Call | RFCS-2022
Project number | 101112657

REECOL Ecological rehabilitation and long term monitoring of post mining areas

Deliverable 3.3

Document on identification of main climate change impacts on post-mining rehabilitation schemes

Author | beneficiary

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Version | Date VERSION 1 | 30.07.2024

Dissemination level PU

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ABBREVIATIONS

ANN	Annual (January — December)
AR4 (IPCC AR4)	the Fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5 (IPCC AR5)	The Fifth Assessment Report of the Intergovernmental Panel on Climate Change
ARPEGE	global numerical weather prediction model by Meteo France (Action de Recherche Petite Echelle Grande Echelle)
ČHMÚ	the Czech Hydro-Meteorological Institute
CMIP	Coupled Model Intercomparison Project
CMIP6	Coupled Model Intercomparison Project phase 6
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRPF	the Regional Forest Property Centre
DEFRA	the Department for Environment, Food and Rural Affairs in the UK
DJF	Winter (December, January, February)
Eionet	European Environment Information and Observation Network
ESGF	Earth System Grid Federation
EUR-44	general CORDEX resolution of 0.44 degree (EUR-44, ~50 km)
EUR-11	CORDEX resolution of 0.11 degree (EUR-11, ~12.5km)
GCM	Global Climate Model / Global Circulation Model
GHG	greenhouse gas(es)
IMGW-PIB	the Institute of Meteorology and the Water Management National Research Institute (PL)
IOŚ-PIB	The Institute of Environmental Protection – National Research Institute (PL)
IPCC	Intergovernmental Panel on Climate Change
JJA	Summer (June, July, August)
KWB	Kopalnia Węgla Brunatnego / Lignite Coal MIne
KWK	Kopalnia węgla Kamiennego / (hard) Coal Mine
MAM	Spring (March, April, May)
PPC	the Public Power Corporation (REECOL partner)
RCM	Regional Climate Model / Regional Circulation Model
RCPs	Representative Concentration Pathways: ▪ RCP8.5 - Rising radiative forcing pathway leading to 8.5 W/m2 in 2100. ▪ RCP6 - Stabilization without overshoot pathway to 6 W/m2 at stabilization after 2100 ▪ RCP4.5 - Stabilization without overshoot pathway to 4.5 W/m2 at stabilization after 2100 ▪ RCP2.6 - Peak in radiative forcing at ~ 3 W/m2 before 2100 and decline
SON	Autumn (September, October, November)
SRES	Special Report on Emissions Scenarios
SSPs	Shared Socio-economic Pathways
TAR	the Third Assessment Report of the Intergovernmental Panel on Climate Change
UI	user interface
WRF	Weather Research and Forecasting

1. INTRODUCTION

The following deliverable is a documentation from Task 3.3. ***Climate change influence on post-mining rehabilitation schemes.***

According to Task 3.3. technical annex description, the main aim of this task is as follows:

The main aim of this task is to analyse interactions between climate change impacts on reclamation schemes for postmining areas. Reclamation schemes identified in Task 3.2. will be analysed taking into account existing impacts/dependencies on climate change (including extreme events) impacts. The baseline list of climate change impacts will be based on the results of the TEXMIN project and followed by a detailed analysis of human factor (impact and health risks for staff involved in the reclamation works) as this factor may be very important during work in conditions of open pit mines or tailing dams). The interactions of changes in temperature and precipitation on technical and biological aspects of land reclamation will be analysed. It will enable to ensure, that the diversity of species with broad range of tolerances will be planted, viable in specific circumstances. The impact of land use and land cover change on the climate in micro-scale will be also taken into consideration. GIG and VALORHIZ will analyse how climate change implies to adapt the technical solutions (species selection) and what ecosystem services are expected to be supplied by the „new" ecosystems and how these expectations will shift with climate change. The results of this tasks will be taken into consideration during the selection of case study areas Task 3.4 and included into WP4 and WP5. Particularly, INERIS in its case study will consider climate change in the selection of the species (WP4 task 4.4). INERIS will bring its field feedback/lesson with Mediterranean plant species tested in field site in the North part of France.

2. METHODOLOGICAL APPROACH

2.1. Methodology and description

The research objective undertaken in this task is part of the worldwide work and research directions, the main goal of which is to minimise the effects of climate change in various areas of life and the economy. Given the significant number of both operating and closed mines in Europe, especially in coal regions in transition, it is necessary to respond to the risks posed by climate change not only for the existing and working mines but also for reclamation & rehabilitation schemes and the safety of post-mining areas. This is all the more important because currently, climate change adaptation issues are not always sufficiently considered as an important part of development dedicated to the mining sector, very often they do not take into account the links and impacts of mining activities on climate change, but also climate change issues are not sufficiently taken into account in the context of post-mining land reclamation plans and rehabilitation activities.

As the REECOL project is mainly focused on developing and testing new solutions for post-mining site reclamation and ecosystem rehabilitation in selected coal regions in transition, it is important to analyse the interaction of climate change impacts in the context of the post-mining site redevelopment plans. In contrast to the standard approach, this process does not involve restoring the site to its condition before activities started, but focuses on ensuring that the widest possible ecosystem services can be provided on the anthropogenically transformed site.

As part of the preparatory work, various projects completed (or still ongoing) under various European programs were analyzed, taking into account studies of the impacts of climate change, as well as site development and redevelopment. Results of these analyses are described in **Chapter 2.2.** In the following steps, the approach and conclusions and results from some of the projects analyzed were used as a basis for our own work.

As a starting point of works focused on analysing how climate change may impact the reclamation schemes, the GIG-PIB team analysed the ongoing climate change trends in REECOL regions and the extreme events potential, with particular reference to their exposure, sensitivity and capacity to adapt to the negative effects of climate change. The assessment of the vulnerability of the post-mining areas to the climate change and evaluating climate risks & impacts began with defining the climatic phenomena that could negatively affect the possibilities of rehabilitating the post-mining areas and returning them to the economic circulation.

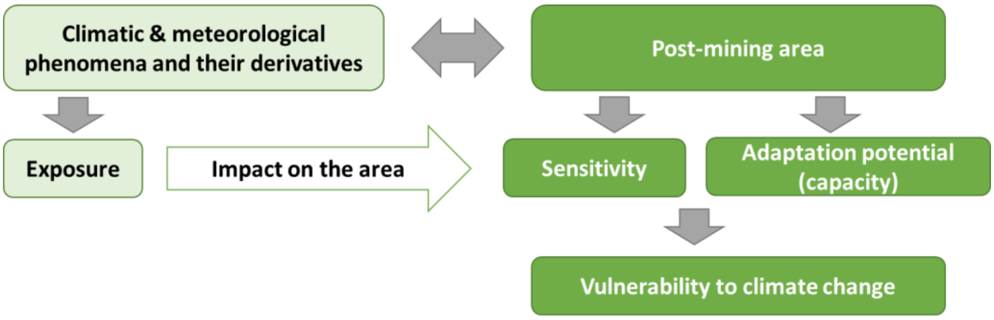

Figure 1. The visual representation of the logic behind the assessment of the post-mining areas' vulnerability to climate change

Source: IOŚ-PIB, 2023

Therefore, **chapter 3** presents the theoretical basis for the analyses and briefly summarizes the baseline climatic conditions for each region where the REECOL project test site is located. Due to the reclamation context, Köppen-Geiger climate classification and its changes was used as a point of reference. In next step, existing climate change scenarios have been examined, including both Shared Socioeconomic Pathways (SSP's) and Representative Concentration Pathways (RCP), with consideration of the impact of changes in key meteorological and climatic factors, corresponding to these scenarios, on the local conditions of the test site in REECOL regions. Results of these studies are presented in **Chapter 4**.

Chapter 5 summarizes identified types of impact and presents the developed impact matrix tool, facilitating the assessment of the impact of a given climatic and meteorological factor and their derivatives on a given aspect/component relevant to the remediation process. Also regional adaptation possibilities, based on ND-GAIN Index, have been taken into consideration, to provide broad overview of differences in local conditions between countries. Based on a detailed analysis of how climate change may impact the adaptation of specifici rehabilitation scheme in general and technical solutions (including selection of species) & potential ecosystem services in particular, more detailed guidelines have been proposed.

2.2. Overview of climate change-related projects

This subsection summarises the most important results of the analysed, previously implemented projects that took into account climate change issues and were, in a way, our starting point for further activities. Both the completed and currently ongoing projects under various programmes were examined. A detailed table summary of information on individual projects can be found in **Annex 1.**

The primary list of climate change impacts was based on the results of the **TEXMIN**[1] project (*The impact of extreme weather events on mining operations*), with an additionally expanded detailed analysis of the human factor (impact and health risks for personnel involved in remediation work). Within the TEXMIN project, the innovative integrated risk management tool was developed to link the environmental impacts, associated risks and mitigation methods caused by extreme weather events[2].

The coal mining industry is managing risks and their consequences more effectively in Australia by using an interactive online risk management system known as **RISKGATE**[3] elaborated within The Australian Coal Industry's Research Program (ACARP). Developed RISKGATE contains detailed information about seventeen high-consequence risk areas (called topics in the system) for open-cut and underground coal mines. **RISKGATE** topics are focused on industry activities - mining, processing, transport and storage. The existing topics include fires; strata control for underground mining; ground control for open-cut mining; tyres; isolation; collisions; explosions and explosives; manual tasks; trips, slips and falls. The RISKGATE tool was one of the inspirations of the approach undertaken in the **TEXMIN** project, where the risk was also calculated based on a two-parameter matrix. The probability has been quantified based on the statistics (calculated mathematically), especially for climate events or based on the opinion of experts, for non-climate events. This way, the calculated and categorised risk for climate

[1] https://gig.eu/en/texmin
[2] texmin.gig.eu/images/foto/TEXMIN_Integrated%20risk%20management%20tool%20with%20Users%20Guide.zip
[3] http://www.riskgate.org/

and non-climate events allows – in the TEXMIN tool - to identify preventive measures that can be applied in the mining sector

The general approach of the **EWENT**[4] project is also very similar and served as an inspiration. EWENT project (*Extreme Weather impacts on European Networks of Transport*) starts by identifying the hazardous events, their probability and consequences and proceeds to assess the expected economic losses caused by extreme weather events. The approach is finished by mitigation and risk control measures. The methodological approach in the EWENT project is based on a generic risk management framework that follows a standardised process from identification of hazardous phenomena (extreme weather), followed by impact assessment and closed by mitigation and risk control measures.

