# LIFE Prespa Waterbirds

*Bird conservation in Lesser Prespa Lake: benefiting local communities and building a climate change resilient ecosystem*

## *Action A.6*

## *Assessment of habitat vulnerability to climate change to establish "climate change proof" wetland vegetation management*

**DELIVERABLE 2**

**Protocol for the implementation of the climate-change "habitat vulnerability" assessment and associated management actions**

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# 1 Introduction

This protocol is the second and final deliverable of action A.6 («Assessment of habitat vulnerability to climate change to establish "climate change proof" wetland vegetation management») of the «LIFE PRESPAWATERBIRDS» project. The National Observatory of Athens (NOA) is in charge of this action, running from September 2016 until March 2018 (including a 3-month extension period). Action A.6 directly informs wetland vegetation dynamics (Action A.1), management guidelines (Action A.2), and stream mouth restoration (Action A.3) thus ensuring that the relevant management actions (C.1, C.2 & C.3) are sustainable and effective under future climate change scenarios.

Here we detail the implementation of the climate-change "habitat vulnerability" assessment (Deliverable 1; Action A.6) and its incorporation into management action. The protocol forms an innovative tool helping management action planning and is specifically intended for use in other Mediterranean lake-wetland conservation projects. It will be presented to University students and site managers of Greek wetlands in the framework of Action E.4 («Summer school for wetland management and monitoring techniques»).

## 1.1 Action A.6: Aims

The direct and indirect impacts of ongoing and future climate change on Mediterranean lake-wetland systems are widely studied. However, recommendations from such studies are seldom translated into management actions. The large-scale nature of most climate change impact assessments is often to blame. Small-scale climate-change impact studies, which focus on specific lake-wetland environments and/or settings, are required to advise management actions. In this way, management actions are sustainable and (cost-) effective under future climate change scenarios.

Action A6 aims to assess the impact of climate change on the alluvial shorelines of Lake Lesser Prespa. Reedbeds along these shorelines offer crucial bird nesting sites, whereas seasonally flooded "wet meadows" (located landward of the reed-belt) constitute important fish spawning grounds and bird foraging areas. Two of the major threats faced by the target bird species in the study area concern (i) food constraints due to the limited "wet meadow" foraging areas available for target species and (ii) low breeding output due to reedbed wildfires destroying nests. Both threats are strongly influenced by hydro-climatic variables, specifically catchment precipitation and lake level fluctuations. We summarise below the main links between these threats and hydro-climatic variables; however, for a detailed analysis see Deliverable 1, Action A.6.

Long-term droughts (>12 months) strongly impact upon lakeshore habitats as they decrease seasonal water level fluctuations and force a drop in lake level, occasionally to below the base of the sluice in the channel providing an outlet to Lake Greater Prespa. Under such conditions, there is limited or no seasonal flooding of the wet meadow environments, while the shoreline advances lake-wards to within the reedbeds. Thus the aerial extent of the available open shallow foraging environments and fish-spawning grounds greatly decreases. A significant part of the current nesting sites is also very vulnerable to fire under conditions characterized by low lake levels and drought, as these (i) facilitate widespread fire-access to desiccated reedbeds, and (ii) increase the fire frequency / magnitude. Projected future climate change will amplify these threats as periods with low lake levels, droughts and high air temperature will increase.

## 1.2 Proposed interventions

Action A.6 has devised management guidelines that protect the availability of foraging/fish-spawning areas and nesting sites of targeted bird species under (i) the lowest projected future water levels and (ii) intensive future drought/fire conditions. These guidelines take an ecosystems-based approach: by looking at hydrological cycles and traditional land-use, specific management interventions were recommended. These guidelines aim to make management actions C1, C2 & C3 "climate proof" – that is, sustainable and effective under future climate change scenarios.

A full analysis of the impacts of projected climate changes in the Prespa Basin and associated management guidelines is given in Deliverable 1 (Action A.6). The proposed interventions are, however, summarized below:

- Shoreline vegetation management should maintain open areas in the altitudinal range from 849 m to 851 m, thus safeguarding the availability of wet meadows and open shallows under all projected water levels in the distant future. Annual vegetation clearance is best to take place during the seasonal lake level lowstand around October. Reedbeds should be cleared up to 20 cm below the seasonal lowstand lake-level; this strategy ensures that shallows are available during the following spring/summer, irrespective of wet/dry conditions.

- Wet meadows / shallows may double as fire-breaks. General reedbed vegetation management should keep this criterion in mind when selecting locations for clearance. Meadows that merge into wet meadows are particularly effective fire-breaks. Between cultivated fields and shoreline reed beds should always be a strip of (wet) meadow land. In absence of such buffer zone, fires started on cultivated fields may spread directly into the reedbelt.

- Reedbeds (i) in front of stream-mouths and (ii) in the Koula isthmus channel should be entirely removed. Thus shallows will be available under all lake levels, and the access of fish to streams is facilitated. Clearance along these corridors also prevents the lateral spread of reed fires. Vegetation in drainage ditches should be removed, as fires often spread from these locations into the shoreline reedbeds.

