Chapter 26
Evaluation of Four Climate Changes Scenarios on Groundwater Resources of the Escusa (Castelo De Vide) Aquifer, Central Portugal

José Paulo Monteiro and António Chambel

Abstract In countries with advanced environmental management systems, numerical models are often used in the planning and management of sustainable groundwater resources. Toward that end, we evaluated the influence of climate change on karstic groundwater resources of the Escusa (Castelo de Vide) aquifer using a finite-element discrete continuum flow model, allowing the use of 1-D, 2-D and 3-D finite elements in the same computational mesh. The model was calibrated by the regional field measurements. Since this coupled model simulates fluid movement in, and exchange between, multiple domains, it was possible to monitor flow processes such as recharge (diffuse and concentrated infiltration), flux inside the aquifer (quick in caves and conduits and slow in the rock mass), and concentrated discharge (karstic springs) and diffuse discharge to wetlands and other porous hydrogeological units. Four different climate scenarios were analyzed with respect to their influence on future aquifer discharge rates. These scenarios (by the Hadley Centre for Climate Prediction and Research) reflected global and regional climate predictions for 50 and 100 year periods. The variation in groundwater discharge rates from the Escusa aquifer was evaluated in relation with discharge to the Sever River and granitic rocks in contact with the aquifer in its northern part. All the climate-based simulations show a decline in the discharge rates of the groundwater aquifer. Another important finding is that the discharge rates per month change and sometimes it is possible to have an increase in the discharge during the first half of the year and a reduction in the second half of the year.

Keywords Karstic aquifer • Modelling • Climatic changes

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26.1 Introduction

One possible way to evaluate the influence of the climatic changes on the groundwater flow regime is the use of numerical models based on distributed parameters. This kind of models can be used to investigate the aquifers hydraulic behaviour and, additionally, after calibration and validation, to simulate the pollutant or heat transport associated to a vector flux field.

The existence of a numerical model, which was calibrated using the field data for the karstic aquifer of Escusa, also called Castelo de Vide, in the central part of Portugal (Fig. 26.1), created a possibility to evaluate the impacts of different climate change scenarios for this aquifer. The model using the finite element numerical technique has some new potentialities when compared with the most commonly used ones to simulate the groundwater flux in a very heterogeneous media, as it is the case of karstic systems. This model permits the simulation of fluid fluxes simultaneously in one-dimensional, bi-dimensional and tri-dimensional domains. This potential permits the simulation of the duality of flow processes in karstic environments, reflected in the processes of recharge (diffuse and concentrated infiltration), in the vector flux field inside the aquifer (quick in caves and conduits and slow in the rock mass) and, finally, in the occurrence of concentrated discharge (karstic springs) and diffuse discharges in contact with wetlands or with porous hydrogeological unities connected with the karstic system [5].

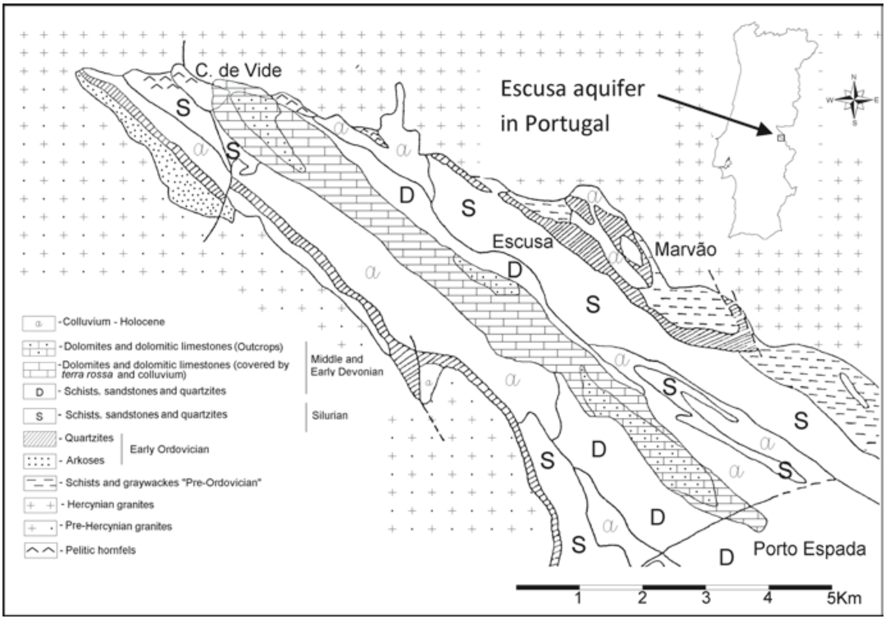

Fig. 26.1 Local geology and structure of the Castelo de Vide syncline (where the aquifer of Escusa is settled) and its location in Portugal. The general basis was adapted from Fernandes et al. [2] and Perdigão & Fernandes [17], adjusted by field work (geometry of carbonate rocks)

