Estimation of future drought and (wetland) fire risk up to 2070 in Prespa

Report for Activity A4 of the project "Prespa's Green and Blue LifeLines" headed by the Society for the protection of Prespa

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T. van der Schriek, A. Karali, K.V. Varotsos, G. Kitsara & C. Giannakopoulos,
CLIMADAPT Research Group,
Institute for Environmental Research and Sustainable Development,
National Observatory of Athens (Greece), 2023

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[1] Institute for Environmental Research and Sustainable Development, National Observatory of Athens, I. Metaxa & Vas. Pavlou, Lofos Koufou, P. Pendeli, Athens, GR 152 36, Greece

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Abbreviations & Glossary

BA Burnt Area

CEMS Copernicus Emergency Management Service

EFFIS European Forest Fire Information System

FWI Fire Weather Index

GCM Global Climate Model

GWIS Global Wildfire Information System

IPCC Intergovernmental Panel on Climate Change

RCM Regional Climate Model

RCP Representative Concentration Pathway

SPEI Standardized Precipitation Evapotranspiration Index

SPP Society for the Protection of Prespa

UTC Coordinated Universal Time

Fire hazard: a condition *or* material that may start -*or* contribute to the spread of- a fire (or, in other words, *anything that is apt to initiate or enhance a fire*).

Fire risk: the likelihood that a fire will occur because of a fire hazard, and the extent and severity of the damage (harm potential) which may be caused.

Fire season: in the Mediterranean, the annual BA is for >90% caused by wildfires over the months June-July-August-September; these months are termed “Fire Season”.

Hydro-year: hydrological year in the Mediterranean, from October (year 1) to September (year 2).

Wet Season: 6 months, from October (year 1) to March (year 2), when usually the largest amount of precipitation falls in Mediterranean regions.

1. Introduction

This report concerns activity '**A4. Estimation of future droughts and (wetland) fire risk up to 2070 in Prespa**' of the "Prespa's Green and Blue LifeLines" project. It addresses the increasing threat of wildfires, which pose a significant risk to the biodiversity of the riparian zones in the Prespa Lake catchment area.

The aim of this action is the creation of a wetland landscape fire risk index, specifically for the Prespa catchment area, under three future climate change scenarios. This action is led by National Observatory of Athens and consists of the following components:

[1] Fire danger modelling, using the Fire Weather Index (FWI) and observational meteorological data, to establish current fire hazard in Prespa related to climate conditions. The Standardised Precipitation Evapotranspiration Index (SPEI), a drought index sensitive to temperature, will be calculated over the observational period. Both indices will be assessed, together with relevant meteorological data, to create a new wetland fire risk index for Prespa;

[2] Wetland fire risks will be estimated under three future climate change scenarios (RCP 2.6, RCP4.5 and RCP8.5), with business-as-usual management, up to 2070. State-of-the-art climate models, at a horizontal resolution of 12km developed within the EURO-CORDEX initiative, will simulate future climate data that drive the fire hazard (FWI) and drought (SPEI) indices, and the Prespa wetland fire risk index. Future changes compared to the observational period will be assessed.

1.1 Background

Climate change impact projections suggest increases of 40-100% in burned areas due to Mediterranean wildfires, depending on the scenario and region, over the course of the 21st century **[1 *and references herein*]**. For the development of future-proof fire management across the Prespa basin, it is essential to have up-to-date projections of (wetland) fire-risk for the near to medium future, up to 2070. Such projections will also help to raise regional awareness of climate change impacts, increase the willingness to take adaptation measures and allow access to diverse funding mechanisms.

Few wildfires in Greece are due to natural causes **[2-4]**. Lightning-caused fires account for ~3 percent of the total number of fires. The rest of the fires with known causes have been categorized as accidental / negligence (~35%) and as deliberately started (~27%); the origin of many fires (~37%) is classified as due to "unknown causes". Most of them (>60%) are suspected to be deliberately set (accessed 15/02/2023, at: https://www.fireservice.gr/el/synola-dedomenon). Arson fires, fires from burning garbage dumps, and power line fires are the most destructive since they usually occur on days with high wind and temperatures. Arson fires (usually related to land-use issues) are specifically a problem, both due to the cost of fighting them and to the fact that even when firefighting efforts are successful arsonists merely wait for more difficult conditions and try again.

The money and effort devoted to coping with wildfires in Greece is significant. In terms of aerial forces, the country should probably be rated first in the world on a per-hectare-protected basis. However, the poor results of the last few years clearly indicate that there is need for improvement, especially regarding knowledge and organization of the entire effort. Specifically, there is a clear need for better landscape management, legislation and serious fire prevention efforts involving all local stakeholders (shepherds, farmers, and residents).

2. Fire danger

This study looks at present and future wildfire **hazards** that are related to meteorological conditions, and thus directly affected by climate change. Furthermore, it will assess future **wetland fire risk** (which involves combined evaluation of wetland fire hazard, ecological losses and ignition sources).

A **fire hazard** is **a condition *or* material that may start -*or* contribute to the spread of- a fire** (or, in other words, *anything that is apt to initiate or enhance a fire*).

> This study will use the **Fire Weather Index (FWI)** to assess the **fire hazard** related to weather. The **weather** is an important variable when it comes to potential wildfires. The level of air humidity, drought conditions, the amount of wind, and the temperature all play a part in creating (un)favorable conditions for wildfires. Furthermore, the **dryness and type / availability of fuels** (such as grass, fallen timber, and wood) is also an important fire hazard related to climate.

A **fire risk** is defined as **the likelihood that a fire will occur because of a fire hazard**, and the extent and severity of the damage (harm potential) which may be caused.

> Wildfire risk is the **probability** and **consequence of a wildfire** burning in an area. Wildfire risk involves wildfire hazard (including weather conditions), potential human / ecological / economic losses, and ignition sources. Identifying wildfire hazard is an important first step in assessing the risk of wildfires.

2.1 Climate and wildfires

Climate is the average weather at a location over a minimum period of 30 years. Climate change, including increased heat, extended drought, and a dry atmosphere, is seen as a key driver in increasing the risk and extent of wildfires. Climate directly influences wildfire hazard through the level of air humidity, drought conditions, wind velocities, and air temperature.

Natural ignition (mainly lightning) accounts for 10-20% of Mediterranean wildfires **[2-4]**. The remaining fires are caused by human actions, either through accidents / negligence (40%) or arson (50%). Weather conditions greatly influence the extent of wildfires once ignited. Heat waves combined with drought periods may lead to very large wildfires over the fire season (June-July-August-September). Hydrological drought (calculated over a period of 12 months or more) may also cause increased wildfire activity over the months outside the fire season **[1 *and references herein*]**.

2.2 FWI and SPEI indices

In addition to meteorological variables, this study uses two key indices that are linked to wildfire danger: the Fire Weather Index (*hereafter*: FWI) and the Standardised Precipitation Evapotranspiration Index (*hereafter*: SPEI).

The **Fire Weather Index (FWI)** is a daily meteorologically based system used worldwide to estimate fire danger in a generalised fuel type (i.e., mature pine forest; **[5] [6]**), see Figure 2.1. It accounts for the effects of fuel moisture and wind on fire behaviour and spread. The higher the FWI is, the more favourable the meteorological conditions are to trigger a wildfire.

The **meteorological inputs** to the daily FWI calculations are the values, at 12UTC, of: 2-m air temperature, 10-m wind speed, 2-m relative humidity, and accumulated precipitation during the previous 24 hours were used. The 12 UTC was used as a proxy for local noon values required as input to FWI as proposed by several studies for the Mediterranean and Greece (e.g., **[7] [8]**). For a more detailed description of the FWI system and its subcomponents, see appendix 1.

At EU level, the Fire Weather Index is mapped in 7 classes (very low, low, moderate, high, very high, extreme and very extreme). The values for the FWI are provided in Table 2.1.

Figure 2.1: The Fire Weather Index (FWI) and its input data.

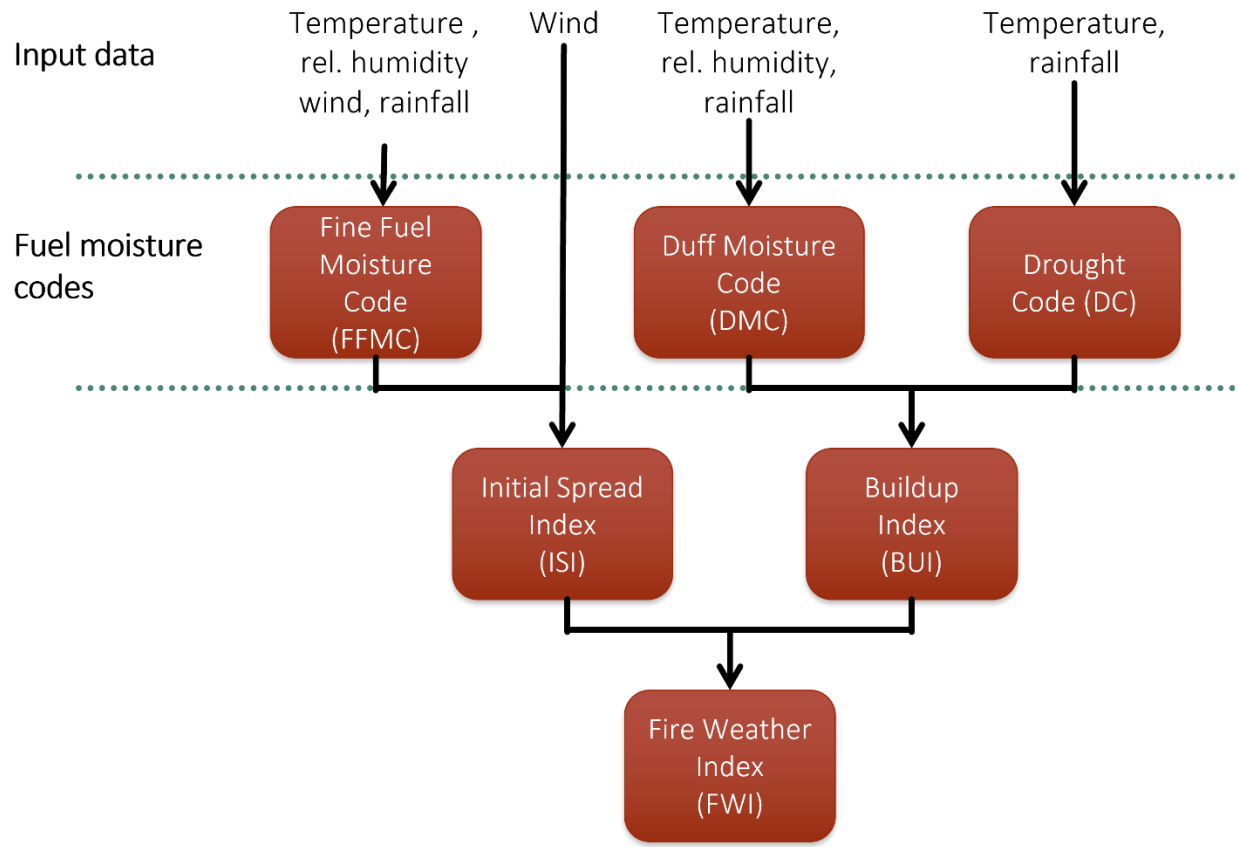


Table 2.1: FWI values and Fire Danger Classes

FIRE DANGER CLASSES	FWI VALUES
VERY LOW	<5.2
LOW	5.2> = FWI <11.2
MODERATE	11.2> = FWI <21.3
HIGH	21.3> = FWI <38.0
VERY HIGH	38.0> = FWI <50.0
EXTREME	50.0> = FWI <70.0
VERY EXTREME	>70.0

The FWI can directly be compared to operational FWI products used worldwide. Since 2007, the FWI has been adopted at the EU level by the **European Forest Fire Information System** (EFFIS) network of the Copernicus Emergency Management Service (CEMS) the to assess fire danger level in a harmonized way across Europe and the Mediterranean. The **Global Wildfire Information System** (GWIS) also adopted the FWI as the reference for operational fire danger forecasts. For the future wildfire risk assessment, the **Copernicus Climate Change Service** also selected the FWI.

Useful websites with accurate and up-to-date information on wildfires (past, present and future) in the EU and the Mediterranean region are given in Table 2.2.

Table 2.2: Up-to-date information on wildfires (past, present and future).

