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Quantifying and modelling the contribution of streams that recharge the Querença-Silves aquifer in the south of Portugal

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Abstract. The water balance of the mesocenozoic aquifers of the Algarve, in the south of Portugal has traditionally been estimated considering only direct (“autogenic”) recharge from rainfall occurring in the area of the aquifers. Little importance has been attributed to so-called allogenic recharge, originating from streambed infiltration from runoff generated outside the aquifers, particularly in the Palaeozoic rocks to the north where runoff is high. The Querença-Silves (QS) aquifer is the most important aquifer of the region both for irrigation and public water supply. Several important and sensitive surface/groundwater ecotones and associated groundwater dependent ecosystems exist at the springs of the natural discharge areas of the aquifer system. A numerical flow model has been in constant development over the last few years and currently is able to reproduce the aquifer’s responses to estimated direct recharge and abstraction for the years 2001–2010. However, recharge calculations for the model do not take into account allogenic recharge infiltration along influent reaches of streams. The quantification of allogenic recharge may further improve the assessment of water availability and exploitation risks. In this paper an attempt is made to quantify the average annual contribution of allogenic recharge to the QS aquifer, based on monitoring data of the principal water courses that cross the aquifer system. Significant uncertainties related to surface runoff generated within the aquifer area, as well as areal recharge were identified and the consequences for the optimization of spatial distribution of transmissivity in the groundwater flow model are also addressed.

1 Introduction

Groundwater and surface water systems have conventionally been approached as independent resources. More recently, an integrated approach towards effective management began to consider groundwater and surface water bodies as a single resource (e.g. Winter et al., 1998; Sophocleus, 2002; Ransley et al., 2007). Furthermore, losses of biodiversity and ecosystem functioning and services for development have led to an increasing concern regarding the need for sustainable management of water, both for human consumption and ecosystems that depend on water. An important objective of the Water Frame Directive (WFD) is to prevent further deterioration and protect and enhance the status of aquatic ecosystems and terrestrial ecosystems depending directly on them (e.g. riparian ecosystems and wetlands), with regard to their water needs. Therefore, a comprehensive understanding of the complex interactions occurring between groundwater and surface water is needed in terms of both quantity and quality (Winter et al., 1998; Sophocleus, 2002; Bailly-Comte et al., 2008). In karst systems these groundwater–surface water (GW–SW) interactions are particularly more complex as they occur through fractures and conduits. Bailly-Comte et al. (2009) present a conceptual model of GW–SW interactions in the case of a karst aquifer of the south of France. The characterisation of these GW–SW interactions is likely to significantly improve the assessment of availability and exploitation risks of groundwater systems, while indicating the potential of groundwater contamination by polluted surface water or vice-versa.

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Recharge of karst systems (and all aquifer systems in general) may be autogenic when it occurs directly from precipitation over the karst aquifer area (diffuse and concentrated infiltration), or allogenic when originated from streambed infiltration from upstream surface runoff in low permeable rocks into sinking or losing streams (Andreo et al., 2008; Taylor and Greene, 2008; Janza, 2010).

Since the early 80s the water balance of the mesocenozoic aquifers of the Portuguese Algarve region has been characterised exclusively based on autogenic recharge estimates, overlooking GW–SW interactions and thus not taking into account stream recharge by infiltration along influent reaches of streams, namely across streambeds or in local sinkholes. The study of recharge for the Querença-Silves (QS) aquifer system is particularly important for an integrated management of surface and groundwater resources, since it is the largest and the most productive aquifer system of the Algarve region (Stigter et al., 2009). Of great regional importance, both for public water supply and irrigation, it has demonstrated to be an important key to the water supply system during the 2004/2005 drought (Monteiro, 2006, Stigter et al., 2009). Over the last few years a numerical groundwater flow model for the QS aquifer system has been in constant development as the result of ongoing research on monitoring and modelling of aquifer systems, an overview of which can be found in Hugman et al. (2011). As stated in Monteiro et al. (2012), the observed resilience of the QS aquifer during drought periods such as 2004/2005 that the numerical flow model is not entirely able to reproduce (reproducing smaller recovery rates) may be related to the fact that only autogenic recharge rates were taken into account in the model.

Reis (2007) presents incomplete estimates of stream recharge on the aquifers of the Algarve region. New estimates of volumes involved in the GW–SW interactions of the QS aquifer system were assessed by Salvador et al. (2012) through the application of a water balance approach based on monitoring data and the BALSEQ_MOD model (Oliveira et al., 2008). The results demonstrated that streambed infiltration may indeed be relevant enough to affect the overall water balance of the QS aquifer. Notwithstanding, recharge appears to be largely overestimated when compared to previous data, and the results comprise a number of uncertainties, particularly related to surface runoff estimations that have not been dealt with so far. The present paper aims to address these uncertainties while providing new estimates of mean annual stream recharge through a water balance based on the available monitoring datasets of the main streams that cross the aquifer system, completed with partially calibrated surface flows estimates where monitoring data was unavailable. Additionally, it will provide an indication of the degree of groundwater dependency of the stream network in hydraulic connection with the aquifer.

Secondly, the papers aims to show how different scenarios of increased recharge, within the quantified limits of uncertainty, affect the inverse calibration of transmissivity of the groundwater flow model, as well as what the potential effects are for the groundwater head recovery following the 2004/2005 drought, based on transient model runs.

