Using remote sensing data to assess the impact of wildfires in groundwater recharge in the Vieira de Leiria- Marinha Grande aquifer – Portugal

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Abstract

Wildfires impact lives of many people worldwide not only for their environmental implications, but also the social, cultural, and economical losses inherent to these events. Although the consequences of wildfires have been documented by several authors over the years, the impacts in groundwater are still poorly understood.

The region of Marinha Grande - Portugal is essentially supplied by groundwater from the Vieira da Leiria-Marinha Grande Aquifer for domestic and industrial uses, however, very little is known about the hydrological consequences of the fire occurred in Leiria Pine Forest in October 2017, responsible for the devastation of about 86% of the forest. Understanding the impacts of wildfires in groundwater quality and quantity is imperative to propose effective management and adaptation measures and guarantee future supply.

In the present study, remote sensing NDVI data from MODIS satellite database and climate data from the E-OBS database for the period of 2001-2020 were used to estimate crop adjusted potential evapotranspiration (PET_{CA}) in the study area. Climate and Soil property data were inserted in the Easybal software, developed by the Hydrology Group of the Universitat Politècnica de Catalunya (UPC, Barcelona, Espanha), to simulate groundwater recharge in both burnt and unburnt areas of the Leiria Pine Forest. The results show a decrease in PET_{CA} due to the removal of the vegetation by the fire and an increase groundwater recharge in the aquifer of about 15% in the first year, 7% in the second and 3% in the third year when compared to the expected values. The increase is probably not exclusive related to the decrease in evapotranspiration, it is also conditioned by geological and pedological characteristics of the area, smooth topographic gradient, negligible runoff, high infiltration rates and specific climate conditions.

For the future and with the objective of optimizing recharge estimates and the assessment of the impacts of wildfires in this and other areas, there are some recommendations: (1) the installation of a monitoring network for the shallow aquifer; (2) monitoring meteorological parameters to compare, correct and validate satellite data; (3) collection of rainwater and groundwater samples for chloride analysis, and (4) development of studies focused on understanding the climatological factors and soil properties influencing groundwater recharge in the region.

Keywords: groundwater recharge; remote sensing; PET; wildfires

Introduction

Wildfires impact lives of many people worldwide and cost billions of euros in direct and indirect damage, not only due to their environmental implications, but also the social, cultural, and economical losses they may cause (Turco *et al.,* 2019).

The effects of wildfires on the environment include removal of the soil-protection vegetation, ash deposition, changes in the physical properties of rocks and soil and, impacts in the water cycle leading to changes in water quantity and quality. These effects have been documented in several studies worldwide (e.g. Greenbaum *et al.,* 2021; Loiselle *et al.,* 2020; Robinne *et al.,* 2020; Hawtree *et al.,* 2015; Smith *et al.,* 2011; Shakesby and Doerr, 2006, Neary *et al.,* 2005).

The removal of the vegetation cover affects not only the soil properties but also changes the rates of important hydrological processes such as evaporation, transpiration, and interception (Poon and Kinoshita, 2018; Nolan *et al.,* 2015). The unprotected soil is more susceptible to erosion and the changes in infiltration rates might pose a threat to the water supply in groundwater dependent regions affected by wildfires (Balocchi *et al.,* 2020).

Several studies report that climate and land-use changes are the main drivers for the increasing number of wildfires, as well as their intensity and extent, making them reach areas nowadays where they rarely occurred in the past (Feyen *et al.,* 2020; EU, 2018; Santos *et al.,* 2019; Bladon *et al.,* 2014).

According to data from the Portuguese Institute of Conservation of Nature and Forests (ICNF), the probability risk of occurrence of a fire with a burned area higher that 1000 km² in Portugal increased from 30 to 61% between 2000 and 2017, respectively. Although the Mediterranean region is known by its high susceptibility to fires and Portugal is one of the countries most affected by fires in Europe (Beighley & Hyde, 2018), these events as well as their effects in the atmosphere, soil and water resources are still poorly evaluated, especially when it comes to understanding the qualitative and quantitative impacts on groundwater resources.

Understanding its causes and assessing impacts is the best way to learn how to better adapt to wildfires, preventing not only economic, social and environmental damages, but also ensuring a better management of resources under stressful climate conditions (Rhoades et al., 2019; Hallema et al., 2016).

The Leiria Pine Forest is a unique woodland area that started to be planted more than 700 years ago, in the 13th century, during the reign of King Afonso III and later by his son, King D. Dinis to contain to break the development and restraint the degradation of the dune system close to the city of Leiria. The forest was very important to the development of the region, and it has cultural and historical meaning not only to the region, but to the country.

After a prolonged dry summer with extreme temperatures, a fire occurred in October 2017 in the Marinha Grande region, Portugal burning about 86% (11 hectares) of the Leiria Pine Forest (‘Pinhal de Leiria’) also called the King’s Pine Forest (Pinhal do Rei).

Objectives

The main objective of this study is to evaluate the effects of wildfires in groundwater recharge in the shallow portion of the Vieira de Leiria-Marinha Grande aquifer.

To achieve it the following specific research objectives are defined: (1) Prepare a database containing the fountains, springs, wells and boreholes known in the area; (2) Identify recharge and discharge zones and elaborate a conceptual model of the region; (3) Use satellite data in order to get spatial distributed information on vegetation indices and climate variables; (4) Determine Crop Adjusted Evapotranspiration for the burnt and unburnt areas of the Leiria Pine Forest and, (5) Estimate groundwater recharge for the area for the period of 2001-2020 using EasyBal, a programme designed to calculate water balances of water in soil (Serrano-Juan & Vazquez-Suñe, 2015).

Methodology

Aquifer and water points information were collected using data from SNIRH, the Portuguese National Information System of the Water Resources; and, organized together with remote sensing data in a database that was set up to manage all the available data. Field work was proceeded to get geophysical and borehole information on the groundwater level depth and help elaborating a conceptual model of the study area.

Climate variables and vegetation indices data from 2001-2020 were taken from the E-OBS platform and MODIS satellite, respectively. The use of remote sensing data was chosen in order to overcome the absence of spatial and temporal distributed monitoring data in the area. These data were processed using Python and R codes in order to get monthly values that could be applied in the recharge simulations.

Recharge simulations were done using Easybal v10.9 (Serrano-Juan & Vazquez-Suñe, 2015) developed by the Hydrogeology Group of the Polytechnic University of Catalonia to provide a better understanding on how the changes over time my affect the shallow portion of the Vieira de Leiria-Marinha Grande aquifer.

Regional settings

The study area consists of the Vieira de Leiria-Marinha Grande aquifer with an area of about 320 km². It is located in the district of Leiria (Central Portugal) and comprises four municipalities: Alcobaça, Marinha Grande, Leiria and Nazaré.

The climate in the area is classified as Mediterranean Temperate with average annual rainfall of about 750 mm (based on the data from E-OBS for the period of 2001-2020). It presents strong seasonality in precipitation distribution due to latitude, orography, and continental-oceanic influences. June, July and August are the driest months, and November, December and January are the wettest ones, with higher precipitation values. The average temperature is approximately 16°C with relatively low and high values in winter and summer, respectively. Besides the high seasonal variability, the region also presents strong interannual climatic variability, with precipitation values ranging from 400mm in a very dry year to 1100mm in a wet year.

The topographic gradient in the study area is relatively low and the altitudes range between over 170 m above sea level in the southeast to around 0 m (shore with Atlantic Sea) in the northwest part. Although the topographic gradient is smooth if we consider the whole extent of the study area, the dune system causes local abrupt topographic differences that may interfere in the hydrological conditions of the shallow aquifer.