A project integrating the issues of climate change and post-mining land reclamation is the **LIFE-IP COALA**[5] project (*IP LIFE for Coal Mining Landscape Adaptation*). The objective of this integrated project (IP) is to successfully implement the Moravian-Silesian Region's (MSR) adaptation strategy, to increase the region's climate resilience, improve the quality of the environment for its inhabitants, and support the region's sustainable development. LIFE-IP COALA aims to introduce a system of adaptation and mitigation in the region as a part of the common agendas of the local governments and the MSR. The goal is to improve the use and coordination of tools, involve key stakeholders, establish partnerships with similar regions in the EU and contribute to the successful transformation and long-term improvements of the region. The project will contribute directly to the implementation of the MSR's regional adaptation strategy (Adaptation Strategy of the Moravian-Silesian Region to the Impacts of Climate Change) and the National Strategy on Adaptation to Climate Change in the Czech Republic. The developed methodologies, procedures and collected examples of good practices of the participating regions will translate into an effective and efficient process of adaptation to climate change. The project and its pilot actions are focused on post-mining areas and their landscapes.

For example, the aim of **EUCLEIA**[6] (*European climate and weather events: Interpretation and attribution*) was to develop the means to provide reliable information about weather and climate risks by developing an event attribution system for Europe. This system has demonstrated the capability to deliver reliable and user-relevant attribution assessments on a range of timescales; on a fast-track basis in the immediate aftermath of extreme events, on a seasonal basis based on a state-of-the-art modelling system and annually to the scientifically prestigious annual attribution supplement of the Bulletin of the American Meteorological Society. The capabilities of event attribution have been evaluated on a set of test cases involving heat waves, cold spells, floods, droughts and storm surges.

Within the **RAIN**[7] (*Risk Analysis of Infrastructure Networks in response to extreme weather*) project, its formulated vision was to provide an operational analysis framework that identifies critical infrastructure components impacted by extreme weather events and minimises the impact of these events on the EU infrastructure network. The project has a core focus on land-based infrastructure with a much wider consideration of the ancillary infrastructure network in order to identify cascading and interrelated infrastructure issues.

The project **CLIMATECOST**[8] (*Full costs of climate change*) has identified and developed a consistent framework for climate change and socio-economic development, including mitigation schemes. Using these scenarios, the project has quantified the effects of future climate change (the 'costs of inaction') in physical terms and evaluated it as economic costs under varying circumstances, both for the European Union (EU) and other major negotiator countries (China, India). The study has quantified the improvements in air quality from mitigation (co-benefits) for Europe, China and India, and assessed these in terms of physical and economic benefits. The results show numerous co-benefits of great impact arise under these mitigation scenarios, which lead to local and immediate benefits.

At the core of the **ENSEMBLES**[9] integrated project was the development of the first global, high-resolution, ensemble-based, modelling system for the prediction of climate change and its impacts. The Earth system models were combined into a multi-model ensemble system, with common output for seasonal, decadal and centennial

[4] https://cordis.europa.eu/project/id/233919
[5] https://www.lifecoala.cz/index-en.html
[6] https://cordis.europa.eu/project/id/607085/reporting/fr
[7] http://rain-project.eu/about/the-scope-of-the-project/
[8] https://cordis.europa.eu/project/id/212774
[9] https://climate-adapt.eea.europa.eu/en/metadata/publications/ensembles-final-report

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time scales. The new techniques pioneered in ENSEMBLES include a coordinated approach to seasonal to decadal prediction, probabilistic climate change projections, development and assessment of alternative approaches to the sampling of modelling uncertainties, use of a GCM/RCM matrix to provide an ensemble of plausible realisations of detailed regional climate change, improved estimates of regional climate impacts and their uncertainties through a systematic and integrated approach to climate and impacts modelling.

Climate modelling studies as well as scenario development have also been the subject of project work, especially for Central and Eastern European Countries. **CLAVIER**[10] project focused on ongoing and future climate changes in Central and Eastern European Countries, using measurements and existing regional scenarios to determine possible developments of the climate and to address related uncertainty. In turn within the **CECILIA**[11] project, the high spatial and temporal resolution of dense national observational networks at high temporal resolution and of the CECILIA regional model experiments will uniquely feed into investigations of climate change consequences for weather extremes in the region under study.

A wide range of projects addressing the issue of climate change are also currently being implemented under the program Interreg Central Europe which encourages cooperation on shared challenges in central Europe. Completed projects include, the **DEEPWATER-CE**[12] project, wherebyattempts were made to develop a comprehensive and integrated approach to implementing solutions for managed aquifer recharge - MAR. The project is a response to climate change which results in more and more extreme weather events, such as droughts and floods and is posing a growing problem for the sustainable supply of good quality water to the people. Ongoing projects include for example **Clim4Cast**[13] *(Central European Alliance for Increasing Climate Change Resilience to Combined Consequences of Drought, Heatwave, and Fire Weather through Regionally-Tuned Forecasting).* Recognising the direct threats posed by drought, heatwaves, and fire weather events to human well-being and the environment, Clim4Cast aims to address the existing gap by introducing operational tools for monitoring, prediction, and raising awareness. The project's uniqueness lies in the development and implementation of multi-temporal forecasting, a crucial aspect currently missing in existing tools. The output of Clim4Cast will serve as an early warning system, empowering diverse stakeholders and facilitating integration into national legislative frameworks. Also noteworthy are projects such as **GreenScape CE**[14] **(***Climate-proof landscape through renaturing urban areas in Central Europe*), **LOCALIENCE**[15] (*Developing resilience against extreme weather threats caused by climate change at local level in Central Europe*), **MESTRI-CE**[16] (*Smart Management and Green Financing for Sustainable and Climate Neutral Buildings in Central Europe*), **MISSION CE CLIMATE**[17] (*Climate Resilient Communities of Central Europe*), **Ready4Heat** (*Development of municipal strategies and action plans to improve heat resilience in cities*). As shown, the projects mentioned above touch on various elements related to ongoing climate change.

It is also worth noting that there is also a **GREENPACT**[18] project setting up partnerships between companies and entrepreneurs taking into account societal challenges and climate change with an entrepreneurial mindset.

The range of ongoing projects studying the impact of climate change on various sectors of the economy is very wide. However, the review indicates that the relationship between observed and projected changes in weather conditions, particularly in the context of the reclamation of post-mining areas, has not been the subject of detailed analysis, which confirms the need for this aspect to be the part of REECOL project.

[10] https://cordis.europa.eu/project/id/37013/pl
[11] https://cordis.europa.eu/project/id/37005
http://www.cecilia-eu.org/
[12] https://programme2014-20.interreg-central.eu/Content.Node/DEEPWATER-CE.html
[13] https://www.interreg-central.eu/projects/clim4cast/
[14] https://www.interreg-central.eu/projects/greenscape-ce/
[15] https://www.interreg-central.eu/projects/localience/
[16] https://www.interreg-central.eu/projects/mestri-ce/
[17] https://www.interreg-central.eu/projects/mission-ce-climate/
[18] https://www.interreg-central.eu/projects/greenpact/

3. CLIMATE BASELINE CONDITIONS

3.1. Introduction and theoretical background

The term "climate" corresponds to the weather conditions that prevail in a specific region throughout a particular period . These parameters can be the mean values and/or the variability of these values ranges from months to thousands of years. The World Meteorological Organization defines 30 years as a classical period for averaging these parameters (IPCC 2013).

Weather conditions can be made up of any one of several climate variables such as temperature, precipitation, humidity, wind and atmospheric pressure. Weather is a characteristic of the climate at a given point in time and is experienced over shorter periods , typically on a day-to-day or even hour-to-hour basis. Meteorological conditions can often have a huge impact on human and social activities through extreme events such as storms, heavy rainfall, flooding, heatwaves, lightning, droughts and strong winds.

The climate varies even between closely set locations. The main aspects of climate variation are latitude, elevation from sea level, distance from the sea, vegetation and the presence or absence of mountains. Weather patterns can also vary between years, decades and much longer periods. Climate changes with the interaction of the five major climate system components: the atmosphere (air), the hydrosphere (water), the cryosphere (ice and permafrost), the lithosphere (earth's upper rocky layer) and the biosphere (flora and fauna). Over long periods, the climate is determined by the amount of system energy and where this energy is channelled.

The Köppen–Geiger climate classification system stands as the most widely used method for categorising climates. In 1884, Wladimir Köppen introduced and subsequently refined a system that divides climates into five primary groups: A (tropical / equatorial), B (arid / dry), C (warm temperate), D (continental / snow), and E (polar). Each group is distinguished by a second letter representing the seasonal precipitation type, and a third letter characterizes the summer heat, ranging from very cold to hot. However, for the polar climates (E) no precipitation differentiations are given, only temperature conditions are defined (Kottek *et.al.* 2006). The classification is presented in Figure 2 with the basic criteria presented in Table 1.