Four different scenarios were analysed with respect to the influence of climatic changes on the aquifer discharge rates in the future. The climatic models used were based on different scenarios created by the Hadley Centre for Climate Prediction and Research, with predictions for 50 and 100 years, using global and regional models defined for the latitude of Portugal. The study was based on the 40 years of climatic measurements, with evaluation of monthly recharge rates to the aquifer. Then, the expected variation of the discharge rates to the main stream crossing this aquifer, the Sever River, depending mainly on its groundwater, was studied according the four different future scenarios, as well as the variation in groundwater discharge rates from the aquifer to the granitic rocks in contact with the aquifer in its northern part.

26.2 Geologic Setting

The Castelo de Vide syncline is a periclinal structure with an axis oriented in NW-SE direction (Fig. 26.1). The length of the structure along its axis is about 40 km; the maximum width perpendicular to the axis is about 10 km. The contact of the syncline with the surrounding rocks is marked by Ordovician quartzites (Arenig). Towards NE these quartzites are in direct contact with the Hercinian intrusive Nisa granites, marked by metamorphic contact rocks (hornfels), whereas toward SW they overly the Pre-Hercinian Portalegre granites, with arkoses in the basis marking the transgression of the early Ordovician rocks over the granites. Locally, rocks of the "slate and greywacke complex" are present beneath the NE limit of the Arenig quartzites. The geostructure of this syncline was described by Teixeira [21], Gonçalves et al. [4], Perdigão & Fernandes [17], Fernandes et al. [2]; Perdigão [16], Perdigão [15], Perdigão [14] and Silva and Camarinhas [19].

The carbonate rocks that form the aquifer of Escusa in the centre of this pericline are predominantly dolomites [19] which are classified as dolostones. The effects of active karstic processes at field scale are responsible for the presence of lapiaz, swallow holes, sinking streams, flowing from the neighbouring low permeability schists, and frequent collapse of the roof of shallow dissolution cavities. The thickness of the carbonate formation is about 200 m, but the maximum depth drilled up to now is 139 m. The area corresponding to the limits presented in the map in Fig. 26.1 is of 7.9 km^2.

The carbonate formation is covered in most of its extension by *terra rossa* and colluvium deposits resulting, respectively, from the weathering of the carbonate rocks and from the mechanical weathering of the surrounding crystalline rocks (predominantly fragments of the Ordovician quartzites).

26.3 Hydrogeologic Setting

The highly fractured Ordovician quartzites that form the flanks of the Castelo de Vide Syncline are present in two divergent branches. A group of few wells screened in this aquifer supply a private water plant. The waters have a very low TDS (always lower than 50 mg/l) with Ca-Na-Cl facies. The recharge of this aquifer occurs trough the quartzites and arkoses. The characterization of their hydraulic parameters is presented in Oliveira [13].

The Silurian and Devonian schists, sandstones and quartzites (schists are largely predominant), with a thickness of more than 200 m, are in direct contact with the underlying Ordovician fractured aquifer. In hydrogeological terms these rocks are of very low permeability, defining both the confining layer of the Ordovician fractured aquifer and the "impermeable" substratum of the carbonate aquifer of Escusa, which represents the uppermost aquifer in this sequence, in the nucleus of the syncline (top of the Devonian sequence). A very simplified schematic cross section showing the aquifers in the Castelo de Vide System is presented in Fig. 26.2. The hydrogeology of the Escusa carbonate aquifer was described in Monteiro [9, 10].

The artesian well presented in Fig. 26.2 was built by the private water plant and the quartzite aquifer was found at a 100 m depth and the arkoses at 205 m. Screened only over the entire thickness of the Ordovician quartzites, the hydraulic head at the time of drilling was 15 m above the ground level.

