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The importance of temporal scale when optimising abstraction volumes for sustainable aquifer exploitation: A case study in semi-arid South Portugal

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SUMMARY

Aquifer sustainable yields are often defined as a single value based on long-term averages or annual values of recharge. However, these time scales can be too coarse for the systems to which they are being applied and can lead to over- or underexploitation of groundwater. A numerical model of the Querença-Silves aquifer in Portugal is used to develop hypothetical scenarios in which abstraction rates for public water supply are adapted at various time-scales and are defined based on a percentage of the recharge which occurred during the previous period. The purpose is to understand the effects and feasibility of varying the temporal scale at which groundwater abstraction is modified in order to maximise sustainable yield and minimise freshwater losses. Results show that, for the Querença-Silves aquifer, reducing the time scale for which sustainable yield is defined allows for an increase in withdrawal volumes whilst maintaining the sustainability of the system. In fact, not reducing the temporal scale leads to an irretrievable loss of freshwater during recharge periods. Furthermore, predicted seasonal changes in rainfall for Portugal will make taking the temporal scale of the system into account more important, as the concentration of recharge into a shorter period will lead to faster depletion.

1. Introduction

Many aquifers in the world possess high storage capacity and water quality, allowing them to constitute a prime source of water for human consumption and agriculture, even in dry seasonal periods when rainfall is scarce and surface water is fast depleted (Van Camp et al., 2010). The concept of safe yield has been recognised since the beginning of the last century (Lee, 1915; Theis, 1940). It has since been defined by Sophocleous (1997) as the attainment and maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge. The concept of sustainability appeared in the early 1980s, and is centred on the idea of managing rates of resource use so as to meet the needs of the present generation without compromising the needs of future generations (Alley and Leake, 2004). This led to a shift in focus from safe yield to sustainable yield, defined as the development and use of groundwater resource in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley et al., 1999; Sophocleous, 2000; Custodio, 2002). However, in practice it is often calculated as a percentage of the long-term average recharge. Bredehoeft (2002) demonstrates that it is in fact the changes that occur to recharge and discharge caused by abstraction, rather than simply recharge, that influence sustainable yield. Kalf and Woolley (2005) give a review of the evolution of the concept of safe to sustainable yield and discuss the methodology of determining sustainable yield based on principles of conservation of mass at the water basin scale. Zhou (2009) goes on to suggest that the sustainable yield cannot be simply calculated as a single value using the water balance; it requires assessing the dynamic response of the groundwater to the introduced pumping regime, which is rarely performed. Recently Hugman et al. (2012) demonstrated that the temporal and spatial distribution of recharge and abstraction had a significant effect on maximum sustainable yield, and that the magnitude of this effect was influenced by the aquifer system properties.

Maimone (2004) points out that the idea that there exists a single, correct sustainable extraction rate for a given system is inaccurate and thus sustainable yield must be defined for a specific period of time. It must be recognised that yield varies over time along with the conditions which influence it (Sophocleous, 1997). Most recent attempts to determine maximum sustainable yields have made use of optimisation–simulation techniques in order to establish the optimal abstraction rates for specific criteria of

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sustainability (Das and Datta, 2001; Shiau and Wu, 2007; Roumasset and Wada, 2010; Kang et al., 2011; Yin et al., 2011), generally based on long-term averages or annual values. In a few cases a smaller time scale has been considered (Peralta et al., 2011; Yin et al., 2011; Kang et al., 2011). Rejani et al. (2009) retroactively determine the optimal distribution and monthly pumping rates for a specific time period. Yin et al. (2011), Shiau and Wu (2007) and Sedki and Ouazar (2011) take into account the (four-) seasonal variation of maximum sustainable yield for representative average, wet and dry years. The defined sustainable yield in all of these cases ends up being based on historical averages and generally aimed at reducing and/or avoiding overexploitation by defining a single maximum value which is guaranteed not to cause negative effects. However in regions where there is significant inter- and intra-annual variability, such as the Mediterranean, a single value of sustainable yield may not accurately represent the amount of groundwater available to be sustainably abstracted. Applying sustainable yields based on historic averages and not taking into account the variability inherent in these systems may in fact lead to an underestimation of sustainable yield and consequent freshwater loss through discharge.

Maximising the amount of an available freshwater resource is fundamental in regions where this resource is scarce, including Mediterranean regions such as Southern Portugal. Current climate change studies are predicting short-term shifts in seasonal distribution and an increase in inter-annual variability of rainfall in Mediterranean regions (Giorgi, 2006; Santos and Miranda, 2006; Stigter et al., in press). More specifically, rainfall is predicted to be concentrated in the winter, with significant reductions in spring and autumn. On an inter-annual basis, extreme events (high rainfall and droughts) will be more frequent. Hugman et al. (2012) have shown that this increase in seasonal variability can lead to larger freshwater loss during the wet season, in particular if groundwater abstraction is largely concentrated during the dry months, which is often the case.

For the current study, a numerical finite element groundwater flow model for a case study in the south of Portugal is used to run a number of so-called transient cyclic state scenarios where the abstraction rates for public water supply are determined for various time-scales (ranging from daily to annual) as a fixed percentage of the recharge during the previous time-period. The purpose is to understand the effects and feasibility of defining groundwater abstraction rates at various time scales in integrated water supply systems to maximise sustainable yield and minimise freshwater losses.

2. Methods

2.1. Study area

The Querença-Silves (QS) aquifer system, built up of karstified carbonate rock, constitutes the most important groundwater reservoir in South Portugal (Algarve province), due to its large area (324 km^2) and significant recharge. The main outlets of the aquifer are springs located at the aquifer boundaries, particularly the Estômbar springs in the west, where the aquifer borders the Arade river, which forms an estuary. Important and sensitive surface/groundwater ecotones and associated groundwater dependent ecosystems exist at the location of these springs, many of them classified as protected areas.