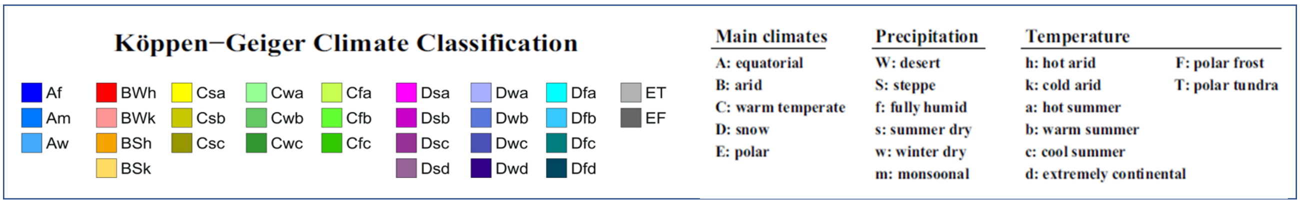

Figure 2. The colour-coded list of the climate sub-types according to the Köppen-Geiger system
Source: own study, based on: Kottek et.al., 2006; http://koeppen-geiger.vu-wien.ac.at/pdf/Paper_2006.pdf and Beck, H., Zimmermann, N., McVicar, T. et al. (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214 https://doi.org/10.1038/sdata.2018.214; amended in 2020

The classification is based on threshold values and seasonality of monthly air temperature and precipitation (Beck *et.al*. 2018; Arnfield 2023). Notably, the warmest six-month period defines the summer (Ǩoppen, Volken & Brönnimann, 2011). This way, aside from five main classes, the Köppen-Geiger system classifies climate into 30 sub-types:

- **A***:* tropical or equatorial zone (represented by blue colours on most maps, as presented in **Figure 2**), which has three subdivisions: **Af** – without dry season; **Am** – with a short dry season and **Aw** – with a winter dry season;
- **B**: arid or dry zone (represented by red, pink, and orange colours on most maps), divided into categories related to regions such as hot, arid deserts (**BWh**); cold, arid deserts (**BWk**); hot, arid steppes (**BSh**); and cold, arid steppes (**BSk**);
- **C**: warm/mild temperate zone (represented by green colours on most maps), broken into categories based on when the dry seasons occur in the zone, as well as the coldness of the summer or the warmth of the winter (see Figure 2 and Table 1);

- **D**: continental zone (represented by purple, violet, and light blue colours on most maps), similar to zone C, broken into categories based on when the dry seasons occur in the zone, as well as the coldness of the summer or the warmth of the winter;
- **E**: polar zone (represented by grey colours on most maps), separated into tundra regions (**ET**) or snow and ice regions (**EF**).

Table 1. The Köppen–Geiger climate classification – key criteria

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18$ °C
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25\,(100 - P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\,P_{th}$
BS	Steppe climate	$P_{ann} > 5\,P_{th}$
BW	Desert climate	$P_{ann} \leq 5\,P_{th}$
C	**Warm temperate climates**	-3 °C $< T_{min} < +18$ °C
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3$ °C
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10$ °C
ET	Tundra climate	0 °C $\leq T_{max} < +10$ °C
EF	Frost climate	$T_{max} < 0$ °C

Source: Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 15, 259-263. DOI: 10.1127/0941-2948/2006/0130.

The Köppen system's primary five groups are based on the type of vegetation that thrives in each climate, rendering it a valuable tool for analysing ecosystem conditions (Köppen, Volken & Brönnimann, 2011). Additionally, this connection between climate and plant life in a specific region can serve as a bridge between climate change and its impact on the flora and fauna of that region. The wide use of this classification reflects the fact that climate has since long been recognised as the major driver of global vegetation distribution (Yang *et.al.* 2015).

The references to the Köppen-Geiger climate classification used in the following sections are based on the updated world map of Köppen-Geiger climate classification has been based on temperature and precipitation observations for the period 1951-2000 published by Kottek *et al.* (2006), Rubel and Kottek (2010) and Rubel *et al.* (2017)[19]. World maps for the observational period 1901-2002 are based on recent data sets from the Climatic Research Unit (CRU) of the University of East Anglia[20] and the Global Precipitation Climatology Centre (GPCC)[21] at the German Weather Service. World maps for the period 2003-2100 are based on ensemble projections of global climate models provided by the Tyndall Centre for Climate Change Research[22].

The main results comprise an estimation of the shifts of climate zones within the 21st century by considering different IPCC scenarios. The largest shifts between the main classes of equatorial climate (A), arid climate (B), warm temperate climate (C), continental / snow climate (D) and polar climate (E) on global land areas are estimated as 2.6 - 3.4% (E to D), 2.2 - 4.7% (D to C), 1.3 - 2.0% (C to B) and 2.1 - 3.2% (C to A) (Rubel & Kottek 2010).

According to the newest analysis & assessment of 67 climate models from the *Coupled Model Intercomparison Project phase 6* (CMIP6), Beck *et.al.* (2023) foresee that from 1991–2020 to 2071–2099, 5% of the land surface

[19] Available at: https://koeppen-geiger.vu-wien.ac.at/
[20] https://www.uea.ac.uk/groups-and-centres/climatic-research-unit
[21] https://www.dwd.de/EN/ourservices/gpcc/gpcc.html
[22] https://tyndall.ac.uk/

will transition to a different major class under the low-emissions SSP1-2.6 scenario, 8% under the middle-of-the-road SSP2-4.5 scenario, and 13% under the high-emissions SSP5-8.5 scenario.

Present and future Köppen-Geiger climate classification global maps are derived from the works of Beck *et.al* (2018[23]). The present Köppen-Geiger classification map was derived from three climatic datasets for air temperature (WorldClim V1 and V2, and CHELSA V1.2) and four climatic datasets for precipitation (WorldClim V1 and V2, CHELSA V1.2, and CHPclim V1), whereas the future Köppen-Geiger classification was produced using monthly historical and future air temperature and precipitation data from the CMIP5 archive (Taylor, Stouffer & Meehl, 2012) and the future scenario, was based on Representative Concentration Pathway 8.5 (RCP8.5). These are presented in Figure 3.

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[23] As publisher amendment from 2020

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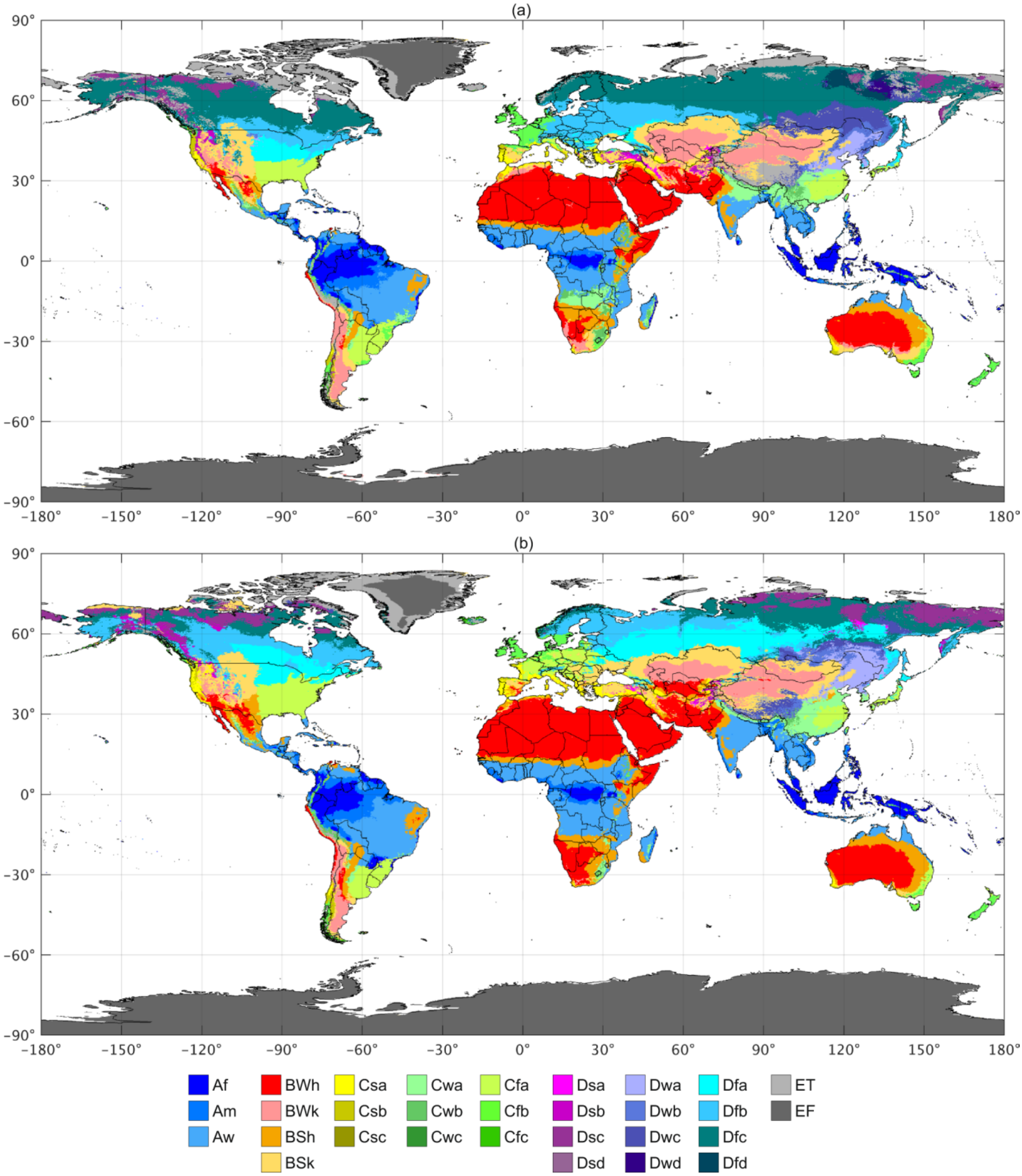

Figure 3. The present (a) and future (B) Köppen-Geiger climate classification maps at 1-km resolution

Source: Beck, H., Zimmermann, N., McVicar, T. et al. (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214 https://doi.org/10.1038/sdata.2018.214; amended in 2020

In accordance with the ranges of the different climate zones in Europe (see Figure 4), pilot sites of REECOL project are located in different climatic zones (Table 2).