As also can be seen in Fig. 26.2, the carbonate aquifer is located in the bottom of a "U" shaped valley. This is important for the control of the recharge processes related with swallow holes developed near the contact with the schists that are responsible by concentrated recharge. Another recharge process is related to lateral diffusive infiltration from the colluvium deposits existing in some areas near its lateral limits (frequently referred as "allogenic drainage"). This is a secondary process due to the limited extension of these deposits.

In the rare zones where other lithologies contact with the carbonate rocks at lower altitudes, the water transfers towards the adjacent hydrostratigraphic units. These conditions occur only at the NW extreme of the aquifer. During precipitation events, the stream water infiltrates when the limits of the carbonate aquifer are met.

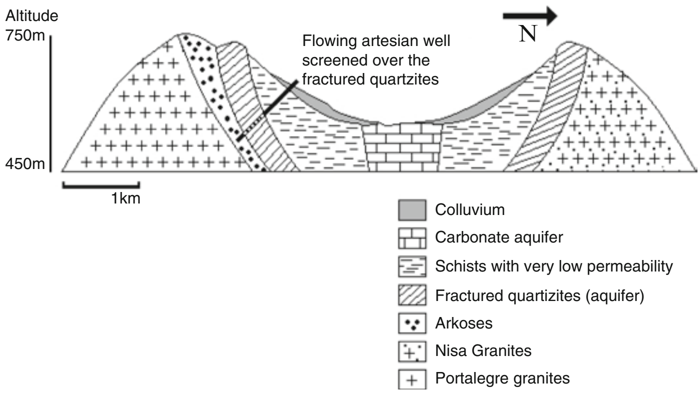

Fig. 26.2 Schematic N-S cross-section of the aquifers present in the Castelo de Vide Syncline. The carbonate rocks correspond to the aquifer of Escusa. Note that the scales are approximate and aspects as the thickness and depth of the formations are completely fictive

This is true for the entire stream network, except for the Sever River, which corresponds to the main discharge area of the aquifer. The drainage density over the carbonate aquifer is almost zero, and, in practical terms, infiltration equals the average precipitation values minus the evapotranspiration in addiction to the runoff generated laterally in the low permeability slopes surrounding the aquifer. It seems also that the NW limits of the aquifer, where the streams diverge from the limits of the carbonate rocks, correspond to a zone where water transferences take place from the carbonate aquifer toward the adjacent lithologies. In this area, the carbonate rocks are in contact with granites and tectonized hornfels, having a higher permeability than the schists limiting the aquifer in almost its entire extension (Fig. 26.3).

26.4 Conceptual Flow Model and Hydrogeological Analysis for Several Scenarios of Future Climatic Changes

As seen in Fig. 26.3, three sectors, as well as the discharge areas, are identified inside the Escusa aquifer. In the area of Escusa, the flow diverges toward Castelo de Vide and toward the Sever River (Rio Sever). In the Porto Espada sector, the predominant flow is toward the Sever River. Therefore, the flow from the Porto Espada and Escusa sectors contributes to the major discharge area of the aquifer, and the Sever River. Near Castelo de Vide, discharge is towards the low permeability lithologies in contact with the carbonate aquifer in that area. The remaining area of contact of the aquifer with adjacent lithologies is with "impermeable" series and thus no more outflow areas are considered. According the variation of recharge values, the groundwater divides are displaced toward the area of the river or the area of Castelo de Vide.

The average annual recharge for aquifer long-term water balance is about 450 mm/year. Considering that hydraulic head values in the discharge areas are also well-known, the conceptual flow model [6] can be expressed in terms of a steady state flow problem, for which only one unknown variable exists and that is the hydraulic conductivity. This problem can be solved using a numerical flow model. The solution provides a homogeneous equivalent hydraulic conductivity value [7] allowing a steady state characterization of the flow domain at a regional scale. This accommodates the long-term mass balance of the aquifer and sectors expressed in the conceptual flow model presented in Fig. 26.3.

