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THEMATIC ISSUE

Modeling the spatial and temporal distribution of coastal groundwater discharge for different water use scenarios under epistemic uncertainty: case study in South Portugal

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Abstract The following paper presents a discussion of spatial and temporal distribution of groundwater discharge estimates at a regional scale for two coastal aquifer systems in the Algarve region. A finite element distributed parameter groundwater flow model is applied to analyze the effect of uncertainties regarding definition of model boundary conditions and seasonality on estimated values. Finally, estimates of sustainable yields are provided based on predefined sustainability criteria and the importance of well location is analyzed. Steady-state simulations indicate a range of average annual coastal discharge between 6.5×10^6 and 15×10^6 m^3/year from the Albufeira-Ribeira de Quarteira aquifer, and 4.5×10^6 and 11.3×10^6 m^3/year from the Quarteira aquifer, as well as significant spatial variation. Transient simulations show that seasonal variability inherent to these systems can lead to inversions of hydraulic head gradient during short periods. Model results indicate that coastal discharge rates are between 1.5 and 2 times higher during the peak winter months than during the minimum in the summer, and as such seasonality has a larger impact on discharge rates than BC conceptualization. Up to 3.31×10^6 m^3/year could be abstracted from existing well fields without causing seawater intrusion problems. Historical levels of abstraction are not within the selected sustainability criteria. However, by placing abstraction further from the coast sustainable yield increases. This work is part of ongoing research that aims to identify and characterize groundwater flow from the coastal strip towards the continental platform, taking into account structural geology, marine geology and the effects of the hydrological/hydrogeologic conditions on the associated ecosystems.

Keywords Coastal groundwater discharge · Numerical modeling · Uncertainty · Surface/groundwater interface · Integrated water resources management · Groundwater dependant ecosystems

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Introduction

Integrated approaches considering groundwater and surface water bodies as a single resource must be adopted for sustainable management (Winter et al. 1998; Sophocleous 2002). Water use for human needs must take into account effects on other environmental users to fit the concept of sustainability (Alley et al. 1999; Sophocleous 2002; Custodio 2002). This has led to an increasing body of work on the interaction between groundwater and fresh water bodies such as rivers, lakes and wetlands (e.g. Sophocleous 2002; Eamus and Froend 2006). Research on the interactions between groundwater and the sea until recently has been mainly focused on seawater intrusion (e.g., Zhang et al. 2004; Kerrou et al. 2010; Watson et al. 2010; Lu et al. 2011; Koussis et al. 2012; Gaaloul 2012; Ghassemi et al. 2012), despite recognition that submarine groundwater discharge (SGD) can have a significant impact on marine ecology (Taniguchi et al. 2002; Burnett et al. 2006).

The term Submarine Groundwater Discharge (SGD) has been given several definitions, depending on whether it merely takes into account freshwater discharge or also includes re-circulated water seepage (Taniguchi et al. 2002). The most consensual definition is described in Burnett et al. (2006) as “any flow of water out across the sea floor”. Whether SGD includes a large component of freshwater or not, also referred to as coastal groundwater discharge (CGD), depends on the local hydrogeological conditions, i.e. aquifer lithology, aquifer type and hydraulic gradients, as well as the groundwater balance and how it is affected by human activities (abstractions).

SGD or CGD may be determined using different methodologies, depending on the scale of interest. For small-scale local estimates of groundwater discharge field measurements are most adequate, for instance using seepage meters or tracer methods (Burnett et al. 2006). These may be accurate locally but difficult to upscale to regional values. In the latter case, regional water balances may be set up to get initial estimates of shallow and deep freshwater outflow at the coastline (e.g. Stigter et al. 2013b). For more representative estimates of such freshwater discharge fluxes along the coastline groundwater flow models tend to produce the most reliable estimates (e.g. Andersen et al. 2007). Such models may consider or neglect the freshwater–saltwater interface and density-driven flow, depending on the purpose of the study (Zhang et al. 2001; Koussis et al. 2012; Ghassemi et al. 2012; Bakker and Schaars 2013; Llopis-Albert and Pulido-Velazquez 2013). The advantage of groundwater flow models is that they can be used to test hypotheses of outflow, boundary conditions and groundwater extraction scenarios, and subsequently be used to show the past or future evolution of fresh groundwater outflow under changing pumping practices, and consequences for groundwater-dependent ecosystems (GDEs). Notwithstanding, a crucial task when using such models is to characterize and assess the different levels of uncertainty that are inherent to the process. Uncertainty may be divided into epistemic uncertainty and variability. The first is related to the modeler’s uncertainty of how to represent the phenomenon or the lack of information to fully describe the phenomenon. Some of this uncertainty is reducible by collecting more data. The latter is due to the complex behavior of natural processes and can only be partially diminished by collecting more data. Hence, uncertainty analysis must take these two sources into account.

CGD and SGD are known to occur and have been observed at several locations in the Algarve region in the south of Portugal, in the Ria Formosa lagoon near the city of Faro (e.g. Leote et al. 2008; Stigter et al. 2013b), where submarine springs have been observed and their impact on local ecosystems has been studied (Encarnação et al. 2013). The aquifers in these areas are mostly in contact with the sea, discharge occurring at sea level and as SGD. The increase of tourism along the coast during the 1970’s led to a rise in water demand, in particular for public supply and green area irrigation. Irrigated agriculture also required large amounts of water. Initially demand was met with groundwater (Monteiro and Costa 2004), and the increase in groundwater abstraction led to a decrease in water quality in some areas, partly due to local overexploitation and consequent seawater intrusion. At the beginning of the twenty-first century, surface water replaced groundwater for public supply and currently all publicly owned boreholes are either inoperative or held in reserve in case of lack of water emergencies. However, the drought during 2004 and 2005 highlighted the limitations of this single source strategy as well as the crucial role of groundwater as part of the more complex concept of integrated water resource management (Stigter et al. 2009).

Reintroducing groundwater abstraction as part of an integrated management scheme requires quantifying and understanding available resources to avoid overexploitation. Several efforts during the past few years have begun to analyze the factors that influence sustainable groundwater use in the region (Hugman et al. 2012; Salvador et al. 2012; Stigter et al. 2013a; Hugman et al. 2013; Stigter et al. 2014). Apart from issues of adequate groundwater quantity and quality for human needs, there is a need to determine criteria for sustainability which take into account other users such as GDE. Various GDEs have been identified in the Algarve, mostly related to springs and streams connected to groundwater bodies (Reis 2007; Salvador et al. 2012; Fernandes 2013), but little attention has been given to the dependence of marine ecosystems on fresh groundwater discharge.

