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Models to predict the impact of the climate changes on aquifer recharge

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Abstract Climate change is a statistically significant alteration of the climate variables in terms of their distribution both in time and in space. These changes will have a direct impact on the hydrological system and an indirect impact on the quality of the surface and groundwater resources. This paper deals with the impact of climate change on groundwater recharge. Several models to estimate recharge are presented, among them the daily sequential water balance model is the most appropriate to attain this goal. Climate changes may be predicted using climate models. Average precipitation and temperature values are outputs of these models. For a case study area of north Portugal, theoretical forecasted precipitation and reference evapotranspiration series are used to study the impact of precipitation change in groundwater recharge. For a scenario of 70% of actual precipitation, recharge would decrease to 45% of the estimated actual recharge.

Key words climate change; Portugal; recharge; recharge assessment; water balance models

INTRODUCTION

Climate change is a statistically significant alteration of climate variables in terms of their distribution, both in time (amount and intensity) and in space, as well as in their intrinsic variability in a significantly broad framework of time.

Climate change affects the water cycle primarily through changes in precipitation and temperature. These changes will have a direct impact in terms of surface runoff, evapotranspiration (ET), infiltration, recharge, and an indirect impact on the quality of surface and groundwater resources. At a secondary level, changes in the vegetation cover due to climate change also impact the water cycle. Changes in temperature regimes affect ET and consequently water depletion from the soil, water losses from lakes, and other surface water reservoirs. Changes in patterns, frequencies and intensities of precipitation affect runoff, infiltration, average soil moisture content and recharge. Climate change can also affect groundwater quality; in the southern areas, more prone to extended spells of drought, soil salinization due to processes associated to ET, and capillary rise of water can pose a threat to groundwater quality. Changes in temperature might also affect the chemical and biological equilibrium in the vadose zone, affecting water quality. Even more significant is the impact of flash floods (generated by extreme events of precipitation) on groundwater pollution, as these phenomena usually discharge a significant amount of contaminants into the soils, surface water bodies and aquifers. On coastal aquifers, sea level rises due to climate change promote an advance of the sea water/freshwater interface so promoting saline intrusion and the loss of coastal aquifers areas.

However, one of the major impacts of climate change, due to the combined effect of change in the temperature and precipitation regimes, is on aquifer recharge. This is the subject of this paper.

METHODS TO PREDICT GROUNDWATER RECHARGE

General

The choice of a model or method to compute recharge derives from the conceptualization of the recharge process of a study area. This conceptualization is based on the physical system, its geometry, all the inputs and outputs of water and its locations. The computation of recharge is based on mass balances between water coming in, going out or being stored in the water system. These mass balances are generally water-mass balances but can also be any substance-mass balance diluted in water. Models to compute recharge may be grouped into mass balances above the saturated zone and mass balances in the saturated zone. Only the water mass balances are considered in this paper.

Water mass balances above the saturated zone

These are predictive models as they quantify recharge by computing the processes prior to recharge occurrence (precipitation, infiltration, water stored in the surface and in the vadose zone). The soil daily sequential water balance is an appropriate method to estimate deep percolation and hence recharge. This method requires knowledge of the climatic data to characterize precipitation and reference ET, and knowledge of medium characteristic parameters, that depend on the complexity of the selected model. These models allow for estimation of distributed recharge in a region, produce results by recharge episode, and may be applied to any geological medium (intergranular, fissured, karstic or more than one type). However, the more general application is for intergranular, as the soil storage is more easily quantified, and preferential pathways are less important.

Water mass balances in the saturated zone

These are response models as they represent the reaction of the groundwater medium to the recharge process. Several methods are available depending on the hydrogeological setting, for instance: (a) surface flow hydrograph separation; (b) spring discharge quantification; (c) flow quantification in aquifer sections; (d) saturated zone storage change (water level change); and (e) combination of these methods, also including human water abstractions. These methods are integrative for a region and may compute recharge by episode.

Surface flow hydrograph separation method In this method base flow and direct runoff are separated. Base flow is an estimate of recharge that occurs in the area defined by a watershed when all groundwater flow inside the watershed discharges to the surface water streams inside that watershed (i.e. there is a co-incidence between the watershed and the hydrogeological basin). The hydrogeological settings more favorable to observe this requisite are local systems of metamorphic and igneous rocks, with intergranular or fissured porosity. In some cases of sedimentary rocks with intergranular porosity, even if stratified, this requisite may still be found. The surface flow hydrograph separation method is probably the easiest recharge calculation method to use, as it does not require medium characteristic parameters, and only requires knowledge of daily precipitation and flow series.