- The clearance of shoreline plots should take place on a rotational multi-annual basis to further the gradual thinning-out of the reedbelt zone. Stimulating larger inter-annual water level fluctuations, between 848.50 m and 850.60 m, in combination with rotational clearance at seasonal lowstands, would mimic shoreline conditions under traditional land-use and natural lake level variability. Such integrated sluice and vegetation management would yield most benefits: shallow areas become available under all projected lake levels, nutrients / biomass around the lake are reduced, the potential spread of reedbed fires is diminished and the reedbed species-composition may diversify.

- Finally, new wet meadows may be created around alluvial shorelines of Greater Prespa Lake, for example along the isthmus and mouth of the Aghios Germanos River. These shallow areas would be characterized by different lake level and (lower) water temperature conditions. As such, they would complement the available shallows around Lesser Prespa Lake, and offer alternative/additional foraging- and fish-spawning areas. In the light of uncertainties associated with future projections, it is best to offer multiple mitigation strategies thus increasing the chances on a positive outcome.

## 1.3 Dissemination

The proposed interventions are a prime example of climate change "ecosystem-based" adaptation measures, the first of its kind for lake-ecosystems in the Eastern Mediterranean. These prototype measures are also applicable to other, similar, shallow lake-wetland ecosystems in the Mediterranean.

The experience gained will be efficiently communicated to stakeholders through workshops aimed at University students and site managers of Greek wetlands (Action E.4). Specifically, the climate change "vulnerability assessment" protocol will be promoted as a tool for lake-wetland conservation projects at these workshops, thus multiplying the climate change adaptation effects.

# 2 Protocol

Here we detail the step-by-step implementation of the climate-change "habitat vulnerability" assessment (Deliverable 1; Action A.6) and its incorporation into management action planning.