Database / Website	Address	Type information
European Forest Fire Information System (EFFIS)	https://effis.jrc.ec.europa.eu/	Information on current fire season including forecasts up to 6-days ahead; long-term fire weather forecasts (on a monthly – seasonal basis); wildfire risk viewer.
Global Wildfire Information System (GWIS)	https://gwis.jrc.ec.europa.eu/	Current situation viewer including forecasts up to 10-days ahead, active fires and 1-day lightning forecasts; long-term fire weather forecasts (on a monthly – seasonal basis); country-regional fire statistics & maps.
Copernicus Climate Change Service	https://climate.copernicus.eu/fire-weather-index	Fire weather indicators for Europe from 1970 to 2098 derived from reanalysis and climate projections.

The **SPEI is a multi-scalar drought index** based on climatic data. It determines the onset, duration and magnitude of drought conditions with respect to normal conditions (i.e., averaged conditions over the entire period of analysis). SPEI has an intensity scale in which both positive and negative values are calculated, identifying wet and dry events. It can be calculated for time steps of as little as 1 month up to 48 months or more. It needs monthly **temperature** (when PET is based on Thornthwaite equation **[9]**) and **precipitation** data for its calculation. The inclusion of temperature along with precipitation data allows SPEI to account for the impact of temperature on a drought situation. The output is applicable for all climate regimes, with the results being comparable because they are standardized.

With the use of temperature data, SPEI is an ideal index when looking at the impact of climate change in model output under future scenarios.

The different SPEI timescales are relevant for: meteorological drought (1-month timescale), agricultural drought (3 to 6-month timescale), hydrological drought (12-month timescale), and socioeconomic drought (24-month timescale). Mediterranean wildfires during the fire season (June-July-August-September) are particularly sensitive to drought over the previous 6 to 12 months (SPEI-6 and SPEI-12, respectively). For a more detailed description of the SPEI, its calculation and references, see appendix 1.

The Standardised Precipitation Evapotranspiration Index has 7 moisture categories. The values for the SPEI are provided below in Table 2.3.

Table 2.3: SPEI values and Moisture Categories.

Moisture Category	SPEI values
Extremely Wet	>2.0
Very Wet	1.50 to 1.99
Moderately Wet	1.00 to 1.49
Near Normal	-0.99 to 0.99
Moderately Dry	-1.00 to -1.49
Severely Dry	-1.50 to -1.99
Extremely Dry	-2.00<

3. Forest wildfires in the Prespa catchment (including riparian areas)

Burnt Area data from forest wildfires in Prespa were downloaded from the European Forest Fire Information System (EFFIS at https://effis.jrc.ec.europa.eu/). The Rapid Damage Assessment module of EFFIS provided the daily update of the perimeters of burnt areas in Europe for fires of about 30 ha or larger, from 2003 until 2017, twice daily. Since 2018, the use of Sentinel-2 imagery allows the detection of fires below the 30 ha threshold and it is estimated that the areas mapped in EFFIS represent about 95% of the total area that burns in the EU every year.

Over the 2002-2019 period, the largest forest wildfires and the greatest cumulative burned area occurred in the eastern and southern parts of the catchment (Fig. 3.1); none of the areas was burned more than once over this period. The (open) forests and shrublands that burned in the eastern and southern parts of Prespa, are rooted in dry soils on limestone and are consequently highly susceptible to summer drought. Forest wildfires in these parts of the catchment occurred from July to September (Fig. 3.2).

In the (north-) east of the Prespa catchment, wildfires were on average smaller, and no areas burned repeatedly over the observation period (Fig. 3.1). The deciduous forest and shrublands that dominate this part of the catchment are rooted in soils on granitic rocks, which are relatively wet/deep and with a high groundwater table due to the impermeable characteristics of the rocks below. Thus, these areas are less susceptible to summer drought than the western and southern catchment areas. Fires in this part of the catchment occurred from July to October, and once in December (Fig. 3.2).

Riparian forests are located around the lake-margins and the streams entering the lakes. Most streams and their forests are found to the NE and E of the catchment, which is underlain by impermeable granitic rocks and has consequently a high stream density. Forest wildfires do not start in these riparian woodlands due to their (relatively) high wood-moisture content and humidity. Riparian woodlands may be affected by large forest fires that occur in the surrounding mountains during heatwaves.

Forest wildfire ignition is mainly related to land-use activities, when fires are started either deliberate (to clear land for building or agro-pastoral use) or due to carelessness, and to the electrical power infrastructure. Ignition predominantly causes forest wildfires over the fire season (June to September). Smaller forest wildfires are occasionally recorded in autumn to early winter.

Wildfires over the fire season in the Prespa catchment are related to fire hazard as computed by the FWI (days with “very high” to “very extreme” fire danger, FWI>38; Table 2.1). “Very extreme” FWI values (>70) are associated with heatwave and drought conditions, which are **strongly linked** to large forest fires **[1]**.

Autumn forest wildfires are related to days with very high fire danger (FWI>38), while their ignition is most likely deliberate as fire conditions over these months are sub-optimum. It should be noted that at least 60% the total burnt area over the period 2002-2019 was burned during the **extreme fire season of 2007**, when there were several clusters of successive days with “very extreme” fire danger values throughout the fire season.

Figure 3.1. Burned area from large wildfires (> ~30 ha) and number of wildfire occurrences from 2002-2019 (*after*: GWIS, downloaded 12/02/2023 from https://gwis.jrc.ec.europa.eu/apps/country.profile/maps).

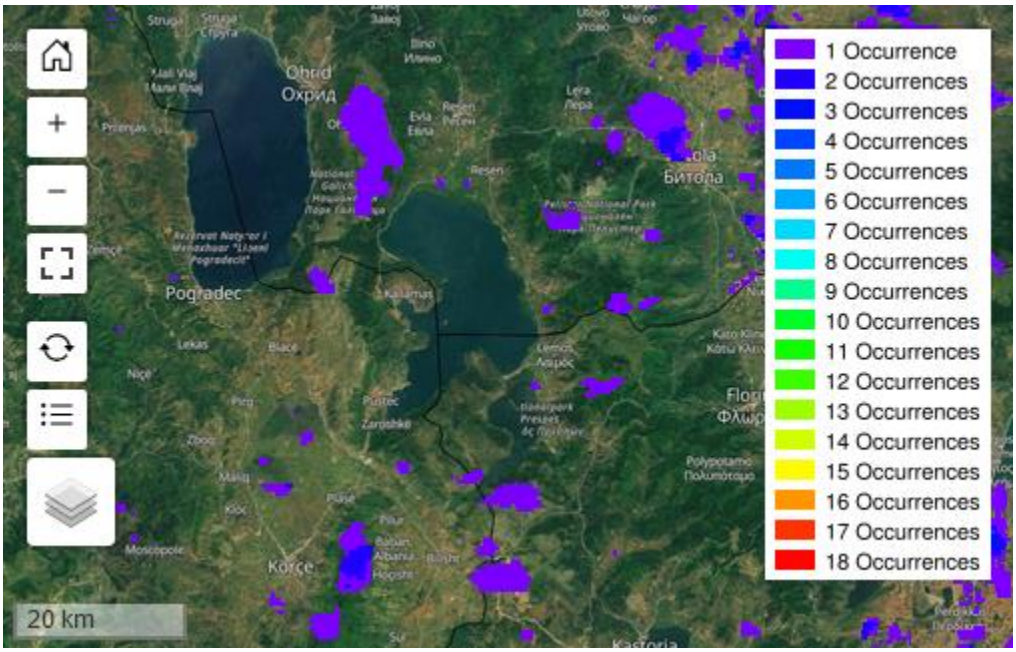
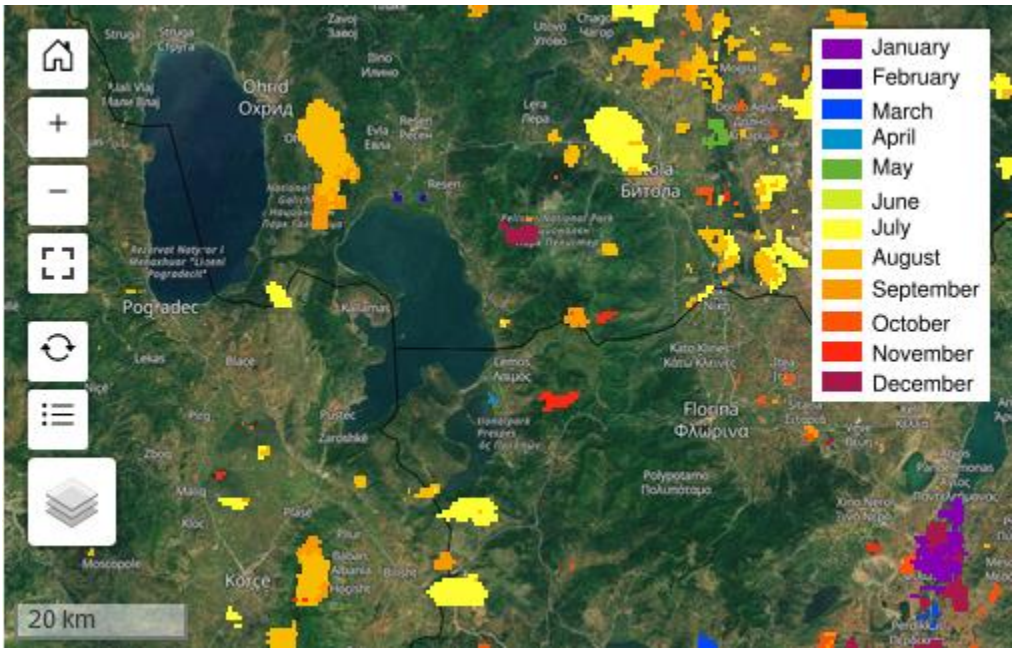


Figure 3.2. Burned area from large wildfires (> ~30 ha) and timing of wildfire occurrences from 2002-2019 (*after*: GWIS, downloaded 12/02/2023 from https://gwis.jrc.ec.europa.eu/apps/country.profile/maps).



4. Wetland reedbed fires

Wetland reedbed wildfires pose a significant threat to the biodiversity of the riparian zones and streams in Prespa. Reedbed fire hazard is assessed using the SPP database of wetland fires, covering the Greek part of the shorelines of Greater and Lesser Prespa Lakes, spanning 2007-2022. The SPP also provided local meteorological station data that were used to assess weather conditions at the time of the individual wetland fires.

Wetland fires mainly burn reedbeds that are located [i] around the Prespa Lakes' shorelines and [ii] in the streams/drainage ditches crossing the agricultural fields surrounding the lakes. Reed stalks are green for one year and remain standing, withered, for a further 3-4 years. These withered stalks are highly flammable.

Wetland shrubs and trees, on the other hand, are very difficult to burn (due to their high wood-moisture content) and even function as firebreaks. It has been observed that late winter to spring reedbed fires in drainage ditches were stopped by trees, as reed does not grow in their shadow. Overall, these riparian woods seldomly catch fire (and never before July) due to their high moisture content.

Large wetland reedbed fires took predominantly place from February to the end of March and account, over the period 2007-2022, for a cumulative burnt area of ~1008 ha. This equals to 92% of the total burnt reedbed area (~1094 ha) over the observation period. Minor fires were recorded in April and (once) in August, affecting drainage ditches. However, in 2020 and 2021 two larger reedbed fires occurred for the first time late in season, one in April and one in May (burnt area 30-40 ha, per fire). See Table 4.1 for a summary of the annual timing and burned wetland area over 2007-2022.

All reedbed fires were started by land-use practices (see text-box, below). Fire conditions are sub-optimum in late winter to spring, when all reedbed fires started (section 4.1) It appears that these fires usually **take place before crop growth** on the fields surrounding the reedbeds.

Reedbed fires over the observation period (2007-2022) started in the agricultural fields, and in the reedbeds of the adjacent drainage ditches, that border **Lesser Prespa Lake**. These fires are ignited annually by farmers, in late winter to spring, to clear the fields prior to cultivation and to clear drainage ditches from vegetation. Occasionally, these fires expand into the lake-marginal reedbeds (**cause 1 of reedbed fires:** negligence related to agricultural practices).

Some fires are started directly in reedbeds where these border agricultural fields, to expand these fields for the sowing/cultivation season (**cause 2 of reedbed fires:** arson related to land-grabs). Falling lake levels stimulate this illegal expansion as more land becomes suitable for agriculture.

No detailed data are available on reedbed fires in the other lake-sharing countries (Albania and North Macedonia). However, European data suggest (Figs. 3.1 & 3.2) that large reedbed fires take place in North Macedonia around springtime in fields bordered by agricultural lands. It is assumed that the causes for ignition are the same as the ones mentioned above.