The main goal of this paper is to assess and quantify the epistemic uncertainty with regard to the parameterization and the definition of boundary conditions while building a groundwater flow model to provide estimates of the spatial and temporal distribution of freshwater discharge along the coastline at a regional scale. This is done for two coastal aquifer systems in the Algarve region for which preferential CGD and near-shore SGD have been observed at specific locations, the cause of which is studied with the help of the groundwater flow model. Off-shore SGD is being investigated in the scope of a multidisciplinary research project that seeks to identify and characterize groundwater flow from the coastal strip towards the continental platform, taking into account structural geology, marine geology and the effects of the hydrological/hydrogeological conditions on associated ecosystems. In the current paper the model is further used to simulate different past and present scenarios of groundwater pumping, to provide an estimate of sustainable yields based on a predefined criteria, and to analyze the importance of well location on these yields.

Study area

The Algarve region, the southernmost province of Portugal, is characterized by a warm Mediterranean climate, and the coastal zone can be defined as semi-arid based on the precipitation to potential evapotranspiration ratio (Estrela et al. 1996). For the Algarve mean annual temperature and precipitation are around 17 °C and 650 mm, respectively. The precipitation regime is irregular, having intermittent periods with heavy rains in the winter and a long dry period in the summer.

The two coastal aquifer systems under study are the Albufeira-Ribeira de Quarteira (ARQ) and Quarteira (QRT) (Fig. 1). A thorough hydrogeological description of the region was made by (Almeida et al. 2000). Subsequent research in the area has contributed to the further understanding of the ARQ and QRT aquifer systems, namely by Bronzini (2011), Costa (2006), Costa et al. (2013), Monteiro et al. (2002), Monteiro et al. (2005) and Monteiro et al. (2007). The following section comprises a synthesis of the available information.

The aquifer systems develop mostly within the Miocene and Jurassic lithologies, occasionally separated by low permeability Cretaceous formations. Dolomites and occasionally limestones, karstified to a certain degree and depth, make up the Jurassic formations, reaching up to 700 m thickness. In both aquifer systems, these formations crop out in the north, with a Miocene and Cretaceous cover to the south. The Miocene formation is composed of sands and fossiliferous sandy limestones (occasionally karstified), dipping six degrees in a S–SW direction. Thickness increases towards the S and E, reaching 80 m in the ARQ and up to 180 m in the QRT. They are almost entirely covered by low permeability clayey consolidated sand and gravel deposits of the Plio-Quaternary, which can reach 40 m thickness. In some locations of the QRT this low permeability layer causes the underlying aquifer to become confined, revealed by the existence of artesian wells in some areas close to the city of Quarteira (Almeida et al. 2000). The Algibre flexure, along the northern border, separates the two aquifer systems from the Querença-Silves aquifer system. The ARQ is limited to the west by outcrops of low permeability Cretaceous marls and marly limestones. A fault line limits the QRT to the east; however, there are indications that it may in fact be hydraulically connected to the neighboring Campina de Faro aquifer system. The Ribeira de Quarteira stream, along the eastern border of the ARQ and the western border of the QRT, separates the two systems and coincides with a significant fault line. There is a piezometric jump between the systems, indicating that there is no hydraulic connection between the two (Almeida et al. 2000).

Both aquifers are known to discharge into the sea as well as into the Quarteira stream (Almeida et al. 2000; Reis 2007). The piezometric maps of average hydraulic heads in Fig. 1 show the direction of flow towards the stream. Lower reaches of this stream are considered to be a GDE

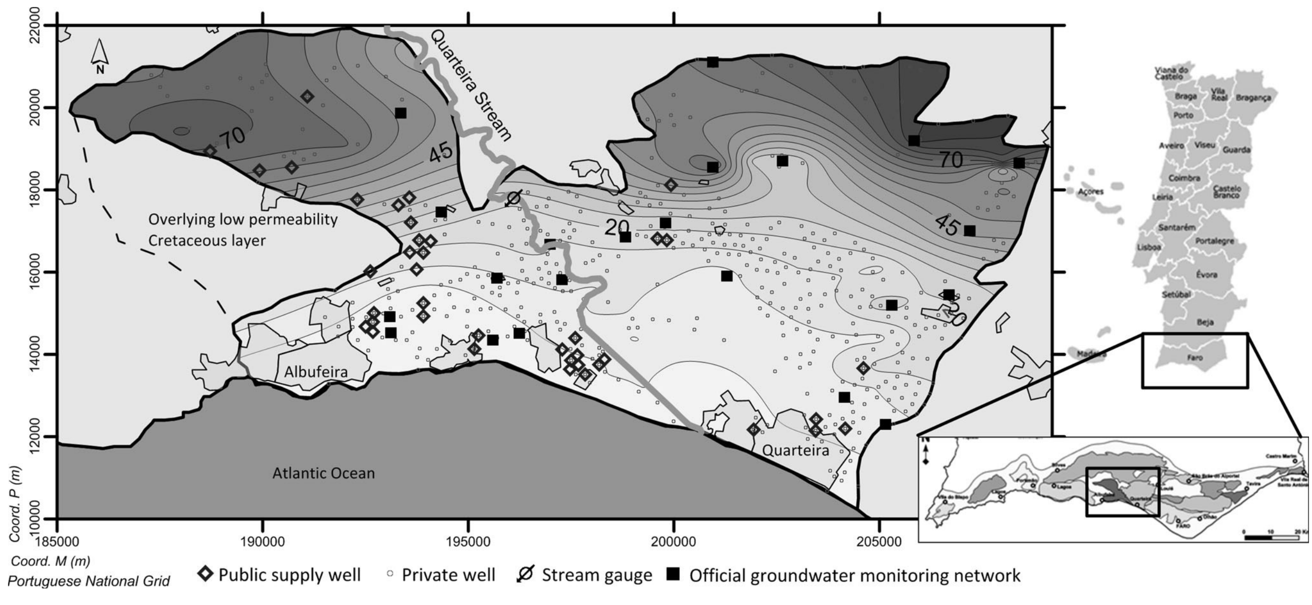

Fig. 1 The Albufeira-Ribeira de Quarteira and Quarteira aquifer system; piezometric map for average hydraulic heads; location of boreholes and official monitoring points

(Fernandes 2013). Of particular ecological interest is the presence of *Narcissus willkommii,* an extremely rare species only known to exist here (Carapeto 2006). Of further interest are several inter- and subtidal springs along the ARQ coast line, in particular at Olhos d'Agua location. One of the earliest references, Lopes (1841) described this discharge as follows: "Between Albufeira and the Valongo fort, several freshwater springs break out along the beach, hence they call this place Olhos d'Agua and within the sea in the same direction and not far out another very large one breaks out". Recently Encarnação et al. (2013) compared meiofauna assemblages at Olhos d'Agua and a control site and found that the discharge of groundwater stimulated an increase in biodiversity. Meiofauna is a major component of marine ecosystems and plays a significant role in energy transfer, acting as a link between primary producers and higher trophic levels. The higher diversity of organisms in the lower levels of the trophic chain increases the number of links in the food web. This leads to a more robust ecosystem with the ability to support a more diverse range of organisms at higher trophic levels (Encarnação et al. 2013).

