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Impact of wildfires on spatial and temporal evolution of groundwater recharge in an Atlantic pine forest: An integrated approach using field, remote sensing and modeling.

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ABSTRACT

Study region: Leiria Pine Forest (Portugal)
Study focus: Climate change, including higher temperatures, drier atmosphere and prolonged droughts, is increasing the risk, extent and impacts of wildfires in Southern Europe. This study investigates extreme wildfires impacts on groundwater recharge in the Leiria Pine Forest, integrating field and remote sensing data with modelling tools to simulate recharge in burnt and unburnt areas from 2001 to 2023.
New hydrological insights for the region:Results: show a decline in crop-adjusted potential evapotranspiration due to vegetation loss after the fire, resulting in increased recharge rates. Groundwater recharge increased from 20 % of annual precipitation pre-fire to over 40 % in the first-year post-fire in the burnt area, gradually stabilizing at around 30 % by 2023. This contrasts with the unburnt area, where recharge rates remained stable. This increase is influenced by geological and pedological characteristics, favorable topography which promotes low runoff and high infiltration rates, and specific climatic conditions. The low water-holding capacity of the sandy arenosols in the burnt area, promotes faster infiltration, increasing recharge. Contrary to other studies, soil water repellence seems to have limited influence in this area due to local climate and soil conditions. Predicting the consequences of wildfires in groundwater is complex process, nevertheless the application of multiple methodologies increases result reliability.

1. Introduction

Wildfire impacts on the lives of many people worldwide and cost billions of euros in direct and indirect damage, not only due to their environmental implications but also due to the social, cultural and economic losses they may cause (Turco et al., 2019). These events usually happen as a combination of several factors including CO_2-driven climate warming, drought, heat waves, land use management and human activities (Bladon et al., 2014; Calheiros et al., 2020; Santos et al., 2019; WMO, 2024). The increase in the number, frequency, intensity, severity and extent of wildfires have been reported in several regions around the world, reaching areas like Ireland, Finland and Latvia, where they rarely occurred in the past (Feyen et al., 2020; Libonati, 2024; San-Miguel-Ayanz et al.,

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The consequences of forest fires on the environment have been documented in several studies worldwide (Basso et al., 2022; Ferrer et al., 2021; Greenbaum et al., 2021; Havel et al., 2017; Hawtree et al., 2015; Loiselle et al., 2020; Neary et al., 2005; Paul et al., 2022; Pereira et al., 2021; Rhoades et al., 2019; Robinne et al., 2020; Rodríguez-Jiménez et al., 2024; Rust et al., 2019; Shakesby and Doerr, 2006; Smith et al., 2011; Taboada et al., 2021) and include the removal of the soil-protecting vegetation, ash deposition, changes in the physical properties of rocks and soil, and changes in water quantity and quality. These impacts also modify the rates of important hydrological processes such as evaporation, transpiration and interception (Nolan et al., 2015; Poon and Kinoshita, 2018).

Post-fire immediate and long-term reduction in evapotranspiration (ET) have been reported in several studies. According to Dore et al. (2010) in pine forests at the United States, post-fire evapotranspiration was lower for 10–11 years after occurrence of the fire. Ma et al. (2020) reported an average decrease in evapotranspiration of 36 % during the first year and 23 % over the first 15 years after fire, respectively, related to pre-fire values and in California's Sierra Nevada. Besides the effect directly related to the removal of the vegetation, the influence of fire severity in evapotranspiration behavior after wildfires has also been reported (Poon and Kinoshita, 2018; Atchley et al., 2018). Changes in land cover and fire severity can also alter soil infiltrability, increasing runoff. Paul et al. (2022) evaluated hydrologic characteristics changes after wildfire events in several papers and 66 % found that wildfires generally increased surface runoff, with a median increase of approximately 60 %. According to Moody et al. (2008), there are three possible reasons for this: (1) removal of porous and organic layers that acted like obstacles, increasing friction during runoff; (2) pore compaction and sealing due to raindrop splash, intensified by vegetation removal; and (3) the water repellency effect caused by heating.

The Mediterranean region is known for its high susceptibility to wildfires and according to data from the Portuguese Institute of Conservation of Nature and Forests (ICNF), the likelihood in Portugal of a wildfire burning an area greater than 1000 km^2 increased from 30 % to 61 % between 2000 and 2017, and this trend is expected to keep rising due to the increase in the number of extreme weather events reported in the country (Beighley and Hyde, 2018). Studies suggest that climate change plays an important role in the increasing wildfire occurrence and according to Calheiros et al. (2020), in the Iberian Peninsula, fire regimes and climate variability are deeply connected since high fire incidence is highly related to extreme weather events such as heatwaves and droughts, as well as to unusual atmospheric circulation and thermodynamic patterns.

Even though Portugal is one of the countries most affected by wildfires in Europe (Beighley and Hyde, 2018) the qualitative and quantitative impacts of these events on groundwater resources are still poorly evaluated. Understanding wildfire impacts is the best way to learn how to adapt to them, not only by preventing and controlling damages, but also by ensuring better management of

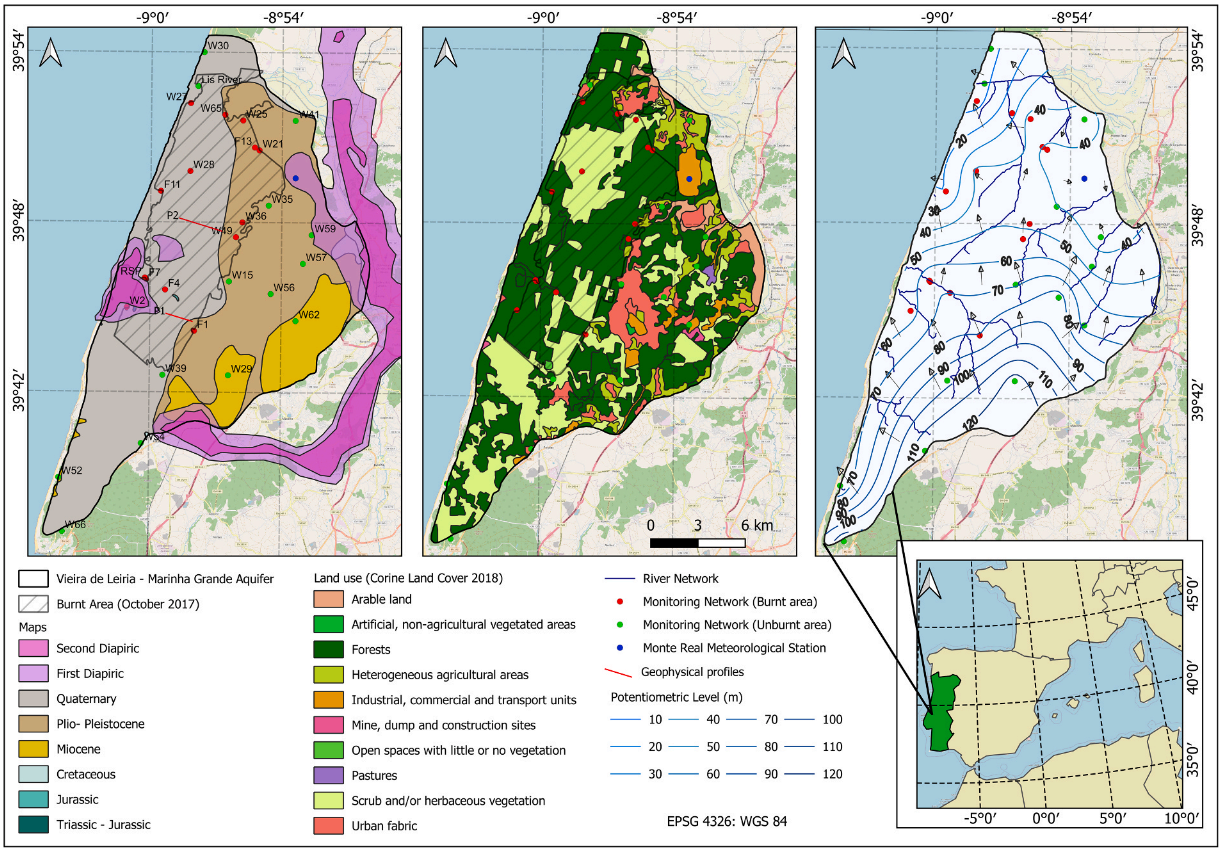

Fig. 1. (a) Geological map of the study area with the GPR profiles (P1 and P2); (b) Land use map; (c) Groundwater potentiometric surface map.

resources under stressful climate conditions (Hallema et al., 2017; Loiselle et al., 2020; Rhoades et al., 2019). The impact assessment of wildfire events is essential to understand the physical processes occurring in the watershed, but in many cases, technical difficulties such as the impossibility of predicting where wildfires occur, the lack of monitoring networks and challenging access in areas after wildfires make this task very complex. Remote sensing techniques have been frequently used (e.g., Silberstein et al., 2013; Ebel et al., 2016; Gemitzi et al., 2017; Yang et al., 2022; Hoeltgebaum and Dias, 2023) to overcome these limitations in investigating watershed responses to climate and land cover changes, disturbances and extreme weather events (Rodrigues et al., 2019).

The Leiria Pine Forest ('Pinhal de Leiria') is a unique Atlantic coastal forest and woodland with 11 080 ha planted more than 700 years ago to stabilize sand dunes offering significant environmental, economic, cultural, social and historical value to both the local area and the entire country (Arroteia, 2018; Morais, 1936; Silva and Batalha, 2011). The area of the pine forest almost coincides with the area of a porous multi-layer aquifer system (Marinha Grande – Vieira de Leiria aquifer) that locally guarantees the needs of water for public and industrial water supply and supports dune habitats and ecosystem services (Almeida et al., 2000). In October 2017, a heatwave triggered several wildfires across Portugal, including one in the Marinha Grande region that burned approximately 86 % of the Leiria Pine Forest in just two days (ICNF, 2017, 2019).

The starting hypothesis proposes that wildfires impact groundwater recharge by altering vegetation cover and soil properties. The main objective of this study is to investigate and evaluate how groundwater recharge in the Vieira de Leiria-Marinha Grande aquifer is affected by these events by integrating meteorological, hydrological, hydrogeological and remote sensing data into a Soil Water Balance model (Thornthwaite and Mather, 1955) to calculate and compare groundwater recharge evolution in the burnt and unburnt areas over time. Groundwater estimation results were analysed and compared across both pre-fire (2001–2017) and post-fire (2017–2023) periods, considering both burnt and unburnt areas.