Spring discharge method The spring discharge is an estimate of recharge. This method requires the knowledge of the area drained by the spring, which is not an easy value to obtain. Due to the structure of the groundwater flow paths and its significant water volumes this method is mainly applicable for karstic hydrogeological settings. For the other hydrogeological media, despite the possible occurrence of large flow springs, it is likely that diffuse discharge exists in significant amounts, which makes the quantification of discharge difficult.

Flow quantification in aquifer sections This method is applicable to any hydrogeological medium requiring the knowledge of the recharge area upgradient, the measuring section, the constant monitoring of the piezometric level in both sides of the section, and the aquifer transmissivity along the measuring section. These requirements make the application of the method more difficult.

Water level change This change is a direct consequence of recharge. Time for the application of this method is very short. For the application of this method it is required that in a study volume, the difference between groundwater flow entering and leaving the system is negligible in relation to the water level rise. This method also requires the characterization of effective porosity in the depth of water level oscillation.

Models to predict the impact of the climate change on aquifer recharge

Among the presented methods for aquifer recharge estimation, the soil daily sequential water balance models are the only models with prediction characteristics. This feature allows estimating distributed recharge and allows forecasting the impact of climate changes on aquifer recharge. To use these models with this purpose, it is necessary to forecast precipitation and reference ET series (on a daily basis, because the time step is daily). Also, if the climate change leads to a land cover change, the infiltration/direct runoff properties of the ground surface may change and these may be incorporated in the model.

The methodology developed to separate surface flow into direct runoff and base flow could also be used to estimate the impact of climate change on groundwater recharge, provided daily surface flow series (besides daily precipitation series) could be forecast. However, as mentioned before, this methodology is a response one instead of a predictive one. This incongruence between the surface flow forecast purpose and the recharge assessment response methodology is due to the fact that surface flow is the result of base flow (besides direct runoff) and not the opposite, which means that to produce surface flow series base flow series should have been estimated previously.

In another way, to some extent it seems reasonable to use the results of the response methods, when there are recharge estimates for long time series. For instance, if a law has been established between recharge and precipitation and if a reduction of precipitation to 80% of the actual precipitation is forecast in the future, one may look at the recharge estimates that corresponded in that series to the value of 80% of precipitation. This approach would imply that the same precipitation distribution and ET conditions would exist in the future, with the only difference being the amount of precipitation.

From the presented discussion it is concluded that the most adequate approach to estimate groundwater recharge for different climatic conditions is the soil daily sequential water balance (DSWB). The main challenge is to forecast a series of daily precipitation and daily reference ET.

Climate change scenarios and impacts on aquifers

To access climate change impacts, especially on the water cycle, reliable climate models are required. It is also necessary to have projections of socio-economic developments and responses to climate change in order to define anthropogenic emissions of greenhouse gases and aerosols. These anthropogenic emissions (coupled with any natural climate change trends) are usually referred to as emission scenarios. The values ascribed to these emission scenarios are part of the input to the climate models, that then proceed to model the possible climate changes associated with each socio-economic evolution (or emissions scenarios). The outputs from the climate models are precipitation and temperature average values for a certain area after a certain amount of time (usually predictions for 2070 or 2100), amongst other parameters.

According to SIAM (2001), climate change scenarios developed for Portugal predict an average temperature increase between 4ºC in winter and 9ºC in summer and an average general decrease in precipitation of 10–20%. However, this precipitation decrease is not uniform throughout the year, with a predicted decrease of up to 30% in spring, and between 35 to 60% in autumn, compared with an increase of 20–50% in winter (SIAM, 2001), pointing towards an evolution of increased concentrated precipitation events and longer drought spells. The changes are not uniform across the Portuguese territory; the sharpest decreases in precipitation are predicted for the southern areas (Alentejo and Algarve), while small areas in northern Portugal might show a small increase in precipitation. Temperature increase affects ET and, according to Novo (2003), for temperature increases between 2 and 12ºC (the extremes of temperature increase for Portugal, according to SIAM, 2002), and using as a rough estimation the Turc formula with an average precipitation of 1000 mm year^{-1}, ET can increase from 11% to 61%. As far as aquifers are concerned, these changes affect recharge and the amount of water extracted from soil and aquifers through ET.