Finally, **minor** areas are burned in spring near the (Greek) shores of **Great Prespa Lake**, at locations where there are access roads. These reedbeds are not bordered by agricultural or pastoral fields. These fires are likely started by fishermen, wanting to create fish-spawning grounds, or cattle/shepherds that want green (fresh) vegetation (**cause 3 of reedbed fires:** arson related to land-use).

Table 4.1: Timing of reedbed fires and cumulative surface area burned. Wet season precipitation (October to March) is included, and particularly wet years are highlighted in blue.

YEAR	MONTHS	HECTARES BURNED	6-MONTH PRECIPITATION (OCT-MAR; MM)
2007	3	45	324
2008	1,2	115	419
2009		0	376
2010		0	793
2011		0	493
2012	3	51	274
2013		0	640
2014	2,3	115	300
2015	4	16	645
2016	2,3	197	408
2017	2,3,8	8	311
2018		0	563
2019	2,3	332	297
2020	2,4	84	404
2021	3,5	74	471
2022	2,3,4	35	483

4.1 Prespa reedbed fires: summary of findings

All major reedbed fires (2007-2022) around Lesser Prespa Lake occurred from late winter until the end of spring.

Fire danger related to weather conditions (for example, drought, humidity, temperature) is relatively low over **these months** (section 4.2). However, reedbed **fire-ignition related to land-use** activities (field-& drainage clearance, field expansion, pastoral / spawning ground clearance) is **concentrated over this period**.

Fire danger related to weather conditions is much higher **during summer** than in late winter to spring. However, the **(near) total absence** of **reedbed fires over the fire season** (June-July-August-September), indicates the absence of wetland fire-ignition due to human causes. As the agricultural fields surrounding the wetlands are heavily cultivated from late spring onwards, fire-ignition is avoided by farmers and fires actively suppressed as these threaten their crops.

Recorded reedbed fires along Lesser Prespa Lake repeatedly burned the same zones. Some areas burned up to 6-7 times over the 2007-2022 period (Pili, Opagia and Slatina), whereas most other reedbed areas burned 2-4 times. Only a very small portion of the total (Greek) reedbed area around Lesser Prespa Lake burned once or not at all over the 16 year observation window.

The areas that most frequently burned all border productive agricultural fields, or are directly connected to those through reedbeds in drainage ditches / streams.

Large reedbed fires along the shoreline of **Great Prespa Lake** are much rarer. Here, large areas of reedbeds did not burn at all over the years from 2007-2022. Minor fires along the Greek shore of Great Prespa Lake are concentrated on grazing / fishing areas near access roads. In North Macedonia, some larger fires are recorded along the northern shoreline, where there are agricultural fields and tourist facilities nearby. All the reedbed fires in North Macedonia also burned over the late winter to spring seasons.

The cause of all registered reedbed fires is therefore directly related to land-use activities in late winter and spring time**.** Fires related to field/drainage ditch **clearance** are ignited on days without rainfall and snow cover. Fire-spread to reedbeds in this case is related to ***negligence***. However, ignition related to **field expansion** through ***arson*** intend the fire to spread to the wider reedbeds. These fires are ignited during days with weather conditions favourable to fire-spread (see below) and are more difficult to extinguish.

4.2 Reedbed fire hazards

Based on the available data, key **climate-related hazards** associated with **wetland reedbed fires** were identified for the Prespa catchment. **Analyses focused** on **climate conditions** from late winter to the end of spring, as well as **weather characteristics** at the time of reedbed fires, over the observation period (2007-2022). In the next paragraphs we discuss briefly which variables were assessed to determine their respective influence on wetland fire hazard.

The daily to (multi-)monthly **FWI cannot** be linked to the outbreak of large reedbed fires over **late winter to springtime**. Some of the largest reedbed fires (e.g., in 2008, 2014, 2016) are characterized by (very) low FWI values (of below 10; see table 2.1), whereas no FWI values are available for the largest fires in 2019 due to data-recording problems. **Extreme FWI values over summer** indicate enhanced fire danger for wetlands and reedbeds, but historical data suggest that there is no intentional ignition of reedbeds over this period. The main fire danger to wetlands in summer is related to the spread of upland forest fires to the lowlands; historical data suggest that this rarely happens under current land-use and climate conditions. However, if the economical motives change in the future (e.g., lake-shore development), summer wetland fire-danger may increase abruptly.

Also, **the SPEI** values (on various timescales, from monthly to 12-month averages) **cannot** be linked to the outbreak of large reedbed fires from late winter to springtime, over the observation period.

Dead reed stalks are highly combustible. Reedbeds fires have been registered only one or two days after a rainfall event; reedbed fires are not taking place when there is rainfall. However, data-analysis suggests that the **number of dry days** before a reedbed fire starts **is not** a significant factor to determine fire hazard.

No specific return time can be distinguished between reedbed areas that are repeatedly burned. Areas may burn every year (for example, Pili: yearly reedbed fires from 2019 to the end of 2022). This indicates that the multi-annual **build-up of dead reed** material **does not** play a dominant role in fire spread.

Two key climate-related hazards linked to wetland reedbed fires have been identified. Wet season (Oct-Mar) precipitation is strongly associated with cumulative burnt area over this period, as is heavy lowland snowfall followed by thaw. Specifically, the two climate-related reedbed fire hazards are:

- **Wet season precipitation <500mm** (~65th percentile of long-term wet season precipitation). Precipitation **above** this threshold is linked to very limited / no reedbed fires. When wet season precipitation is <500 mm, large reedbed fires are more likely to occur. Over the observation period, 12 out of 16 years had a wet season precipitation below 500mm; 9 out of these 12 years are characterized by (extremely) large cumulative burnt wetland areas.
- **Heavy lowland snowfall, followed by late winter / early spring thaw.** Heavy snowfall flattens reedbeds and thus greatly enhances fire-spread. This mechanism was observed in 2019, when ~332 Ha of reedbeds burned along the shorelines of Lesser Prespa Lake (about 30% of the total cumulative burnt area over the 16 years from 2007 until 2022).

Furthermore, two additional hazards were identified that influence, individually or together, fire spread and total burnt reedbed area on the day of fire-ignition. These **two hazards are influenced by the weather at the time of ignition** and should be included in any wetland fire warning system. However, there is no correlation between these variables, that occur regularly over the months of interest, and cumulative burnt wetland area.

The two key weather-related hazards are:

- **Wind speeds of >3 m/sec (or >3 on the Bofort Wind Scale)**. Below this threshold there appears to be very limited fire spread and thus burnt area. Days with wind speeds above this threshold occur regularly over the months of interest.
- **Maximum temperature of >10^{o}C (Feb & Mar)**. High maximum temperatures (for February & March) are observed on ~70% of the days that have reedbed fires. It appears therefore a factor that aids (but does not determine) fire spread in reedbeds.

5. Prespa Wetland Fire Risk Indices

To determine **wetland fire risk** in the Prespa catchment, it is necessary to categorise the main fire hazards in the area, potential ecological losses, and ignition sources / locations. Separate wetland fire risk indices must be created for two periods: [i] late winter to spring, when only reedbed fires burn (high ignition rate / frequency due to annually burning land-use related fires), and [ii] the fire season (June-July-August-September), when large forest wildfires may threaten all wetland environments (from riparian forests to reedbeds). However, the wetland fire ignition rate and frequency over the fire season is (much) lower than in late winter to springtime.

5.1 Reedbed fire risk index (late winter to end of spring)

Given the differences in ignition sources / frequencies and potential ecological losses, the reedbeds in the Prespa catchment have been divided into **two areas** that reflect the different reedbed fire risks around Lesser- and Great Prespa Lake, respectively. These risk assessments cover the period from late winter to the end of spring, when the fire hazard associated with agricultural / pastoral fire-ignition is severe.

The **reedbeds of Lesser Prespa Lake** border intensively cultivated agricultural lands and/or are connected to streams & ditches that drain agricultural land. The cultivated areas experience annually multiple fires for field clearance and expansion, concentrated in February and March, but extending into May. After these months, fire ignition is absent in the observational record. Globally significant waterbird nesting sites are in the lake-fringing reedbeds, with breeding taking place in spring. The potential ecological losses associated with late winter to spring reedbed fires are thus severe.

The risk classes for Lesser Prespa reedbed fires are given in Table 5.1, whereas the risk assessment is given in Table 5.2. Please notice the percentage of the years to experience low, high and extreme fire risk in the Lesser Prespa region (Table 5.1). Appendix A details the creation of these risk classification.

Table 5.1: Risk classes for reedbed fires around Lesser Prespa Lake, based on data over the observation period (2007-2022).

Risk classes	Chances fire	Burnt Reedbed Area	Percentage years	Potential Ecological losses
Low	20%	2%<	**35%**	Minimal
High	75%	2-30%	**60%**	Significant
Extreme	>90%	>30%	**5%**	Severe

Table 5.2: Wetland (reedbed) fire risk index for **Lesser Prespa Lake** for late winter until the end of spring.

RISK	Climate-related fire hazard		Potential Ecological Loss	Ignition sources / rate	Rational Risk classification
	P_{wet}	Lowland snowfall			
Low	>500 mm	No	Severe; nesting sites of globally significant waterbirds populations are located in the reedbeds of Lesser Prespa Lake. Late winter to early spring fires may destroy nests and prohibit breeding (leading to population decline of endangered species).	Annual ignition of numerous fires in late winter to spring for field clearance / expansion. Repeated large fires (often annually) – all reedbeds were burned at least once over 2007-2022.	Large reedbed fires are not documented under high wet season precipitation and absence of lowland snowfall.
Low	>500 mm	Yes			Large reedbed fires are not documented under high wet season precipitation. Lowland snowfall enhances fire spread danger significantly, but total burnt area during wet years is very limited. Potential ecological losses are therefore limited.
High	<500 mm	No			Reedbed fires occur frequently when wet season precipitation <500mm. Fire ignition under weather conditions with wind and/or high temperatures (that occur every year) may lead to large fires and significant ecological losses.
Extreme	<500 mm	Yes			Reedbed fires occur frequently when wet season precipitation <500mm. Flattened reedbeds (due to lowland snowfall) lead to extreme potential fire spread. Any fire ignition may lead to large fires and significant ecological losses.

The **reedbeds of Great Prespa Lake** border cultivated lands for a much smaller proportion of its margin; furthermore, these lands are cultivated less intensively. Large reedbed fires along the shoreline of Great Prespa Lake are infrequent. Documented reedbed fires occur near grazing / fishing areas, near access roads, and along the northern shoreline, where there are agricultural fields and tourist facilities. There are no globally significant waterbird nesting & breeding sites located here.

As the fire frequency / size and potential ecological impact is limited, fire risk categories are adjusted accordingly. The risk classes for Great Prespa reedbed fires are given in Table 5.3, whereas the risk assessment is given in Table 5.4. Appendix A details the creation of these risk classification.

Table 5.3: Risk classes for reedbed fires around Great Prespa Lake, based on limited data over the observation period (2007-2022).

Risk classes	Chances fire	Burnt Reedbed Area	Percentage years	Potential Ecological losses
Low	5%<	1%<	**35%**	Minimal
Medium	40%	1-5%	**65%**	Minor

Table 5.4: Wetland (reedbed) fire risk index for **Great Prespa Lake** for late winter until the end of spring.

RISK	Climate-related fire hazard		Potential Ecological Loss	Ignition sources / rate	Rational Risk classification
	P_{wet}	**Lowland snowfall**			
Low	>500 mm	No	Limited; large reedbed areas without critical ecological habitats.	Intermittent; occasional fires from late winter to the end of spring for field / shore clearance. The extent of fires is limited, and large expanses were not burned over 2007-2022.	Reedbed fires are not documented under high wet season precipitation and absence of lowland snowfall.
	>500 mm	Yes			Reedbed fires are not documented under high wet season precipitation. Lowland snowfall may lead to fire spread (limited burnt area in wet years). Potential ecological losses are limited.
Medium	<500 mm	No			Reedbed fires occur frequently when wet season precipitation <500mm. Weather conditions with wind and/or high temperatures may lead to large fires. However, fire ignition is low and ecological losses limited. Thus, the risk is classified as medium.
Medium	<500 mm	Yes			Reedbed fires occur frequently when wet season precipitation <500mm. Fire ignition is low and ecological losses limited. Flattened reedbeds (due to lowland snowfall) lead to significant potential fire spread. However, observed total burned area is limited. Thus, the risk is classified as medium.