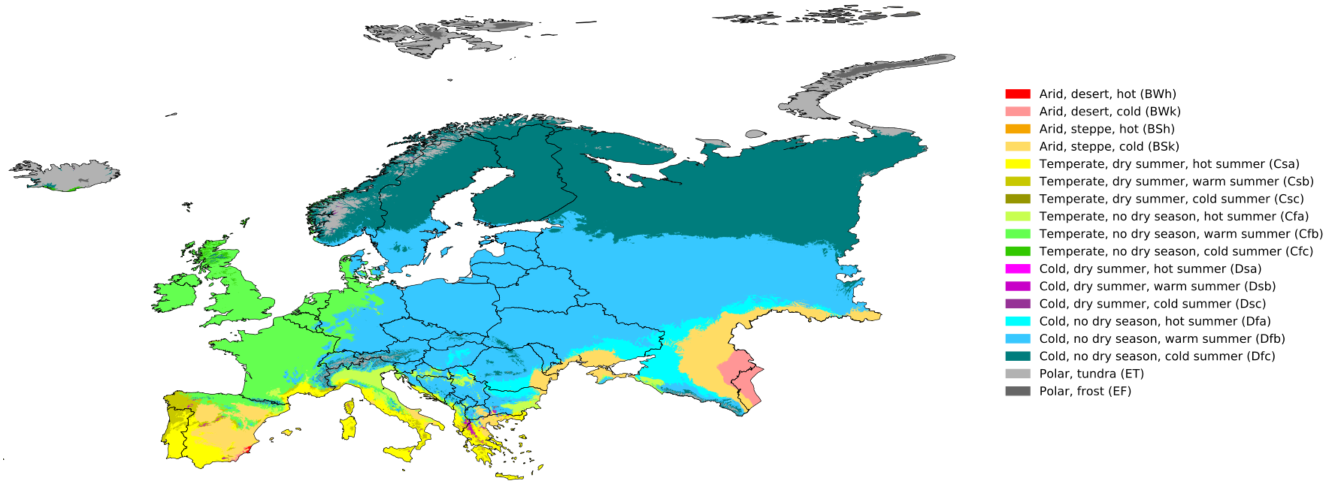

Figure 4. The Köppen-Geiger climate classification map of Europe

Source: Beck, H.E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., Wood, E. F., Present and future Köppen-Geiger climate classification maps at 1-km resolution. Nature Scientific Data. DOI:10.1038/sdata.2018.214., CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=74673589

Table 2. The location of the REECOL sites in accordance with the Köppen-Geiger climate classification

REECOL location	Köppen–Geiger climate classification		Explanation
Amynteon Lignite Field, Region of Western Macedonia / Regional units of Florina and Kozani(**GR**)	Cfa	Humid subtropical climate, moist with mild winters, wet all seasons with hot summers	Mild winters, hot summers and more evenly distributed precipitation throughout the year. Average temperature of warmest month 22°C or above, and at least six months averaging above 10°C. Coldest month, with an average temperature of 2.1°C and highest temperature of 6.4°C.
Ptolemais Lignite Field, Region of Western Macedonia / Regional unit of Kozani (**GR**)	Cfa	Humid subtropical climate, moist with mild winters, wet all seasons with hot summers	Mild winters, hot summers and more evenly distributed precipitation throughout the year. Average temperature of warmest month above 22°C and at least six months averaging above 10°C. Coldest month, with an average temperature of 2.4°C and highest temperature of 6.1°C.
Sośnica Coal Mine, Upper Silesia (**PL**)	Dfb	Humid continental climate, warm summer subtype (hemiboreal climate)	An average temperature in the warmest month below 22°C. Summer high temperatures in this zone typically average between 21–28°C during the daytime. The average temperatures in the coldest month are generally far below the −3°C or 0°C isotherm. Frost-free periods typically last 3–5 months. No seasonal significant precipitation difference.
Boleslaw Śmiały Coal Mine, Upper Silesia (**PL**)	Dfb		
Wujek Coal Mine, Katowice, Upper Silesia (**PL**)	Dfb		
Jóźwin open-pit / Konin Brown Coal Mine, Wielkopolska (**PL**)	Dfb		
Radovesice dump / Most Basin, North Western Bohemia (**CZ**)	Dfb	Humid continental climate, warm summer subtype (hemiboreal climate)	
Mazingarbe (**FR**)	Cfb	Temperate oceanic climate	Coldest month averaging above 0°C, all months with average temperatures below 22°C, and at least four months averaging above 10°C.. No significant precipitation difference between seasons

REECOL location	Köppen–Geiger climate classification		Explanation
Velenje Coal Mine (**SI**)	Dfc	Subarctic With Cool Summers And Year Around Rainfall	Coldest month averaging below 0°C and 1–3 months averaging above 10°C. No significant precipitation difference between seasons.

Source: https://www.plantmaps.com/koppen-climate-classification-map-europe.php
Louloudis, G., Louloudis, E., Roumpos, C. et al. (2021) Forecasting Development of Mine Pit Lake Water Surface Levels Based on Time Series Analysis and Neural Networks. Mine Water Environ 41, 458–474 https://doi.org/10.1007/s10230-021-00844-5
Louloudis, G.; Roumpos, C.; Louloudis, E. et al. (2022). Repurposing of a Closed Surface Coal Mine with Respect to Pit Lake Development. Water 14, 3558 https://doi.org/10.3390/w14213558

The assessment of the vulnerability of the post-mining area to climate change and climate risks began with defining the climatic phenomena that may negatively affect the possibilities of rehabilitating post-mining areas and returning them to economic circulation.

Taking into account the analyses of past and future climate conditions specific to the study area, the research determined the already existing climatic phenomena to which both the post-mining areas and the still ongoing mining activities are exposed to, as well as any future phenomena resulting from the intensification of current or newly emerging risks. The findings are presented in Chapter 3.2. *Baseline conditions in REECOL regions and* Chapter 4.3 *Climate change scenarios in REECOL regions.*

3.2. Baseline conditions in REECOL regions

The analysis of baseline climate conditions is an essential step, as it provides an objective reference point for assessing potential future changes. Primarily, establishing baseline values allows for an understanding of the current climatic conditions in a given region, encompassing parameters such as temperature, precipitation, wind speed, and others. Identifying baseline climate values also enables the assessment of natural climate variability, taking into account seasonal and annual fluctuations. This is crucial to differentiate typical changes from those that may result from anthropogenic factors, such as greenhouse gas emissions or other human activities. Furthermore, baseline analysis is a key tool in assessing the effectiveness of adaptive strategies and developing risk management plans associated with climate change.

3.2.1. Poland

The REECOL sites analysed in the project (listed in Table 2) are located in two provinces: the Wielkopolska region and the Silesia region (Figure 5). Although the distance between the provinces is not great and they are in the same continental zone according to the Köppen–Geiger climate classification, local conditions differ a little. Therefore, analyses of baseline conditions were carried out separately for each region.

In the final section of this chapter, information on past trends is summarised, presenting information on how climate and weather conditions have evolved in 2023 relative to previous decades.

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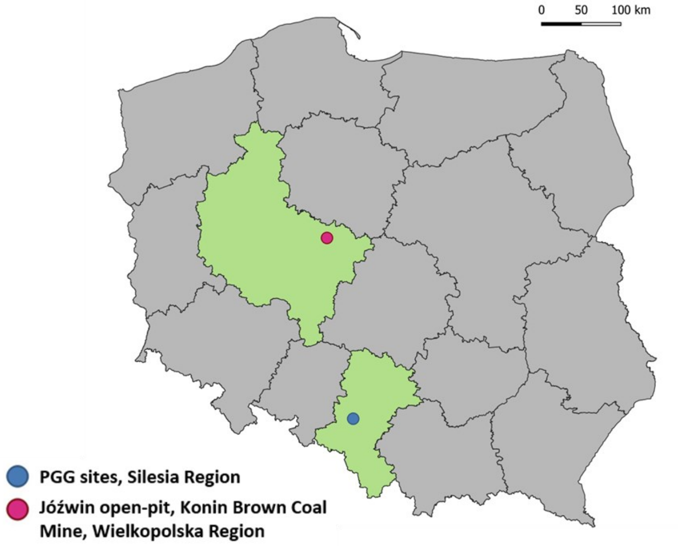

Figure 5. The location of REECOL sites in Poland
Source: own elaboration

The **Silesia Region** (**Upper Silesia)** climate closely corresponds to Central European weather patterns, exhibiting a transient nature due to the frequent migration of air masses with diverse physical attributes. It combines elements of both oceanic and continental climates. Throughout over 60% of the year, polar sea air from the west dominates the region, bringing winter thaws, extensive cloud cover, and precipitation in the form of rain and snow. In summer, this air mass results in cooling, increased cloudiness, and subsequent precipitation. Around 30% of the year, polar-continental air masses from Eastern Europe and Asia influence the region, while Arctic air, originating from northern Scandinavia and Greenland, impacts the area for approximately 6% of the days in the year. Mediterranean air, being recorded for only 2% of days a year, leads to rapid winter warming and periods of intense summer heat. The remaining 2% of days witness air flows from various other regions. Annual precipitation averages fall within the 700-800 mm range, with summer rainfall predominating over winter.

In July, the lowest average monthly rainfall, not surpassing 60 mm, occurs near the northern border of the Upper Silesian Coal Basin. The central part of the region experiences monthly rainfall between 80 and 100 mm in July. The spatial distribution of precipitation in January mirrors that of July, with reduced average monthly totals not exceeding 40 mm. The number of days with precipitation varies throughout the year and on location. As the analysed sites are located in the central part of the upper Silesia region, below the information based on data from a meteorological station located in Katowice is presented. The results from this station confirm the regional predominance of precipitation in summer over winter (Figure 6).

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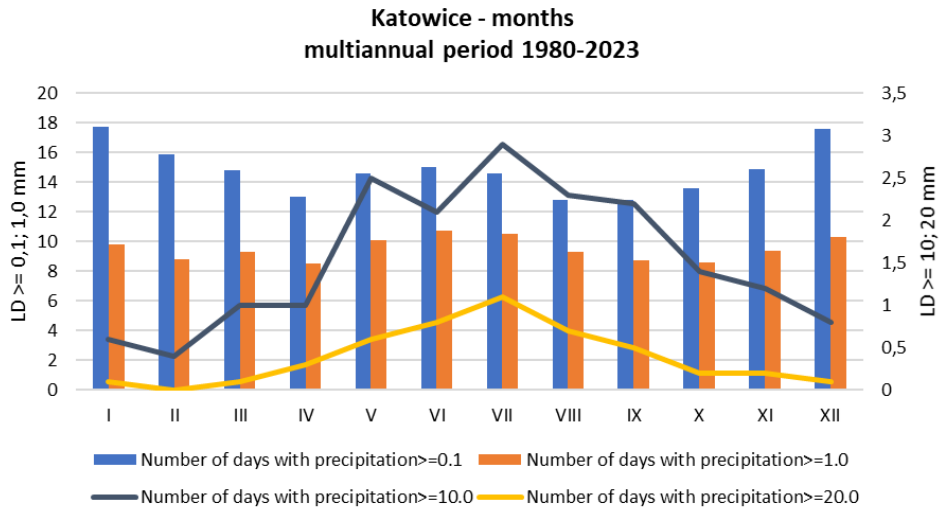

Figure 6. The average number of days with precipitation per month in Katowice in period 1980 – 2023.