According to the data from the Corinne Land Cover Project from 2018, developed by the Copernicus Land Monitoring Service, more than 70% of the study area is covered by forest, non-agricultural vegetation areas, scrub, herbaceous vegetation, and pastures. Besides, there are agricultural activities and several factories that produce products like glass operate in the area.

The forested area known as Pinhal de Leiria covers approximately 111 km² of the study area and consists of a maritime pine tree plantation from the XIII century with the aim to contain the invasion of sand dunes inland close to the city of Leiria.

The first reports of wildfires in the region are from 1806 (Silva & Batalha, 1859) and since then, several others have been reported throughout history. The most recent occurred in October 2017 and burnt about 86% of the Pinhal de Leiria forest, changing completely the characteristics of the land cover and land use.

Nowadays, more than three years after the fire, only 11% of the area was reforested and specialists are worried about the development of eucalyptus trees and the presence of invasive species like acacias that may make the recovery and development of the new pine trees even more difficult.

The study area is located in the Lis River basin and part of the Vouga, Mondego, Lis e Ribeiras do Oeste river management plan (APA, 2016). The dominant orientation of the rivers and streams is NE-SW, but there are also rivers with E-W direction region, which coincides with the direction of the main geological faults.

Conceptual Model

The study area is located in the northern section of the Lusitanian basin with the Nazaré fault representing the border to the central section (Dias et al., 2013) and its sedimentary deposits range from the Upper Cretaceous to Holocene in the study area. The shallow aquifer is located mainly in the Holocene sedimentary deposits (approximately 11700 years) are mainly consisted by beach sands and sand dunes extended along the coast. The beach sands consist of small width but continuous deposits on the littoral. The sand dunes represent the majority of the Quaternary deposits in the area and extend up until 7.5 km inland between São Pedro de Moel and Marinha Grande (Zbyszewski and Torre de Assunção, 1965). The sand dunes are composed by well-sorted very fine to fine sands and can develop structures able to reach more 50 m height creating preferential infiltration zones.

Plio- and Plistocenic sedimentary deposits (11700 years to 5.3 My) consist in fine to medium sands with conglomerates and yellowish gray clay intercalations. The Pliocene sedimentary outcrops in the area are likely a result of the steep topographic gradient, as more recent Quaternary dune deposits have overlaid the Pliocene units in less steep coastal areas.

The shallow portion of the Vieira de Leiria-Marinha Grande aquifer is composed by the Quaternary sand dunes and Pliocene sandstone units that have high hydraulic conductivity and infiltration rates. Due to the characteristics presented before, the dunes can increase the effective precipitation and consequently, groundwater recharge.

The regional groundwater flow direction in the aquifer that is mainly from SE-NW, turning into almost E-W in the southern portion of the aquifer and although the main discharge occurs along the western border of the aquifer to the Atlantic Ocean, local discharge zones mainly related to the main rivers exist in the area and are verified in the field by the presence of coastal and inland springs.

The hydrogeological conceptual model of the aquifer system was elaborated based on the geological maps, river network and information in the bibliographic references, as well as GPR and groundwater level data obtained during fieldwork (Figure 1). Results from the Ground Penetrating Radar (GPR) investigations show that the water level is located about 2 meters below the surface, reaching up to 10 meters in specific areas and that despite the predominance of sand dunes there are several small clay layers (possibly iron enriched) intercalated that may represent low conductivity zones, locally reducing infiltration.

The main discharge zone is the Atlantic Ocean in the Western boarder of the aquifer but the Lis River and others smaller streams like the São Pedro de Moel Stream act like local discharge zones, influencing the hydrological regime. The water level is normally found two to four meters depth, reaching surface in some areas.

Before the forest fire occurred in October 2017, the vegetation in the area was composed essentially by pine trees, with average root depth of about four meters (Appelo & Postma, 2005). After the fire, in the burnt area, the vegetation that was completely removed initially, started to grow, but instead of the original pine trees, it was substituted by bushes and shrubs with an estimated average root depth of about half meter. This change in vegetation may alter the hydrological regime, not only due to the decrease in evapotranspiration and interception rates, but also due to changes in soil characteristics (soil water repellency, formation of macropores, etc.).

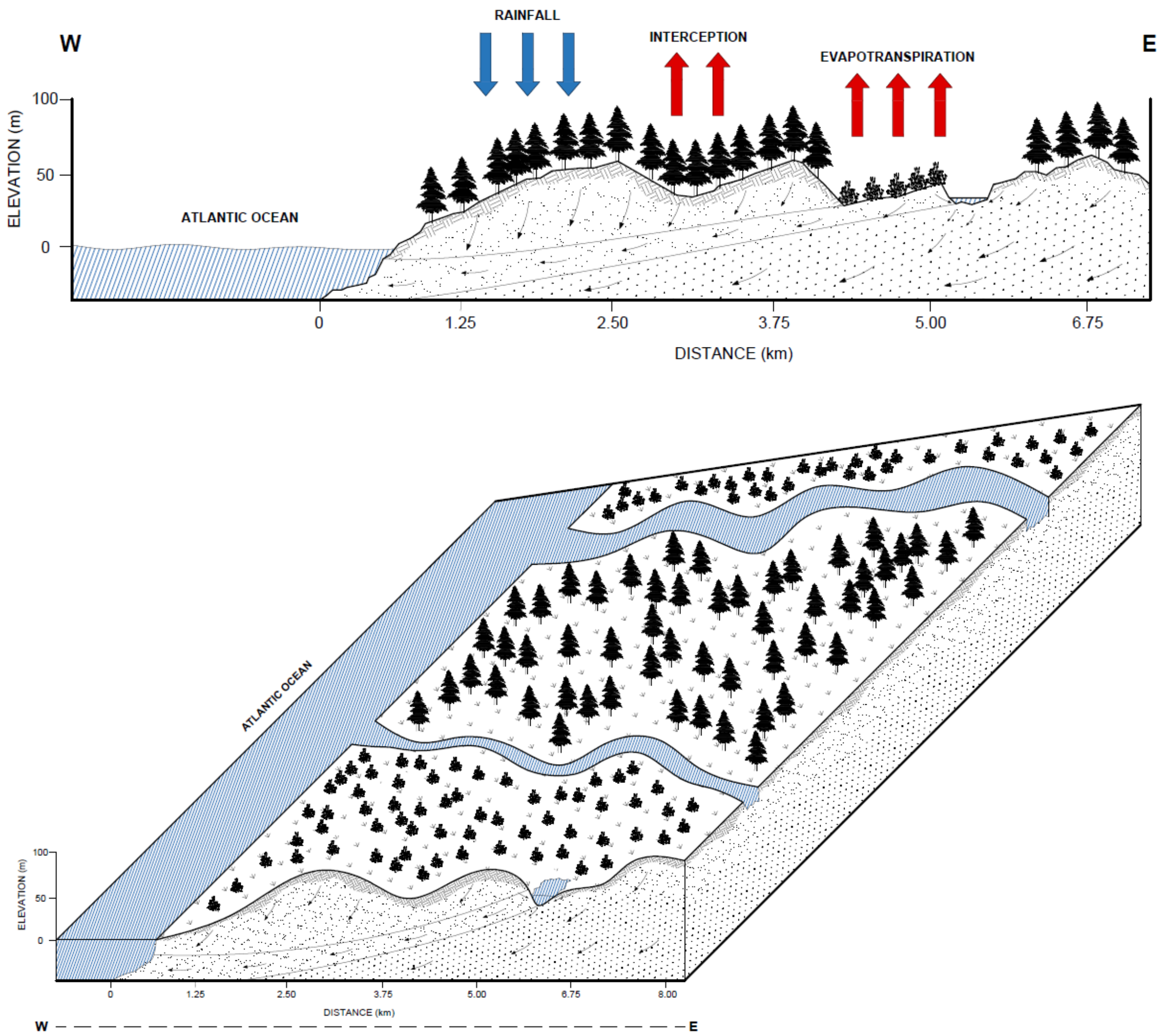

Figure 1 - Hydrogeological Conceptual model developed for the study area.