2. Study area

The study area is a gently sloping coastal plain of about 320 km^2 located in the Centre of Portugal (western Iberian Peninsula) and extends between the 39º37'N and 40º55'N latitude parallels and is bounded to the west by the Atlantic Ocean and to the east by the 8º50'W longitude meridian (Fig. 1). The climate in the area is classified as Warm summer Mediterranean (Csb), according to the Koppen-Geiger climate classification (Kottek et al., 2006). According to the database from the Monte Real meteorological station, the average annual temperature and precipitation for the period from 2001 to 2023 are 15°C and 750 mm, respectively. Precipitation has large interannual variability, ranging from 285 mm in a very dry year to 1100 mm in a wet year. The topographic gradient is relatively low and the altitudes range between sea level on the coast and a maximum of 170 m above sea level in the southeast. Nevertheless, the

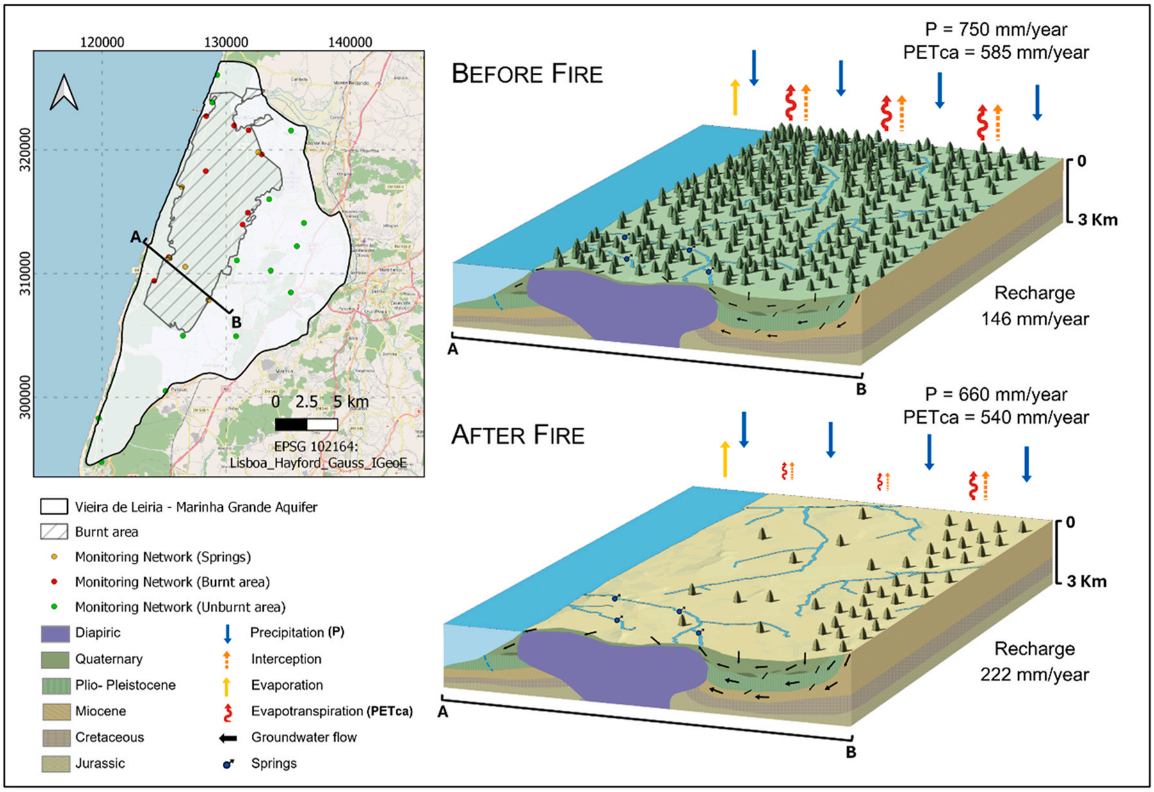

Fig. 2. Conceptual Model of the aquifer before and after the fire.

presence of an extensive coastal dune system causes local abrupt topographic differences that may interfere in the hydrological conditions of the unconfined aquifer. Data from the Corinne Land Cover Project in 2017 (Copernicus Land Monitoring Service, 2018) just before the wildfire shows that more than 70 % of the study area is covered by forests, non-agricultural vegetated areas, shrubs, herbaceous vegetation and pastures, with approximately 30 % of that comprising the historic Leiria pine forest (Fig. 1).

The study area is located within the Lis River basin (Almeida et al., 1999). The region's rivers and streams predominantly follow a NE-SW orientation, though some rivers also run E-W, reflecting the primary geological fault directions. The geology of Lis River basin is composed primarily of sandstones, gravel, limestones and mudstones (Antunes, 2001). The main river in the area is the Lis River, along with its tributaries. The source of the river is at Fontes (Leiria District) at an altitude of approximately 120 m in a limestone-rich region, highly sensitive to seasonal variations in flow (Lacasta et al., 2016; Ribeiro et al., 2012). The river flows southwestward for roughly 40 km before discharging into the Atlantic Ocean at Vieira de Leiria. To manage seasonal variability, several weirs have been constructed along the river to help stabilize upstream water levels. In addition to the Lis River, another important surface water body in the region is the Ribeira de São Pedro de Moel, a 6 km stream located centrally within the study area. This stream is particularly relevant as it is the only permanent river in the Leiria Pine Forest area, where most of its tributaries tend to dry up during the summer months. Its perennial nature plays an essential role in the local hydrology.

The Vieira de Leiria-Marinha Grande aquifer is a porous multi-layer aquifer system with about 320 km^2 consisting mainly of Pleistocene, Pliocene and Miocene sands, overlaying Lower Cretaceous sandstones (Almeida et al., 1999, 2000; Dias et al., 2013; Kullberg et al., 2006; Kullberg, 2000; Kullberg et al., 2013; Zbyszewski, 1965; Zbyszewski and Torre de Assunção, 1965). The shallow portion of the aquifer is composed of the Quaternary sand dunes and Pliocene sandstones that have hydraulic conductivities ranging from 10 to 30 m day^{-1} (Almeida et al., 2000; Kullberg et al., 2013; Miguens, 2008; Zbyszewski, 1965). The regional groundwater flow direction in the aquifer is mainly from SE-NW towards the coastline, turning to SW-NE in some parts, and although the main discharge occurs along the western border of the aquifer to the Atlantic Ocean, local discharge zones mainly related to the presence of the Lis River and others smaller streams are verified in the field by the presence of several springs (Almeida et al., 2000). The presence of diapiric structures may influence not only the groundwater flow, but also groundwater quality in the region (Calvín et al., 2023; Casacão et al., 2023; Davison and Barreto, 2019; Dias, 2017; Kullberg et al., 2013; Zbyszewski and Torre de Assunção, 1965) Fig. 2

A hydrogeological conceptual model of the study aquifer was developed to better illustrate the geological and hydrogeological set up, improving the understanding of the main processes of the hydrological cycle affected by the wildfire. Several data sources were used including: digital elevation model, land cover and soil maps (Copernicus Land Monitoring Service, 2018; Infosolo, 2020), geological and hydrogeological data (Lacasta et al., 2016; lLNEG, 2020; Ribeiro et al., 2012; Zbyszewski, 1965; Zbyszewski and Torre de Assunção, 1965), river network (SNIRH, 2024), bibliographic references (Arroteia, 2018; Calvín et al., 2023; Dias et al., 2020; ICNF, 2019; Johnson, 1967; Kullberg et al., 2013; Marques, 2010; Morais, 1936), and fieldwork data such as Ground Penetrating Radar

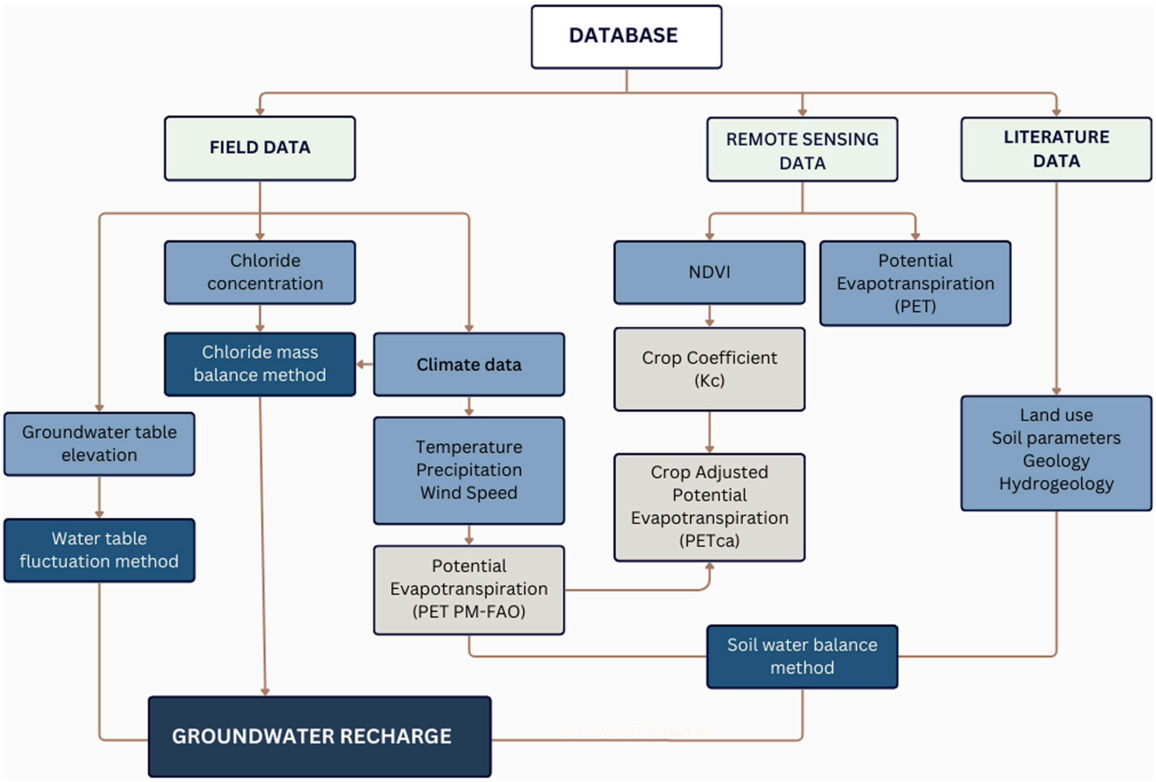

Fig. 3. Flowchart illustrating the data used and the steps for each method groundwater recharge estimation.

(GPR) logs and groundwater level measurements (Fig. 1). The GPR investigations revealed that the water level is situated approximately 2 m below the surface, with depths of up to 10 m in certain areas following the local topographic gradient imposed by the dune system. Although the region is predominantly composed of sand dunes, interstratified clay layers have been identified in well logs, which can decrease the infiltration rate in localized regions (Zbyszewski and Torre de Assunção, 1965). The most relevant hydrological processes occurring in the area are precipitation (especially from October to May), evapotranspiration and interception, both connected to the characteristics of the vegetation and extremely influenced by the occurrence of the wildfire.

The forest known as Pinhal de Leiria covers approximately 40 % of the study area and consists of a maritime pine tree forest from the 13th century initially planted to stop the degradation of the nearby dune system. This forest has been crucial to the region's development, offering significant environmental, economic, cultural, social and historical value to both the local area and the entire country (Arroteia, 2018). The first reports of wildfires in the region are from 1806 (Silva and Batalha, 2011) and since then, several others have been reported throughout history. The most destructive ones registered in the last couple of decades happened in 2003 and 2017, changing completely its land cover characteristics.

