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Regional spatial-temporal assessment of groundwater exploitation sustainability in the south of Portugal

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INTRODUCTION

Groundwater was the main source for public supply in the Algarve, in the south of Portugal, until the end of the 20th century, after which it was replaced by surface water supplied by large reservoirs. The large drought that hit the region in 2004 and 2005 revealed the problems related to a water supply strategy based on a single source. It is well-known that in semi-arid regions such as the Algarve, the seasonal and annual variations in rainfall are extreme. The intensity and frequency of occurrence of extreme droughts will most likely increase significantly in the future (Giorgi, 2006; Santos, Miranda, 2006). Research on climate scenarios and impacts for groundwater resources and dependent ecosystems in the Algarve is currently ongoing, in the scope of the CIRCLE-Med project CLIMWAT (Stigter et al., 2009b), using regional climate model data from the PRUDENCE and ENSEMBLES projects. Integrated water resource management will be essential in the near future, including surface and groundwater resources, as well as alternative resources such as treated wastewater for irrigation. Within this scope, a qualitative and quantitative screening of groundwater sources for integration into the public water supply system of the Algarve region has been performed (Stigter et al., 2009a). Current work aims to address the regional quantification of groundwater availability and exploitation sustainability, as well as their dependence on factors such as the spatial and temporal distribution of recharge, aquifer heterogeneity and the location of the pumping wells.

GROUNDWATER RECHARGE VERSUS CONSUMPTION

The present state of development of the Algarve hydrogeology allows the definition of 17 aquifer systems with regional importance, shown in Fig. 1 (Almeida et al., 2000). The most productive aquifers are built up of karstified limestones and dolomites. The six most important aquifers for public water supply are characterized in Tab. 1. Many of the other aquifer systems are directly and indirectly exploited for irrigation. Due to its large area and significant recharge, as well as the high degree of karstification, aquifer system M5, known as Querença-Silves, constitutes the most important groundwater reservoir.

Table 1. Characterization of aquifer systems with regional expression in the Algarve.

Aquifer system		Main aquifer lithology	Area (km^2)	Recharge (hm^3 yr^{-1})
M2	Almádena – Odeáxere	lmst, dlmt	63.49	16.6
M3	Mexilhoeira Grande – Portimão	lmst, dlmt, sand	51.71	10
M5	Querença – Silves	lmst, dlmt	317.85	93.4
M8	S. Brás de Alportel	lmst, dlmt	34.42	5.5
M9	Almansil – Medronhal	lmst, dlmt	23.35	6.5
M14	Malhão	lmst, dlmt	11.83	3

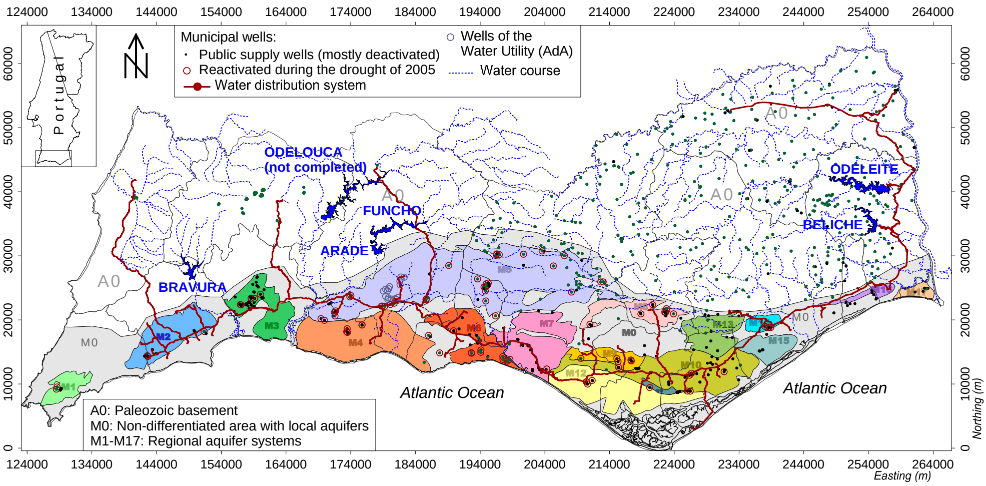

Figure 1. Location and geometry of the aquifer systems in the Algarve also shown is the location of the the municipal wells (mostly abandoned) and surface water reservoirs.