Recharge was originally estimated for the ARQ as 8.7 hm^3/year (Almeida and Silva 1990), based on an average rainfall of 500 mm and considering recharge rates of 50 % for the Jurassic and 15 % to the Miocene lithologies. Almeida et al. (2000) suggest similar recharge rates for QRT, resulting in an estimated recharge of 15×10 m^3/year with an average 600 mm of rainfall. Based on these values the average annual recharge for these two systems is 23.7×10^6 m^3/year. More recently recharge was estimated with a daily sequential water balance model, based on daily rainfall and evapotranspiration data to quantify deep infiltration (Oliveira 2006). An average recharge rate for the two systems was estimated at 40 % of 754 mm/year, corresponding to an average recharge of 44.5×10^6 m^3/year. A detailed description of the used method can be found in Oliveira (2006). Comparing the two recharge rate estimates and considering an average rainfall of 593 mm/year as calculated by Nicolau (2002) for the period 1959/60–1990/91, total average recharge ranges between 25.1×10^6 m^3/year (Almeida and Silva 1990; Almeida et al. 2000) and 33.1×10^6 m^3/year (Oliveira 2006; Monteiro et al. 2007).

Groundwater abstraction for public supply from these systems saw a steady increase from the 1950s until the 1990s, when supply was replaced by surface water (Monteiro et al. 2003, 2007). In their review of existing public supply boreholes in these two systems, Monteiro et al. (2003) report the existence of 26 in ARQ and 15 in QRT at the end of the 1990s as can be seen on Fig. 1. According to data from the Municipal Councils, these wells abstracted 8.43×10^6 m^3/year during 1999, the last year they were fully in use. Currently these boreholes are inactive and mostly abandoned. There are no specific data available on abstraction for private water use, such as irrigation; however, these values were estimated by Almeida et al. (2000) as 3.5×10^6 and 9.0×10^6 m^3/year for the ARQ and QRT systems, respectively. The sum of these abstractions account for 64–84 % of the estimated average annual recharge, depending on which recharge estimate is used.

Methods

Several efforts to simulate the ARQ and QRT aquifer systems using numerical models have been undertaken for various purposes (Monteiro et al. 2002, 2003, 2007; Costa 2006; Costa et al. 2013). The focus of the development of these models has been towards the accurate representation of regional hydraulic head and potential for seawater intrusion, with little attention being given to the spatial distribution of discharge along the coastline and stream. As of yet none of these numerical models have presented a definitive representation of the surface/groundwater interface, mostly due to a lack of field data to properly define them. All previous variants of the numerical model considered aquifer limits as defined by Almeida et al. (2000), a constant head boundary condition (BC) equal to mean sea level along the coastline and no-flow BC at the remaining limits. Previous authors proposed various conceptualizations for stream BC. Constant head BC equal to terrain elevation was imposed on nodes coinciding with the entire reach of the Quarteira stream by Costa (2006). This resulted in groundwater discharge into the stream simulated along stream reaches that are known to be influent, mostly upstream. To resolve this Monteiro et al. (2007) applied constant head BCs (equal to terrain elevation) only along the lower reaches of the stream where a connection between groundwater and stream is known to exist. Subsequently, Costa et al. (2013) applied flow constraints in an attempt to eliminate infiltration that was still being simulated along lower reaches of the stream.

Boundary condition types and conceptualization for groundwater flow models, as defined in this paper, are well explained in Reilly (2001). All these conceptualizations suffer limitations in representing the behavior of the system. Boundary conditions as defined in Costa (2006) and Monteiro et al. (2007) lead to groundwater discharge along stream reaches which are known to be influent, whilst the constraints applied by Costa et al. (2013) ignore infiltration observed along the upper reaches of the stream. Although influent and effluent reaches of the Quarteira stream have been identified, currently there are insufficient data on stream flow for additional calibration of the model.

Numerical model

The numerical model follows the aquifer limits as defined by Almeida et al. (2000), a constant head boundary condition (BC) equal to mean sea level along the coastline and no-flow BC at the remaining limits.

The recharge rate determined by Oliveira (2006) (approximately 40 %) was applied to the spatial distribution of rainfall proposed by Nicolau (2002), resulting in 33.1×10^6 m^3/year of average annual recharge.

Transmissivity (*T*) values were estimated by Costa (2006) through inverse modeling under steady-state conditions taking into account pumping for public water supply. He first proposed the spatial zoning and distribution of *T* and then performed calibration using the Gauss–Marquardt–Levenberg method, implemented in the nonlinear parameter estimation software PEST (Doherty 2002). Costa et al. (2013) applied the same values of *T* obtained by Costa (2006) as the correlation between observed and simulated hydraulic head was adequate and did not justify the effort of re-calibration. As shown in Fig. 2, changes in BC do not significantly affect the correlation between observed and calculated hydraulic heads.

The defined conceptual flow model was translated into a 2-D finite element mesh with 5453 elements and 2914 nodes, using the groundwater flow modeling code FEFLOW (Diersch 2014). The following formula expresses the physical principles at the basis of the simulation of the hydraulic behavior of the aquifer system:

$$S\frac{\partial h}{\partial t} + \operatorname{div}(-|T| \cdot \overrightarrow{\operatorname{grad}} \cdot h) = Q, \tag{1}$$

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

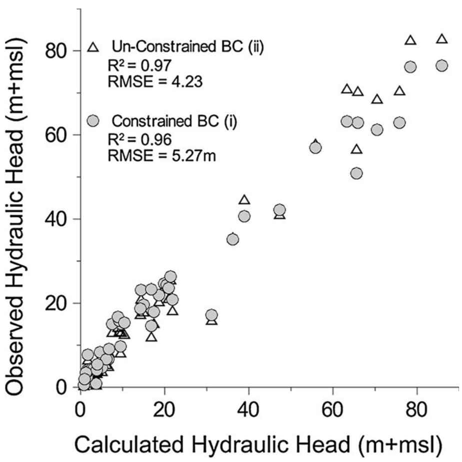

Fig. 2 Plot of observed *versus* calculated hydraulic head obtained from model with unconstrained (ii) and constrained (i) stream BC variants, as well as their respective correlation coefficients (R^2) and root mean square error (RMSE)

Steady-state simulations: epistemic uncertainty and groundwater use variability

The model variants and scenarios described in this section are all simulated under steady-state conditions. To represent the epistemic uncertainty, two model variants are applied representing the two extremes of BC conceptualization: (1) constant head equal to elevation along the lower effluent reach, with constraints to guarantee no recharge from the stream to the aquifer, according to Costa et al. (2013); and (2) constant head equal to elevation along the entire stream without constraints, according to Costa (2006).

