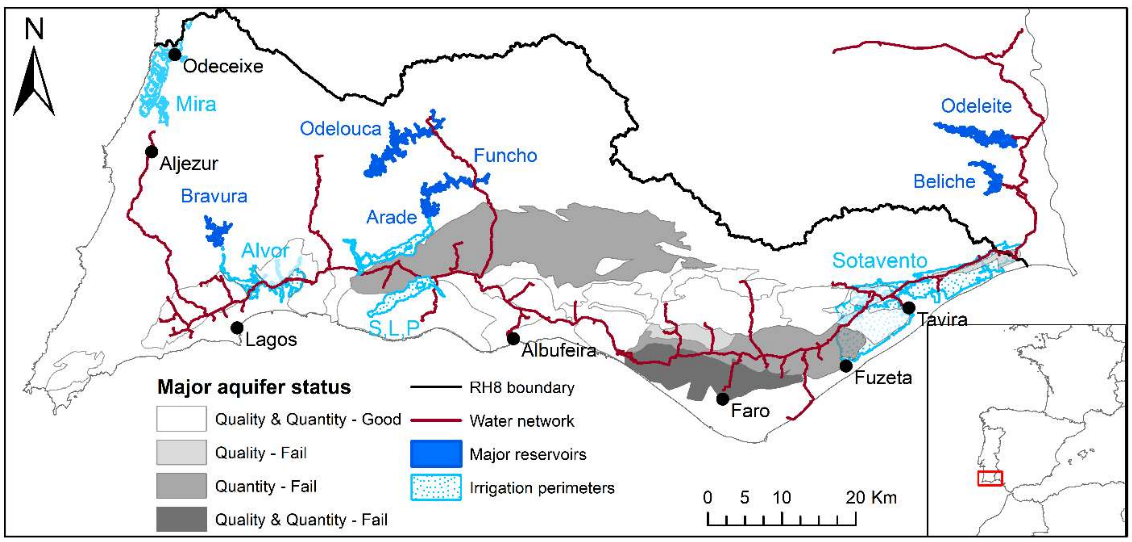


Figure 6-1 Algarve region showing the locations of key surface water reservoirs and the multi-municipal water supply network along with aquifers and their proposed status under the 3rd River Basin Management Plan, and the surface water-fed irrigation perimeters.

The ephemeral rivers identified for MAR were shown in Figure 5-1 and Table 5-3 along with their estimated annual river flows. Long term average rainfall is 628 mm/yr, and potential evapotranspiration almost double this at 1210 mm/yr (APA, 2022).

Future climate for the Algarve region was estimated using the EURO-CORDEX Regional Climate Models and RCP scenarios and indicates that annual rainfall is predicted to decrease by >20%, mostly during the spring, summer and autumn periods, with a 30% reduction in wet days under the RCP8.5 scenario (Soares et al., 2017). However, relative precipitation changes at the 95th and 99th percentiles indicate an increase of 10-20% and 20-70% respectively, indicating an increase in extreme, high intensity events are predicted. Over the same period and scenario, the change anomaly for temperature is almost 3.5 °C, with an associated increase in potential evapotranspiration of 150 mm/yr(IPMA, 2022), which will potentially have a large impact on ephemeral flows.

The major aquifers found along the coast of the Algarve region (Figure 6-1) were formed during two phases of extension of a meso-Cenozoic basin, forming aquifers that include karstic and fractured limestones of Jurassic age, permeable limestone units of the Lower Cretaceous, sandy limestones of Miocene age, and sands and gravels of Plio-Quaternary age. These form multi-layer aquifers both within and across units, separated by lower permeability weathered clays and silts. Along the coast, the connectivity between the aquifer units is often disconnected by a series of faults perpendicular to the coast, forming several relatively small aquifers (12 to 117 km^2) with similar hydro-stratigraphy (Almeida et al., 2000). To the north of the sedimentary basin limit, hard rocks (schists and greywackes) with low permeability are found, generating the river flows captured by the major reservoirs.

6.3 Methods and Data

6.3.1 Preliminary identification of potential MAR schemes

Catchments upstream of potential aquifers with areas >20 km^2 were identified, excluding those where the flow is already captured by a large surface water reservoir. Aquifers were identified based on the groundwater bodies defined in the RBMP, and MAR objectives were identified based on the current groundwater / surface water supply pressures in the surrounding area (largely based on the Regional Water Efficiency Plan (APA, 2020)).

All identified MAR schemes were assumed to require a river abstraction/intake to the MAR scheme, transfer pipework to the recharge site, preferably under gravity, and pre-settlement basin to reduce suspended sediment prior to recharge. Recharge infrastructure will be site-specific, not only in terms of the recharge method, but also the number, size and design of these elements, based on the geology and hydrogeology at site and aquifer capacity. It is assumed that MAR schemes will not operate when river flows fall below a minimum environmental flow (but this is unknown at this stage), and their maximum capacity will be limited by the design capacity of the MAR infrastructure (i.e., no intermediate storage will be provided). Recovery infrastructure will also be necessary. In some cases, boreholes can be used for both recharge and abstraction, otherwise separate infrastructure will be needed to abstract the water and route into the network.

6.3.2 Rainfall runoff modelling

6.3.2.1 GR4J Model

Rainfall-runoff modelling was undertaken for selected catchments to extend the measured flow timeseries and to enable estimation of climate change impacts on river flow and availability of water for MAR.

The GR4J model is a daily lumped four-parameter rainfall-runoff model, belonging to the family of soil moisture accounting models (Perrin et al., 2003). The GR4J model has been in use for over 20 years and continues to be widely used (Mathevet et al., 2020; Sauquet et al., 2021).

The model structure is presented in Figure 6-2[2] after Perrin et al., (2003). The model takes catchment average rainfall depth, *P* (mm), and potential evapotranspiration, *E (mm),* as inputs to the model, and estimates daily river flow, *Q* (mm). This data was obtained from the ERA-5 Land dataset (Muñoz-Sabater et al., 2021) on a 9 x 9 km grid, from which catchment average *P* and *E* were calculated.

The model first determines net rainfall by subtracting *E* from *P*, or calculates a net evapotranspiration capacity P_n. When P_n is greater than zero, P_s fills the production store, where the first adjustable parameter (x_1) governs the maximum capacity of this store. Water is lost from the production store by evaporation and by percolation leakage, which is calculated as a power function of the store content.

Linear routing with unit hydrographs is undertaken on P_r, the total water percolating from the production store, and of the flow component not routed through the production store (P_n – P_s). This flow is split 90% to unit hydrograph 1 (*UH1*), and 10% to unit hydrograph 2 (*UH2*), and these simulate the time lag between the rainfall event and the resulting streamflow peak. Both unit hydrographs depend on the same time parameter (x_4), expressed in days (real values >0.5 days).

A groundwater exchange term, *F*, acts on both the UH1 and UH2 flow components, and is calculated based on the level of the routing store, its reference capacity, and water exchange

[2] Reproduced from: https://webgr.inrae.fr/en/models/daily-hydrological-model-gr4j/

coefficient (x_2). The capacity x_3 represents the one day ahead maximum capacity and is used to simulate long streamflow recessions where necessary.

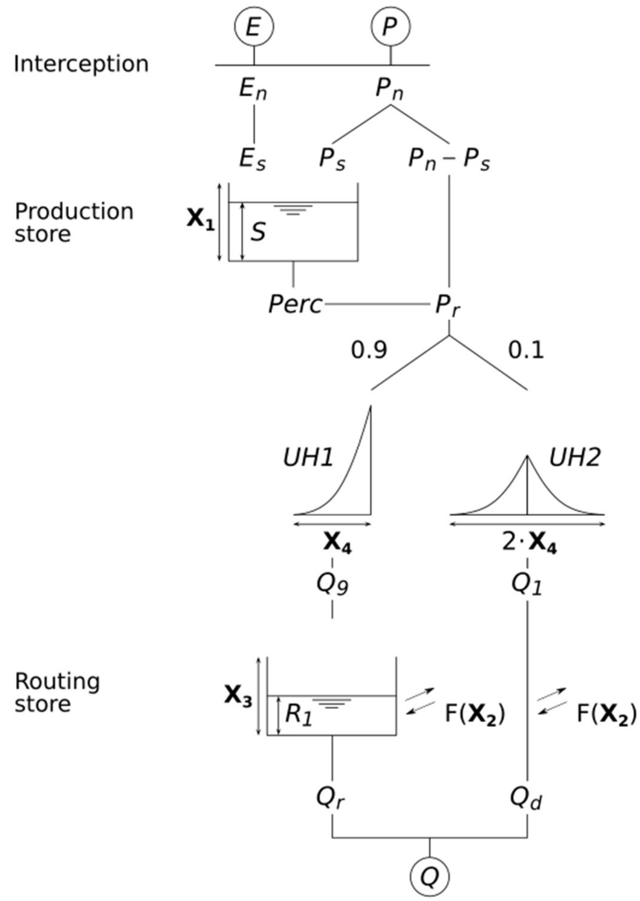


Figure 6-2 GR4J Model Schematic.

Thus, the model has four adjustable parameters:

x_1 is the maximum capacity of the production (SMA) store (mm);

x_2 is the groundwater exchange coefficient (mm);

x_3 is the one day ahead maximum capacity of the routing store (mm); and

x_4 is the time base of the unit hydrograph (in days).

All four parameters are real numbers. x_1 and x_3 are positive, x_4 is greater than 0.5 and x_2 can be either positive, zero or negative.

For all the modelled catchments, measured river flow data is publicly available (SNIRH, 2021), with records of variables lengths, with data collection ending by 2008.

6.3.2.2 Uncertainty analysis

An estimate of predictive uncertainty of modelled river flows is needed, particularly when considering the costs of implementing MAR. Stochastically sampling to obtain the posterior parameter distribution using Markov-chain Monte-Carlo (MCMC) methods can be computationally expensive, therefore for this regional study, the iterative ensemble smoother (Chen and Oliver, 2013) implemented in PESTPP (White, 2018) was used in a similar way to Bennett et al. (2021) who used PESTPP IES with the Sacramento rainfall-runoff model (19 flexible parameters) finding IES to be an efficient and powerful method for conditioning model parameters and providing robust uncertainty analysis in the spirit of Bayesian statistics. Each realization starts as a sample of the prior probability distribution, being conditioned to become a sample of the posterior probability distribution. The model is only evaluated once for each member of the ensemble.

Prior parameter probability distributions were based on those reported in from a study of over 400 catchments (Perrin et al., 2001). Measurement noise was added to the observations using a standard deviation (SD) of 0.1 at flows ≤ 1 m^3/s, increasing to a SD of 1 for flows > 9 m^3/s, based on the variation in river stage vs. river flow data for catchment 29E/01H.

6.3.3 MAR methods and aquifer capacity

As the results of the meta-analysis (Chapter 4) indicated that in-channel MAR was unlikely to provide the water resource benefits needed in the Algarve, a wider range of MAR methods has been considered here including spreading methods, such as infiltration basins or trenches, and boreholes/wells. In general, spreading methods are more suitable where permeability at the surface is high, the aquifers are unconfined and the water table is relatively shallow, to avoid excessive losses in rewetting of the unsaturated zone (e.g., Perzan et al 2022). Boreholes / wells are usually suitable for all types of aquifers, but particularly where recharge at depth to a specific aquifer unit is required. Reuse of existing large-diameter shallow wells, known as poços, could be suitable particularly where recharge to an unconfined, shallow aquifer is needed.

Information on aquifer properties is limited (particularly for storativity or specific yield) to pumping tests (Almeida et al., 2000; Costa et al., 2020), analysis of operational data using the Logan method (Logan, 1964) from pumping water levels and abstraction rates, and values from calibrated groundwater models (Hugman, 2009). For each of the potential MAR schemes, a broad location within the aquifer was selected for recharge based on the river location and location of the proposed MAR water use. The appropriate aquifer properties, groundwater levels and ground elevations were then identified for that area to determine the unsaturated zone thickness.

For MAR by boreholes or wells, the borehole design recharge rate can be defined as the maximum volume of water that can be recharged into an aquifer via a borehole at a constant rate for a given time and borehole design (radius), constrained by the maximum allowable hydraulic head change. In a similar way to (Shandilya et al., 2022), this is assessed with the Theis equation:

$$s(r,t) = H_0 - H(r,t) = \frac{Q}{4\pi T} W(u), \text{where } u = \frac{r^2 S}{4Tt} \qquad \textbf{\textit{(1)}}$$

Where *s* is the drawdown at radius, *r* (m) from the pumping borehole, at time, *t* (days) H_0 the hydraulic head before pumping, *S* the aquifer storage coefficient, *T* the transmissivity (m^2/d), and the Well Function, *W(u)* is the approximation to the exponential integral, $W(u) \approx -\gamma - ln(u)$ where $\gamma = 0.577215664$, the Euler-Mascheroni constant.

Under recharge, the maximum heads will occur at the borehole, and recharge rates can be constrained by a maximum head change (Δh_{max}). Although for deep confined aquifers, MAR can take place under pressure, for relatively small, shallow aquifers, especially where aspects of the hydrogeological conceptualisation are uncertain, this is not recommended due to the risks of groundwater flooding. Therefore, Δh_{max} is defined as the difference between the seasonal maximum in groundwater levels and the ground level (for a defined recharge duration and borehole radius):

$$\Delta h_{max} = \frac{Q_{bhmax}}{4\pi T} W\left(\frac{r^2 S}{4Tt}\right) \qquad \textbf{(2)}$$

Solving for Q_{bhmax} gives the design borehole recharge rate:

$$Q_{bhmax} = \frac{4\pi T \Delta h_{max}}{W\left(\frac{r^2 S}{4Tt}\right)} \qquad (3)$$

We assumed a maximum of 60 days continuous recharge (t = 60 days), and a borehole radius of 0.15m, considering drilling equipment typically available in the Algarve. Multiplying the borehole design recharge rate by the proposed number of boreholes provides a preliminary estimate of the design capacity of the MAR scheme (Q_{MAR}). The limitations of this method are that interference effects between recharge boreholes are not considered and it is assumed that the boreholes are location sufficiently far apart to limit interference.

For MAR by large-diameter wells (poços), the results of a step-injection test (Costa et al., 2020) was used, whilst for MAR by infiltration basins, the infiltration rate (1 m/d) was defined based on field trials in the Rio Seco catchment, in the absence of further data, where infiltration rates of 1 m/d were obtained (MARSOL, 2016), and Q_{MAR} defined based on an assumed surface area for infiltration and the infiltration rate.

6.3.4 Quantifying MAR Recharge

The concept of water available for MAR is demonstrated in Figure 6-3, where water can be captured from a river only once a minimum flow condition (i.e., an environmental constraint) is exceeded until the maximum design capacity of the proposed MAR scheme is reached. Flows above this level cannot be captured unless the design capacity (Q_{MAR}) is increased.

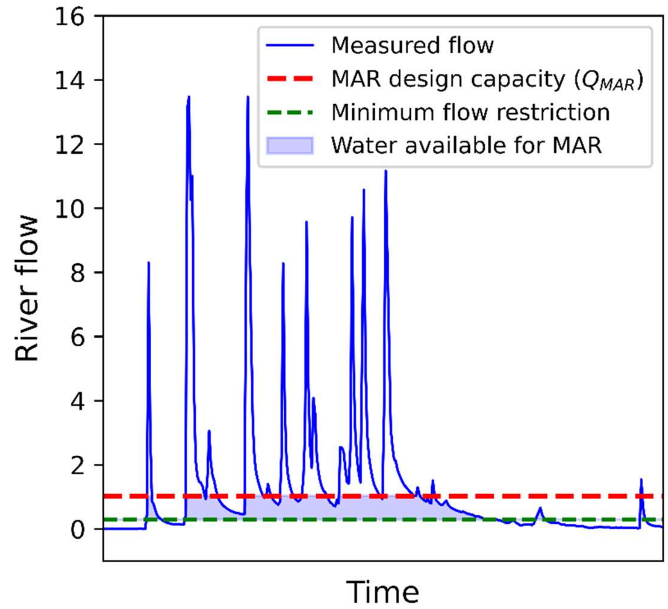


Figure 6-3 The concept of water available for MAR demonstrating the relationship to measured flow, MAR design capacity, and a minimum river flow that must be maintained.

The modelled river flow time series were used in conjunction with each MAR scheme capacity to quantify the potential MAR recharge from each scheme. The following rules were applied to the flow time series (Q) to estimate MAR recharge (Q_R):

$$Q_R = 0 \qquad \text{for } Q \leq Q_{MIN}$$

$$Q_R = Q_{MAR} \qquad \text{for } Q \geq Q_{MIN} + Q_{MAR}$$

$$Q_R = Q - Q_{MIN} \qquad \text{for } Q > Q_{MIN} \text{ and } Q < Q_{MIN} + Q_{MAR}$$

Where Q_{MIN} is the defined minimum flow, and Q_{MAR} is the maximum design flow at the potential MAR facility. Firstly, Q_R was estimated for a baseline scenario of recent historic conditions from 2000 – 2021. These were calculated for all members of the IES ensemble to produce a distribution of Q_R for each of the modelled catchments.

For catchments which were not modelled, a linear regression was used to relate annual average river flow to annual average Q_{MAR} for a range of potential MAR design flows (Q_{MAR}) for the modelled catchments.

6.3.5 Climate change assessment

The impact of climate change on Q_R was estimated using an ensemble of models from the EURO-CORDEX project, including several regional and forcing general circulation models for the Algarve region (IPMA, 2022). The modelled historical (1971-2000) rainfall and PET were used in conjunction with the RCP4.5 and RCP8.5 projections. The resulting percentage changes were applied to the observed historical (1971-2000) rainfall and PET from ERA5 to generate catchment-specific climate adjusted rainfall and PET. These time series were used in combination with the GR4J ensemble of parameter sets and the MAR rules to estimate Q_R under climate change. This also allowed comparison to the recent historical baseline (2000-2021).

6.3.6 Water quality assessment

The available surface water quality data was obtained from SNIRH (2022), for the closest monitoring location upstream of the proposed abstraction for MAR and compared to the threshold values for achieving good quality status under the WFD, as presented in the RBMP (APA, 2016).

6.4 Results

6.4.1 Potential MAR Schemes

Potential catchments for MAR are shown along with the potential receiving aquifers in Figure 6-4.

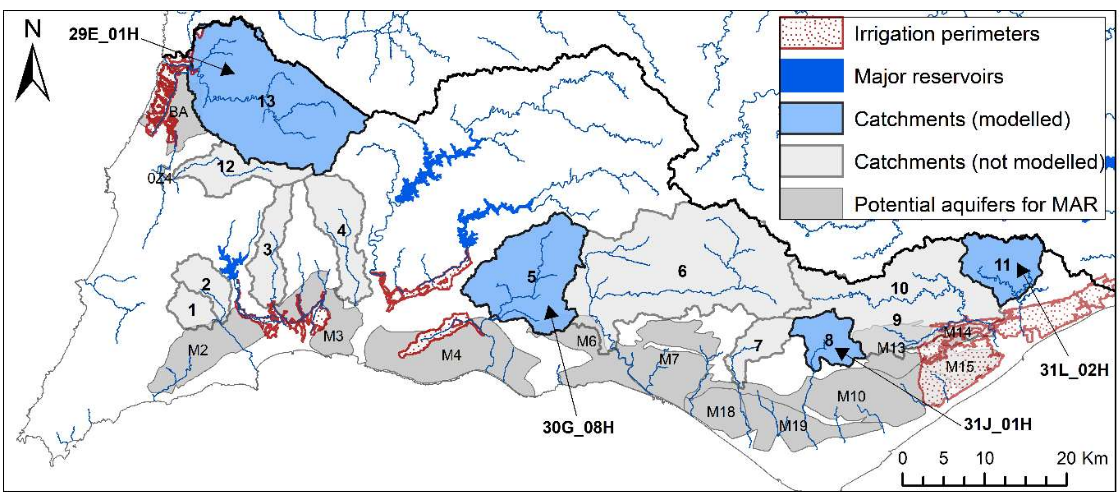


Figure 6-4 Location of potential catchments (modelled and non-modelled) and potential aquifers for MAR.

Catchment areas up-gradient of aquifers range in size from 32-433 km^2. Of the 11 catchments, 7 are < 100 km^2, with larger catchments identified in the northwest of RH8

(Ref. 13: 250 km^2), and the two catchments (Refs. 5 and 6) draining the Querença-Silves aquifer (total 567 km^2).

All the aquifers identified are those defined in the RBMP, except for the Areias, arenitos e cascalheiras do litoral do Baixo Alentejo (BA). These Pleistocene-age sediments occur south of Odeceixe in a shallow basin, overlying impermeable basement. Where these occur further to the north in the areas surrounding Cavaleiro and Almograve, south of the River Mira, they form an unconfined aquifer rarely exceeding 25 m thickness but supporting groundwater-fed irrigation (Soares Lima, 2020). Site visits found many large diameter wells in the area, indicating that groundwater has been used historically, and perhaps indicating sufficient permeability for the aquifer to be used in conjunction with MAR.

Suitable MAR methods were limited to infiltration by engineered basins, or by recharge boreholes or wells. The recharge method was selected for each aquifer based on the aquifer type and groundwater levels. Infiltration basins are appropriate only for phreatic aquifers with shallow water tables to avoid excessive losses in the unsaturated zone. Recharge by boreholes was considered for semi-confined to confined aquifers and unconfined aquifers with large unsaturated zones. For M15, M19, and in the irrigation perimeter east of Tavira, recharge could be achieved by infiltration basins, or by using existing poços (large diameter wells), as there are more than 60 poços in each of these areas. For a typically constructed poço (~20m deep, 4.5 m diameter, static water level 10 m below ground level), pumping tests indicate a recharge rate of 2,500 m^3/d could be achieved for a single well (Costa et al., 2020). Recharge by these existing wells could reduce the land required for infiltration basins significantly (e.g., approximately 16 m^2 for a large-diameter well vs. 2,500 m^2 for an infiltration basin for the same recharge, not including land needed for pre-settlement, pipe connections etc).

Objectives for MAR were identified based on location of water and suitable aquifer for MAR along with the location of existing water users and water supply networks. We found river flows in locations close to all four surface water-fed irrigation perimeters where these are adjacent to, or overlie, aquifers (Figure 6-1). The irrigation perimeters are currently supplied from the large reservoirs. Capturing the flows from smaller rivers and using the underlying aquifer for seasonal storage, before re-abstracting the water during the growing season is a form of MAR known as Aquifer Storage and Recovery (ASR)). in these locations can therefore reduce the demand on the main water supply reservoirs. These schemes can reduce demand on the main reservoirs, and water only needs to meet irrigation water quality standards, therefore treatment on re-abstraction is not required. The existence of irrigation supply pipework to users reduces the requirement for additional pipework. The other main MAR objective identified is to develop and maintain a strategic groundwater reserve in the M6 and M7 aquifers for use during major droughts.

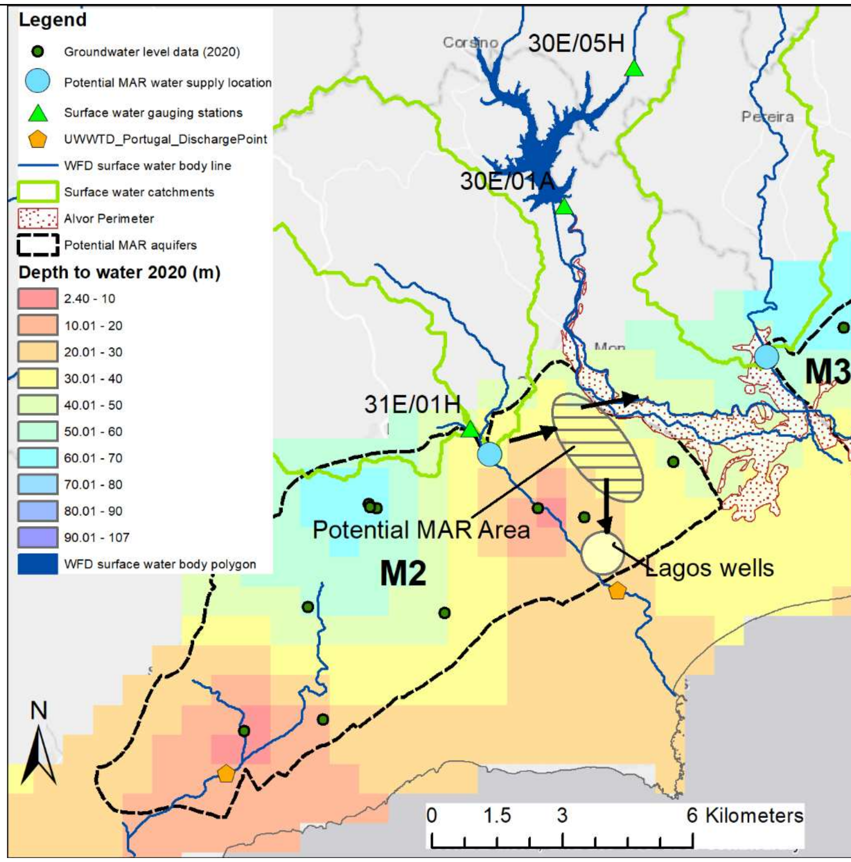
For each potential MAR scheme, the MAR recharge rate (Q_{MAR}) for each scheme was defined based on the method described in Section 6.3.4, with the aquifer properties and design parameters presented in Table 6-1. Initial areas for MAR were identified for each catchment – aquifer combination, with location plans presented in Tables 6-2 to 6-13, which also show the unsaturated zone thickness (or the difference between ground level and hydraulic head for confined aquifers) based on groundwater levels from October 2020. These potential MAR schemes on the following pages should be considered initial ideas linking where the water is available, where it could be stored, and where the benefits could be achieved, to guide further investigations.

Table 6-1 Aquifer capacity and infrastructure requirements for MAR

Aquifer	Method to estimate Q_{MAR}	Transmissivity T (m²/d)	Storativity, S (-)	Maximum continuous recharge duration, t (days)	Maximum head change at borehole (Δh max, m)	MAR recharge method	No.	QMAR (rounded to nearest 1000 m³/d)
M2	**Theis**	196	0.075	60	39.77	BH	4	23000
M3	**Theis**	230	0.001	60	59.52	BH	6	49000
M4	**Theis**	250	0.001	60	64.38	BH	2	19000
M6	**Theis**	2000	0.001	60	10	BH	4	43000
M7	**Theis**	1125	2.40E-04	60	16.83	BH	4	40000
M13	**Theis**	500	1.00E-03	60	10	BH	5	14000
M14	**Theis**	500	0.001	60	16.7	BH	4	19000
M15	**Measured**	Based on Rio Seco MARSOL results (Oliveira et al., 2015b)				IB	5	63000
M18	**Modelled**	Based on Standen et. al., 2022 (see Chapter 7)				IB	1	13000
M19	**Measured**	Based on pumping tests in Costa et. al., 2021				Poços	10	25000
East of M15	**Extrapolated**	Based on Rio Seco MARSOL results (Oliveira et al., 2015b)				Poços	15	38000
BA	**Extrapolated**	Based on Rio Seco MARSOL results (Oliveira et al., 2015b)				IB	5	63000

MAR recharge methods were selected from dedicated boreholes (BH) with standard diameter of 0.15 m and recharge rate calculated based on the aquifer properties outlined in equation *(3)*, off-line engineered spreading or infiltration basins (IB) with recharge rate 12,500 m^3/d, or reusing existing large diameter wells (poços) with recharge rate of 2,500 m^3/d.