2 Study area

The Central Algarve is characterised by a Mediterranean climate, with dry and warm summers and cool wet winters. Mean annual temperature for the 1980–2010 climate normal is 17.5 °C, whereas rainfall varies between 670 and 740 mm. The Querença-Silves (QS) aquifer system is located in the Algarve region, south of Portugal (Fig. 1). This karst aquifer formed by Jurassic carbonate sedimentary rocks covers an irregular area of 324 km^2 from Querença (to the east) to the Arade River (to the west) (Monteiro et al., 2006). The system is divided into subunits with distinct hydraulic behavior (Almeida et al., 2000), being delimited by the Algibre thrust to the south and by the Triassic-Hettangian rocks to the north (Terrinha, 1998). The Estômbar springs on the west limit constitute the main discharge area of the system towards the Arade River, supporting several important groundwater dependent ecosystems (GDEs).

The stream network that crosses the QS aquifer system initiates its course in the low permeability rocks of the Serra region where drainage density is high, more than 3.5 km km^{-2} (Almeida, 1985). It flows through the aquifer system in the karst carbonate rocks where infiltration rates are very high and, therefore, drainage density is between 0 and 2 km km^{-2} (Almeida, 1985). These differences between hydrogeological conditions suggest the occurrence of substantial contribution of allogenic recharge towards the QS. Several field campaigns have allowed the georeferencing of influent and effluent points and reaches of the stream network crossing the QS area (Reis, 2007; Monteiro et al., 2012). Monteiro et al. (2012) incorporated the stream network into the numerical flow model of the QS and imposed specified-head boundary conditions (also known as a Type 1 or Dirichlet boundary) to investigate into the factors controlling the spatial distribution of the GW–SW interactions. The stream network is divided into two watersheds: the *Meirinho stream* drainage basin to the west and the *Quarteira* stream basin to the east (Fig. 1). The *Quarteira* stream changes denomination several times along its way, ultimately resulting from the confluence of the *Algibre* stream with the *Alte* stream (see Fig. 1). These streams are also fed by a number of springs within the area of the aquifer.

3 Methods

A wide range of methods are available to assess GW–SW interactions, based on hydrograph separation (see review by Brodie and Hosteler, 2005), modelling (Sophocleus and Perkins, 2000; Monteiro et al., 2012), tracing (Lerch, 2005), temperature (Constantz et al., 2008), and water balance

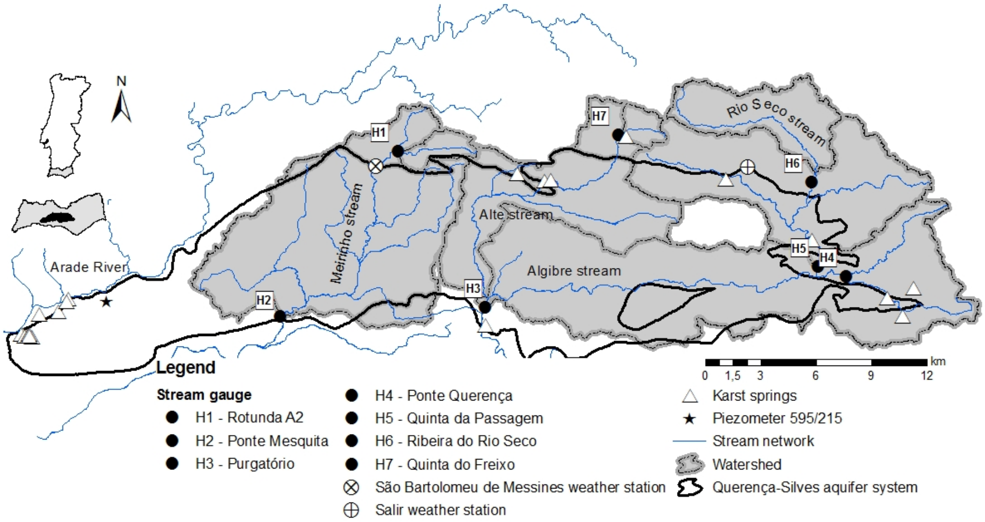

Fig. 1. Location of study area, characterising the surface–groundwater relationships; also shown is the location of the stream gauges, weather stations, piezometer 595/215 and springs.

(Salvador et al., 2012), among others (see review by Winter, 1995 and Brodie et al., 2007). The most commonly used approach may be hydrograph separation (Opsahl et al., 2007). According to Ransley et al. (2007), two types of approaches seems to exist: (i) measurement techniques and (ii) modelling techniques. This study combines these two approaches. Firstly, to estimate stream recharge, a water balance approach was applied using the available datasets of the specific monitoring network installed by the Water Basin Authority (*ARH Algarve*) to quantify volumes entering and leaving the aquifer systems of the Algarve through stream flow. Secondly, the stream recharge estimates were integrated into the numerical groundwater flow model of the QS aquifer system.