Source: Own elaboration, based on the data from the Institute of Meteorology and the Water Management National Research Institute (IMGW-PIB),

There is also a variation in the sum of days with precipitation over the analysed period. The average number of days per year with precipitation exceeding 1.0 varied in Katowice from 103 to 174 days for the period 1980 – 2023 (Figure 7).

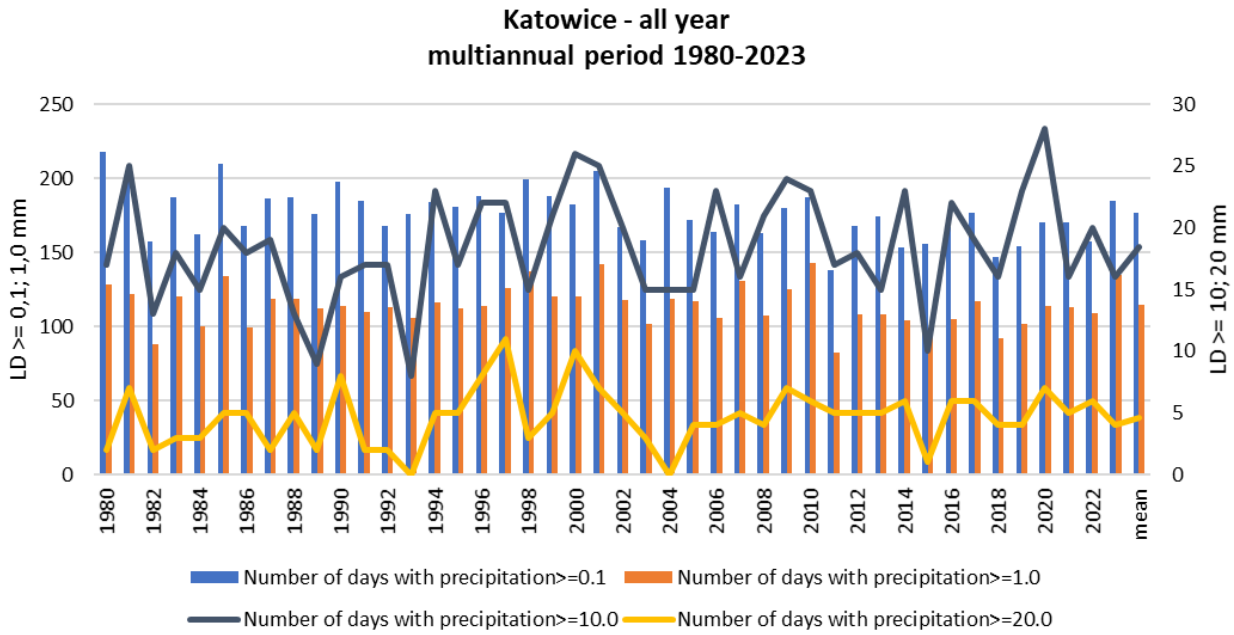

Figure 7. The number of days with precipitation in Katowice in period 1980 – 2023.

Source: Own elaboration, based on the data from the Institute of Meteorology and the Water Management National Research Institute (IMGW-PIB),

The average annual air temperature ranges from 7°C to 8,4°C. July sees the highest average monthly temperatures, ranging from 14-16°C, while January records the lowest, fluctuating between -2°C and -4°C. Annual maximum temperatures range between 12°C and 13°C, while annual minimum temperatures vary from below 1°C to above 4°C. In the multi-year period 1981 - 2019, the lowest recorded daily temperature was -27.7°C in January 1987, while the highest daily temperature: 37.2°C in August 2013 (Table 3).

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Table 3. A summary of the absolute maximum and minimum daily air temperature (°C) for individual months in the multi-year period 1981 - 2019 at the synoptic station Katowice-Muchowiec.

Month	Air temperature [°C]	
	Maximum	Minimum
I	14,6 1993 1994	−27,4 1987
II	18,8 1990	−26,2 1985
III	22,0 1990	−18,0 2018
IV	29,5 2012	−8,2 2002
V	32,2 2005	−2,8 2007
VI	34,6 2000	2,7 1984
VII	35,4 2013	4,8 1991
VIII	37,2 2013	3,1 1984
IX	34,4 2015	−0,8 2002 2013
X	26,6 2001	−8,0 1991
XI	20,4 2002	−16,3 1989
XII	18,2 1989	−24,4 1996

Source: data from Institute of Meteorology and Water Management National Research Institute (IMGW-PIB)

West winds dominate Upper Silesia, with the northern part experiencing a 20% average annual frequency of west winds. South-west winds are slightly less common, occurring in approximately 19% of cases, followed by northwest winds at 10%. South winds play a crucial role, constituting about 19% of occurrences, while northeast winds are the least frequent at around 8%. Silences are rare, comprising only 1% of all cases, with higher incidence in the central and southern parts of the region at 9% and 8%, respectively. The average annual wind speed in the Upper Silesian region ranges from below 2 m/s to 5 m/s.

The climate of the **Wielkopolska region** is characterised by typical Central European features with a significant influence of oceanic conditions. It is one of the driest and warmest regions in Poland, dominated by polar-marine air masses. This leads to cooler summers and milder winters compared to the more continental eastern part of the country. Average annual precipitation ranges between 500–550 mm, with areas in the Gniezno Lake District and southern Kuyavia receiving 50–100 mm less. Precipitation deficits are particularly notable in the eastern part of the region. The rainfall is irregular—annual differences in precipitation can reach up to 250%. The distribution of rainfall throughout the year or the growing season is also uneven. More rainfall during the summer is noted near water bodies and river valleys that lie on storm tracks. A characteristic feature of Wielkopolska's climate is the frequent, though irregular occurrence of dry periods, which negatively affect plant development. In the two decades from 1981 to 2000, long-lasting dry periods (over 30 days) occurred in 9 years. These dry periods are observed in dry, average, and wet years alike. The highest number of rainy days occurs in winter, but the largest amounts of rainfall

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are recorded in summer. Rainfall intensities of ≥5 mm per day constitute about 75% of the total rainfall during the growing season, with their frequency not exceeding 26%. The average annual temperature is about 8.2°C, dropping to 7.6°C in the north and reaching up to 8.5°C in the southern and western extremes. The thermal maximum occurs between July and September, with an average temperature of around 19°C, while the thermal minimum is noted between January and February, with average air temperatures of around -5°C. Extreme temperature values in summer can reach up to +38°C, and during the harshest winters, they drop to nearly –30°C. Lower temperatures are recorded in habitats located in river valleys, particularly in meadow areas and agricultural fields, partly due to increased evapotranspiration from cultivated lands. Western winds predominate in the Wielkopolska region. The most common are light winds, with speeds ranging from 2.5–3.5 m/s. The flat nature of the region allows for an undisturbed flow of air masses, which impacts air quality and prevents the accumulation of pollutants in one place. Cold fronts, often accompanied by storms, significant temperature fluctuations, and increased wind speeds, frequently move across the region during the summer.

According to the meteorological data, the strong upward trend in air temperature observed over many years in Poland continues. Since 1951, the annual temperature increase is estimated to be 2.1°C. The trend coefficient value shows only slight variation across the different climatic regions of the country. The year 2023 in Poland was the second warmest year of the 21st century. The average air temperature across Poland in 2023 was 10.0°C, which was 1.31°C higher than the long-term annual average (climatological normal period 1991-2020) (IMGW, 2024). In Silesia region (areas encompassing Sośnica Coal Mine, Boleslaw Śmiały Coal Mine and Wujek Coal Mine sites) the average air temperature was 10.0°C, which was 1,42°C higher than the long-term annual average in the region, whereas, in Wielkopolska region (including the area encompassing the Jóźwin open-pit mine) the average temperature was 10,9°C, which was 1.52 degrees higher than the long-term annual average there.

The average daily values of air temperature (area average for Poland) tended to fall between the quantiles of 5% and 95% of the mean temperature (determined based onf measurements in 1991-2020). Episodes of heat waves, i.e., those in which the average daily air temperature exceeded the values of the 95% quantile of this element, were more frequent and more prolonged than cold waves in the past year (see Figure 8). The anomaly index, which represents deviations from the average annual temperature for the period 1991-2020, ranged from 0.5°C to 2°C (IMGW, 2024).

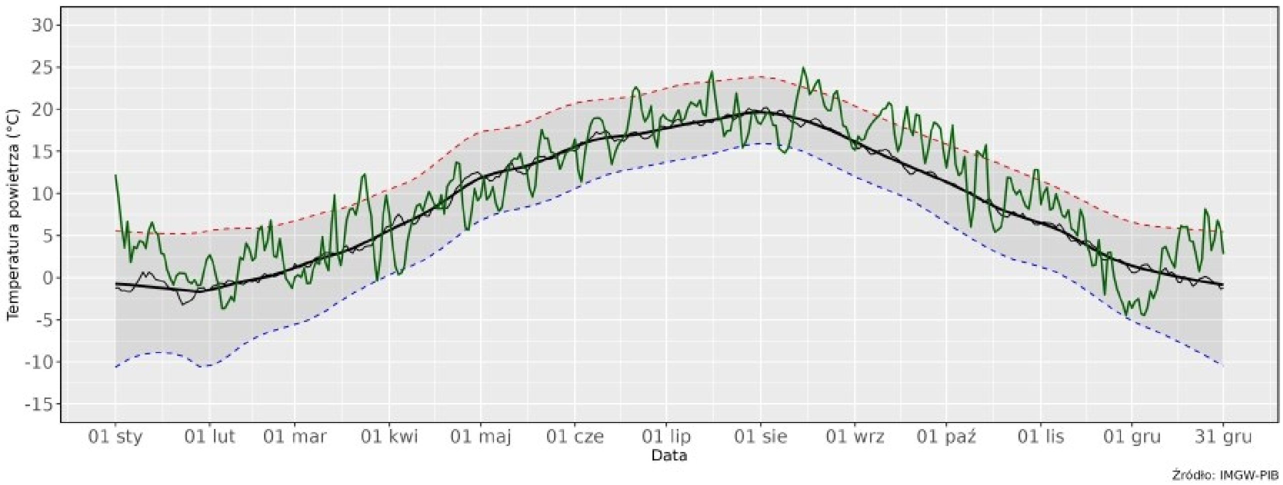

Figure 8. The variability of area average daily air temperature in Poland from January 1, 2021, to December 31, 2023, against the multi-year values (1991-2020).