Table 6-2 Potential MAR scheme M2 – Almádena - Odeáxere

<table>
<tr><td>Aquifer:</td><td colspan="3">M2 - ALMÁDENA - ODEÁXERE</td></tr>
<tr><td>Main MAR objective:
To support enhanced groundwater abstraction at former Lagos municipal wells (Portelas) / to support Alvor irrigation system.</td><td colspan="3" rowspan="2">
</td></tr>
<tr><td>Potential MAR scheme:
MAR infrastructure located in NE part of M2. Recharge via new boreholes east of Rib. Bensafrim. Re-abstraction at Portelas municipal boreholes, or at new recharge boreholes.

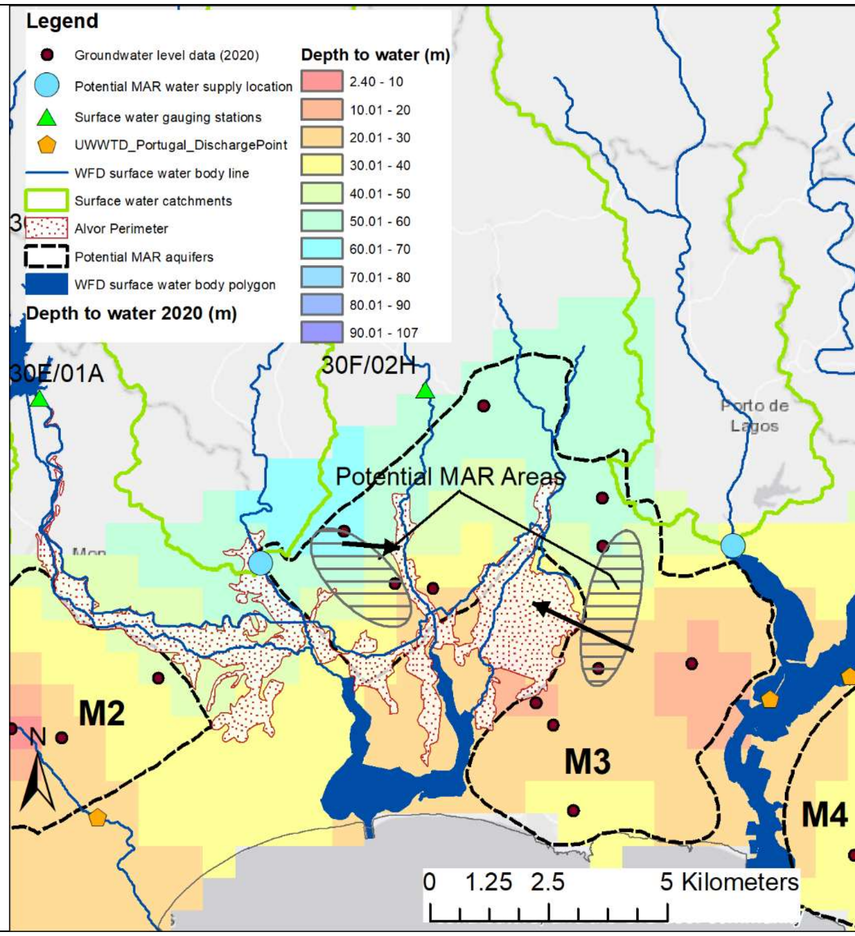
Potentially could support Alvor irrigation system, but M3 has higher water availability.</td></tr>
<tr><td>Water source(s):</td><td colspan="3">2 potential catchments with catchment areas of 22 and 29 km^2
Ribeira de Bensafrim (main channel + tributary)
Flow gauge: 31E/01H, other ungauged</td></tr>
<tr><td>Water quality:</td><td colspan="3">Data only available for western catchment. Historical pesticides and ammoniacal nitrogen > threshold value, recommend further sampling of both tributaries. Water quality may preclude MAR with this source.
Quality monitoring station: 31E/01 Bensafrim at Ribeira de Bensafrim</td></tr>
<tr><td>Average annual water availability (Mm^3/yr)</td><td colspan="2">4</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">Assumed recharge capacity per borehole: 2,750 – 9,000 m^3/day (Portelas well field had 5 bores with highest daily abstraction rates of 1000 – 2900 m^3/day.

Number of boreholes: 4</td></tr>
<tr><td>Transmissivity (m^2/d)</td><td>87
305</td><td>Hugman (2009)
25th percentile, Almeida (2000)</td></tr>
<tr><td>Storage coefficient (-)</td><td>0.075</td><td>Hugman (2009)</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td>39.77</td><td>Minimum, SNIRH</td><td rowspan="3">Q_{MAR}
23,000 m^3/d</td></tr>
<tr><td>time (recharge duration, days)</td><td>60</td><td>Conservative estimate</td></tr>
<tr><td>Radius (m)</td><td>0.15</td><td>Conservative borehole diameter for calculations</td></tr>
</table>

Table 6-3 Potential MAR scheme M3 – Mexilhoeira Grande - Portimão

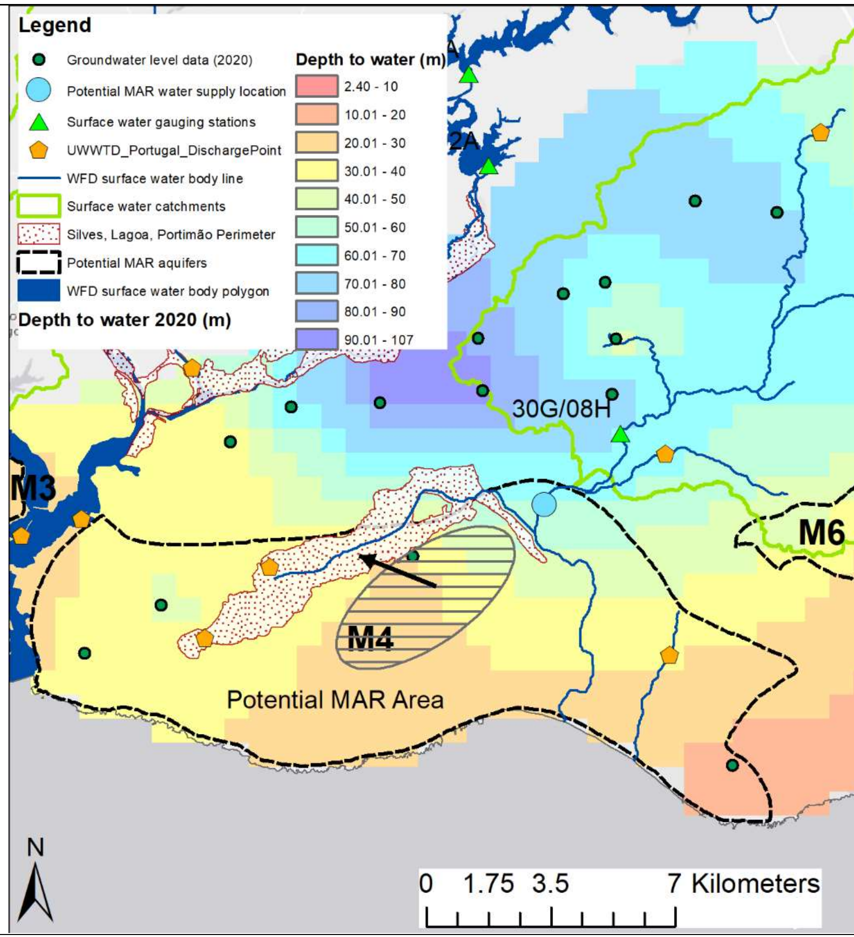
<table>
<tr><td>Aquifer:</td><td colspan="3">M3 – MEXILHOEIRA GRANDE - PORTIMÃO</td></tr>
<tr><td>Main MAR objective:
To support Alvor irrigation system

Potential MAR scheme:

River abstraction at 2 points upstream of tidal limit, recharge by boreholes into the northwestern part of the aquifer (Jurassic limestones), and southeastern part (Miocene). Re-abstraction and supply into Alvor irrigation system</td><td colspan="3">
</td></tr>
<tr><td>Water source(s):</td><td colspan="3">2 potential catchments, Ribeira de Arão (47 km²) and Ribeira de Boina (68 km²)
Flow gauge: None in catchments, flow assessed using 30F/02H</td></tr>
<tr><td>Water quality:</td><td colspan="3">Western catchment - no sampling for pesticides.
Eastern catchment - only sporadic tributyl phosphate occurrence.
Quality monitoring station: 30F/51 Canafechal (Ribeira de Arão), 30F/52 Porto Lagos and 30F/50 Rasmalho (both Ribeira de Boina)</td></tr>
<tr><td>Average annual water availability (Mm³/yr)</td><td colspan="2">18 Mm³/yr</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">Assumed recharge capacity per borehole: 8,200 m³/day.

Number of boreholes: 6</td></tr>
<tr><td>Transmissivity (m²/d)</td><td>230</td><td>25th percentile, Almeida (2000)</td></tr>
<tr><td>Storage coefficient (-)</td><td>0.001</td><td>Estimate, no aquifer data</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td>59.5</td><td>Minimum, SNIRH</td><td rowspan="3">***Q_{MAR}***
49,000 m³/d</td></tr>
<tr><td>time (recharge duration, days)</td><td>60</td><td>Conservative estimate</td></tr>
<tr><td>Radius (m)</td><td>0.15</td><td>Conservative borehole diameter for calculations</td></tr>
</table>

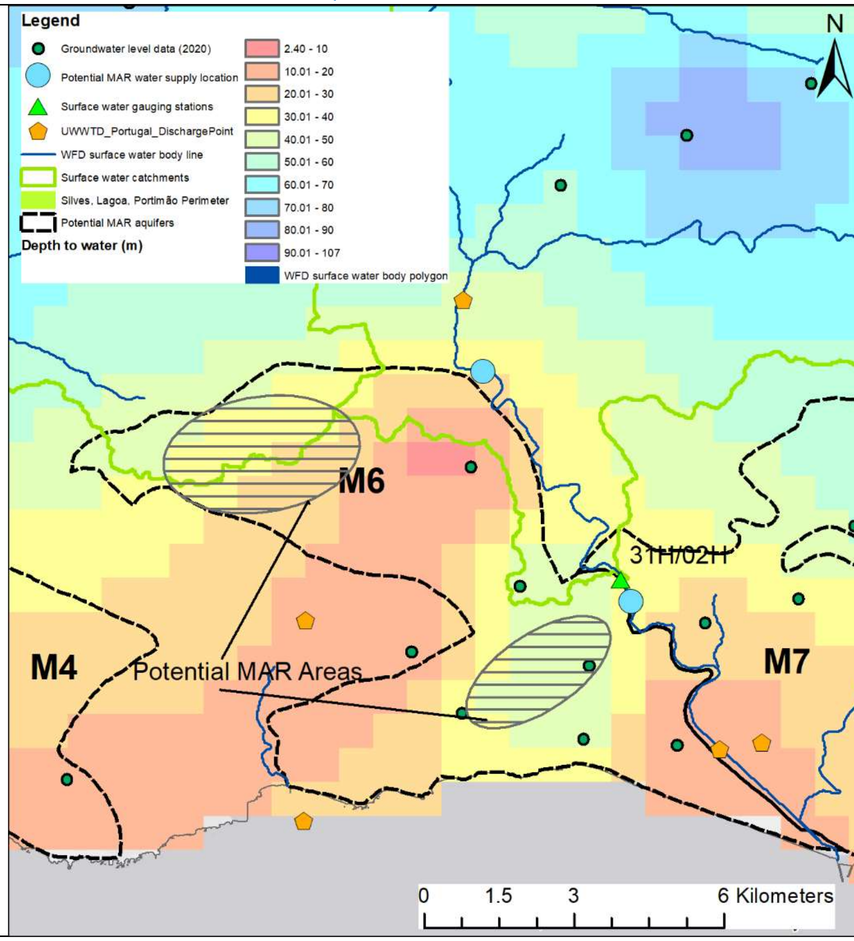
Table 6-4 Potential MAR scheme M4 – Ferragudo - Albufeira

<table>
<tr><td>Aquifer:</td><td colspan="3">M4 - FERRAGUDO - ALBUFEIRA</td></tr>
<tr><td>Main MAR objective:
To support Lagoa part of the Silves, Lagoa e Portimão irrigation system
Secondary objectives:
To support M4 aquifer status and current groundwater abstraction</td><td colspan="3" rowspan="2">
</td></tr>
<tr><td>Potential MAR scheme:
ASR scheme to recharge water from Ribeira de Alcantarilha by boreholes into M4, south of the Lagoa irrigation system. Re-abstraction by boreholes and supply into irrigation system using existing supply network.</td></tr>
<tr><td>Water source(s):</td><td colspan="3">Ribeira de Alcantarilha with 134 km^2 catchment
Flow gauge: 30G/08H</td></tr>
<tr><td>Water quality</td><td colspan="3">Sporadic high concentrations of ammoniacal nitrogen exceeding threshold values, possible related to WTP.
Quality monitoring station: 30G/08H Ponte Mesquita on Ribeira da Alcantarilha</td></tr>
<tr><td>Average annual water availability (Mm^3/yr)</td><td colspan="2">3 Mm^3/yr</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">Assumed recharge capacity per borehole: 9,573 m^3/day.

Number of boreholes: 2</td></tr>
<tr><td>Transmissivity (m^2/d)</td><td>250</td><td>Range 200-600 Almeida (2000)</td></tr>
<tr><td>Storage coefficient (-)</td><td>0.001</td><td>Estimate, no aquifer data</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td>64.38</td><td>Minimum of 604/70, SNIRH</td><td rowspan="3">Q_{MAR}
19,000 m^3/d</td></tr>
<tr><td>time (recharge duration, days)</td><td>60</td><td>Conservative estimate</td></tr>
<tr><td>Radius (m)</td><td>0.15</td><td>Conservative borehole diameter for calculations</td></tr>
</table>

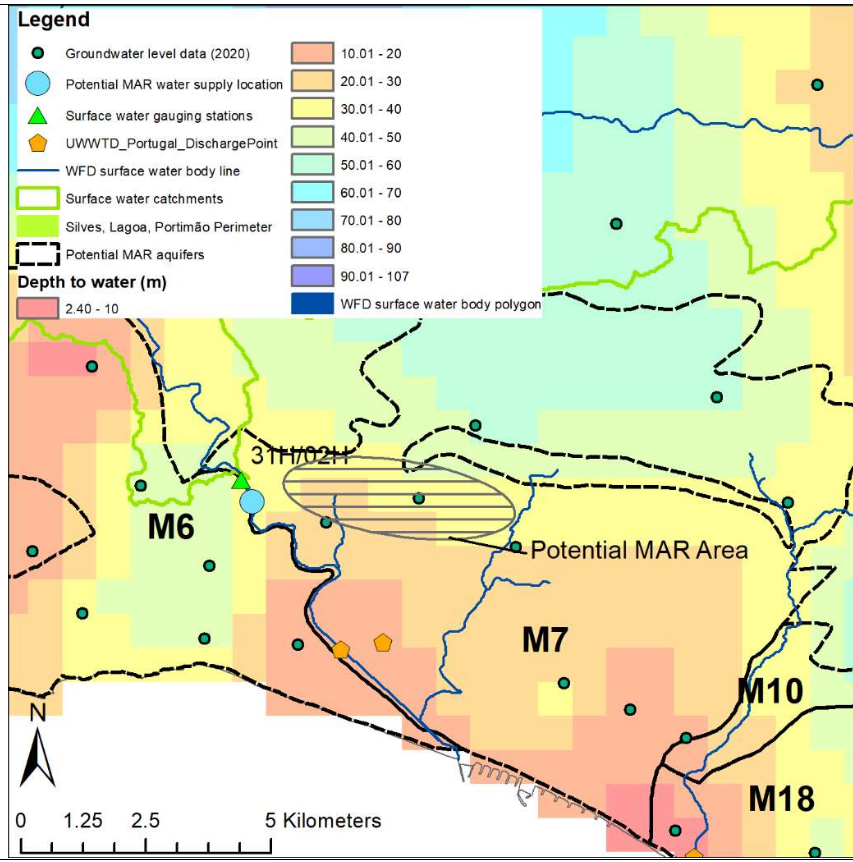
Table 6-5 Potential MAR scheme M6 – Albufeira – Ribeira de Quarteira

<table>
<tr><td>Aquifer:</td><td colspan="3">M6 - ALBUFEIRA - RIBEIRA DE QUARTEIRA</td></tr>
<tr><td>Main MAR objective:
Maintain good WFD status.
Secondary objectives:
Support current and future abstraction

Potential MAR scheme:
MAR scheme to abstract water from the Ribeira da Quarteira and recharge by boreholes at potentially two locations in M6, in the northern part into the Jurassic (1), or into the Miocene further south (2), depending on the local needs. Given the quantities of water available, both may be possible.</td><td colspan="3">
</td></tr>
<tr><td>Water source(s):</td><td colspan="3">Ribeira da Quarteira with 433 km^2 catchment
Flow gauge: 31H/02H</td></tr>
<tr><td>Water quality</td><td colspan="3">Investigation of sporadic exceedences of threshold value for lead needed.
Quality monitoring station: 31H/02 Ponte Rodoviária on Ribeira da Quarteira</td></tr>
<tr><td>Average annual water availability (Mm^3/yr)</td><td colspan="2">34 Mm^3/yr</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">Assumed recharge capacity per borehole: 6,210 - >10,830 m^3/day.

Number of boreholes: 4</td></tr>
<tr><td>Transmissivity (m^2/d)</td><td>235</td><td>Median from Almeida (2000) conservative as T from pumping tests much higher >2,000</td></tr>
<tr><td>Storage coefficient (-)</td><td>0.001</td><td>Estimate, no aquifer data</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td>10 (North)
44.3 (South)</td><td>Limited data in north, 605/324 used for south (SNIRH)</td><td rowspan="3">QMAR
43,000 m^3/d</td></tr>
<tr><td>time (recharge duration, days)</td><td>60</td><td>Conservative estimate</td></tr>
<tr><td>Radius (m)</td><td>0.15</td><td>Conservative borehole diameter for calculations</td></tr>
</table>

Table 6-6 Potential MAR scheme M7 – Quarteira

<table>
<tr><td>Aquifer:</td><td colspan="3">**M7 – QUARTEIRA**</td></tr>
<tr><td>Main MAR objective:
Maintain good WFD status.
Secondary objectives:
Support current and future abstraction</td><td colspan="3" rowspan="2">
</td></tr>
<tr><td>Potential MAR scheme:
MAR scheme to abstract water from the Ribeira da Quarteira and recharge by boreholes into northwest part of M7 into the Miocene, using same source of water as for M6.</td></tr>
<tr><td>Water source(s):</td><td colspan="3">Ribeira da Quarteira with 433 km^2 catchment
Flow gauge: 31H/02H</td></tr>
<tr><td>Water quality:</td><td colspan="3">Investigation of sporadic exceedences of threshold value for lead needed.
Quality monitoring station: 31H/02 Ponte Rodoviária on Ribeira da Quarteira</td></tr>
<tr><td>Average annual water availability (Mm^3/yr)</td><td colspan="2">34 Mm^3/yr</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">Assumed recharge capacity per borehole: 9,900 m^3/day.

Number of boreholes: 4</td></tr>
<tr><td>Transmissivity (m^2/d)</td><td>1125</td><td>Average of Miocene pumping test values, Almeida (2000)</td></tr>
<tr><td>Storage coefficient (-)</td><td>0.00024</td><td>Average of pumping test values - Miocene</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td>16.8</td><td>Minimum of 605/107 (SNIRH)</td><td rowspan="3">***Q_{MAR}***
40,000 m^3/d</td></tr>
<tr><td>time (recharge duration, days)</td><td>60</td><td>Conservative estimate</td></tr>
<tr><td>Radius (m)</td><td>0.15</td><td>Conservative borehole diameter for calculations</td></tr>
</table>

Table 6-7 Potential MAR scheme M18 – Campina de Faro – Subsistema Vale de Lobo

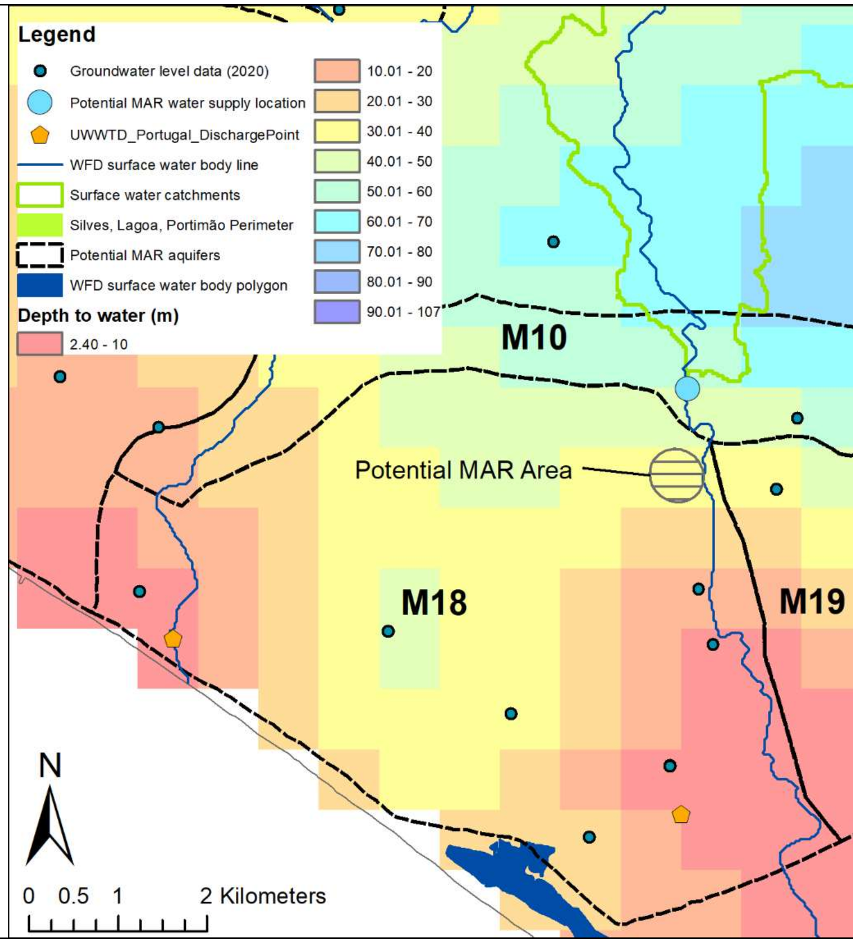
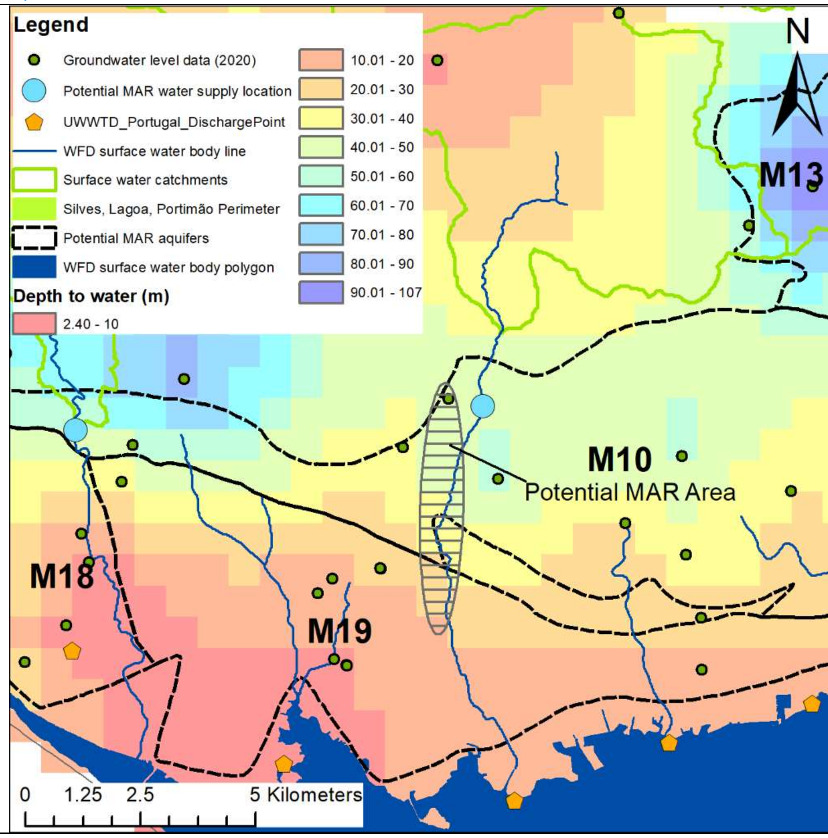
Aquifer:	**M18 - CAMPINA DE FARO - SUBSISTEMA VALE DE LOBO**		
Main MAR objective: Form part of solution to protect aquifer from SWI (previous modelling concludes this measure is insufficient alone (Standen et al., 2022))			
Potential MAR scheme: MAR scheme to recharge water from Ribeira da São Lourenço through Miocene 'window' in northern part of aquifer.			
Water source(s):	Ribeira da São Lourenço with 34 km^2 upstream catchment, **Flow gauge: 31I/01H Sítio de Igreja (not on SNIRH database)**		
Water quality:	No major concerns identified, but limited data available **Quality monitoring station: 31I/01 S. Lourenco/Areeiro on Ribeira da São Lourenço**		
Average annual river flow (Mm^3/yr)	1.25 Mm^3/yr		Preliminary design
Parameter	Value	Source & notes	Assumed recharge capacity per borehole: 2,500 m^3/day. Number of boreholes: 5
Transmissivity (m^2/d)	See detailed hydrogeological modelling presented in Chapter 7		
Storage coefficient (-)			
Unsaturated zone thickness (m)			***Q_{MAR}*** **12,500 m^3/d**
time (recharge duration, days)			
Radius (m)			

Table 6-8 Potential MAR scheme M19 – Campina de Faro – Subsistema Faro and M10 - S. João da Venda - Quelfes