3.1 Stream recharge

A water balance approach was applied in order to estimate the contribution of stream recharge to the QS aquifer. It was considered that the surface water flow measured in the main streams when they flow out the aquifer area can be expressed as

$$Q_{\mathrm{out}} = Q_{\mathrm{in}} + Q_{\mathrm{d}} + Q_{\mathrm{b}} - R_{\mathrm{s}} - E \qquad (1)$$

where Q_{out} is surface water outflow from the aquifer; Q_{in} is upstream surface water inflow to the aquifer, generated upstream, in low permeability rocks of the Serra region; Q_{d} is surface runoff generated within the aquifer area; Q_{b} is groundwater contribution in effluent reaches recorded as base flow in the downstream gauging station; R_{s} is stream recharge to aquifer, i.e. infiltration occurring in sinkholes and influent reaches; and E is direct evaporation from the streams (all in mm or m^3). E was considered insignificant due to the short watershed time of concentration.

Daily flow records from the monitoring network shown in Fig. 1 were provided by the *ARH Algarve*. The water balance was applied for an average year to stream gauges H2, H3 and H5 (only data referring to complete hydrological years (Oct–Sep) were used, 6 yr (1996 to 2000; 2004 to 2006), 5 yr (2005 to 2010) and 8 yr (1998; 2000 to 2007), respectively). The available data allowed the water balance expressed by Eq. (1) to be rewritten into Eq. (2) for stream gauge H3.

$$\begin{aligned} &Q_{\mathrm{out}}(\mathrm{H3}) \\ &= Q_{\mathrm{out}}(\mathrm{H5}) + \text{ measured } Q_{\mathrm{in}}\ (\mathrm{H4}) + Q_{\mathrm{in}}(\mathrm{Alte}) \\ &+ Q_{\mathrm{in}}(\mathrm{Algibre}) + Q_{\mathrm{d}}(\mathrm{Alte}) + Q_{\mathrm{d}}(\mathrm{Algibre}) + Q_{\mathrm{b}} - R_{\mathrm{s}} - E \end{aligned} \qquad (2)$$

where Q_{out} is surface outflow from the aquifer in stream gauge H3; Q_{out} (H5) is surface flow in stream gauge H5; Q_{in} (H4) is surface flow in stream gauge H4; Q_{in} (Alte) is upstream surface inflow to the aquifer generated in low permeability rocks of the *Alte* stream watershed; Q_{in} (Algibre) is the remaining (not accounted for in Q_{out} (H5) and Q_{in} (H4) variables) upstream surface inflow to the aquifer, generated in the *Algibre* stream watershed; Q_{d} (Alte) and Q_{d} (Algibre) are surface runoff generated within the aquifer area in the *Alte* stream and *Algibre* stream watersheds, respectively; Q_{b} is groundwater contribution in effluent reaches recorded as base flow in stream gauge H3; R_{s} is stream recharge to aquifer; and E is direct evaporation from the streams (all in mm or m^3).

An exponential relation between Q_{out} data and precipitation (P) data allowed estimates of Q_{out} for a 30 yr average P. The 30 yr P average of the *São Bartolomeu de Messines* (for stream gauge H2) e *Salir* (for gauges H3 and H5) weather stations (Fig. 1) were firstly used to establish a relation with average P used in the calculations of the remaining variables of Eqs. (1) and (2), as the latter cover a different period.

Watersheds were redefined from the boundaries provided by the National Water Authority (*Instituto da Água, I. P.*) through the InterSIG tool, to which the Portuguese 1:25 000 military maps and the stream network from the Geografic Army Institute (*Instituto Geográfico do Exército - IGeoE*) were overlayed in a GIS environment. The catchment area of the *Nave do Barão* Polje (white area on the map of Fig. 1) was not included in the water balance since generated runoff causes ponding and results in evaporation and slow infiltration into the karst depression, thus not contributing to stream flow.

The monitoring network is recent, installed by the end of 2004 (Reis, 2007), and for technical reasons, upstream gauging stations are not registering total surface flow generated in the watershed outside the aquifer area. To overcome this problem, Q_{in} volumes were estimated based on a simplified rainfall-runoff model, expressed by Eq. (3), using precipitation data for the period 1960–1990 (Nicolau, 2002), evapotranspiration data for the period 1931–1960 (Atlas do Ambiente, 1974) and recharge rates expressed as percentage of precipitation. Exact rates are not known, but for the Paleozoic schists and greywackes they are generally very low. To incorporate uncertainty in the calculations, two values were considered: 10 % (scenario a) and 5 % (scenario b).

$$Q = P - \mathrm{ET} - R \tag{3}$$

where Q is surface runoff, P is precipitation, ET is evapotranspiration and R is recharge (all in mm or m^3). Nevertheless, Q_{in} monitoring data was used to assess estimated Q_{in} volumes. An exponential relation between register Q_{in} and P data allowed estimates of Q_{in} for a 30 yr average P. The 30 yr P average of the *Salir* weather station (Fig. 1) was firstly used to establish a relation with average P used in the calculations of the remaining variables of the Eqs. (1) and (2), as the latter cover a different period.

The water balance described in Eq. (3) was also applied to estimate Q_{d} based on the areas where the carbonate rock layers are covered by sedimentary deposits, using the areal recharge rates proposed by Vieira and Monteiro (2003) (for more see Sect. 3.2 of the present text). In the carbonate rock outcrop areas, generated runoff was seen to be negligible. The available data from the work of Oliveira et al. (2008) allowed estimating a different Q_{d}. Therefore, both estimates were later incorporated into the water balance expressed by Eqs. (1) and (2), as scenarios A and B (see Table 1 for detailed scenario descriptions).