Boundary conditions in FEFLOW can be constrained by physical limits, allowing the representation of a broad variety of specific boundary properties (examples include seepage faces, pumps with a minimum water level, and temporal rivers) (Diersch 2014). Constant head BCs can be constrained by a minimum and maximum flow rate. Stream BCs in scenario (1) are constrained by a maximum flux = 0 m^3/d, which means that the head BC is only active in case of water flowing out.

Variability in groundwater abstraction is simulated using several abstraction scenarios. Previously described generations of the numerical model simulated both the natural state of the system, with no pumping (scenario a), as well as taking into account pumping for public water supply (scenario b). Withdrawal rates for public water supply, determined from Municipal Council data, were imposed on nodes corresponding to the location of public supply wells. Withdrawals for private use had so far been ignored due to a lack of definitive data. In order to obtain a better understanding of the range of possible discharge rates, additional abstraction rates for private use for each aquifer system, estimated by Almeida et al. (2000), were distributed uniformly over nodes corresponding to the location of private boreholes currently in use. Abstraction for private supply is taken into account in two scenarios: abstraction for public and private supply (scenario c); and only abstraction for private supply (scenario d). Scenario (c) represents groundwater use at the end of the 1990s, whilst scenario (d) should be indicative of current groundwater use, after public supply wells were abandoned. Table 1 presents a summary of all model variants and groundwater use scenarios.

Transient cyclical simulations: average seasonal variability

The high seasonal variability of rainfall in semi-arid climates such as occurs in the Algarve can lead to significant

Table 1 Summary of water use scenarios and BC model variants applied in the analysis

BC variant		Water use scenario		Code	Steady state	Transient state
i	Constant head equal to elevation along lower effluent reaches; constraints imposed to only allow discharge	a	Natural state/no abstraction	ia	x	x
		b	Abstraction for public supply	ib	x	
		c	Abstraction for public and private supply	ic	x	x
		d	Abstraction for private supply	id	x	
ii	Constant head equal to elevation along the entire stream	a	Natural state/no abstraction	iia	x	x
		b	Abstraction for public supply	iib	x	
		c	Abstraction for public and private supply	iic	x	x
		d	Abstraction for private supply	iid	x	

fluctuations in groundwater levels and flow rates. It is necessary to take into account the temporal variability of these systems when discussing available groundwater, as single average annual values can give misleading results (Hugman et al. 2013).

Transient cyclical scenarios were simulated to demonstrate the effect of the seasonality of recharge and abstractions on ARQ and QRT discharge rates. In these simulations, monthly distributions of recharge and abstractions for an average year are repeated in a cyclical manner until conditions are reached that can be considered as "quasi-steady state", i.e. varying between seasons within one year, but not changing between years.

Recharge was calculated based on average monthly distributions of rainfall proposed by Nicolau (2002). Only the two extremes of water use scenarios (a and c) were considered, to reduce the amount of simulations. Both BC variants (i and ii) were taken into account, to maintain the epistemic uncertainty assessment. Abstraction rates for public and private wells were distributed over the months of the year based on average monthly values registered for public supply wells between 1991 and 2001.

As simulated transient cyclical scenarios are represented as average seasonal variations based on monthly mean recharge rates, they do not follow historically observed responses of hydraulic head to recharge and pumping schemes. This makes calibration of the storage coefficient S inexact at this point. A rough trial and error calibration of the value of S was carried out by manually varying a uniform regional value of S and comparing annual fluctuations of simulated and observed hydraulic heads. On average, hydraulic head time series from piezometers in the ARQ and QRT show seasonal variations in the order of 2–10 m. It was found that S values between 0.01 and 0.05 resulted in seasonal variations of head comprising the range of observed values.

Sustainable extraction scenarios

Several simulations were developed to analyze the effect of groundwater abstraction for public supply on the sustainability of the aquifer system. Pumping rates to public supply wells were determined as a percentage of average annual recharge and varied by 5 % across a range of transient simulations. Total amount of annual abstraction equal to a percentage of average annual recharge was distributed over the year according to average monthly values registered for public supply wells between 1991 and 2001. Abstraction from private supply wells was not varied (hence maintained at the levels of scenarios (c) and (d)), as this represents a more likely scenario for water management. The obtained pumping rates were applied to the model variant with lowest storage coefficient ($S = 0.01$) representing the worst-case scenario: (see Sect. 4.2). In order to test whether locating abstraction further away from sensitive areas (coast and stream) would increase the sustainable abstraction rate, all public supply wells within 1.5 km were removed and all pumping concentrated in the remaining wells.

Results and discussion

Steady-state BCs and groundwater use scenarios

Figure 3 shows simulated discharge rates for the various BC variants and groundwater use scenarios of the steady-state simulations. Here the discharge rates for the various discharge areas (stream, ARQ Coast, and QRT Coast) are compared.

Stream BC type does not appear to have a significant impact on coastal discharge under natural conditions. On the other hand, groundwater discharge to the stream increases in scenario (ii) to compensate for the recharge from the stream (infiltration) in other reaches. Stream infiltration increases once groundwater withdrawals are included. It is interesting to note that this induced recharge reduces the effect of abstraction on coastal discharge rates for the (ii) BC scenarios. Subsequently, the difference between coastal discharge estimates for different BC variants increases with increase in groundwater abstraction.