<table>
<tr><td>Aquifer:</td><td colspan="3">M19 - CAMPINA DE FARO - SUBSISTEMA FARO, M10 - S. JOÃO DA VENDA - QUELFES</td></tr>
<tr><td>Main MAR objective:
To improve quantity and quality WFD status
Secondary MAR objective:
Maintain supply for current groundwater users.</td><td colspan="3" rowspan="2">



</td></tr>
<tr><td>Potential MAR scheme:
MAR scheme to recharge water from Rio Seco by expansion of existing infiltration basin scheme, by development of off-line infiltration basins or existing large-diameter wells (poços)</td></tr>
<tr><td>Water source(s):</td><td colspan="3">Rio Seco catchment is 40 km^2
Flow gauge: 31J/01H</td></tr>
<tr><td>Water quality:</td><td colspan="3">No major concerns identified, occasional ammoniacal nitrogen exceedences appear to be historical and not on-going.
Quality monitoring station: 31J/01 Coiro Burra, on Rio Seco</td></tr>
<tr><td>Average annual river flow (Mm^3/yr)</td><td colspan="2">4.4 Mm^3/yr</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">10 poços recharging at 2,500 m^3/d each</td></tr>
<tr><td>Transmissivity (m^2/d)</td><td colspan="2" rowspan="6">Infiltration rates achieved in Rio Seco infiltration basins around 1 m/d (Oliveira et al., 2015b)</td></tr>
<tr><td>Storage coefficient (-)</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td rowspan="3">Q_{MAR}
25,000 m^3/d</td></tr>
<tr><td>time (recharge duration, days)</td></tr>
<tr><td>Radius (m)</td></tr>
</table>

Table 6-9 Potential MAR scheme M19 – Campina de Faro – Subsistema Faro, M10 - S. João da Venda - Quelfes, and M11 – Chão de Cevada – Quinta de João de Ourém

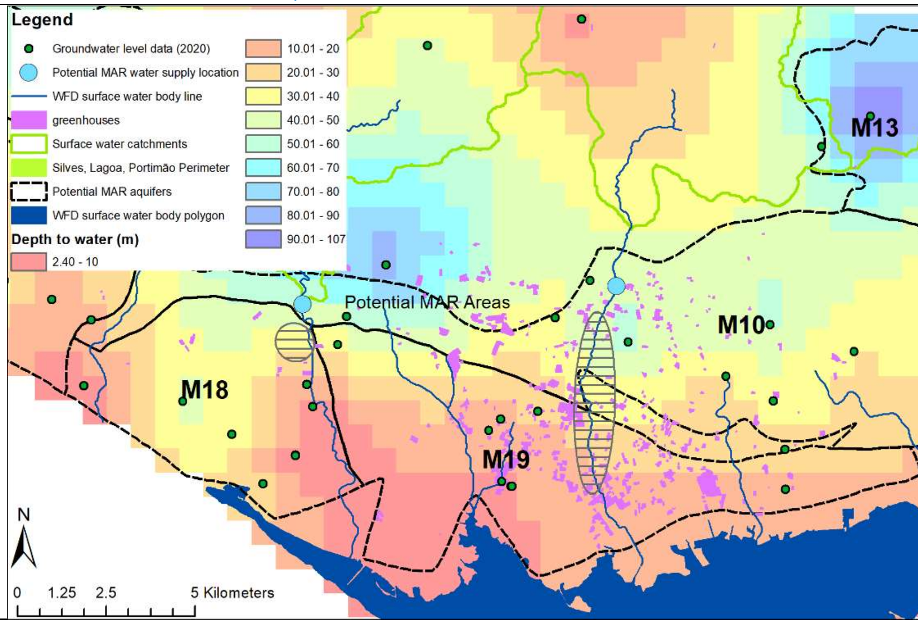
<table>
<tr><td>Aquifer:</td><td colspan="3">M19 - CAMPINA DE FARO - SUBSISTEMA FARO, M10 - S. JOÃO DA VENDA - QUELFES, M11 - CHÃO DE CEVADA - QUINTA DE JOÃO DE OURÉM</td></tr>
<tr><td>Main MAR objective:
To improve quantity and quality WFD status
Secondary MAR objective:
Maintain supply for current groundwater users.</td><td colspan="3">
</td></tr>
<tr><td colspan="4">Potential MAR scheme:
MAR scheme to recharge greenhouse runoff through existing large diameter wells (poços) or dedicated infrastructure</td></tr>
<tr><td>Water source(s):</td><td colspan="3">Greenhouse roof runoff (total area 4.75 km^2 in M19, M10, M11)</td></tr>
<tr><td>Water quality</td><td colspan="3">Not assessed within this scope, the water source is rain water</td></tr>
<tr><td>Average annual water availability (Mm^3/yr)</td><td colspan="2">2.83 Mm^3/yr</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">Individual schemes needed depending on greenhouse construction, aquifer properties and existing wells</td></tr>
<tr><td>Transmissivity (m^2/d)</td><td colspan="2" rowspan="5">Site-specific assessment needed</td></tr>
<tr><td>Storage coefficient (-)</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td rowspan="3">Estimated MAR Recharge:
1.4 Mm^3/yr in total, assuming 50% of greenhouse roof area</td></tr>
<tr><td>time (recharge duration, days)</td></tr>
<tr><td>Radius (m)</td></tr>
</table>

Table 6-10 Potential MAR scheme M13 – Peral - Moncarapacho

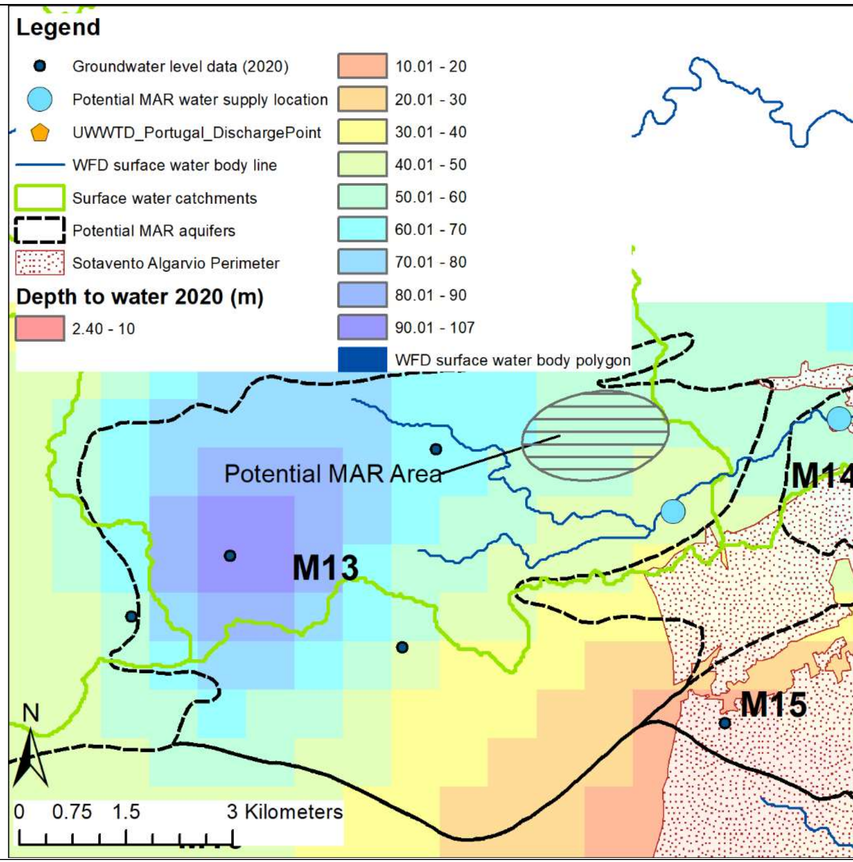
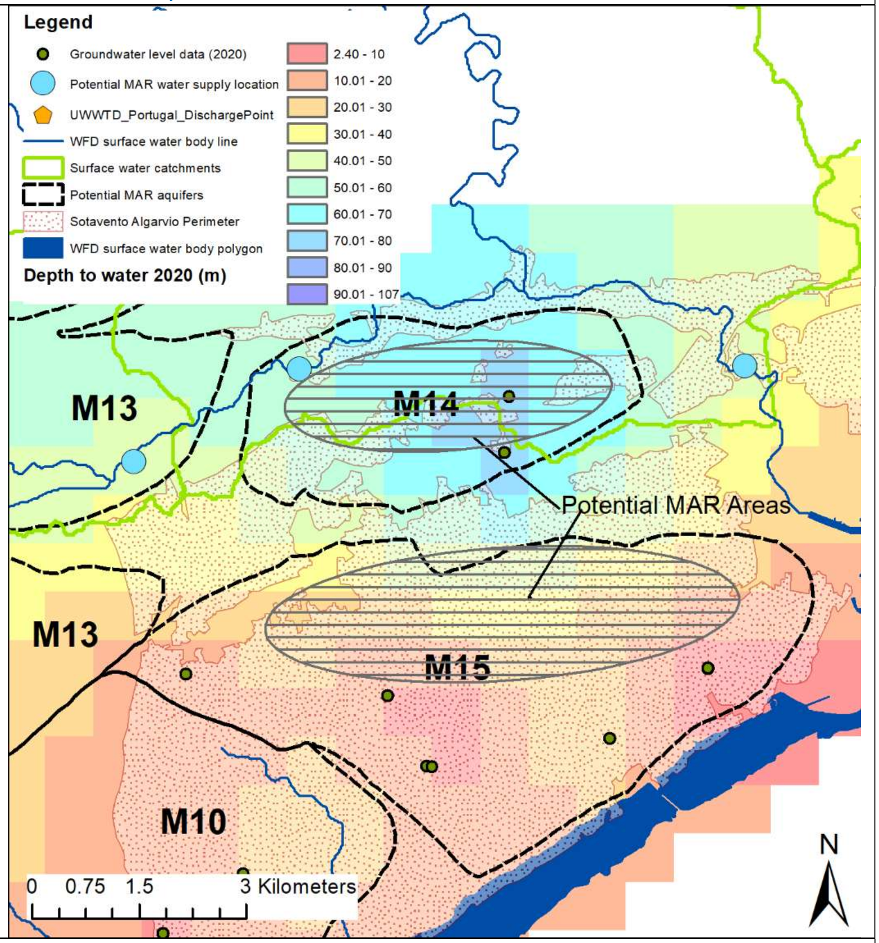
Aquifer:	**M13 - PERAL - MONCARAPACHO**		
Main MAR objective: Support Sotavento irrigation perimeter Potential MAR scheme: ASR scheme to recharge water from the Rio Séqua and recharge by boreholes into northeast part of M13, re-abstract and supply to Sotavento irrigation perimeter, located to the south.			
Water source(s):	Rio Séqua, with catchment area of 43 km^2 at this location. **Flow gauge: 31K/03H**		
Water quality	No water quality concerns identified based on assessment of existing data **Quality monitoring station: 31K/50 Ponte Asseca, Rio Sequa ou Gilão**		
Average annual water availability (Mm^3/yr)	9 Mm^3/yr		Preliminary design
Parameter	Value	Source & notes	Assumed recharge capacity per borehole: 2,900 m^3/day. Number of boreholes: 5
Transmissivity (m^2/d)	500	Estimate, no data	
Storage coefficient (-)	0.001	Estimate, no data	
Unsaturated zone thickness (m)	10	Large seasonal range, 10-90m, SNIRH)	***Q_{MAR}*** **14,000 m^3/d**
time (recharge duration, days)	60	Conservative estimate	
Radius (m)	0.15	Conservative borehole diameter for calculations	

Table 6-11 Potential MAR scheme M14 – Malhão and M15 – Luz-Tavira

<table>
<tr><td>Aquifer:</td><td colspan="3">M14 - MALHÃO, M15 - LUZ - TAVIRA</td></tr>
<tr><td>Main MAR objective:
Support Sotavento irrigation perimeter</td><td colspan="3" rowspan="2">
</td></tr>
<tr><td>Potential MAR scheme:
ASR scheme to recharge water from the Rio Séqua and recharge by boreholes into M14, and potentially by infiltration basins or trenches into M15</td></tr>
<tr><td>Water source(s):</td><td colspan="3">Rio Séqua, with catchment area of 133 km^2 at this location, and potentially Ribeira do Almargem
Flow gauge: 31K/03H</td></tr>
<tr><td>Water quality:</td><td colspan="3">No water quality concerns identified based on assessment of existing data
Quality monitoring station: 31K/03 Bodega and 30K/51 Carcavaia, both on Ribeira de Alportel</td></tr>
<tr><td>Average annual water availability (Mm^3/yr)</td><td colspan="2">28 Mm^3/yr</td><td>Preliminary design</td></tr>
<tr><td>Parameter</td><td>Value</td><td>Source & notes</td><td rowspan="3">Assumed recharge capacity per borehole: 4,800 m^3/day (M14), 322 m^3/day (M15)

Number of boreholes: 4 (M14)
Infiltration basin(s) more suitable for M15</td></tr>
<tr><td>Transmissivity (m^2/d)</td><td>500 (M14)
104 (M15)</td><td>Estimate
Average of logan values Almeida (2000)</td></tr>
<tr><td>Storage coefficient (-)</td><td>0.001 (M14)
0.001 (M15)</td><td>Estimate
Estimate</td></tr>
<tr><td>Unsaturated zone thickness (m)</td><td>16.7 (M14)
5 (M15)</td><td>SNIRH database</td><td rowspan="3">Q_{MAR}
M14: 19,000 m^3/d
M15: 63,000 m^3/d</td></tr>
<tr><td>time (recharge duration, days)</td><td>60</td><td>Conservative estimate</td></tr>
<tr><td>Radius (m)</td><td>0.15</td><td>Conservative borehole diameter for calculations</td></tr>
</table>

Table 6-12 Potential MAR scheme East of Tavira

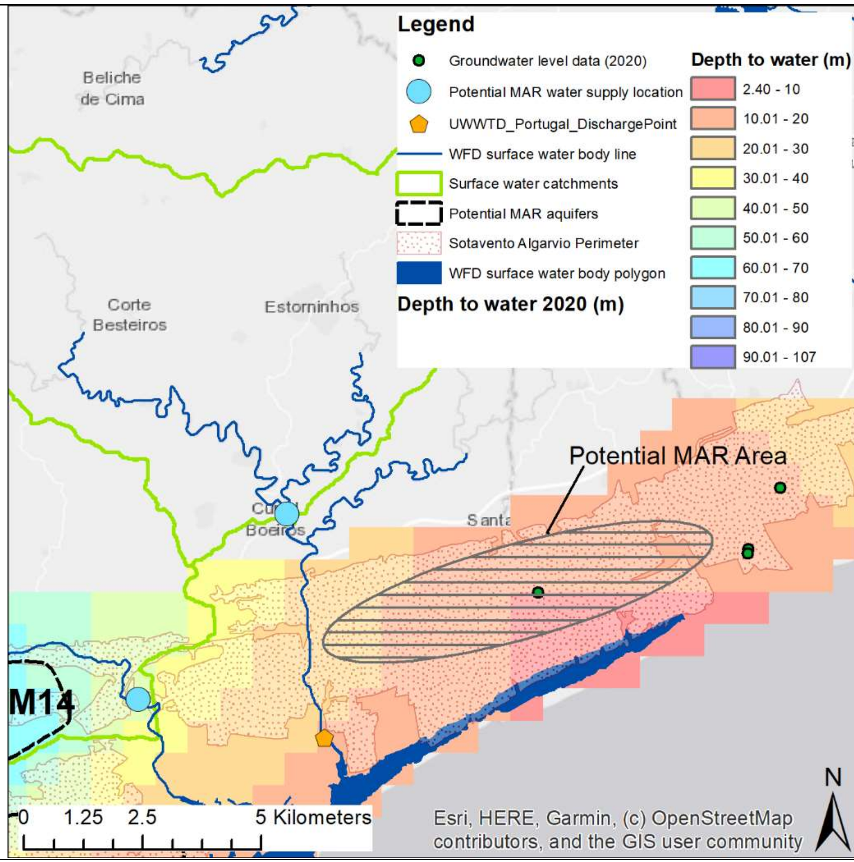
Aquifer:	East of Tavira		
Main MAR objective: Support Sotavento irrigation perimeter			
Potential MAR scheme: ASR scheme to recharge water from the Ribeira do Almargem and recharge by infiltration basins / trenches into shallow aquifer east of Tavira, reabstract into Sotavento irrigation perimeter			
Water source(s):	Ribeira do Almargem, with catchment area of 61 km^2 at this location, and potentially Ribeira do Almargem **Flow gauge: 30L/02H**		
Water quality	No water quality concerns identified based on assessment of existing data **Quality monitoring station: 31L/50 Cerro Almargem on Ribeira de Almargem**		
Average annual water availability (Mm^3/yr)	11 Mm^3/yr		Preliminary design
Parameter	Value	Source & notes	Infiltration basin(s) probably more suitable, number and size to be confirmed and reuse of existing poços
Transmissivity (m^2/d)	No aquifer property data available, Plio-Quaternary aquifer, possibly underlain by permeable units		
Storage coefficient (-)			
Unsaturated zone thickness (m)			***Q_{MAR}*** **38,000 m^3/d**
time (recharge duration, days)			
Radius (m)			

Table 6-13 Potential MAR scheme South of Odeceixe (Areias do litoral do Baixo Alentejo)

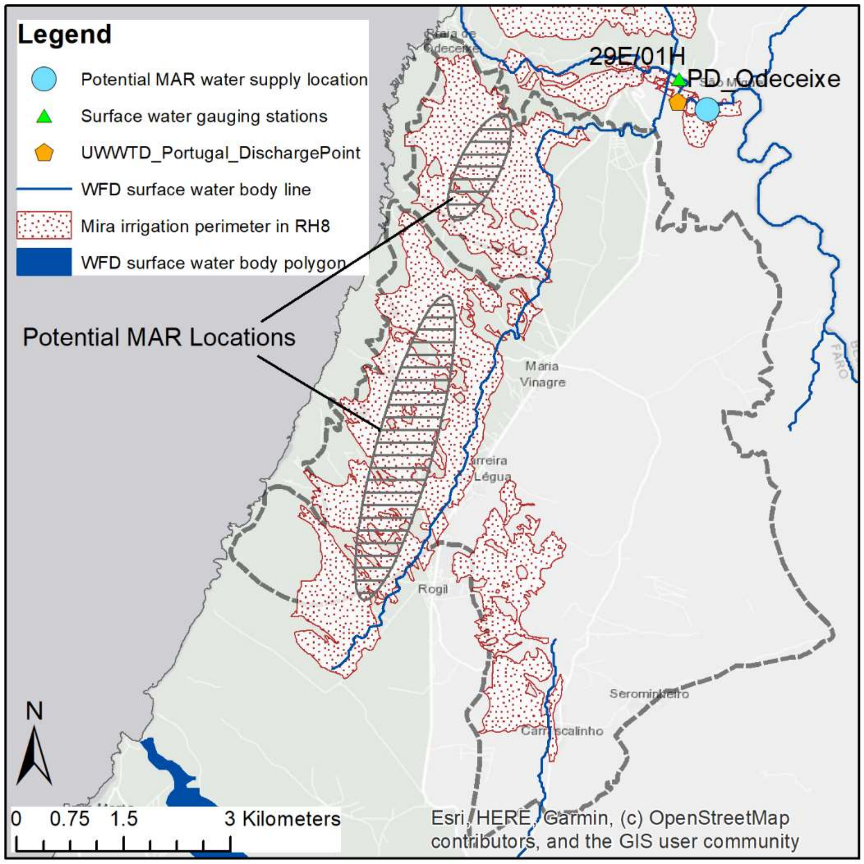
Aquifer:	**Areias do litoral do Baixo Alentejo**		
Main MAR objective: Support Mira irrigation perimeter in RH8	 		
Potential MAR scheme: ASR scheme to recharge water from the Ribeira de Seixe and recharge by infiltration basins / trenches into shallow aquifer 'Areias do litoral do Baixo Alentejo', which underlies the majority of the Mira irrigation perimeter that falls within RH8. Re-abstraction by boreholes into irrigation system			
Water source(s):	Ribeira de Seixe, with a catchment area of 250 km^2. **Flow gauge: 29E/01H**		
Water quality	No water quality concerns based on assessment of existing data **Quality monitoring station: 29E/01 Furadoiro-Odeceixe on Ribeira da Seixe**		
Average annual river flow (Mm^3/yr)	34 Mm^3/yr		Preliminary design
Parameter	Value	Source & notes	Infiltration basin(s), 5 x 12,500 m^2
Transmissivity (m^2/d)	No aquifer property data is available for this aquifer.		
Storage coefficient (-)			
Unsaturated zone thickness (m)	No groundwater level data for unsaturated zone estimate.		***Q_{MAR}*** 63,000 m^3/d
time (recharge duration, days)			
Radius (m)			

Table 6-14 provides a summary of the surface water catchment areas, their potential receiving aquifers, identified MAR objectives, selected MAR method and design recharge rate (Q_{MAR}).

Table 6-14 Potential catchments, aquifers, and objective combinations for MAR and potential MAR method and design flow rate

Catchment Reference	River	Catchment Area to MAR abstraction (km^2)	Potential Receiving Aquifer(s)	Primary MAR Objective	MAR Type	MAR Recharge Rate (Q_{MAR}) m^3/d
1	Bensafrim	51	M2	Support emergency municipal groundwater abstraction at Lagos	BH	23,000
2	Bensafrim (tributary)					
3	Arão	115	M3	Support Alvor irrigation perimeter	BH	49,000
4	Boina					
5	Alcantarilha	134	M4	Support part of Silves, Lagoa and Portimão irrigation perimeter	BH	19,000
6	Quarteira	433	M6	Strategic drought groundwater resource	BH	43,000
			M7			40,000
7	São Lourenço	32	M18	Support sustainable abstraction, reduce risks of SWI	BH	12,500
8	Seco	34	M10/M19		Poço	25,000
9	Sequa ou Gilão	43	M13	Support Sotavento Irrigation Perimeter	BH	14,000
10	Alportel	90	M14		BH, IB	19,000
			M15		Poço	63,000
11	Almargem	61	East Tavira		Poço	38,000
12	Alfambras	51	0Z4 / BA	No MAR objective identified	-	-
13	Seixe	250	BA	ASR to support Mira irrigation perimeter in RH8	IB	63,000

6.4.2 Rainfall-runoff modelling

Four catchments were selected from the potential MAR catchments for rainfall-runoff modelling, with a range of catchment characteristics and locations within the Algarve region selected (Table 6-15 and Figure 6-4).

Table 6-15. Selected river flow gauging stations and their flow characteristics

Gauging Station	River	Geology	Catchment area (km^2)	Annual average flow (Mm^3/yr)	Annual average unit flow ($m^3/yr/km^2$)	Average number of days flow greater than zero (days/yr)	No. years measured flow data >90% complete
29E/01H	Seixe	Schists / Greywackes	250	34.2	137,064	351	2
30G/08H	Alcantarilha	Jurassic Limestone	112	2.6	23,014	81	12
30L/02H	Almargem	Schists / Greywackes	61	11.4	185,051	119	27
31J/01H	Seco	Jurassic-Plio-Quaternary sediments	40	4.4	110,296	130	18

The modelling was carried out based on the method described in Section 6.3. Modelled flows are shown in Figure 6-5 for the mean of the ensemble and all the ensemble members compared to the measured flows during the calibration period(s). Catchment-specific calibration periods were selected based on the availability and quality of the measured data. The timing and duration of the flow events are reasonably well matched, although the modelled flows cannot match the recorded peak flows. There are also some instances where flow events occur in the data that are not recorded by the model, possibly reflecting areal variations in intensity of rainfall that are not seen in the gridded rainfall data.

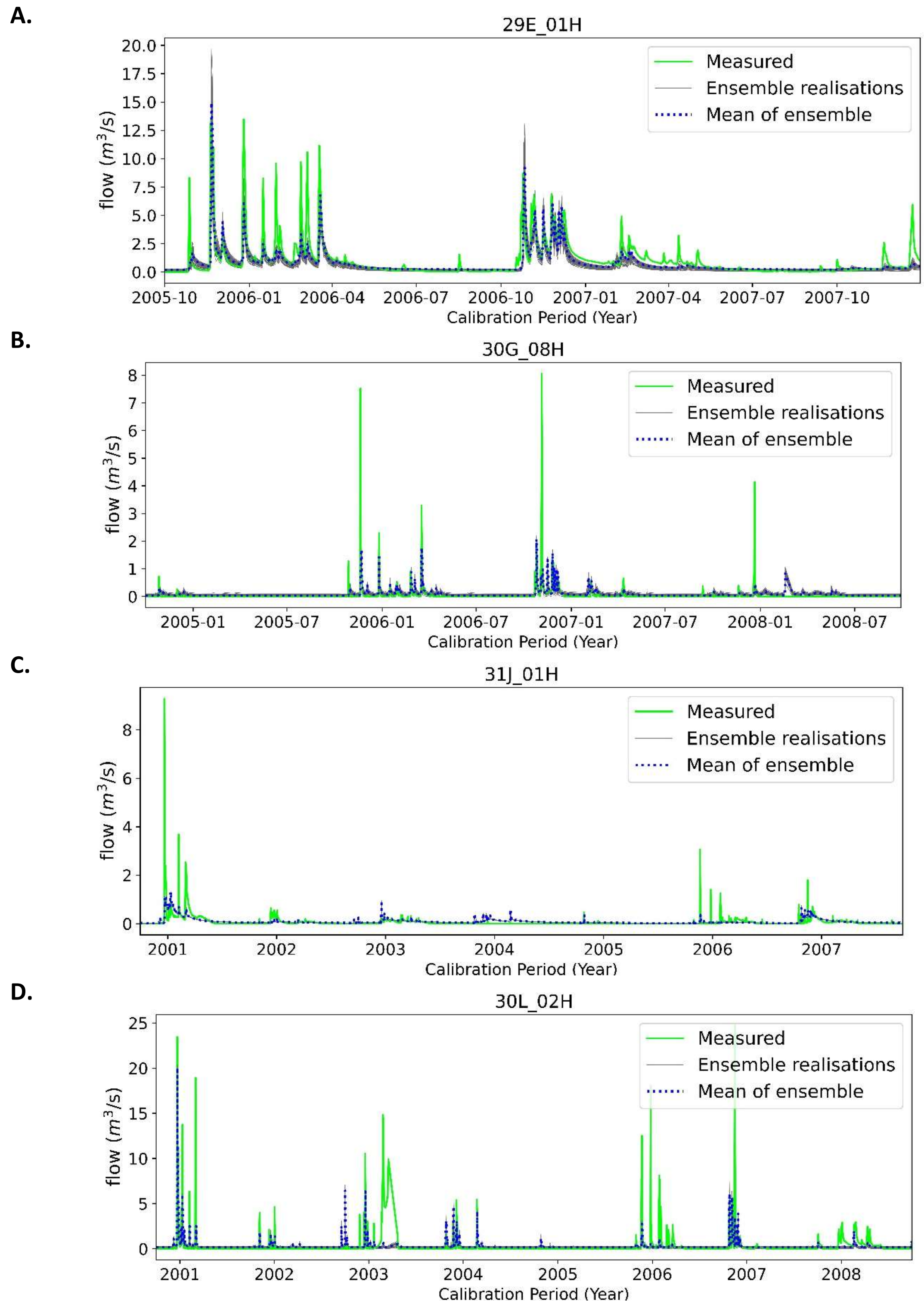
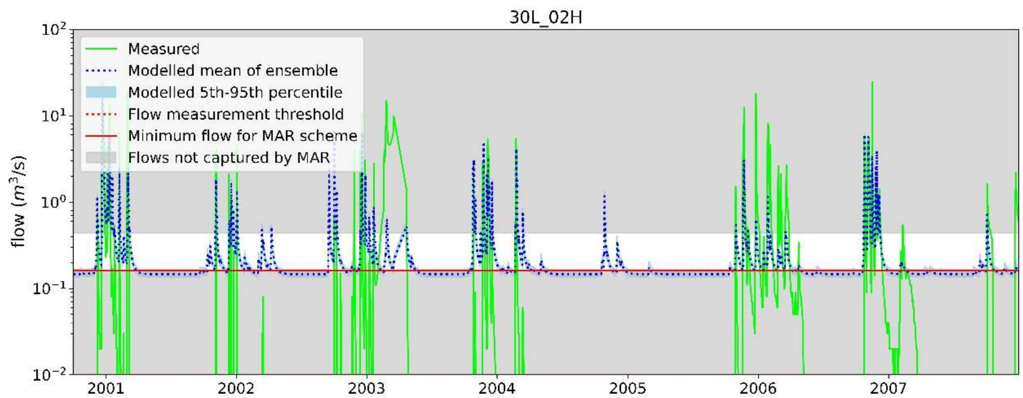


Figure 6-5 Measured vs. Simulated Rainfall-Runoff (measured data in green, each member of ensemble in grey (not always visible beneath mean of ensemble in blue dashed) for A. 29E_01H (Ribeira de Seixe), B. 30G_08H (Ribeira da Alcantarilha), C. 31J_01H (Rio Seco) and D. 30L_02H (Ribeira de Almargem).