The estimation of aquifer recharge is a crucial and continuously ongoing task. Stigter et al. (2009a) provide an overview of some of the applied methods. Recent research has taken into account parameters such as daily precipitation, soil texture, moisture content and vegetation cover, allowing a deeper insight into the processes controlling recharge and its temporal evolution (Mendes Oliveira, 2009). Fig. 2 presents the estimated mean annual recharge volumes for the entire Mesocenozoic strip (M0-M17 in Fig. 1), the 17 main aquifer systems (M1-M17) and the six most relevant aquifers for public water supply.

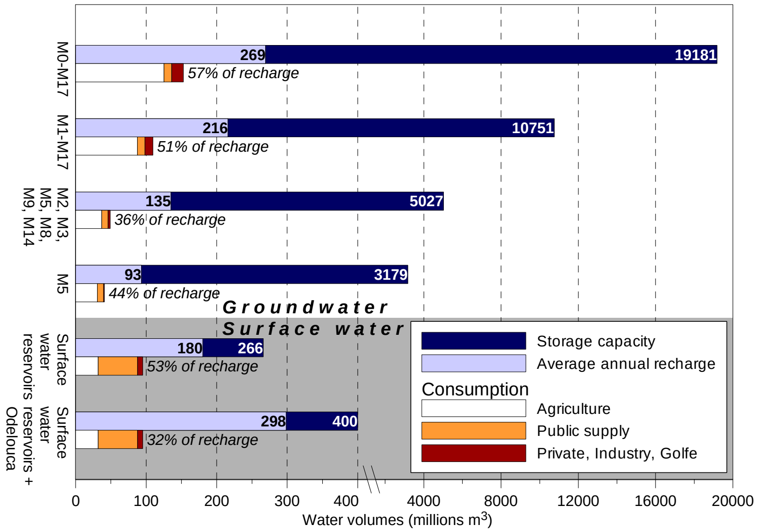

Figure 2. Storage capacity, mean annual recharge and water consumption volumes for groundwater and surface water in the Algarve; for groundwater the three categories refer to: the Mesocenozoic strip (M0-M17), the aquifer systems (M1-M17) and the main aquifers for public supply (M2, M3, M5, M8, M9, M14); for consumption, the labels indicate total volumes as a percentage of mean annual recharge.

For the area of non-differentiated aquifers and aquitards (M0) recharge was considered 10% of mean precipitation calculated in a GIS using the data Nicolau (2002). Roughly estimated total storage capacities are also presented in Fig. 2, considering an aquifer thickness of 100 m and effective porosity of 10%. Though these estimates are extremely simplified, they allow a good perception of their magnitude as compared to surface water storage, also presented in Fig. 2 (based on observed values). For instance, the total estimated storage of the Mesocenozoic strip is about 50 times higher than that of the surface reservoirs including Odelouca, currently in the phase of completion. It is also 70 times the mean annual groundwater recharge volume. The question is what fraction of storage is exploitable, both on a short-term (i.e. yearly) and long-term basis.

Fig. 2 also presents the present-day groundwater consumption volumes, and there distribution among users. The numbers are based on a detailed study of available data, provided by the Regional Water Utility, the Portuguese Ministry of Agriculture and literature (Do Ó e Monteiro, 2006). Agriculture is by far the main consumer of groundwater, with a total of approximately 150 hm^3 withdrawn from the Mesocenozoic strip, 47% of mean annual recharge. Total consumption amounts to 57% of recharge. Though groundwater is the main source for irrigation (165 hm^3), irrigation with surface water is gaining importance, allocating increasing water volumes.

SUSTAINABLE YIELD ANALYSIS

Safe yield was initially 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. Subsequently, the emphasis shifted to sustainable yield (e.g. Sophocleous, 2000; Custodio, 2002), which reserves a fraction of safe yield for ecological demands. This fraction depends on factors such as climate (variability), hydrogeological setting, location of the wells and the presence of groundwater dependent ecosystems. The concept of sustainable yield (or volume) can be studied by analyzing different groundwater recharge/capture/discharge scenarios.. Capture is defined by Lohman et al. (1972) as the sum of the increase in recharge and decrease in discharge, caused by abstractions due to pumping. Capture predominantly results in a decrease of groundwater discharge and a removal of water from storage. In this paper the analysis is performed for the largest aquifer system, Querença-Silves (M5), and compared to the simulation results of a groundwater flow model. A period of six (hydrological) years is considered, starting in October 2001, when the MPWSS was fully operational and groundwater consumption was comparable to the present-day picture.