Estimation of evapotranspiration based on MODIS products

Climate data

The daily observational dataset for the climate variables used in this study was obtained from the EU-FP6 project UERRA and the Copernicus Climate Change Service, and the data providers in the ECA&D project, named E-OBS. The dataset is constructed through interpolations of meteorological observations sourced from the European National Meteorological and Hydrological Services (NMHSs) or other data holding institutions. In this study, version 23.1 was used for the variables daily mean temperature (TG), daily minimum temperature (TN), daily maximum temperature (TX), daily precipitation sum (RR), with a 0.1-degree grid ensemble for the period of 1995 to 2020.

In order to avoid uncertainties that may arise from the interpolation and homogenization techniques from E-OBS (Hamouda & Pasquero, 2021) a correction factor was calculated for the precipitation data, using observational data from eight meteorological stations from the Portuguese System of Water Resources (SNRH) close to the study area. The data from SNRH was not used directly in the study due to the absence of a full time series for the needed parameters in the proposed temporal interval. The corrected values are about to 50% higher than the ones obtained directly from E-OBS, this is probably related to the fact that E-OBS considers points outside the study area in its interpolations.

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a can be defined as a measure of surface reflectance that can be used to perform analysis of vegetation using remote sensing data (Nunes et al., 2016; Carlson and Ripley, 1997). It has been widely applied to monitor vegetation density, heath, and growth, as well as to monitor droughts and predict wildfires risk zones.

This index returns values from -1,0 to 1,0 that represents different kinds of land cover. For instance, negative values normally correspond to clouds, water and snow cover, values close to zero are related to rock and bare soil. Values between 0.1 and 0.4 represents scrubs, bushes and grassland while high values between 0.6 and 1 indicate a denser vegetation such as tropical and temperate forest vegetation (Weier and Herring, 2013).

The NDVI index from the MOD13Q1.006 (Didan, 2015) products were used from the Terra satellite with spatial resolution of 250 meters and an interval of 16 days. A total of 922 images were acquired, being 461 for the area burnt in the fire in October 2017 and the same number for the unburnt areas of the Leiria Pine Forest. The monthly values obtained for the burnt and unburnt areas varied between 0.753 – 0.299, and 0.725 – 0.471, respectively (Figure 2).

The NDVI index for the area burnt on the fire of October 2017 has been bigger than the index for the unburnt area over all the time series. It could be related to the fact that although the unburnt area corresponds to approximately twice the size of the burnt one, the land cover in the burnt area has always been essentially the pine forest, while in the unburnt area, the land cover distribution is much more diverse, including cities, factories, agricultural areas, pastures and scrubs, that will likely reduce the overall average of the NDVI index.

The abrupt decrease observed in the NDVI series of the burnt area reflects the change in vegetation just after the fire, while in the unburnt area, the values keep the trend observed in the previous years. This sharp decrease is related to the loss of biomass and the reduction of leaves (reduction in chlorophyll absorption).

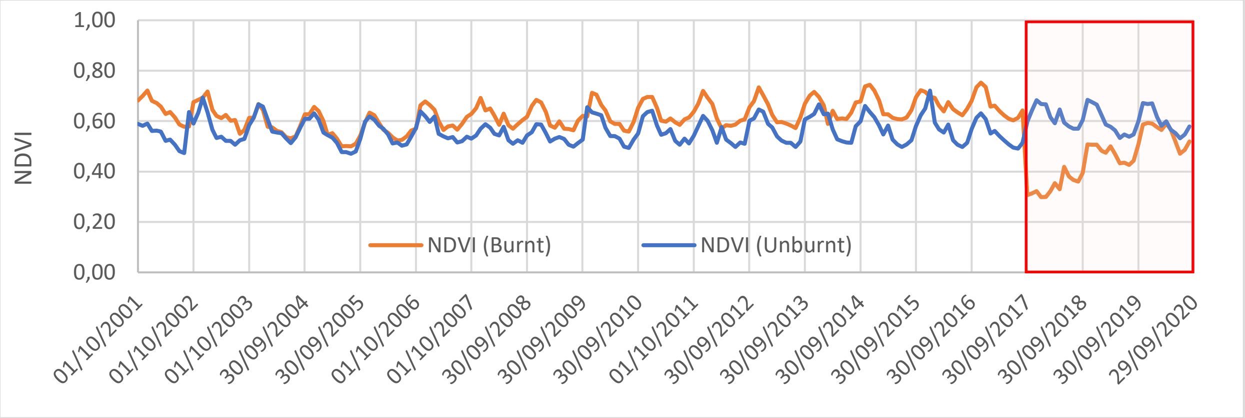

Figure 2 - NDVI indices for the burnt and unburnt areas in the Leiria Pine Forest from 2001 -2020. The red rectangle marks the period after the fire.

<u>Potential Evapotranspiration (PET) and Evapotranspiration (ET)</u>

The definition of Potential Evapotranspiration (PET) according to Rosenberg (1974) is “the evaporation from an extended surface of [a] short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water” (Kirkham, 2014).

Evapotranspiration is the combined loss of water by transpiration, release of water through plants leaves, and the evaporation from the soil surface, in a given area and during a specific period of time (Porkony, 2019; Kirkham, 2014).

Several methods can be applied to determine PET, from the simpler ones, purely empiric, to the more complex ones. These methods can be direct like lysimeters or indirect such as the methodologies developed by Thornthwaite (1948), Blaney-Criddle (Doorenbos e Pruitt, 1977), Hargreaves (Hargreaves, 1994) e de Penman-Monteith FAO (PM-FAO) (Allen et al.,1998).

Remote sensing data from MODIS has been applied in several regions to estimate ET presenting good correlations between NDVI and ET (Cherif et al., 2013; Nagler et al., 2005).

ET and PET values were taken from the MODIS database (MOD16A2GF.006 Terra Net Evapotranspiration) with an interval of 8 days and a resolution of 500m for the period of 2001 -2020 for the burnt and unburnt areas in Leiria Pine Forest (Running, 2017). A total of 3680 images were acquired being 1820 (ET and PET) for the area burnt in the fire in October 2017 and the same number for the unburnt area.

The monthly average evapotranspiration values obtained for the burnt and unburnt areas varied between 21.37 – 101.19, and 22.58 – 98.2, respectively. The lower values are observed in winter between December-January and the higher ones in the summer from Jun-July. Regarding

PET, the values range from approximately 30 to 250 mm/mm along the time series and the correlation between the data observed in the bunt and unburnt areas is about 0.998. Since the PET is a parameter that consider the ideal conditions and a specific (constant) type of vegetation for both cases, it is expected that the values do not change much over time even after the fire.

Crop Coefficient

The crop coefficient values represent the combination of effects plants may suffer due to changes in several parameters such as crop characteristics, plant height, rate of development, leaf area index, planting date, degree of canopy cover, canopy resistance, soil and climate conditions and management practices (Porkony, 2019).

These values are normally calculated experimentally, but since the use of vegetation indices like NDVI obtained from satellite can help estimate parameters related to vegetation phenology, they can also be used as a tool to monitor the Kc variations in time and space (Duchemin et al., 2006). The estimation of Kc from the NDVI composites taken from MODIS was calculated according to approach developed by Duchemin et al. (2006), summarized in Equation (1) and applied in the literature for several crop species (Nunes et al., 2016; van der Slik, 2014; Ferrara et al., 2010; Campos et al., 2010; Vuolo et al., 2008).

$$Kc = a.\left(NDVI - NDVI_{\min\_Kc}\right) \qquad (1)$$

According to the proposed methodology, the relation between NDVI and Kc must be obtained using the months where the crop transpiration occurs under low stress conditions, to do so, a filtering of the extremes (very dry and very wet months) was done in the NDVI dataset. The filtering was done considering that the Kc values would be only used if the rainfall and ET deficit were both lower than the thresholds established based on the maximization of the correlation between NDVI and Kc (Rainfall < 22.93 and ET Deficit < 229.02). After the filtering procedure, the correlation between the NDVI and Kc increased from 0.47 to 0.60 for the time series.