Divergence between measured and modelled also occurs at very low flows. River flows have a minimum recorded flow of 0.01 m^3/s, with a measurement resolution of 0.01 m^3/s. Rainfall-runoff models using exponential functions cannot model zero flows, and even with the best matched parameter sets the 'tail' of the modelled flows indicate flow where measured flows are <0.01 m^3/s.

The under-recording of the peaks is unlikely to present a problem for estimation of water available for MAR, as these peaks are likely to be far higher than the engineered capacity for MAR. However, the use of modelled flows at low flows could have a large impact on the modelled MAR recharge, resulting in over estimating MAR recharge where modelled flows are greater than measured. This was corrected by setting minimum flows (Q_{MIN}), above which a MAR scheme operate. Minimum flows were set to the flows at which the modelled flows diverge from measured for each catchment, as shown in Figure 6-6, which presents flows on a log scale. The Q_{MIN} selected were 0.3 m^3/s (29E_01H), 0.1 m^3/s (31J_01H), 0.16 m^3/s (30L_02H) and 0.06 m^3/s (30G_08H). These may result in conservative (low) estimates of MAR recharge but given that an unknown environmental flow requirement may be imposed on any MAR scheme, this approach allows a simple rainfall-runoff model to be used to estimate MAR recharge.

A.



B.

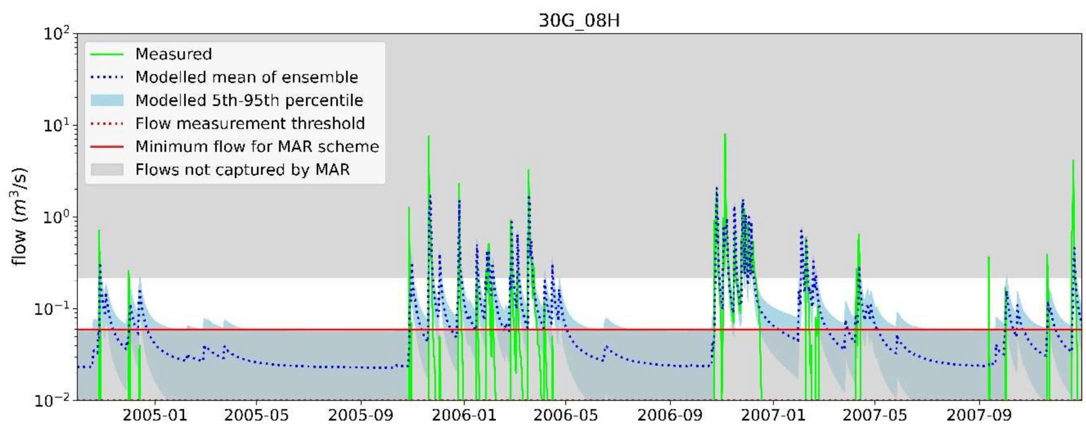


Figure 6-6 Measured vs. modelled river flows on log scale, demonstrating the selection of Q_{MIN} at the point where measured and modelled flows diverge to address model limitations.

Annual MAR recharge varies considerably between years during the baseline period as shown in Figure 6-7, as expected for the highly variable river flows.

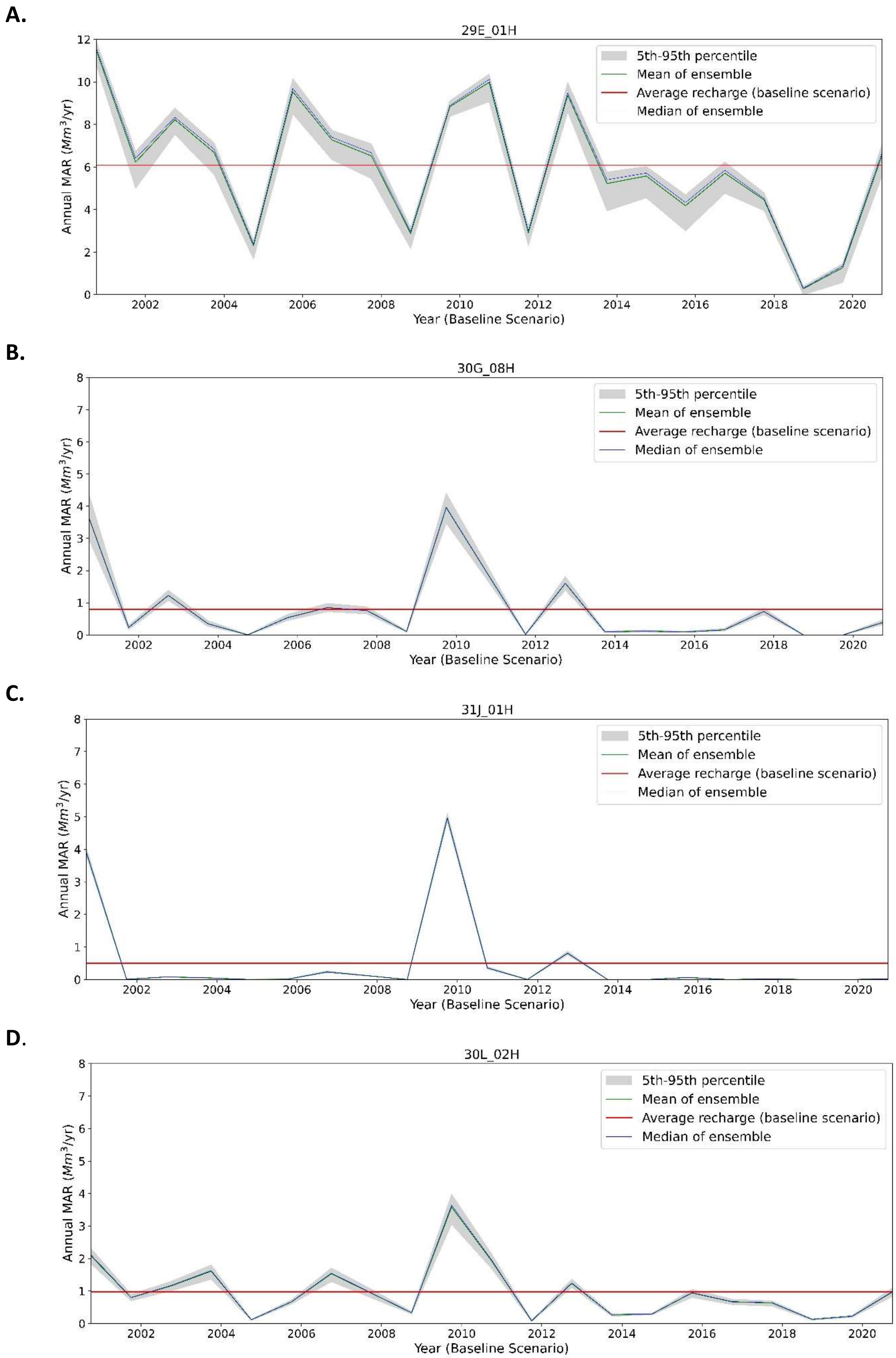


Figure 6-7 Annual Q_R achieved during baseline period for each of the modelled catchments.

6.4.3 Regional MAR estimation

For the baseline period (2000-2021), the annual average MAR recharge (Q_R) achieved for each of the modelled catchments based on a range of MAR design capacity, Q_{MAR}, are shown in Figure 6-8. The median of the ensemble is presented along with the 5th - 95th percentile values, indicating that uncertainty in Q_R varies considerably, from very little at 31J/01H (Rio Seco), to >1 Mm^3/yr at Q_{MAR} of 40,000 m^3/d for 30G_08H and 29E_01H. The uncertainty is positively correlated with river flow and reflects the increased measurement error at higher flow rates.

Estimated Q_R based on climate change scenarios are also shown on Figure 6-8 for the RCP4.5 and RCP8.5 scenarios for 2041-2070, alongside the QR predicted for the observed historical period (1970-2000) used in development of the climate models. In all cases, the observed historical resulted in higher Q_R for a given Q_{MAR} than either of the two climate change scenarios. However, the recent historical baseline (2000-2001) in some cases is very different. At 29E_01H, the large catchment on the west coast adjacent to the Alentejo boundary, the recent baseline is significantly wetter than the observed historical, resulting in higher Q_R for the baseline than for the observed historical, perhaps indicating that MAR predicted under climate change may be overly pessimistic. However, at the 31J_01H (Rio Seco), a very small catchment in the central Algarve, the MAR estimate during the baseline scenario is lower than all the climate scenarios, indicating the vulnerability of small catchments to increasing flow intermittency under climate change, that is already occurring with greater impacts than regional models suggest. The results for 30G_08H and 30L_02H show recent baseline MAR estimates falling between the observed historical and the RCP4.5 scenario for 2041-2070.

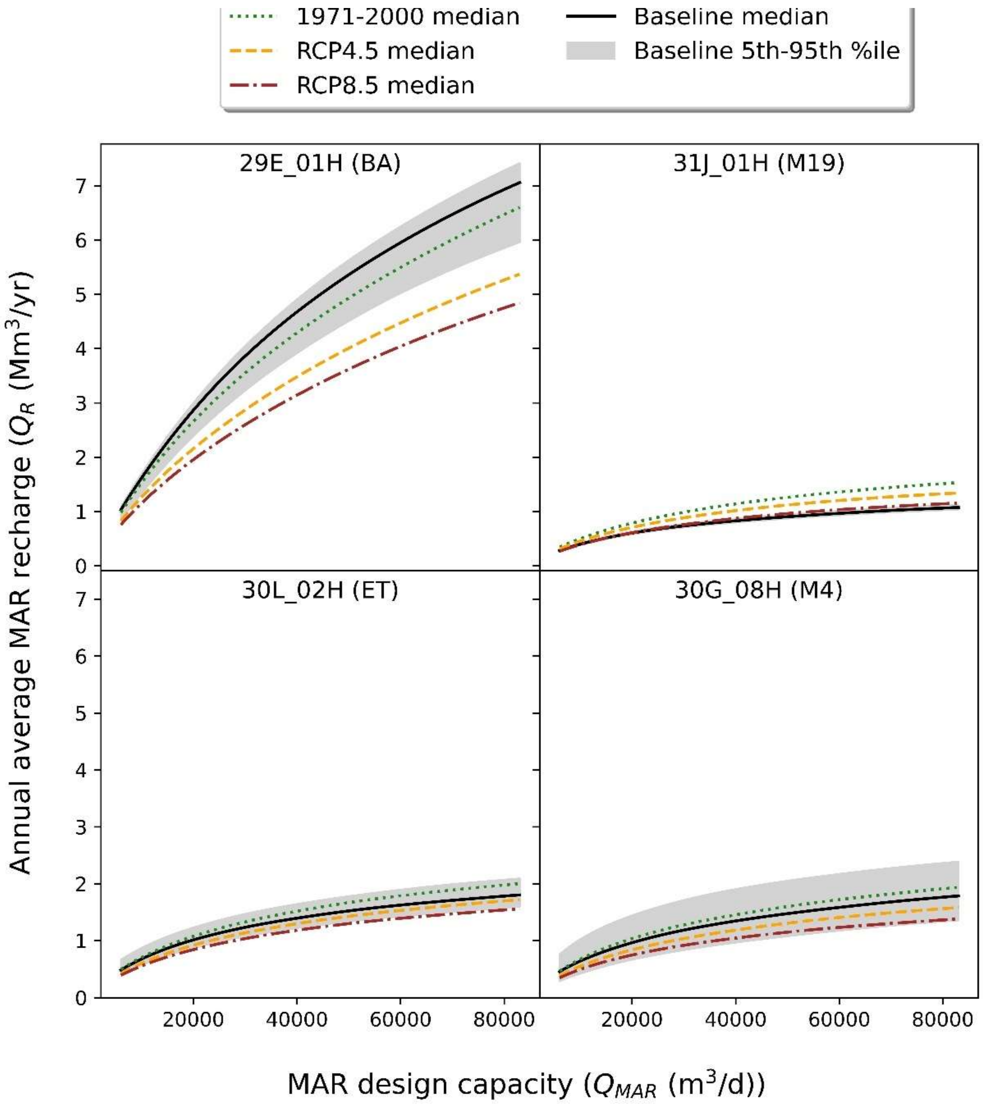


Figure 6-8 Estimated annual average MAR recharge for a range of MAR design recharge rates (Q_{MAR}) for each of the modelled catchments, for the baseline 2000-2021 scenario (including 5-95th percentile ensemble results), and the medians of observed historical period (1971-2000) and the RCP4.5 and 8.5 scenarios for the 2041-2070 period.

Climate change impacts on Q_R for a Q_{MAR} of 30,000 m^3/d are shown in Table 6-16, showing the decrease in Q_R under the RCP4.5 and 8.5 scenarios for 2041-2070. Relative percent changes for those catchments where the climate change predictions are consistent with the recent baseline conditions (30L_02H and 30G_08H), indicate that decreases in Q_R of between 8 – 13%, and 16-23%, are predicted for the RCP4.5, and RCP8.5, scenarios respectively.

Maintaining Q_R at the baseline rates requires additional design capacity due to the reduction in available river flows, and therefore the need to capture a greater proportion of river flow during less frequent flow events, to maintain the same Q_R under climate change. A feature of MAR schemes is that Q_{MAR} can be relatively easily increased by adding additional recharge boreholes / basins etc. over time, to mitigate the effects of climate change and maintain baseline Q_R. However, as shown in Table 6-16, there is greater benefit in maintaining Q_R in catchments with higher annual flows, where the same increase in Q_{MAR} will increase Q_R by 1.26 Mm^3/yr at 29E_01H, compared to only 0.2 Mm^3/yr for 30L_02H. For each of these catchments there will be an optimal Q_{MAR} considering the cost vs. water resource benefit.

Table 6-16 Climate change impacts on average annual MAR Recharge, Q_R, and additional design capacity, Q_{MAR}, needed to maintain baseline Q_R under climate change scenarios

Catchment	Baseline MAR, Q_R (Mm^3/yr) for Q_{MAR} of 30,000 m^3/d	Q_R 2041-2070 under RCP4.5 scenario (Mm^3/yr)	Q_R 2041-2070 under RCP8.5 scenario (Mm^3/yr)	Relative % change in RCP4.5 Q_R (%)	Relative % change in RCP8.5 Q_R (%)	Additional Q_{MAR} to maintain baseline Q_R under RCP4.5 scenario (m^3/day)	Additional Q_{MAR} to maintain baseline Q_R under RCP8.5 scenario (m^3/day)
29E_01H	3.86	2.87	2.60	-25.6*	-32.6*	18,000	26,000
31J_01H	0.73	0.88	0.76	20.5*	4.1*	-	-
30L_02H	1.24	1.14	1.04	-8.1	-16.1	16,000	26,000
30G_08H	1.19	1.04	0.92	-12.6	-22.7	20,000	34,000

*Percentage change not presented for climate scenario as Q_R estimates not consistent with recent baseline.

To estimate MAR recharge for catchments that were not modelled, linear regression between annual average river flow and Q_R was estimated for a range of Q_{MAR} for the modelled catchments. An example for a Q_{MAR} of 30,000 m^3/d is shown in Figure 6-9(A). These relationships were used to estimate Q_R for the remaining catchments of interest based on annual average river flow (either gauged or estimated), and the respective Q_{MAR} from Table 2 (Figure 6-9(B)). Many factors affect Q_{MAR} (e.g., budget, land availability, soil and aquifer properties and unsaturated zone thickness), therefore the impact on MAR recharge achieved for a range of Q_{MAR} are also shown on Figure 6-9 (B).

The error bars indicate the range of Q_R achieved based on the ensemble of rainfall-runoff models, indicating that uncertainty generally increases with increasing annual average river flow, except for catchment 30G_08H, which experiences higher uncertainty in Q_R. Uncertainty in river flows for the unmodelled catchments is clearly uncertain, but likely to be positively correlated with river flow. The uncertainty in MAR recharge for unmodelled catchments was estimated based on one selected catchment (29E_01H), and the appropriate Q_{MAR} of each potential MAR scheme to provide an indication of the potential uncertainty in the Q_R estimates for the unmodelled catchments.

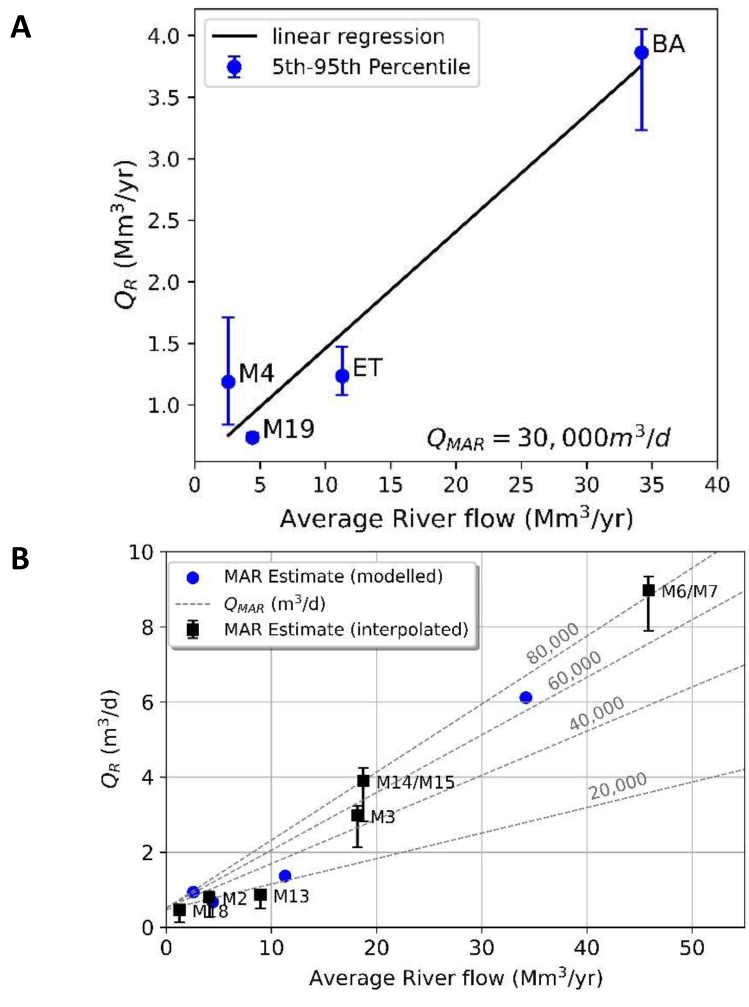


Figure 6-9 (A) Linear regression of annual average MAR recharge based on annual average river flow for a MAR design recharge rate of 30,000 m³/d (r^2 = 0.94) based on the modelled catchments 29E_01H (aquifer: BA), 31J_01H (aquifer: M19), 30G_08H (aquifer: M4) and 30L_02H (aquifer: East Tavira). (B) Annual MAR recharge estimates for modelled (labelled on A) and interpolated (labelled on B) catchments using MAR design recharge rates in Table 6-14.

6.4.4 Source water quality

An assessment of the surface water quality based on the nearest surface water monitoring stations to the proposed surface water abstractions for MAR was undertaken (shown in Figure 6-10), using all available data (samples collected between 1995 and 2020). All potential catchments have at least one surface water monitoring location except for catchment 2. Full results are presented in the Appendix 1. Generally, the catchments have little agricultural or urban development and contamination risks are low. Furthermore, the proposed abstractions for MAR are upstream of water treatment plant (WTP) discharge in all but two cases (catchments 5 and 6).

Surface water quality meets the requirements of the Groundwater Directive with only rare exceptions, and MAR with this source of water should not present undue risks to achievement of good water quality status for the receiving groundwater body. No water quality concerns were identified at the majority of locations, and at a further 4 locations, only a single exceedance of a single individual pesticide occurred (in all cases for tributylphosphate). Two locations with historical ammoniacal nitrogen (NH_4) concentrations were identified (catchments 5 and 8), but these do not appear to be ongoing, and may reflect improvements in wastewater collection and treatment since the analysis started in 1995. Only water from Ribeira de Bensafrim (catchment 1) regularly fails to meet the groundwater threshold values (for NH_4, chloride and pesticides), and may be unacceptable to use for MAR.

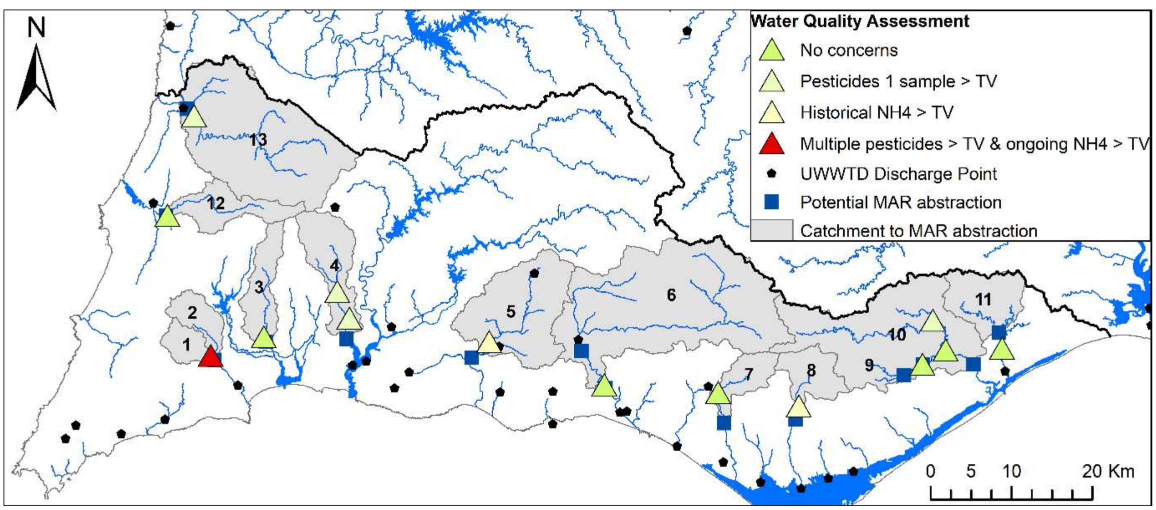


Figure 6-10 Location of selected surface water quality monitoring stations and exceedances of the groundwater threshold values (TV), proposed surface water catchments and abstraction locations for MAR, and existing Urban Wastewater Treatment Directive (UWWTD) 98/15/EC discharge point locations.

6.4.5 Summary of estimated MAR recharge

The estimated annual average additional recharge that MAR schemes could achieve across the Algarve region (RH8) is 27 Mm^3/yr for an estimated cost of 60 M€ as shown in Table 6-17.

Table 6-17 Summary of potential MAR options in the Algarve Region

Potential Receiving Aquifer(s)	Catchment Ref.	Water source for MAR	Estimated Annual Average MAR Recharge, Q_R (Mm^3/yr)	5^{th}-95^{th} percentile Q_R (Mm^3/yr)	Proportion of annual river flow captured for MAR (%)	Estimated Cost (M€)
M2	1,2	Rib. de Bensafrim	0.8	0.3 – 1.0	20	1.8
M3	3,4	Rib. de Arão & Boina	3.0	2.1 – 3.2	16	6.6
M4	5	Rib. de Alcantarilha	0.9	0.6 – 1.4	37	2.0
M6	6	Rib. da Quarteira	4.5	7.9 – 9.3	10	9.9
M7			4.5		10	9.9
M18	7	Rib. de São Lourenço	0.5	0.1 – 0.6	37	1.1
M19/M10	8	Rio Seco	0.68	0.65 – 0.71	15	1.5
M13	9	Rio Sequa ou Gilão	0.9	0.5 – 1.0	10	2.0
M14	10	Rib. de Alportel	3.9	2.8 – 4.3	21	8.5
M15						
East Tavira	11	Rib. de Almargem	1.4	1.2 – 1.6	12	3.1
BA	13	Rib. de Seixe	6.1	5.2 – 6.4	18	13.4
Total		-	**27.2**	**21.4 – 29.5**	-	**59.6**

MAR is unlikely to be possible for M2 due to the water quality risks identified in Ribeira de Bensafrim, but none of the other catchments appear to have significant water quality issues. The MAR estimate from Rio Seco is small in comparison to the other options, and the recent historical period indicates that river flows in this small stream is already lower than predicted by the RCP8.5 scenario for 2041-2070, limiting the potential for MAR recharge in this area. The adjacent Ribeira da São Lourenço catchment is expected to be similarly affected.

Based on this initial assessment, MAR in M3, M6, M7, M13-M15, in the area east of Tavira, and the area south of Odeceixe appear to have higher chances of success on water quality and climate change considerations. These schemes could provide a water resource benefit of 24 Mm^3/yr, to support the irrigation perimeters at Alvor, Sotavento, and the Mira within RH8, as well as developing / maintaining a strategic emergency groundwater resource in M6/M7, close to the major population center of Albufeira.