As far as small aquifers are concerned these changes could mean that they might not benefit from the increase in winter precipitations due to their small storage capacity; the same might not be true for large aquifers as their storage capacity is large enough to accommodate the possible extra recharge due to the concentrated precipitation in winter, if runoff does not take over (SIAM, 2002). So, for aquifer recharge, not only are temperature and precipitation changes important, but size might also play a role in water replenishment. The increase in ET also increases the soil salinization and salt leaching to the aquifers (through infiltration across the saline accumulations generated during the high ET periods).

To study the impacts of these changes on groundwater, precipitation and temperature values (or the ET calculated from these temperatures) must be input into recharge models. Climate models do not provide daily data, so while models to generate daily data series are not widely available, a possible approach to generate these series is to pick up actual daily (precipitation, temperature, etc.) series and rearrange them in accordance with the average trends of change given as output by the climate models for each of the emissions scenarios considered (cf. Novo, 2002).

Application to a Portuguese case study area

In this section the applicability of the soil DSWB model is demonstrated. This approach was carried out for the Azores islands by Novo (2003, 2004), where recharge variation was estimated as a function of the scenarios of precipitation change. Considering average annual precipitation values of about 2000 mm year^{-1}, Novo (2003) found average recharge changes from –3.7% (for –0.3 mm day^{-1} precipitation scenario) up to –30.8% (for a scenario with an average precipitation reduction of 25%).

To test the suggested approach, the BALSEQ model was used (Lobo Ferreira, 1981; Lobo Ferreira & Delgado Rodrigues, 1988). Besides daily precipitation and monthly potential ET, this model requires the initial soil moisture content (hi) and two parameters, the runoff curve number (NC) and the maximum amount of water available for ET (AGUT).

This study used average series of daily precipitation and potential ET calculated for the watershed above the streamgauge station of Ponte Velha Capitão, located in a contributor stream at the right bank of the Douro River, near Alfândega da Fé village. The period studied stretched from 1 October 1982 to 30 September 1990. Taking as a starting point the series of precipitation calculated for that period (source precipitation series—SPS), the following precipitation changing scenarios were used: 90% of SPS, 80% of SPS, and 70% of SPS. The series were calculated in two forms: (a) applying the percentage factor to the SPS, or (b) considering a cutoff value for daily precipitation so that the sum of daily precipitation values larger than that cutoff value would result in the required percentage of SPS. The first form consists of just diminishing the daily amount of precipitation, while the second form consists of assuming that climatic changes always produce more intensive precipitation episodes, so that the lower daily values were discarded and only the higher (more intense precipitation) were considered.

In this study it was assumed that potential ET remains the same. NC value was set at 80, AGUT was set at 100 mm, hi was set at 0 mm. The studied average annual rainfall was 727 mm year^{-1} and the potential ET was 1339 mm year^{-1}. The results obtained using the SPS (actual situation P) or the fraction of the SPS (90% P, 80% P, 70% P), or the precipitation above a cutoff value (90% P (≥2.8), 80% P (≥4.8), 70% P (≥6.5)), are represented in Table 1 and Fig. 1. The cutoff values were 2.8 mm day^{-1} for 90% of SPS, 4.8 mm day^{-1} for 80% of SPS, and 6.5 mm day^{-1} for 70% of SPS. For the studied scenarios, annual recharge values may be as low as 0% of the actual recharge for the low rainfall years (1982–1983), or may be as high as 96% for the high rainfall years (1989–1990). As can be observed in this Table, the distribution of precipitation plays an important role, which explains why the 1985–1986 hydrological year, with lower precipitation than the 1982–1983 hydrological year, still allows the computation of important recharge values.

Table 1 Recharge computation for the 1982–1990 precipitation series, and fraction of recharge forecast for different precipitation scenarios in relation to the 1982–1990 estimated recharge.