5.2 Summer wetland fire risk

Wetland fires over the **fire season**, from **June until the end of September**, along the streams and shorelines of both Prespa Lakes are **infrequent/rare** and limited in extent. Globally significant waterbird nesting sites are mainly located along the northern shores of Lesser Prespa Lake; the breeding season is finished in summer (limiting potential fatalities). As most reedbeds of Lesser Prespa are surrounded by (irrigated) agricultural fields and farmers actively avoid fire-ignition, the potential for **extensive ecological losses is limited**.

Wildfires over the fire season in the Prespa catchment are related to fire hazard indicated by the FWI. Especially the (consequent) number of days with **"very extreme" fire danger (FWI >70),** associated with drought / heatwave and low relative humidity conditions, are strongly linked to large forest fires. Consecutive "very extreme" fire danger days usually occur between June and September.

Under "very extreme" fire danger conditions, some riparian woodlands and wetland reedbeds may be affected by large forest fires that originate in the surrounding mountains. The total burned wetland area between 2002 to 2019, related to such fires, is very limited. It is confined to the western and southern parts of the catchment area (where forest and shrubland grow on a limestone substrate; see chapter 3). All burned wetland areas are associated with the extreme fire season of 2007, which was characterized by several multi-day clusters with very extreme FWI values (>70).

The European "Copernicus Climate Change Service" presents FWI data over the fire-season for entire Europe at NUTS-3 level. A key threshold is the number of days per year with a FWI >45 that is chosen by the European Forest Fire Information System (EFFIS) to define very high danger in Europe. Averaged for the entire region of Florina, there were **~24 days with very high fire danger** over the fire seasons from 1985 to 2005 (https://cds.climate.copernicus.eu/cdsapp#!/software/app-tourism-fire-danger-indicators-projections?tab=overview). Forest wildfires are more likely to occur on these days.

The **fire risk to forest (mountain) environments** during the **fire season** is deemed **medium on days with FWI >45**. The **fire risk to forest (mountain) environments** during the **fire season** is deemed **high on days with FWI >70 ("very extreme").**

When there are multiple sequences of consecutive days with FWI>70 over the fire season**, forest wildfire risk is severe,** based on the historical fire size and the potential ecological impact on rare forest habitats.

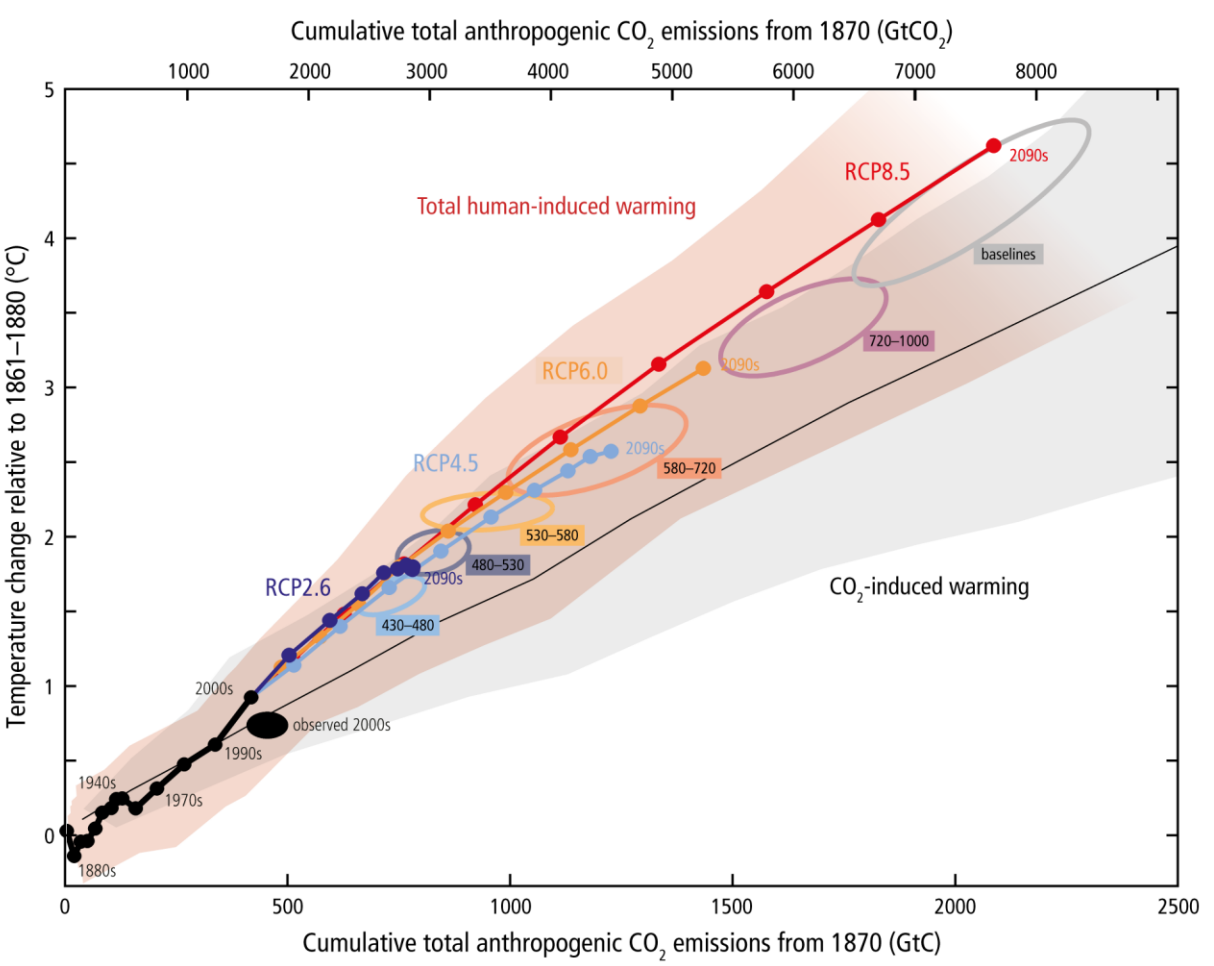
However, the **fire risk** to **wetland environments** during the **fire season** is deemed **low-medium on days with FWI >70**, based on the historical wetland fire frequency & size of burned wetland areas, as well as the limited potential ecological impact.

6. Future climate projections: approach

This study assesses the impact of future climate change on wetland fire hazard & risk in the Prespa Lake catchment area under business-as-usual land-use and fire management scenarios. These scenarios assume that the key variables remain stable, including land-use & cover, vegetation distribution & types, fire-suppression methods, fire-ignition causes and climate-fire-vegetation feedbacks. Such assumptions are common for modelling studies, to make outcomes comparable to the present-day situation.

Wetland wildfire hazard and risk were assessed under three future climate change scenarios based on RCP2.6 (ambitious mitigation policies), RCP4.5 (moderately ambitious mitigation policies), and RCP8.5 (business as usual, no mitigation); see Figure 6.1. For more information on these scenarios, see the IPCC's synthesis report on "Future Climate Changes, Risks and Impacts" at https://ar5-syr.ipcc.ch/topic_futurechanges.php.

Figure 6.1: Representative Concentration Pathways (RCPs) used in this study are RCP2.6, RCP4.5, and RCP8.5. Currently, pathways RCP4.5 is considered the most likely (up to 2,5°C warming by 2090s).



State-of-the-art climate models, at a horizontal resolution of 12km developed within the EURO-CORDEX initiative (available at the Climate Data Store: https://cds.climate.copernicus.eu), simulated future climate data for the Prespa area up to 2070. Specifically, three RCMs and four GCMs were used in different pairs, to create six climate model simulations (Table 6.1).

Three Regional Climate Models: The HIRHAM5 (https://backend.orbit.dtu.dk/ws/portalfiles/portal/51950450/HIRHAM.pdf) RCM of the Danish Meteorological Institute (DMI); the RACMO22E (https://cdn.knmi.nl/knmi/pdf/bibliotheek/knmipubTR/TR302.pdf) RCM of the Royal Netherlands Meteorological Institute (KNMI); and the RCA4 (https://www.smhi.se/en/research/research-departments/climate-research-at-the-rossby-centre/ rossby-centre-regional-atmospheric-model-rca4-1.16562) RCM of the Swedish Meteorological and Hydrological Institute (SMHI).

Four Global Climate Models: driven by EC-EARTH global climate model (https://ec-earth.org/); the CNRM-CM5 of the Météo France Institute (https://www.umr-cnrm.fr/); the HadGEM-ES of the Met Office Hadley Centre (https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model/climate-models/hadgem2); and the MPI-ESM-LR of the Max Planck Institute for Meteorology (https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018MS001400).

Table 6.1: The six climate models used in this study.

EURO-CORDEX RCM / GCM pairs (resolution of ~12km)				
Institute	*RCM*	*GCM*	**GCM-RCM pair**	**Extracted variables**
DMI	HIRHAM5	EC-EARTH	EC-EARTH_r3i1p1_HIRHAM5	All variables, except evaporation & FWI
KNMI	RACMO22E	CNRM-CM5	CNRM-CM5_r1i1p1_RACMO22E	All variables, except evaporation & FWI
KNMI	RACMO22E	HadGEM2-ES (MOHC)	HadGEM2-ES_r1i1pi_RACMO22E	All variables, except evaporation & FWI & wind
SMHI	RCA4	EC-EARTH	EC-EARTH_r12i1p1_RCA4	All variables
SMHI	RCA4	HadGEM2-ES (MOHC)	HadGEM2-ES_r1i1p1_RCA4	All variables, except wind
SMHI	RCA4	MPI-ESM-LR	MPI-ESM-LR_r1i1pi_RCA4	All variables

The following variables were extracted for model grid-points across the Prespa area (Table 6.1): daily minimum (Tmin) and maximum (Tmax) temperature, daily precipitation, maximum windspeed, and evaporation. In addition, simulated data were used to calculate the SPEI (3, 6, 9 and 12 months) and the FWI (both for months 1-4, and for months 5 to 10).

This study also uses projections from the European "Copernicus Climate Change Service" regarding FWI over future fire seasons and snowfall under different climate scenarios. Specifically, **FWI values** for Europe from 1970 to 2098 are derived from reanalysis and climate projections, accessed at: https://cds.climate.copernicus.eu/cdsapp#!/software/app-tourism-fire-danger-indicators-projections?tab=overview.

Snow indicators for Europe from 1986 to 2100 are derived from reanalysis and climate projections, accessed at: https://cds.climate.copernicus.eu/cdsapp#!/software/app-tourism-mountain-indicators-projections?tab=app.

7. Climate change projections

This chapter presents the simulated future climate variables that are relevant to fire danger, and specifically: daily minimum and maximum temperature (Tmin and Tmax, resp.), daily precipitation, the maximum windspeed, open water evaporation and snow cover. Results are shown as an ensemble mean of the selected RCMs model simulations spanning 1971-2070.

7.1 Future changes in minimum and maximum temperature

High maximum temperatures (for February & March) are observed on ~70% of the days that have reedbed fires. It appears therefore a factor that aids (but does not determine) fire spread in reedbeds (section 4.2).

Both the minimum and maximum temperatures show large increases under all scenarios, by 1-4 °C around 2070, as displayed in figures 7.1 and 7.3 (smallest to largest increases: RCP2.6 → RCP4.5 → RCP8.5). There are also large projected monthly increases in maximum temperature under all scenarios, of around 2-4 °C (Fig. 7.2).

The overall increase in monthly maximum temperatures over the months experiencing reedbed fires (late winter to spring; figure 7.2) indicates a future increase in this fire hazard (for further analysis see chapter 8).

Figure 7.1: future annual averaged **maximum** temperature under scenarios RCP2.6, RCP4.5 and RCP8.5 (1971-2070).