Mean annual recharge (MAR) of the QS aquifer system was calculated as 93 hm^3 (93×10^6 m^3), based on detailed spatial distribution calculations of rainfall (Nicolau, 2002), the Kessler method (1965) for recharge in areas of carbonate rock outcrops and soil water balance/storage models linked to evapotranspiration for sedimentary outcrops (Vieira and Monteiro, 2003). New recharge estimates were made with the FAO dual crop coefficient method (Allen et al., 1998), taking into account parameters such as daily precipitation, soil texture, moisture content and vegetation cover (Oliveira et al., 2008) and resulting in a 10% higher estimated recharge (hm^3). Recently Monteiro et al. (in press) and Salvador et al. (2012) analyzed the interactions between the QS aquifer and the main streams which interact with it. They found that this, until now ignored, contribution to recharge had a significant impact on the aquifer systems hydrologic behaviour and water balance. However there is currently very little data on stream flow, which makes an in-depth analysis difficult at the current time.

Currently around 10% of MAR is exploited for urban water supply ($\sim$10 $hm^3 = 10 \times 10^6$ m^3/year) (Stigter et al., 2009), but this value is expected to drop, now that the new surface water reservoir of Odelouca will become operational. An average annual withdrawal of 31 hm^3 is estimated for irrigation (Nunes et al., 2006) that is mostly located in the western part of the aquifer system, as shown in Fig. 1. Until the end of the 20th century groundwater was the main source for public supply in the south of Portugal, after which it was replaced by surface water supplied by large reservoirs. The drought that occurred in this region during 2004 and 2005 highlighted the limitations of this single source strategy as well as the crucial role of groundwater as a source for public supply. The conjunctive use and management of multiple water sources for different water-consuming activities, as part of the more complex concept of integrated water resource management, will be essential both in the near and distant future (Stigter et al., 2009).

The large seasonal and annual variations in rainfall of semi-arid regions such as the Algarve are well known (Stigter et al., 2009) and research points towards an increase in frequency and intensity of droughts in the future (Giorgi, 2006; Santos and Miranda, 2006; Stigter et al., in press). This is likely to lead to a higher pressure on sources of water supply in the region. In order to optimise the balance between groundwater exploitation and conservation, there is a need to quantify sustainable levels of development.

Recent research has been performed on climate scenarios and their impacts on groundwater resources and dependent ecosystems in the Central Algarve, in the scope of the CIRCLE-Med project CLIMWAT (Stigter et al., 2011, in press). For the Central Algarve, although mean annual rainfall is expected to decrease only slightly in the short-term, i.e. up to 2050, and despite a certain degree of uncertainty inherent in climate change scenarios, significant shifts in seasonal distribution and inter-annual variability are predicted. Rainfall will be more concentrated in the winter season, with large reductions in spring and autumn. Calculations show that this in fact will lead to a slightly higher percentage of rainfall contributing to recharge (Stigter et al., 2011), but the question is if it can be stored long enough to be used for irrigation and public supply in the spring and summer seasons. Moreover, the inter-annual variability in both rainfall and recharge will increase. In the long-term, 2070–2100, the work of Stigter et al. (2011, in press) shows that a significant reduction in both rainfall and recharge is predicted.

2.2. Numerical model

The model used in this paper is the result of ongoing research in relation with monitoring and modelling of aquifers at the University of Algarve. A more detailed review of the evolution and applications and current state of this model can be found in Hugman et al. (2012). Among several recent investigations, the model was used by Vieira et al. (2011) who developed a decision model for water utilities to determine the best operation for large-scale multisource water supply systems. Most recently Salvador et al. (2012) used the model to investigate stream-aquifer interactions and

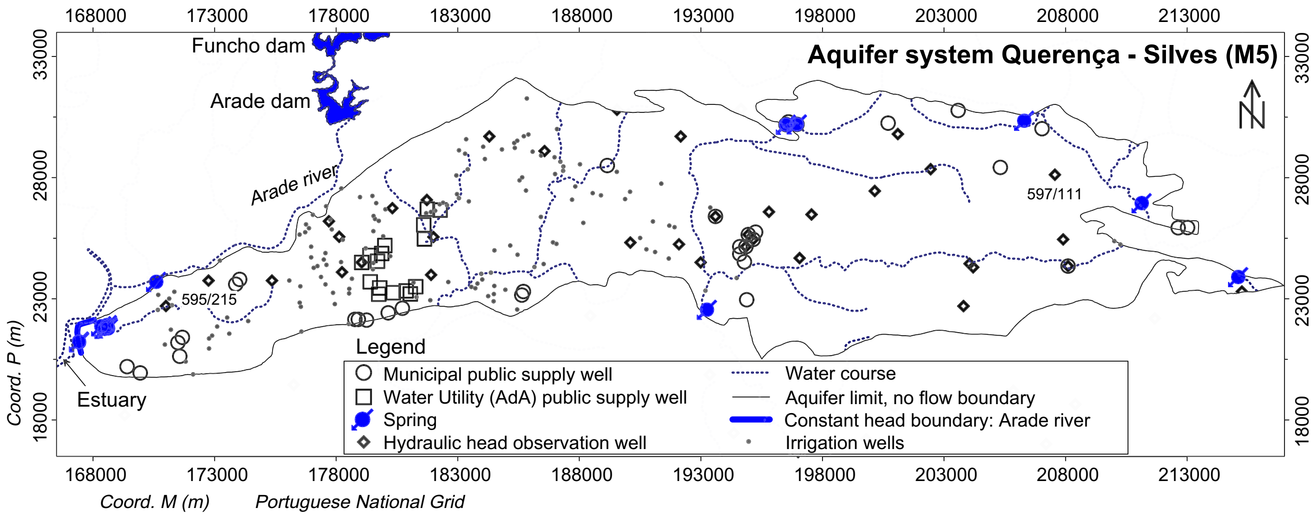


Fig. 1. Overview of the Querença-Silves aquifer system, location of wells, springs and the boundary condition of the Arade estuary.

showed that these can have a significant effect on the regional water balance. However there is still insufficient data to properly quantify and represent these phenomena and therefore they are not yet considered in the model.

Areal recharge rates are based on values proposed most recently by Oliveira et al. (2008). They estimated the average recharge as 45% (100 hm^3/year) of the rainfall and also obtained a detailed spatial distribution of recharge rates, which was applied to both steady-state and transient versions of the model. To perform transient simulations the available areal distributions of recharge were grouped into classes of 10% (0–10%, 10–20%, etc.) and the average of each class was applied to the respective area so as to reduce (computational) workloads. Recharge input functions were calculated for each recharge rate class, with quarter daily time steps, using daily precipitation values obtained at the weather station of São Bartolomeu de Messines (30H/03UG) located near the central northern border of the aquifer and found to be representative for the area.