In October 2017, following a prolonged dry summer with extreme temperatures, a devastating fire burned about 86 % (9.5 ha) of the Leiria Pine Forest (ICNF, 2019). Before the wildfire, vegetation in the area was composed essentially by maritime pine trees, with an average root depth of about four meters (Appelo and Postma, 2005). Post-fire the vegetation that was completely burnt started gradually to grow, but instead of the original pine trees, it was rapidly replaced by bushes and shrubs with an estimated average root depth of about half a meter. This change in the type of vegetation and root depth affects the hydrological regime, by altering the evapotranspiration and interception processes, as well as the soil properties, such as the water-repellency and the formation of macropores, leading to shifts in infiltration and runoff rates that affect groundwater recharge (Luo et al., 2020; Nyman et al., 2014; Rasouli et al., 2019; Salgado et al., 2024).

3. Materials and methods

3.1. Database

A GIS database was built integrating information on soil (Infosolo, 2020), land use (Copernicus Land Monitoring Service, 2018), geology and hydrogeology (lLNEG, 2020; SNIRH, 2024), climate data from local meteorological station (Monte Real) and remote sensing data from MODIS satellite (normalized difference vegetation index and evapotranspiration) (MODIS, 2019). Fig. 3 illustrates the steps methodology steps followed in the study.

3.1.1. Climate data

The daily observational dataset for the climate variables (minimum temperature, maximum temperature, precipitation and wind speed) from 2001 to 2023 used in this study was obtained from the Monte Real meteorological station located in the Monte Real air base from the Portuguese Air Force (Fig. 1).

3.1.2. Potential Evapotranspiration (PET) and Evapotranspiration (ET)

Potential evapotranspiration (PET) and evapotranspiration (ET) values were taken from the MODIS database (MOD16A2GF.006 Terra Net Evapotranspiration products) with an interval of 8 days and a resolution of 500 m for the period of 2001–2023 for the burnt and unburnt areas in Leiria Pine Forest (Running et al., 2019). These data were compared to the PET values calculated using the PM-FAO method (Allen et al., 1998), recognized as the standard methodology to calculate PET.

3.1.3. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) can be defined as a measure of surface reflectance used to perform analysis of vegetation characteristics using remote sensing data (Carlson and Ripley, 1997; Nunes et al., 2016), and it has been widely applied to monitor vegetation density, health, and growth, as well as to monitor droughts and predict wildfires risk zones. This index returns values ranging from −1–1 that represent different kinds of land cover. The NDVI index from the MODIS satellite (MOD13Q1.006 Terra MODIS Vegetation products) (Didan and Huete, 2015) with a spatial resolution of 250 m and an interval of 16 days was used to estimate the crop coefficient in the study area. The use of remote sensing data was chosen to overcome the absence of spatial and temporal distributed monitoring data in the area.

3.1.4. Groundwater table elevation

Groundwater level and chemical data (pH, electrical conductivity, temperature and Oxidation-Reduction potential (ORP)) were monthly collected in 22 wells and 5 springs from March 2022 to September 2023, with the aim of assessing the aquifer's hydrological response to precipitation events. Additionally, a geophysical investigation using ground-penetrating radar (GPR) was conducted to estimate groundwater level depths along two transects oriented in the NW-SE direction. These profiles were selected to cover areas lacking groundwater monitoring points (Fig. 1).

3.2. Remote sensing data processing and interpretation

3.2.1. Crop Coefficient (K_c)

Crop coefficient (K_c) values reflect the combined influence of various factors that can affect plants, including crop characteristics, plant height, growth rate, leaf area index, planting date, canopy cover extent, canopy resistance, as well as soil, climate conditions, and management practices (Pokorny, 2019). While K_c values are typically determined experimentally, vegetation indices like NDVI, obtained from satellites, may be used to estimate parameters related to vegetation phenology, allowing for the monitoring of K_c variations over time and space (Duchemin et al., 2006). In this study, K_c was estimated using satellite-derived NDVI values based on Duchemin et al. (2006) methodology, which has been widely applied in the literature for several crop species (Campos et al., 2010; Ferrara et al., 2010; Nunes et al., 2016; Van Der Slik, 2014; Vuolo et al., 2008).

$$K_c = \alpha(NDVI - NDVI_{\min}) \quad \text{(Eq. 1)}$$

where K_c is the crop coefficient, α is the angular coefficient of the adjusted line, NDVI is the normalized differential vegetation index values and $NDVI_{min}$ is the NDVI for K_c= 0.

The relation between NDVI and K_c 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, considering that the K_c values would only be used if the rainfall and ET deficit were both lower than the thresholds established based on the maximization of the correlation between NDVI and K_c. The FAO Irrigation and Drainage Paper nº56 (Allen et al., 1998) establish that the K_c values should not be lower than 0.3 which is the value that represents bare soil with occasional precipitation, therefore for pine forests with NDVI below 0.5 the K_c will remain constant at 0.3. By plotting the NDVI against the K_c values and using linear regression, equations relating these parameters will be adjusted and applied to the NDVI series from before and after the fire taken from MODIS to generate a temporal series of K_c.

3.2.2. Reference Evapotranspiration – PM-FAO Method (ET_0)

Precise estimations of evapotranspiration (ET) 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).

The reference evapotranspiration (ET_0) was estimated using the Penman-Monteith method (PM-FAO) (Allen et al., 1998) using data from 2001 to 2023 taken from the meteorological station of Monte Real, located in the study area.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \frac{900}{T}\gamma u_2 \delta_e}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{(Eq. 2)}$$

where, Δ is the rate of change of saturation specific humidity with air temperature (Pa K^{-1}); R_n is the net irradiance (MJ m^{-2} day^{-1}); T is the air temperature at 2 m (K); G is the ground heat flux (MJ m^{-2} day^{-1}); u_2 is the wind speed at 2 m height (m s^{-1}); δe = vapor pressure deficit (kPa) and γ is the psychometric constant (γ ≈ 66 Pa K^{-1}).

3.2.3. Crop Adjusted PET (PET_{CA})

The values of Crop Coefficient (K_c) and ET_0 were used to obtain the crop adjusted potential evapotranspiration (PET_{CA}) for the burnt and unburnt areas (Allen et al., 1998). The PET_{CA} consists of an adjustment of the PET considering the vegetation in the study area and is calculated according to Eq. 3.

$$PET_{CA} = ET_0 \cdot K_c \quad \text{(Eq. 3)}$$

where K_c is the crop coefficient, ET_0 (mm·$year^{-1}$) is the potential evapotranspiration calculated using the PM-FAO method (Allen et al., 1998), and PET_{CA} (mm·$year^{-1}$) is the crop adjusted evapotranspiration in the area.

The results calculated using the PM-FAO method were compared to the data from MODIS satellite in order to evaluate the accuracy and the limitations of remote sensing data. 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 500 m for the period of 2001–2020 for the burnt and unburnt areas in Leiria Pine Forest (Running et al., 2019).

3.3. Soil water balance and recharge simulations

3.3.1. Soil Water Balance

The groundwater recharge simulations were conducted for the burnt and unburnt areas of the Leiria Pine Forest using a spatially distributed version of the Soil Water Balance model (Eq. 4) (Thornthwaite and Mather, 1955) for the period of 2001–2023 and the interpretation was divided into two periods: before and after the forest fire occurred in October 2017.

$$R = P - AET - Rn + \Delta S \quad \text{(Eq. 4)}$$

where R = groundwater recharge (mm $year^{-1}$); P = precipitation (mm $year^{-1}$); AET = actual evapotranspiration (mm $year^{-1}$); Rn = runoff (mm $year^{-1}$) and ΔS = change in soil water storage (mm $year^{-1}$).

The model consists of a discretization of the Soil Water Balance equation into a Python framework called PCRaster based on the approach defined by Karssenberg et al. (2010), where the equations are parameterized by functions of the spatial datasets. The main datasets consist of: climate data (temperature and precipitation) from the Monte Real meteorological station, PET_{CA} calculated using the NDVI index, land use data and soil classifications, soil property data (field capacity, initial humidity, permanent wilting point, rootzone, soil depth, runoff threshold) and the digital elevation map (DEM).

The flowing calculations are performed for each cell of the model to simulate water movement through the system. Precipitation enters the system as the primary water input and interacts with vegetation canopy through the interception module, that simulates the capacity of the vegetation to hold water. Precipitation exceeding this capacity is given by effective precipitation, while the water lost to the canopy is represented by the canopy evapotranspiration. The runoff module calculates and removes excess precipitation as surface runoff, while water that infiltrates the soil is divided between soil evapotranspiration and storage (Fig. 4).

The field capacity, wilting point and soil depth values are an average of the experimental results available on the Infosolo database from Marques (2010). The root zone parameter (Rz) represents the depth of the root zone of trees and depends on factors such as tree species, age, climate, soil type, and the presence of preferential pathways or obstacles (Andivia et al., 2019). Since the Leiria pine forest is predominantly composed of pine trees, this species was used in estimating the Rz. The estimation was based on the relationship between chloride concentrations in the unsaturated zone and root depth, as described by (Appelo and Postma, 2005). In the Leiria Pine Forest, the Rz was assumed to be 4 m before the fire, reflecting the established pine-dominated vegetation. After the fire, as new, more shrubby vegetation began to emerge, the Rz was reduced to 0.5 m.

The runoff threshold refers to the overland flow from precipitation and will be highly dependent on its intensity. In practical terms, precipitation that exceeds a given threshold is assigned as runoff by the model, while values below the threshold represent water infiltrating the soil. This parameter was estimated based on the geological and geomorphologic characteristics of the study area, considering that 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. This approach is a simplification of the runoff process, since it accounts only for the infiltration-excess mechanism of runoff generation, neglecting the saturation-excess mechanism, which may lead to the underestimation of runoff in areas prone to saturation-excess overland flow, especially due to the poor assessment of the antecedent soil moisture conditions. Nevertheless, considering the previously mentioned characteristics of the study area, the spatial resolution and the temporal scale of the simulations, the model simulations provide an effective representation of the processes observed in the field.

The total recharge in the aquifer was calculated by doing the weighted average considering the total areas of the burnt and unburnt areas (Eq. 5).

$$R_{aquifer} = \frac{[(A_{Burnt} \times R_{Burnt}) + (A_{Unburnt} \times R_{Unburnt})]}{A_{Total}} \tag{Eq. 5}$$

where, $R_{aquifer}$ = total groundwater recharge (mm year^{-1}); A_{burnt} = area of the burnt area (km^2); R_{burnt} = groundwater recharge in the burnt area (mm year^{-1}); $A_{unburnt}$ = area of the unburnt area (km^2); $R_{unburnt}$ = groundwater recharge in the unburnt area (mm year^{-1}); A_{total} = total area of the aquifer (km^2).

3.3.2. Water Table Fluctuation

The Water Table Fluctuation method is a technique developed by (Healy and Cook, 2002) for estimating groundwater recharge.