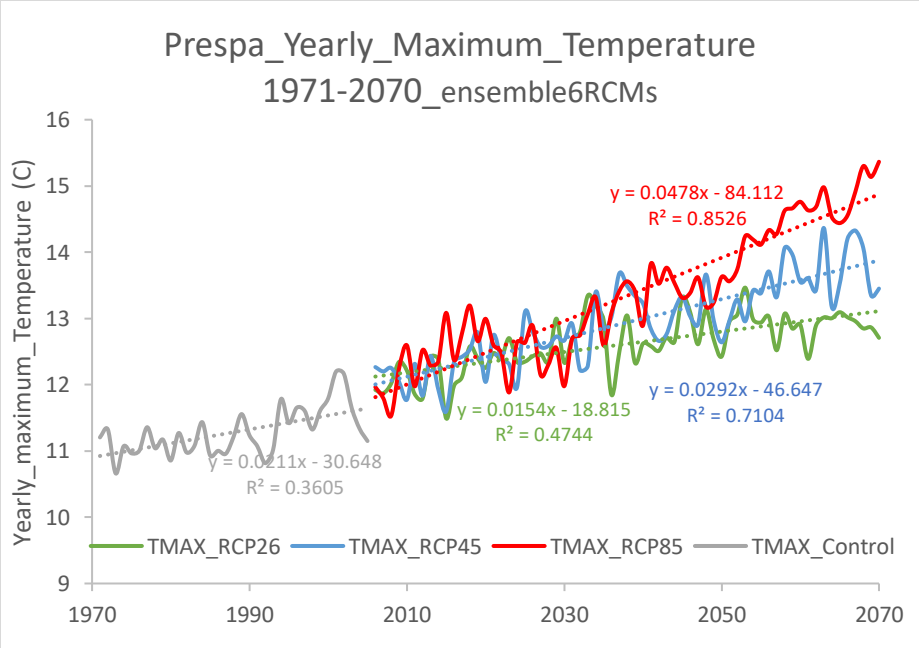


Figure 7.2: averaged **maximum monthly temperature** changes (control vs future scenarios).

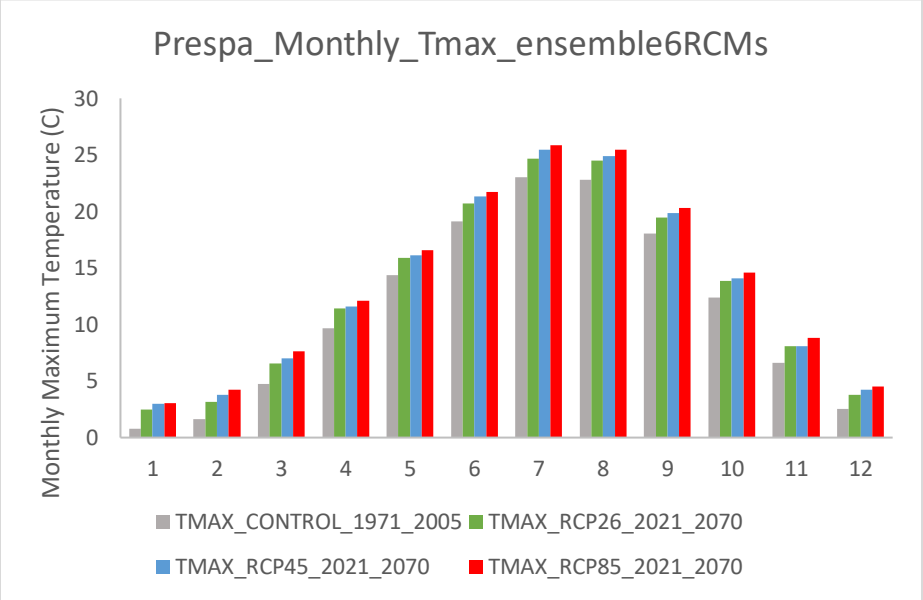
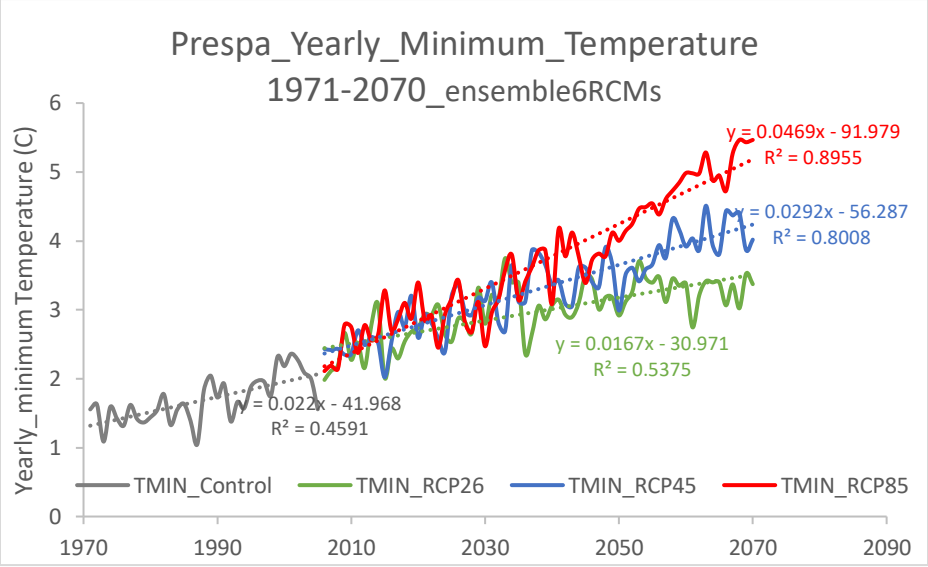


Figure 7.3: future annual averaged **minimum** temperature under scenarios RCP2.6, RCP4.5 and RCP8.5 (1971-2070).

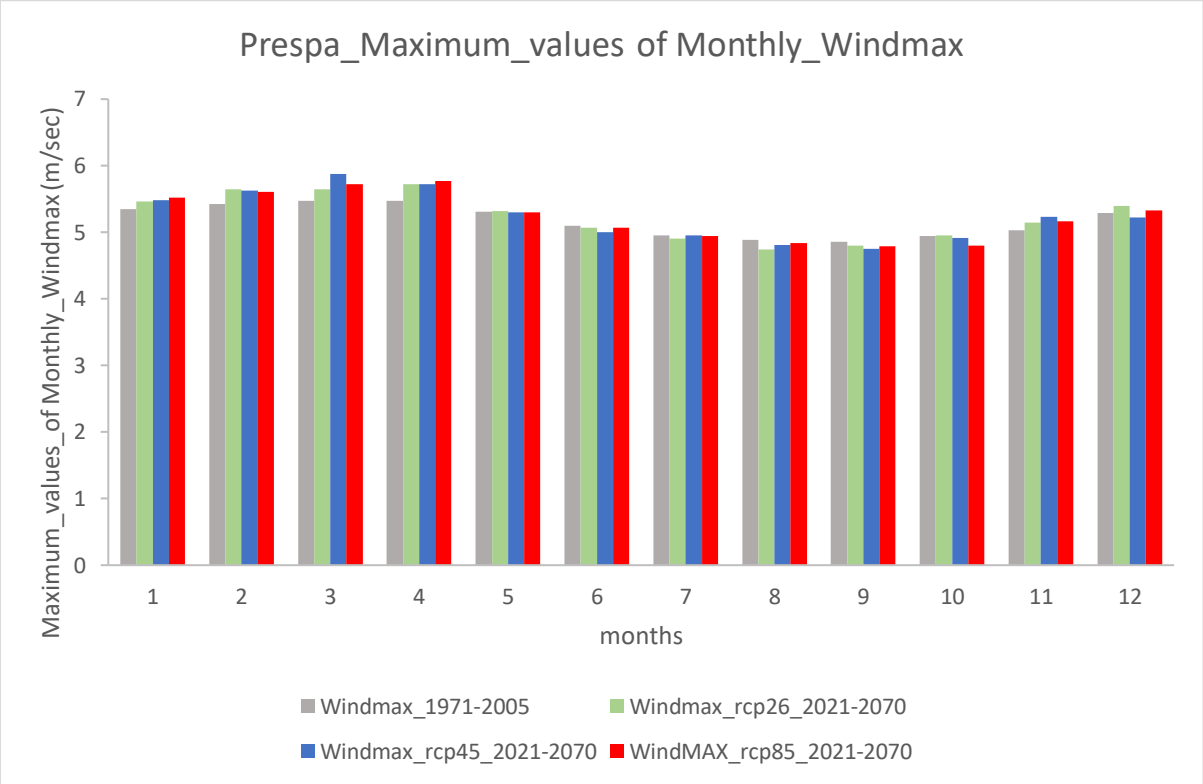


7.2 Future changes in maximum windspeed

Below the threshold of 3 m/sec (~3 Bofort), there appears to be very limited fire spread in wetlands and thus burnt reedbed area. Days with wind speeds above this threshold occur regularly over the months of interest.

The model suggests no significant change in days with windspeeds above 3 Bofort, but future variability may increase. Maximum windspeed increases slightly from November until the end of April (Fig. 7.4). There are no indications that the wetland fire hazard associated with windspeeds >3 Bofort changes in the future.

Figure 7.4: the montly averaged maximum windspeeds for the control period and under future scenarios in Prespa.



7.3 Future changes in precipitation

Wet season (Oct-Mar) precipitation above 500mm (~65th percentile of historical wet season precipitation) is linked to very limited / no reedbed fires. When wet season precipitation is **below** this threshold, large reedbed fires are more likely (see section 4.2).

Monthly average precipitation does not change significantly between historical and future periods (1971-2000 vs 2041-2070), or between scenarios (Fig. 7.5). From April to October, and in December, monthly average precipitation declines. March experiences no change, while precipitation in November, January and February increases. All changes are non-significant.

The overall precipitation trend appears to decline under RCP4.5 and RCP8.5, whereas future precipitation variability increases under these scenarios (Fig. 7.6). Future average hydro-yearly, wet- and dry season precipitation under RCP2.6 are not different from the historical period. The future change in average hydro-yearly (Oct-Sep) precipitation is only significant under scenario RCP8.5. When future precipitation is broken down into a wet- and dry period, there is only a significant decrease in precipitation for the dry season under RCP8.5.

The decreasing frequency of future years with precipitation >500mm is significant under scenarios RCP4.5 and RCP8.5. Over the historical period, precipitation above this threshold occurred 35% of the years. In the future (2041-2070), years with precipitation above 500mm only happen 22% (RCP4.5) or 18% (RCP8.5) of the time. This **decrease in the frequency of wet years** (with precipitation >500mm) is significant.

Figure 7.5: monthly precipitation for the control period and under future scenarios RCP2.6, RCP4.5 and RCP8.5 (up to 2070) in Prespa.