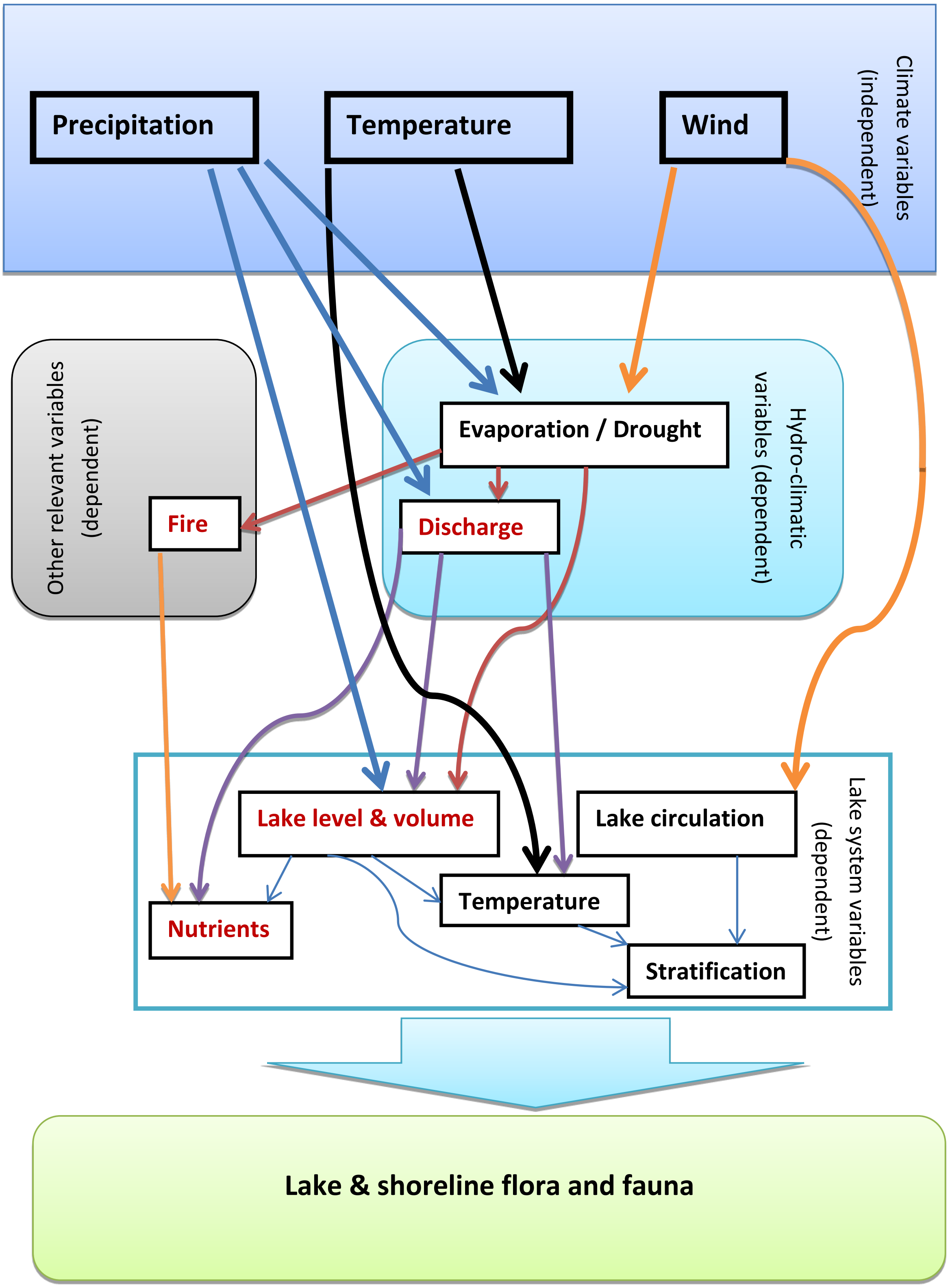
## 2.1 Climate change impacts

The main impacts of climate change on lake systems are illustrated in the flow chart below. Changes in independent and/or dependent hydro-climatic variables trigger a complex set of interactions, impacting on different components of lake systems. We have limited the climate variables in the flow chart to those that are the most relevant for lake system change.

Lacustrine changes may also be forced by human actions that either directly or indirectly affect the lake system. Variables that may strongly be affected by human actions are given in red in the flow chart. For example, human actions may affect water abstraction, pollutant levels, and discharge/fire characteristics, thus influencing lake level / volume and nutrient loading. These actions may both be independent and dependent on climate change: for instance, increased water abstraction for irrigation may be caused by land-use changes and/or as a reaction to reduced precipitation.

The specific reaction upon a given climatic change is unique for each lake system, being for example dependent on: i) the regional climate (e.g. precipitation, evaporation and wind characteristics), ii) catchment shape and size, iii) geomorphological and geological catchment characteristics (determining e.g. discharge characteristics and hydrological network), iv) groundwater table and -flow, v) vegetation and land-use, and vi) lake characteristics (e.g. bathymetry, volume, open/closed system, (not) evaporation dominated). These diverse factors determine lake-specific water balances (i.e. the dominant water input & loss parameters).

Given these complex relationships, it is essential that all impact assessments start with clear research questions, that link specific threats to clearly defined hydro-climatic variables.


Precipitation
Temperature
Wind
Climate variables (independent)
Other relevant variables (dependent)
Fire
Evaporation / Drought
Discharge
Hydro-climatic variables (dependent)
Lake level & volume
Lake circulation
Temperature
Nutrients
Stratification
Lake system variables (dependent)
Lake & shoreline flora and fauna

## 2.2 Protocol: assessment of habitat vulnerability to climate change

Here follows a step-by-step description of the implementation of the climate-change “habitat vulnerability” assessment (Deliverable 1; Action A.6) and its incorporation into management action. It is intended as an innovative tool to help management action planning for lake-wetland conservation projects.

### [1] Design of the research question & objectives

***General*** To determine the vulnerability of lake habitats to climate change impacts, it is essential to pose clearly defined research questions that link specific habitats, and/or threats to these habitats, to specific hydro-climatic parameters.

Only when critical hydro-climatic parameters are defined, it is possible to test the hypothesis *if* projected climate change will significantly impact upon the lake habitats of interest. Major hydro-climatic parameters that (in-)directly affect lake habitats, include: precipitation & snow fall, evapotranspiration, temperature, wind, discharge, lake temperature, lake level and lake volume.

***Specific: Action A.6*** Two of the major threats faced by the target bird species in the study area concern (i) food constraints due to the limited “wet meadow” foraging-area availability, and (ii) low breeding output due to reedbed wildfires destroying nests.

Long-term droughts (>12 months) strongly impact upon lakeshore habitats as they decrease seasonal **water level fluctuations** and force a **drop in lake level**. Under such conditions, there is no seasonal flooding of the present wet meadow environments, while reedbeds are (partially) dry. Thus the available open-shallow foraging environments and fish-spawning grounds greatly decrease. A significant part of the current nesting sites is also very vulnerable to fire under conditions characterized by **low lake levels** and **drought**, as these (i) facilitate widespread fire-access to desiccated reedbeds, and (ii) increase the fire frequency / magnitude. Finally, with changing **lake-surface temperatures** the timing of fish-spawning (and thus prey available) also changes.

*Research questions:* (1) Will lake level fluctuations change under future climate projections; (2) will extreme lake level lowstands change under future climate projections; (3) do fire-risk and drought magnitudes/frequencies changes under future climate projections; (4) are lake surface temperatures set to change under future climate projections?

*Objectives:* To devise management guidelines that protect the availability of foraging/fish-spawning areas and nesting sites of targeted bird species under (i) the lowest projected future water levels, (ii) changing lake water surface temperatures, and (iii) intensive future drought/fire conditions.