The estimated annual withdrawal for irrigation of 31 hm^3 (Nunes et al., 2006) was divided equally amongst 150 nodes of the model, which represent 150 private wells known to be located within the irrigated areas. Under transient conditions abstraction was simulated at a constant rate over the period between the last week of May and the end of September. Withdrawals for public water supply were applied to nodes representing wells that belong to the Water Utility *Águas do Algarve* (*AdA*). Boundary conditions are defined as constant head of 0 m along the Arade estuary in the west (Fig. 1) representing the aquifers' connection with the sea, and no-flow for the remaining part. Boundary conditions were not defined for the several small springs at the border of the aquifer in the central and eastern sectors, as model variants including these constraints become more complex and no longer adequately represent the observed hydraulic behaviour, with minor impacts on the regional water balance. Attempts are currently ongoing to include these springs in the numerical model, in order to better comprehend the aquifers behaviour at a local scale.

The defined conceptual flow model was translated into a 2-D finite element mesh with 11,663 nodes and 22,409 triangular finite elements. The mesh was generated taking into account aquifer geometry and the location of the main discharge areas. The physical principles at the basis of the simulation of the hydraulic behaviour of the aquifer system are expressed by:

$$S\frac{\partial h}{\partial t} + \mathrm{div}(-[T]\cdot \vec{\mathrm{grad}}\cdot h) = Q \tag{1}$$

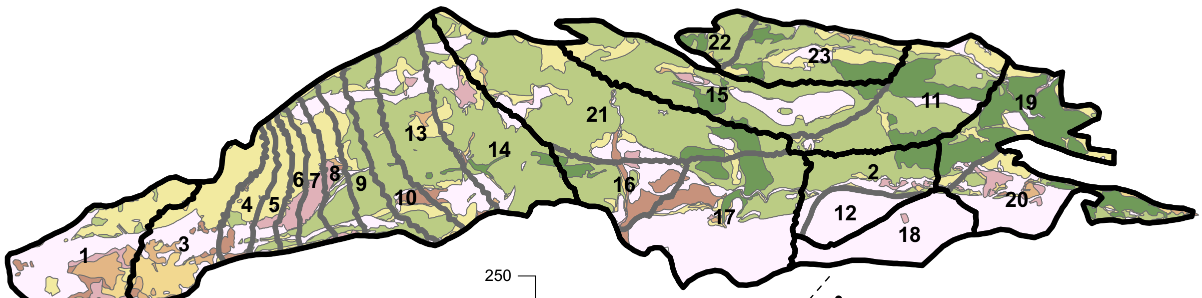
where T is transmissivity [$L^2\,T^{-1}$], h is the hydraulic head [L], Q is the volumetric flux per unit volume [$L^3\,T^{-1}\,L^{-3}$], representing sources and/or sinks and S is the storage coefficient [–].

T was estimated by inverse modelling under steady-state conditions. Calibration was performed using the Gauss–Marquardt–Levenberg method, implemented in the nonlinear parameter estimation software PEST (Doherty, 2002). The entire aquifer system is supported by carbonate rocks, therefore, the hydraulic property zones cannot be simply defined by using the geological data. Despite the lithologic uniformity, the aquifers' regional flow pattern reveals a complex internal heterogeneous structure, the zonation of which was established based on available data (piezometric and discharge in natural outflow areas). In total 23 T zones were defined as shown in Fig. 2.

The spatial distribution of the storage coefficient (S) was calibrated by trial-and-error for a model run from 2002 to 2006, using data from the official monitoring network of the Regional Water Basin Administration (RWBA), and then validated against data from 2006 to 2009. All available data from piezometers in the aquifer system was analysed and grouped according to the response of hydraulic head to recharge and discharge events. This resulted in eight separate zones, the location of which was intersected with areas of equal T. Results from the distribution of S show a satisfactory fit with observed head time series, an example of which is shown in Fig. 3. A more detailed description of the development, calibration and validation of the numerical model can be found in Hugman et al. (2012).

2.2.1. Transient cyclic state scenarios

Transient cyclic state scenarios were used to compare the effect of considering different time scales when determining sustainable yields. To simplify this theoretical exercise, it was only performed using the public supply wells, i.e. irrigation activities and their inherent seasonality were not considered in this case. Each scenario considered different time scales when calculating abstraction rates and timings, as shown in Table 1. Time scales were 1 day, 1 month, 3 months, 6 months and 1 year. Abstraction rates at public water supply boreholes for each time period (i.e.: day, month, 3 months, etc.) were calculated as 70% of total recharge during the previous time period. This value was derived from Hugman et al. (2012) who showed that, under current climate conditions and pumping regimes, an abstraction rate of approximately 70% of MAR would be sustainable for the specific criteria of not causing gradient inversion at the border with the estuary. This "no-inversion" criterion is



Zone	T (m^2 s^{-1})	S	Zone	T (m^2 s^{-1})	S
1	0.729	0.05	13	0.334	0.075
2	0.001	0.01	14	0.466	0.075
3	0.596	0.075	15	0.001	0.075
4	0.370	0.075	16	0.505	0.03
5	0.317	0.075	17	0.027	0.03
6	0.287	0.075	18	0.031	0.001
7	0.303	0.075	19	0.007	0.02
8	0.309	0.075	20	0.010	0.02
9	0.316	0.075	21	0.004	0.03
10	0.299	0.075	22	0.001	0.005
11	0.033	0.075	23	0.001	0.005
12	0.073	0.01			

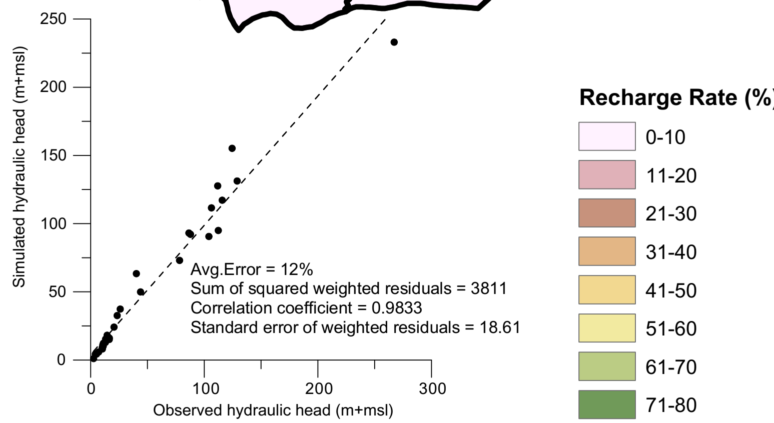


Fig. 2. Map of chosen transmissivity zones (grey lines) and storage coefficient zones (black lines) as well as spatial distribution of recharge ratio (top), optimised values obtained by calibration (bottom left) and resulting plot of modelled versus observed hydraulic heads (bottom right).