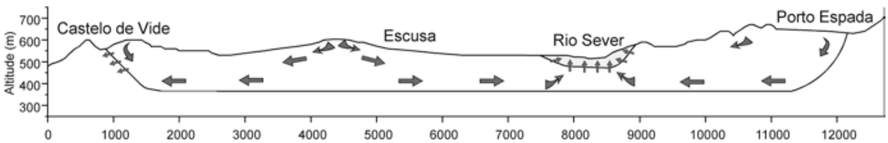

Fig. 26.3 Schematic cross-section showing the predominant flow directions and discharge areas of the Escusa (Castelo de Vide) carbonate aquifer. The distances along the axis are given in meters. The biggest arrows represent the predominant flow directions. The small arrows, crossing the aquifer boundaries represent the position of discharge areas

The hydraulic conductivity values calculated by the numerical and analytical solutions were compatible with a steady state description of the aquifer at the regional scale in terms of the existence of the defined sectors and in terms of the long-term water budget. The presented formulation to calculate hydraulic conductivity circumvents the need of knowing values that quantify the outflow volumes in the discharge areas of the aquifer.

The hydraulic conductivity values were calculated by means of two distinct theoretical conceptions for the interpretation of the aquifer hydraulic behaviour. In both cases, the known variables were the flow domain geometry and average hydraulic head values in discharge areas. The first solution was based on a numerical flow model where hydraulic conductivity was independent of hydraulic head and thus treating the aquifer as confined. The second solution which is analytical considers the aquifer whose water table is bounded by a free surface having a shape defined by the equilibrium between infiltration and hydraulic parameters characterizing each of the aquifer sectors.

The calculated values must be regarded as an equivalent hydraulic conductivity characterizing the entire flow domain [7]. A complete equivalence between the real heterogeneous medium and the idealized one is impossible. Therefore, the relation between the calculated equivalent hydraulic conductivity and the real values is defined, in a limited sense, according to certain criteria that must be equal for both media [18]. In the present case, the used criteria was based on flow equivalence and, additionally, on the definition of the global flow pattern of the aquifer.

The calculated values of hydraulic head using both the methods cannot be used in any other context other than the characterization of the aquifer steady state flow pattern at a regional scale. The description of the aquifer behaviour under specific stress conditions that are different from the average recharge values is impossible without a characterization of a parameter distribution considering the flow domain heterogeneity.

However, the obtained solutions allow the analysis of some crucial basic questions that shall be answered before the decisions required to build a more sophisticated model. This allows the analysis of more complex problems related to the parameters distribution in a flow domain where transient and diffuse flow are overlapped in a very complex pattern. First of all, it is possible to confirm the possible existence of the aquifer sectors proposed for defining the conceptual flow model. These sectors are present in an “artificial flow domain” similar to the real aquifer in terms of geometry, location of discharge areas and average water balance. Moreover, the global flow pattern can be described by different solutions based on a confined or unconfined description of the system.

Point values of hydraulic conductivity were calculated by the interpretation of pumping tests [8], which had permitted the estimation of hydraulic conductivity values characterising the fractured carbonate rock matrix and the nonfractured rock matrix. For the dissolution channels present in the carbonated rocks it is only possible to determine orders of magnitude for hydraulic conductivity in a simplified theoretical framework.

Groundwater undergoes geochemical evolution as it moves throughout flow systems. Therefore, hydrochemical and isotopic trends [1, 3] in each of the three sectors were also identified [11, 12, 20]. The results show that the predominant hydrochemical processes affecting water composition in the carbonate aquifer are the dissolution of carbonate rock minerals, mainly dolomite and accessory calcite. The saturation index (SI) values show that the Castelo de Vide sector tends to show a less accentuated trend to undersaturation with respect to calcite and dolomite than waters collected in the other two aquifer sectors (Fig. 26.4). At the same time, the TDS of samples taken in the Castelo de Vide sector are characterised by the highest values in the aquifer. This is reflected by the electrical conductivity (EC) values of water in this sector, whose average values are about 100 μS/cm higher than the values registered in the Escusa and Porto Espada sectors.

The described trends in the spatial distribution of EC and SI related with calcite and dolomite reflect the regional flow pattern defined in the conceptual flow model. Also, the observed hydraulic behaviour of the aquifer in the identified hydrochemical trend seems to be related to the time residence of water which must be longer in the Castelo de Vide sector due to the fact that the secondary outflow controlling the flow pattern in the NW area is toward relatively low permeable lithologies, that have a limited capacity to assimilate the transference's from the carbonate rocks. On the other hand, the flow toward the Sever River is more effective and thus the residence time of water flowing from the Escusa and Porto Espada sectors must be shorter, as shown by the presence of less mineralised waters and lower values of the SI with respect to calcite and dolomite.