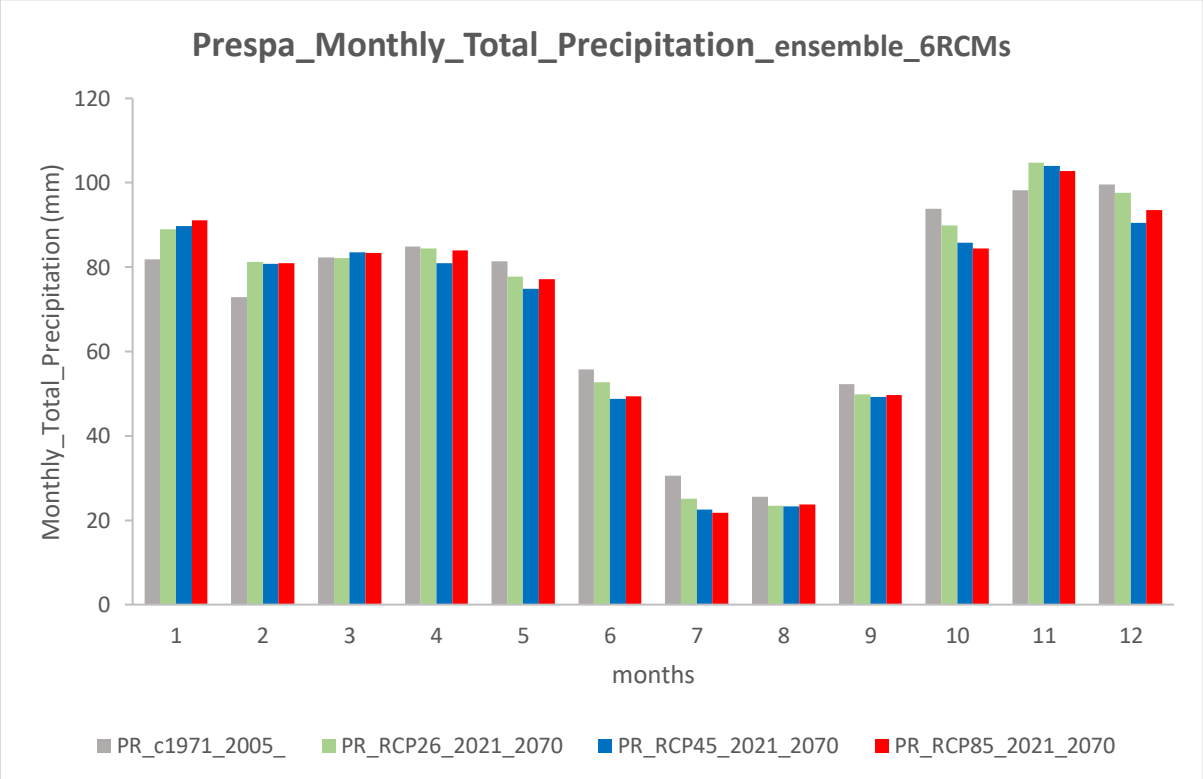
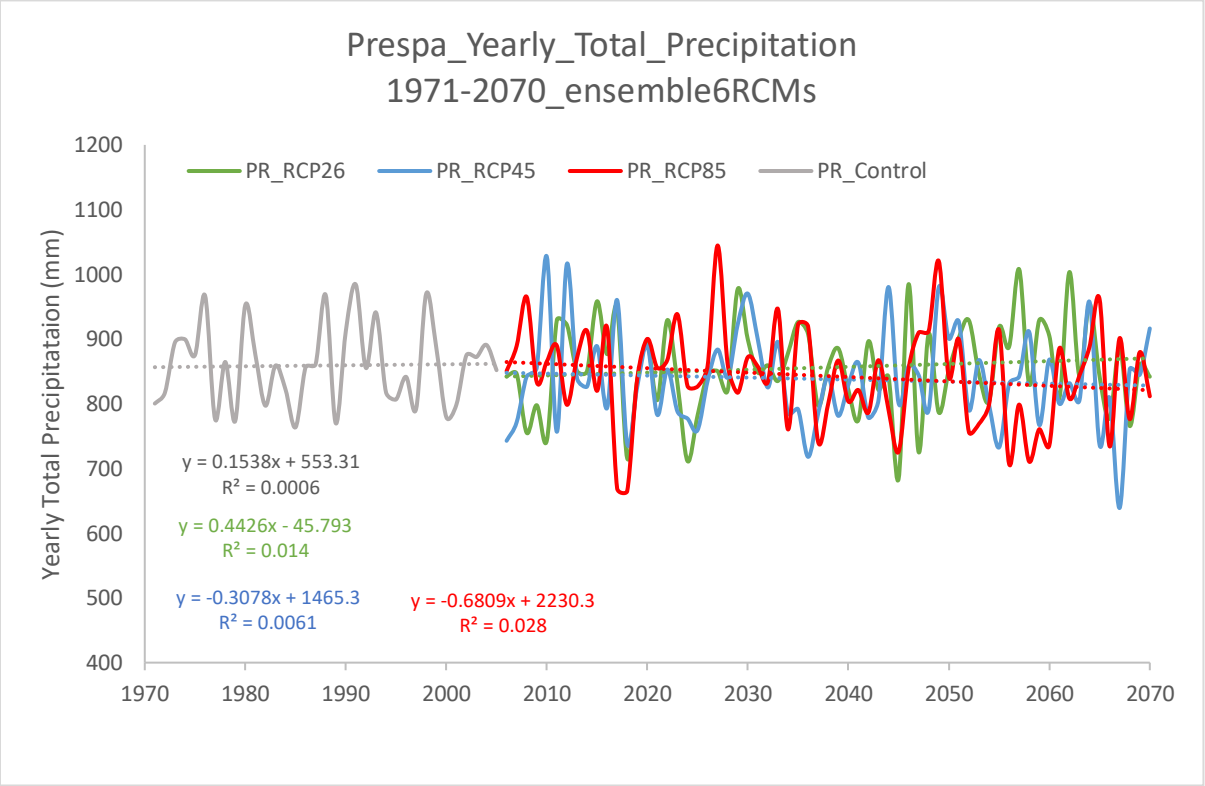


Figure 7.6: annual precipitation projections from 1971 until 2070 under scenarios RCP2.6, RCP4.5 and RCP8.5.



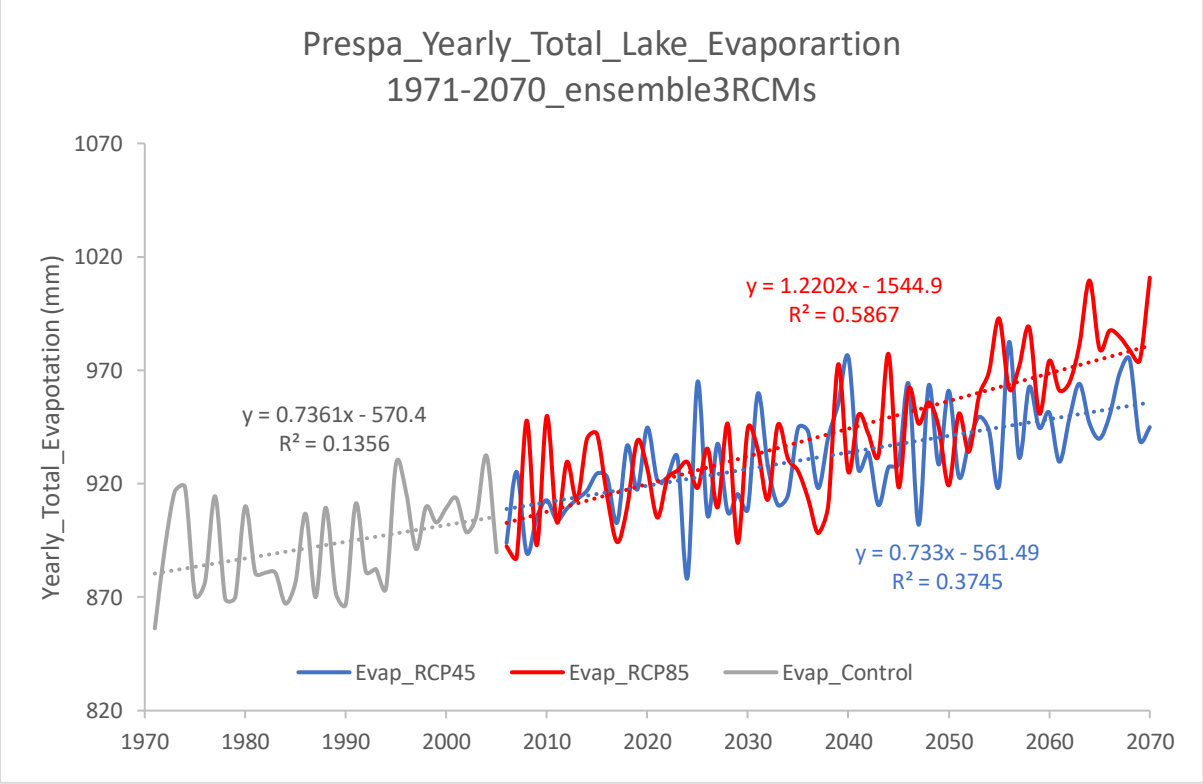
7.4 Future changes in lake evaporation

Lake evaporation is not directly related to wetland fire hazard. However, decreasing wet season precipitation (Oct-Mar; section 7.3) and snow cover (section 7.7), combined with increasing lake evaporation will lead to lower water levels of Great Prespa Lake. The outflow of Lesser Prespa Lake is controlled by a sluice, which may limit or avoid a long-term decline in water level here.

Lower water levels of Great Prespa Lake may lead to desiccation of riparian zones (especially at their upper limits) and easier access of fire to the reedbeds. Furthermore, falling water levels may stimulate (illegal) expansion of agricultural fields into the riparian zone, which is often cleared using arson.

Future lake (open water) evaporation increases significantly from February until the end of November. There is a strongly increasing trendline under scenarios RCP4.5 and RCP8.5 (Fig. 7.7): by 2070 there may be up to 60mm (RCP4.5) to 100mm (RCP8.5) extra lake evaporation. Under such scenarios, lake water levels of 840m or lower are becoming very likely. Note that there is no model outcome for evaporation under RCP2.6.

Figure 7.7: projected annual open water evaporation changes from 1971 until 2070 under scenarios RCP4.5 and RCP8.5.



7.5 Future snow cover changes

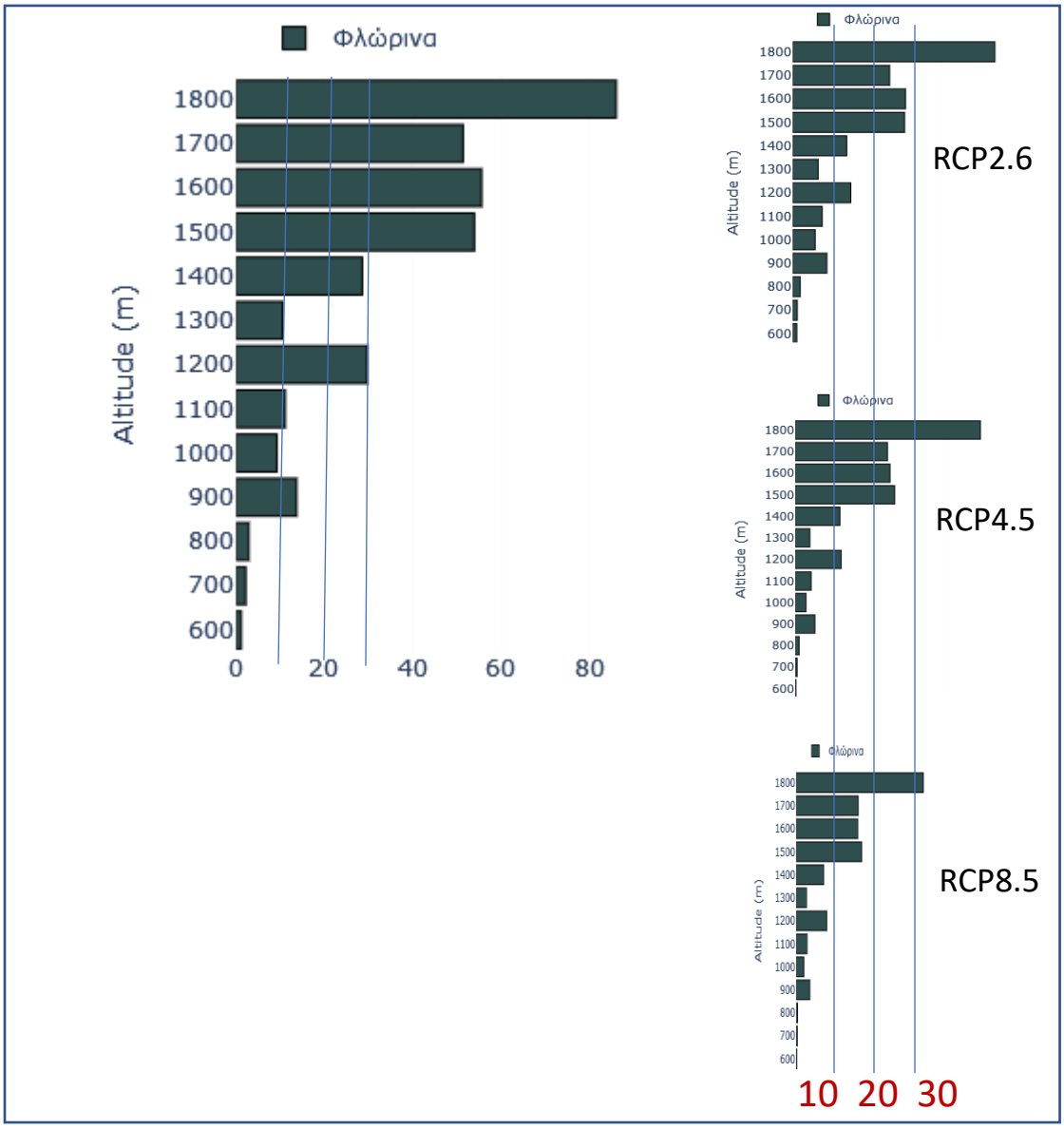
Snow cover is not directly related to wetland fire hazard. However, decreasing snow cover and wet season precipitation will decrease runoff and groundwater recharge. This may make riparian environments around streams, and away from the lake margins, drier during summer and more vulnerable to forest wildfires during the fire season. The decrease in snow cover is one of the factors that will drive the lowering of water levels of Great Prespa Lake.

For this study we retrieved on 28/02/2023 from the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/cdsapp#!/software/app-tourism-mountain-indicators-projections?tab=app) projections regarding historical and future snow cover in the province of Florina. These projections are based on the "Mountain Tourism Meteorological and Snow Indicators" (MTMSI) C3S dataset, on the scale of NUTS level 3 regions. Multi-model statistics are derived from multiple global climate model (GCM) and regional climate model (RCM) pairs for three climate change scenarios: RCP2.6 (2 GCM/RCM pairs) and RCP4.5 and 8.5 (9 GCM/RCM pairs each).