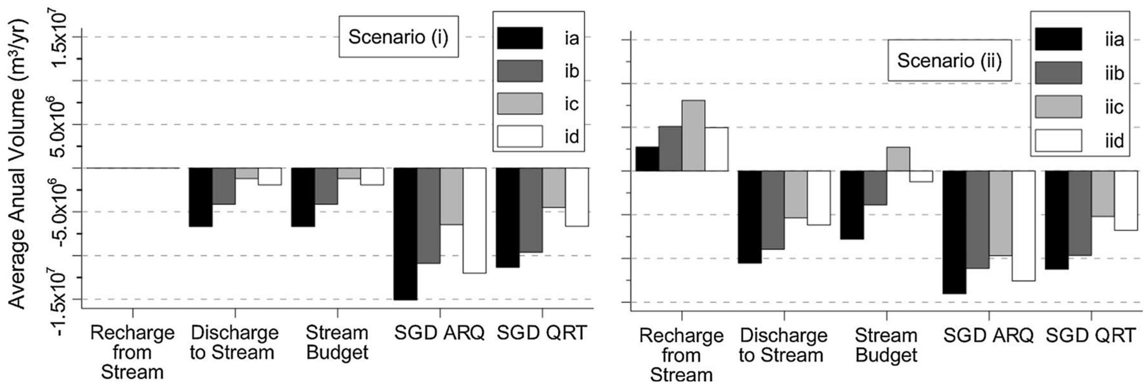

Fig. 3 Comparison of water budget components for the two boundary condition model variants (i and ii) and groundwater use scenarios (*a*–*d*)

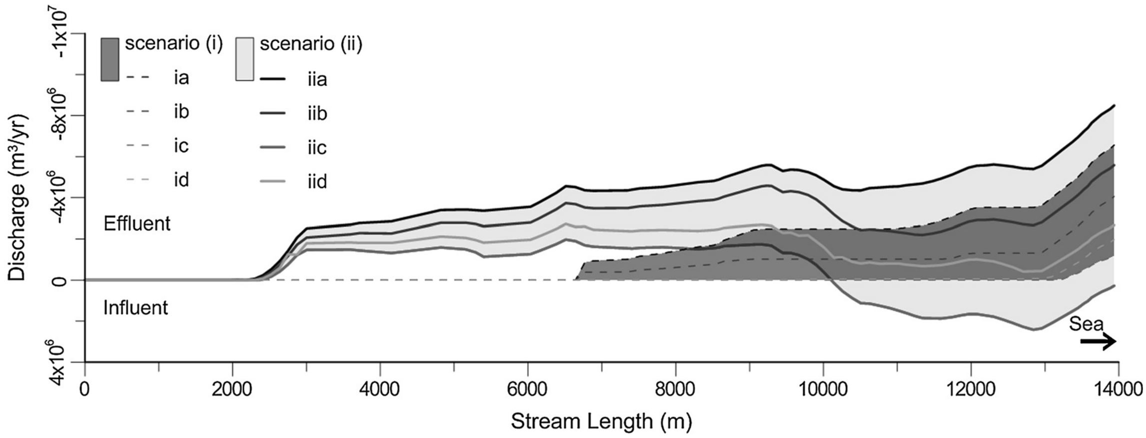

Fig. 4 Cumulative simulated discharges along the Quarteira stream; water use scenarios are, from *top* to *bottom*, *a*, *b*, *d* and *c*

An average annual flow of 43.2×10^6 m^3, from 2001 to 2012, was measured by a stream gauge installed at the northern limit of the aquifer systems (Fig. 1). Therefore, recharge from the stream can be considered as being within an acceptable range. However, as there are no stream flow measurements for the lower reaches of the stream, it is impossible to determine how accurately the model simulates this process.

The only scenario to result in an influent stream budget is scenario (iic). This is due to the drawdown caused by the pumping close to the stream, which leads to both a decrease in discharge to the stream and increase in induced recharge from the stream. Considering the large seasonal variability in the region of both rainfall (and. therefore. stream flow) and water use, it is likely that this induced recharge may be overestimated as drawdown will be greatest during periods in which the stream is most frequently dry. This is discussed further in the following section when discussing the cyclic transient state scenarios.

As described previously, the interaction between the stream and aquifer system is not yet clear. Water can be seen in the stream all year round from the mouth to approximately 7 km upstream. Stream elevation at this point is approximately 15 m above mean sea level, meaning that the water is fresh and not intruding from the sea. There are no data on whether the stream gains or loses water above this point during the wet season. However, it is certain that it does not gain water during the dry season. The cumulative plot of simulated discharge values along the stream length gives a representation of flow down the length of the stream (Fig. 4). For the constrained BC variant (i) no interaction occurs above the 7-km point. Downstream from the 7-km point, the stream is effluent for water use scenarios (a) and (b). Once abstraction for private use is taken into account, aquifer contribution to stream flow reduces significantly and only occurs within the last kilometer. Thus, scenarios (ia) and (ib) match observed behavior, whilst (ic) and (id) do not. This suggests that private use may be overestimated or the spatial distribution of the abstraction rates is inaccurate and too concentrated near the stream. The surface/groundwater interaction for BC variant (ii) is almost completely opposite. All water use scenarios have an overall effluent stream behavior between km 2 and km 9 from the aquifer's northern border. There

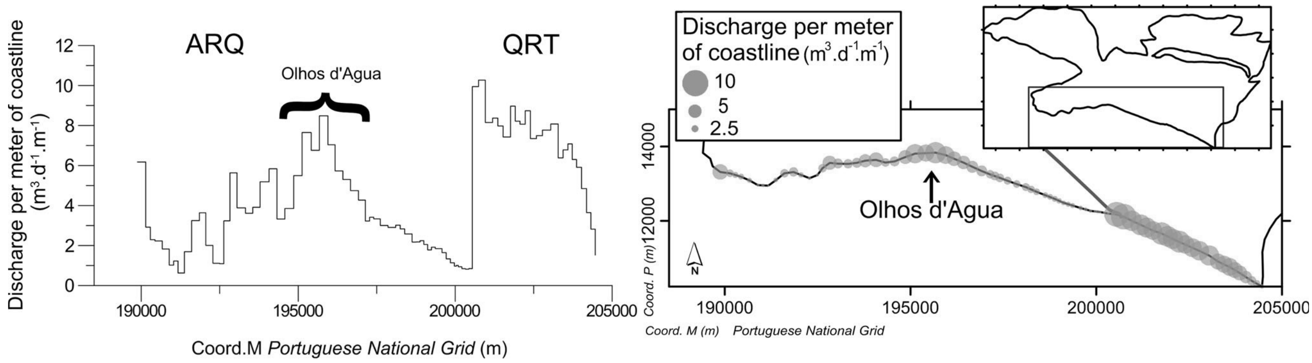

Fig. 5 Calculated coastal freshwater discharge per meter of coastline for scenario (*ia*)

are small occurrences of groundwater recharge from the stream, but they are not significant. The stream becomes influent at km 9 in all scenarios. In the natural state scenario (iia) it quickly recovers, becoming effluent for the remainder of its course. The remaining water use scenarios only revert to effluent streams much closer to the sea. Scenario (iic) is the only water use scenario in which the stream is simulated as dry along the lower (known to be) effluent reach. This is likely due to the same reasons discussed for scenarios (ic) and (id). There is sufficient discharge along the upstream reaches in scenarios (iia), (iib) and (iid) to offset any losses along the lower reach and thus maintain water in the stream. However, there are no data or reports of discharge along the upper reaches of the stream to validate this conceptualization.