In the Castelo de Vide sector, the residence time of water is longer due the low permeability of the lithologies receiving outflow from carbonate rocks in the secondary discharge area of the aquifer near Castelo de Vide. Therefore, the amount of total dissolved solids in water is more important than in the other aquifer sectors because the chemical processes of carbonate dissolution are closest to equilibrium. This is reflected by the highest values of EC in the Castelo de Vide sector. Due to the rapid outflows toward Sever River (Rio Sever), residence times are shorter in the Escusa and Porto Espada sectors. Here, the water is more undersaturated with respect to the dissolution of carbonate minerals than in Castelo de Vide sector, and the EC is also lower. The elevation of the recharge area in the Porto

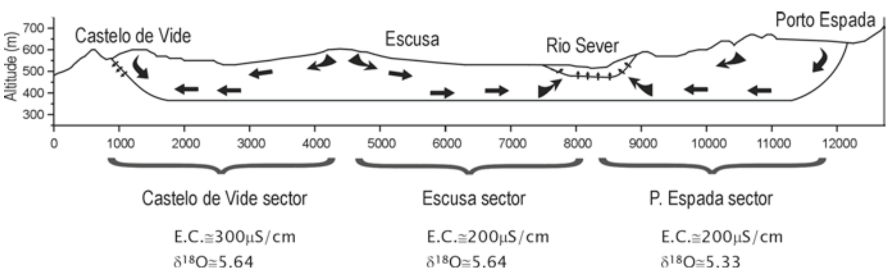

Fig. 26.4 Hydrochemical trends identified in the aquifer and aquifer sectors

Espada sector is about 100 m higher than in the other sectors. Depletion in ^{18}O is observed allowing distinguishing the isotopic composition of water in this sector.

Another hydrochemical trend identified in the aquifer is related to $\delta^{18}O$ ratio values. Lower values of $\delta^{18}O$ represent a depletion of the ^{18}O which is the heaviest isotope in relation with the lighter isotope ^{16}O. This property is of particular utility in diverse hydrologic applications, namely in the identification of groundwater origin in aquifers characterised by the existence of recharge areas with different altitudes. That altitude effect was detected in the Castelo de Vide Aquifer, where measured values of $\delta^{18}O$ show that in the Porto Espada sector water is depleted about 0.3‰ in ^{18}O with respect to the Castelo de Vide and Escusa sectors [12]. Those changes in values of $\delta^{18}O$ are related to the fact that average altitude in the Porto Espada sector is around 650 m, and about 520–550 m in Castelo de Vide and Escusa sectors.

The identified trends of hydrochemical processes at regional scale which allow an indirect confirmation of the defined conceptual flow model for the aquifer are summarised in Fig. 26.4. Based on the conceptual model in Fig. 26.3 and the recharge-infiltration balance which varies from year to year, a simulation for the next 50 and 100 years was performed based on four climatic scenarios defined by the Hadley Centre for Climate Prediction and Research. Table 26.1 reflects the expected modifications in the precipitation values according the four scenarios, two of them for 50 years and the other two for 100 years. The values can be compared with the averages of a 40 years series (1959–1998), as shown in the same table. Figure 26.5 presents the average transference volumes from the aquifer to Sever River (upper diagram) and for the granitic rocks in contact with the aquifer in the area of Castelo de Vide (down diagram). In this figure, it can be noticed that the

Table 26.1 Monthly precipitation considering four scenarios defined by the Hadley Centre for Climate Prediction and Research for the latitude of the Escusa aquifer, two for the year 2050, two for the year 2100

	Observed values (mm)	Previewed monthly average (mm)			
		2050		2100	
	Average of 40 years	HadCM3 B2a	HadCM3 A2c	HadCM3 B2a	HadRM2
Jan	117.02	117.21	106.84	81.43	44.38
Feb	105.40	117.10	81.48	108.20	58.27
Mar	72.83	91.47	55.13	98.41	94.72
Apr	72.43	75.69	70.91	84.98	101.91
May	68.59	83.34	65.44	76.82	102.88
Jun	34.13	41.16	32.56	38.23	32.44
July	7.19	6.16	5.46	6.27	6.15
Aug	8.25	6.06	5.30	6.05	4.45
Sept	45.13	30.69	29.96	30.05	13.74
Oct	93.53	66.31	61.26	54.90	32.28
Nov	114.39	88.19	73.44	54.90	35.57
Dec	120.21	105.78	112.03	67.32	46.67
Total	859.08	829.16	699.80	707.57	573.47