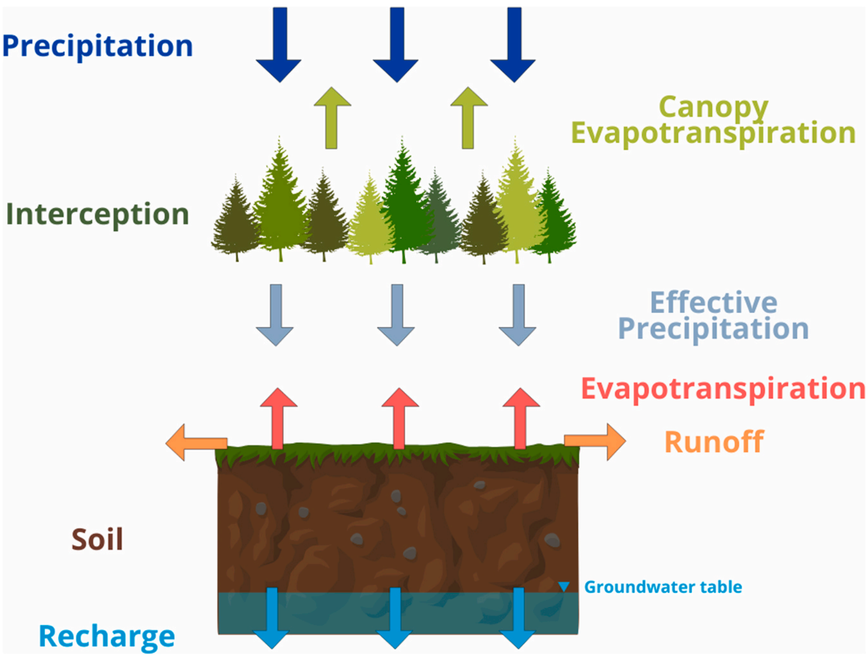

Fig. 4. Conceptual design of the recharge model applied (Adapted from Cantarella, 2022).

This methodology has become a widely used in several studies (*e.g.,* Addisie, 2022; Crosbie et al., 2005; Delin et al., 2007; Delottier et al., 2018; Gorantla et al., 2020; Gumuła-Kawęcka et al., 2022; Hung Vu and Merkel, 2019; Maréchal et al., 2006; Nimmo et al., 2014; Obuobie et al., 2012; Tashie et al., 2016; Yang et al., 2018; Yin et al., 2011; Zhang et al., 2020) and is based on the assumption that in unconfined aquifers, rises in groundwater levels are caused by recharge arriving at the water table. The Water Table Fluctuation method (Healy and Cook, 2002) was applied using the measures of the changes in the water table over the period from October 2022 to September 2023 in 22 wells distributed among the burnt and unburnt areas. The specific yield (Sy) was estimated using the values available in the literature (Gorantla et al., 2020; Johnson, 1967; Marques, 2010; Morris and Johnson, 1967) and validated through experiments conducted in the laboratory using reconstructed soil samples. By comparing water table elevations at the beginning and end of the hydrological year, it was possible to estimate groundwater recharge in the aquifer using Eq. 6 (Healy and Cook, 2002).

$$RWTF_{aquifer} = S_y\left(\frac{\Delta h}{\Delta t}\right) \quad \text{(Eq. 6)}$$

where $RWTF_{aquifer}$ = groundwater recharge (mm year^{-1}), S_y = specific yield (%), Δh = hydraulic head variation (mm) and Δt = time interval (year).

3.3.3. Chloride Mass Balance

The Chloride Mass Balance is based on the principle that chloride is a conservative tracer, meaning it does not react chemically with other components of the natural system. So, groundwater recharge was calculated using chloride concentrations from 52 groundwater samples distributed between the burnt and unburnt areas and 19 rain samples collected between March 2022 and September 2023 using the equation from Allison and Hughes (1978) (Eq. 7).

$$RCl_{aquifer} = P\cdot\left(\frac{Cl_{rain}}{Cl_{groundwater}}\right) \quad \text{(Eq. 7)}$$

where $RCl_{aquifer}$ is groundwater recharge (mm year^{-1}), P is precipitation (mm year^{-1}), Cl_{rain} is the chloride concentration in precipitation (mg L^{-1}), and $Cl_{groundwater}$ is the chloride concentration in groundwater (mg L^{-1}).

4. Results

4.1. Estimation of the Crop Coefficient (Kc)

In the pre-fire period dataset (October-2001 to September-2017), the NDVI values for the region affected by the October 2017 fire (burnt area) exhibited values slightly higher (0.50–0.75) than the unburnt area (0.47 – 0.72) (Fig. 5). This disparity can be attributed to the fact that, despite the unburnt area being roughly twice the size of the burnt one, the land cover within the burnt area predominantly consisted of pine forest, while the unburnt area encompassed a more varied land cover distribution, including urban areas, industrial facilities, agricultural lands, pastures, and shrubbery (Fig. 1). These diverse compositions regarding the land cover type results in a lower overall average of the NDVI index.

Abrupt declines in NDVI indicate alterations in vegetation composition associated with the depletion of biomass and a decrease in foliage following a wildfire event. This phenomenon is observable within the burnt area, where the NDVI values decrease more than 50 % when compared to the average from the precious years. The unburnt area demonstrates NDVI trends consistent with those observed in preceding years. A similar trend, marked by the reduction of the NDVI in the burnt area, can be observed in August-2003, related to a wildfire of smaller proportion hit the area burning about 25 % of the forest. The crop coefficient for the years before the fire

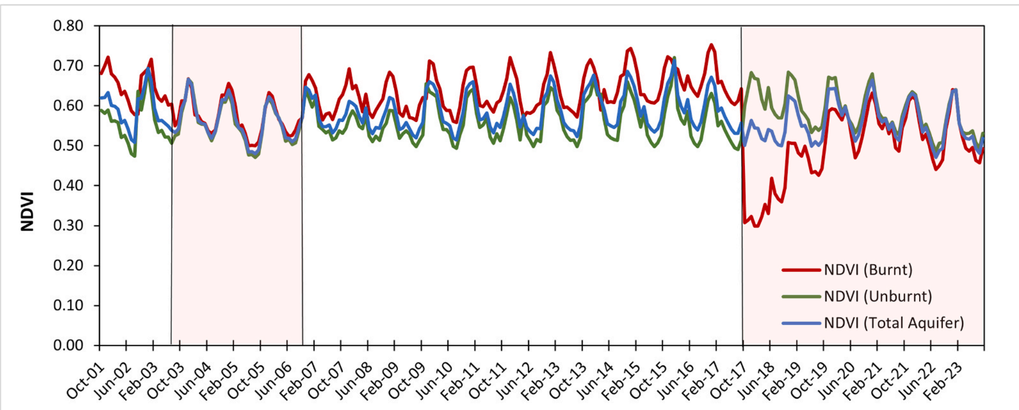

Fig. 5. NDVI indices for the burnt, unburnt and total areas of the Leiria Pine forest from October 2001 to September 2023. The pink rectangles indicate the post-fire periods in August 2003 and October 2017.

occurred in October 2017, the second and third years after the fire and after 4 years following it were estimated using the correlation shown in Eqs. 8 to 10 (Fig. 6) according to the methodology described by (Duchemin et al., 2006).

$$Kc_{(pre-fire)} = 1.8841(NDVI - 0.6067) \tag{Eq. 8}$$

$$Kc_{(post-fire2nd\ and3rd\ years)} = 2.1775(NDVI - 0.6067) \tag{Eq. 9}$$

$$Kc_{(post-fire4+years)} = 1.9062(NDVI - 0.584) \tag{Eq. 10}$$

The pre-fire Kc values exhibit a range of 0.27–0.86, with the lower and higher values consistently observed during the months of July and August and December and January, respectively. This pattern aligns with the observed trends in NDVI and precipitation. Allen et al. (1998) have established a robust correlation between Kc and soil moisture content, which serves as a limiting factor for evapotranspiration, explaining the decrease in K_c during drier months (July-August) and the subsequent increase during wetter months (December-January).

The same methodology was applied to the post-fire years, and while the correlations observed before the fire (0.60), in the second and third years after the fire (0.47) and over four years after the fire (0.72) are statistically significant, no discernible relationship between NDVI and Kc exists in the first year following the fire. This absence of correlation is likely attributed to the absence/very low amount of vegetation. During this period, when vegetation is inactive, evapotranspiration is predominantly controlled by soil evaporation, consequently, the only controlling factor for water evaporation in this case is the soil moisture content. Accordingly, crop coefficients of 0.6 and 0.3 were adopted for wet and dry months, respectively, following the methodology proposed by Allen et al. (1998).

During the second and third years after the wildfire, the vegetation in many areas primarily consisted of invasive species, manifesting as bushes and shrubs. The relationship between NDVI and Kc in this period (Eq. 9) resembles the equation described by Campos et al. (2010) for vineyards, which supports the hypothesis that the prevailing vegetation type is characterized by smaller stature and a more shrub-like.

Four years following the wildfire, the observed relationship between the NDVI and Kc becomes very similar to the pre-fire relationship, reflecting the vegetation recovery process within the area (Fig. 6). This phenomenon occurs due to the gradual recovery and re-forestation post-fire, leading to an increase in NDVI values as vegetation coverage improves.

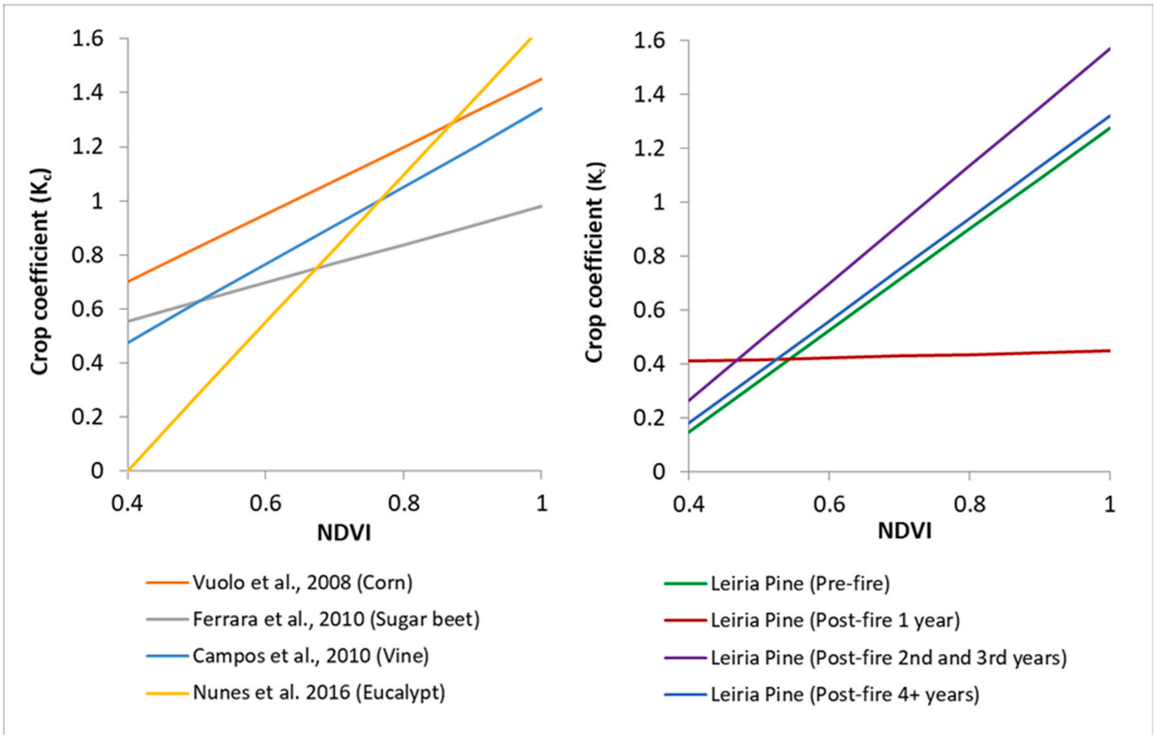

Fig. 6. Relation between crop coefficient and NDVI indices taken from the literature for several crop species and the values for the Leiria Pine forest before and after the fire.