Projections indicate that the annual number of days (from August to July) with a snow depth of more than 30cm are decreasing across all altitudes in the future (Florina province). Figure 7.8 shows historical data versus simulated scenarios (RCP2.6, RCP4.5 and RCP8.5). Over the historical period (1986-2005), there were 10-20 days per year when snow depth was >30cm between altitudes of 900-1400m, whereas altitudes from 1500-1700m saw 55-60 of such days. The future period 2041-2060 shows a decrease in days with snow >30cm across all scenarios: at altitudes of 900-1400m 3-10 days/year are projected, and at altitudes from 1500-1700m 15-25 days/year are projected. The largest decreases are therefore projected in the higher mountains: here projections suggest up to 30 fewer days (i.e., one month!) with snow cover exceeding 30cm.

Note that lowland snowfall (i.e., 800-900m in Prespa) decreases non-significantly. Therefore, the fire hazard associated with lowland snowfall is not expected to change (see chapter 5).

Figure 7.8: annual number of days (from August year 1 to July year 2) with snow depth >30cm using a groomed snow simulation. Top left inset figure: historical data (1986-2005). Inset figures to the right: annual days with snow depth >30cm, under 3 different climate scenarios, for the future period 2041-2060.



8. Drought Indices

This chapter summarises the simulated future drought indices that are relevant to fire danger, and specifically the SPEI and the FWI. The indices are driven by the simulated climate variables (section 7).

8.1 Future changes in the drought index (SPEI)

The **SPEI** (on various timescales, from 1 to 12-months) **cannot** be linked to the outbreak of large reedbed fires over late winter to springtime over the historical period.

There are no significant changes in future very- to extreme wet events (SPEI>1.5), or in future severe- to extreme dry events (SPEI<-1.5) for the SPEI in March (see table 2.3 explaining SPEI classes). However, the SPEI-6 in March (covering the wet season) shows that events of both >1.5 and <-1.5 will happen 2-5% more under RCP4.5 and RCP8.5, compared to the control period. This suggests that the multi-month dry/wet variability increases, in line with the findings regarding future precipitation (section 7.3).

8.2 Future changes in the fire danger index (FWI)

The daily to (multi-)monthly **FWI cannot** be linked to the outbreak of large reedbed fires in Prespa over **late winter to springtime**. Overall, the future FWI over these months continues to be low and is not indicative of the wetland (reedbed) fire hazard over these seasons.

However, **wildfires** over the **fire season** are related to **fire hazard** as indicated by the daily FWI**.** Very high danger in Europe is defined by the European Forest Fire Information System (EFFIS) as the number of days per year with a Fire Weather Index greater than 45. On average, there were **~24 very high** fire danger days (FWI>45) per year in the province of Florina.

Days with FWI values of >45 over the fire season are projected to increase under all scenarios and all future periods (Table 7.1). In the near future (up to 2040), the number of such days will **increase** by 20-25%. Over the future period 2041-2060, there are even **stronger increases** of 27% (RCP2.6), 33% (RCP4.5) and 47% (RCP8.5). Up to the end of this century, these strong increases in number of days with FWI>45 over the fire season will **continue** for scenarios RCP4.5 (50%) and RCP8.5 (108%). There is only a small decrease under RCP2.6 (to 24%) compared to the preceding 2041-2060 period.

Table 8.1: Percentage increases in future days with very high fire danger (FWI>45) over the fire season (June-July-August-September) under three climate scenarios (RCP2.6, RCP4.5 and RCP8.5).

FUTURE PERIOD	RCP2.6	RCP4.5	RCP8.5
2021-2040	23%	21%	24%
2041-2060	27%	33%	47%
2069-2098	24%	50%	108%

Large forest fires in the Prespa catchment are associated with drought / heatwaves and low relative humidity conditions, corresponding to successive days with “very extreme” FWI values of >70. Such large wildfires occur mainly from June-September in the Prespa catchment.

Large wildfires, originating in the mountains, may spread to riparian woodlands around streams and in extreme cases to riparian environments around the lakes. On average, there were **~3 very extreme** fire danger days (FWI>70) per year in Prespa.

Days with FWI values of >70 over the fire season are projected to increase under scenarios RCP4.5 (+40%) and RCP8.5 (+109%) in 2041-2070. Only under scenario RCP2.6 a slight future decrease (-8%) is projected.

9. Future fire hazard and risk

To determine future **wetland fire risk** in the Prespa catchment, we use the risk classification and the areal / seasonal subdivision as explained in chapter 5. Wetland fire risk assessment combines evaluation of the main fire hazards in the area, potential ecological losses, and ignition sources / locations.

This **evaluation** looks specifically at the **impact of future climate change** (up to 2070) on wetland fire hazards related to climatic and weather variables (section 4.2). The other variables in the wetland fire risk matrix (i.e., potential ecological losses and ignition sources / locations) are considered stable for the purpose of this study.

9.1 Reedbed fire risk index (late winter to end of spring)

Future climate change will have impacts on:

1. One key **climate-related hazard** that is linked to wetland reedbed fires: annual wet season (Oct-Mar) precipitation of >500mm.
2. One key **weather-related hazard** that influences fire spread and total burned area on the day of fire-ignition: **maximum temperatures of >10°C** (for February & March).

The future risk classes for Lesser Prespa reedbed fires are given in Table 9.1, whereas the risk assessment is given in Table 9.2. See appendix A for an explanation of the calculation of the risk tables.

Future years with "low" risk, related to abundant wet season precipitation, are decreasing (from 35% to 20%) compared to the historical period. Also, rising temperatures will create more frequently favourable conditions for fire-spread. Both changes explain the increase in years with high fire risk. Two other factors that influence reedbed fires, i.e., lowland snowfall and windspeed, are not projected to change significantly.

Furthermore, the decreasing precipitation and upland snowfall, and increasing evaporation, will cause lower water levels for Lesser Prespa Lake. This may increase the incentive for field expansion into the reedbed zone through arson (and therefore fire ignition frequency).

Table 9.1: Risk classes for reedbed fires around Lesser Prespa Lake for the future period 2041-2070.

Risk classes	Chances fire	Burnt Reedbed Area	Percentage years	Potential Ecological losses
Low	20%	2%<	**20%**	Minimal
High	75%	2-30%	**75%**	Significant
Extreme	>90%	>30%	**5%**	Severe

Table 9.2: Wetland (reedbed) fire risk index for **Lesser Prespa Lake** for late winter until the end of spring for the future period 2041-2070.

RISK	Climate-related fire hazard		Potential Ecological Loss	Ignition sources / rate	Rational Risk classification
	P_{wet}	Lowland snowfall			
Low	>500 mm	No	Severe; nesting sites of globally significant waterbirds populations are located in the reedbeds of Lesser Prespa Lake. Late winter to early spring fires may destroy nests and prohibit breeding (leading to population decline of endangered species).	Annual ignition of numerous fires in late winter to spring for field clearance / expansion. More incentive for field expansion (stable / falling lake level) and more years with high Feb – Mar maximum temperatures.	Large reedbed fires are not documented under high wet season precipitation and absence of lowland snowfall.
Low	>500 mm	Yes			Large reedbed fires are not documented under high wet season precipitation. Lowland snowfall enhances fire spread danger significantly, but total burnt area during wet years is very limited. Potential ecological losses are therefore limited.
High	<500 mm	No			Reedbed fires occur frequently when wet season precipitation <500mm. Fire ignition under weather conditions with wind and/or high temperatures (occurring more frequently in the future) may lead to large fires and significant ecological losses.
Extreme	<500 mm	Yes			Reedbed fires occur frequently when wet season precipitation <500mm. Flattened reedbeds (due to lowland snowfall) lead to extreme potential fire spread. Any fire ignition may lead to large fires and significant ecological losses. Future extreme maximum temperatures in Feb-Mar will also increase in frequency (facilitating fire-spread).

The future risk classes for Great Prespa reedbed fires are given in Table 9.3, whereas the risk assessment is given in Table 9.4. See appendix A for an explanation of the calculation of the risk tables.

Wetlands around Great Prespa lake have a much lower historical fire frequency and burnt area extent than those around Lesser Prespa lake (chapter 3). Together with the absence of bird nesting sites of globally endangered waterbird species, which limits potential ecological losses due to fire, this leads to a different risk classification (chapter 5) than for Lesser Prespa.

Compared to the historical period, future years with "low" risk due to abundant wet season precipitation are decreasing (from 35% to 20%). Also, rising and extreme maximum temperatures will create more frequently favourable conditions for fire-spread in February to March. These changes explain the increase in years with medium fire risk (from 65% to 80%).

Lowland snowfall and windspeed are not projected to change significantly. However, the decreasing precipitation and snowfall, and increasing evaporation will cause lower stable lake levels for Lesser Prespa Lake. This may increase the incentive for field expansion into the reedbed zone through arson (and therefore fire ignition frequency). This variable cannot be accounted for in this risk assessment, as it is an unquantifiable assumption. However, it should be closely monitored in the field.

Table 9.3: Risk classes for reedbed fires around Great Prespa Lake for the future period 2041-2070.

Risk classes	Chances fire	Burnt Reedbed Area	Percentage years	Potential Ecological losses
Low	5%<	1%<	**20%**	Minimal
Medium	40%	1-5%	**80%**	Minor

Table 9.4: Wetland (reedbed) fire risk index for **Great Prespa Lake** for late winter until the end of spring for the future period 2041-2070.

RISK	Climate-related fire hazard		Potential Ecological Loss	Ignition sources / rate	Rational Risk classification
	P_{wet}	**Lowland snowfall**			
Low	>500 mm	No	Limited; large reedbed areas without critical ecological habitats.	Intermittent; occasional fires from late winter to the end of spring for field / shore clearance. More incentive for field expansion (falling lake level) through arson and more years with high Feb – Mar maximum temperatures.	Reedbed fires are not documented under high wet season precipitation and absence of lowland snowfall.
	>500 mm	Yes			Reedbed fires are not documented under high wet season precipitation. Lowland snowfall may lead to fire spread (limited burnt area in wet years). Potential ecological losses are limited.
Medium	<500 mm	No			Reedbed fires occur frequently when wet season precipitation <500mm. Weather conditions with wind and/or high temperatures may lead to large fires. However, fire ignition is low and ecological losses limited. Thus, the risk is classified as medium.
Medium	<500 mm	Yes			Reedbed fires occur frequently when wet season precipitation <500mm. Fire ignition is low and ecological losses limited. Flattened reedbeds (due to lowland snowfall) lead to significant potential fire spread. However, observed total burned area is limited. Thus, the risk is classified as medium.

9.2 Wetland fire risk during the fire season (June-July-August-September)

Wildfires over the fire season in the Prespa catchment are strongly related to the number of days with **"very extreme" fire danger, with an FWI >70** (section 5.2). Under "very extreme" fire danger conditions, some riparian woodlands and reedbeds may be affected by large forest fires that originate in the mountains surrounding the catchment. The total burned wetland area from 2002-2019, related to such fires, is limited. It is confined to the western and southern parts of the catchment area (where forest and shrubland grow on a limestone substrate; see chapter 3).

On average, there were **~3 very extreme** fire danger days (FWI>70) per year in Prespa. **Days with FWI values of >70** over the fire season are projected to increase under scenarios RCP4.5 (+40%) and RCP8.5 (+109%) in 2041-2070. Only under scenario RCP2.6 a slight future decrease (-8%) is projected.

Although the forest fire hazard increases, potential spread to riparian environments is likely limited due to the high moisture content of these habitats. Furthermore, the potential for large-scale ecological losses is limited, given that the breeding season is finished in summer (limiting potential fatalities). Also, globally significant waterbird nesting sites are mainly located along the northern shores of Lesser Prespa Lake and surrounded by (irrigated) agricultural fields and farmers who actively avoid fire-ignition, thus limiting the potential for ignition from wildfires originating in the surrounding mountains.

This analysis assumes that fire-ignition (frequencies / causes) remain stable in the future. However, increasing access roads to forests and the construction of windfarms and solar energy parks strongly increases the fire risk due to carelessness or related to power-grid infrastructure. This risk-increase cannot be quantified at present, but any developments should be closely monitored.