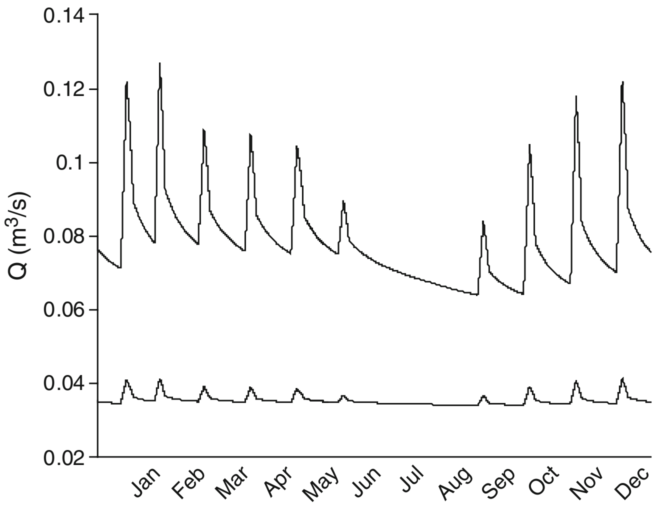

Fig. 26.5 Average transference values from the aquifer to the Sever River (upper diagram) and for the granitic rocks in contact with the aquifer in the area of Castelo de Vide (down diagram). Simulation based in the monthly average recharge volumes of 40 years (period 1959–1998)

discharge to the Sever River, when compared with the discharge to the granitic rocks is significant. Even so, the more abundant vegetation in this area is surely related with this water transfer.

In order to evaluate the impact of the future climatic scenarios, a simplification was made, considering that the recharge episodes in each month happen in a period of a quarter of the month, about a week. The representation of the discharge in the two areas (river and granitic rocks) was then compared with the four different future scenarios: (1) HadCM3 B2a (50 years), (2) HadCM3 A2c (50 years), (3) HadCM3 B2a (100 years) and (4) HadRM2 (100 years). The results are represented in Fig. 26.6 and the differences found between the actual discharge regimen and the simulated scenarios are more important than it seems by the observation of the figure.

Respecting scenario 1 (HadCM3 B2a), for 50 years (see Table 26.1), there is a slight trend to an intensification of recharge in the first semester (January-July), which can represent an increment in the reserves in the dry period (June-September), with more capacity for abstractions, and a slight reduction in the transferences to the Sever River between September and December. There are not significant transfers of waters toward the granitic rocks in the Castelo de Vide area in this scenario.

Concerning scenario 3 (HadCM3 B2a), for 100 years, it presents some similarity with scenario 1, but the increment of recharge in the beginning of the year only begins in the second half of the first semester. In this case, the increment of storage in the aquifer in the driest period is almost no sensitive. On the other hand, the decrease in the outputs between September and December is more evident on the water transfers to Sever River, which can be significantly affected in the last part of the year. Also in the last part of the year, the transfers to the granitic rocks decrease slightly.