## [2] Data collection and assessment

***General*** Following the establishment of clear research questions and objectives, the next step is to identify, collect and assess the available hydro-climatic records in the study area.

Collected hydro-climatic data should be representative for the catchment area. There are two main data-sources: local records and national/European databases. For large catchment areas, reliable and sufficient **climate data** can usually be extracted from national/European databases. However, national meteorological stations may not be evenly distributed and certain areas may lack coverage altogether, as is the case in Greece and most Balkan countries. Here, local climate in small- to regional-scale catchment areas may ***significantly differ*** from adjacent regions due to topographic influences. Therefore, the collection of **local climate records** is very important when dealing with smaller catchment areas such as Prespa. These data may be collected from a variety of sources, such as (non-)governmental institutions, companies and private individuals. Furthermore, lake-specific ***hydrological data*** are rarely collected at a national level; existing data also need to be collected locally.

The eventual study design and methodology is dependent on the available quality and quantity of hydro-climatic data. These data are also key for the calibration of model data and records from (gridded) databases, thus affecting the reliability of the study results.

***Specific: Action A.6*** Observational data used in the relevant action were mainly obtained from the "Society for the Protection of Prespa", which possesses all major meteorological and hydrological records spanning 1951-2016 in the Prespa catchment from the three lake-sharing countries.

Principal records include: (i) monthly stage heights (1951-2004) of Lake Greater Prespa from the Hydrological Institute of Skopje (FYROM; the only lake record subjected to quality control) and of Lake Lesser Prespa (1969-2016) from the local Koula station; (ii) a single precipitation record created from monthly precipitation series (1951-2004) from seven stations (containing basic equipment) located adjacent to the lakes at ~860 m, using the surface integration method (Direct Weighted Averages and Thiessen Polygons); and (iii) monthly evaporation based on a 23-year record with a standard Class A-Pan instrument (Koula station; Greece) and extended using the Penman method to cover the entire 1951-2004 observation period. Class-A-Pan evaporations tend to overestimate lake evaporation; therefore a Pan-coefficient of 0.8 was introduced to convert the 54-year Pan-Evaporation series into a Lake-Evaporation series. Additionally, temperature and precipitation data for Lake Lesser Prepa were extracted from the European E-OBS gridded dataset, which contains series of daily observations from meteorological stations throughout Europe and the Mediterranean (accessed through the National Observatory of Athens).

## [3] Methodology and approach

***General*** The design of any study or assessment of lacustrine habitat vulnerability to climate change, is dependent on the available hydro-climatic records and models. Climate records are always available in Europe, even if the solution may be (very) coarse for the selected study area. Dependent on their resolution, the analytical results may be more or less accurate. Hydrological data are often partially available at best; the most pertinent data for lake-habitat assessments include lake temperature, -chemistry, -level and -volume.

For an assessment of the impact of climate change on lake-shore vegetation, the focus of Action A.6, lake level and/or lake surface area data are of prime importance. Furthermore, observational records are very important, especially for local to regional-scale studies. These records allow (i) the validation / calibration of models, and (ii) the establishment of empirical models and thresholds. Three main study designs, each dependent on the availability of specific data, may assess the impact of climate change:

1. Lake level data are available for more than one decade. There are several options. **[a]** Lake level may be modelled with the "Lake Water Balance" method, if inflow and outflow records are available (including groundwater, precipitation, evaporation, water abstraction and fluvial discharge). The LWB may be used for future projections, fed by climate model data. However, full in-/outflow records are rarely available. In such case, missing data must be modelled (introducing an unknown error factor) or alternative methods [b] and [c] must be used. **[b]** A linear extrapolation model is created using lake level and key hydro-climate data (e.g. precipitation, precipitation minus evaporation, discharge). This linear extrapolation model can be used for future projections, fed by modelled climate data. However, this approach may not work if lake level is artificially controlled (e.g. through a sluice, water abstraction, river diversions). **[c]** Specific lake level stages / stage-bands may be linked to certain climate-related thresholds (e.g. based on precipitation and/or drought indices). Data from future climate projections can be tested against these thresholds. This latter approach may be more robust, for example when records are lacking in detail and/or are of poor quality.
2. If no lake level data are available, a record of lake surface area changes may in some cases be reconstructed based on aerial / satellite imagery. Surface areas may then be linked to specific lake level stage-bands through fieldwork. Subsequently, specific lake surface areas / lake level stage-bands may be linked to certain climate-related thresholds (e.g. based on precipitation and/or drought indices). Data from future climate projections can be tested against these thresholds. This approach is cruder than the first option.
3. No lake data are available and no record of lake surface area changes can be reconstructed. In this case, fieldwork may establish the near-shore bathymetry of the lake. Data from future climate projections can be used to calculate how much the surface area will decrease if precipitation, evaporation and discharge changes. Such method is quite crude (giving a minimum estimate) and works mainly for closed lakes.