The analysis starts with the definition of a so-called "safe storage volume" (S_{safe}), below which undesirable effects may occur as a result of overexploitation, such as the drying up of groundwater dependent streams and wetlands or the intrusion of seawater. The mean annual recharge is considered to adequately represent the safe storage volume. Considering a simple black box model, the hypothetical evolution of aquifer storage is then calculated for different discharge scenarios, using the following equations:

$$S_t = (1-f)\times(S_{t-1} + Rn_{\{(t-1),t\}} - W_{\{(t-1),t\}} + Ra_{\{(t-1),t\}}) \tag{1}$$

$$Q_{\{(t-1),t\}} = f(S_{\{(t-1),t\}} + Rn_{\{(t-1),t\}} - W_{\{(t-1),t\}} + Ra_{\{(t-1),t\}}) \tag{2}$$

$$Rn_{\{(t-1),t\}} = \frac{P_{\{(t-1),t\}}}{\overline{P}} \times \overline{Rn} \tag{3}$$

where: S_t and S_{t-1} are the aquifer storage at time t and t-1, respectively, with a discrete time step of one hydrological year, $P_{\{(t-1),t\}}$ is precipitation between hydrological years t-1 and t, $Rn_{\{(t-1),t\}}$ is natural recharge, $W_{\{(t-1),t\}}$ is withdrawal $Ra_{\{(t-1),t\}}$ is artificial recharge (irrigation return flow) and $Q_{\{(t-1),t\}}$ is groundwater discharge for the same period; f is the fraction of surplus contributing to discharge. Surplus is the defined as the storage at the beginning of the preceding year plus the difference between natural and artificial recharge and abstractions throughout the year. Equation 2 indicates that a higher surplus will result in a higher discharge. For the first considered year ($S_{t=1}$), S_0 is considered 75% of the natural recharge of the preceding year. The latter is calculated as a ratio of observed to mean annual precipitation times mean annual recharge (Equation 3).

On average 45 hm^3 of water is pumped yearly from the Querença-Silves aquifer system, with an average annual recharge rate of 93 hm^3. In the dry year of 2005 abstractions are believed to have been exceeded 70 hm^3. The hypothetical scenarios of available water volume are generated by varying parameter f between 0 (no outflow) and 1 (100% outflow). The curves defining each of the six scenarios (0, 20, 40, 60, 80 and 100% groundwater outflow) are drawn in Fig. 3, where S is plotted as a fraction of S_{safe} storage volume.

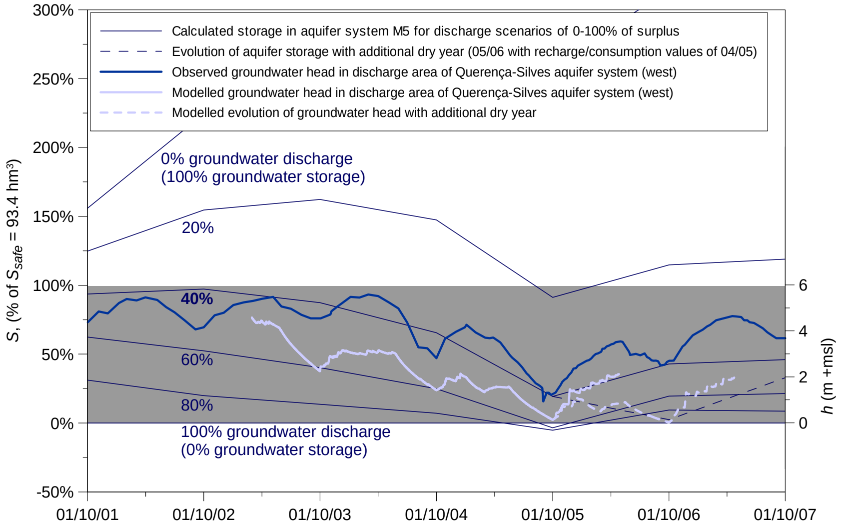

Figure 3. Scenarios of the evolution of available water volumes as a percentage of safe storage volume in the Querença-Silves aquifer system (M5), as well as modeled and observed time series of groundwater levels in the discharge area. Dashed lines indicate potential evolution with a second consecutive dry year.

In the scenario of 0% groundwater discharge, naturally unrealistic, all surplus is stored in the aquifer. In the opposite, equally unrealistic scenario of 100% outflow, no surplus exists and available water volumes are 0% of safe storage. The remaining four discharge scenarios are all hypothetically realistic, but the question is which one, if any, represents a more or less truthful simulation of reality. Naturally, the equations greatly simplify the actual behavior of the systems. For instance, groundwater discharge depends on the spatial and temporal distribution of recharge, whereas the impact of abstractions also depends on the location of the pumping wells. Moreover, in reality discharge is not a fixed percentage of the available water volume in the aquifer, but will be higher in wet years and lower in dry years.