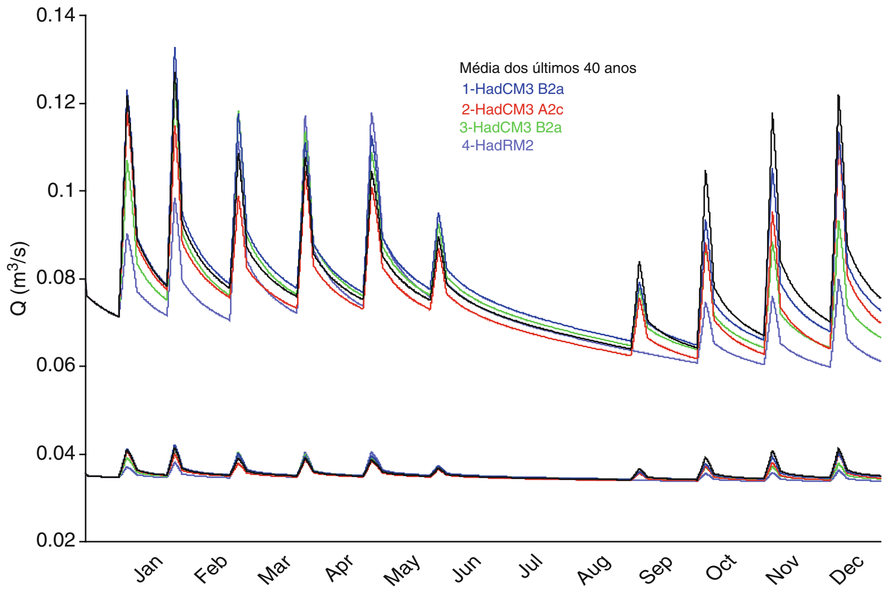

Fig. 26.6 Average transference values from the aquifer to Sever River (upper diagram) and for the granitic rocks in contact with the aquifer in the area of Castelo de Vide (down diagram). Simulation based in the monthly average recharge volumes for 40 years (1959–1998) and in the four established hypothetic future scenarios

Concerning scenario 2 (HadCM3 A2c), for 50 years, there is a general trend to a reduction in the recharge. The same is true as the previous ones, the tendency increases in the end of the year. In this case, the storage in the aquifer during the driest months tends to a reduction.

Scenario 4 (HadRM2), for 100 years, is the one that shows more differences in relation with the actual average trends. Excepting the period between March and May, in which a slight increment of recharge is expected, in all the other parts of the year there are a strong reduction in the flow of the Sever River, changing clearly the transfers from the aquifer (by less than half). Also the transfers to the granitic rocks in the area of Castelo de Vide are negligible when compared with the actual ones.

26.5 Final Remarks

The analysis of the evolution of water resources with expected future climatic changes is of high importance for the planning and management in the future. The application of modelling to predict the evolution of the Escusa (Castelo de Vide) aquifer with four different climatic change scenarios defined by the Hadley Centre for Climate Prediction and Research resulted in different predictions but with the common conclusion: With changes in all the analysed scenarios, all the simulations show a decline in the discharge rates of the aquifer groundwater. Other important conclusion is that the discharge rates per month change and sometimes it is possible to have an increment of the discharges in the first half of the year and a reduction in the second half of the year. Some scenarios affect the water resources and the environment more than others. One can also benefit from the water storage in the dry period of the year, even if it causes a reduction in the aquifer recharge rates.

References

1. Appelo A, Postma D (1996) Geochemistry groundwater and pollution. Balkema (ed), Rotterdam, p 536
2. Fernandes AP, Perdigão JC, Peres AM (1973) Notícia explicativa da folha 28-D (Castelo de Vide) Carta Geológica de Portugal 1/50000 [Explanatory notice of map 28-D (Castelo de Vide) Geological Map of Portugal 1/50000]. Serv. Geol. Port, Lisboa, p 44
3. Freeze A, Cherry J (1979) Groundwater. Prentice-Hall, Englewood Cliffs, p 604
4. Gonçalves F, Perdigão JC, Coelho AVP, Munhá JM (1978) Notícia explicativa da folha 33-A (Assumar) Carta Geológia de Portugal 1/50000 [Explanatory notice of map 33-A (Assumar) Geological Map of Portugal 1/50000]. Serv. Geol. Port, Lisboa, p 37
5. Kiraly L (1998) Modeling karst aquifers by combined discrete channel and continuum approach. Bull Centre Hydrogéol Neuchâtel 16:77–98
6. Monteiro JP (2001a) Characterization of a carbonate aquifer for the application of a regional discrete continuum flow model (Castelo de Vide carbonate aquifer – Alentejo, Portugal). PhD. Thesis presented to the Faculty of Sciences of the University of Neuchâtel. Neuchâtel Centre of Hydrogeology – CHYN, Switzerland, p 143
7. Monteiro JP (2001b) Calculation of equivalent hydraulic conductivity as unknown variable of a boundary value problem in a carbonate aquifer (Castelo de Vide, Portugal). Proceedings, 3rd international conference on future groundwater resources at risk. UNESCO, Lisbon, 25–27 June, Theme 2, pp 235–242
8. Monteiro JP (2001c) Interpretation of pumping tests and evaluation of the order of magnitude for hydraulic parameters characterising dissolution channels in the Castelo de Vide carbonate aquifer (Portugal). Proceedings, 3rd international conference on future groundwater resources at risk. UNESCO, Lisbon, 25–27 June, Theme 9, pp 673–680
9. Monteiro JP, Silva ML (1992a) Estudo hidrogeológico dos calcários dolomíticos de Escusa (Portalegre) [Hydrogeological study of dolomitic limestones of Escusa (Portalegre)]. A.P.R.H. Rev. Assoc. Port. Rec. Hídr, Lisboa, pp 13–19
10. Monteiro JP, Silva ML (1992b) Aspectos da hidrogeologia e qualidade das águas associadas à formação carbonatada de Escusa (Castelo de Vide) [Hidrogeological aspects and water quality associated with the carbonate formation of Escusa (Castelo de Vide)], vol VI. Geolis, Lisboa, pp 19–32, fasc. 1 e 2
11. Monteiro JP, Silva ML (1994) Influência da actividade antrópica na qualidade das águas da formação carbonatada de Escusa (Castelo de Vide) [Influence of antropic activities in the water quality of the carbonate formation of Escusa (Castelo de Vide)]. Actas del congresso celebrado en Alcalá de Henares sobre Análisis y Evolución de la Contaminación de las Aguas Subterráneas. Dep. de Geologia de La Universidad de Alcalá, Madrid, Tomo II, pp 455–467
12. Monteiro JP, Silva ML, Carreira PM, Soares AM (1997) Aplicação de Métodos Geoquímicos Isotópicos à Interpretação da Hidrodinâmica do Aquífero Carbonatado da Serra de S. Mamede (Castelo de Vide) [Application of isotope geochemical methods to the hydrodynamics interpretation of the Serra de S. Mamede (Castelo de Vide) carbonate formation]. VII Congresso de Espanha de Geoquímica, Ed. Cedex, pp 544–551