Hydrological year	P (mm a^{-1}) [actual situation P]	R (mm a^{-1}) [actual situation P]	R (%) [scenario: 90%P]	R (%) [scenario: 90%P(≥2.8)]	R (%) [scenario: 80%P]	R (%) [scenario: 80%P(≥4.8)]	R (%) [scenario: 70%P]	R (%) [scenario: 70%P(≥6.5)]
1982–1983	650	94	51%	67%	22%	54%	0%	40%
1983–1984	742	183	83%	89%	65%	81%	46%	72%
1984–1985	860	344	84%	89%	68%	81%	52%	61%
1985–1986	621	177	80%	88%	58%	66%	36%	36%
1986–1987	662	153	75%	78%	53%	68%	31%	54%
1987–1988	849	243	80%	77%	60%	60%	39%	33%
1988–1989	498	0	–	–	–	–	–	–
1989–1990	932	424	87%	96%	73%	84%	59%	76%
Average	727	202	81%	86%	63%	74%	45%	57%

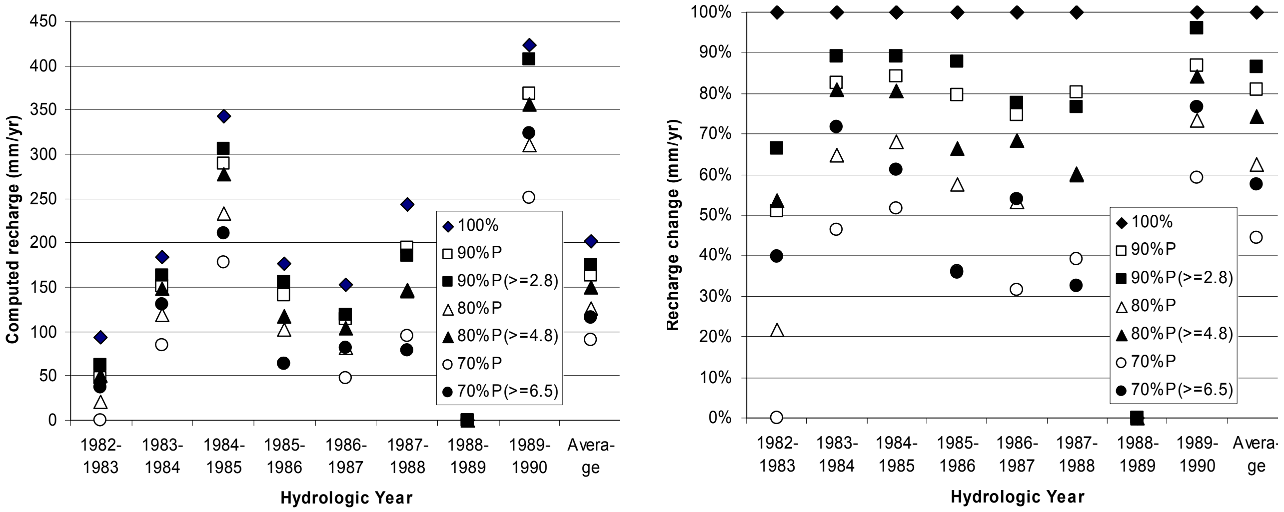

Fig. 1 Results of the BALSEQ model in absolute values and relative values.

CONCLUSIONS

This paper intended to demonstrate the ability of the soil daily water mass balance methodology to deal with the study of the impact of climatic changes on groundwater recharge. It has been shown how different precipitation series may influence groundwater recharge. For the studied time series, for 70% of precipitation scenario, average forecast recharge values would lower recharge to 45% of the recharge calculated for the original precipitation series. The distribution of yearly recharge values shows how precipitation distribution is important in the calculated recharge. This means that the forecasting of precipitation series scenarios is of major importance in the study of the impact of climate change on groundwater recharge. Moreover, it also proves the adequacy of the daily water balance models in carrying out these studies in relation to other models.

For example, it has been mentioned how groundwater recharge could be forecast for climate change scenarios using laws that relate actual groundwater recharge with precipitation. For this approach it must be assumed that precipitation in the future follows the same distribution patterns of the analysed series, which means that it does not take into account the variability of precipitation distribution in the definition of the recharge value.

For their predictive properties, the daily water mass balance methods are the more adequate to forecast the impact of climate change on groundwater recharge. A more elaborate study is envisaged where the ET series and the AGUT values may vary with the vegetation development stage. So, besides precipitation and ET, the area occupied by vegetation and the characteristics of vegetation are required. Oliveira (2003, 2004) presented a soil daily sequential water balance model that takes these characteristics into account. The main needs now are to be able to forecast precipitation series, reference ET series, areas occupied by vegetation, and to predict the vegetation type (which implies the knowledge of their vegetative cycle, and their characteristics that condition ET).

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