The United Kingdom Institute of Hydrology (UKIH) smoothed minima approach (Gustard et al., 1992) adopted for intermittent streams (AdUKIH) (Aksoy et al., 2008) was applied for base flow separation (Q_{b}). This technique uses the minima of non-overlapping consecutive periods from daily flow time series, subsequently connecting turning points from this minima series. Aksoy et al. (2008) compared the AdUKIH approach with a recursive digital filter (RDF) base flow separation method and concluded the AdUKIH approach is better if a drainage-area-based block size is used. To estimate the block size the authors present the following expression:

$$N = 1.6A^{0.2} \tag{4}$$

where N is the block size (days) and A is the drainage area of the hydrological watershed (km^2). Afterwards, a monthly relation between Q_{b} and Q_{out} allowed estimating Q_{b} for a 30 yr average Q_{out}.

The base flow index (BFI) as described by Gustard et al. (1992) is the proportion of base flow in the river's runoff. The BFI was estimated as the proportion of base flow in Q_{out}, as it provides indication of the groundwater dependency degree of the stream network in hydraulic connection with the aquifer system.

3.2 Numerical groundwater flow model

The numerical groundwater flow 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 of this model, the first variants of which were implemented by Monteiro (2003, 2006), can be found in Hugman et al. (2011). Areal recharge rates were originally based on values proposed by Vieira and Monteiro (2003). They estimated mean annual recharge as approximately 93 $\mathrm{hm}^3\,\mathrm{yr}^{-1}$ for areas where carbonate rocks occur as outcrops (using Kessler method, 1965) or covered by different types of sedimentary deposits (using soil water balance/storage methods combined with Coutagne (1954), Turc (1954) and Thornthwaite (1948) methods to estimate real evapotranspiration), based on detailed spatial distribution of precipitation for the period 1959/1960–1990/1991 (Nicolau et al., 2000 and Nicolau, 2002). More detailed areal recharge rates were recently proposed by Oliveira et al. (2008) based on the numeric model of sequential daily water balance BALSEQ_MOD. Mean annual recharge was estimated as 100 $\mathrm{hm}^3\,\mathrm{yr}^{-1}$. Oliveira et al. (2011) updated this estimate to 94 $\mathrm{hm}^3\,\mathrm{yr}^{-1}$, however areal recharge rates are not yet available. For this paper, scenarios considering values and spatial distribution of recharge from Vieira and Monteiro (2003) and Oliveira et al. (2008) were analyzed.

The estimated annual withdrawal for irrigation of 31 hm^3 (Nunes et al., 2006) was applied to 150 nodes of the model, which represent 150 private wells known to be located within the irrigated area. Withdrawals for public water supply, which are approximately 10 $\mathrm{hm}^3\,\mathrm{yr}^{-1}$ (Stigter et al., 2011), were applied to nodes representing Municipal Council wells from which until recently most public water supply was abstracted. Previous versions of the model merely consider boundary conditions defined as constant head along the Arade estuary in the west and no-flow for the remaining part (Stigter et al., 2011; Hugman et al., 2011). In order to analyze

Table 1. Scenarios detailed description.

Scenario	Description
a	Upstream surface inflow to aquifer (Q_{in}) was estimated based on a simplified rainfall-runoff model, expressed by Eq. (3) where recharge rates were considering to be 10 % of precipitation.
b	Upstream surface inflow to aquifer (Q_{in}) was estimated based on a simplified rainfall-runoff model, expressed by Eq. (3) where recharge rates were considering to be 5 % of precipitation.
A	Surface runoff generated within the aquifer area (Q_{d}) was estimated based on the areal recharge rates proposed by Vieira and Monteiro (2003) for the areas where the carbonate rock layers are covered by sedimentary deposits (runoff generated in carbonate rock outcrop areas was seen to be negligible).
B	Surface runoff generated within the aquifer area (Q_{d}) was estimated based on the areal recharge rates estimated with the BALSEQ_MOD proposed by Oliveira et al. (2008).
1	Surface outflow from the aquifer (Q_{out}) for stream gauge H3 was estimated based on an exponential relation with precipitation (P) considering 5 complete hydrological years (October to September) 2005/2006; 2006/2007; 2007/2008; 2008/2009; 2009/2010. $R^2 = 0.79$.
2	Surface outflow from the aquifer (Q_{out}) for stream gauge H3 was estimated based on an exponential relation with precipitation (P) considering 4 complete hydrological years (October to September) 2005/2006; 2006/2007; 2007/2008; 2008/2009. The 2009/2010 hydrological year was considered as a possible outlier. $R^2 = 0.89$.
i	Surface outflow from the aquifer (Q_{out}) for stream gauge H5 was estimated based on an exponential relation with precipitation (P) considering 8 complete hydrological years (October to September) 1998/1999; 2000/2001; 2001/2002; 2002/2003; 2003/2004; 2004/2005; 2005/2006; 2006/2007. $R^2 = 0.79$.
ii	Surface outflow from the aquifer (Q_{out}) for stream gauge H5 was estimated based on an exponential relation with precipitation (P) considering 7 complete hydrological years (October to September) 1998/1999; 2000/2001; 2001/2002; 2003/2004; 2004/2005; 2005/2006; 2006/2007. The 2002/2003 hydrological year was considered as a possible outlier. $R^2 = 0.83$.
Base (A)	Areal recharge rates proposed by Vieira and Monteiro (2003) were incorporated in the numerical flow model. No-stream recharge was considered.
Base (B)	Areal recharge rates proposed by Oliveira et al. (2008) were incorporated in the numerical flow model. No-stream recharge was considered.