The **fire risk to forest (mountain) environments** during the **fire season** is deemed **high** on days with **FWI >70 ("very extreme").** Such days are increasing in the future scenarios RCP4.5 (+40%) and RCP8.5 (+109%). Forest wildfires will become more frequent in the future, given the strong link between days with FWI > 70 and forest wildfire ignition.

The **fire risk to wetland environments** during the **fire season** is deemed **low-medium on days with FWI >70**, based on the limited historical impact on wetland fire frequency & size of burned wetland areas, as well as the limited potential ecological impact.

10. Summary and conclusions

This report assessed if (wetland) wildfire hazards in the Prespa Lake catchment are related to specific meteorological conditions and thus influenced by climate change. Secondly, it evaluated how future climate change may affect (wetland) wildfire hazard and risk.

10.1 Historical Forest wildfires: description & conditions

Over the period from 2002 up to 2019, the largest forest wildfires occurred in the eastern and southern parts of the Prespa region, on dry limestone soils. In the (north-) east of the Prespa catchment, wildfires were on average smaller. No areas were burned more than once over this period.

Forest wildfires did not start in riparian woodlands, likely due to their (relatively) high wood-moisture content and humidity. Riparian woodlands were (very) infrequently affected by large forest fires that were triggered in the surrounding mountains during heatwaves.

Large forest wildfires over the fire season (JJAS) in the Prespa catchment are related to "very extreme" FWI values (>70) that are associated with heatwave and drought conditions. It should be noted that at least 60% the total burnt area over the period 2002-2019 was burned during the extreme fire season of 2007, when there were several clusters of successive days with "very extreme" fire danger values throughout the fire season.

10.2 Historical Wetland Reedbed wildfire fires: description & conditions

Reedbed fire hazard was assessed using the SPP's database of wetland fires in the Greek part of the Prespa catchment (spanning 2007-2022) and Koula meteorological station data (regarding weather conditions at the time of the individual wetland fires).

The largest reedbed fires (2007-2022) took place in February and March. Fire danger related to weather conditions (for example, drought, humidity, temperature) is low over these months. Reedbed **fire-ignition is related to land-use** activities (i.e., field- & drainage clearance, and field expansion, through arson) and takes place from the end of January until May. These fires are ignited during days when weather conditions are favourable to fire-spread.

Wetland fire danger related to weather conditions is much higher during summer. However, the **(near) total absence** of **reedbed fires over the fire season** (June-July-August-September), reflects the absence of fire-ignition due to human causes. Fields surrounding the wetlands are heavily cultivated from late spring onwards, fire-ignition is avoided by farmers and fires actively suppressed as these threaten their crops.

The same areas are repeatedly burned by reedbed fires. Some areas burned up to 6-7 times over the 2007-2022 period (Pili, Opagia and Slatina), whereas most other reedbed areas burned 2-4 times. Only a very small portion of the total (Greek) reedbed area around Lesser Prespa Lake burned once or not at all.

10.3 Reedbed fire hazards & climate

Fire-ignition is related to annual field clearance; therefore, the annual *ignition* rate is stable. However, the total Burnt Area in the case of fire-ignition is linked to climatic variables.

Two key climate-related hazards linked to wetland reedbed fires have been identified:

- **Wet season precipitation <500mm** (~65th percentile of long-term wet season precipitation). Precipitation **above** this threshold is linked to very limited / no reedbed fires. Over the observation period, 12 out of 16 years had a **wet season precipitation of less than 500mm**; 9 out of these 12 years are characterized by (extremely) large annual burnt areas.
- **Heavy lowland snowfall, followed by late winter / early spring thaw.** Heavy snowfall flattens reedbeds and thus greatly enhances fire-spread. This mechanism was observed in 2019, when ~332 Ha of reedbeds burned along the shorelines of Lesser Prespa Lake (about 30% of the total cumulative burnt reedbed area over the 16 years from 2007 until 2022!).

Two additional weather hazards were identified that influence, individually or together, fire spread and total burned reedbed area on the day of fire-ignition:

- **Wind speeds of >3 m/sec**. Below this threshold there appears to be very limited fire spread and thus burnt area. Days with wind speeds above this threshold occur regularly.
- **Maximum temperature of >10^{o}C (Feb & Mar)**. High maximum temperatures (for February & March) are observed on ~70% of the days that have reedbed fires. It appears therefore a factor that aids (but does not determine) fire spread in reedbeds.

However, it should be noted that these weather conditions are common and occur regularly every year. These conditions cannot be correlated to burnt reedbed area; however, they are of interest for use in a reedbed fire-warning system.

10.4 Future climate projections

Wetland wildfire hazard and risk were assessed under three future climate change scenarios (RCP2.6, RCP4.5 and RCP8.5)**.** State-of-the-art climate models, at a horizontal resolution of 12km, simulated future climate data up to 2070.

Simulated climate variables, relevant to fire danger, included: daily minimum and maximum temperature (Tmin and Tmax, both increasing significantly), daily precipitation (non-significant decrease; variability increasing), windspeed no significant change), open water evaporation (increasing significantly) and snow cover (significant decreases in upland areas).

Future drought indices that are relevant to fire danger, and specifically the SPEI index (no significant change; variability increasing) and the FWI (significant increase over fire season) were calculated using the simulated climate variables.

Over the historical period, precipitation above the 500mm threshold occurred 35% of the years. In the future (2041-2070), years with precipitation above 500mm will only happen 20% of the time.

10.5 Reedbed fire risk: present & future

Wetland fire risk involves combined evaluation of wetland fire hazard, ecological losses and ignition sources.

Risk assessments were divided into **two areas** (Lesser- and Great Prespa Lake, respectively) and over **two time-periods** (late winter to the end of spring, and the fire season, respectively). This was done because of significant differences in fire ignition frequencies and potential ecological losses, between these two areas and time-periods.

Wetland fire risk in spring

Historically, major wetland fires took only place from late January to May. Their ignition is related to land-use (field and drainage-ditch clearance by fire), but large burnt reedbed areas are linked to years with wet season precipitation of <500mm and to heavy lowland snowfall. High daily maximum temperatures are also linked to significant fire-spread potential. See Appendix 1 for the calculations behind the risk tables.

Future years with "low" risk, related to abundant wet season precipitation (P>500mm), are decreasing (from 35% to 20%) compared to the historical period. Also, rising temperatures will create more frequently conditions that are favourable for fire-spread. Both changes explain the 15% increase in years with high fire risk (Tables 10.1 and 10.2). Lowland snowfall and windspeed are not projected to change significantly.

Summary table 10.1: Lesser Prespa Lake margins wetland fire risk changes (present vs. future)

Risk classes	Chances fire	Burnt Reedbed Area	Present years	Future years (2041-2070)	Potential Ecological losses
Low	20%	2%<	**35%**	**20%**	Minimal
High	75%	2-30%	**60%**	**75%**	Significant
Extreme	>90%	>30%	**5%**	**5%**	Severe

Summary table 10.2: Great Prespa Lake margins wetland fire risk changes (present vs. future)

Risk classes	Chances fire	Burnt Reedbed Area	Percentage years	Future years (2041-2070)	Potential Ecological losses
Low	5%<	1%<	**35%**	**20%**	Minimal
Medium	40%	1-5%	**65%**	**80%**	Minor

The decreasing precipitation and upland snowfall, and increasing evaporation, will cause lower lake levels. This may increase the incentives for field expansion into the reedbed zone through arson (and therefore fire ignition frequency). This variable cannot be accounted for in this risk assessment, as it is an unquantifiable assumption; it should be closely monitored in the field.

Wetland fire risk in summer

Wetland fires over the **summer fire season** (**June to end September)** along the Prespa streams and shorelines are historically **rare** and limited in extent. Under "very extreme" fire danger conditions, some riparian woodlands and reedbeds may be affected by large forest fires that originate in the surrounding mountains.

The **fire risk** to **wetland environments** during the **fire season** is deemed **low-medium on days with FWI >70**, based on the historical wetland fire frequency & size of burned wetland areas, as well as the limited potential ecological impact.

On average, there were **~3 very extreme** fire danger days (FWI>70) per year in Prespa. **Days with FWI values of >70** over the fire season are projected to increase under scenarios RCP4.5 (+40%) and RCP8.5 (+109%) in 2041-2070. Only under scenario RCP2.6 a slight future decrease (-8%) is projected. Forest wildfires will become more frequent in the future, given the strong link between days with FWI > 70 and forest wildfire ignition.

This analysis assumes that fire-ignition (frequencies / causes) remain stable in the future. However, increasing road-access to forests and the construction of windfarms and solar energy parks strongly increases the fire risk due to negligence or related to the power-grid infrastructure. This risk-increase cannot be quantified at present, but any developments should be closely monitored.

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Appendix A

SPEI

For a full (regularly updated) description of the SPEI and its calculation, plus full references, please refer to https://spei.csic.es.

To summarise, this index uses the monthly difference between precipitation and PET (Potential Evapotranspiration) which is a simple water balance methodology that is calculated at different time scales to obtain SPEI values. Different time scales are useful for monitoring drought conditions in different hydrological sub-systems. The SPEI is a standardized variable, and it can therefore be compared with other SPEI values over time and space. For its standardization, long records (>30 years) are required; if records are compared, these need to have been standardized using the same record-length.

FWI

The FWI system consists of six components each measuring a different aspect of fire danger. The first three primary sub-indices are fuel moisture codes and are numerical ratings of the moisture content of litter and other fine fuels (FFMC sub-index) indicating the relative ease of ignition and flammability of fine fuel, the average moisture content of loosely compacted organic layers of moderate depth (DMC sub-index) and the average moisture content of deep, compact organic layers (DC sub-index). The two intermediate sub-indices, ISI and BUI, are fire behaviour indices. The Initial Spread Index (ISI) is a numerical rating of the expected fire rate of spread. It combines the effect of wind and FFMC on rate of spread without the influence of variable quantities of fuel. The Buildup Index (BUI) is a numerical rating of the total amount of fuel available for combustion that combines the DMC and the DC. The resulting index is the Fire Weather Index (FWI), which combines ISI and BUI. FWI represents the frontal fire intensity and can be used as a general index of fire danger. A more analytical description of the FWI system and its subcomponents as well as the equations for its calculations can be found in **[5]** and **[6]**.

Calculations behind the Prespa wetland fire risk tables

1	2	3	4	5	6
Risk classes	Chances fire	Burnt Reedbed Area	Present years	Future years (2041-2070)	Potential Ecological losses
Low	20%	2%<	**35%**	**20%**	Minimal
High	75%	2-30%	**60%**	**75%**	Significant
Extreme	>90%	>30%	**5%**	**5%**	Severe

Wetland fire risk tables were constructed for the Prespa Lakes, for the main wetland fire-period from late January until May. These fires are ignited by land-use practices; after May fire-ignition is actively suppressed and no major wetland fires are documented. The calculations behind the wetland fire risk tables (Jan-May) are briefly explained below; it should be noted that the potential impact of wetland fires on the ecology is severe during this period (see section 5), depending on the total burnt area.

Column 1: wetland fire risk classes based on the chances a wetland fire ignites (column 2), the average area burnt once a fire ignites (column 2), and the potential ecological losses (column 6).

Column 2: the chance of a wetland fire occurring during years when (a) wet season precipitation is >500mm (risk class: Low), (b) wet season precipitation is <500mm (risk class: High), and (c) wet season precipitation is <500mm & there is significant lowland snowfall (risk class: Extreme). Calculations are based on the observational record spanning 2007-2022 (16 years):

> **cumulative years** with fires falling in category (a) *or* (b) *or* (c)
> **/ total years** falling in category (a) *or* (b) *or* (c).

Column 3: an estimation of the cumulative wetland surface area burnt by fires taking place in years with (a) wet season precipitation is >500mm (risk class: Low), (b) wet season precipitation is <500mm (risk class: High), and (c) wet season precipitation is <500mm & there is significant lowland snowfall (risk class: Extreme). Estimates are based on the observational record spanning 2007-2022 (16 years): total burnt annual wetland area (percentage) per year with fires falling in category (a) *or* (b) *or* (c).

Columns 4 & 5: percentage of years over the periods 1971-2000 and 2041-2070 (based on model simulations), respectively, when (a) wet season precipitation is >500mm, (b) wet season precipitation is <500mm, and (c) wet season precipitation is <500mm & there is significant lowland snowfall.

Column 6: potential ecological losses were estimated based on the wetland burnt area during years with(a) wet season precipitation is >500mm, (b) wet season precipitation is <500mm, and (c) wet season precipitation is <500mm & there is significant lowland snowfall. Estimates are based on the observational record spanning 2007-2022 (16 years).

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