Legend to figure: Daily average 2023 - green line; multi-year average - black line,
quantiles: 95% (red line) and 5% (blue line) - smoothed by locally weighted polynomial regression

Source: Institute of Meteorology and Water Management National Research Institute (IMGW-PIB), https://www.imgw.pl/wydarzenia/charakterystyka-wybranych-elementow-klimatu-w-polsce-w-2023-roku-podsumowanie

The area-averaged total precipitation in Poland for 2023 was 656.2 mm, which represents 107.3% of the norm based on measurements from 1991-2020. According to Kaczorowska's classification, the year 2023 is considered average. In terms of the rank classification of area-averaged total precipitation since 1951, it ranks 17th. The spatial variation in annual precipitation sums for 2023 indicates that they ranged from 80% to 130% of the long-term norm

(1991-2020) with the area around Konin, precipitation was about 90-100% of 80% of this norm, while the pilot areas in the Silesian Voivodeship had around 110-115% (IMGW, 2024).

3.2.2. Greece

The climate in Greece is typical of the Mediterranean climate. A great variety of climate subtypes are encountered in different regions of Greece, due to the influence of topography (mountainous bodies along the country) on the air coming from the Mediterranean Sea (moisture source).

The REECOL sites, shown in Figure 9 and listed in Table 2, are Ptolemais Lignite Field, where three lignite reserves are exploited: Mavropigi, Kardia, and South Field, and Amynteon Lignite Field, where the Public Power Corporation (PPC) of Greece has exploited three lignite reserves in the past: Anargiroi, Amynteon, and Lakkia. The PPC has terminated the lignite exploitation activities in Amynteon Lignite Field, whereas in Ptolemais Lignite Field, Mavropigi and South Field mines are still in operation. The distance between these sites is not great, and they are in the same continental zone according to the Köppen–Geiger climate classification.

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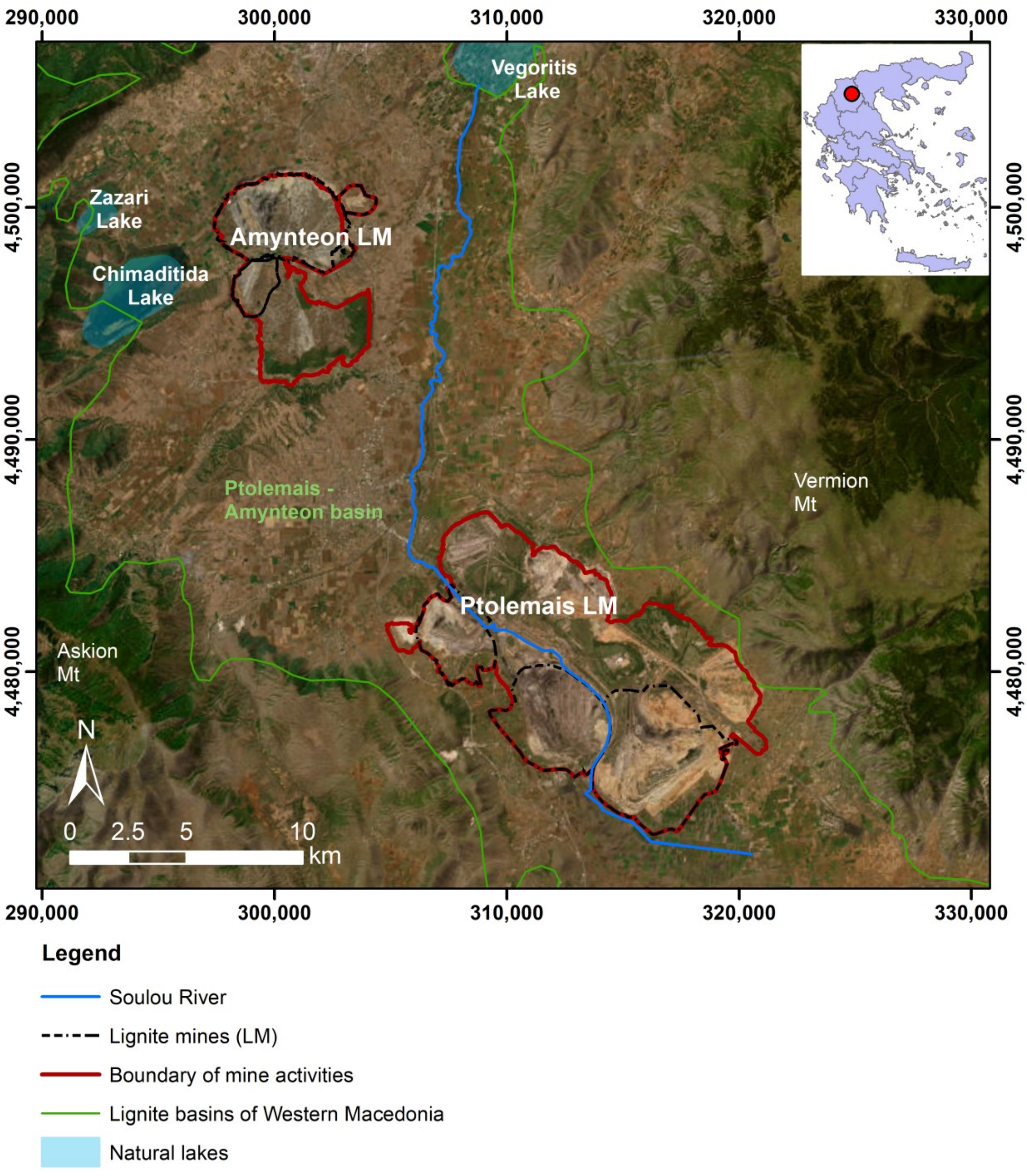

Figure 9. Location of REECOL sites in Greece

Source: Louloudis et al. 2022

Specifically in Amynteon (Louloudis *et al.* 2021) and Ptolemais area (Louloudis *et al.* 2022), the climate is characterised by mild winters, hot summers and more evenly distributed precipitation throughout the year, presenting a Köppen climate classification of Cfa, which is consistent with the updated 1-km resolution global maps of the Köppen-Geiger climate classification (Beck et al. 2018). In terms of climatology, the year can be divided mainly into two seasons, the warm and cold periods. These regions are marked by hot and wet summers, with high dew temperatures even during the day, and by mild rainy winters.

In these regions, the coldest months are January and February, while the warmest months are July and August. In the Amynteon region, the minimum, average monthly temperature was recorded in January 2017 (– 2.24 ^{o}C), while the maximum, average monthly temperature was recorded in 1978 (27.1 °C). January presents the wettest month, with maximum monthly precipitation of ~270 mm and average precipitation of 39 mm. According to the meteorological data of Amynteon weather station (altitude 581 m), the average annual temperature ranges between 9.9-15.5 °C, with an average value of 12.2 °C (± 1.2 °C s.d.). The mean annual precipitation ranges between 173-819 mm, with an average value of 487 mm (± 146 mm s.d.).

According to the meteorological data of Kozani weather station (same altitude as the Ptolemais lignite field, 626 m), the average annual temperature is 13.3 °C (± 0.8 °C s.d.), and the average annual rainfall is 498 mm (±132 mm s.d.), There is a visible trend of long-term increase in precipitation after 1990, however during the period of the last five years a decreasing trend is evident.

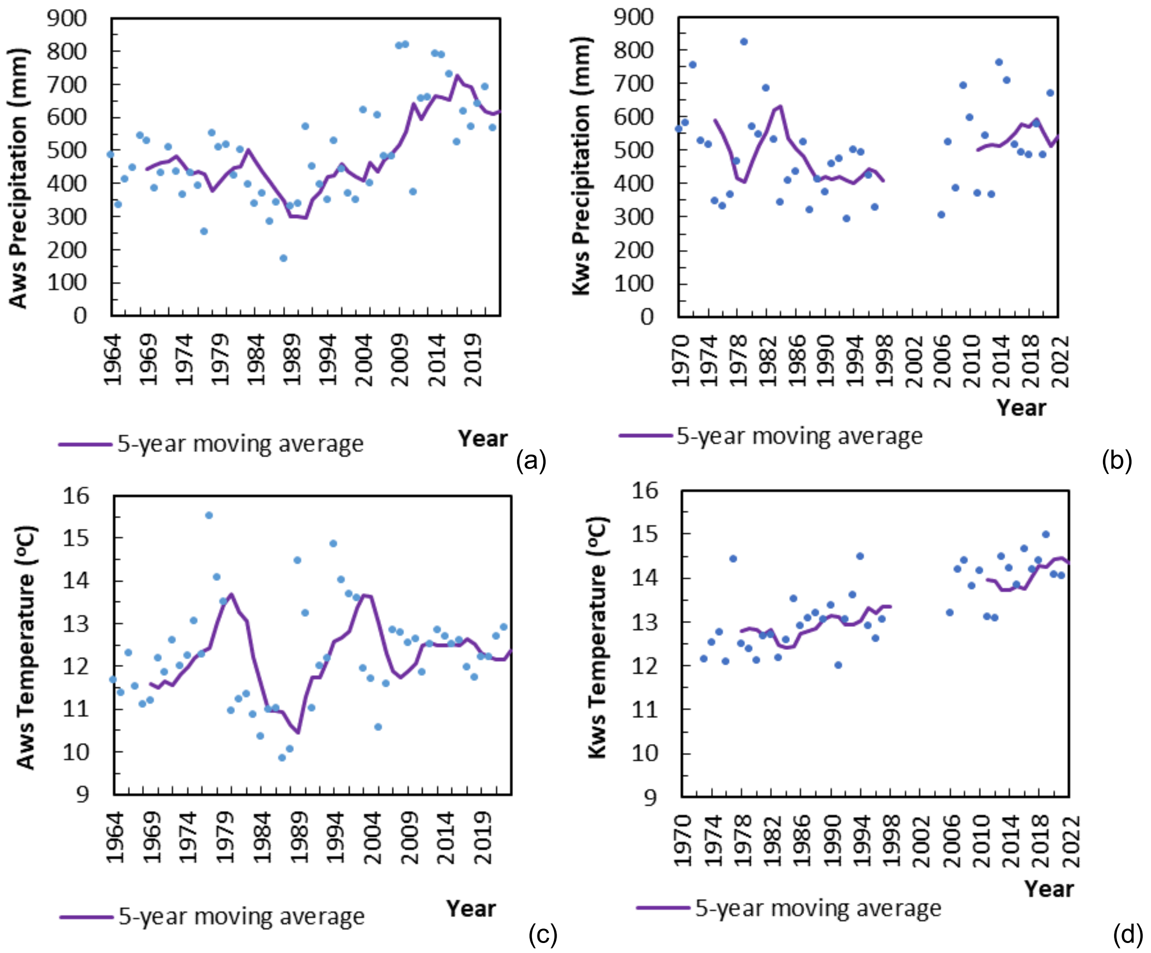

Figure 10. The Mean Annual (a) rainfall and (c) temperature from the Amynteon weather station (Aws), and the Mean Annual (b) rainfall and (d) temperature from the Kozani weather station (Kws), northern Greece.