the effect of stream recharge on the aquifer system, fluid flux (also known as Neuman or Type 2) boundary conditions were applied along nodes corresponding to the main stream network. It was assumed streams are hydraulically connected to the QS aquifer system along their entire extent. This is known to not be the case; however currently there is insufficient data to apply a more complex representation of these connections as discussed by Monteiro et al. (2012).

The defined conceptual flow model was translated to a finite element mesh with 11 663 nodes and 22 409 triangular finite elements. The direct solution was implemented using a standard finite-element model based on the Galerkin method of weighted residuals (Huyakorn and Pinder, 1983). The physical principles at the basis of the simulation of the hydraulic behaviour of the aquifer system under steady state conditions are expressed by:

$$S\frac{\partial h}{\partial t} + \mathrm{div}(-[T]\cdot\overrightarrow{\mathrm{grad}}\cdot h) = Q \qquad (5)$$

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

The spatial distribution of T was estimated by inverse modelling under steady-state conditions for both recharge variants and the various scenarios with and without considering recharge along the streams. Calibration was performed using the Gauss-Marquardt-Levenberg method implemented in the nonlinear parameter estimation software PEST (Doherty, 2002), which provides a numerical solution to the problem of minimizing a function over a space of parameters of the function, and significantly reduces the workload of complex calibrations of non-linear problems. For transient versions of the model, the spatial distribution of the S was calibrated by trial-and-error based on piezometric data for the period of 2001 to 2009, as the smaller amount of variables did not justify the increased complexity of implementing PEST under transient conditions. A more in depth

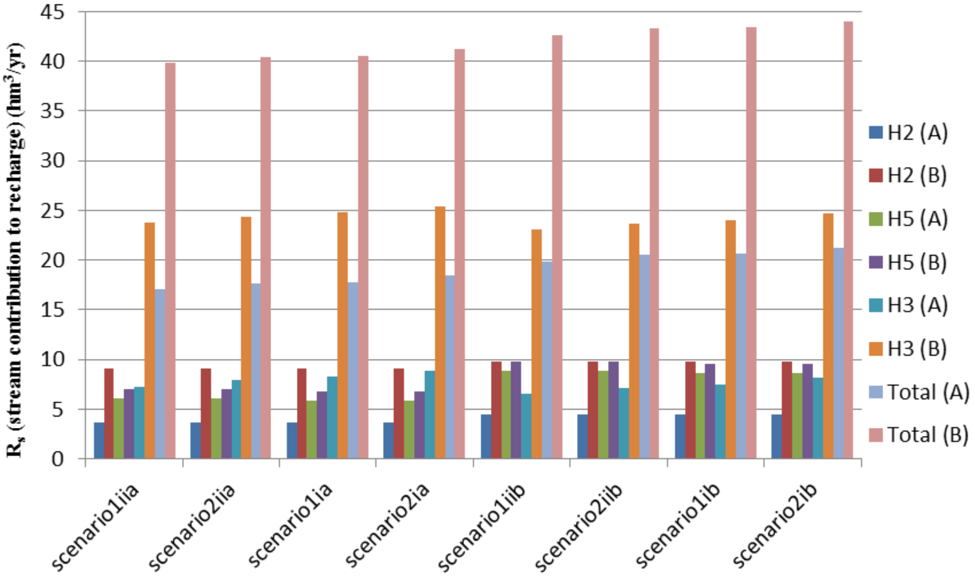

Fig. 2. Total stream recharge and for individual stream gauges (see Fig. 1 for location) for different tested scenarios (see Table 1 for detailed scenario descriptions). **(A)** and **(B)** refer to surface runoff generated within the aquifer area considering areal recharge rates from Vieira and Monteiro (2003) and BALSEQ_MOD (Oliveira et al., 2008), respectively.

description of these calibrations can be found in Hugman et al. (2011).

4 Results and discussion

4.1 Stream Recharge

In order to incorporate uncertainties, different scenarios were taken into consideration in stream recharge estimations (see Table 1 for detailed scenario descriptions). Table 2 shows an example of partial calibration of the calculation of Q_{in} for stream gauges H4 and H7 (see Fig. 1 for location). Only data referring to complete hydrological years (October–September) were used to estimate upstream surface water inflow to the aquifer, 3 yr (1998 to 2000; 2007) for stream gauge H4 and 3 yr (2005 to 2007) for stream gauge H7. It can be seen that the estimates are not far from the observed values, particularly with regard to scenario a (considering 10 % infiltration), despite the relatively simple water balance calculations. The available data for stream gauges H1 and H6 (3 and 2 complete hydrological years, respectively) was insufficient to establish a relation with P.