6.5 Integration of MAR into the Water Resource System

6.5.1 Supporting public irrigation perimeters with MAR

The extent to which MAR could replace surface water in the public irrigation perimeters is summarised in Table 6-18. MAR can form a significant proportion of the total water demand in the Alvor (32%) irrigation perimeter, which is usually supplied from the Bravura reservoir. This is significant because during recent droughts irrigation supplies were temporarily stopped to maintain urban supplies as a priority, and reliable supplies are needed for all users during drought periods.

Table 6-18 MAR as a percentage of total irrigation demand in the public irrigation perimeters

Irrigation Perimeter	Reservoir	Estimated demand (Mm^3/yr)	Average MAR Estimate (Mm^3/yr)	MAR as % of total demand
Alvor	Bravura	9.5	3.0	32%
Silves, Lagoa e Portimão	Arade	13.8	0.9	7%
Sotavento	Odeleite, Beliche	22	6.2	28%
Mira	Santa Clara	30	6.1	20%

Known alternatives to Bravura dam during droughts are limited to reducing losses in the irrigation system (2 Mm^3/yr; 4 €/m^3/yr), reactivation of former municipal boreholes (0.9 Mm^3/yr, no costs available), and in the long term, treated water reuse with the closest WTP at Lagos generating 4.0 Mm^3/yr, with anticipated costs of 2.6 €/m^3/yr. All these water resource options appear to be necessary to meet the irrigation demand, particularly during drought periods.

The potential water sources in the vicinity of Bravura, along with their benefits, costs and infrastructure requirements are described in Table 6-19.

Table 6-19 Summary of Supply and Demand Options for Bravura zone / Alvor irrigation perimeter

Name	Type	Horizon	Water Resource Benefit (Mm^3/yr)	Unit Cost (€/m^3/yr)	Infrastructure requirements
Reactivation of 3 x Portelas boreholes (M2)	Supply (SMAASA)	Short	0.9	-	Maintenance and re-commissioning
Reactivation of 3 x M3 boreholes	Supply (SMAASA)	Short	1.5	-	Maintenance and re-commissioning
Reducing losses in irrigation system	Demand (RH Alvor)	Short	2.0	4.0	Significant works to line, cover and pressurise the irrigation network (already commenced)
MAR in M2 to increase abstraction at Portelas*	Supply (RH Alvor)	Medium	0.8	2.19	River intake, pipeline to new recharge and abstraction boreholes and supply pipework
MAR in M3 to support Alvor irrigation perimeter or increased abstraction at M3 boreholes	Supply (RH Alvor)	Medium	3.0	2.19	River intake x 2, pipeline(s) to new ASR boreholes (or separate recharge and abstraction boreholes), pipeline(s) to deliver into suitable point in irrigation network
Treated wastewater reuse in agriculture	Supply	Long	4.0	>2.62	Transfer from Lagos WTP, in second priority, control of seawater ingress to network needed, therefore costs probably higher.

*Not considered further due to water quality assessment

In the Sotavento irrigation perimeter, Stigter et al. (2006) identified that involuntary MAR has been occurring since irrigation with surface water commenced in 2001, resulting in groundwater levels no longer having significant seasonal fluctuations. The limitation in the Sotavento irrigation perimeter is likely to be the aquifer storage, however by managing groundwater levels and abstraction, MAR can be used to maximise seasonal groundwater storage. MAR in M13, M14, M15 and in the shallow aquifer east of Tavira could comprise 28% of the total Sotavento irrigation demand, and potentially groundwater abstraction could be increased above the annual average MAR to manage groundwater levels in these aquifers to avoid waterlogging of the roots of permanent crops and reduce groundwater spring discharge.

The Mira irrigation perimeter covers 1,855 ha within RH8, south of the River Seixe, and is supplied with only 1.5 Mm^3/yr from Santa Clara reservoir (of 30-37 Mm^3/yr total), along the Canal do Rogil (ABM, 2021). Therefore, MAR can form >100 % of the demand in the irrigation perimeter in RH8, but furthermore, MAR could form 20% of the total Mira irrigation demand. MAR in RH6 (Alentejo) has not been considered as part of this work, however, the same permeable formations are known to occur in this region, and in addition to the River Seixe, the water not used for irrigation from Santa Clara during the winter months, but is still released into the irrigation network. If captured, this could be an additional source of water for MAR. A strategic transfer of water from Santa Clara reservoir to the Algarve (via the Rogil canal) is already being considered as one of the long-term measures considered in the RWEP, and potentially this could be augmented/replaced by MAR.

6.5.2 Strategic groundwater resource

The aquifers M6 and M7 are used for private irrigation of agriculture, tourism and golf. River flows in the Ribeira da Quarteira used for MAR schemes in both M6 and M7 to increase aquifer storage can develop a strategic groundwater resource (average 9 Mm^3/yr) for use during drought periods to augment urban supplies. Potentially this could be further supported by reducing groundwater abstraction in these aquifers by replacing groundwater with treated wastewater reuse in agriculture, as approximately 2.9 and 2.8 Mm^3/yr are available from the nearby Vilamoura and Vale Faro WTP respectively, based on 2021 wastewater production rates.

6.5.3 Campina de Faro

Groundwater is used in the Campina de Faro aquifers for the golf, tourism and agriculture sectors, with current abstraction in M18, M19 and M11 totalling 12.80 Mm^3/yr. Long-term annual recharge for these aquifers is estimated to be significantly lower than this at 8.83 Mm^3/yr. As already identified by Hugman & Doherty (2022) abstraction reductions of at least 70% are needed, and MAR with the local sources is insufficient to solve the problem of SWI (Standen et al., 2022a).

Table 6-20 Summary of Supply and Demand Options for Campina de Faro

Name	Type	Horizon	Water Resource Benefit (Mm^3/yr)	Unit Cost (€/m^3/yr)	Details
MAR at Ribeira da São Lourenço	Supply	Short	0.5	2.19	Limited water availability in Ribeira da São Lourenço, many years with zero flow, and low resilience of this option to climate change.
MAR at Rio Seco	Supply	Short	0.7	2.19	Water availability also limited in Rio Seco.
MAR from greenhouse roof runoff	Supply	Medium	1.4	-	Assumes that runoff from 50% of greenhouse roof runoff in M19, M10 and M11 can be captured and recharged.

Name	Type	Horizon	Water Resource Benefit (Mm^3/yr)	Unit Cost (€/m^3/yr)	Details
Direct reuse in golf course irrigation of treated wastewater Quinta do Lago*	Supply	Short	0.76	2.46	Volumes available do not include proportion already re-used for golf course irrigation
Direct reuse in golf course irrigation of Treated wastewater Vale do Lobo*	Supply	Short	0.16	2.46	Only small volumes available
Direct reuse in golf course irrigation of Treated wastewater Faro Noroeste*	Supply	Short	1.50	2.46	Relatively small volume available, but located close to the Vale do Lobo sector
Direct reuse in golf course irrigation of Treated wastewater Faro-Olhão*	**Supply**	**Medium**	**5.82**	**2.46**	**This is the only source that can provide sufficient water to meet the needs of the Vale do Lobo sector.**
Demand reduction measures at Golf Courses (medidas Tur_02, Tur_03)	Demand	Medium	0.39** (0.26 Tur_02 + 0.125 Tur_03)	4.28	Efficiency savings by reducing irrigated areas, changing type of grass and plants, and by reducing water demand in tourism sector. Benefits proportioned based on number of golf courses / area included in measures.

*Reuse of treated wastewater in golf courses is estimated in the water efficiency plan to cost 13.81 M€ for a total of 5.62 Mm^3/yr , which includes golf courses in the Vale do Lobo sector and others. **Water resource benefit proportioned based on number of golf courses / tourist areas within Campina de Faro compared to totals in Water Efficiency Plan.

In this area, MAR can only form a very small component of the solution, particularly as the recent baseline (2000-2021) water available for MAR is already less than even the RCP8.5 scenario, due to the vulnerability of ephemeral streams with small catchments to climate change.

6.5.4 MAR to balance climate change impacts on natural recharge

For the aquifers where MAR has been identified, the predicted water resource benefits from MAR have been compared to the historical and predicted recharge estimates for these aquifers under climate change, as shown in Table 6-21.

In aquifers M3, M6, M7, M14 and M15, the predicted MAR recharge is significantly greater than the predicted reduction in natural recharge due to climate change based on the RCP4.5 scenario for 2041-2070, even accounting for the potential 8 – 13% reduction in MAR recharge due to climate change. This demonstrates that MAR is likely to be available to support the irrigation perimeters (in M3, M14 and M15), and to develop a strategic groundwater resource (in M6 and M7) and these benefits will not be negated by the predicted reduction in natural aquifer recharge at least in the medium term (2041-2070).

Table 6-21 Comparison of historical and projected natural recharge to the additional recharge that could be achieved through MAR in these aquifers

Aquifer (Groundwater body in RH8)*	Historical Recharge Estimate (Mm^3/yr)	Projected Recharge RCP 4.5 2041-2070 (Mm^3/yr)	Reduction in recharge from historical to 2041-2070 (Mm^3/yr)	Potential Q_R from MAR (baseline) (Mm^3/yr)
M2 - ALMÁDENA - ODEÁXERE	9.921	9.007	0.914	0.8
M3 - MEXILHOEIRA GRANDE - PORTIMÃO	6.773	6.173	0.6	3
M4 - FERRAGUDO - ALBUFEIRA	10.371	9.772	0.599	0.9
M6 - ALBUFEIRA - RIBEIRA DE QUARTEIRA	7.613	6.902	0.711	4.5
M7 - QUARTEIRA	11.095	10.034	1.061	4.5
M18 - CAMPINA DE FARO - SUBSISTEMA VALE DE LOBO	2.944	2.649	0.295	0.5
M19 - CAMPINA DE FARO - SUBSISTEMA FARO	4.962	4.43	0.532	0.7
M13 - PERAL - MONCARAPACHO	9.197	8.263	0.934	0.9
M14 - MALHÃO	2.273	2.052	0.221	3.9
M15 - LUZ - TAVIRA	3.577	3.211	0.366	

*Aquifer recharge estimates only available for the aquifers considered to be groundwater bodies under the WFD.

In other aquifers the predicted volumes available for MAR are similar in magnitude to the predicted decreases in recharge under the RCP4.5 scenario, compounding the limitations of MAR in the M2, M4, M18 and M19 aquifers. It is expected that MAR would be more difficult to implement where the primary objective is to balance reductions in natural recharge, however, this could be considered particularly for M4 to maintain good status under the WFD into the future.

6.5.5 Regional Impact

Of the most suitable MAR schemes identified, a water resource benefit of 24 Mm^3/yr could be achieved, comprising 10% of the current total water use in the Algarve. In comparison to other strategic water resource options, desalination would provide 8 – 16 Mm^3/yr, a new river abstraction at Pomarão in the Guadiana basin pumped to storage in Odeleite / Beliche reservoir would generate 30 – 60 Mm^3/yr, and reuse of treated wastewater directly in irrigation is estimated be in the order of 20 Mm^3/yr. Therefore, MAR with these schemes can deliver water resources benefits of similar magnitude to the other strategic options being considered. This is discussed further in Chapter 8.

The next Chapter (Chapter 7) presents the numerical modelling of the case study - Vale do Lobo sector of the Campina de Faro aquifer.

Chapter 7: Case Study – Vale do Lobo Numerical Modelling

This Chapter is based on the published paper:

Standen, K., Hugman, R., and Monteiro, J. P. (2022a). Decision-Support Groundwater Modelling of Managed Aquifer Recharge in a Coastal Aquifer in South Portugal. Front Earth Sci (Lausanne) 10, 1–14. doi: 10.3389/feart.2022.904271.

and technical report of the Groundwater Modelling Decision Support Initiative (GMDSI):

Hugman, R., Doherty, J., and Standen, K. (2021). Model-Based Assessment of Coastal Aquifer Management Options. A GMDSI worked example report. South Australia doi: 10.25957/a476-x588.

This Chapter presents the development of a decision-support groundwater model in the Vale do Lobo sector (M18) of the Campina de Faro aquifer to determine whether MAR can increase groundwater levels sufficiently to protect the existing groundwater abstractions from SWI. The modelling is carried out using MODFLOW6 with linked recharge sub-models, with uncertainty quantification and reduction undertaken with tools of the PEST suite.

Although Chapter 6 concludes that the flows from Ribeira da São Lourenço are small in comparison to the overall deficit in the Vale do Lobo sector of the Campina de Faro aquifer (M18), there was considerable local interest from the regulator and groundwater users to determine whether MAR could be a feasible solution to over-abstraction in this small (32 km^2) coastal aquifer. As it was recognised that ephemeral flow would be insufficient, all local sources of treated wastewater were used for MAR in the modelling, recognising that appropriate levels of additional treatment prior to recharge would be required.

Details of the study area and conceptual model are provided in Section 7.1, an outline of the problem, modelling rationale and design are described in Section 7.2 and 7.3. The numerical model configuration is described in Section 7.4, the data assimilation and uncertainty quantification process in Section 7.5, with discussion and conclusions presented in Section 7.6.

7.1 Study area

The study area is located to the west of Faro, capital of the Algarve province of Portugal, and comprises the western part of the Campina de Faro aquifer system, known as the Vale do Lobo (VL) sector as shown in Figure 7-1.

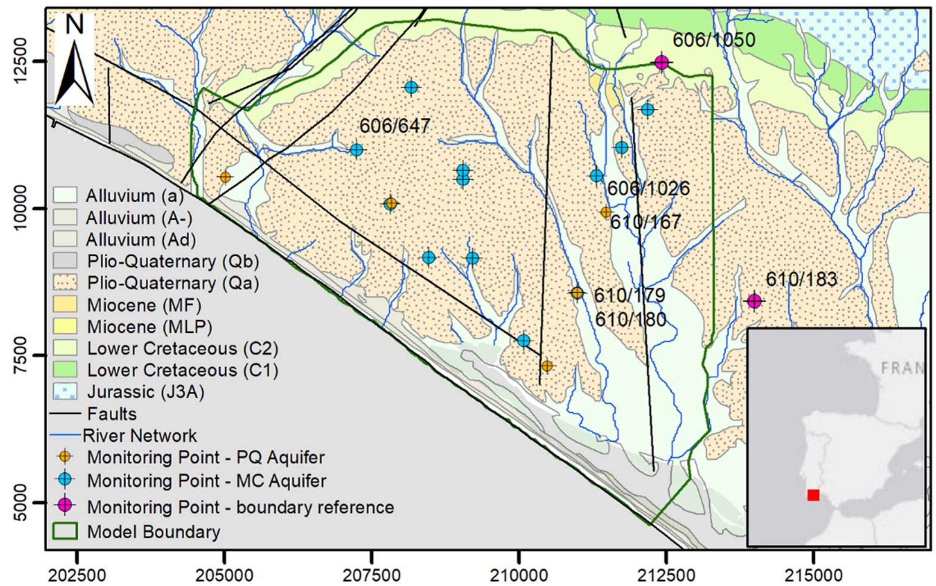


Figure 7-1 Location and main hydrogeological features of the Vale do Lobo aquifer system, including piezometer locations.

The aquifer covers an area of 32 km^2. Groundwater from this coastal aquifer has been used extensively for irrigation over the last 50 years, for golf, tourism, and agricultural purposes. Long term annual average rainfall is approximately 600 mm/yr largely falling between November and April, whilst potential evapotranspiration is approximately 1600 mm/yr with a substantial excess over rainfall during the summer months (DRAP-ALGARVE, 2021). Most irrigation is applied between the months of March and October and is almost entirely supplied from groundwater. Consequently, hydraulic heads are now below sea level across much of the aquifer (0 to -9 m above sea level (asl)), and several boreholes can no longer be used due to chloride concentrations of 927 – 2,242 mg/l measured in 2019 (Fernandes et al., 2020). Currently the VL sector does not meet the regulatory requirement of 'good' quantitative status under the EU WFD, where groundwater abstraction is required to be less than 90% of average annual recharge. The aquifer is at risk of further deterioration and losing 'good' status based on water quality considerations considering that the Portuguese threshold value for chloride is 250 mg/l (APA, 2016). Stakeholders are interested in understanding to what extent Managed Aquifer Recharge (MAR) can be part of the solution to reverse the decline in hydraulic heads and prevent further SWI, recognising that achieving an aquifer-scale solution to SWI is a very ambitious aim, likely to require a combination of methods.

The VL sector is bounded to the east by an administrative boundary which divides the western sector of the aquifer (at risk of SWI), from the Faro sector to the east, where the problems affecting groundwater status are related with excess nitrates due to agriculture (Stigter et al., 2011). These sectors were defined to enable appropriate independent measures for each sector to be defined in the River Basin Management Plans (RBMPs) (APA, 2016) to meet WFD requirements. To the northwest, the VL boundary is defined by the Carcavai fault zone. An outcrop of Lower Cretaceous strata forms the northern boundary of the VL sector, with Jurassic sediments forming a karstic aquifer further to the north.

The aquifer is formed of a thick sedimentary sequence of superimposed sedimentary basins of Mesozoic and Cenozoic age, underlain by Palaeozoic basement. The VL sector is comprised of two aquifer units, an upper phreatic sand to sandy clay aquifer of Plio-Quaternary (PQ) age, and a lower semi-confined aquifer of calcareous sandstones and limestones of mainly Miocene (MC) age, as shown in Figure 7-2. A clay aquitard, with an average thickness of 10 m, separates these two aquifers. The PQ is absent at the northern boundary of the VL and increases to a maximum thickness of around 70 m in the south-east, where it is postulated that PQ sediments infilled a karstic depression in the MC surface (Carvalho et al., 2012). The PQ is highly heterogenous with 5 distinct layers mapped (Manuppella et al., 2007).

Although deep borehole records are limited, correlation with offshore and onshore borehole logs suggest that the MC aquifer reaches a depth of 350 m below mean sea level at the coast. It is underlain by the same low permeability marls of Lower Cretaceous age that form the northern boundary of the aquifer (Lopes et al., 2006). In addition to the faulted north-western boundary of the aquifer, two NNW-SSE-oriented faults transect the eastern part of the VL area (Manuppella et al., 2007). Their locations are somewhat uncertain; it is possible that their alignment is closer to that of the streams than depicted in Figure 7-1. A strike-slip fault is also located parallel to the coast approximately 1 km inland.

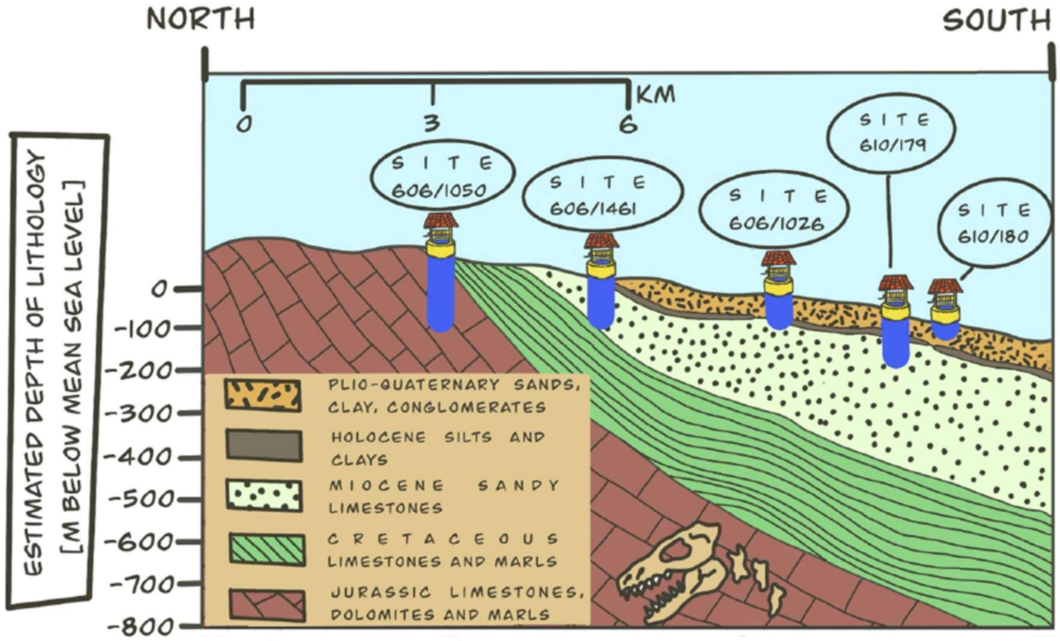


Figure 7-2 Conceptual cross section of the Vale do Lobo sector of the Campina de Faro aquifer, showing the location of key observation points and their depths (Juchem, 2021).

Most groundwater abstraction is now from the MC aquifer, although the PQ aquifer was exploited historically by shallow, large diameter wells (Almeida, 1985). Current groundwater abstraction is estimated at 6.45 Mm^3/yr (APA, 2020), based on measured abstraction for the major groundwater users, and estimated abstraction based on land cover and crop type for the smaller users who are not required to submit abstraction returns. Detailed borehole construction records are limited, and it is often unclear if, and where, abstraction is occurring from the phreatic aquifer.

The environmental regulator, the Agência Portuguesa do Ambiente (APA), estimates long term annual diffuse recharge to the VL sector is 3.46 Mm^3/yr . However, diffuse recharge is limited by the weathered red clays found at the surface, and it is recognized that a major, but unquantified, source of water to the aquifer is likely to be groundwater flowing laterally from the northern boundary from Cretaceous and Jurassic strata (Almeida et al., 2000; Hugman, 2016).

Hydraulic heads are regularly monitored by APA and are available for boreholes in the long-term monitoring network (SNIRH, 2021). Additional heads measured monthly by the groundwater users in piezometers and abstraction boreholes were also made available for use in this study. The location of hydraulic head time series used for history matching are shown in Figure 7-1.

Piezometric contours of the MC aquifer, along with selected hydraulic head time series, are shown on Figure 7-3 (A). The contours show that hydraulic heads are below sea level (between 0 and -9 m asl) across most of the aquifer, with the lowest values in the centre and north of the aquifer, resulting in radial flow towards this depression. Time series from three boreholes with the longest period of record are shown in Figure 7-3(B), indicating that hydraulic heads were already declining during the 1980's, possibly reaching a new equilibrium since the late 1990's with higher seasonal variation, in both the PQ and MC aquifers. Hydraulic heads in the PQ are only measured in 5 locations, but these generally show slightly higher heads with reduced seasonal fluctuations compared to heads in the MC. Piezometers 610/179 (MC) and 610/180 (PQ) are adjacent to one another and represent the only location where heads are measured simultaneously in both aquifers.

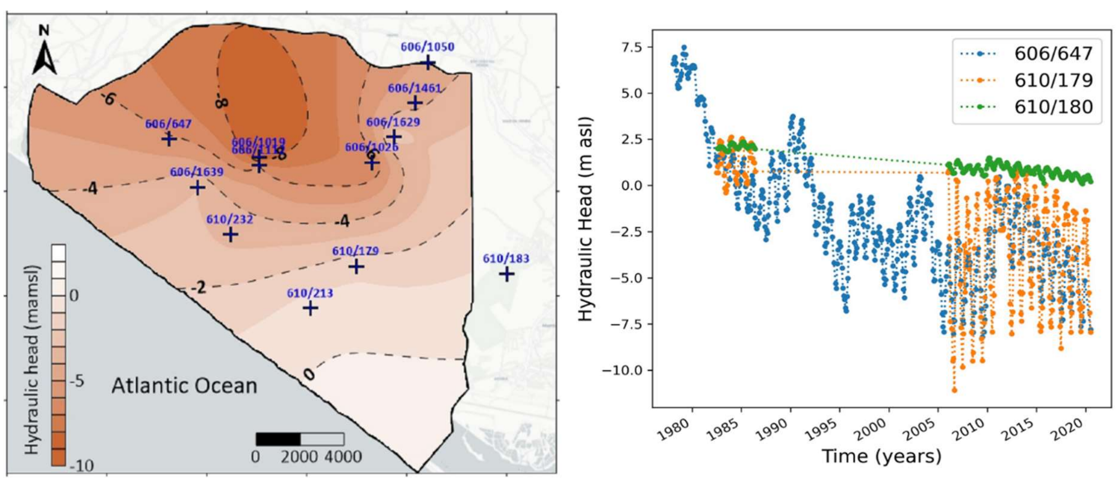


Figure 7-3 Hydraulic head contours from semi-confined aquifer, October 2018 (A), Selected hydraulic head time series at piezometer locations 606/647 (semi-confined), 610/179 (semi-confined), and 610/180 (phreatic) (B)

Time series measurements of chloride concentrations over time are only available at 4 locations in the VL sector, with 2 of these exhibiting increasing trends (SNIRH, 2021). A monitoring program during 2019/2020 encountered chloride concentrations up to 2,200 mg/l in abstraction boreholes, with land managers reporting that several boreholes are no longer used as their chloride concentrations are too high for irrigation (Fernandes et al., 2020).

Previous numerical modelling studies covering this area have included density-driven flow (DDF) models to investigate SWI (Hugman, 2016), assessment of nitrate contamination in the eastern sector of the Campina de Faro (Costa et al., 2021), and to assess the potential of using greenhouse runoff as water source for MAR (Costa et al., 2020). More recently, Hugman et al., (2021) investigated sustainable abstraction rates to avoid SWI, concluding that a reduction in abstraction of at least 70%, and possibly as much as 95% in the VL sector may be needed to prevent SWI.

7.2 The problem

It is clear the current rates of abstraction from the VL sector are unsustainable. Meeting the water balance requirement of the WFD will not prevent SWI. Without other mitigation measures, groundwater abstraction would need to be reduced to 30% of current rates in VL, possibly even less (Hugman and Doherty, 2022). This would be exceedingly difficult to achieve in practice. There are few viable alternatives, and these are expensive, e.g., replacing groundwater use with desalinated seawater.

MAR has been identified as a potential mitigation measure. However, additional treatment is likely to make it an expensive option, as the water available for MAR is limited, and legal issues would need to be overcome. Before committing to further investment in investigating MAR options, decision-makers need to understand whether it is likely to prevent SWI in this aquifer.

7.2.1 MAR design and water availability

Two types of water are potentially available for MAR in this area: (1) ephemeral river flow, and (2) treated wastewater. The Ribeira da São Lourenço (1) flows from north to south close to the eastern boundary of the aquifer, with average annual flow of 1.25 Mm^3/yr between 1996 and 2008. Flow occurs on average 77 days per year. No flow is recorded in some years. Preliminary MAR design limits the average MAR recharge from this source to 0.5 Mm^3/yr (Standen et al., 2022b).

Treated wastewater (2) is available from three treatment works in the area: Quinta do Lago, Vale do Lobo and Faro Noroeste. In 2020, available volumes were 0.76 , 0.16 and 1.50 Mm^3/yr respectively (written communication, Águas do Algarve, S.A.).