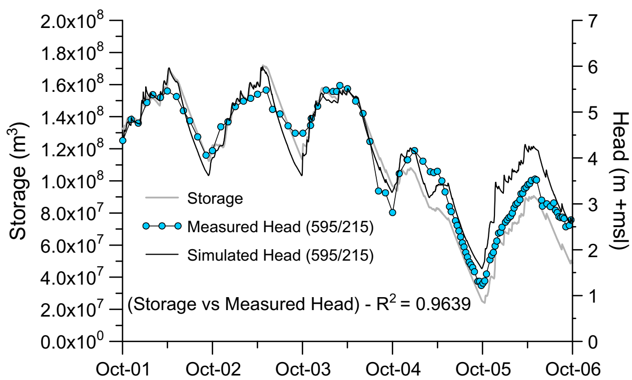


Fig. 3. Observed and simulated hydraulic head at piezometer 595/215 and simulated storage of the QS.

closely linked to that of continuous freshwater discharge into the estuary, thereby avoiding salinization of the estuarine springs at the end of the dry season, to preserve the current ecosystem status described by Silva et al. (2012). 70% of MAR corresponds to a sustainable volume of approximately 70 hm^3/year, which coincidentally is roughly the average annual volume of water supplied by the Water Utility for public consumption in the Algarve region between 2008 and 2010 (Table 2).

Two variants of temporal distribution of recharge were developed (Table 1): (a) recharge for the hydrological year (October to October) of 2007/2008; and (b) recharge for the entire hydrological year of 2007/2008 concentrated in the recharge events that occurred during the months of November, December and January. Variant (a) is representative of an average hydrological year, with recharge spread over 8 months, whilst variant (b) represents predicted changes in seasonal distribution with the same amount of recharge concentrated in less time.

2.2.2. Hypothetical abstraction scenarios

In a subsequent phase, pumping rates for the same time scales were determined for the period between October 2001 and September 2009 based on observed rainfall data, and applied to the existent numerical model of this period. An additional time scale of five years was included, in which the withdrawal rate is based on the average of the five previous years, in order to analyse the effect of not accounting for inter-annual variations in recharge (i.e. this scenario corresponds to a non-interactive water supply management). To make the current analysis more realistic (less theoretical), real estimated abstraction rates for irrigation (31 hm^3/year, c.a. 30% of MAR), distributed over a period from mid-May to the end of September, were maintained. In order to accommodate for this withdrawal volume for irrigation, public supply pumping rates were calculated as 40% of the recharge (instead of 70%) during the previous time period (Table 1). For the shorter time-scale, i.e. day and month scenarios, this means that abstraction for public supply mainly occurs outside the irrigation season (in autumn and winter), which is not the case for the longer time-scale scenarios.

Results were compared to calibrated simulations that consider actual withdrawal rates for irrigation and public supply. The goal of this exercise is twofold: (i) see how much more groundwater could have been abstracted from the QS aquifer in the period 2001–2009 whilst confirming to the proposed sustainability criteria, thereby reducing the pressure on the surface water reservoirs and avoiding the disruption of the water supply system during the drought of 2005; (ii) study the effect of different time scales on volume and timing of abstractions and the consequences for the status of the aquifer and dependent ecosystems, in response to the requirements of European Union (EU) Directive 2000/60/EC, known as the Water Framework Directive.

3. Results and discussion

3.1. Transient cyclic state scenarios

Results for all scenarios are compared based on variations of hydraulic head at piezometers 595/215 and 597/211 (location indicated in the map of Fig. 1). Hydraulic head at monitoring point 595/215 demonstrates a good correlation with the variation of storage

Table 1
Description of scenarios used to compare the effect of considering different time scales to determine pumping rates on sustainable yield.

Scenario	Recharge		Time scale	Abstraction rates for public water supply	Irrigation
Transient cyclic-state	a	Cyclical recharge for the hydrological year (October to September) of 2007/2008	1 day	70% of recharge during the previous day	n/a
			1 month	70% of recharge during the previous month	
			3 months	70% of recharge during the previous 3 months	
			6 months	70% of recharge during the previous 6 months	
			1 year	70% of recharge during the previous year	
	b	Cyclical recharge for the entire hydro-year of 2007/2008 concentrated during November–January	1 day	70% of recharge during the previous day	n/a
			1 month	70% of recharge during the previous month	
			3 months	70% of recharge during the previous 3 months	
			6 months	70% of recharge during the previous 6 months	
			1 year	70% of recharge during the previous year	
Hypothetical abstraction (2001–2009)		Estimated recharge from October 2001 to September 2009	1 day	40% of recharge during the previous day	31 hm^3/year from mid-May to the end of September
			1 month	40% of recharge during the previous month	
			3 months	40% of recharge during the previous 3 months	
			6 months	40% of recharge during the previous 6 months	
			1 year	40% of recharge during the previous year	
			5 years	40% of recharge during the previous 5 years	

Table 2
Monthly volumes of public water supplied by the Water Utility to the region of the Algarve (AdA, 2012).