The results of all variables considered on the water balance expressed by Eqs. (1) and (2) are presented in Table 3, with the exception of stream evaporation E, which was considered insignificant due to the short watershed time of concentration, and stream recharge (R_{s}), which is presented in Fig. 2. For stream gauge H3, two different scenarios were considered relatively to Q_{out} (30 yr average): scenario 1 where all 5 complete hydrological years were used in the exponential relation between Q_{out} and P ($R^2 = 0.79$); and scenario 2 where the hydrological year 2009/2010 was considered an outlier and excluded ($R^2 = 0.89$). There is approximately 6 $hm^3\,yr^{-1}$ difference of Q_{out} between scenarios 1 and 2; this demonstrates the need for continuous records of stream flow, as a low number of records may influence and limit the conclusions than can be drawn. It was interesting to note that in two consecutive years (2006/2007 and 2007/2008), with only 30 mm difference in P, Q_{out} was relatively identical but Q_{b} had double the difference. The explanation for this difference may be related to intensity and duration of rainfall episodes, as hydrograph analysis of surface flow entering (Q_{in}) and leaving (Q_{out}) the aquifer system shows that short and less intense episodes tend to be totally absorbed by the system, while for intense rainfall events stream discharge peaks greatly increase downstream. Other explanations may be related with the system initial conditions and karst conduits carrying capacity, as it may influence flow direction and streams reaches may change from influent to effluent and vice-versa. It seems therefore important to study precipitation variability (e.g. rainfall intensity-duration-frequency curves (IDF)) and increase knowledge on karst conduits locations and their response to rainfall episodes. Bailly-Comte et al. (2008) demonstrated the importance of the system initial state and Bailly-Comte et al. (2009) studied temperature-conductivity in stream flow, karst conduits and groundwater to better understand whether the water present in these karst conduits is originated by surface flow, base flow, or by both. For stream gauge H5 two different scenarios were also considered: scenario i where all 8 complete hydrological years were used in the exponential relation between

Table 2. Comparing upstream surface inflow to aquifer (Q_{in}) from monitoring data with estimations resulting from Eq. (3).

Gauging station	Catchment area (km^2)	P (mm)	Q$_{\mathrm{in}}$ (hm^3) (measured)	Q_{in} (hm^3) (estimated)	
				Scenario a (10 % infiltration)	Scenario b (5 % infiltration)
H4 – Ponte Querença	32.15	788	5.26	5.66	6.71
H7 – Quinta do Freixo	3.98	762	0.74	0.88	1.10

Table 3. Results of Eq. (1) and Eq. (2) variables – surface water outflow (Q_{out}) and inflow (Q_{in}) to aquifer, surface runoff generated within the aquifer area (Q_{d}), base flow contributions (Q_{b}), base flow index (BFI) for different tested scenarios and stream gauge catchment areas (for scenarios detailed description see Table 1.)

	Stream gauge						
	Scenario	H2	Scenario	H5	Scenario		H3
Q_{out} (hm^3/ano)	all	0.67	i	12.79		1	22.62
			ii	11.79		2	16.51
Q_{in} (hm^3/ano)	a	3.29	a	12.76	Q_{out} (H5)	i	12.79
						ii	11.79
					Q_{in} (H4)	all	5.26
	b	4.04	b	15.55	Alte	a	3.11
						b	3.69
					Algibre	a	0.51
						b	0.65
Q_{d} (hm^3/ano)	A	1.05	A	0.17	Alte	A	0.94
						B	2.63
	B	6.41	B	1.09	Algibre	A	1.49
						B	16.32
Q_{b} (hm^3/ano)	all	0.05	i	5.70		1	6.05
			ii	4.92		2	0.59
BFI	all	0.07	i	0.44		1	0.27
			ii	0.42		2	0.03
Catchment area (km^2)		111		93			282

Q_{out} and P ($R^2 = 0.79$) and scenario 2 where the hydrological year 2009/2010 was considered an outlier and excluded ($R^2 = 0.83$). Differences of Q_{out} between scenarios i and ii are of 1 hm^3 yr^{-1}, and more likely related to base flow rather than precipitation, since the *Fonte Benémola* spring discharges into the stream upstream of this stream gauge. As demonstrated by BFI estimates (Table 3), around 42–44 % of stream flow (Q_{out}) in stream gauge H5 derives from groundwater contributions (Q_{b}). According to Environment Agency (2011), BFI values above 0.5 (50 % base flow) are generally considered to be "significantly groundwater dependent". Therefore, the *Algibre* stream may be considered as groundwater dependent ecosystem (GDE), and it should be protected accordingly. The most significant contributions of streams to aquifer recharge (see Fig. 2 for stream recharge results for different scenarios) occur in the eastern sector of the aquifer, particularly between stream gauges H3 and H5 and upstream of H5. Clearly, the contribution of streams to aquifer recharge estimated in scenario B, where surface runoff generated within the aquifer area (Q_{d}) was based on the BALSEQ_MOD areal recharge rates (Oliveira et al., 2008), is much higher, particularly between H5 and H3. This is directly related to the higher calculated surface water runoff generated in the carbonate rocks within the *Algibre* stream watershed. These differences found between Q_{d} (Algibre) estimated for scenarios A and B (Table 3) were found to be likely related to the lower evapotranspiration values that the BALSEQ_MOD model estimates for direct recharge calculations, which appear to be underestimated. It seems that the latter lead to an overestimation of areal and total recharge by this method, though there are other factors that need to be considered. For instance, the error related to the field monitoring data and the establishment of the stage discharge rating curve must be assessed. Moreover, monitoring data are currently relatively scarce and incomplete. It appears that a number of stream reaches, both entering and leaving the system, are currently not monitored, which might have a relevant effect on the calculations despite attempts to minimize this effect. Despite these uncertainties, the simple comparison between surface water inflow to the aquifer (Q_{in}) and surface runoff generated within the aquifer area (Q_{d}), as presented in Table 3, shows that most stream flow is generated outside the aquifer area, therefore it can be considered that stream recharge is mainly allogenic recharge.