The preferred MAR design would employ surface infiltration basins recharging into the PQ, thereby avoiding direct injection into the MC, and allowing soil-aquifer treatment in the unsaturated zone. However, the current understanding of the permeability of the PQ and the presence of the aquitard suggests this option is unlikely to be feasible. Therefore, recharge is proposed by boreholes into the MC, at locations close to the water sources, as shown on Figure 7-4. All boreholes were had a maximum MAR recharge rate of 2500 m^3/d, with actual recharge depending on water availability. For MAR from Ribeira da São Lourenço a total recharge rate of 12,500 m^3/d was provided by 5 boreholes, each in separate, but adjacent grid cells.

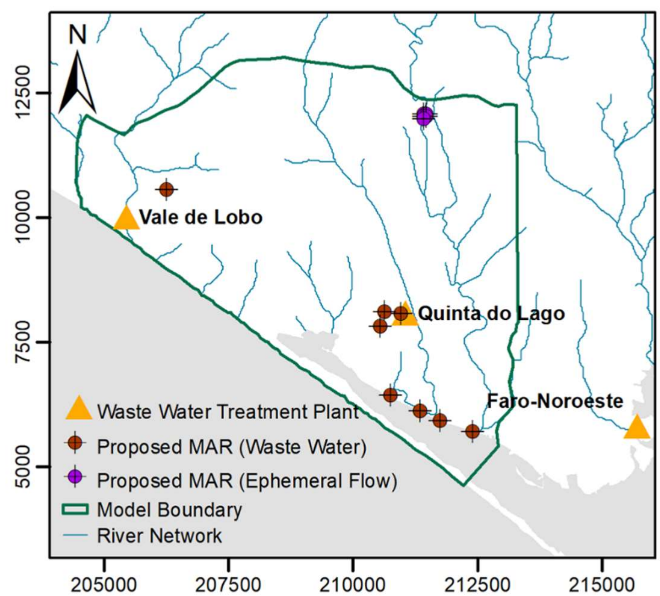


Figure 7-4 Locations of wastewater treatment plants, and proposed MAR borehole locations.

7.3 Modelling rationale and prediction

7.3.1 Rationale

To model the physical coastal aquifer processes requires density-coupled flow and transport models. These need fine spatial and time discretization, with typically very long run times, and are susceptible to numerical instability. They also require the offshore part of the system to be characterized and included in the model, yet these aspects of the system are often poorly known. Sharp-interface codes offer an alternative, but simulated outcomes can be quite sensitive to initial conditions, definition of the coastal boundary condition, and they still require the offshore portion to be modelled explicitly (Bakker and Schaars, 2013; Coulon et al., 2021).

To achieve a fast and stable numerical model, process complexity is reduced by using a constant-density model. It is assumed that the changes in density do not play a large role in the aquifer response during the simulation period. Although this simplification will introduce some error, this will likely be small in comparison to other sources of uncertainty in the model(Caers, 2011; Doherty and Moore, 2021). The prediction cannot be based on chloride concentrations; therefore, an alternative prediction is described in Section 7.3.2 below.

The model structure is simplified in terms of reducing the model layers and extent. The rigid structure of the offshore portion of the model is replaced by flexible parameters which represent the offshore extent. This allows us to stochastically account for the uncertainty in aquifer structure and properties offshore through physically abstract parameters. It removes the need for an offshore extent entirely, reducing the number of grid cells significantly, whilst also avoiding hard wiring assumed (but unknown) offshore structure and properties into the model. The number of layers is then limited to main hydro-stratigraphic units that are likely to control the hydraulic head response to the current pressures, and the proposed artificial recharge.

Initial assessment of the water volumes available compared to the estimated aquifer water balance indicates that these volumes may be insufficient to achieve the aquifer-scale improvements in hydraulic heads necessary to prevent SWI. However, given the uncertainties in the water balance, and the interest from regulators and stakeholders in MAR, the modelling presented herein investigates the feasibility of MAR in more detail.

7.3.2 The prediction

Modelling undertaken herein aims to determine whether MAR can prevent SWI, an ambitious but important aim. The depth of the fresh-seawater interface as a function of hydraulic head can be obtained using the Ghyben-Herzberg relationship (Bear and Verruijt, 1987), based on the assumptions of static equilibrium, stationary seawater, and assuming that a sharp interface exists between fresh and salt water:

$$\boldsymbol{z = \alpha * h} \tag{4}$$

where z is the position of the interface below sea level [m], α [-] is defined as $\rho_f/(\rho_s - \rho_f)$, where ρ_f [M/L^3] *and* ρ_s [M/L^3] are the fresh water and sea water densities respectively, and h is the hydraulic head [m]. The minimum value of hydraulic head that ensures the fresh-seawater interface does not rise above a specified depth can be calculated using equation 1.

The effectiveness of MAR is assessed on its ability to maintain hydraulic heads at levels that ensure that the interface remains deeper than a critical value at specified locations (e.g., deeper than the base of existing abstraction boreholes). This is admittedly a coarse metric. It ignores the effects of dispersion, the (potentially wide) transition zone between fresh and seawater, and up-coning in response to individual abstractions. However, it is a metric that allows preliminary assessment at the aquifer scale of the feasibility of the scheme. Modelling in this context cannot ensure that MAR will be successful; however, it can determine if MAR will not be successful. As the purpose of this exercise is to assess whether it is worth exploring these schemes further, such a prediction is sufficient, and more robust, than attempting to simulate the full complexity of processes and structure.

7.4 Numerical model development

The groundwater model was constructed using MODFLOW6 (MF6) (Langevin et al., 2021), using the open source Flopy environment (v.3.3.4) (Bakker et al., 2016). The model has three stress periods: an initial steady state period to obtain representative heads and abstraction rates for the start of the second stress period; a transient period from October 2000 to October 2020. A third stress period extends the model for 20 years incorporating MAR, with the same hydrological inputs and abstraction rates from the calibration period. It was not possible to start from a pre-development scenario, due to a lack of head data from this time.

The model was discretized with 400 x 400 m cell size, with quadtree mesh refinement applied using the open-source software, GRIDGEN (Lien et al., 2015). Cell sizes were reduced adjacent to potential drains and the MAR borehole locations. The model has 3 layers representing the phreatic aquifer, the aquitard, and the semi-confined aquifer (all layers were necessary to capture the hydraulic head response under MAR).To avoid discontinuous layers, the upper layer was assigned a minimum thickness where necessary.

The lumped parameter recharge model, LUMPREM (Doherty, 2021a), was used to estimate both recharge and groundwater withdrawal for irrigation, based on daily rainfall and potential evapotranspiration from the Faro-Patacão meteorological station (DRAP-ALGARVE, 2021). The LUMPREM model schematic and its' links to the MF6 model is shown in Figure 7-5.

Recharge is modelled in LUMPREM and applied to layer 1 (the phreatic aquifer) of the MF6 model, at rates depending on rainfall, irrigation, evapotranspiration, and the capacity and current volume of the soil-moisture store. Recharge occurs up to the potential evapotranspiration rate until the soil moisture store is empty, with rates decreasing as the volume of the soil moisture store decreases (the shape of this function is controlled by the gamma parameter). Transfer of rainfall-recharge to layer 3 (the semi-confined aquifer) is limited by the presence of the clay aquitard separating the two aquifers.

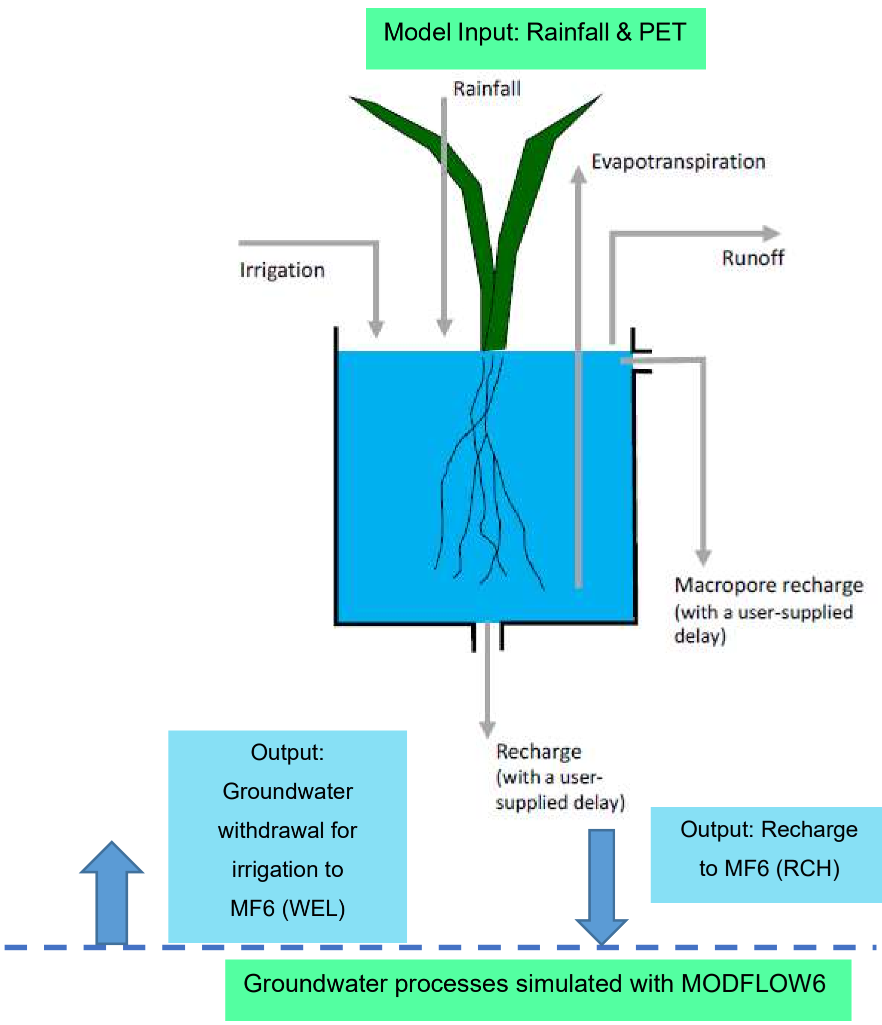


Figure 7-5 Aspects of the unsaturated zone water balance simulated by LUMPREM, and the links to MODFLOW6.

Using LUMPREM allowed estimation of groundwater abstraction based on irrigation demand, thereby accounting for missing abstraction data. It can be integrated with MF6 and PEST by the Python package Lumpyrem (Hugman, 2021). The combined model (MF6 + LUMPREM) includes LUMPREM models for each of the major groundwater users, the extensive agriculture (non-metered) group, and non-irrigated land. Recharge was applied to areas defined by grid intersection with the respective land uses. Total groundwater withdrawal for irrigation was applied as time-varying total abstraction rates for each group, these are then sub-divided between individual abstraction wells. The locations of irrigated areas and abstraction boreholes/wells are shown on Figure 7-6 in relation to the model grid and boundaries.

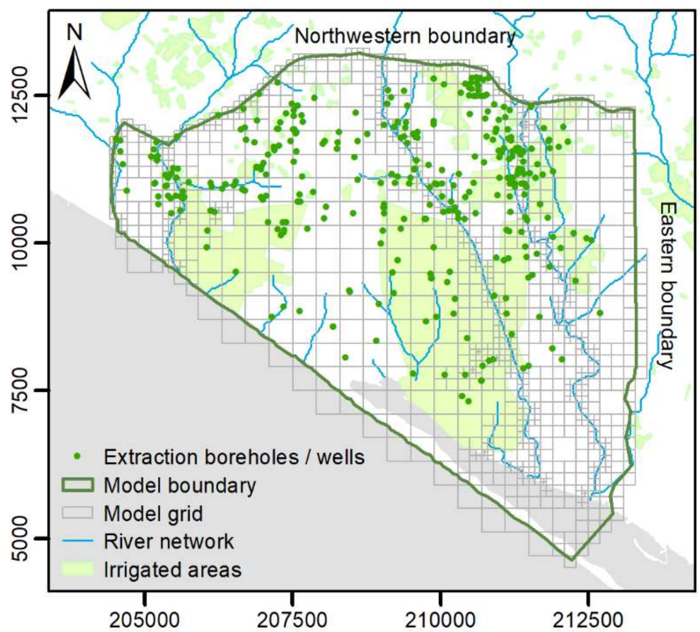


Figure 7-6 Irrigated areas and abstraction boreholes / wells, with model domain, grid and boundaries.

The inland boundaries are represented by Cauchy (i.e., general head) boundary conditions applied to the semi-confined aquifer. These represent the inflows to the MC aquifer from the Jurassic aquifer to the north, and the eastern sector of the Campina de Faro aquifer to the east). The heads vary according to time series measured at 606/1050 and 610/183 for the northwestern, and eastern boundaries respectively (at locations shown on Figure 7-1). Definition of the coastal boundary condition for the semi-confined aquifer is described in Section 7.4.1, whilst for the phreatic aquifer, a head correction of 1.0124 was applied, based on the method of Lu et al., (2015). For all the boundaries, conductance is time-invariant, as are heads for the coastal boundary.

7.4.1 Coastal boundary

As previously described, there is little to no data on hydraulic properties or system behaviour in the offshore portion of the aquifer system. Rather than attempt to simulate it explicitly, the offshore conditions are represented implicitly with a general head boundary, using the approach described in (Hugman and Doherty, 2022). This enables the model domain to be limited to the onshore portion of the system, where freshwater conditions are assumed to prevail. In turn, this allows us to ignore the effects of density differences and employ a fast-running model that enables data assimilation and uncertainty analysis.

General head boundaries require specification of head and conductance parameters. Conceptually, these parameters represent the linkage between the model and the offshore portion of the system. However, they omit the effects of changes in offshore storage and assume that the dynamics of offshore flow do not change significantly during the simulated period. As such, these head and conductance parameters take on a somewhat “abstract” nature. As they are no longer physically-based, these parameters are no longer useful recipients for expert knowledge. And as they are not informed by measured data, uncertainty can be large.

The approach described in Hugman and Doherty (2022) enables the transfer of expert knowledge to these abstract parameters using a simple-complex model pair. The “complex” model simulates physical processes which are omitted from the “simple” model. The complex model is simulated for an ensemble representative of stresses and hydraulic properties. Values for the abstract parameters in a corresponding “simple” are calculated for each realization. This allows the statistical distribution of abstract parameters to be characterized.

For the VL, this is achieved with use of a complementary two-dimensional DDF model (using SEAWAT (Langevin et al., 2008)) of the VL semi-confined aquifer. It was run for a long pre-development period (during which flow is towards the sea), followed by a post-development (land-ward flow) period. A total of 100 stochastic realisations were created, sampling from the prior probability distribution of aquifer properties and inland heads based on the aquifer conceptualization (expert knowledge).

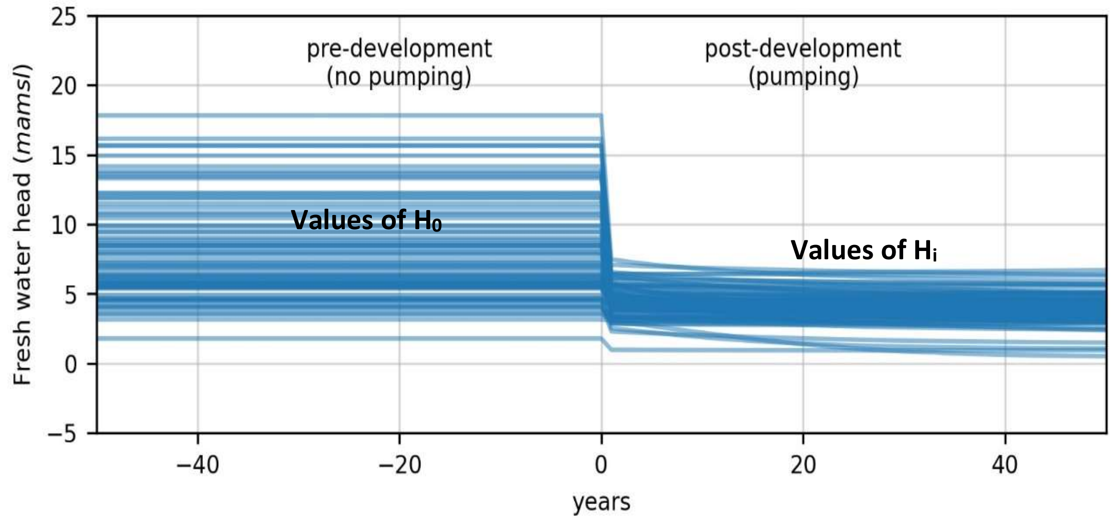


Figure 7-7 Simulated heads for the pre-development and post-development period at the coastal boundary demonstrating how the distributions of H_0 and H_i and corresponding values of q_0 and q_i were obtained (Hugman & Doherty 2022).

By recording head and flow for both pre- and post- development conditions for each realization as shown in Figure 7-7, values of head and conductance at the coastal boundary were obtained through the following equations:

$$q_o = (H_o - h)c \quad (5)$$

$$q_i = (H_i - h)c \quad (6)$$

for sea-ward flow and land-ward flow conditions respectively. These two equations can be solved for the two unknowns *h* and *c*. The solutions are:

$$c = \frac{q_o - q_i}{H_o - H_i} \quad (7)$$

$$h = \frac{q_o H_i - q_i H_o}{q_o - q_i} \quad (8)$$

Where H is the freshwater head at the coastline [m], q is groundwater flow under the coastline [m^3/d], and for a general head boundary along the coastline, h represents the head [m], and c the conductance [m^2/d]. The subscripts o and i represent outflow (pre-development) and inflow (post-development) conditions respectively. Values of H_o and H_i and values of q_o and q_i are obtained from the complex model for each realization. The mean and covariance of the heads and conductance can be calculated to form the combined covariance matrix:

$$C\left(\begin{bmatrix}\boldsymbol{h}\\ \boldsymbol{c}\end{bmatrix}\right) = \begin{bmatrix}\boldsymbol{\sigma_h^2} & \boldsymbol{\sigma_{hc}}\\ \boldsymbol{\sigma_{ch}} & \boldsymbol{\sigma_c^2}\end{bmatrix} \quad (9)$$

Where c is the value of $\log_{10}$ conductance [$\log_{10}$ m^2/d] at the coastal boundary, σ_h^2 is the variance of heads, σ_c^2 is the variance of $\log_{10}$ conductance, and σ_{hc} and σ_{ch} are the variance of head with $\log_{10}$ conductance, and the variance of $\log_{10}$ conductance with head respectively.

The values of h and c for a single point are used to characterize the full length of the coastal boundary by pilot points. However, values of h and c are expected to show some degree of spatial correlation along the boundary. Therefore, a joint probability distribution is required. Values were selected from a probability distribution that has the mean of $\begin{bmatrix}\underline{\boldsymbol{h}}\\ \underline{\boldsymbol{c}}\end{bmatrix}$ and whose covariance matrix is $\boldsymbol{C}\left(\begin{bmatrix}\boldsymbol{h}\\ \boldsymbol{c}\end{bmatrix}\right)$ based on a maximum distance over which spatial correlation could be expected, by specifying an exponential decay of h correlation with distance, i.e., an exponential variogram, from which a covariance matrix can be obtained using the PPCOV utilities in PEST. The mean values of this prior probability distribution, together with the covariance matrix, form the basis of regularized inversion through which model calibration is achieved. The coastal boundary condition parameters characterised in this manner are thus informed by expert knowledge. This enables representation of uncertainty, whilst constraining it as much as is reasonable.

7.5 Data assimilation and uncertainty quantification

7.5.1 Methods

For the combined model a solution of minimum error variance (MEV) was sought using PEST_HP (Doherty, 2020), employing a highly-parameterized approach. A unique solution was obtained using Tikhonov (preferred value) regularization. This was followed by history-matching and uncertainty quantification (and reduction) using PESTPP-IES (White, 2018).

7.5.2 Parameterisation and prior information

An array of 962 pilot points distributed across the model domain, layers and boundaries allowed spatial variation of parameters. For aquifer properties these included horizontal hydraulic conductivity (K) for all layers (and thus for ratio-linked vertical hydraulic conductivity), specific yield (layer 1), and storativity (layer 3). Pilot points were placed manually, located between observation points and abstraction well/borehole locations, and between these features and the model boundaries. Pilot points were also included along model boundaries and drains to allow spatial variation in boundary condition parameters.

Recharge and groundwater withdrawal for irrigation vary by land use zones linked to LUMPREM models, the parameters of which are adjustable. Prior to coupling LUMPREM and MF6, LUMPREM model parameters were first calibrated against measured abstraction rates. Obtained values were subsequently used as initial parameter values when calibrating the combined model. LUMPREM provided a time series of groundwater abstraction totals for each major groundwater user, and these were subdivided into groundwater abstraction rates at each abstraction point with a multiplier. As the abstraction rates at each well were unknown, the multipliers were allowed to vary if needed during the calibration process.

The prior estimates of parameters, including the LUMPREM parameters, are shown in Table 7-1, with the mean of the prior probability distribution representing preferred values in the regularization. The model is parameterized with a total of 1,437 adjustable parameters. Parameter field uniqueness is achieved through numerical regularization which seeks minimum departure of each parameter from a user-specified “preferred value”. For spatially varying parameters, covariance matrices are used instead of regularization weights to ensure smoothness of emergent parameter fields.

Table 7-1 Prior parameter summary

Type	Number of parameters	Mean of Prior Probability Distribution	Lower Bound	Upper Bound	Log_{10} Standard Deviation	Mean of Posterior Probability Distribution	Log_{10} Standard Deviation
Hydraulic conductivity, horizontal, layer 1	141	0.5	1.0E-04	1.0E04	0.5	0.65	0.47
Hydraulic conductivity, horizontal, layer 2	141	0.1	1.0E-04	1.0E04	0.5	0.13	0.45
Hydraulic conductivity, horizontal, layer 3	141	10	0.0001	10,000	0.5	11.41	0.39
Specific yield, layer 1	141	0.1	0.01	10,000	0.173	0.110	0.170
Storativity, layer 3	141	1.0E-05	1.0E-08	1.0E-03	0.5	4.75E-06	0.49
GHB Conductance, Layer 3, NW boundary	22	100	0.0001	10,000	1.25	93.72	1.22
GHB Conductance. Layer 3, E boundary	17	100	0.01	10,000	1.25	1220.23	1.25
GHB Conductance, Layer 1, Sea boundary	21	5.00	0.001	10,000	1.25	6.78	0.24
GHB Conductance, Layer 3, Sea boundary	21	0.645	0.01	10,000	0.515	0.646	0.516
GHB Head, Layer 3, Sea boundary	21	5.47	1.00	10,000	0.275	5.46	0.271
Drain Conductance	155	1.0	0.01	10,000	0.5	1.0	0.50
Individual well multipliers*	197	0.008 – 1.0	1.0E-6 - 0.008	0.1 - 1.0	1	0.001 - 0.979	0.99
LUMPREM – IRVF	8	0.29 – 0.6	0.1	0.8	0.25	0.1 – 0.8	0.11
LUMPREM – gamma	8	0.54 – 1.0	0.01	10.0	0.75	0.37 – 10.0	0.62
LUMPREM – crop factor	8	0.48 – 1.2	0.1	3.0	0.125	1.16 – 3.0	0.11
LUMPREM – Ks	9	0.1	0.0001	10.0	1.25	0.01 – 1.43	0.72
LUMPREM – l	9	0.26 – 0.54	0.2	0.8	0.125	0.2 – 0.8	0.12
LUMPREM - m	9	0.38 – 0.55	0.01	2.0	0.5	0.1 – 2.0	0.25
LUMPREM - scale	8	0.4 – 1.0	0.01	10.0	0.75	0.4 – 1.0	0.75
Recharge scale	7	0.125	0.01	1.0	0.75	0.01 – 0.30	0.45

*Initial value for individual well multipliers obtained by dividing the total 1.0 by the number of wells in the abstraction group. Upper bounds limited in certain abstraction groups to avoid a single well representing too large a fraction of abstraction from each group.

7.5.2.1 Observations and weighting

In total, 5103 observations were included as history matching targets. A total of 12 hydraulic head time series from the semi-confined, and 5 from the phreatic aquifer were used as history-matching targets. At one location, head differences between the two aquifers were also included as observations (610/179 and 610/180 in Figure 7-3 (B)). Metered quantities of groundwater abstraction reported to APA from 2010 onwards were also included as observations.

First-order temporal variations were calculated by subtracting each observation from the previous observation, giving equal importance to the temporal changes in the observation borehole time series as the actual measurement value (White et al., 2014; Foster et al., 2021; Hugman et al., 2021).

Soft data was also incorporated, with drains set at ground level across the entire model domain, and observations of zero flow included, where appropriate.

The weighting scheme aimed to give equal importance to matching of heads and abstraction rates in the history-matching process. Heads were sub-divided into several observation groups to increase the weight of boreholes in different layers, and those that exhibited different responses. Groundwater abstraction observations also were sub-divided to account for large difference in the temporal resolution of observations between the groups.

7.5.2.2 History matching and uncertainty quantification

The PESTPP-IES iterative ensemble smoother generates alternative, calibration-constrained, parameter realizations, by sampling from a selected probability distribution (White, 2018). The parameter realizations are then iteratively adjusted until the model outputs attain a better fit to observations. In this case, the linear approximation to the posterior probability distribution was used as the starting point for PESTPP-IES, as often this can provide a better starting point for the process (Gallagher and Doherty, 2020).

Noise was added to the non-zero weighted observations by replacing the observation weights used during the history matching process with the inverse of the standard deviation of measurement noise. These were applied to heads (0.1 m) and pumping rates (0.5 – 2.5 m^3/d), with larger uncertainty applied to the non-metered groundwater users. The PEST utility RANDOBS was used to generate realisations containing noise-enhanced observations. The number of realisations (200) was selected to be more than double the number of uniquely identifiable pieces of information in the calibration dataset (90) identified by the PEST utility SUPCALC (Doherty, 2021b) following other recent studies (Hayley et al., 2019).

7.6 Results

7.6.1 Calibration

The resulting MEV parameter set achieved a good fit to measured observations of both hydraulic heads and groundwater abstraction. In general, a better fit was obtained for heads in the semi-confined aquifer compared to the phreatic (as shown in Figure 7-8). This is not surprising, as there are fewer head observation points in the phreatic aquifer. The PQ formation is known to be highly heterogeneous, and it is difficult to determine if, and where, abstraction is occurring from this phreatic aquifer. As the fit of 610/167 only improved once abstraction was permitted from both aquifers, this suggests that abstraction is occurring from the PQ in this area.