Scenario results show that abstraction from private boreholes has a greater impact on stream discharge and QRT coastal discharge than abstraction for public supply, whilst the opposite occurs for ARQ coastal discharge to a lesser extent. This is due to the spatial distribution of pumping over the two systems. As shown in Fig. 1, there is a large concentration of private boreholes located near the stream, and private supply abstraction is estimated at 2.5 times higher from QRT than from ARQ. On the other hand, public supply abstraction is greater from the ARQ and hence the greater impact on coastal discharge from this system for scenarios (b) and (c).

Taking a closer look at the spatial distribution of discharge along the coastline reveals that although discharge along the QRT is relatively uniform, ARQ shows a more heterogeneous distribution. Figure 5 illustrates the variation in discharge rate for scenario (ia), in which no abstraction is in effect, to remove any potential interference from pumping. Higher discharge rates along the ARQ coast coincide with inlets at the coastline. Effectively this is due to the BC being further inland and, therefore, creating a higher hydraulic gradient at these points. The area with the highest discharge rate coincides with the Olhos d'Agua beach where many significant intertidal springs exist. In fact, between 30 and 35 % of ARQ coastal discharge occurs along the inlet corresponding to Olhos d'Agua. Apart from coinciding with the most inland point of the coastline, it is also the most direct path between the high recharge Jurassic lithologies to the north and the discharge area. Although there is no definitive data on sub- and intertidal spring flow rates or distribution to confirm these simulations, the results do offer an explanation for the high concentration of springs at Olhos d'Agua. The model is an equivalent porous model and does not in fact represent conduit flow, characteristic of limestone areas. However, the dissolution process associated with karst conduit development accelerates along preferential flow paths (more water leads to more dissolution) (Groves and Howard 1994; Domenico and Schwartz 1997). Therefore, it is conceivable that the preferential flow suggested by the model could have favored karst development along the path to Olhos d'Agua.

On the other hand, this behavior may also just be an artifact of the conceptual model. Some authors suggest that the Jurassic lithologies may extend under the low permeability Cretaceous formation in the west portion of the ARQ (see Fig. 1), and connect with the Miocene in the south (Bronzini 2011). However, due to the complex geological structure of the area it is unclear whether a hydraulic connection exists. Ongoing fieldwork is currently attempting to answer this question, applying geophysical methods to determine the thickness and angle of the overlying cretaceous layer. Should these results show that there is a connection, overall groundwater budget values will not change; however, the spatial distribution of discharge from the ARQ system will probably be different.

Spatial variation in discharge rates reinforces the need to take into account the location of abstraction when defining sustainable yields (Hugman et al. 2012). On the one hand there is a greater likelihood of seawater intrusion if abstraction is located closer to low discharge rate areas,

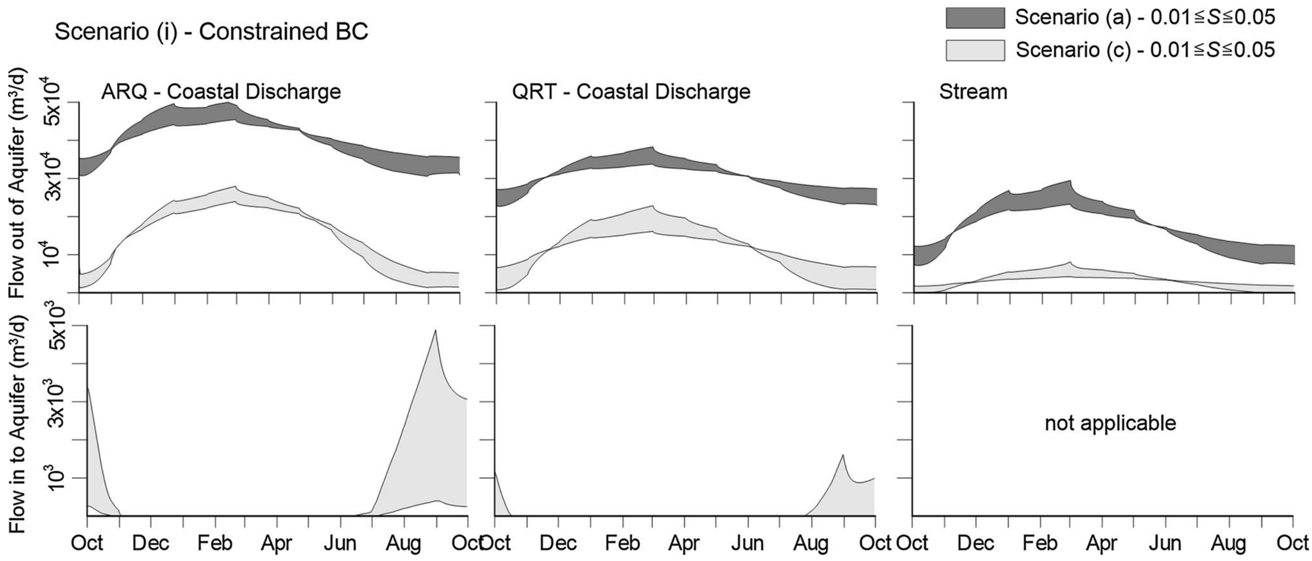

Fig. 6 Simulated flow out of (*top*) and into (*bottom*) the aquifer system, along the ARQ coastline (*left*), the QRT coastline (*middle*) and along the stream (*right*), for an average recharge year, considering constrained BCs at the stream (scenario (i)); results are shown for a range of storage coefficients (*S*) and for abstraction scenarios (*a*) (natural state) and (*c*) (maximum pumping rates)

and on the other there will be a greater effect on intertidal springs and SGD (and subsequently any GDEs) if pumping is closer to these areas. This is a highly complex matter and the available groundwater resources and the needs of the various water users have yet to be properly identified and quantified. Impact of SGD on the marine ecosystems has been demonstrated (Encarnação et al. 2013) but a quantifiable relationship has yet to be defined. Currently there are ongoing efforts to identify and measure SGD along the ARQ and QRT coast which should lead to a better comprehension of ecosystem variations between sites seen by Encarnação et al. (2013).