4.2 Numerical groundwater flow model

As was expected, there was an overall rise in values of T to compensate for the added recharge from the main streams for extreme stream recharge scenarios 2ib and 1iia (Fig. 3) (see Table 1 for detailed scenario descriptions). The most significant changes between stream recharge and no-stream recharge (Base) scenarios are seen in the easternmost zones, along the *Algibre* and *Rio Seco* streams, as well as a mostly uniform increase of T over the western half of the aquifer system. Model variants which take into account recharge from the streams were found to be better able to approximate average values of measured hydraulic head than their equivalent Base variant.

Although the model variants which consider recharge estimated using BALSEQ_MOD (scenario B) resulted in a better match between observed and simulated heads, the obtained spatial distribution of T appears to be less realistic with more of a "patchwork" distribution and large variations of T between neighbouring zones. It is of note that the most significant decrease in residuals (|measured – simulated head|) for all the variants is focused around the observation points located in the northern and eastern areas of the system. This highlights the models' difficulty in simulating these areas and a need for a better understanding of the factors influencing hydraulic behaviour in this part of the aquifer system.

The main purpose of previous efforts to model the QS aquifer system has always centred on assessing the risk of salt-water intrusion along the aquifer systems boundary with the Arade estuary. So far the numerical models have been able to obtain a good match between simulated and observed data, having managed to replicate the non-occurrence of intrusion during the latest drought (Stigter et al., 2011). Until now, these efforts have relied on models with hydraulic parameters calibrated without taking into account potential recharge from streams. In order to determine if the non-occurrence of inversion could be attributed to stream contribution to recharge, the obtained distributions of T were applied to a transient version of the numerical model, previously described in Stigter et al. (2011) and Hugman et al (2011). Unfortunately the variations in hydraulic head shown in Fig. 4 are inconclusive, as hydraulic head in both scenarios (A and B) reach values similar to their equivalent Base scenarios during the summer of 2005. This is likely due to effect of higher overall T, which leads to greater discharge and subsequently a faster "draining" of the system as can be seen in the top graph in Fig. 4. Obtaining a definitive answer to this issue would require a new calibration of the spatial distribution of S, as the range of variations of simulated head for the period of 2001 to 2009 no longer matches observed ranges.

Apart from the significant issue of salt-water intrusion, there is a need to protect and preserve the important GDEs that exist along the streams associated to the QS. In its current stage, the numerical model does not take into account local scale surface–groundwater interactions. Monteiro et al. (2012) showed that streams varied between an influent and effluent nature along their length; however it was unable to properly quantify the local scale water balance due to a lack of data on stream flow at the time. Now that allogenic recharge has been shown to have a significant effect on the water balance at a regional scale, the subsequent step should be to determine the spatial distribution of this recharge along the length of the streams and its effects at a local scale. This would best be done by the application of Type 3 or Cauchy boundary conditions, which consist in the use of a fluid transfer coefficient, the value of which can be varied when affecting transferences from the aquifer to the river or from the river toward the aquifer. Thus, if the influent and effluent reaches are mapped, the values of this variable can be adjusted in order to control the intensity of transferences for specific reaches of the streams so as to match observed values of stream flow.

5 Conclusions

The results reveal that the quantification of allogenic recharge clearly contributes to improving the assessment of water availability and exploitation risks. The contribution of streams to recharge of the QS aquifer is clearly significant, despite certain uncertainties that exist during the quantification of this variable. The simple sensitivity analysis shows that the largest uncertainties are related to surface runoff generated within the aquifer area, as well as areal recharge, both much higher when determined by the BALSEQ_MOD method. The high values are related to the much higher runoff considered in certain carbonate rock formations, as well as the much lower considered evapotranspiration values of that method. It seems that the latter leads to an overestimation of areal and total recharge by this method, though there