4.2. Reference Evapotranspiration (ET_0) – PM-FAO Method

The results calculated using the PM-FAO method (Allen et al., 1998) in the pre-fire period dataset, range from 32 to 206 mm/month with an average of 120 mm/month, and between 39 and 200 mm/month with an average of 116 mm/month, in the post-fire period. The higher values are observed during the summer months when the temperature is higher (July and August) and the lower ones during the winter (December and January).

Although the PET estimated using the PM-FAO method (PET PM-FAO) and PET MODIS yield similar values during winter months, as temperature rises, the PET-MODIS results surpass those obtained through PM-FAO method up to 45 % (Fig. 7). The PM-FAO results were compared to PET extracted from the MODIS (PET MODIS) satellite and presented a strong correlation for the complete time series and it does not present significant changes when evaluated separately for pre- and post-fire periods ($r^2 \cong 0.95$) (Fig. 8).

4.3. Crop Adjusted Potential Evapotranspiration (PET_{CA})

Comparative analysis of the PET_{CA} values between the unburnt area and the burnt area present a high correlation ($r^2 \cong 0.82$) in the pre-fire period, which is drastically reduced in the post-fire period ($r^2 \cong 0.48$) (Fig. 9). Nevertheless, during the pos-fire period a sharp reduction in PET_{CA} for the burnt area can be observed and is aligned with expectations due to the considerable loss of vegetation (Fig. 10).

Approximately two years after the fire, PET_{CA} values in the burnt area begin to approach those of the unburnt area, though they do not fully return to pre-fire levels. The slow recovery of PET_{CA} values suggests a gradual regrowth of vegetation in the impacted zone. However, while the increase in PET_{CA} indicates some recovery of vegetation cover, it may be due to the spread of different species rather than the restoration of the original pine forest.

4.4. Groundwater recharge estimation

4.4.1. Soil Water Balance

The annual recharge rates within the unburnt area over the pre-wildfire period (2001–2017) were calculated at 132 mm/year, contrasting with a higher mean recharge rate of 146 mm/year within the burnt area, respectively corresponding to approximately 18 % and 19 % of the average total precipitation of 750 mm/year recorded in the Monte Real meteorological station.

Although there is a strong correlation between groundwater recharge in the burnt and unburnt areas during pre-fire period (Fig. 11), the data indicates that recharge patterns slightly differ between them, regardless of wildfire occurrence (Fig. 12). Before the fire, yearly groundwater recharge in the burnt area exceeded that of the unburnt area by approximately 5 %, increasing to about 15 % in the post-fire period. This phenomenon can be attributed to the distribution of land use within these areas. While the burnt area predominantly comprises forested land, the unburnt area exhibits a more diverse land cover with a higher degree of land impermeability, leading to greater variability in infiltration and a decrease in groundwater recharge rates (Fig. 12).

In the post-fire period from 2017 to 2023, the recharge rate in the unburnt area decreased to 111 mm/year, which represents approximately 17 % of the average total precipitation (661 mm/year). This indicates a minimal impact of the wildfire on recharge dynamics in this portion of the aquifer, as compared to the pre-fire period. In contrast, the burnt area experienced a significant increase in groundwater recharge, averaging 222 mm/year over the six years following the fire, accounting for about 34 % of total precipitation. This reflects a notable 15 % increase in recharge compared to pre-fire values (Fig. 13).

Groundwater recharge in the unburnt area remained relatively stable and unaffected by the wildfire, while the burnt area exhibited consistently higher post-fire recharge rates, ranging between 10 % and 25 % greater than those in the unburnt region during the same years. Focusing on the hydrological year of 2022 (October 2022 to September 2023), recharge in the unburnt area reached 162 mm,

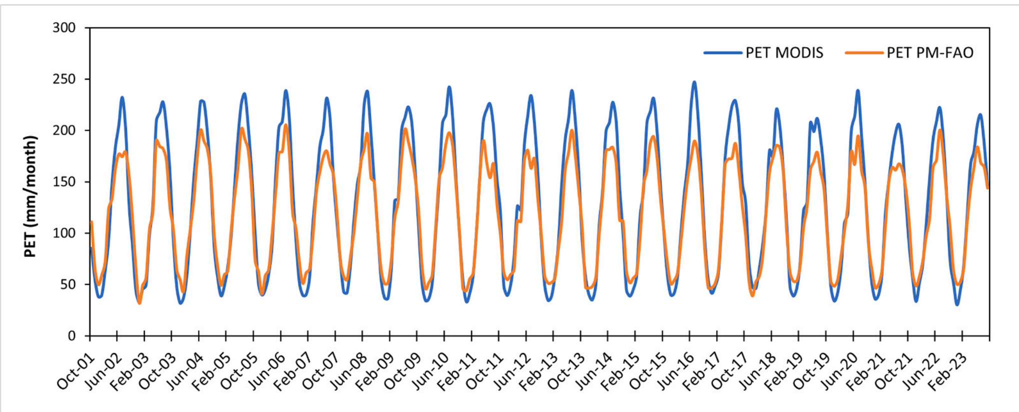

Fig. 7. PET calculated using the PM-FAO method (Allen et al., 1998) and PET extracted from MODIS satellite (Running et al., 2019) for the period from October 2001 to September 2023 in the Leiria Pine Forest.

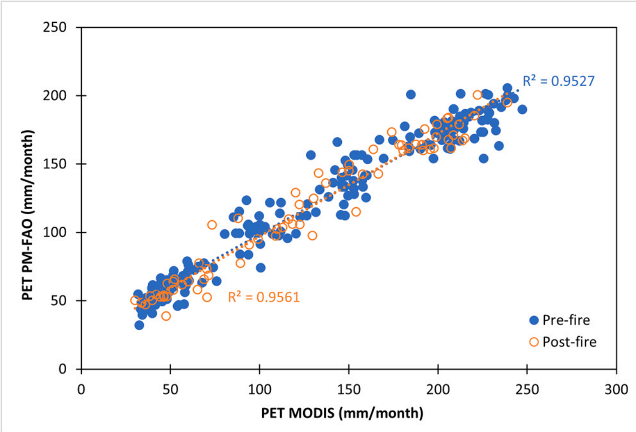

Fig. 8. Correlation between the PET from MODIS satellite (PET MODIS) and PET estimated using the PM-FAO method (PET PM-FAO) for the for the pre- fire period (October 2001 to September 2017) and post-fire period (October 2017 to September 2023).

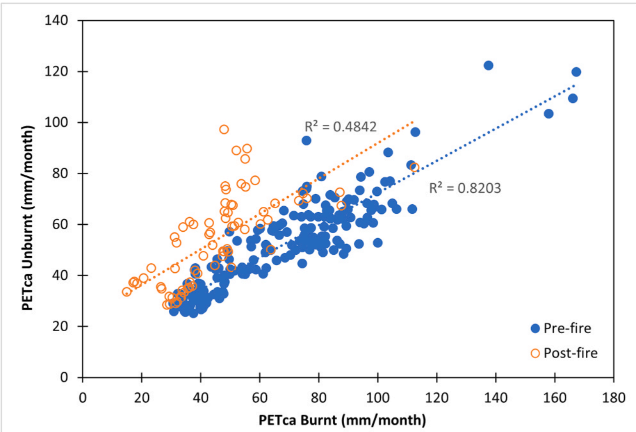

Fig. 9. Correlation between the PET_{CA} estimated using data from MODIS satellite (PET MODIS) and PET_{CA} estimated using the PM-FAO method (PET PM-FAO) for the for the pre- fire period (October 2001 to September 2017) and post-fire period (October 2017 to September 2023).

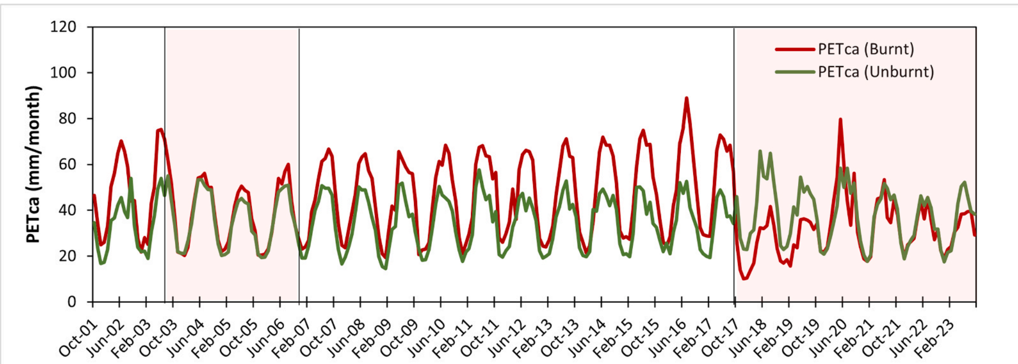

Fig. 10. Crop adjusted potential evapotranspiration (PET_{CA}) for the burnt and unburnt areas of the Leiria Pine Forest from October 2001 to September 2023. The pink rectangles indicate the post-fire periods in August 2003 and October 2017.

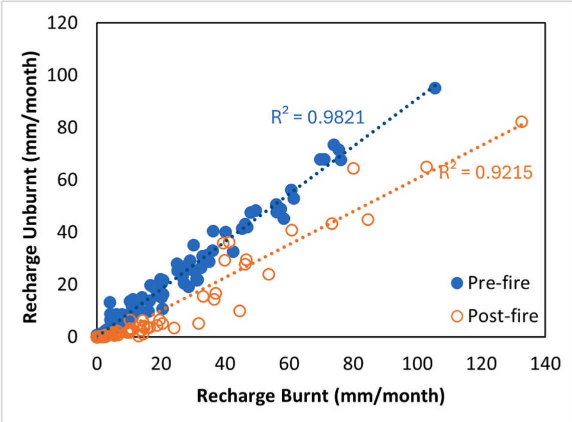

Fig. 11. Correlation between the groundwater recharge estimates for the for the pre- fire period (October 2001 to September 2017) and post-fire period (October 2017 to September2023).