The FAO Irrigation and Drainage Paper nº56 (Allen et al., 1998) stablishes that the Kc values should not be lower than 0.3 which is the value that represents a bare soil with occasional precipitation. Therefore, for pine forests with NDVI below 0.5 the Kc will remain constant at 0.3.

By plotting the NDVI against the Kc values and using linear regression, an equation relating these parameters will be adjusted and applied to the NDVI series from before the fire (2001-2017) taken from MODIS to generate a temporal series of Kc for the Leiria Pine Forest.

The correlation obtained is shown in Equation 2 and it was very similar to the ones obtained in other studies for the crop coefficient of pine trees (Nunes et al., 2016). The parametrization of the Kc is a limitation of the research, because although the obtained relation is consistent for the data, several factors including soil and canopy properties, climatic conditions and crop characteristics might affect the outcome of the calculations.

$$Kc = 1.8109.\left(NDVI - 0.3251\right) \qquad (2)$$

The values of crop coefficient calculated using the NDVI from the MODIS satellite before the fire range from 0.32 to 0.77 along the times series and the lowest ones are usually observed between July and August while the higher ones between December and January which follows the NDVI, and precipitation patterns. According to Allen et al. (1998), there is a strong relation between the Kc and the soil humidity, that acts like a limiting factor for evapotranspiration, which explains why Kc decreases in the drier months (July-August) and increase in wet ones (December-January).

Although the correlations before the fire (0.60) and two years after the fire (0.64) are significant, in the first year after the fire, the NDVI vs. Kc relation do not exist. This is probably related to the death of the vegetation. In this case, when the vegetation is inactive, the evapotranspiration is controlled mainly by the evaporation in the soil, which means that the only factor controlling the evaporation of the water will be the soil humidity. A correlation with $r^2=0.43$ was obtained between the Kc 1 year after the fire and the precipitation in the area, which is very low to stablish a valid equation, so using the values proposed in Allen et al. (1998), crop coefficients of 0.6 and 0.3 were assumed in the wet and dry months, respectively.

After two years of the fire, a new correlation ($r^2=0.64$) can be observed between NDVI and Kc in the Leiria Pine Forest area. This is probably related to the progressive growth of vegetation in the burnt area, which makes the NDVI start increasing slowly as new species start to develop in the area.

Although the Portuguese Institute of Forest Conversation estimates a reforestation of 2400 ha by 2022, nowadays, the vegetation in many parts of the area is essentially composed by bushes and scrubs from invaders species. The relation 2 years after the fire is given by Equation 3 and it is similar to the one described by Campos et al. (2010) for vines, which corroborates the hypothesis of the predominance of a smaller and more scrubby type of vegetation.

$$Kc = 1.7428.\left(NDVI - 0.2607\right) \qquad (3)$$

It can be observed that the trends from before and 2+ years after the fire are parallels to each other, but the curve from before the fire has a lower crop coefficient for the same NDVI values and, consequently a lower water use than the one from after the fire.

Reference Evapotranspiration (ET_0) – Hargreaves Method

Precise estimations of evapotranspiration are essential in the evaluation of water resources availability and crucial in recharge estimation procedures. ET may be affected by several parameters including climatic factors (solar radiation, temperature, wind velocity), crop parameters and soil properties (Allen et al., 1998). A broad variety of methods have been used to calculate ET, considering not only their precision, but also the availability of data.

After the publication of the FAO 56 Report, the Penman-Monteith method was defined as the standard methodology to estimate the reference evapotranspiration (ET0), although it requires climatic data that are not often available for many regions. So based on the available data, the ET_0 was estimated using the Hargreaves Method (HS) (Hargreaves & Samani, 1985), which is a semi empirical method that uses extraterrestrial radiation and temperature data to estimate daily ET_0 according to Equation 4.

$$PET_{HS} = C_H.0.408R_0.(T + 17.8)\sqrt{T_{max} - T_{min}} \qquad (4)$$

Where, CH is the Hargreaves coefficient, the values of 0.408 corresponds to the inverse of the latent heat flux of vaporization at 20◦C, R0 is the extraterrestrial radiation in mm.day-1 evaporation equivalent and T is the daily mean temperature (◦C) and Tmax and Tmin are the daily maximum and minimum temperature values, respectively. The climatic data for the period of 1995 to 2020 was taken from the E-OBS database for the study area and applied to the HS equation.

The results show that although correlation between the time series is high (r^2=0.980) the data from MODIS shows values up to 40% higher than the ones estimated by the methodology proposed by Hargreaves (PET-HS). We can observe that the values are very similar for both methods in the winter months and as the temperature gets higher, the values for the satellite get higher than the ones obtained by the Hargreaves Method.

In order to double check the accuracy of the PET values obtained by the Hargreaves method and their representativeness of the study area, PET values were estimated using the Penman-Monteith (PM-FAO) method using the data from the Monte Real Meteorological station for the period of January/2002 to December/2009. The location of the meteorological station and the period analyzed was chosen based on the available data. The results are shown in Figure 3.

The results obtained using the HS and PM-FAO methods present very similar values for the analyzed period with a high correlation (r^2 =0.955) between them, and although the PET values from MODIS are higher than the PET-HS and PET-PM-FAO they also present good correlations. Therefore, the satellite is most likely systematically overestimating the PET values in the summer months decreasing the reliability of the direct use of satellite data in the simulations.

The MOD16 algorithm is based on the Penman-Monteith equation adapted to remote sensing, and according to Ruhoff et al. (2011), presents two main constraints: the estimation of the stomatal conductance and the estimation of the evaporation directly from the soil, that may vary from 0 to 80%, especially in areas with low leaf area index. The estimation of ET using remote sensing techniques is not made directly, instead it uses other remote sensing products such as land surface temperature, vegetation indices and leaf area index. Thus, its results depend on the quality of the input data that sometimes have very low spatial resolution (110 km) when compared to the output resolution (1 km).

PET and ET data estimated using MODIS (MOD16 products) satellite are consistent when the landcover classification is correct. Otherwise, parameters like vapor pressure deficit and minimum air temperature for stomatal conductance constrains are wrongly selected resulting in less accurate ET estimations (Ruhoff et al., 2011).

Benali et al. (2012) reported low accuracy of the MODIS satellite data in the coastal stations. The authors believe that it is probably related to the spatial variation of relative humidity due to thermal inertia, which would influence the energy available for sensible heating on the surface and, therefore. According to them, the position of the Azores anticyclone during the summer, allows mesoscale circulations to dominate the surface flow, favoring sea breezes and enabling advection masses of moist air from the sea to the land, which increases the fog periods in summer in the center of the West Portuguese coast, where the Leiria Pine Forest is located. This could explain the higher accuracy in the winter months and the increase in the satellite values in the summer.

Crop Adjusted PET (PET_{CA})

The values of Crop Coefficient (Kc) and PET-HS were used to obtain the values of the crop adjusted potential evapotranspiration (PET_{CA}) that will be applied in the recharge calculations. The PET_{CA} consists of an adjustment of the PET considering the vegetation in the study area and is calculated by multiplying the PET and the Kc.