***Specific: Action A.6*** A Lake Water Balance could not be created for Lesser Prespa Lake as too many variables were unknown. Method 1c (see above) was employed as the lake level was artificially controlled. Critical hydrological data for this action were lake temperature and lake level / volume; observational records were available for both parameters. Future lake water levels were linked to precipitation and drought values, based on modern analogues. Specific lake level stage-bands were linked to specific precipitation thresholds; future precipitation projections were linked to these thresholds to derive impact projections. Shorelines associated with different lake levels were plotted on detailed maps of the lake margins.

A linear extrapolation model with a very good correlation was created between daily maximum temperature and lake surface temperature. This linear extrapolation model was used to assess future lake surface temperature projections, fed by modelled climate data.

Climate-change impact projections cover the period 2071-2100 (distant future). Impact projections are assessed by the Regional Climate Model RCA4 of the Swedish Meteorological and Hydrological Institute (SMHI) driven by the Max Planck Institute for Meteorology global climate model MPI-ESM-LR under two RCP future emissions scenarios, the RCP4.5 and the RCP8.5, with the simulations carried out in the framework of EURO-CORDEX. Temperature, evapo(transpi)ration and precipitation over the Prespa catchment were simulated with this high horizontal resolution (12 × 12 km) regional climate model. To assess fire risk, the Canadian Fire Weather Index (FWI) was used, while the Standardized Precipitation Index (SPI) was used for the definition of drought.

## [4] Establishing base-line data: approach

Observed hydro-climate, fire and lake-shoreline data were analysed to establish robust base-line conditions and thresholds against which to compare future hydro-climate projections.

***Lake level data*** The upper and lower limits of the water level of Lesser Prespa Lake, as well as the changes in seasonal fluctuations, were evaluated. The observational record covers the years from February 1969 until December 2016, albeit with a few gaps. The principal aim was to distinguish and define “natural” lake level variability, in order to inform the water level management regime. The situation prior to 1976 can be taken to represent the most “natural” conditions. The Prespa Lakes were fully communication up to this date, while large-scale water storage and abstraction schemes were not yet operating. Average seasonal water level fluctuations of Lesser Prespa Lake ranged from 0.65 m to 0.75 m. Longer-term (multi-annual) water level fluctuated between 851 and 849 m. The sluice-system that operates since 2005 in the Koula outflow channel strongly dampens both seasonal water level fluctuations as well as long-term lake level variability. Extreme lake level lowstands below the base of the sluice at 849.58 m occasionally occur.

***Threshold values*** A set of four key lake level analogues has been defined on the basis of the available water level data of Lesser Prespa Lake. These analogues are linked to absolute precipitation thresholds.

**[A]** Significant lake level lowstands are defined as hydrological years (October $_{\text{year1}}$ to September $_{\text{year2}}$) when water levels are <850 m for 12 months, while water levels are below 849.58 (the base of the sluice) for 5 months and more. Under such conditions the sluice would be closed for the entire hydro-year. These lowstands occur when the 6-month cumulative wet season (Oct-Mar) precipitation is **below 370 mm** (20th percentile). This wet season rainfall affects water levels up to 12 months ahead as next seasonal lake lowstand will be below 850 m for 5-7 months.

The associated SPI-6 (for March) ranges between -1.1 to -1.7. The related conditions are described as "moderate dryness" (> -1.5) to "severe dryness" (<-1.5); such events occur once every 10 to 20 years (Table 3.2).

**[B]** Extreme lake level lowstands, when water level is at or below 849 m. These lowstands occur when **two subsequent wet seasons receive less than 370 mm** of precipitation each. Two such wet seasons in a row affect water levels up to 12 months ahead as the lake will remain below 849.60 m for this entire period.

The associated SPI-24 (for March after the 1st year receiving <370 mm wet season precipitation) is at -2.1 and indicates "extreme dryness" occurring once in 50 years.

**[C]** Lake level lowstands, when water levels are below the 850 m stage-height for 7 months or more. Under such conditions the sluice would be closed for the most of the hydro-year. Such lowstands occur when the 6-month cumulative wet season (Oct-Mar) precipitation is **below 415 mm** (40th percentile). Wet season precipitation values that fall within this category are observed frequently, as indicated by the percentiles.

The associated SPI-6 (for March) ranges between -0.6 and -1.0, and related conditions are described as "mild dryness" that take place once in 3 years.

**[D]** Lake level highstands, when water levels are above the 850 m stage-height for the entire hydro-year. Under such conditions the sluice would not be closed; consequently there is continuous outflow from Lesser Prespa Lake through the Koula channel to Greater Prespa Lake. Hydro-annual lake level is approximately "stable" under these conditions. Such highstands are highly infrequent, occurring only when the 6-month cumulative wet season (Oct-Mar) precipitation is **above 560 mm** (90th percentile).

The associated SPI-6 (for March) ranges between 1.0 and 1.4, and related conditions are described as "moderate wet" that take place once in 10 years.