Year	October	November	December	January	February	March	April	May	June	July	August	September	Total (m^3)
2008	5.3E+06	4.3E+06	4.1E+06	4.0E+06	4.4E+06	4.6E+06	5.0E+06	5.5E+06	6.8E+06	8.6E+06	9.2E+06	6.6E+06	6.8E+07
2009	5.7E+06	4.7E+06	4.2E+06	3.8E+06	3.7E+06	4.6E+06	5.7E+06	5.8E+06	7.1E+06	9.4E+06	9.1E+06	7.2E+06	7.1E+07
2010	5.4E+06	4.0E+06	3.8E+06	3.4E+06	3.4E+06	4.0E+06	5.2E+06	5.7E+06	7.0E+06	9.1E+06	9.3E+06	7.1E+06	6.7E+07
Average	5.5E+06	4.3E+06	4.0E+06	3.7E+06	3.8E+06	4.4E+06	5.3E+06	5.6E+06	6.9E+06	9.0E+06	9.2E+06	7.0E+06	6.9E+07
Seasonal total (m^3)	3.7E+07	3.7E+07	3.7E+07	3.7E+07	3.7E+07	3.7E+07	3.7E+07	3.2E+07	3.2E+07	3.2E+07	3.2E+07	3.2E+07	6.9E+07

in the aquifer system (Fig. 3) and is therefore considered to be a good indicator for the state of the aquifer system. Hydraulic head at monitoring point 597/111 was included in order to observe the effect of the abstraction scenarios on the eastern sector of the aquifer system. Fig. 4 shows the variation of hydraulic head simulated for the various time scales under scenario (a) and scenario (b). The temporal distribution seen in the six-monthly time scale scenario is similar to that seen currently, with most of extraction occurring during the dry months and lowest values occurring at the end of September. This matches the current situation of higher extraction for irrigation and public water supply during the spring and summer months.

Daily and monthly time scale scenarios both show sharp declines in hydraulic head during the wet months and a rise during the dry summer months at observation point 595/215. Scenarios which consider time scales larger than three months do not show this behaviour at this observation point, with hydraulic head declining during the dry months and less significant drops during the wet months. However variation of hydraulic head at observation point 597/111 is the same across all time-scale scenarios. This effect is due to the location of the public supply wells in the south-western corner of the aquifer, near the main natural discharge area. In effect the shorter time-scales (daily and monthly) lead to high pumping rates during short pulses (i.e.: shortly after it rains) which captures the direct recharge in the south-western area, but mainly removes water from storage in this area and therefore has a significant effect on hydraulic head at 595/215. Subsequently, recharge that occurred in the eastern sector of the aquifer causes storage and hydraulic heads to recover in the west. On the other hand, longer time scales (particularly 3 and 6 months) lead to the recharge that occurs in the south-western area being lost as discharge, and the subsequent slow recharge being captured during the following months.

Lowest minimum hydraulic heads at observation point 595/215 are seen for daily, monthly and six-month time scales. For the two shorter time scales this is due to the characteristics of the public supply wells (concentrated in space, relatively to the entire aquifer where recharge takes place) and those of the abstraction regime (concentrated in time). In the case of the 6 month time scale this is due to the temporal discrepancy between the occurrence of recharge and abstraction, with most of the abstraction occurring in the dry season, when a significant volume of recharge has been lost to natural discharge. Yearly time scale leads to hydraulic heads which are continuously closest to the average, although they also lead to declines during the dry months. Although this time scale seems to have the least impact, it represents an inefficient use of

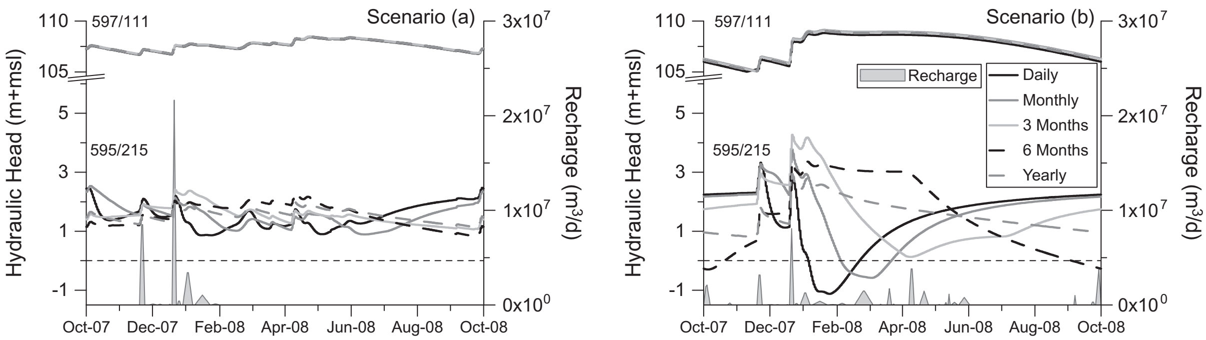


Fig. 4. Variation of hydraulic head at piezometers 595/215 and 597/111 for the hypothetical abstraction rates considering current temporal distribution of recharge (scenario a, left) and considering predicted temporal distribution of recharge (scenario b, right); for location of the piezometers see Fig. 1.

the freshwater resource, with high groundwater losses during the wet months.

Although the net yearly balance of all time scales in these theoretical scenarios are equal, shorter (daily and monthly) time scales lead to higher groundwater levels during the dry summer months. Consequently they also lead to enlarged freshwater losses during the summer. It can be argued that concentrating abstraction during the wet period, rather than during the dry period, would be more efficient and allow for recovery and a potential buffer if for any reason more groundwater would be needed due to drought or high demand. Moreover, lowering the hydraulic potential of an aquifer in the recharge season involves lower risks of possible negative consequences such as seawater intrusion or drying up of springs and streams, due to a higher potential for recovery. The latter is also visible in scenario (b). The sharp declines in hydraulic heads at 595/215 seen for the daily and monthly time scales are significantly more intense than in scenario (a), resulting in gradient inversions, although they recover rapidly. This demonstrates that the use of a fixed percentage of recharge to define maximum abstraction rate for a given time period is an inadequate method with which to determine maximum sustainable yield, and that it should be target based, such as a minimum discharge rate, water level and/or water quality standards. Based on such a target condition abstraction rates could be adapted at adequate intervals, to permit maximum withdrawal rates without causing undesired impacts. The recovery during the dry months indicates that overexploitation during the wet months, though it should be avoided, will likely lead to less severe negative effects than overexploitation during the summer, due to the protective buffer of storage which is significantly depleted after the winter. The six-monthly and yearly time scale scenarios have a similar though more pronounced behaviour to their equivalents in scenario (a): hydraulic heads reach lower values (and cause gradient inversion in the case of the six-monthly time scale scenario) due to a larger amount of recharge being lost to discharge caused by the concentration of recharge in a shorter time period. Unlike in scenario (a), the three-monthly time scale in scenario (b) shows a rise in hydraulic heads during the dry months. This is due to the longer dry season resulting in the cessation of abstraction in scenario (b), thus allowing heads to recover. The latter does not occur in scenario (a) as the dry season is too short.