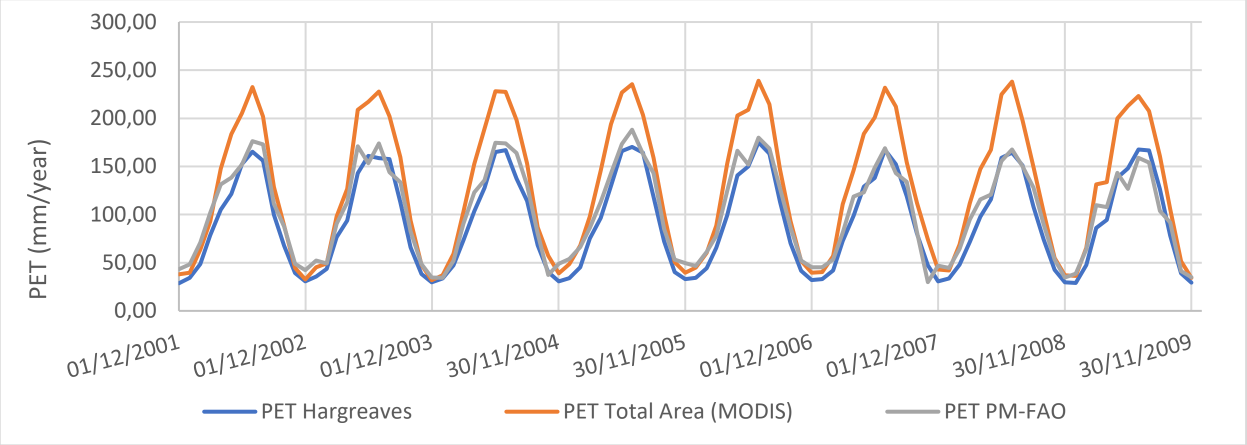

Figure 3 – Comparison of PET values obtained using different methods for the study area.

The relation between these parameters is given by Equation 5.

$$PET_{CA} = PET_{HS} \times K_c \quad (5)$$

Where Kc is the crop coefficient calculated from the NDVI obtained in MODIS database, PET-HS is the potential evapotranspiration calculated using the Hargreaves method (Hargreaves & Samani, 1985), and PET_{CA} is the crop adjusted evapotranspiration in the area.

PET_{CA} was calculated for both burnt and unburnt areas based on the different Kc time series obtained from the NDVI data. By comparing the PET_{CA} from the Burnt and Unburnt areas we immediately notice that the unburnt area has lower values than the burnt area, it is a reflex of the behavior of the crop coefficient due to the more homogeneous (vegetated) land cover in the burnt area than in the unburnt.

The graph shows an abrupt decrease in the PET_{CA} in the burnt area after the fire, which is completely according to the expectations due to the significant reduction in the vegetation after the fire. About 6 months after the fire, the PET_{CA} starts increasing gradually reaching similar values from the average PET_{CA} before the fire, suggesting a recover of the vegetation as discussed in the previous chapters.

Another interesting observation is that in the middle of 2003, the values of PET_{CA} in the burnt area reduce reaching the same range observed in the unburnt zone, and gradually increasing until recover average values in 2007. This behavior is probably related to a fire occurred in the Leiria Pine Forest in August 2003 that burnt about 25% of the forest. Since its magnitude was much smaller than the fire from 2017 (that burnt 86% of the forest) the effects in the PET_{CA} are not as strong but can be seen in the time series.

The use of PET and ET data from MODIS is a limitation in this study because it is too high compared to the other methodologies applied. Nevertheless, despite the overestimation of this parameters by the satellite in the study area, the relation between PET (MODIS) and ET (MODIS) is still valid, even though the values themselves are not.

Groundwater recharge

According to Freeze & Cherry (1979), “groundwater recharge can be defined as the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table within the saturated zone”. In simple terms, it can be described as the descending water flow that when infiltrating, reaches the aquifer system resulting in an additional volume to the groundwater reservoir. This process is based on the complex combination between energy and moisture occurring in the zone between atmosphere and subsurface (Smerdon, 2017).

Although groundwater recharge is one of the main parameters to be evaluated when we think about groundwater management and availability, its estimation in very challenging, because it is hard to measure it directly and shows high spatial and temporal variability, adding uncertainties to the estimations (Healy, 2010).

Estimate groundwater recharge requires a broad knowledge and understanding not only on the water flow, but also the climate and geological conditions in the area in order to represent in the best way possible the main processes occurring. There are several methods to estimate recharge, like the Thornthwaite-Matter method (1955), Penman-Grindley method (Penman, 1950; Grindley, 1967), chloride mass balance (Allison & Hughes, 1978), water level fluctuation method (Healy & Cook, 2002), application of numerical models, among other tools. The choice about the best method to each case will depend on the availability of data, precision required in the analysis, the size of the system to be analyzed and the hydrogeologic conditions.

In most of the cases, the absence of data is a major limitation when performing this type of analysis, and to overcome this, it is necessary to adequate the methodology considering the best possible representation of reality that can be achieved with the available data (Healy, 2010).

Remote sensing tools have been extensively applied in recharge estimations (e.g. Khan et al., 2020; Gemitzi et al., 2017) due to their capability of provide reasonably quality data with longer temporal and spatial distribution. The main limitations imposed by the use of these techniques when compared to meteorological models are related to mainly to cloud cover, scale factor and low data acquisition frequency (Ruhoff et al., 2011).

The present work aimed to investigate the possible effects of forest fires in groundwater recharge and, in order to achieve it, data with good temporal (before and after the fire) and spatial (burnt and unburnt areas) distribution was needed. Since the study area does not have an established monitoring network and observational datasets were not available, the use of remote sensing data was considered the best option to estimate groundwater recharge even considering the limitations imposed by this decision.

Recharge model

The groundwater recharge simulations were conducted for the burnt and unburnt areas of the Leiria Pine Forest using the Easybal software developed by the Hydrology Group of the Universitat Politècnica de Catalunya (UPC) for the period of 2001-2020 and the interpretation was divided in two periods: before and after the forest fire occurred in October 2017.

The Easybal software uses climate data (temperature and precipitation), PET and soil property data (field capacity, initial humidity, permanent wilting point, rootzone, lamination value) to determine groundwater recharge in a daily, monthly and annual temporal scale.

The daily climate data (temperature and precipitation) time series was taken from the E-OBS database for the period of 2001-2020 and processed using Python. NDVI indices taken from the MODIS satellite with an interval of 16 days for the period of 2001-2020 were used to estimate vegetation crop coefficient (Kc) based on empiric relations cited in the references. The crop coefficient is used to calculate the adjusted evapotranspiration (PET_{CA}) depending on the type of vegetation in a given area. Kc values reflect land cover changes imposed by the wildfire. Irrigation was neglected in the area since it consists mainly of forest.

Besides the climate time series data, Easybal also need soil parameters that were estimated based on the references available for the study area and calibrated during the simulations. The field capacity and wilting point values used are an average of the experimental results available on the Infosolos database from Marques (2010).

It is widely known that plants and their roots are able to affect soil physical properties like infiltration rate, moisture content and aggregate stability (Gyssels et al., 2005).

These effects influence directly the water balance, since the presence of plants not only interfere in the evapotranspiration parameter but is also able to decrease runoff by increasing infiltration capacity of the soil. The root zone parameter was defined based on the relation between chloride concentrations in the unsaturated zone and root depth of the vegetation explained in Appelo & Postma (2005). The higher chloride concentrations in the soil profile are present in the rooted upper zone. Below the heathland, the chloride concentrations are low and variate very little, and the higher values can be seen in the first meter of the soil profile while below the pine trees, the chloride concentrations are much higher and vary widely, with the higher concentrations presented in the first 4 meters of the soil profile (Moss & Edmunds, 1989; Appelo & Postma, 2005).