In order to interpret the accuracy of the scenarios, they can be compared to observed groundwater head time series, which are related to aquifer storage volume. Time series are shown in Fig. 3, for a well located in the discharge area of the aquifer system. First of all it can be seen that the yearly trends are correctly portrayed by this simple analysis. Second, it appears that the 40% surplus discharge scenario (*f* = 0.4) most correctly follows the observed water level trend. The choice of the axis limits (minimum and maximum water levels) for the time series plot may be a matter of debate. The maximum observed values are considered to provide a correct indication of the 100% aquifer storage volume, whereas 0 m represents the limit below which overexploitation occurs, resulting in zero discharge at the springs and causing seawater intrusion.

When considering the 40% outflow scenario, total storage can be calculated for the six main public supply aquifers, based on known (estimated) abstractions and recharge rates. Fig. 4 provides the results, as % of maximum storage, 133 hm^3. The figure also gives an idea of potential storage and discharge volumes for higher pumping rates and compares values to reservoir storage evolution. This comparison cannot be straightforward, since 0% available volume in an aquifer implies overexploitation with possible negative consequences, whereas in reservoirs 0% indicates a dry reservoir, with no further possibility of exploration.

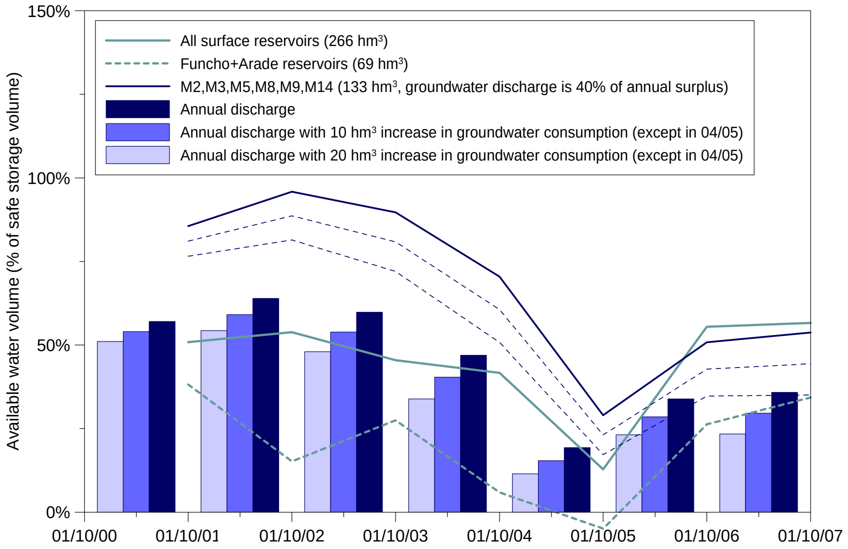

Figure 4. Evolution of annual storage and discharge volumes in the six main public supply aquifers, using f=0.4 (40% of surplus is outflow). Also shown are higher consumption scenarios (dashed lines).

The development of steady-state and transient groundwater flow models for the M5 aquifer system is described and discussed by Monteiro et al. (2006, 2007) and Stigter et al. (2009a). The conceptual flow model was translated to a finite element mesh with 11663 nodes and 22409 triangular finite elements. Transmissivity values were optimized by inverse calibration of the model and allowed a significant improvement of the simulation reliability of the observed regional flow pattern (Stigter et al., 2009a). Current work focuses on further calibration of the transient model, which involves optimization of the storage coefficient, among others. Fig. 3 shows the results of a simulation run for the groundwater head of the same observation well. Despite the lower simulated groundwater levels, the tendency and amplitude of oscillation are correctly simulated. During calibration of the transient model it was clearly noticed that groundwater pumping from private wells in 2005 started earlier than usual, namely in January (rather than in May). To simulate the larger drawdowns in that year, 17 hm^3 had to be added to the annual 31 hm^3 considered in the model for irrigation. This fact clearly indicates the "double-negative" aspect of droughts, i.e. lower recharge and higher (uncontrolled) pumping. When simulating a second consecutive dry year following 2004/2005, with the same recharge and extraction values as 2005, it was observed that the groundwater head in the discharge area dropped to values close to 0 m above mean sea level (msl). Longer droughts could therefore potentially lead to overexploitation, gradient inversion, drying up of springs and local seawater intrusion at the western border.

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