The plot of cumulative abstracted volumes for each time scale for any given year in scenarios (a) and (b), shown in Fig. 5, gives a clear image of the temporal distribution of abstraction for each timescale. Fig. 5 highlights that daily and monthly time scales for scenario (a) and additionally the three-monthly time scale for scenario (b) result in periods of no abstraction during the dry season. Taking this into account alongside the results shown for hydraulic head for the same scenarios (sharp declines during wet season with recovery during dry season) it shows that applying a single maximum value of percentage of recharge as an abstraction rate at a single time scale does not lead to the best solution for the QS aquifer. In addition, it should be noted that abstraction rates for the daily time scale scenario are entirely unfeasible based on the pumping capacity at the municipal well field, so that this scenario is theoretical. Moreover, given the seasonality of water demand for irrigation and public supply (further enhanced by tourism), if no alternative water source would be available, such short time-scale abstraction regimes would be completely unfeasible. However, as will be discussed in the following section, in this area surface water reservoirs do provide a solid alternative (they currently in fact supply most of the drinking water). In addition, for systems with lower storage capacity, such as several smaller karst aquifers found in the Algarve region (Stigter et al., 2009), short time scale abstraction regimes would likely be necessary, as recharge is rapidly lost through discharge.

Abstraction rates need to take into account how the system reacts to recharge (for example when recharge reaches the well fields); therefore pumping schedules should be defined on the same time scale as the aquifer system's variation in order to maximise the sustainable yield. However, as was shown in Fig. 4 the aquifer system does not work on a single time scale, with recharge from different areas of the aquifer reaching well-fields at different times, which makes defining the optimal time scale as well as the maximum sustainable yield a complex task. The optimal solution would be to have a monitoring network coupled to a numerical simulation–optimisation model able to determine real-time estimates of maximum sustainable yield. In practice this is not yet feasible. A reasonable compromise would be to define an acceptable time scale for which to determine sustainable yields. Gleeson et al. (2012) refer that for groundwater systems with a short residence time, the mean residence time is a good starting point for discussing planning horizons. There are currently ongoing efforts to determine residence times for the QS aquifer using tracer tests. These studies should complement the analysis presented here and help to determine an optimal time scale for management of this system.

The QS aquifer offers an interesting case due to the location of most of the abstraction relative to the main recharge areas, which leads to the time-lag of several months for most of the recharge to reach the well fields. As is seen in particular in scenario b for the daily, monthly and three-monthly time scales, hydraulic head is still rising slightly 5–6 months after the last recharge event, which shows the significant storage capacity of the QS aquifer. This could allow for pre-emptive planning of pumping schedules and rates taking into account actual recharge events, leading to both an increase in efficiency of use of the renewable resource which is fresh groundwater, whilst also minimising the risk of overexploitation during droughts.

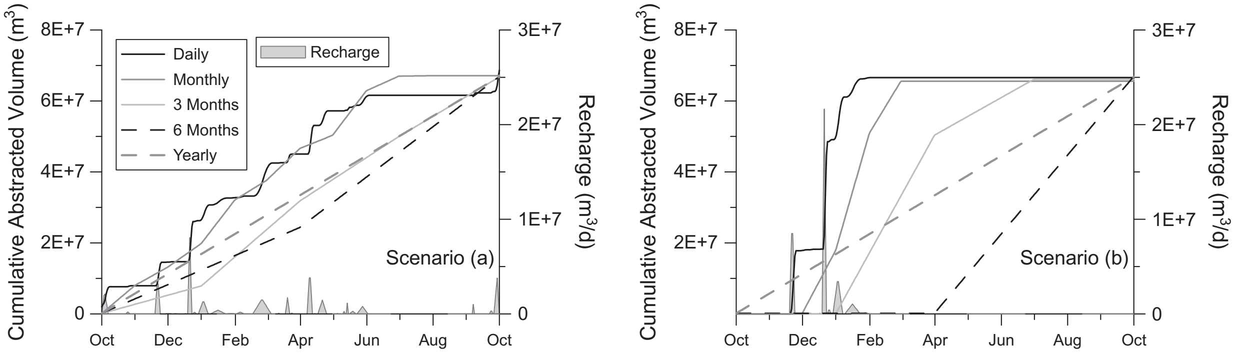


Fig. 5. Cumulative abstracted volumes per cyclical year of the considered time scales for scenario a (left) and scenario b (right).

As discussed by Gleeson et al. (2012) and Holman and Trawick (2011), making the best use of available resources is, obviously, beneficial for the sustainable development of groundwater resources. Amongst other measures, Holman and Trawick (2011) suggest offsetting the timing of peak demand and timing of least resources. This principle could be applied to the QS by offsetting demand on surface water sources by using alternative groundwater sources for supply. Gleeson et al. (2012) go on to underscore the need for an adaptive management, able to adjust to changing conditions in order to reach long term sustainability goals. Such a management scheme would be more robust and able to cope with an uncertain environment, and it would need to be adjusted at the optimal time scale for a given aquifer system in order to maximise its efficiency.

3.2. Hypothetical abstraction scenarios

Fig. 6 presents total annual abstraction volumes resulting from the pumping schemes determined for each of the considered time scales from October 2001 to September 2009, as compared to measured withdrawals by *AdA* (the Water Utility) and from Municipal wells during the same period. Values of estimated yearly recharge are also shown. As is to be expected, intra-annual (daily, monthly, three-monthly and six-monthly) time scale abstractions result in similar annual volumes, which follow inter-annual variations in recharge. Annual time scale pumping follows the same distribution, but with a one-year time lag, whilst the five year time scales result in abstraction volumes without correlation with inter-annual variations. All hypothetical scenarios result in significantly higher annual abstraction volumes than measured for all years except during the drought year 2004/2005. One-yearly and five-yearly time scales lead to a higher total abstracted volume during the entire 8 year period than the remaining time scales. This is due to the fact that (due to their larger temporal extent) abstraction rates are determined based on recharge values from previous years (2000/2001 in the case of 1 year time scale and 1996/1997 to 2000/2001 for 5 year time scale). As the recharge during these previous periods was larger than that during the periods covered by the remaining time scales, total abstraction rates become higher.