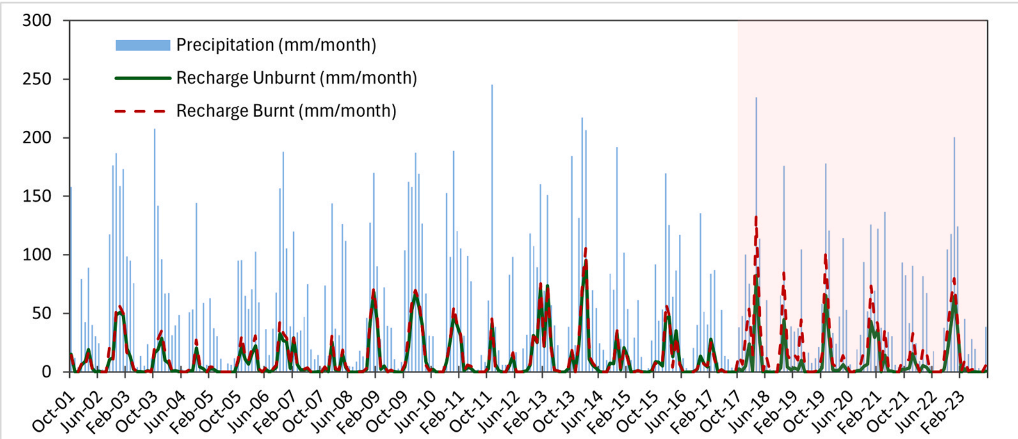

Fig. 12. Average groundwater recharge in the burnt and unburnt areas of the Vieira de Leiria-Marinha Grande Aquifer (the period after the fire is represented inside the pink rectangle).

equivalent to 23 % of the total precipitation (661 mm). In the burnt area, recharge was significantly higher at 239 mm, corresponding to 34 % of precipitation during the same period.

4.4.2. Water Level Fluctuation method

In the hydrological year of 2022, groundwater recharge estimates derived using the Water Table Fluctuation yielded values of 168 mm for the unburnt area and 177 mm for the burnt area. These recharge values correspond to approximately 25 % of the total annual precipitation. Water Table Fluctuation in the monitored wells over the analyzed period is shown in Fig. 14.

The estimated recharge using this method is directly influenced by the specific yield values, which according to the literature (Gorantla et al., 2020; Johnson, 1967; Morris and Johnson, 1967) ranged from 0.11 to 0.27 based on the geological and soil characteristics of the monitored locations. These specific yield values are consistent with those observed in the field and reported for regional soil and geological conditions in the study area by Marques (2010). To increase accuracy, these values were validated through laboratory experiments, which produced a narrower range of 0.10–0.21, reflecting the heterogeneous nature of the subsurface environment.

4.4.3. Chloride Mass Balance

The chloride concentration in precipitation for the hydrological year of 2022 was measured at an average of 4.77 mg/L, based on monthly sampling. Chloride concentrations in groundwater in the burnt and unburnt areas showed average concentrations of 31.15 mg/L and 32.80 mg/L, respectively. To ensure accuracy and avoid anomalies resulting from outlier events, extreme values above the 90th percentile were excluded from the analysis. Groundwater recharge estimates using the Chloride Mass Balance were calculated at 161 mm for the unburnt area and 169 mm for the burnt area, representing approximately 24 % of the total annual precipitation. These estimates align closely with those derived from the Water Table Fluctuation method, which were discussed in

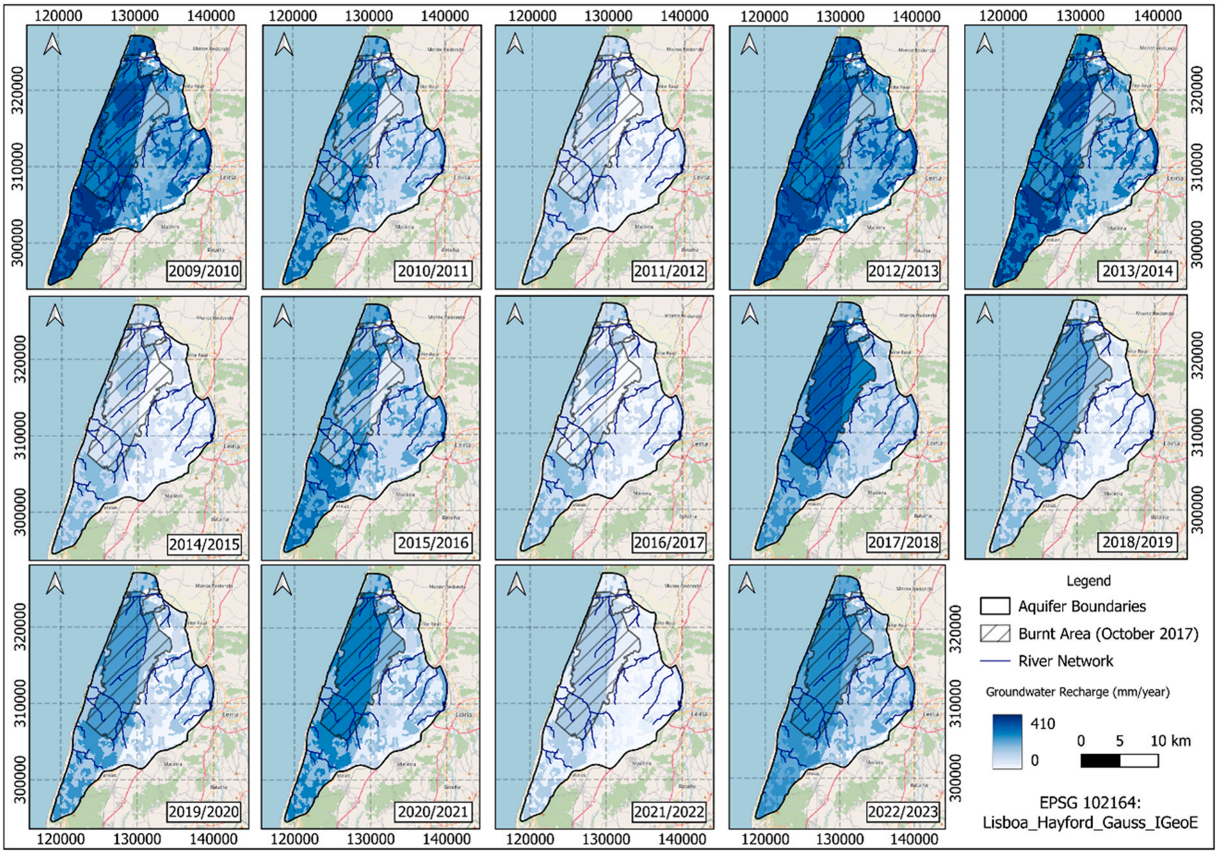

Fig. 13. Distribution of spatiotemporal groundwater recharge. The burnt area is limited by the dashed polygon.

Section 4.4.2.

5. Discussion

5.1. Remote Sensing data application

The utilization of NDVI data derived from satellite images to monitor temporal changes in vegetation characteristics has been extensively documented in the literature (Davis et al., 2023; Gandhi et al., 2015; Qiu et al., 2024; Yoo et al., 2024; Zhang et al., 2013). In the Leiria Pine Forest, the contrast in NDVI values observed after the wildfire very pronounced, showing the significant impact of fire on vegetation health and density. Nonetheless, even within the pre-fire dataset, differences in land use characteristics are highlighted by differences in NDVI. While the burnt area was nearly entirely covered by forest vegetation, predominantly consisting of pine trees, the unburnt area included impermeable surfaces such as urban developments, resulting in lower NDVI values compared to the burnt area. These observations underscore the complexity of using NDVI as a proxy for vegetation dynamics and emphasize the necessity of considering local land use characteristics and their effects on NDVI values.

The MOD16 algorithm is a remote sensing-based adaptation of the Penman-Monteith equation, which is subject to two primary limitations, the estimation of: (1) stomatal conductance; and, (2) soil evaporation (Ruhoff et al., 2011). The satellite estimations are not made directly, instead, the algorithm employs other remote sensing products such as land surface temperature, vegetation indices, and leaf area index. These parameters may present inconsistencies related to spatial and temporal resolutions, influencing the quality of the input data and consequently, the accuracy of the results (Running et al., 2019).

Benali et al. (2012) reported low accuracy of the MODIS satellite data in the coastal stations. The authors suggest that this observation could be attributed to spatial variations in relative humidity influenced by thermal inertia, that may impact the energy available for sensible heating at the surface. According to their findings, during summer, the position of the Azores anticyclone allows mesoscale circulations to dominate the surface airflow, favoring sea breezes and facilitating advection of moist air masses from the sea to the land, which leads to increased fog occurrences during summer in the central region of the West Portuguese coast, where the Leiria Pine Forest is located. This phenomenon potentially explains the higher accuracy of MODIS satellite data during winter months and the overestimated values during the summer season.

Therefore, considering the limitations imposed by PET_MODIS values obtained from the satellite, the results obtained using the PM-

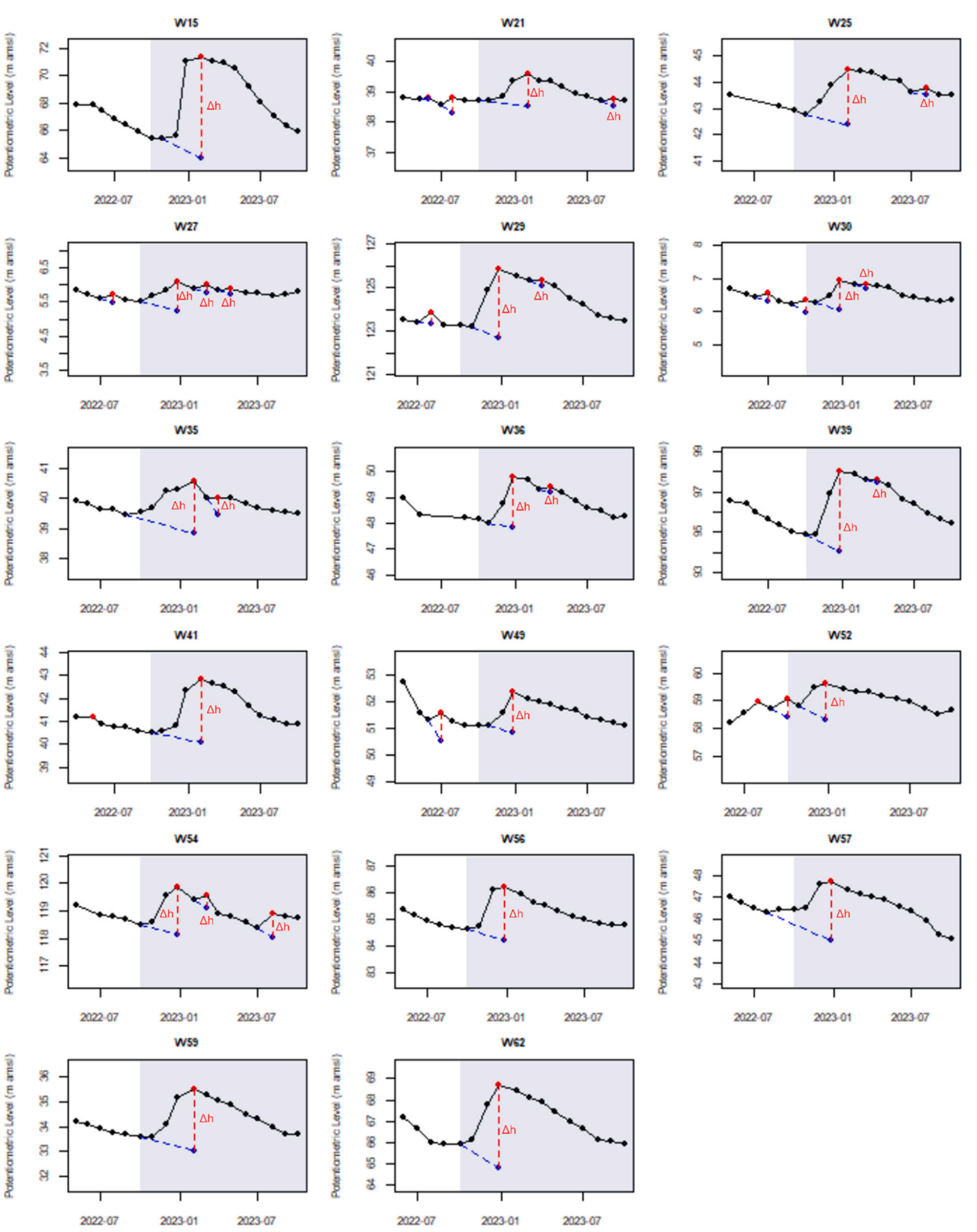

Fig. 14. Potentiometric level variations in the monitored wells. The adjusted curves used to calculate the water table variation are given in blue and Δh is shown by the dashed red line. The gray rectangle limits the hydrological year from October 2022 to September 2023.