***Lake Surface Temperature*** Linear regression was used to establish the relationship between observed monthly maximum air temperature and lake surface temperature of Lesser Prespa Lake. E-OBS maximum monthly air temperature and local monthly lake surface temperature were found to be highly correlated (r=0.978), and statistically significant (95th percentile bootstrap confidence intervals: 0.973 – 0.982). The relationship can be described by the following formula, where (y) is monthly lake surface temperature and (x) is monthly maximum air temperature: $y = 0.9924x + 0.8762$. This correlation can be used for future estimates of lake temperature based on model projections of air temperature, given the very strong correlation between variables.

***Lake-shore changes*** To assess the impact of water level variability on (i) shoreline position and (ii) the reed / wet meadow zone around the margin of Lesser Prespa Lake, several data were analysed, including: aerial photographs (1945, 1970, 1979, 1982, 1992, 1995 and 2008), high-resolution satellite images (accessed through GoogleEarth_Pro), digital elevation models of the shoreline, geological and topographical maps.

Shorelines associated with seasonal high lake levels (spring-summer) are located at the landward edge of the continuous reedbeds during near normal to wet years (SPI-6 in March >0). However, during moderate to severe dry years (SPI-6 in March < -1.1), the shoreline over the same time-period is located within the reedbelt. During the seasonal low lake level period (autumn-winter), the shoreline fluctuates within the reedbed zone. The seasonal lowstand shoreline is at the outer edge of the continuous reedbeds during moderate to severe dry years (SPI-6 in March < -1.1). The shoreline remains at the outer edge of the reedbelt during multi-seasonal extreme lowstands (extreme dryness, SPI-24 in March < -2).

The width of the reedbeds fringing Lesser Prespa Lake has been remarkably stable over the period covered by the water level record (1969-2016). The installation of a weir and, especially, the sluice system greatly reduced long- and short-term natural lake level variability. Vegetation belts became fixed in a narrow altitudinal zone. Wet meadows are only maintained through agricultural management practices (e.g. mowing/burning and cattle grazing). The abandonment of traditional agricultural around the 1960s led to reedbeds expanding into these formerly open, periodically flooded, areas.

Prior to weir/sluice installation, significant changes in water level were followed by significant changes in the location/width of the reed-belt and wet meadows. Falling levels led to the lakeward-shift of wet meadows; consequently the expansion of reeds within the lake was balanced by a removal of older reedbeds at the landward margin. Large lake level rises led to abandonment and drowning of cultivated fields near the shore, their occupation by young reeds and drowning of the deepest reedbeds; thus again a renewal of the reedbeds took place. Traditional land-use in relation to longer-term lake level change therefore led to the removal of nutrients (oxidation, ploughing, cattle-feed, reed-burning) and renewal of reed, while limiting the width of the reedbelt. This likely led to less dense, younger and more species-diverse reedbeds compared to the present situation. Secondly, there is no longer a significant flow between the lakes (thus less fluxing out of pollutants/nutrients). Both factors increase the pollutant/nutrient concentration thus amplifying eutrophication and affecting (likely) reedbed density / species composition.

***Reedbed fires*** There is a systematic record of reedbed fires around the Greek shoreline of Lesser Prespa Lake spanning the years 2007-2016, based on data collected by the SPP from: SPP photo archive, SPP drone photo archive, Prespa Park Wetland Management Committee reports, and Prespa Park Management Body reports. Fires are on record for six years (2007, 2008, 2012, 2014, 2015 and 2016). Lake levels were near 850 m, except for 2008, when they were 30 cm lower.

Most fires occur in February and March, during the wet season and under rising seasonal lake level. The timing is related to fires started by farmers to clean fields and drainage ditches. Fires started in fields adjacent to reedbeds, or in vegetation clogging drainage ditches that directly connected to reedbeds. Reedbeds located on higher grounds (+850 m) were particularly susceptible to fire. Fires around the isthmus were hampered in their spread by the presence of water bodies and channels. The observed invasion of reeds into channels and channel mouths is facilitating the spread of fire. Fires in 2008 were most widespread and likely facilitated by the low lake levels in that year.

The record contains too few data for statistical analyses. However, none of these fires started during a period that can be characterized as “dry” based on SPI-3 and SPI-6 values. Fires during the years 2014 to 2016 even started under moderate wet conditions. A link between reedbed fires and drought does therefore not seem plausible.

## [5] Future climate projections

Model output of daily mean and maximum temperature, daily total precipitation and evaporation for the closest model grid point to the study region of Prespa were extracted. Daily output from RCA4 regional climate model developed at the Swedish Meteorological and Hydrological Institute (SMHI) driven by the Max Planck Institute for Meteorology model MPI-ESM-LR has been used (hereafter SMHI-MPI). SMHI-MPI has a horizontal resolution of about 12 km × 12 km. Precipitation data were analysed per Oct-Sep (12 month) wet-dry cycle, as is customary for hydrological records in the Mediterranean and for river basins with significant snowfall.