Source: Louloudis et al. 2022 and Louloudis et al. 2021

3.2.3. France

The **'Nord-Pas-de-Calais'** region corresponds to a typically oceanic climate where thermal amplitudes are low and the weather is cloudy for a large part of the year (only 1650 hours of sunshine per year). The native vegetation is composed of nearly 1250 species including ferns, horsetails, lycopods, conifers, dicotyledons and monocotyledons. This relatively poor vegetation diversity compared to the rest of the country is mainly due to the Quaternary glaciations where most of the flora was eliminated from these regions. Despite this poor diversity, the different habitats of the region allow the development of a specific and emblematic flora, including the *Viola curtisii*, the *Liparis loeselii*, and the *Apium repens* which are protected species.



Figure 11. Pictures of the the Viola curtisii, the Liparis loeselii, and the Apium repens species

Winters are mild and summers are rather cool. There are significant climatic contrasts within the region: the oceanic character being more marked on the coasts than inland and the reliefs being the most watered by precipitation. The annual average temperature is around 11°C, with an average temperature of 5°C in the winter and an average of 17°C during the summer. The average annual precipitation sums vary from 600 to 750mm.

Table 4. The climatic data in the four representative cities in the Nord-Pas-de-Calais region between 1981 and 2010.

City	Temperature						Precipitations per year (mm)	Sunshine per year (hours)
	in winter (°C)		in summer (°C)		absolute (°C)			
	Min.	Max.	Min.	Max.	Min.	Max.		
Lille	1.7	7.1	12.9	22.3	-19.5	41.5	741.4	1628
Cambrai	1.5	6.5	12.6	22.2	-19.8	38.2	610.8	NA
Dunkerque	3.6	7.7	14.7	20.3	-18.0	38.3	679.7	NA
Boulogne-sur-Mer	3.3	7.4	13.9	19.7	-13.6	35.4	702.6	1684

According to several climatological studies, the region is the second French region most affected by climate change behind the Aquitaine region. If the temperature does not increase much and remains sustainable for several decades, it is more the increase in precipitation (the number of rainy days doubled between 1955 and 2016 in the city of Boulogne for example) and natural disasters which concern the region. Since the beginning of the 21st century, several extreme climatic events have been recorded in the Nord-Pas-de-Calais region including three tornados in 2000, 2008 and 2013 of EF2, EF4 and EF2 respectively (EF = Enhanced Fujita scale), and massive floods in 2024. In 2100, a significant part of Calaisis, Dunkerquois and Audomarois would be underwater. A large part of the region's coastline is also affected by marine erosion, which results in a continuous retreat of the coastline and consequences on seaside constructions (already visible today in certain places such as Wissant or Équihen-Plage). To fight against climate change, a regional observatory of the impact of climate change on forest ecosystems was set up in the 2000s, led by the Regional Forest Property Centre (CRPF).

The French pilot site (basin beneath an old coal mine) is located in the Mazingarbe, a city of the Pas-de-Calais department (62). It is situated in the watershed of Le Surgeon, La Fontaine de Bray, La Loisne and Le Fossé d'Aisnes et d'Auchy. The potential for runoff is low whereas the sensibility to the phenomenon of upwelling is strong. The capacity of water infiltration in the sub-soil is moderate to strong.

The closest weather station is Lille-Lesquin (50.57°N 3.10°E; 47 m above sea level; inland) in the North department (59). It is situated about 40 km far away from the pilot site. Data collection in this station (Météo France;

https://www.infoclimat.fr/) started in 1951 for temperatures (T). The survey (1951-2024) evidences an average T of 10.86°C, a minimal T° of 7.08°C and a maximal T° of 14.35°C. The temperatures and precipitation collected each 17th of July during this period reveal an increasing linear trend for these parameters (Figure 12).

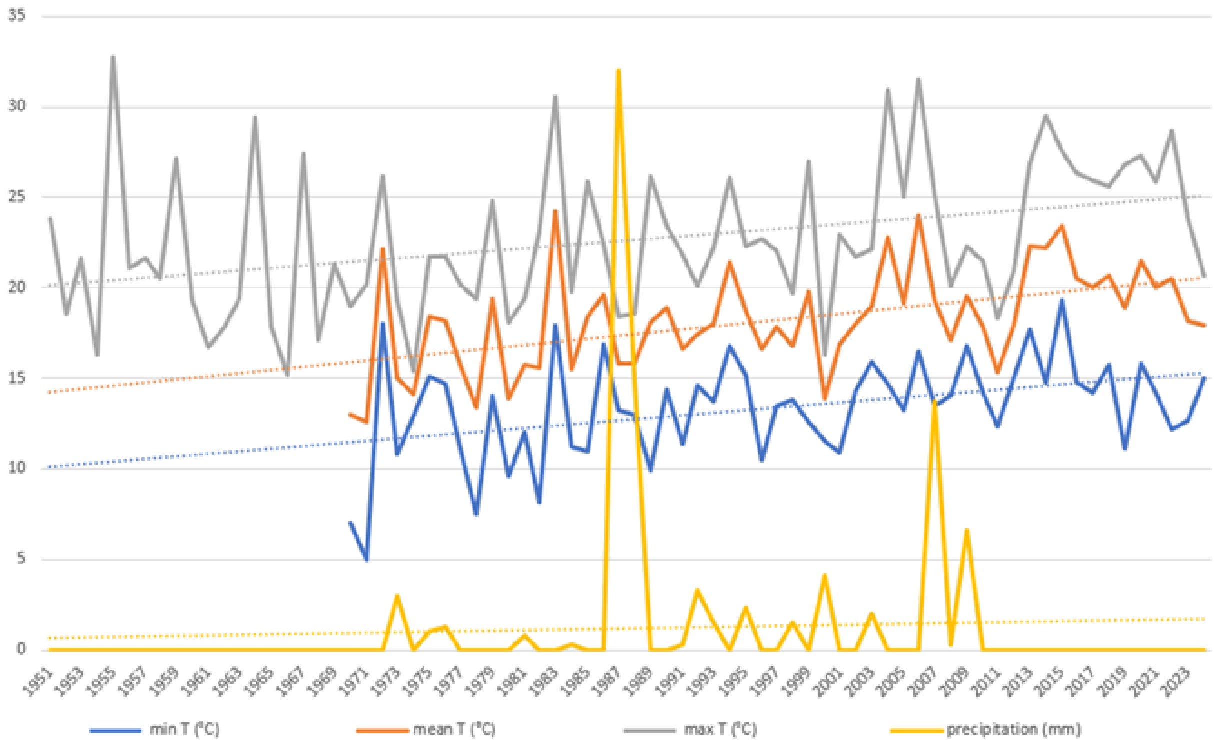

Figure 12. The temperatures (minimal, mean, maximal) and the precipitation data in the Lille-Lesquin weather station between 1951 and 2023.

Legend to the figure: The dashed lines indicate the linear tendency for temperature and precipitation

In addition, the compilation of data collected between 1971 and 2020 shows an increased trend for temperature (1°C over 49 years) and sunshine which might increase dry periods, drought and consequently wildfire in the future (Table 5). From this survey, no trend is evidenced concerning precipitation and extreme events such as measured by the maximal speed during windstorms.

Table 5. Temperature, sunshine, precipitation and windstorm data in Lille-Lesquin weather station over three timelines of 29 years

Dates	[1971-2000]	[1981-2010]	[1991-2020]
Mean T (°C)	10.3	10.8	11.3
Sunshine (hours)	114	135	136
Precipitation (mm)	742.7	742.5	740
Max windstorm (km h^{-1})	133.5	136.8	136.8

Explanation to the table: The values for temperature and sunshine are the monthly averages per year for each timeline. The values for precipitation are the total annual precipitation per year for each timeline. The values for windstorm correspond to the maximum value collected per timeline.

The modification of climate might influence the health and resilience of the vegetation selected for the reclamation and promote invasive species.

The old coal mine has a slope of 8-35%. As the pilot site is beneath the old coal mine, extreme events such as intensive precipitation could lead to erosion and landslides which could modify or destroy habitats and ecosystems after reclamation.

3.2.4. Czech Republic

The Czech Republic is situated in the middle of Europe. The location of the European continent is the main cause of significant regional climate variability. As there is an exceptionally dense network of long-term measuring stations in Europe, which is further complemented by several distance measurements, analyses of change trends are (perhaps except in North America) significantly more accurate than anywhere else on the planet. The temperature of the European continent increased by an average of 1.2 °C over the last century, of which 0.45 °C has increased over the last three decades, almost half the global level. While the average growth trend across Europe has been around 0.1 °C / 10 years in the last century, it has more than doubled in the last 30 years.

The Most Coal Basin area is known for its largest Czech brown coal deposit. It is situated in the region of North Western Bohemia - Czech mining region (Figure 13). The main mining companies are the North Bohemian Mines, j.s.c. and the Seven Group j.s.c. The main mining localities are the Bílina open pit mine, the Libous open pit mine, the Vrsany open pit mine and the CSA open pit mine. The Most Coal Basin is in general known as the dry part of the Czech Republic.