So being, the Rz in the Leiria Pine Forest was assumed to be 4m before the fire considering that the vegetation consisted mainly of pine trees and 0.5m after the fire, when new and more shrubby vegetation started to grow in the area.

The lamination was estimated based on the characteristics of the study area. The high infiltration capacity and hydraulic conductivity of the very well-sorted sand dunes, combined with the low slope topography suggest that runoff in the area would only occur in exceptional cases and can be neglected in normal conditions. Based on this, several simulations were performed using different lamination values and it was set on 300 mm/month, considering that above this value, the recharge estimations do not get affected (Runoff = 0).

Several studies report that the use of monthly time steps can substantially underestimate groundwater recharge (e.g. Mileham et al., 2009), so in order to account the concentrated recharge caused by high events, the recharge simulations included a direct groundwater recharge of 20% of the precipitation (Stigter, 2014).

The Easybal model is a simplification of the reality, and the limitations in its application in this study case include: (1) it does not provide a spatially distributed estimation of groundwater recharge, instead, it presents an average (daily, monthly or annual) value; (2) Easybal does not consider some soil properties that may influence recharge in cases of wildfires such as soil water repellency; (3) The soil parameters insert in the model are based on the available references, (4) errors related to the use of remote sensing data to estimate PET$_{CA}$, and (5) Groundwater recharge is the output of the model and values of AET used in the calculations are not discriminated.

Simulations Results

The first step to understand the changes in groundwater recharge after the fire is to understand it before the event. In order to have a better picture of its behavior and increase the accuracy in the analysis, a normalized recharge was calculated to be applied in the comparisons as what would be expected if the fire had never happened.

This normalized recharge was estimated using monthly averages of the crop coefficient time series from before the fire (oct2001-sep2017) to calculate a normalized PET$_{CA}$, that were extrapolated to the period after the fire in the burnt and unburnt areas. After that, these values were compared to the ones observed for groundwater recharge in the area.

Although the annual recharge obtained in the results for the U$_A$ are slightly lower than the expected values obtained using the normalized average calculations, the average recharge do not vary much between the periods before and after the fire and both cases present correlations with $r^2= 0.97$. Since the expected values were obtained based on the monthly average of the times series and replicated for all the years, interannual variability is not taken into account, which may lead to the small differences between the expected and observed values. Besides, these differences can be seen in the time series both before and after the fire, which is another indication that it is probably not related to the event itself.

The same simulations were made in the burnt area (B$_A$) of the Leiria Pine Forest and the results show that the average annual groundwater recharge in the burnt area (BA) in the period before the fire was approximately 37% of the precipitation in the area, and the results are very similar using the times series data and the expected values ($r^2=0.99$). After the fire, the groundwater recharge in the BA increases about 50% in the first year, 30% in the second and 17% in the third year when compared to the expected values.

The correlation between the simulated groundwater recharge and the expected recharge values drops from an $r^2=0.99$ to $r^2=0.78$ in the years after the fire due to the removal of the vegetation and the decrease in the PET$_{CA}$ that would not occur in normal conditions.

The total recharge in the aquifer was calculated by doing the weighted mean of the B$_A$ and the U$_A$ obtained from the Easybal simulations plus a direct recharge of 20% of precipitation ((RBurnt + (2 x RUnburnt))/3 + Direct Recharge) and the results are presented in Figure 4. According to the simulations presented in the study, the groundwater recharge is slightly smaller in the U$_A$ after the fire and considerably higher in the B$_A$, which means that the aquifer recharge should be globally higher than the expected after the event.

Results show that the groundwater recharge in the aquifer before the fire was about 40% of precipitation and increases approximately 15% in the first year, 7% in the second and 3% in the third year after the fire when compared to the expected values. The correlation between the simulated and expected data before the fire is $r^2=0.994$ and after the fire it decreases a little to $r^2=0.95$.

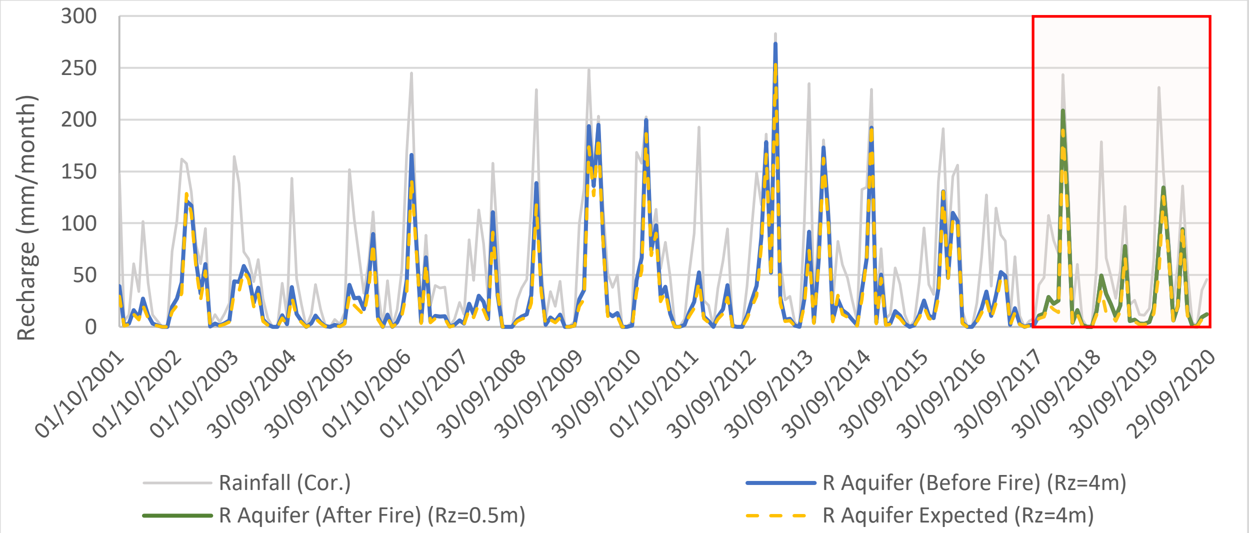

Figure 4 - Groundwater recharge in the total extent of the Vieira de Leiria-Marinha Grande Aquifer.

This attenuation in the increasing when comparing the recharge in the aquifer and in the B_A is probably because the B_A corresponds only to 1/3 of the area while the Unburnt non-affected area corresponds to 2/3 of it, provoking this dilution in the increase of the recharge.

In order to verify these results, the total recharge of the Vieira de Leiria-Marinha Grande Aquifer was also calculated using the directly the NDVI data obtained from MODIS satellite. The results simulated have a r^2=0.988 correlation with the ones obtained by the weighted average of BA and UA for the period before the fire and r^2= 0.976 after.

Impact of Wildfires

Several communities around the world are supplied by water coming from forest catchments that are potentially vulnerable to wildfire and climate change (Hallema, 2016). So, understanding the adverse effects of wildfires on the hydrological processes that govern water quantity and quality in these regions is especially important to propose effective management and adaptation measures (Loiselle et al., 2020).

In order to evaluate the impacts of wildfire events it is essential to understand the physical processes occurring in the watershed. Sometimes, technical difficulties such as the lack of monitoring networks and difficult the access in areas after wildfires, make hard to assess the impacts of these events in the field. Because of this, remote sensing techniques have been applied by many researchers (e.g. Ebel et al., 2016; Malagó et al., 2017) to investigate watershed responses to climate change, land cover changes, disturbances, and extreme weather events (Rodrigues et al., 2019).

The impacts of wildfires can be felt not only in the environmental sphere, but they can also represent economic, social and cultural losses to the population through properties and cultural patrimony destruction, damages in infrastructure, biodiversity and human life losses (Efthimiou et al., 2020).