Effects of the hypothetical pumping rates calculated for the period of 2001–2009 for the different time scales, are compared with calibrated simulations of actual pumping rates for the same period in Fig. 7. Up to a six-monthly time scale, variations in hydraulic head show that their seasonal amplitude increases with the length of the time scale used to determine pumping rates. This is explained by the fact that for the shortest (daily and monthly) time-scales abstraction for public supply occurs in the wet seasons (autumn and winter), capturing groundwater and keeping heads relatively low (or attenuating their rise), whereas in the spring and summer seasons, groundwater is only withdrawn for irrigation, not for public supply, avoiding larger drawdown. Irrigation was considered in these runs to make the application more realistic, as it will be difficult for farmers to obtain water from an alternative source, despite the ongoing debate on the reuse of treated wastewater (Costa et al., 2006). Increasing time-scales cause greater shifts between the timing of abstraction for public supply and that of recharge. The most extreme scenario, provided by the six-monthly time-scale, results in all abstractions, for public supply and irrigation, concentrated in the spring and summer months. This scenario, currently in practice, basically corresponds to the philosophy of groundwater as a strategic resource to be used exclusively in the dry season. The simulations show that this scenario results in the largest amplitudes of variations of hydraulic head, indicating a larger amount of freshwater loss (mainly in autumn and winter), as well as the lowest minimum values, with lower storage at the end of the simulation period. The high oscillations in discharge in this scenario, with high peaks in the winter and near-zero discharge in the summer, contrast with those of the one-monthly time scale scenario, where discharge is much more constant. This clearly reveals that for the QS aquifer shorter time scales lead to a more sustainable exploitation, also in terms of environmental flows, with potential for higher sustainable yields.

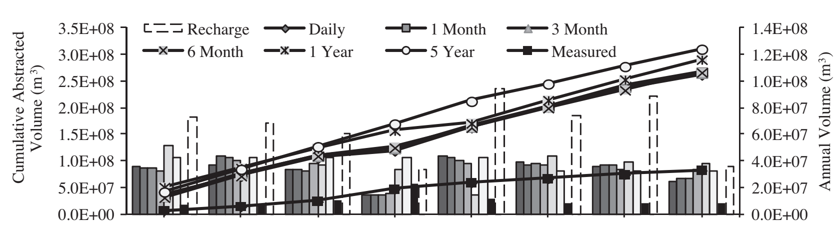


Fig. 6. Cumulative and annual abstracted volumes determined at the various considered time-scales (time scale of the columns increases from left to right) and actual volumes abstracted by the *AdA* Water Utility and from municipal wells during 2001–2009; also shown are values of estimated yearly recharge.

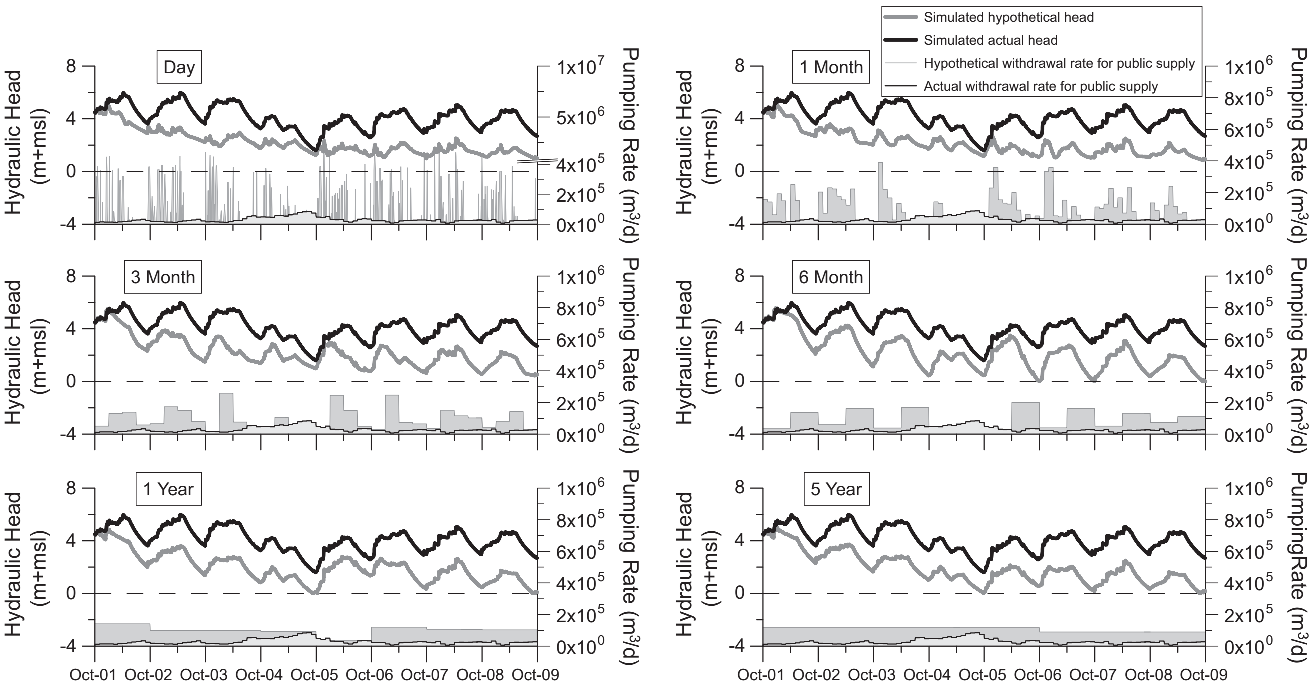


Fig. 7. Variation of hydraulic head at piezometer 595/215 for the considered hypothetical maximum abstraction scenarios; extractions for irrigation during spring and summer months are considered in the model, but not represented here.