Future projections, covering 2071–2100 (hereafter distant future) under the new IPCC RCP4.5 and RCP8.5 scenarios, were compared to 1971–2000 observational data (reference period). Future projections were adjusted with the delta-change method to derive corrected precipitation and temperature records that drive impact models and thresholds. Non-parametric bootstrap confidence intervals for the 95th percentile were employed (for its robustness) to detect statistically significant changes between the data-sets from the reference period and the distant future.

***Precipitation*** Total annual precipitation is set to decrease in the distant future. Under the RCP4.5 scenario, precipitation is decreasing most in late spring and summer compared to the reference period. Under RCP8.5 all months (except for February) show a decline. Statistically, only RCP8.5 hydro-annual is significantly different from the reference period.

Precipitation decreases across all percentiles, under both scenarios, are statistically significant except for the 95th percentile of RCP8.5. Interestingly, there is a different picture when future precipitation is broken down into a wet- and dry period. In this case, there is only a statistically significant decrease in precipitation for the dry season under RCP8.5. The average total precipitation during the wet season is even the same under both future climate scenarios, and not statistically significant different from the reference period.

***Temperature*** Monthly average and maximum temperatures are projected to rise during all months in the distant future. The monthly increases under the RCP4.5 scenario are in the order of 1-3 °C; monthly temperature increases under RCP8.5 are with 3-6 °C, much larger. Maximum monthly temperatures are set to rise slightly more than average monthly temperatures under both scenarios. Analyses indicate that changes in annual average and maximum temperatures are statistically significant under both scenarios.

***Evaporation*** Under the RCP4.5 scenario, evaporation is increasing from spring to summer, compared to the reference period. Under RCP8.5 all seasons except for winter show an increase. When the average annual evaporation and percentiles of the two model scenarios are compared to the reference period, there is a difference in all parameters. Analyses show that the increases in evaporation are statistically significant under both scenarios. **Annual open water surface** evaporation from the lake increases by 60 mm (RCP4.5) to 129 mm (RCP8.5) by the end of this century.

## [6] Projections of climate-change impacts

The impact of the projected future changes in catchment climate on lake level lowstands, shoreline positions, drought, fire risk and lake temperature was evaluated. Impact projections were driven by modelled future catchment precipitation, temperature and evaporation.

***Lake level*** The impact of projected precipitation changes on lake level is based on the application of wet season precipitation thresholds that are associated with specific lake level stage analogues. There appears to be **no significant change** in future lake level lowstands and highstands, based on wet season precipitation thresholds. This is in line with expectations, as there is no statistically significant change in wet season precipitation under both scenarios (RCP4.5 and RCP8.5). However, future lake surface evaporation is set to increase under all scenarios. The increase in evaporation under scenarios RCP4.5/8.5 is in the order of 3 x $10^6$ $m^3$ and 7 x $10^6$ $m^3$, respectively. This may decrease seasonal peak lake levels in the order of 0.05 m and 0.13 m, respectively.

Based on these impact analyses, shoreline fluctuations are expected to remain approximately similar to the reference period. Such long-term stabilization of shorelines is unprecedented in the observational record. The sluice will be entirely closed for at least half of the future period, while it will be fully open for only two years. This implies that seasonal water level fluctuations will be strongly reduced and seasonal peak levels will be earlier in season (March-April), due to sluice operation.

Several uncertainties are inherent to the impact analyses. Subtle changes in future precipitation patterns may suppress water level during lowstand-years further than our estimates indicate. Specifically, hydro-yearly and dry season precipitation under scenario RCP8.5 are statistically different from the reference period, amplifying lake level lowstands. Furthermore, if catchment water abstraction increases in the future, lake lowstands will become more severe (falling deeper below 849 m). Other uncertainties involve changes in the precipitation-runoff relationship. Observed decreases in winter snowfall may continue and lead to significantly less snow-melt generated runoff and thus lower lake levels. On the other hand, if rainfall events become more intense as projected (IPCC 2013), there may be a more effective water transfer to the lake, and less evapotranspiration, thus increasing average water level.

***Droughts*** The pattern of drought in the distant future, based on precipitation under scenarios RCP4.5/8.5, has been calculated. SPI values are based on the time-series 2071-2100, and values are not directly comparable to the reference period, as they are normalized against different time-series. SPI-3, -6, -9, -12 and -24 were calculated for both climate scenarios. The pattern of dry- and wet periods for scenarios RCP4.5 and RCP8.5 are very similar. This is no surprise given the very similar future precipitation patterns under both scenarios.

Comparison of the precipitation percentiles of both scenarios with the reference period is more revealing about the changing nature of wet- and dry periods. Years that are characterized as wet (hydro-annual precipitation above the 75th percentile) and years characterized as dry (hydro-annual precipitation below the 25th percentile) receive both less rainfall under RCP4.5/8.5 compared to the reference period. For wet years this reduction is larger than for dry years.