13. Oliveira MM (1993) Modelação de escoamento e determinação de parâmetros hidráulicos em aquíferos fracturados [Flow modeling and hydraulic parameter determination in fractured aquifers]. Master Thesis in applied and economic geology, Dep. Geol. Fac. Ciênc. Univ. de Lisboa, Lisboa, p 194
14. Perdigão JC (1967a) Os graptolitos e fauna associada da região de Portalegre [Graptholites and associated fauna of the region of Portalegre], vol LII. Com. Serv. Geol. Portugal, Lisboa, pp 65–77
15. Perdigão JC (1967b) Descoberta de Mesodevónico em Portugal (Portalegre) [Discovery of MesoDevonian in Portugal (Portalegre)], vol LII. Com. Serv. Geol. Portugal, Lisboa, pp 27–48
16. Perdigão JC (1972) A fauna dos grés e quartzitos Silúrico-Devónicos de Portalegre [Fauna of the Silurian and Devonian sandstones and quartzites of Portalegre], vol LVI. Com. Serv. Geol. Portugal, Lisboa, pp 5–25
17. Perdigão JC, Fernandes AP (1976) Notícia explicativa da folha 29-C (Marvão) Carta Geológica de Portugal 1/50000 [Explanatory notice of map 29-C (Marvão) Geological Map of Portugal 1/50000]. Serv. Geol. Port, Lisboa, p 18
18. Renard P, de Marsily G (1997) Calculating equivalent permeability: a review. Adv Water Resour 20(5–6):253–278
19. Silva J.M, Camarinhas M.V.F., 1961, Estudo económico dos calcários de Marvão [Economic study of Marvão carbonates], vol. XV. Est. Not. e Trab. do Serv. Fom. Min., pp 315–430
20. Silva ML, Monteiro JP (1999) Aplicação de Métodos Geoquímicos Isotópicos e Modelos de Escoamento ao Aquífero Carbonatado de Castelo de Vide (Serra de S. Mamede) [Application of isotopic geochemical methods and flow model of the carbonate aquifer of Castelo de Vide (Serra de S. Mamede)]. Final report of a groundwater research project. Financed by FCT (PEAM/SEL/557/95). Dep. de Geologia da Faculdade de Ciências (Lisboa), Instituto Tecnológico e Nuclear. Lisboa, 48 pp (Unpublished)
21. Teixeira C (1981) Geologia de Portugal, Vol.1, Precâmbrico, Paleozóico [Geology of Portugal, Vol. 1, Pre-Cambrian, Palaeozoic]. Fund. Calouste Gulbenkian, Lisboa, p 629