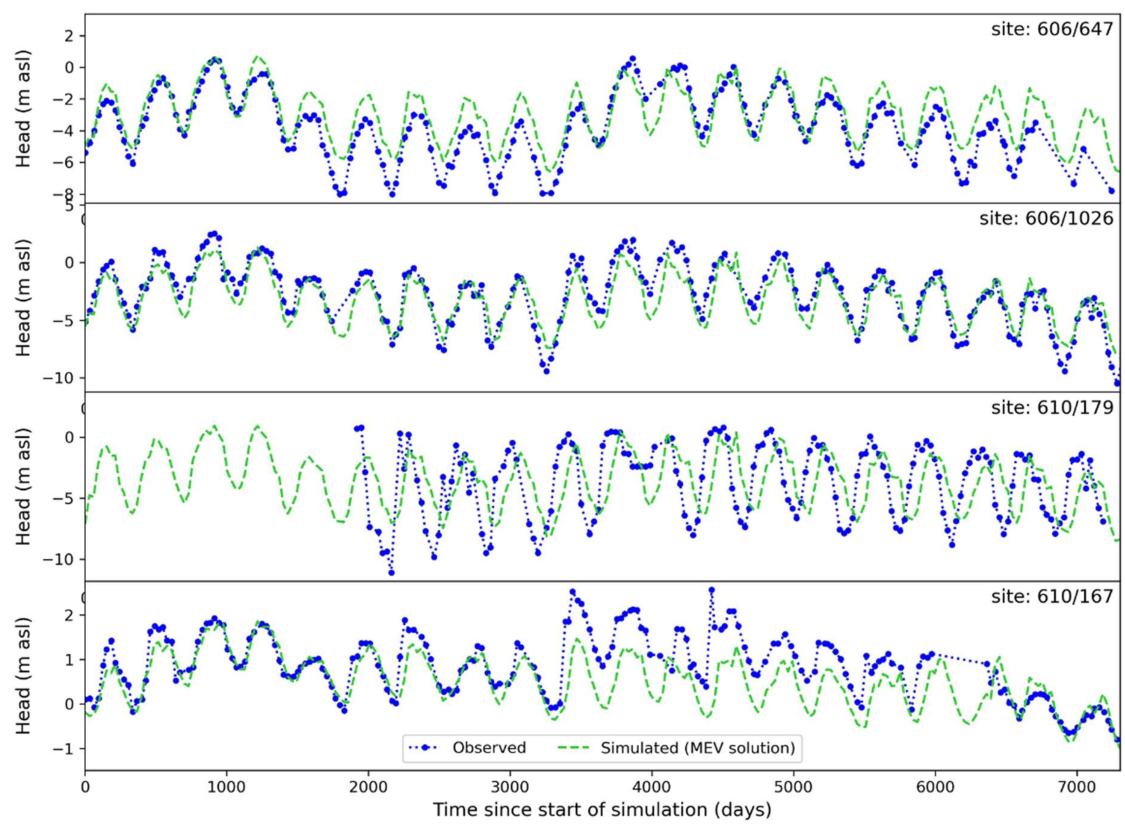


Figure 7-8 Measured and simulated hydraulic heads for 606/647, 606/1026 and 610/179 from the semi-confined aquifer, and 610/167 from the phreatic aquifer.

Simulated and observed abstraction rates are shown in Figure 7-9. In general, simulated abstractions match measured abstractions well, particularly in the central and eastern parts of the model.

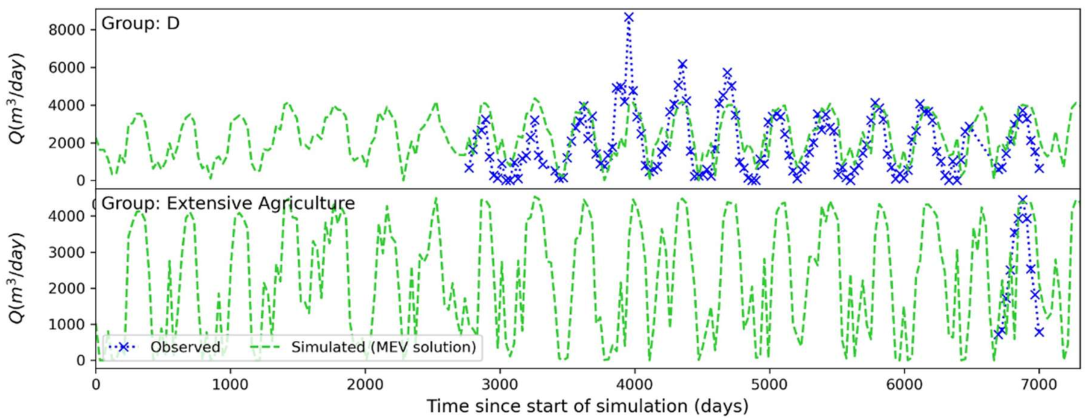


Figure 7-9 Measured and simulated abstraction rates for user group D, and the extensive agriculture group.

Calibrated total annual average recharge values of 0.33 to 0.59 Mm^3/yr, with an average of 0.44 Mm^3/yr, were obtained. These values are an order of magnitude lower than the APA estimate (3.46 Mm^3/yr), which has been recognised as an over-estimate by several authors (Almeida et al., 2000; Hugman, 2016). The calibrated recharge values reflect the conceptual understanding that weathered red clays at the ground surface are of low permeability, limiting diffuse rainfall-recharge to the phreatic aquifer. The lowest recharge rates occur under the non-irrigated land (2 mm/yr), which accounts for 25 km^2 of the total 32 km^2. The other land uses have higher recharge rates (4 – 295 mm/yr) and include irrigation return. Diffuse recharge is largely prevented from reaching the semi-confined aquifer by the presence of the aquitard, with the majority of inflow occurring at depth from the adjacent aquifer systems.

7.6.2 History-matching

Of the 200 realizations, 138 resulted in model convergence. The remaining model runs generally failed due to convergence issues related to drying of the upper layers. History matching results are shown in Figure 7-10 for the same piezometers as Figure 7-8, along with the MEV results. The ensemble encompasses almost all the observations, apart from piezometer 610/179 where heads recover earlier in the year than the model predicts, indicating that abstraction in this location perhaps ceases earlier in the year than expected by the soil-moisture balance. The ensemble resulted in a wider distribution of heads in the phreatic aquifer, as shown by 610/167, where although the temporal variation in heads matches the measured data well, there is a large range of predicted groundwater levels in this location. This occurred despite increasing the weight of the phreatic aquifer observations.

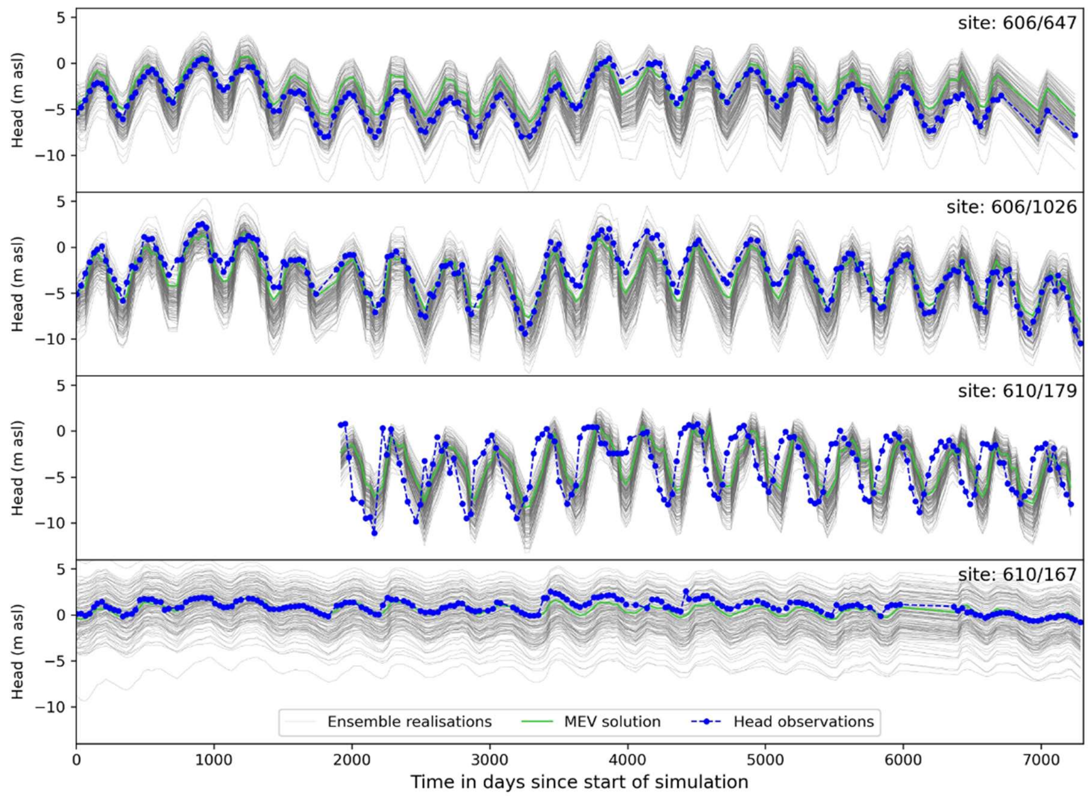


Figure 7-10 Measured and ensemble of simulated hydraulic heads for 606/647, 606/1026 and 610/179 from the semi-confined aquifer, and 610/167 from the phreatic aquifer.

7.6.3 Insights from linear analysis

The spatial distributions of hydraulic conductivity for each layer from the MEV parameter set are plotted in Figure 7-11, along with the corresponding values of the relative parameter uncertainty variance reduction (RUPVR) (Doherty, 2021b).

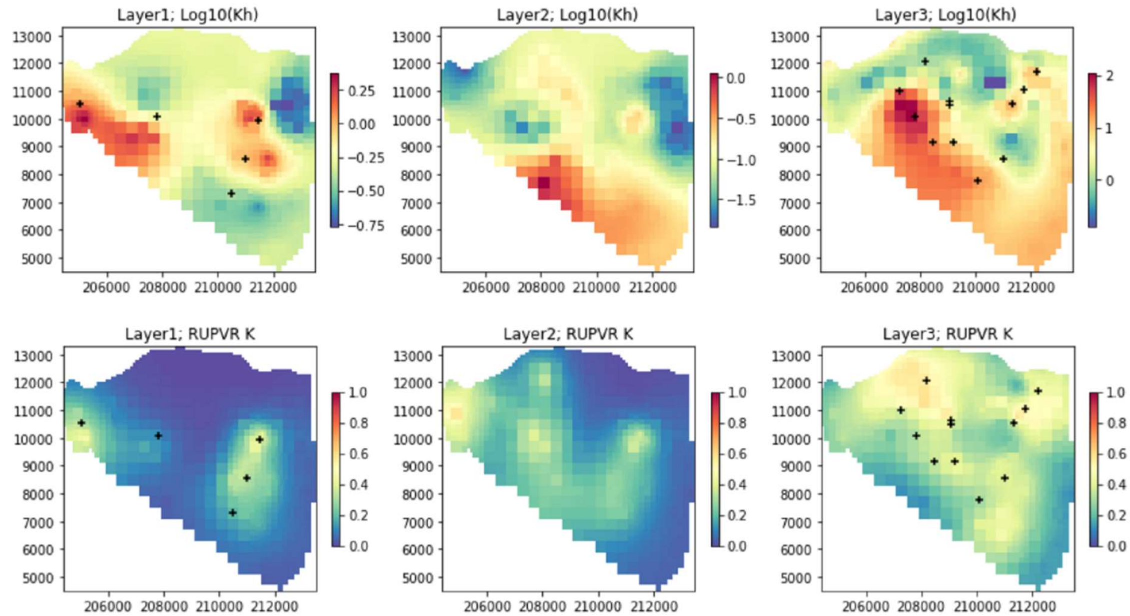


Figure 7-11 Spatial distribution of (log) hydraulic conductivity in layers 1 (phreatic), 2 (aquitard) and 3 (semi-confined) (top, left to right), and RPUVR of hydraulic conductivity in layers 1, 2 and 3 (bottom, left to right), location of hydraulic head observations for each layer indicated by black crosses.

This ratio varies from 0 to 1, with higher values indicating the locations where posterior parameter uncertainty has been reduced in comparison to the prior during history-matching. Of particular interest is the area in the centre of the model, which appears to have relatively higher K in both layer 1 and layer 2, where the RPUVR shows that the uncertainty has been reduced to a greater extent than the surrounding area. This is an important insight, which could justify further site investigation for a potential infiltration basin MAR scheme in this location.

Values of RUPVR were low for pilot points along the boundary conditions, with mean values of 3×10^{-2} to 6×10^{-6} obtained for conductance and head values, indicating that history matching was not effective in reducing uncertainty in the boundary condition parameters, outlining the importance of constraining the prior probability distributions by the method described in Section 7.4.1.

7.6.4 MAR scenario results

The impact of MAR at the locations denoted Marsl (Ribeira da São Lourenço), Marww1 (Quinta do Lago), Marww2 (Vale do Lobo) and Marww3 (Faro Noroeste) is shown in Figure 7-12, where the ensemble of predicted heads is plotted against the minimum head required at each location. Results at abstraction boreholes are not shown, as the impact of MAR is negligible.

At Marsl, the heads are highly dependent on the variability of ephemeral flow, with large increases occurring during recharge periods. However, these are short-lived, falling rapidly to levels similar to the minimum head requirement when additional recharge is not occurring. This indicates that MAR is probably not necessary at this location; a location further downstream would be more beneficial.

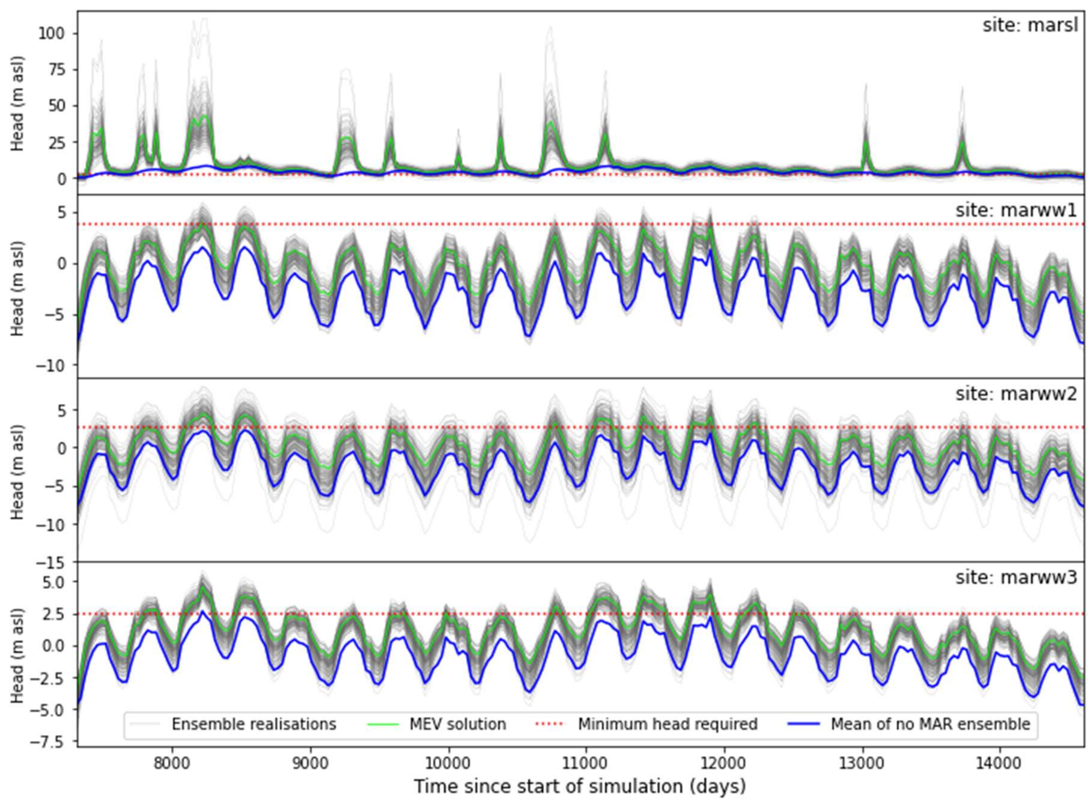


Figure 7-12 Predicted hydraulic heads at MAR locations, showing MEV model results (green), each ensemble member (grey), mean of ensemble (blue), and the minimum head requirement at that location (red dashed).

At the other MAR locations, the minimum head requirement is only met during limited times and for some realisations. A no-MAR scenario was run to identify the head improvements resulting from MAR. The time-averaged head differences show only limited improvement in hydraulic heads as shown in Table 7-2 (averages are not appropriate for Marsl due to the ephemeral flow variability and are not presented).

Table 7-2 Average head differences (m) at MAR locations during 20-year simulation period (MAR scenario minus no-MAR scenario)

Location	5th Percentile	Mean	95th Percentile
Marww1	0.78	2.03	3.36
Marww2	0.28	2.01	3.80
Marww3	0.77	1.62	2.80

Time series of head differences (Figure 7-13), indicate that head improvements occur rapidly after the implementation of MAR.

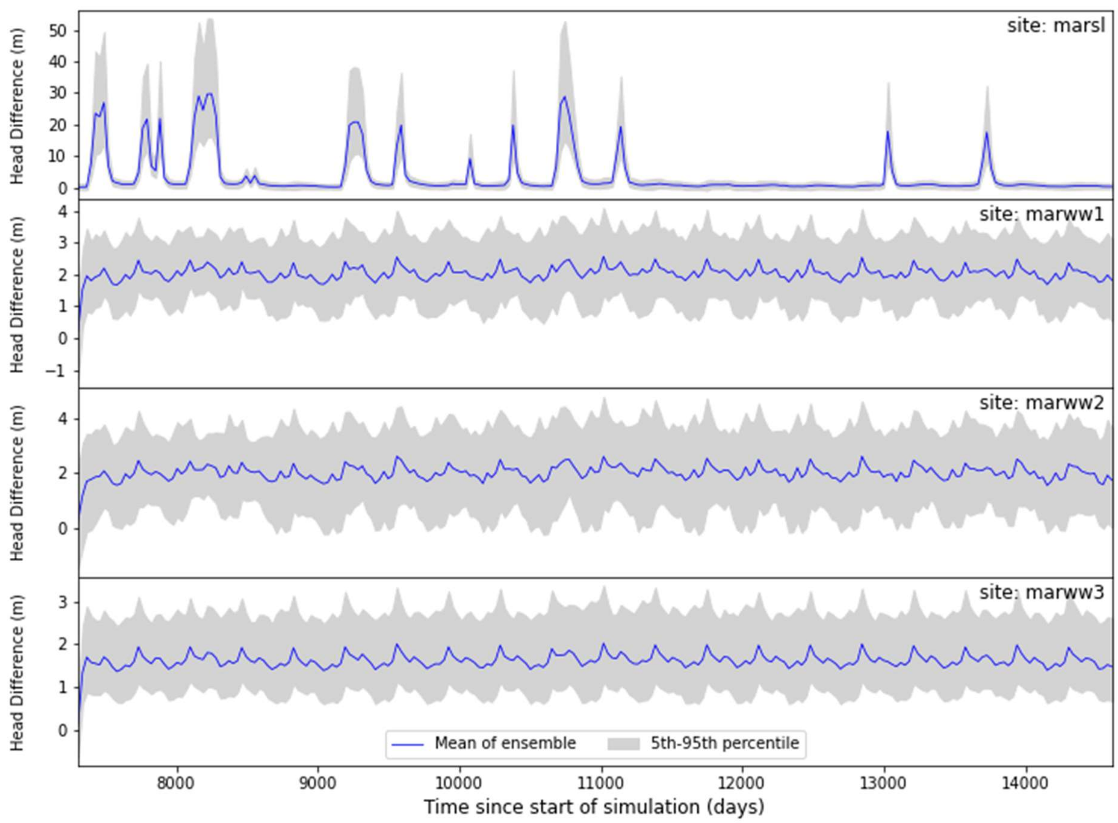


Figure 7-13 Head differences during prediction stress period based on MAR scenario minus No-MAR scenario, with mean of ensemble (blue), and 5th - 95th percentile of ensemble members (grey fill).

These results raise the question whether it is possible to reach the minimum heads under any scenario, remembering that heads for the pre-development period are unknown. This was examined by undertaking an additional scenario with no abstraction (and no MAR). The minimum heads required at each abstraction borehole were compared to the predicted heads

(5th percentile of the ensemble) at those locations, confirming that the minimum heads could be met with a small number of exceptions as shown on Figure 7-14 and in Table 7-3.

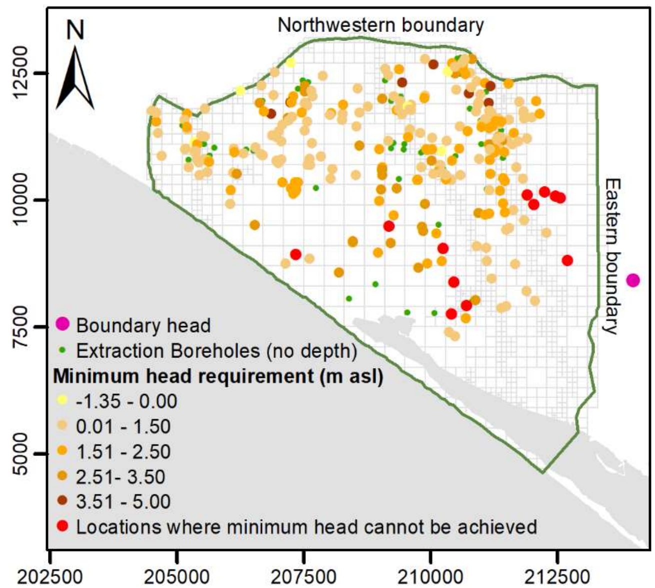


Figure 7-14 Map showing minimum head requirements based on existing abstraction borehole locations, indicating where under the 'No abstraction, No MAR' scenario, minimum heads protective of saltwater intrusion cannot be met (red circles) when compared to 5th percentile of ensemble. Abstraction boreholes included in the model, but where a minimum head requirement cannot be estimated due to lack of borehole construction information are also shown (green dots).

Table 7-3 Minimum heads, mean and 5th percentile of ensemble, and abstraction borehole depths where the minimum head requirement cannot be met under the 'No abstraction, No MAR' scenario (values in bold indicate where minimum heads cannot be met)

Location Reference	Abstraction borehole depth (m)	Minimum head requirement (m asl)	Mean of ensemble predicted heads (averaged over prediction stress period) m asl	5th percentile of ensemble predicted heads ((averaged over prediction stress period) m asl
610/168	170	3.83	**3.79**	**3.15**
610/146	85	1.88	**1.48**	**1.30**
610/203	200	4.50	**4.09**	**3.43**
606/1381	180	4.35	**2.16**	**1.70**
606/1382	178	4.15	**2.16**	**1.70**
606/1383	196	4.50	**2.72**	**2.10**
610/236	106	2.50	2.91	**2.27**
610/255	150	3.38	3.50	**2.93**
610/195	150	3.45	3.62	**2.99**
606/532	120	2.83	3.10	**2.36**
610/170	181	4.26	4.52	**3.72**
610/234	170	4.15	4.84	**3.93**

These occurred where abstraction boreholes are deep (up to 200 m), or where the boreholes were located close to the eastern boundary. Here, the average heads are already low (1.1 m asl), preventing the minimum head requirement from being met close to the boundary. This provides confidence that somewhere between no-abstraction and current abstraction plus MAR, a management solution to protect the aquifer exists.

7.6.5 Summary

For the VL sector, the results showed that MAR using the Ribeira da São Lourenço and the local sources of wastewater was insufficient to increase water levels in the aquifer to prevent SWI at the current abstraction boreholes. A significant reduction in groundwater abstraction, and/or a significant increase in the water available for MAR would be needed to prevent SWI. These results are further discussed in the main discussion and conclusions in Chapter 8.

Chapter 8: Discussion & Conclusions

The Chapter discusses the results from Chapters 4 to 7, in relation to the research questions developed for this thesis:

1. Can an aquifer-scale benefit be achieved by using in-channel MAR methods, and if not, what are the alternatives?
2. Can a regional assessment methodology be developed to quantify the potential for MAR in the Algarve, and to what extent can MAR support the current water resource system?
3. Can numerical models support decision-making for MAR in coastal aquifers, and what adjustments need to be made to these models to quantify and reduce their predictive uncertainty to allow the benefits of MAR to be determined?

The discussion surrounding research question 1 is presented in Section 8.1, along other important aspects relating to implementation of MAR in the Algarve. Research question 2 is discussed in Section 8.2, divided into a discussion of the MAR potential in the Algarve, and a discussion on the methodology. Research question 3 is discussed in Section 8.3, again split into the implications for the Vale do Lobo sector, and a discussion of the methodology and its wider applicability. Finally, the limitations of the studies are presented and areas for future research or investigation are highlighted.

8.1 MAR in the Algarve

Although MAR is mentioned in the WFD legislation as a potential water management solution, there is currently no pathway to obtaining a licence for MAR in Portugal. It is hoped that this will change in the future, given the recent government resolution to promote MAR as a solution to drought and water scarcity providing the risks can be managed. One route to implementation could be that MAR be permitted or promoted under Article 31 of the Water Law, through a Specific Water Management Plans (Planos Específicos de Gestão das Águas (PEGA), perhaps for a group of aquifers where MAR can be beneficial.

All potential sources of water were considered for MAR in the Algarve. Ephemeral rivers were found to have the largest available volumes and are widely distributed across the

Algarve region. If 20% of the annual average river flow were captured, 26 Mm^3/yr could be recharged.

Although large volumes of treated wastewater are available ~20 Mm^3/yr, a preferable alternative use exists in direct reuse for irrigation, for which a regulatory and management approach has already been developed. Given the lack of a licensing process for MAR, it is considered that MAR is more likely to be successful if good quality water is used that meets the Groundwater Directive, therefore there are strong reasons for not considering MAR with treated wastewater at this stage.

Surface water quality of ephemeral river flows has been found to meet the requirements of the Groundwater Directive with only rare exceptions, and MAR with this source of water should not present undue risks to achievement of good water quality status for the receiving groundwater body. No water quality concerns were identified at the majority of locations, and only water from Ribeira de Bensafrim (catchment 1) regularly fails to meet the groundwater threshold values (for NH_4, chloride and pesticides), and may be unacceptable to use for MAR.

Whilst in-channel MAR brings clear local benefits in terms of increasing groundwater levels, improving groundwater quality, and allowing increased use of groundwater for irrigation, the meta-analysis found less evidence that regional water resource benefits could be achieved. With an approximate 1:1 relationship between recharge dam storage capacity and annual recharge, extremely large dams would be needed in the Algarve to achieve water resource benefits of appropriate scale. In-channel MAR is further limited by the lengths of rivers crossing permeable aquifers, the need to avoid tidal sections of rivers, the location of rivers at the boundaries of permeable aquifers and along faults, and finally, the presence of extensive low permeability alluvial deposits.