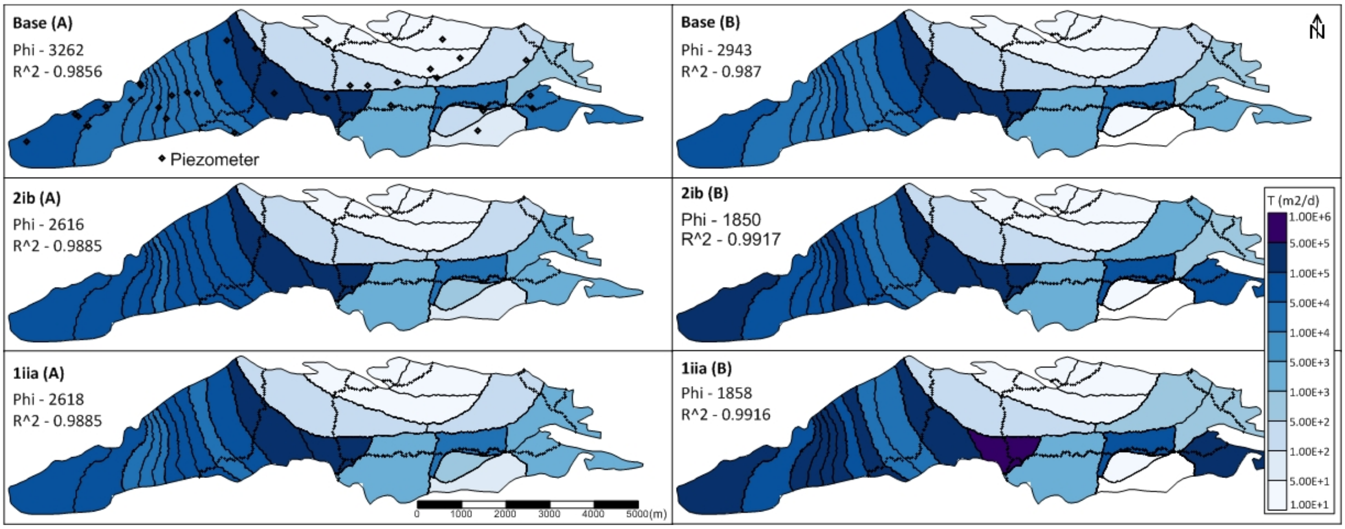

Fig. 3. Spatial distribution of T estimated by inverse modelling considering areal recharge rates from Vieira and Monteiro (2003) and BALSEQ_MOD (Oliveira et al., 2008) for three scenarios of stream recharge (see Table 1 for detailed scenario descriptions) and their respective calibration statistics Phi (sum of squared residuals) and R^2 (coefficient of determination between measured and simulated head).

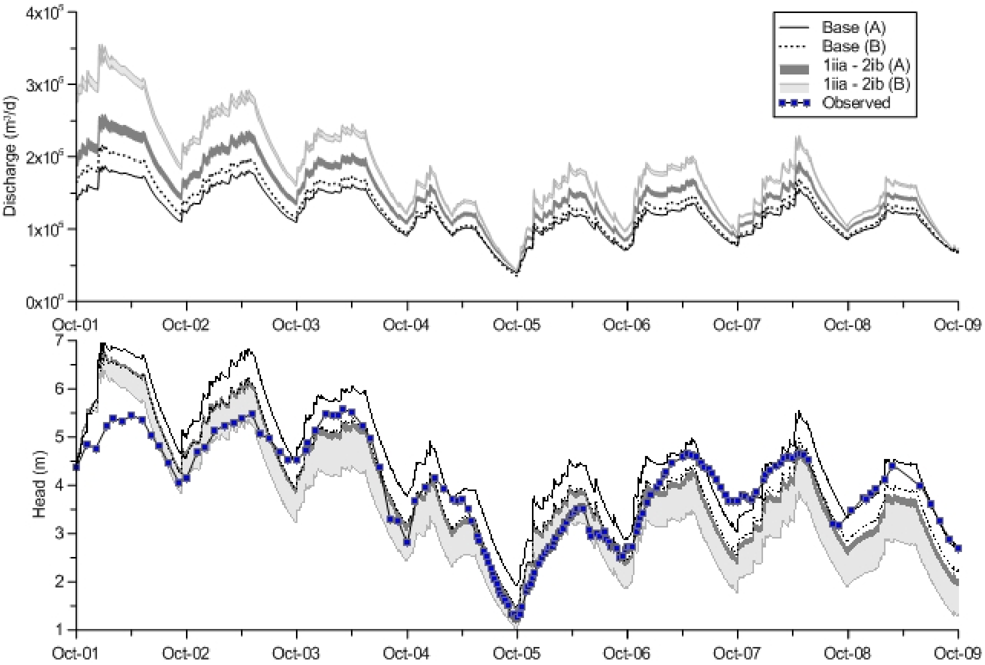

Fig. 4. Simulated discharge and hydraulic head at piezometer 595/215 from 2001 to 2009 for the various distributions of T values.

are other factors that need to be considered. For instance, the error related to the field monitoring data and the establishment of the stage discharge rating curve must be assessed. Moreover, monitoring data are currently relatively scarce and incomplete. It appears that a number of stream reaches, both entering and leaving the system, are currently not monitored, which might have a relevant effect on the calculations despite attempts to minimize this effect. Regarding the groundwater model, the different recharge scenarios considering allogenic recharge indicate that the stream contribution to recharge affects the calibration of the transmissivity and therefore the way the aquifer responds to recharge, abstraction and discharge events, the regional distribution of hydraulic head, as well as the overall water balance. The storage coefficient now needs to be recalibrated for all scenarios to understand if the contribution of stream recharge indeed may cause a better recovery of the groundwater heads following the dry period. Subsequent steps in understanding the influence of allogenic recharge require a more detailed simulation of the local scale interactions between surface and groundwater. This will further allow the quantification of groundwater exported from the aquifer system as base flow.

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