Increasing the time scale to a year and longer mostly reduces the amplitude of variations again, as some of the seasonality of abstraction is removed and a single pumping rate for public supply is maintained all year round. Notwithstanding, these time scales do not take into account the intra-annual variability and therefore may lead to larger losses of freshwater during the recharge season than shorter time scales. Coupled with the results of Hugman et al. (2012), which showed that discharge is accelerated during recharge periods, these results show that the current concept of using aquifers in the Algarve exclusively for storage during the winter is not the most adequate in terms of maximising the use of available freshwater, as a significant fraction can be lost before it is needed. Vieira et al. (2011) show, by creating a water allocation optimisation model, that an integrated water resource management in the region, with interannual planning time horizons, can help to cope with future shortages, by positively enhancing the conjunctive use of the different system water sources.

Although hydraulic head and discharge rates in all hypothetical scenarios are continuously lower than actual values due to hypothetical abstraction rates being largely superior to actual abstraction rates, they show a stabilizing trend following the drought of 2004/2005. Up to three-monthly time scales, discharge and head values for that year are approximately equal to those observed. This is achieved with significantly lower abstraction rates (circa 35% or 8 hm^3, see Fig. 6) during 2004/2005 for the hypothetical scenarios, which highlights that the method applied to determine sustainable yield leads to lower maximum sustainable yields for public supply during time periods when water is needed the most. It should be noted however that these short-scale scenarios show that much larger volumes of water (400% or 75 hm^3) could have been abstracted during the previous three years when merely considering gradient inversion as a sustainability criteria.

It must be kept in mind that the values shown here are considered to be sustainable yields considering the specific criteria of non-occurrence of inversion along the Arade estuary boundary and do not take into account any other potential effects of the pumping regimes. When defining the sustainable yield it is important to take into account all the effects of pumping. For example in the current case, if the limit for acceptable impact was solely defined based on the natural discharge rate then, although the simulated scenarios would be considered to be sustainable, they would not take into account the drawdowns that occur in the northern areas of the aquifer system. Fig. 8 exemplifies this with the difference between simulated hydraulic head at the end of September 2009 with abstraction rates based on a monthly time scale and actual abstraction rates. These drawdowns would likely have an effect on the aquifer–stream interactions, and subsequently on the ecosystems which depend on them, though it is currently not clear to which extent. On the other hand, they could also enhance recharge from the streams carrying water from runoff from the little permeable Paleozoic schists and greywackes upstream, through infiltration in the streambeds. This is presently already an important phenomenon that is being studied in more detail (Salvador et al., 2012). The location and depth of the fresh/saltwater interface in a coastal aquifer such as the QS could also be applied as criteria in determining sustainable yield, as these will have an impact on the quality of groundwater and therefore influence the depth and location of practical abstraction. Of course, this kind of water supply management would only be feasible where an alternative water source exists, as is the case in the Algarve, where large surface water reservoirs currently supply most of the drinking water to the region. Although both these sources are subject to the highest pressures at the same time (i.e.: summer and/or drought), these scenario calculations show that a more efficient water resource management would be possible by coordinating the use from both sources. More groundwater could be abstracted for public supply during the winter months (mixing it with a smaller amount of surface water, reducing treatment problems derived from higher turbidity in surface waters and benefiting from the groundwater's natural hardness), avoiding large depletions of the surface water reservoirs. This would create a source for public supply during the dry season, when groundwater would largely be used for irrigation.

Apart from the issues of availability, there are also technical issues of the feasibility of pumping at such high pumping rates. For

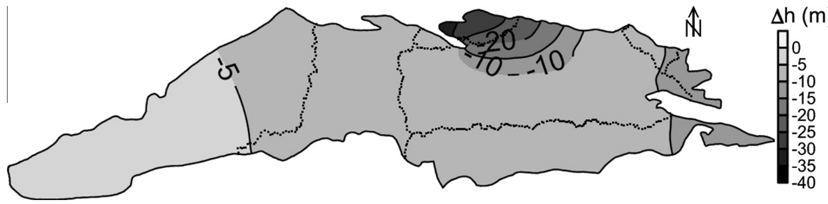


Fig. 8. Difference between simulated hydraulic heads at the end of September 2009 with maximum abstraction rates based on a monthly time scale and simulated heads in the same period with measured abstraction rates.

the daily scenarios pumping rates would not be viable at the present public supply well field. Moreover, representing the karstic nature of the QS aquifer with a single continuum equivalent porous media model, whilst adequate when representing flow at regional scales, may result in significant uncertainty when simulating smaller scale effects such as locations of well fields. Apart from spatial scales, equivalent porous media models do not represent the dual nature of flow in a karst aquifer. To properly quantify time scales for an aquifer such as the QS aquifer, although an equivalent porous media model is adequate, a discrete continuum model would allow for a more detailed comprehension of the various time scales at which the aquifer works.

4. Conclusions

Sustainable yield must be defined based on a ''target condition'', not just a regional water budget, and is dependent on the spatial and temporal dynamics of the system's response to influencing factors such as recharge and pumping. In practice, most efforts to determine sustainable yields define a single value based on long-term averages or annual values of recharge. However, in particular in areas with high seasonal and inter-annual variability such as Portugal, these time scales are too coarse for the systems to which they are being applied and can lead to over- as well as under-exploitation.

The effect of adapting pumping rates based on recharge occurring during the previous time period at several temporal scales was analysed. By developing hypothetical scenarios with a numerical model it was demonstrated that defining a single value based on long term averages does not give an accurate value of sustainable yield. Results show that, for the carbonate rock aquifer of QS, reducing the time scale at which abstraction rates are adapted allows for an increase in withdrawal volumes without surpassing the here considered sustainability criterion of non-occurrence of gradient inversion along the Arade estuary boundary. In fact, not reducing the temporal scale leads to an irretrievable loss of freshwater during recharge periods. Furthermore, scenarios show that predicted seasonal changes in rainfall for the south of Portugal will make taking the temporal scale of the system into account more important, as the concentration of recharge into a shorter period will lead to faster depletion and therefore larger freshwater loss.

Currently groundwater in the Algarve is mainly used for irrigation. Results show that a significant part of annual recharge of the QS aquifer is lost through discharge during the winter which could be used for public water supply allowing water in dams to be conserved for use during the summer. Taken together with the predicted increase in water demand and decrease in availability due to climate change, this is a strong argument in favour of an integrated and adaptive water management scheme for the region, leading to a more robust water supply system within a climate of increasing uncertainty in regards to the availability of freshwater.

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