***Lake surface temperature*** Lake temperatures in the distant future have been based on the linear correlation procedure between maximum air temperature and lake temperature. Daily and maximum air temperature under both scenarios RCP4.5 and 8.5 show statistically significant, large, increases. The large increases are reflected in the lake surface temperature projections. The monthly temperature rises are of the same order as the maximum air temperature increases, which is as expected given the linear correlation between the parameters.

***Fire Weather Index*** To assess fire risk around the Prespa Lakes, the Canadian Fire Weather Index (FWI) was used. Present day simulations covering the period 1971-2000 are used as reference for comparison with future projections for the periods 2031-2060 and 2071-2100 under RCP4.5 and RCP8.5 scenarios. Model output of mean daily maximum temperature and relative humidity, wind speed and daily total precipitation for the closest model grid point to the study region were extracted (SMHI-MPI model) and daily FWI values were calculated. In conclusion, in the future climate, more days with moderate and high fire risk are expected and the fire risk season expands into June and September, changes which are more pronounced under the RCP 8.5 scenario as we approach the end of the century (2071-2100).

## [7] Determining climate-change proof management guidelines

Climate-change proof management guidelines aim to safeguard the availability of foraging/fish-spawning areas and protect the nesting sites of targeted bird species in the near/far future under (i) the lowest projected future water levels, (ii) changing lake water surface temperatures, and (iii) intensive future drought/fire conditions.

These guidelines take an ecosystems-based approach: by looking at "natural" hydrological cycles and traditional land-use, and their effect on maintaining habitat diversity, specific management interventions are recommended.  The ultimate goal of these sustainable and cost-effective management recommendations is their absorption into concrete conservation actions.

When designing climate-change proof management guidelines, it is important to evaluate the following considerations. [A] How does the (part of the) system under study adapt naturally (i.e. without interventions) to climate / environmental change? [B] How did traditional land- and shoreline management / -use  influence the (part of the) system under study? [C] Can modern management mimic past natural adaptation strategies and land-use practices? What are the limitations to such strategies – i.e. which critical parameters change and determine that there can no longer be natural adjustment? [D] How can traditional land-use practices and natural adaptation strategies be incorporated in management guidelines to create dynamic climate change adaptation strategies to increase the resilience of the(part of the) system under study?

Specifically, management guidelines of action A.6 provide: (i) the critical range of low future lake levels that inform the altitudinal range in which "open shallows" should be available; (ii) the possible location of future "shallows" based on the modelled shoreline positions; (iii) advice on the location of key fire-blocking corridors that will prohibit fire to spread into reedbeds under future extremely low lake levels / drought conditions.

***Management Guidelines: shoreline environments*** Open areas should be present in the altitudinal range from 849 m to 851 m to make sure that wet meadows and open shallows are available under all projected water levels in the distant future. Annual vegetation clearance should follow seasonal water level fluctuations. It can best take place around October, coinciding with the seasonal lake lowstand. Reedbeds should be cleared up to 20 cm below the lowstand lake-level; this strategy ensures that shallows are available during the following spring/summer, irrespective of wet/dry conditions.

The clearance of shoreline plots should ideally be on a rotational multi-annual basis, to further the gradual rejuvenation and thinning-out of the reedbelt zone. Stimulating larger inter-annual water level fluctuations, between 848.50 m and 850.60 m, in combination with rotational clearance at seasonal lowstands, would mimic traditional use of the shoreline. Such integrated sluice and vegetation management would yield most benefits: shallow areas become available under all projected lake levels, nutrients / biomass around the lake are reduced, the potential spread of reedbed fires is diminished and the reedbed species-composition may diversify.

Finally, new wet meadows may be created around alluvial shorelines of Greater Prespa Lake, for example along the isthmus and mouth of the Aghios Germanos River. These shallow areas would be characterized by different lake level and (lower) water temperature conditions. As such, they would complement the available shallows around Lesser Prespa Lake, and offer alternative/additional foraging- and fish-spawning areas. In the light of uncertainties associated with future projections, it is best to offer multiple mitigation strategies thus increasing the chances on a positive outcome.

***Management Guidelines: reedbed fires*** Fire-risk management should be integrated in the general reedbed vegetation management. Open shallow areas and wet meadows double as fire-breaks. Their location should therefore also be chosen with this criterion in mind. Meadows that merge into wet meadows are particularly effective fire-breaks. Between the area of bean cultivation and the reed beds should always be a strip of (wet) meadow land; especially at the NW side of the lake, fires started on fields used for bean cultivation spread directly into the reedbelt as there is no buffer zone.

To prevent the lateral spread of fires, reedbeds in front of stream-mouths and in the Koula isthmus channel should be entirely removed. Thus the lateral spread of reedbed fires is prohibited. Vegetation in drainage ditches should be removed, as fires often spread from these sites. Near specific nesting sites, reedbeds may also be entirely removed in corridors perpendicular to the shore; such corridors should preferably be centered on deep water-filled depressions.