FAO method were considered more reliable and accurate to be used in the recharge estimations.

5.2. Groundwater Recharge

Groundwater recharge in the Leiria Pine Forest region is mainly conditioned by precipitation rates, land use, topography, geology, and soil type. Given that precipitation rates do not vary significantly between the burnt and unburnt areas, the observed variations in groundwater recharge prior to the wildfire can be attributed to differences in these other controlling factors.

The application of remote sensing data for estimating groundwater recharge has proven to be a valuable tool, particularly in regions where consistent monitoring networks and/or observational datasets are sparse. This approach provides extensive spatial and temporal insights into hydrological processes, enabling the evaluation of large areas that are otherwise difficult to monitor. However, it also includes significant limitations related to cloud cover, which can obscure satellite imagery and hinder data collection, scale discrepancies between local and satellite observations, and the relatively low frequency of data acquisition, which can introduce gaps in the temporal resolution, potentially reducing the accuracy of recharge assessments.

To overcome some of these limitations and to validate the outputs from the Soil Water Balance model, two well-established and reliable methods, (1) the Water Table Fluctuation method and (2) the Chloride Mass Balance method, were employed for the hydrological year from October 2022 to September 2023, using field data collected monthly and an annual precipitation of 710 mm. Table 1 summarizes the results of groundwater recharge estimates.

Both the Water Table Fluctuation and Chloride Mass Balance methods provided consistent recharge values across the burnt and unburnt areas, reinforcing the reliability of these approaches. Despite the large spatial variability of specific yield values, laboratory-derived parameters were found to align well with values reported in the literature, increasing credibility to the recharge estimates. In the unburnt area, the Soil Water Balance method results are similar with the Water Table Fluctuation and Chloride Mass Balance methods, demonstrating its reliability. However, in the burnt area, this method tends to overestimate recharge compared to the other methodologies applied. Considering the high correlation between the results obtained in the unburnt area, it is likely the observed overestimation of Soil Water Balance results in the burnt area is attributed to the difficulty accurately estimating root depth parameters due to the increased heterogeneity of the vegetation growing in the area after the wildfire. This heterogeneity arises from differences in tree species, the presence of invasive species with varying root depths and water consumption patterns, and the velocity of the reforestation process in the burnt area, which leads trees at different growth stages. These factors impact the water balance and groundwater recharge during the analyzed period. Despite this overestimation, the overall recharge results for the aquifer, calculated through the weighted averaging of outcomes from both the burnt and unburnt areas, are within acceptable bounds and demonstrate a high level of consistency across the three applied methodologies. This consistency not only enhances confidence in the estimates but also underscores the importance of employing multiple methods for groundwater recharge estimation.

5.3. Impact of wildfires

Wildfires trigger a series of events capable of impacting hydrological processes on various temporal and spatial scales. These impacts have been well-documented in several studies and include vegetation depletion, disruption of soil characteristics, and soil erosion in impacted regions (e.g., Crist et al., 2023; Häusler et al., 2018; Nunes et al., 2018; Pacheco and Claro, 2023; Salgado et al., 2024; Sánchez-García et al., 2023; Wu et al., 2021). In general, studies about wildfires effects on the hydrological cycle reveal alterations in the magnitude of the water balance components, namely decrease in interception and transpiration and increase in evaporation and runoff rates (Ebel et al., 2012; Ebel and Moody, 2013; Ma et al., 2020; Moody et al., 2008; Rey et al., 2023; Williams et al., 2022).

The assessment of wildfires impacts in groundwater recharge is a complex task due to the highly multidisciplinary nature of the topic, as well as the absence of a comprehensive conceptual framework able to carefully consider and evaluate the parameters influencing post-fire processes. Besides, critical consideration of location and distinct characteristics of both burnt and unburnt areas is crucial to understand hydrological responses over time. Issues related to data availability and validation of post-fire simulation models are also a limitation in these studies, since baseline groundwater data is not often available (Guzmán-Rojo et al., 2024). Specific characteristics (meteorological variables, vegetation density, soil and geological characteristics) of each area lead to conflicting results in long-term impact studies. In some cases, groundwater recharge is reduced by the decrease in soil moisture and infiltration (*e.g.,* Venkatesh et al., 2020), while in other studies the reduction in interception provokes an increase in recharge (Cardenas and Kanarek, 2014; Ebel et al., 2016).

In the Leiria pine forest, burnt and unburnt areas have distinctive characteristics that may influence the comparative analysis of the

Table 1
Comparison between groundwater recharge values estimated using the three different methodologies and precipitation (P = 710 mm/year) for the hydrological year from October 2022 to September 2023.

	Recharge (Burnt) [mm/year]	P [%]	Recharge (Unburnt) [mm/year]	P [%]	Recharge (Aquifer) [mm/year]	P [%]
Soil Water Balance	239	34 %	162	23 %	186	26 %
Water Table Fluctuation	177	25 %	168	24 %	171	24 %
Chloride Mass Balance	169	24 %	161	23 %	165	23 %

wildfire effects. The burnt area, situated nearer to the coast and characterized by lower elevations, comprises dense forest and shrub vegetation, overlain by sand dunes with high infiltration capacity. In contrast, the higher elevations of the unburnt area, coupled with a less homogeneous land cover and the presence of geological layers with higher clay content, may restrict infiltration and consequently reduce groundwater recharge relative to the burnt area.

5.3.1. Vegetation Loss and Evapotranspiration

Forested areas typically exhibit higher evapotranspiration and lower runoff rates compared to other land covers (Valente et al., 1997). Evapotranspiration is the primary pathway for water loss in the hydrological cycle and is directly influenced by vegetation changes (Neary et al., 2005). The Vieira de Leiria-Marinha Grande aquifer, which underlies the study area, is dominated by forest and shrub cover, particularly in the burnt area, where nearly 100 % of the land is covered by vegetation. In contrast, the unburnt area includes a mix of forest, urban areas, pastures, and agricultural lands. According to (Teklehaimanot et al., 1991) rainfall interception can range from 10 % to 60 % of total precipitation in temperate coniferous forests, mainly influenced by canopy storage and aerodynamic conductance, reducing water availability to infiltration and runoff processes. Wildfires alter plant physiological characteristics, such as leaf structure, leaf cover and root depth, reducing interception and transpiration rates, increasing water availability for infiltration and runoff (Anurag et al., 2021).

These changes are reflected in the NDVI datasets from the Leiria Pine Forest, where the contrast between pre- and post-fire conditions is striking, highlighting the significant impact of the wildfire on vegetation. The decline in the correlation of PET_{CA} between the pre- and post-fire periods, from $r^2 = 0.82$ to $r^2 = 0.48$ () is linked to shifts in vegetation composition, including increased heterogeneity and the spread of invasive species following the fire and the burnt severity of the wildfire occurred.

The post-fire reduction in PET_{CA} in the burnt area further demonstrates the immediate impact of the wildfire on the ecosystem. In the Leiria Pine forest, PET_{CA} values begin to recover approximately two years after the fire, aligning with findings from previous investigations (Häusler et al., 2018), which also observed diminished evapotranspiration levels immediately post-fire, succeeded by a notable recovery in the second year, converging towards pre-fire conditions within the scope of natural variability. This trend was also reported in a study conducted in Australia by Nolan et al. (2014), where evapotranspiration in high severity burnt forest was 41 % lower, over the first two post-fire years. Despite this recovery, it is important to note that it does not indicate full forest restoration of the forest. Rather, the increased evapotranspiration rates are likely driven by the proliferation of non-pine species, such as shrubs and scrubby vegetation typical of Mediterranean climates, which have different water use patterns and high rain interception capabilities (Garcia-Estringana et al., 2010). These findings emphasize the importance of long-term monitoring of post-fire ecosystems to better understand vegetation recovery and the restoring of ecosystem hydrological processes.

According to Poon and Kinoshita (2018) post-fire evapotranspiration is directly connected to fire severity, being 20 % lower in high burn severity, 17 % lower in moderate burn severity, 11 % lower in low burn severity when compared to unaffected areas. The assessment conducted in the Leiria Pine forest by Fernandes and Guiomar (2018), classify the fire severity as extreme to high severity in 82 % of the area, while moderate to low severity was observed in 18 % of the burnt area, which significantly contributes to the decrease in evapotranspiration after the fire.

Differences in annual groundwater recharge during the pre-fire period were observed. Groundwater recharge in the burnt area was higher than in the unburnt area, a pattern that escalated after the fire, since recharge rates in the burnt area increased considerably, while in the unburnt area it does not vary significantly. This result is related to the substantial reduction in evapotranspiration following the loss of vegetation, which allows more water to reach the soil, increasing soil moisture, infiltration rates and groundwater recharge (Anurag et al., 2021; Poon and Kinoshita, 2018). Cardenas and Kanarek (2014) evaluated the soil moisture content in a burnt pine forested area and results show the section where the majority of pine trees were killed, had higher soil moisture (*θ)* and lower electrical resistivity (ER) than the unburned section, which was still populated by live pine trees, suggesting an increase of the infiltration capacity in the burnt areas.

Although post-fire reduction in evapotranspiration and increase in groundwater recharge are directly related, there are conceptual distinctions to be considered in the interpretation of results: (1) while groundwater recharge typically occurs through infiltration of precipitation or surface water into the aquifer, plants may use water directly from the aquifer, from shallower soil moisture or perched water tables in the transpiration process, especially in areas where the root depth reaches the water table; (2) groundwater recharge and evapotranspiration differ in their spatiotemporal dynamics, since in most cases, recharge tends to be episodic following precipitation events, while transpiration follows seasonal and diurnal patterns, and (3) recharge and transpiration can occur in different locations within the same watershed. Nevertheless, given the specific characteristics of the Leiria Pine forest area, the observed reduction in evapotranspiration following fire events is expected to directly enhance aquifer storage. This clear relationship supports an integrated analysis and allows for a straightforward interpretation of these processes within this particular context.