Transient cyclic scenarios of seasonal variation

Figures 6 and 7 present the range of aquifer discharge rates obtained from the transient cyclic scenarios with a range of values of *S* for both BC variants. The effect of pumping and its seasonality, as well as the seasonal distribution of recharge on discharge rates is evident. Furthermore, the seasonal variation in discharge rates at the coast is generally greater than the difference in discharge rate between the two BC variant estimates. This underlines the importance of taking into account seasonality when assessing epistemic uncertainty in groundwater modeling.

Encarnação et al. (2013) found that there was an increase in species diversity during the spring season at the location under SGD influence, but not at the control location. This matches the highpoint of simulated discharge rate (see Figs. 6 and 7). Simulation results confirm that this localized seasonal variation in biodiversity may be linked to discharge from the aquifer system. Natural state scenarios (ia) and (iia) do not present significant differences in terms of coastal discharge for the two BC variants. Groundwater abstraction (scenario c) leads to both a decrease in overall discharge rates as well as an increased amplitude of seasonal variation of discharge. The latter is due to the periods of greater abstraction coinciding with low recharge. This increased amplitude is more evident for BC scenario (ic) than (iic) due to the attenuating effect of induced recharge from the stream in scenario (ii). This effect is partially artificial due to constant BCs, as will be discussed below.

Unlike the steady-state scenario, transient scenarios (ic) and (iic) show occurrences of localized gradient inversion during short periods along the ARQ and the QRT, though much less significant for the unconstrained BC model variant (ii). Despite the systems recovering rapidly at the beginning of the subsequent rain season, water quality in the area could be at stake due to an increased risk of seawater upconing and localized seawater intrusion, particularly in karstified limestone aquifers. Once more, these results demonstrate that ignoring seasonal variation can lead to misleading results. Likewise, the inter-annual variation in recharge will likely have a significant effect on discharge rates. By applying average monthly and yearly rainfall values to determine recharge, this effect has not been considered. Considering that current climate change predictions for the region indicate greater inter-annual variation and greater seasonal concentration of rainfall (Stigter et al. 2014), a more comprehensive analysis of the effect of changes in recharge is necessary.

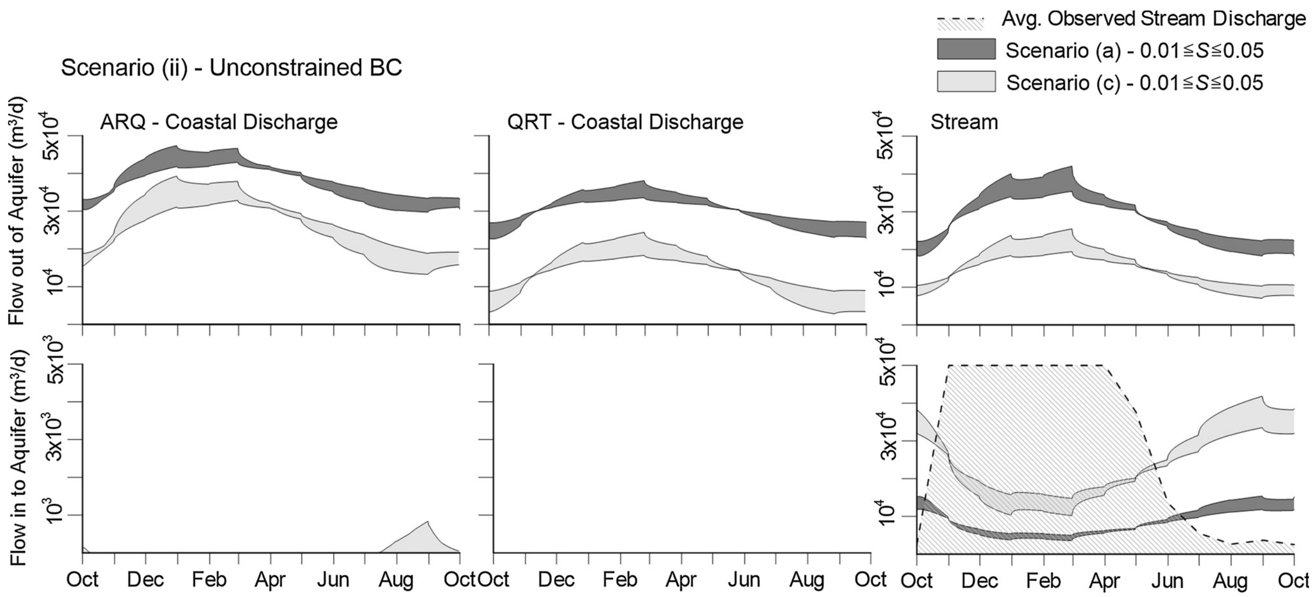

Fig. 7 Simulated flow out of (*top*) and into (*bottom*) the aquifer system, along the ARQ coastline (*left*), the QRT coastline (*middle*) and along the stream (*right*), for an average recharge year, considering unconstrained BCs at the stream (scenario (ii)); results are shown for a range of storage coefficients (*S*) and for abstraction scenarios (*a*) (natural state) and (*c*) (maximum pumping rates); simulated flow from the stream into the aquifer system is compared to observed average stream discharge in the bottom right plot

Induced recharge in BC scenarios (ii) has an inverse behavior to stream discharge. As mentioned previously, the only stream gauge is located at the uppermost limit of the aquifer system (see Fig. 1 for location). Therefore, there are no data on how much water is gained/lost between the aquifer and stream. However, this gauge does provide a value of total available water in the stream before crossing the aquifer. Therefore, it can be stated that this is close to the maximum amount of water that may become recharge, ignoring surface runoff in the small downstream catchment area. Monthly averages of existing data (from 2001 to 2012) are compared to simulated recharge from the stream in the lower right plot of Fig. 7 (maximum values are cut off at 5×10^4 m^3/d in order to fit the plot). During the rainy season (November to May) stream flow is sufficient to satisfy simulated values of groundwater recharge. However, during the remaining months it is significantly lower and thus the model is largely overestimating recharge from the stream during this period, explaining the largely reduced inflow rate at the coastline, as compared to the constrained BC model variant (i). These results show that a more complex model, with time-varying BCs to match the seasonal variation of stream flow, is needed to simulate this effect and further constrain the range of results.