The most obvious and discussed environmental impacts of wildfires are related to the vegetation losses, disruption of soil's physical properties and soil erosion in the affected areas and they have been discussed in many papers (e.g. Coop et al., 2016; Shakesby, 2006). The changes in vegetation and soil properties such as infiltration rates, porosity, conductivity and storage capacity may exert considerable influence on the hydrological functioning of the watershed including alteration of evapotranspiration rates, increasing runoff and sedimentation rates and partitioning of precipitation by forest canopies, ultimately influencing the amount of water that percolates the soil recharging the water table.

Vegetation Loss and Evapotranspiration

Vegetation influences the water cycle in several ways controlling interception processes, water retention, runoff, infiltration rates and transpiration from plant canopy. The evapotranspiration represents the largest loss of water in the hydrological cycle (Neary et al., 2005) and since it consists of the sum of the direct evaporation from soil, plants leaves and water bodies, and the transpiration of the vegetation in a given area, it is widely affected by the occurrence of wildfires due to the changes in plant physiological properties (amount of leaves and root distribution) that control the amount of water being intercepted, evaporated and/or transpired (Anurag et al., 2021).

Forest areas usually evaporate more water than areas covered with shorter vegetation due to greater rainfall interception (Valente et al., 1997). Several studies report a rainfall interception in temperate coniferous forests is between 10-60% of precipitation (Teklehaimanot et al., 1991) and the main factors responsible for that are the bigger canopy storage and aerodynamic conductance.

The modification in plant physiological properties have the potential to induce changes in hydrological processes including groundwater recharge through the decrease in interception, evaporation and transpiration by plants' canopy and consequent decrease in evapotranspiration and increase in the net precipitation available for streamflow (Anurag et al., 2021; Poon & Kinoshita, 2018).

The decrease in the crop adjusted potential evapotranspiration in the burnt area of the Leiria Pine Forest after the fire was 92% in the first year, 18% in the second year and 0% in the third year when compared to the expected values, which suggests a recover of ET after three years due to the growth of new vegetation in the burnt area. We also observe a similar behavior in the period between the end of 2003 and 2006, this is probably related to the fire that happened in August 2003.

Results from Häusler et al. (2018) also show a reduction in ET values in fire-affected areas in Portugal, mostly in the first year after the fire. Analysis in the second year after the fire showed a significant recover in ET values towards the pre-fire conditions that the authors defined as in the natural variations range, although it does not mean that the forest has returned to its former conditions.

The recovery in ET values in the Leiria Pine Forest after the first year may also be related to the fast growth of a bushy and scrubby vegetation in the area just after the fire that according to Garcia-Estringana et al. (2010) has high rain interception in Mediterranean climate, contributing to increase in ET.

The application of NDVI to calculate PET$_{CA}$ may also represent a limitation in terms of recovery evaluation, since besides the changes in vegetation cover contemplated by satellite calculations, the potential increase in SWR and other factors may also limit water storage decreasing ET after the fire (Nunes et al., 2016). Although the reduction in ET certainly contributes to the increase in groundwater recharge (50% in the first year, 30% in the second and 17% in the third year when compared to the expected values) most likely, it is not the only factor responsible for it (Figure 5).

Besides the increase in soil water due to the decrease in ET, in some cases, the loss of vegetation may have other kind of effect. According to Hyde et al. (2007), the removal of the canopy's shades and the insulation provided by the litter, combined with the increase in the heat may lead to hyper-desiccated soils, increasing capillary suction and greater lag times to maximum infiltration rates.

Runoff and Water Repellency

Soils in specific conditions of climate and vegetation may develop soil water repellency (SWR) after the occurrence of a fire. It can decrease infiltration rates and involves physical and chemical processes with important implications for plant growth, soil erosion and runoff (Nunes et al., 2016; Santos et al., 2013). Since SWR development is directly related to the presence of organic matter, it can be found in both fire and non-fire environments.

The water-repellent (hydrophobic) layer is formed when the heat from the fire vaporizes organic substances that are transported downwards and subsequently condensed after temperature decreases (Ferreira et al., 2008; Neary et al., 2005). After it, water cannot infiltrate through, increasing overland flow and surface erosion in the affected regions. According to DeBano (1981) the formation of the water-repellent layer occurs when soil temperature rise above 176ºC and it is destroyed when temperature is above 288ºC.

Despite soil SWR has been reported in many cases worldwide, its mechanisms are not completely clear yet. In fire environments, the effects can be highly variable depending on the soil heating regime, type of organic matter consumed and the amount of available oxygen during burning; in some cases, fires could even decrease the intensity of SWR, while increasing its persistency (Nunes et al., 2016).

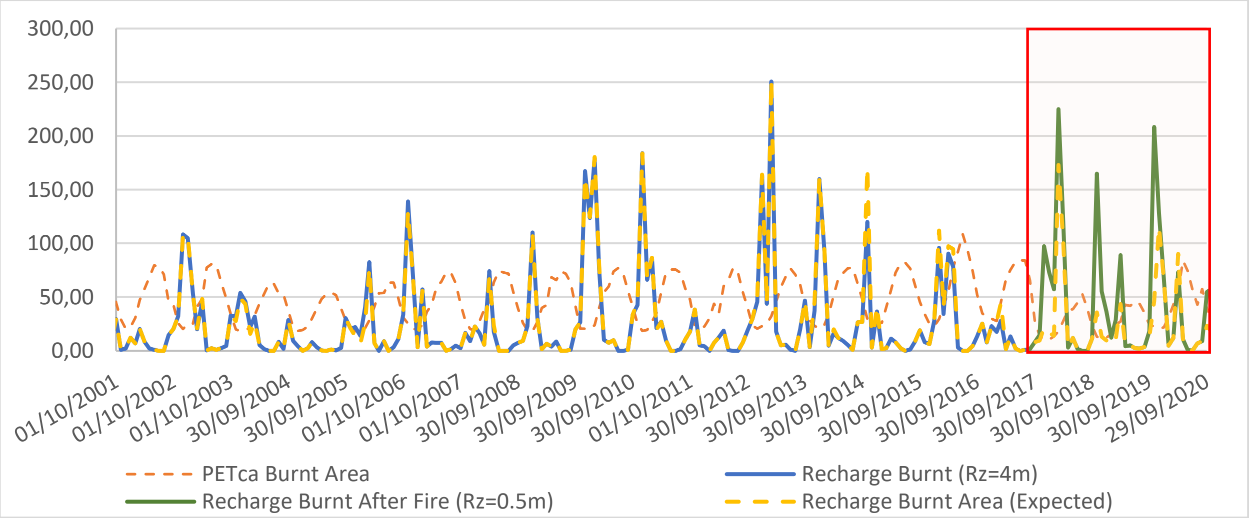

Figure 5 – Relation between PETca and expected and observed groundwater recharge in the burnt area.

SWR is highly variable in time and space and varies nonlinearly with soil moisture content, with the formation of a transition zone between wettable and repellent conditions where the soil can act as repellent or wettable (e.g. Rueda et al., 2015). Although there is not a threshold defined for completely disappearance of the water-repellent layer, according to MacDonald and Huffman (2004), it should be about 10% in unburnt areas up until 28% in severely burnt areas.

According to Coelho et al. (2004), fire severity is a determinant factor in spatial variability of water repellent soils in burnt areas. The higher severity is related to more extreme and homogeneous SWR, while in low severity areas, the effect is more heterogeneously distributed, favoring the development of preferential flow paths which may locally increase infiltration in some areas (e.g. Diamantopoulos et al., 2013).