The Vieira de Leiria-Marinha Grande aquifer, which underlies the study area, is dominated by forest and shrub cover, particularly in the burnt area, where nearly 100 % of the land is covered by forest. In contrast, the unburnt area includes a mix of forest, urban areas, pastures, and agricultural lands, which generally have lower recharge potential due to the presence of impermeable surfaces. These specific characteristics will influence the response to wildfire events and must be carefully considered when comparing results between both sectors.

The employment of NDVI as a metric for PET_{CA} calculation may entail limitations in assessing post-fire recovery, since satellite-derived computations consider alterations in vegetation cover, yet other factors such as heightened Soil Water Repellency (SWR), wind flux, albedo variations and additional variables may also influence water retention and diminish evapotranspiration rates post-fire (Nunes et al., 2016; Veraverbeke et al., 2012). Furthermore, 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.

5.3.2. Runoff and Water Repellency

In post-fire environments, changes in land cover, physical and chemical properties of the soil and fire dynamics can alter soil infiltrability leading to increased runoff, but as vegetations recovers, the soil stabilizes, and this effect tends to be reverted (Pereira et al., 2018). Soil water repellency (SWR) is a complex phenomenon with diverse implications across different environmental contexts. Its effects in fire-prone areas vary depending on factors such as soil heating, organic matter depletion, and oxygen availability during combustion (Nunes et al., 2016). SWR exhibits temporal and spatial variability, demonstrating nonlinear behavior with soil moisture content and forming a transition zone between wettable and repellent conditions (Rueda et al., 2016).

Within burnt areas, reduced interception, increased SWR, and diminished infiltration capacity collectively contribute to heightened runoff generation and erosion rates (Ferreira et al., 2008; Santos et al., 2016). Following a fire, the volatilization of organic substances at high temperatures leads to the formation of a water-repellent layer, which condenses and migrates downward in the soil profile upon cooling (Ferreira et al., 2008; Neary et al., 2005). The presence and persistence of this layer is normally restricted to areas beneath plants canopies and is governed by soil temperature, with formation occurring above 176ºC and destruction above 288ºC (DeBano, 1981).

Fire severity is a determinant factor of SWR spatial variability in burnt regions. Higher severity yields more pronounced and homogenously distributed SWR, while lower severity results in heterogeneously scattered effects, promoting preferential flow paths that may enhance local infiltration (Coelho et al., 2004; Diamantopoulos et al., 2013). Nonetheless, the influence of severity and spatial distribution of SWR varies with the scale of analysis, with significant reductions in overland flow and erosion rates observed in larger systems compared to smaller ones due to water and sediment connectivity (Ferreira et al., 2008). In the context of wildfires, SWR tends to exhibit relatively uniform distribution, except for macropores that foster preferential flow paths, thereby promoting overland flow and sediment transport.

Fernandes and Guiomar (2018) conducted a fire severity assessment in the Leiria Pine Forest, indicating predominant extreme severity (37.1 % of burnt area), high severity (27.4 %), very high severity (17.6 %), and moderate to low fire severity (18 %). Despite the anticipated increase of SWR effects due to the distribution of fire severity, the combustion of pine tree roots generated macropores, mitigating the impact of SWR layer formation. Moreover, the beginning of the wet season following the Leiria fire, coupled with increased precipitation, contributed to the rapid dissipation of the water repellent layer.

The consequences of wildfires depend on specific area characteristics, including topography, soil organic matter content, vegetation, and fire severity, intensity, and extent. In the case of the Leiria Pine Forest, topography follows a gradient from southeast (SE) to northwest (NW), with higher altitudes reaching approximately 180 m situated near the southeastern border, and lower altitudes closer to the shoreline. Despite the relatively gentle slope across the aquifer, the higher altitudes predominantly found in the unburnt area, coupled with the higher degree of soil impermeabilization and the type of vegetation, contribute to increased runoff compared to the burnt area.

Analyzing the pre-fire period, in the unburnt area, the runoff process initiated with lower precipitation volumes compared to the burnt area and, on average, corresponded to approximately 3 % more in relation to the volume of precipitation. In the post-fire period, the runoff trends closely resembled those observed in the pre-fire period for both burnt and unburnt areas. This suggests that gentle topography and well-sorted sand dunes with high hydraulic conductivity facilitate infiltration and minimize overland flow. Additionally, it indicates that the impact of soil water repellency (SWR) was negligible even after the fire event.

5.3.3. Rooting System

The substitution of pine roots by shallower-rooted vegetation species following the fire in the Leiria Pine Forest contributed to the increase of groundwater recharge. According to Neary et al. (2005), the replacement of the deep-rooted trees by plants with shallower root systems may contribute to lower evapotranspiration, possibly increasing soil moisture and consequent, groundwater recharge. These results are aligned to the findings in the Leiria Pine forest, where the simulations modifying the root depth parameter showed deeper roots, such as those of pine trees, can directly abstract water from the shallow aquifer, so their replacement by species with shallower roots limited water uptake to the topsoil layer, enhancing groundwater recharge.

The rooting system plays a critical role in soil stabilization, influencing its effective hydrological depth and flow roughness. During wildfires, soil heating sterilizes the upper layer, leading to various modifications such as soil and organic matter loss, changes in porosity, aggregate stability, nutrient depletion, increased bulk density, sediment yield, and reduced infiltration rates. The loss of microbial populations, invertebrates, insects, and plant roots results in significant alterations in soil properties (Efthimiou et al., 2020; Gyssels et al., 2005; Hyde et al., 2007; Neary et al., 2005)

Macropores, formed through soil cracks, high stone content, and plant roots, can contribute to elevated runoff coefficients observed at the micro-scale following wildfires, contrasting the limited impact observed at larger catchment scales in the Mediterranean region (Shakesby, 2011). Although macropores can impede infiltration rates when filled with ashes and fine soil particles (Martin and Moody, 2001), they can also serve as preferential pathways for water infiltration under certain conditions, potentially increasing it. The extensive macropore systems resulting from the combustion of rotten root systems in burned pine areas may counteract soil water repellency effects and control excessive overland flow (Ferreira et al., 2008).

5.3.4. Soil Properties

After wildfires, changes in soil structure and chemical composition (e.g changes in organic matter content, formation of ash layers) may affect the soil water holding capacity and infiltration rates, and consequently, groundwater recharge (Bodí et al., 2014; Certini, 2005; Certini et al., 2011; Pellegrini et al., 2021). The soil distribution within the aquifer includes four distinct soil types: arenosols (52 %), podzols (40 %), fluvisols (4 %), and cambisols (4 %), with uneven distribution between burnt and unburnt areas. This distribution holds significant importance as the model assigns distinct values for soil parameters to each soil type, influencing the processes governing groundwater recharge. In the Leiria Pine forest, approximately 80 % of the burnt area comprises arenosols, while podzols account for 18 %. In contrast, the unburnt area consists of only 38 % arenosols and 50 % podzols. Arenosols are characterized by low water-holding capacity, which favors groundwater recharge, whereas podzols typically exhibit higher field capacity, enabling them to retain more water and consequently reducing groundwater recharge rates.

According to Xofis et al. (2023), soil properties in sites that have been burned with high intensity, like the study area, appear to be significantly by the fire and the effects may last for more than a decade, and considering the results presented by Dymov et al. (2023), this time could range up until 120 years. Therefore, besides the differences in land use, distinct soil characteristics play a role to some extent in the increased recharge rates observed in the burnt area even before the fire.

6. Conclusions

Wildfires have historically been recognized as natural environmental disturbances essential for many ecosystems. However, the increasing frequency and intensity of wildfire activity, driven by climate change, heightens their direct and indirect impacts on vegetation, soil, and the hydrological cycle.

Various methodologies can be applied in the evaluation of these impacts, but selecting the most suitable approach requires careful consideration of the study area's characteristics and available data. Remote sensing techniques have emerged as valuable tools for overcoming limitations of spatiotemporal data gaps. Nevertheless, the uncertainties related to interpolation errors, atmospheric interference, and satellite precision must be addressed by validating remote sensing data through field observations whenever possible to ensure the robustness and reliability of conclusions.

Groundwater recharge in the aquifer before the wildfire accounted for approximately 20 % of annual precipitation. In the unburnt area the recharge rate remained stable after the fire. However, in the burnt area, groundwater recharge increased to more than 40 % of precipitation in the first-year post-fire, gradually decreasing in the following years and stabilizing at around 30 % by 2023. These fluctuations can be primarily attributed to changes in evapotranspiration rates, which influence key processes such as interception, runoff, and infiltration. In the burnt area, evapotranspiration dropped sharply in the first year after the fire, leading to higher groundwater recharge, not observed in the unburnt area. After the second year, with the re-establishment of some vegetation, including species with varying water demands, evapotranspiration rates start to gradually increase

Soil characteristics also play an important role in influencing groundwater recharge dynamics, since they will determine the capacity of soil to retain and release water, thereby affecting groundwater recharge rates. In the Leiria Pine forest, variations in soil types between burnt and unburnt areas contribute to differences in recharge rates. The sandy arenosols predominant in the burnt area, with their low water-holding capacity, promote faster infiltration, thereby enhancing groundwater recharge. This highlights how soil composition, combined with wildfire-induced vegetation changes, drives recharge variability.

Another factor influencing recharge is soil water repellency (SWR), a condition often exacerbated by wildfires. SWR affects both infiltration and runoff, and its persistence is influenced by fire intensity, soil type, and post-fire climate conditions. However, while several studies highlight the importance of soil water repellency (SWR) after wildfires, its influence in the study area appears limited, possibly due to the small persistence time of the water-repellent layer and the presence of macropores, which facilitate infiltration. Although these findings contrast with other studies that emphasize the lasting impact of SWR after wildfires, it demonstrates the importance of considering local climate and soil conditions when assessing post-fire hydrological effects.

Predicting the hydrological impacts of wildfires on groundwater recharge is a complex task that requires integrating knowledge of land cover changes, soil properties, geology, hydrogeology, and climate variability. The combination of three different well-documented methodologies used to evaluate groundwater recharge increases the reliability of results. Furthermore, the installation of meteorological and groundwater monitoring networks would enhance the accuracy of these models by improving data calibration, leading to a better assessment of both pre- and post-fire recharge conditions. Finally, the long-term monitoring of hydrological patterns in fire-affected landscapes is crucial for developing water resource management mitigation and adaptation strategies, especially in regions facing increasing wildfire risks.

CRediT authorship contribution statement

de Melo Maria Teresa Condesso: Writing – review & editing, Supervision, Resources, Conceptualization. **Nunes João Pedro:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Cordeiro Mariana La Pasta:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mariana La Pasta Cordeiro reports financial support and article publishing charges were provided by Foundation for Science and Technology. Maria Teresa Condesso de Melo reports financial support was provided by University of Lisbon Institute of Civil Engineering Research and Innovation for Sustainability. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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