Determining sustainable groundwater abstractions

Defining *sustainable use* is a complex matter. Different criteria can be taken into account, depending on what is considered necessary for groundwater use to be sustainable. From a resource management point of view, maintaining groundwater quantity and quality is foremost. From an environmental point of view, maintaining ecological flow to GDEs should be added to the previous criteria. The Water Framework Directive (WFD) requires that EU member states implement action plans (which are a mandatory part of the River Basin Management Plans) to meet the general goals of attaining good quantitative and qualitative status of groundwater bodies, as well as good chemical and ecological status of (inland, transitional and coastal) surface water bodies, which in many areas constitute GDEs at least to a certain degree. As such, the main concern for the ARQ and QRT in regards to water quantity and quality relates to avoiding seawater intrusion and protecting the GDE associated with the effluent reaches of the Quarteira stream and submarine springs. Although a relationship between biodiversity and SGD has been identified in the area (Encarnação et al. 2013), minimum flow rates required by the ecosystems have thus far not been determined. In an estuary located nearby the macroinvertebrate community structure was also seen to respond to the seasonal differences in salinity between summer and winter, with a higher impact from groundwater discharge into the channel during winter (Silva et al. 2012). It was, therefore, concluded that changes in macroinvertebrate communities can constitute early warnings of reductions of aquifer discharge, which is particularly useful where monitoring submarine groundwater discharge is difficult. Despite not yet being able to set a minimum target flow for

Table 2 Minimum simulated discharge rates along the coast and occurrence of seawater intrusion for a range of public supply ($P_{pub.s}$) pumping rates; *P* pumping rate, *R* recharge; $P_{private\ supply}$ − 12.5 × 10^6 m^3/year

Scenario	$P_{pub.s}$ (× 10^6 m^3/year)	$P_{pub.s}$/R (%)	P_{total} (× 10^6 m^3/year)	P_{total}/R (%)	SWI	Min.discharge rate (m^3/d)
(ia)	0.00	0	0.00	0	NO	61,000
(ic)	0.00	0	12.50	38	NO	25,700
	1.66	5	14.20	43	NO	20,400
	3.31	10	15.80	48	NO	15,300
	4.97	15	17.50	53	YES	10,200
	6.62	20	19.10	58	YES	5,970
	8.28	25	20.80	63	YES	3,360
(ic) conc. abstraction	0.00	0	12.50	38	NO	25,800
	1.66	5	14.20	43	NO	20,400
	3.31	10	15.80	48	NO	15,700
	4.97	15	17.50	53	NO	10,800
	6.62	20	19.10	58	YES	6,660
	8.28	25	20.80	63	YES	4,180

GDEs as one of the criteria for sustainable use, it is possible to say what the effect of a given pumping scheme will have on the flow distribution and rate. On the other hand, the seawater intrusion criterion is clearly an important one, as it impairs the use of groundwater for drinking water or irrigation, and has been found to occur to a moderate extent in municipal public supply wells in the studied aquifers.

Table 2 summarizes the effects of varying public supply pumping rates and well location. Results from the current numerical model do not take into account the effects of varying density nor transport phenomena between freshwater and seawater. Thus, the effect of pumping on the location of the saltwater–freshwater interface is not analyzed. The inversion of the hydraulic head gradient is used as the criteria for sustainable yield, keeping in mind that, due to the above mentioned phenomena, it is possible that water quality problems may occur prior to reaching these abstraction levels. Inversion of the hydraulic head gradient, allowing coastal waters to flow inland occurs with public supply rates equal or higher than 15 % of the annual recharge with all public wells in use (total pumping rate exceeding 53 %). This amounts to 3.31 × 10^6 m^3/year, significantly lower than the 8.43 × 10^6 m^3/year registered during 1999. When abstraction is concentrated to wells at least 1.5 km away from BCs, gradient inversion only occurs once annual abstraction values are 20 % of annual recharge (4.97 × 10^6 m^3/year). In agreement with Hugman et al. (2012), these results demonstrate that the spatial distribution of abstraction has a significant impact on sustainable yields in coastal aquifers. Furthermore, the difference in minimum discharge rate between distributed and concentrated abstraction increases with the increase in pumping rate. Therefore, although a sustainable level of abstraction to guarantee ecological flow cannot be specified, it can be stated that well location will influence the maximum rate of abstraction that can be maintained without affecting other groundwater users.

Conclusions

A numerical groundwater flow model supplied initial estimates of coastal freshwater discharge for the ARQ and QRT systems as well as sustainable levels of groundwater use. Uncertainty regarding the surface–groundwater interactions along the Quarteira stream was included in the results by simulating two conceptualizations of the BC. Steady-state simulations indicate that the system contributes a range of average annual freshwater to coastal discharge between 6.5 × 10^6 and 15 × 10^6 m^3/year from the ARQ, and 4.5 × 10^6 and 11.3 × 10^6 m^3/year from the QRT. Furthermore, there is significant spatial variation, in particular for the ARQ, with almost 30 % of the discharge from this system occurring at the Olhos d'Agua area.

Seasonal variation in discharge rates is greater than the difference between the two BC variants estimates of average annual discharge rates under steady state. Despite steady-state simulations resulting in consistently positive water budgets, seasonal variability inherent to these systems can lead to inversions of the hydraulic head gradient during short periods. It is likely that the effect of seasonality will increase with the higher concentration of rainfall during shorter periods predicted to occur during the next 50 years in this region. Furthermore, transient simulations of scenario (ii) demonstrated that this conceptualization of the BC leads to overestimates of stream recharge. Future efforts to simulate the ARQ and QRT systems should take into account the seasonal variation of stream flow to characterize the ground–surface water interaction and thus further constrain the range of results.

A preliminary analysis of sustainable levels of groundwater abstraction for public supply was developed, considering the worst-case model variant. Results indicate that historical levels of abstraction are not sustainable, but up to 3.31×10^6 m^3/year could be abstracted from existing well fields without causing an inversion of the hydraulic head gradient. However, by placing abstraction further from the coast, sustainable yield can be increased significantly. As these values are based on simulations that ignore the existence of a saltwater wedge (caused by differences in density between freshwater and saltwater), it is likely that water quality problems would occur at lower abstraction rates.

These results reflect the significant uncertainty that still exists in regards to the hydrogeological knowledge of these systems. In order to further constrain coastal discharge estimates, more detailed data on recharge, stream flow and abstraction rates are required. Although the discussed 2D flow model supplies an estimate of discharge values and distribution, considering the coastal nature of the aquifer system, developing a model that takes into account the freshwater–saltwater interface effect could significantly improve results. Such a model, taking into account the 3D structure of the system, would further constrain discharge rates as well as be a powerful tool to determine areas where freshwater SGD is more likely to occur.

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