The effects of severity and spatial distribution of SWR are highly dependent on the analyzed scale, so overland flow and erosion rates tend to decrease significantly in wider systems when compared to smaller ones due to the connectivity of water and sediment processes. In a catchment scale, the spatial variability of SWR, and the existence of preferential infiltration areas can decrease the impact of SWR on water balance, especially if the fire intensity is not homogenous. (Ferreira et al., 2008).

Among the factors able to affect the water balance, several authors point runoff as a very important one in cases of wildfire (e.g. Chen et al., 2013). The organic matter in the soil contributes to soil structure and porosity and is deeply affected by fires. The loss of vegetation and changes in the soil structure after a wildfire may reduce soil roughness, triggering severe erosion, reducing infiltration rates and increasing the availability of loose sediments (Ferreira et al., 2008).

When speaking specifically about wildfires, normally the SWR tend to be homogeneous, except for some preferential flow paths created by macropores, which favors overland flow and sediment transport. Thus, in burnt areas, the combination of reduced interception and increased SWR, with consequent decrease in infiltration capacity are the main factors responsible to enhance runoff generation and erosion rates (Ferreira et al., 2008).

The understanding of the consequences of wildfires is quite complex because the extension of the effects will be directly linked to specifics characteristics of the area (topography, soil organic matter content, vegetation, etc.) as well as the fire characteristics (severity, intensity, extension). In the Leiria Pine Forest case, we believe that the smooth topography combined with a geological background consisting mostly of very well-sorted sand dunes, with high hydraulic conductivity favors infiltration keeping the overland flow to a minimum, even after the fire.

According to the fire severity analysis in Fernandes & Guiomar (2018) the fire in the Leiria Pine Forest had predominantly extreme (37.1% of the burnt area), high (27,4%) and very high (17,6%) severities. The areas with Moderate to low fire severity were about 18% of the total burnt area.

This distribution was expected to enhance the SWR effect in the area. However, the favoring of macropores formation by the combustion of pine trees' roots probably contributed to hamper the effects of the formation of the SWR layer. Besides, the persistence of this layer is related to the soil moisture content, considering that the fire in Leiria occurred in the beginning of the wet season, the increase in precipitation could have contributed to the fast disappearance of the water repellent layer.

Rooting System

Another very important factor capable of influence the infiltration rates and consequently groundwater recharge, is the rooting system. After a wildfire, the complete elimination of the vegetation may have severe and long-lasting consequences.

The rooting system is responsible for stabilizing the soil, influencing its effective hydrological depth and increasing flow roughness. The prolonged heating of the soil during a fire produces temperatures that essentially sterilize the upper part of the soil killing microbial population, small invertebrates, insects and plant roots. It leads to an increase in soil and organic matter loss, modification of porosity, alteration in aggregate stability, depletion of nutrients, increase in bulk density and sediment yield, and decrease in infiltration (Efthimiou, 2020; Neary et al., 2005; Hyde et al., 2007).

The creation of macropores by soil cracks, high stone content and/or plants roots has been reported to explain why high runoff coefficients after fire are observed in micro-scale studies and are not reflected in catchment scales in the Mediterranean region (Shakesby, 2011; Doerr et al., 2003). While the macropores can be filled with ashes and fine soil particles decreasing even more infiltration rates (Martin & Moody, 2001), in specific conditions these macropores may act as preferential pathways to water infiltration, increasing it instead reducing.

The presence of extensive macropores systems in burnt pine areas due to the combustion of rotten root systems may hamper the SWR effect, helping in the control of excessive overland flow (Ferreira et al., 2008).

According to Neary et al. (2005) vegetation changes have a smaller effect on subsoil properties that influence soil water storage, so they are not likely the main drivers of the catchment hydrological cycle. However, if these vegetation changes affects not only infiltration, but also evapotranspiration, as in the Leiria Pine Forest, it may influence soil water storage.

Different types of plants have different root depths. During the groundwater recharge simulations for the Leiria Pine Forest the root depth parameter (Rz) was modified from 4 meters before the fire to 0.5 meters after it based on the available references and changes in vegetation observed during fieldwork (Appelo & Postma, 2005). Deeper roots like the ones from pine trees can penetrate deeper into the soil and abstract water directly from the shallow aquifer (water level at 2m depth in the study area). After the fire, the weakening and removal of the pine roots and subsequently substitution by other vegetation species (shrubs and bushes) with shallower root depths (Rz=0.5m), that are only able to use water stored in the topsoil layer, may have contributed to the increase in groundwater recharge.

Conclusions

Groundwater recharge estimation is a complex process because it requires comprehension of the physical conditions of the study area as well as all the processes and interactions conditioning recharge. There are several methodologies that may be applied to overcome the challenges involved in these estimations, since most of them consist of simplifications of the reality, choosing the best one should always consider the characteristics of the study area (e.g. climate, soil type, geology, topography) and the quality of the available data.

The use of remote sensing allowed us to overcome the limitations of temporal and spatial distribution of data in the study are, and although its use still presents several uncertainties related to the calculation, interpolation, atmospheric conditions, accuracy of the satellites depending on the physical and atmospheric conditions, they represent a very powerful methodology. Nevertheless, the interpretation of the results should always be critically analyzed and validated using field data when possible. In order to check the results, increase accuracy and give more credibility to the results, the PET data from MODIS was compared to the results calculated using PM-FAO and the Hargreaves method revealing limitations in the use of the ET satellite data.

Understanding how to gather and process satellite information, as well as its limitations considering the algorithms and calculations behind it was a challenging process that helped in the critical analysis and interpretation of the results in each step of the study.

The ET estimations in the Leiria Pine Forest show a significant decrease in the first year after the fire and a fast recovery leading almost to the pre-fire values in the third year after the fire. These results show that the decrease in ET is probably not the only factor increasing recharge in the study area since the simulations estimate an increase of 17% in recharge in the third year after the fire. Other factors such as higher precipitation and/or reduction of ET due to lower atmospheric demand could compensate land cover changes, increasing groundwater recharge (Hawtree et al., 2015). Since the Easybal simulations are mainly controlled by changes in ET and soil properties, an efficient way to enhance its estimations is the improvement in climate and soil property characteristics' data.

It is difficult to isolate the changes in rooting depth, SWR, runoff and climate factors and the interactions among themselves. Nevertheless, the geological background and topographical conditions seem to exert a decisive role in prevent increase runoff in the Leiria Pine Forest, which combined with decreasing ET and presence of preferential flow paths (macropores) could result in the increase in groundwater recharge in the Leiria Pine Forest region.

Although SWR has been reported by several studies as an important factor after the occurrence of wildfires, it does not seem to have a big influence in the study area regardless the severity of the fire. It could be related to the small persistence time of the water repellent layer due to climate conditions after the fire or even the presence of the macropores that favored infiltration in the area attenuating SWR effects.

Thus, predicting the hydrological impacts of wildfires in a watershed is a very complex process that requires a combined understanding of the consequences of land cover and soil properties changes, as well as climate variability (Hawtree et al., 2015). The recharge simulations consist of a simplification of the reality and have several uncertainties and limitations associated. The main limitations detected in the present study include: (1) Model simplifications do not account for SWR; (2) Poor estimation of soil properties based on the references that do not consider possible changes after the fire; (3) Accuracy in the satellite data used to estimate crop adjusted evapotranspiration, and (4) Difficulty in isolating wildfire and climatic variability effects.

Some recommendations in order to continue improve the knowledge brought up about the wildfires impacts on the Vieira de Leiria-Marinha Grande Aquifer by the present research are: (1) Deeper analysis of the meteorological conditions in the study area to better understand the role of climatic variability; (2) Installation of meteorological and groundwater monitoring networks to improve data availability and model calibrations; (3) Collection of monthly samples to gather Cl concentration data for future validation of recharge modelling estimations; and, (4) Investigate the potential impacts on groundwater quality in burnt and non-burnt forest area.

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