Flood-MAR or Ag-MAR were also considered for the Algarve but found unsuitable as the main permanent crops in the region (citrus and avocado) have roots that cannot tolerate standing water. Furthermore, a recent study also indicated that up to 37% of water recharged by this method becomes held in the vadose zone, being unavailable either to plants or to capture by boreholes even after 2 years of recharge (Perzan et al., 2022). This indicates the importance of direct recharge to the saturated zone (i.e., with boreholes) to avoid such losses, especially where the source water is of good quality and no further treatment is needed in the unsaturated zone.

Therefore, the most suitable MAR recharge methods to achieve water management objectives, and maximise the recharge capacity are:

- Infiltration basins (or trenches)
- Boreholes
- Large diameter wells

A challenge for the Algarve is to maximise recharge capacity, with minimal land use, given the high costs of land in the coastal strip of the Algarve. Therefore, the use of boreholes or the reuse of existing large diameter wells where possible is preferred.

8.2 Regional MAR potential

8.2.1 Quantification of regional MAR potential

MAR using ephemeral river flow as the water source can achieve a regional water resource benefit of at least **24 Mm^3/yr**, or **10%** of the current water use in the Algarve, with unit costs lower than almost all other feasible water resource options, by the implementation of 6 individual schemes as shown in Figure 8-1. An important finding is that there is significant potential for MAR to support the surface water-fed irrigation perimeters that has not previously been considered in the Algarve. Employing ASR in the aquifers underlying or adjacent to the irrigation perimeters to provide seasonal (and inter-annual) storage can reduce the reliance on surface water in the major reservoirs, saving **15 Mm^3/yr** for other sectors.

Two of the most promising MAR options are to support the Sotavento irrigation perimeter, where MAR could form 28% of the 22 Mm^3/yr irrigation demand, and the Mira irrigation perimeter, where MAR (in RH8) could form more than 100% of the local irrigation demand, or 20% of the total irrigation demand on the Santa Clara dam.

To support Sotavento irrigation perimeter, a distributed MAR scheme using flows from the Ribeira de Alportel and Ribeira de Almargem to recharge into M13 (Peral - Moncarapacho), M14 (Malhão), M15 (Luz – Tavira) and in the shallow aquifer east of Tavira. In total it is estimated 6.2 Mm^3/yr additional recharge could be achieved. There are around 70 existing large-diameter wells recorded in both M15 and in the area east of Tavira, indicating that these could potentially be used for MAR recharge and subsequent abstraction.

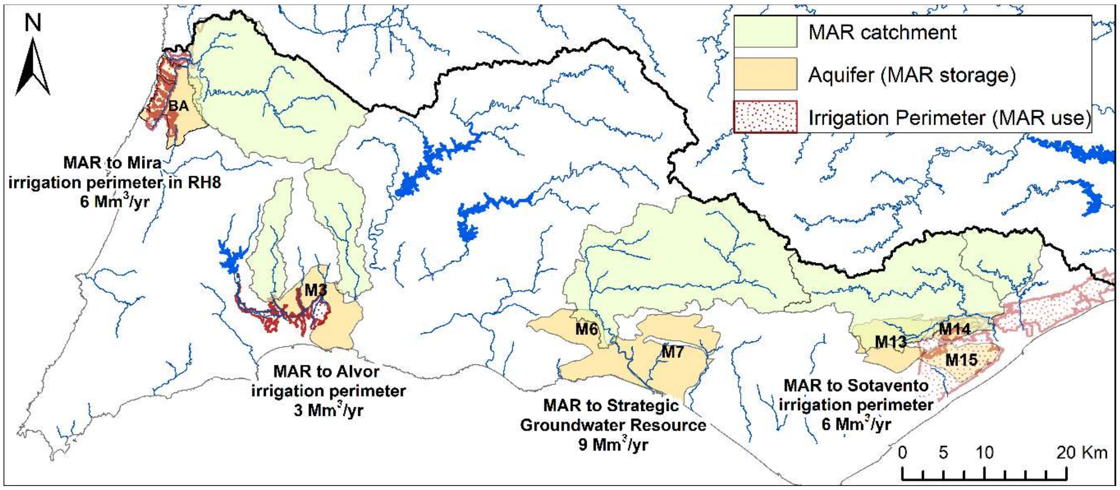


Figure 8-1 Summary of the major potential MAR opportunities for the Algarve Region, Portugal.

There also appears to be significant potential for MAR further north in RH6. In these areas, the water sources have large catchments and high annual average flows, meaning that they are more likely to be resilient to climate change. Potentially MAR could be considered as part of one of the strategic water resource options described in the RWEP, where a transfer from Santa Clara into the multi-municipal system is being considered via the Canal do Rogil. Using water captured for MAR in this area would reduce the impact on Santa Clara reservoir from this option.

MAR in M3 (Mexilhoeira Grande – Portimão) could be used to replace part of the Bravura supply to the Alvor irrigation perimeter respectively. MAR could provide a solution that could potentially be implemented more quickly and at lower cost than direct reuse of treated wastewater, that is also more sustainable than short-term reactivation of groundwater supplies (although MAR could also be used to support this objective). MAR could provide an additional water resource benefit of 3 Mm^3/yr in this area, or 32% of the total irrigation demand of the Alvor irrigation perimeter (9.5 Mm^3/yr).

These savings would reduce the demand on Odeleite, Beliche, Bravura and Santa Clara reservoirs, as well as delivering wider benefits due to the multi-municipal system which can enable water saved from the irrigation perimeters to be supplied to other users (such as urban water supply) without major changes to the water supply infrastructure. One possible mechanism for developing MAR in these areas is for MAR to be implemented and managed by the irrigation associations as they control the current water supplies to the irrigators. Water recovered from MAR storage can then be supplied into the same network, reducing the demand on the surface water reservoir. Incentives may be needed given the cost of implementing MAR is likely to be higher than the current costs of using surface water, considering that the benefits would be realised by all sectors using the surface water dams.

A second important finding is that MAR can also be used to develop and maintain a strategic aquifer resource of around **9 Mm³/yr** in M6 (Albufeira – Ribeira de Quarteira) and the adjacent M7 (Quarteira) for use during drought periods by implementing ASR with water from Ribeira de Quarteira. A network of supply boreholes could re-abstract the water during significant droughts into the multi-municipal network for public supply, following appropriate water treatment. It is not envisaged that this would be used every year, but kept in storage for use during major inter-annual droughts, during which time a decrease in groundwater levels and groundwater storage would need to be accepted, on the proviso that during wet years MAR will recharge the aquifer when needed (in a similar manner to the North London Artificial Recharge scheme in the UK (Jones et al., 2021). For this to be successful, control of existing (and any future) groundwater abstractions close to the scheme is vitally important for this water to be available when needed.

Although climate change is expected to reduce natural recharge by around 10% in the aquifers of the Algarve (RCP4.5, 2041-2070), it has been shown that MAR recharge predicted in M3, M6, M7, M14 and M15 is significantly higher than the expected reductions in natural recharge. This gives confidence that the water resource benefits of MAR to the irrigation perimeters, and to the creation of a strategic resource, can be achieved even once climate change impacts to natural recharge are considered. In other aquifers (M2, M4, M18, M19) predicted MAR recharge is of a similar magnitude to the predicted reduction in natural recharge. This provides an opportunity for MAR to be employed, particularly in M4, to maintain good quantitative status under the WFD in the face of climate change.

Although implemented at multiple locations, MAR can achieve a regional benefit of a similar scale (24 Mm^3/yr) to the longer-term water resource options being considered such as the proposed desalination plant (pilot 8 Mm^3/yr), the proposed abstraction from the River Guadiana with transfer to the Odeleite / Beliche reservoirs (30 – 60 Mm^3/yr), or the 57 short-medium term measures of the RWEP to generate / save 33 Mm^3/yr. Potentially MAR could delay or negate the need for construction of one of these strategic options, or as these options will take many years to be constructed, be used during the construction period to meet demand and increase water supply resilience in the intervening period.

MAR can bring wider benefits including making use of a water resource that otherwise cannot be captured and is rapidly lost to sea, with fewer environmental impacts compared to the expected impact of new surface water dams, long transfer pipelines or desalination plants. Furthermore, as recharge can usually occur under gravity, and treatment requirements are limited to pre-settlement, energy costs for MAR are similar to those for conventional groundwater abstraction. MAR can have positive impact on the WFD surface water objectives, particularly if losses from MAR increase baseflow to rivers and groundwater dependent wetlands. In areas where groundwater is shallow and known to be influenced by irrigation return (such as M15 (Luz-Tavira)), MAR with natural water sources comes with lower water quality risks than direct irrigation with treated wastewater.

Although climate change is expected to reduce water available for MAR in the Algarve and should be considered during planning of MAR, the RCP4.5 scenario for 2041-2070 (covering a 30-year typical design life of civil infrastructure) indicates relatively small reductions in MAR compared to the recent baseline conditions. These can be mitigated by increasing MAR capacity incrementally as climate impacts are realised.

8.2.2 Methodology

Aquifer capacity was assessed quantitatively using the Theis equation using data on ground elevations, groundwater levels and aquifer properties to identify the maximum individual borehole recharge rate that could be attained without causing groundwater levels to rise above the ground surface. This relies on existing data on aquifer properties, which is very limited, and therefore only broad areas within aquifers were identified for MAR at this stage. Ultimately site-specific pumping tests would be needed to confirm the aquifer capacity for MAR at the preferred locations.

Non-linear uncertainty analysis was undertaken on the GR4J rainfall-runoff model using an Iterative Ensemble Smoother to condition an ensemble of parameter sets to measured flow data (where measurement ceased in 2008), augmented by measurement noise. This has advantages over Markov-Chain Monte-Carlo sampling in terms of reducing the computational load, with only 200 ensemble members where the model is only run once for each iteration (typically 6-12 iterations were required). This method allowed the uncertainty in Q_R due to water availability to be quantified. The method was used in a similar way to Bennett et al. (2021) who used PESTPP IES with the Sacramento rainfall-runoff model (19 flexible parameters) finding IES to be an efficient and powerful method for conditioning model parameters and providing robust uncertainty analysis in the spirit of Bayesian statistics.

Estimating Q_R vs. Q_{MAR}, indicated the importance of MAR design capacity as a key design parameter affecting the annual recharge volumes. These estimates are provided for both recent baseline conditions and under the RCP4.5 and 8.5 EURO-CORDEX climate scenarios. At the time of writing, it is understood that only one such similar study exists, where He et al. (2021) examined the future water availability of high-magnitude, low frequency flood events for MAR in California under climate change using similar methods.

A limitation of the methodology is the extrapolation of Q_R estimates to catchments that were not modelled as part of this study, particularly those where annual average river flows were estimated or based on a limited flow time series. The extrapolation of uncertainty ranges to these Q_R estimates is particularly uncertain. Extensions to this work could include identifying the optimum Q_{MAR} at each location, and between locations, particularly once country-specific and itemised costs are available for MAR infrastructure.

An important area for further investigation is the Querença-Silves aquifer (M5), which could not be assessed by this methodology due to the complexity of river-aquifer interactions in the rivers draining this aquifer. Significant MAR potential may exist within this aquifer, not just where surface water exits the aquifer where it is proposed that Ribeira de Quarteira (31H_02H) and Ribeira de Alcantarilha (30G_08H) are used as water sources for MAR. MAR potential within Querença-Silves could be assessed based on the numerical modelling of Salvador et al. (2012) combined with the field knowledge of Reis (2007) and Monteiro et al., (2012) to determine where and how MAR could be implemented.

8.3 Vale do Lobo case study

8.3.1 MAR in the VL sector

The results demonstrate that MAR cannot increase the hydraulic heads sufficiently to attain the minimum heads required, even locally. Therefore, the proposed MAR schemes cannot prevent the seawater interface from reaching the base of the existing abstraction boreholes, and SWI in the VL cannot be mitigated by MAR alone.

The minimum heads can be met for the majority of locations in a 'no-abstraction' scenario, the exception being deep boreholes close to the eastern boundary. Here heads are not sufficiently high enough to prevent SWI extending above the base of the boreholes, indicating that the VL sector cannot be entirely protected from SWI even under this scenario without concurrent management action in the eastern part of the Campina de Faro.

This modelling, in conjunction with that of Hugman and Doherty (2022), identifies for the first time, the true scale of the problem in this area, and how difficult it will be to resolve. A significant reduction in abstraction will be needed in addition to, or as an alternative to MAR. Hugman and Doherty (2022) have shown that abstraction rates would need to be reduced at least to 30% of current rates in VL, possibly even less. Required reduction in abstraction would be less in conjunction with MAR. An integrated approach to water management in the VL sector could use the locally available treated wastewater directly for irrigation as an alternative to MAR. Although this has not been explicitly modelled, the implication of these model results is that the wastewater volumes remain insufficient, and further reductions in abstraction would still be required, or wastewater from further afield, such as Faro-Olhão WTP, would also be needed.

Collecting further information on the aquifer properties and state of SWI, such as geophysics and further water quality studies, adds to the available body of knowledge, but it is time-consuming and expensive. Meanwhile, decisions are not taken. The existing data is already rich in prediction-specific information, as measured water levels are available close to where water level predictions are required. We have demonstrated an approach and associated model to support decision-making with the data currently available. This modelling has limitations, but we are still able to state with a relative degree of confidence that investing in MAR on its own is not going to solve the problem. In conjunction with Hugman & Doherty

(2022), we have demonstrated that substantial further actions are needed to protect groundwater quality in the VL sector.

8.3.2 Modelling methodology

This case study demonstrates the development of a decision-support groundwater model to assess the effectiveness of MAR to prevent SWI in a coastal aquifer system, whilst allowing reduction of prediction uncertainty through data assimilation in a highly-parameterized framework. Process complexity was reduced using a constant-density model, along with a complementary 2D DDF model, to allow stochastic characterisation of the head and conductance along the coastal boundary. This allowed achievement of the fast run times necessary to undertake history-matching and reduce predictive uncertainty.

The model development and deployment were considered simultaneously, with reduced process complexity (constant-density) and structural complexity (modelling the offshore extent and processes as described in Section 7.4.1). The resulting model was capable of uncertainty quantification and reduction, but with limitations in terms of the predictions it can make. For an initial first-order assessment, evaluating the effectiveness of MAR against minimum heads required to prevent the seawater interface encroaching above the base of the current abstraction boreholes is pragmatic, and an acceptable compromise. It permitted a preliminary, aquifer-wide assessment, and allows regulators and stakeholders to understand the benefits and limitations of MAR with a simple metric.

An alternative (or complementary) analysis could use the results from the complementary DDF model to determine the relation between fresh-saltwater interface response to changes in flux across the GHB coastal boundary. If a defensible relation between change in flux and gradient reversal could be established, this would allow the magnitude of change in GHB flux to be used as a metric for effectiveness.

Calibrating with PEST_HP was time-consuming. Balancing the weights of observations of different types and locations required subjective expert knowledge about the important features of the system. To obtain an acceptable fit across all observation groups required testing of multiple weighting strategies. However, obtaining an appropriate calibration allowed the use of linear analysis. This identified (with the RPUVR statistic) that the uncertainty of coastal boundary parameters was not reduced by history-matching. This provided further justification for the method used to stochastically characterise the coastal boundary, which constrained the prior probability distribution. It also enabled the linearized posterior probability distribution to be used as the starting point for PESTPP-IES, reducing the number of model convergence failures during this process (one-third of realizations failed to converge even with this workflow).

Where decisions need to be made relatively quickly to protect the aquifer, the use of a simpler model is beneficial. If building a complex model takes too long, decisions are likely to be taken before such a model is available (Caers, 2011). Furthermore, if a complex model cannot quantify and reduce uncertainty, a likely outcome given the nature of DDF models, then the decision-support such a model can provide is limited.

For future similar modelling studies, such as investigation of the other potential MAR schemes in Table 6-17, it is recommended that similar decision-support groundwater models could be developed but using a simpler recharge model. LUMPREM (along with most recharge models) is highly non-linear and even with pre-calibration in PEST_HP caused significant difficulties in calibration, and resulted in a very wide range of recharge rates across the model domain that may not be realistic. A simpler recharge model, still allowing input of rainfall and PET to allow for prediction under future climate, but combined with new methods for quantifying groundwater abstraction and aquifer-scale recharge are major areas for further research, as dis-entangling recharge and groundwater abstraction is a fundamental problem in hydrogeological modelling and water resources management, particularly in semi-arid, water scarce regions such as the Algarve.

8.4 Limitations of MAR in the Algarve

8.4.1 Campina de Faro

The main limitation of MAR in the Algarve is the lack of water available for MAR, and this is particularly evident in the Campina de Faro aquifer, which suffers from extreme water scarcity with an estimated annual deficit of 4 Mm^3/yr, and a paucity of options to remedy this.

The RCP4.5 scenario period 2041-2070 covers the 30-year typical design life of civil infrastructure and indicates that the smallest catchments in the central Algarve (Rio Seco and Ribeira da São Lourenço) appear to be unsuitable for MAR as recent baseline flows are already lower than the RCP8.5 scenario predictions. This indicates that the already small annual average MAR volumes from these sources (0.7 and 0.5 Mm^3/yr respectively), are likely to decrease further.

These results concur with Schneider et al. (2013), who identified that rivers in the Mediterranean region are likely to be even more intermittent in the future due to climate change, with an increasing number of zero flow events. This is a pattern also emerging from recent literature highlighting the vulnerability of ephemeral rivers to climate change (Pumo et al., 2016; De Girolamo et al., 2022). However, except for these two catchments, it appears that MAR capacity can be increased to maintain MAR recharge rates at least over the medium term (2041-2070).

Natural recharge is also predicted to decrease due to climate change by approximately 10% over the period 2041-2070 (RCP4.5) (APA, 2020), therefore in Campina de Faro, the water available for MAR from the ephemeral rivers would only balance the predicted decrease in natural recharge.

Capture of greenhouse runoff is a potential source of water for MAR in this aquifer, although 50% participation of existing greenhouse owners / managers would be required to attain a water resource benefit of 1.4 Mm^3/yr. Capturing and recharging water from new infrastructure could be mandated through planning regulations, however such widespread participation for existing greenhouses may be hard to attain given without financial incentives to retro-fit water capture and infiltration infrastructure.

The Vale do Lobo numerical model results indicate that the combined water available for MAR from Ribeira da São Lourenço and the WTP at Quinta do Lago, Vale de Lobo and Faro Noroeste is insufficient to meet the deficit and increase groundwater levels sufficiently to prevent SWI impacting existing groundwater abstractions. However, MAR could be part of a solution, but significant reduction in groundwater abstraction will be required. Current estimates indicate at least 70% reduction in abstraction is needed, but this could be reduced if MAR were employed. The modelling also indicated the importance of concurrent management actions in the Faro sector (M19) to achieve the desired improvement in groundwater levels in the VL sector. The reductions in groundwater abstraction are higher than those suggested by the annual deficit in the water balance, due to the need to increase water levels across the aquifer to mitigate SWI.

Although MAR with treated wastewater was considered in this modelling study, it is now far more likely that treated wastewater would be reused directly in agriculture and groundwater abstraction would be reduced. However, the conclusions remain the same, the local sources of wastewater are insufficient, and water from Faro-Olhão WTP is the only source with sufficient volumes to meet the deficit.

Achieving sustainability of water use in the Campina de Faro is a daunting task, given the limitations of MAR and indeed the limitations of treated wastewater in this area, given the considerable expansion of agricultural development, supported by the large number of licensed boreholes / wells that already exist (and whose use cannot be prevented). The regulations preventing new boreholes / wells therefore have little impact. Even during the period of study to develop this thesis (2019 – 2023), there has been further new agricultural development of new citrus and avocado plantations within this aquifer.

8.4.2 Other limitations

The potential for MAR in M2 using water from Ribeira de Bensafrim is limited due to issues identified in the source water quality (ammoniacal nitrogen, multiple pesticides and chloride concentrations), as well as the low annual river flows in this location. The potential volumes from this source have therefore not been considered in the estimated regional total.

MAR in M4 (Ferragudo – Albufeira) is estimated to be small (0.9 Mm^3/yr) compared to Silves, Lagoa and Portimão irrigation perimeter demand (13.8 Mm^3/yr). However, MAR may employed here to meet or maintain environmental objectives as discussed in the following section.

8.5 Achievement of environmental objectives

Achievement of the WFD objectives for ‘good’ quantity and quality status for all groundwater bodies by 2027 is a challenging target. This study has shown that even where the volumetric water balance (groundwater abstraction <= 80% long term average recharge) conditions can be met with MAR, substantial further reductions in groundwater abstraction (at least 70% reduction) or addition of further recharge by MAR are necessary to combat the risks of SWI in the Vale do Lobo sector. Furthermore, it was demonstrated that management action in the adjacent Faro sector was needed to mitigate risks of SWI in the Vale do Lobo sector. These conclusions are mirrored by a wider study which determined that to achieve sustainability in the Algarve, irrigation would need to reduce by 70%, but that this would have an associated reduction on crop yields of 30% (Gelati et al., 2020).

Whilst not all aquifers are facing further deterioration in water quality due to SWI, the fact that five aquifers fail to meet ‘good’ quantity status already, and a further 11 exhibit declining water level trends at an aquifer scale, is cause for concern. These volumetric assessments are based on assessments of both recharge and groundwater abstraction that may have large errors associated with them, and groundwater level trends also need to be assessed over a longer period than the 5 years of the RBMP process. Nevertheless, the results of the draft RBMP are of some concern, and it is important to identify how and where MAR could support the attainment of ‘good’ status.

Development of a strategic groundwater resource in M6 and M7 could help ensure good status is maintained into the future for these aquifers. In the aquifers where MAR is proposed as ASR for irrigation water supplies (e.g., M3, M13, M14, M15) good status could potentially be maintained by a ‘cut to the aquifer’ where a small proportion of recharge is intentionally not re-abstracted each year as per the Arizona water banking scheme (Megdal et al., 2014; Megdal and Dillon, 2015) to be of benefit to the aquifer.

An opportunity has also been identified to use MAR in M4 aquifer specifically to maintain ‘good’ quantitative status into the future, as the water balance is predicted to come under increasing pressure due to climate change, and MAR (0.9 Mm^3/yr) could be used to mitigate the predicted reductions in natural recharge (0.6 Mm^3/yr) due to climate change.

In terms of achievement of WFD objectives, the combined use of groundwater & MAR should not result in a deterioration of status, and aquifer management should aim to maximise groundwater storage and use so that water is available during drought periods. This can then be balanced by filling aquifer storage during wet winters. Potentially this could result in permitted increased drawdown of aquifers in places during drought periods, based on the understanding that MAR plus natural recharge during wet winters will replenish the water used during droughts. In certain aquifers (e.g., Luz-Tavira) some of this drawdown may be necessary to accommodate MAR.

8.6 Further considerations

8.6.1 Management

Portugal has the opportunity to decide how MAR schemes should be licensed within the current legislative framework. For example, the MAR schemes envisaged herein use water from natural catchments, with very little economic or agricultural development in the upstream catchments, and hence there are opportunities for qualitative management of water quality, subject to a water safety plan to identify and manage catchment risks. This could reduce the requirements for quantitative management based on MCL's, limiting the sampling only to the extent to initially confirm that the water source meets the groundwater directive requirements. This approach would be more suitable for these low-risk natural water sources.

Alternatively, a more prescriptive approach based on adherence of source water quality to the groundwater threshold values to ensure compliance with the WFD could be applied, but this has cost implications and if applied too prescriptively could result in water of generally good quality being unacceptable for MAR. Ideally, a risk-based approach, such as that applied to reuse of treated wastewater in irrigation, should be considered.

8.6.2 Technical

Site-specific assessment is necessary for any proposed MAR scheme given the variability in subsurface properties. This will typically include borehole drilling, aquifer testing and regional monitoring. Numerical models may be necessary in conjunction with pilot testing to estimate the MAR scheme losses, and to identify if unacceptable impacts, such as groundwater flooding, are likely to occur. It is generally recommended that MAR schemes are developed gradually, as by their nature they are relatively easily scalable, by adding more boreholes / recharge structures as the effectiveness of the initial boreholes / infrastructures are established. This allows the technical and financial risks of MAR projects to be managed.

Further consideration of water quality of source water, native groundwater and likely geochemical reactions is also necessary, to understand the physical or geochemical reactions that could reduce the ability of the subsurface to accept recharge water (clogging). To understand the likelihood of these reactions it is necessary to characterize the water quality of the source water that is to be used for recharge, the quality of water in the aquifer being recharged, referred to as native water, and interactions that might occur during recharge. It will be necessary to collect samples of the proposed source water (at different times of year and at different flow rates) and, for projects involving subsurface recharge, samples of native water and have them analysed for an array of inorganic constituents along with physical parameters including pH, Eh, dissolved oxygen, and turbidity (ASCE, 2020). The target aquifer material should also be analysed as this can also be a source of further reactions. Geochemical mixing models, e.g., PHREEQC, can then be used to determine which reactions are likely, and if any adjustments to the MAR design or mitigation measures are necessary.

Further aquifer characterisation is required in the area south of Odeceixe, and in the area east of Tavira, to better understand the aquifer extent and properties, to better understand the aquifer capacity for MAR in these areas. This could be achieved by geophysical surveys in addition to the methods described above.

8.7 Overall conclusions

The Algarve suffers from extreme water scarcity, with existing water resources unable to meet the demand, particularly in drought years. Climate change will result in greater demands at a time when less water is available. Conventional water resources now need to be supplemented with alternative water resources, such as MAR, treated wastewater reuse, and desalination, in a way that is cost effective, with the least environmental impacts.

MAR is a low-regret climate adaptation measure, and in the Algarve can potentially provide a water resource benefit of 24 Mm^3/yr, which is 10% of the current annual water demand. MAR can be achieved within the current WFD regulations provided a pathway to obtaining a licence can be developed. MAR can be achieved at lower cost, and without the environmental consequences associated with construction of new dams or desalination plants, and with lower energy requirements. MAR can support public irrigation perimeters, and in conjunction with direct reuse of treated wastewater and reduced groundwater abstraction, provide a strategic groundwater resource for use during drought periods. Further site-specific investigations will be necessary, but the technical challenges and their solutions are well understood from an European and world-wide network of case studies where MAR is already implemented.

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Appendix A: Surface Water Quality Analysis

Included in digital version.

Table A-1: Water Quality Sampling Locations

Table A-2: Surface Water Exceedances of Groundwater Threshold Values

Table A-3: Surface water metal concentrations compared to groundwater threshold values

Table A-4: General water quality parameters

Table A-5: Summary of pesticide analysis

Figure A-1: Location of selected surface water quality monitoring stations for water quality assessment, compared to proposed surface water abstraction locations for MAR, and existing Urban Waste Water Treatment Directive (UWWTD) discharge point locations.