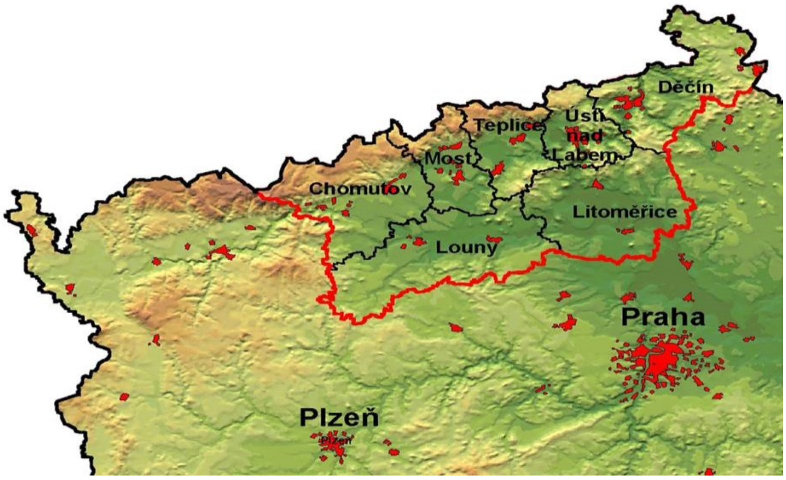

Figure 13. The situation of the Most Coal Basin in the Northwestern Bohemia

We applied data from the Brown Coal Research Institute (VUHU), data gained by mining companies, data gained by the Czech Hydro-Meteorological Institute (ČHMÚ, 2023) and very important data from regional met – stations: Kopisty and Milešovka. The most significant factors for quantifying the climatic changes were temperature and precipitations, although also the pressure and wind have been evaluated. The baseline of the most important graphs is 1961.

Temperature

The region of the Most Coal Basin is a relatively hot area in comparison with the general situation of the Czech Republic, but we did not discover the extreme situation during the last 20 years. The important data are shown in the following graphs. Presented data give evidence of temperatures increasing.

The average temperature for the year 2023 has been 9.9 °C for the Most Basin (NW Bohemia) region. The long-term average for this area is 8.6 °C. The increase in temperature is therefore 1.3 °C compared to the long-term average. The long-term increase in temperatures is evidenced by the graph (Figure 14).

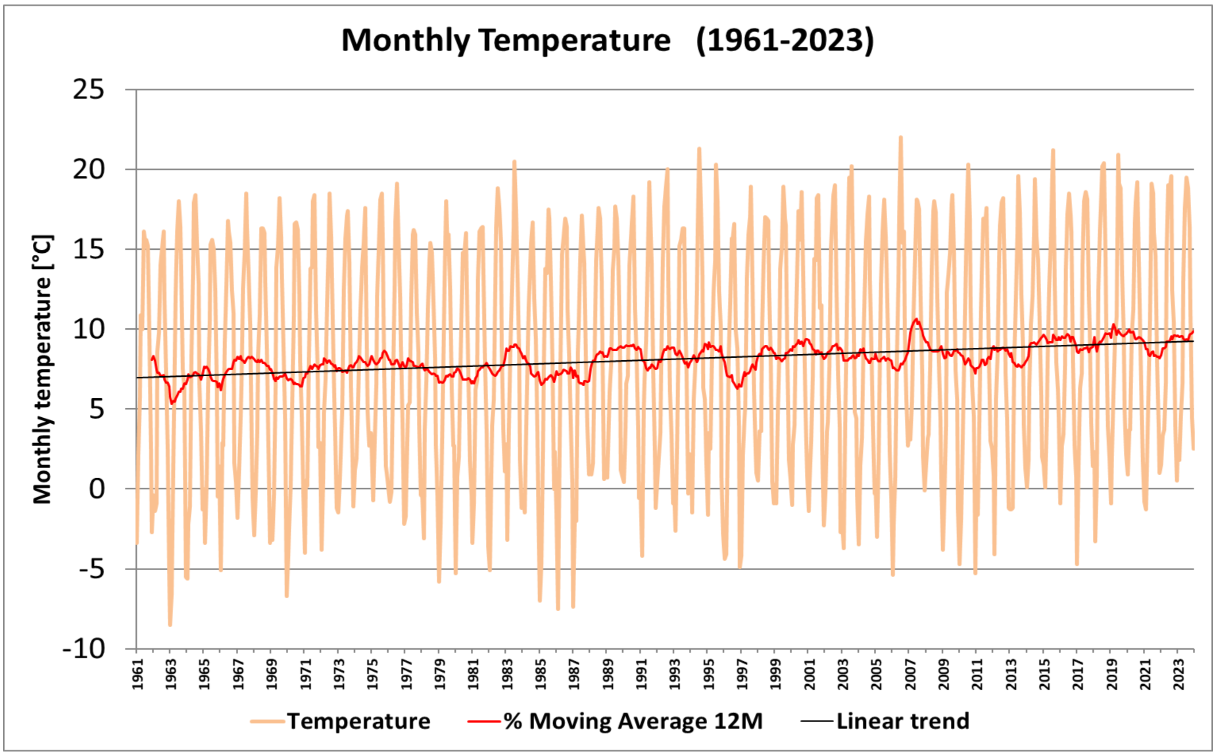

Figure 14. The increase in the average temperature during the 1961 – 2023 period for the Most Basin (NW Bohemia)

Precipitation

The extreme values of rainfall are very important for mining operations. It is observed in the relatively humid period from 2000 to 2010 and the relatively dry period from 2010 to 2019. After 2019, the precipitation level returned to the average value. The minimum and maximum values of rainfall are the source of the main observed incidents. A high level of rainfall is dangerous from the point of view of mining operations, law level of rainfall is danger from point of view of restoration and revitalisation of the landscape.

The average precipitation for the year 2023 is 664 mm. for the Most Basin (NW Bohemia). The long-term average for this area is 640 mm. The increase in precipitation is therefore 24 mm compared to the long-term average (Figure 15).

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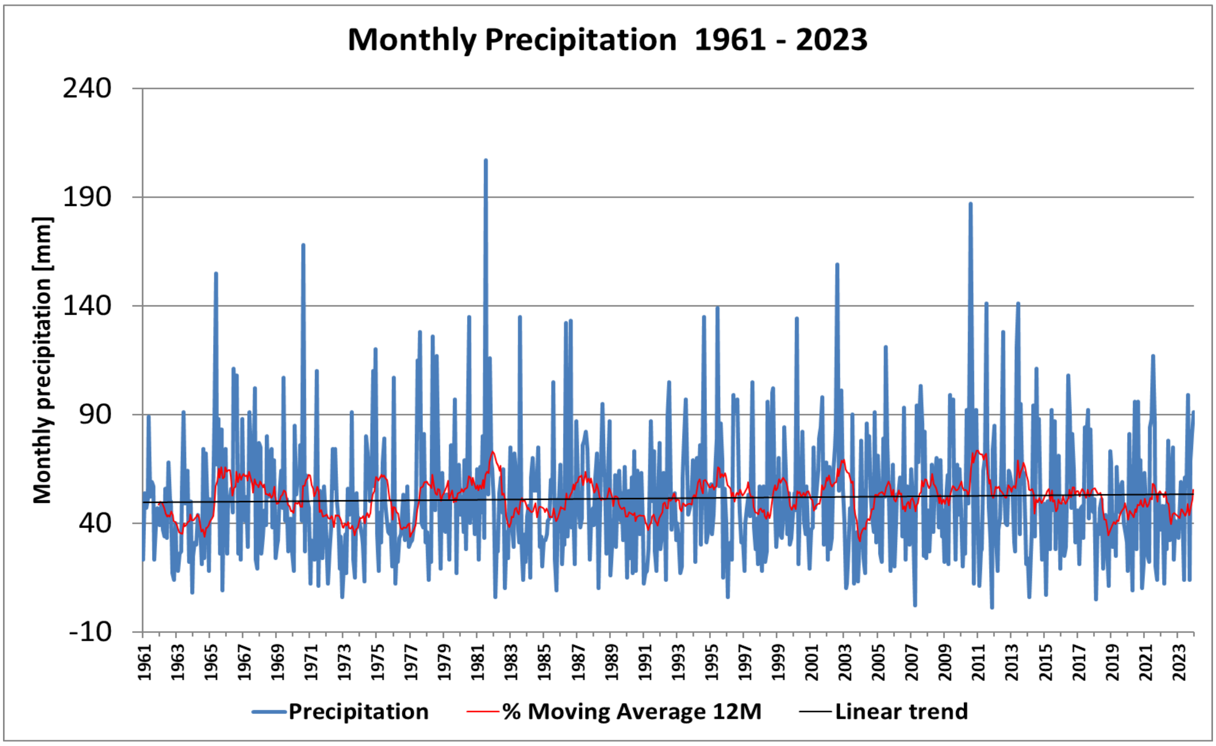

Figure 15. The average precipitation in the 1961 – 2023 period for the Most Basin (NW Bohemia)

3.2.5. Slovenia

Slovenia is a transitional climate area between the Mediterranean Sea, the Alps, the Dinaric Mountains and the Pannonian Basin. Consequently, its climate displays wide local climatic variability and fairly large gradients. The climate in Slovenia is determined by many factors, the most important of which are its geographical location, rugged relief, orientation of mountain ridges and proximity to the sea. The result of the interplay of many factors is a very diverse climate. Thus, we have three dominant types of climate, and their influences intertwine in individual areas: in eastern Slovenia, we have a temperate continental climate, in central Slovenia a subalpine climate (alpine in the mountainous world) and west of the Dinaric-Alpine barrier a sub-Mediterranean climate. The climatic diversity of Slovenia is reflected in the differences between the values of climatic variables and in their daily, seasonal and multi-year variability.

To account for regional differences, six smaller spatial regions within Slovenia were also considered according to the objective climate classification: submediterranean climate, wet climate of hilly region, the moderate climate of the hilly region, subcontinental climate, subalpine climate and alpine climate.

To show the characteristics of seasonal variations, shorter periods within a year were considered, namely four meteorological seasons:

- winter (December, January, February),
- spring (March, April, May),
- summer (June, July, August),
- autumn (September, October, November).

The regional diversity of Slovenia contributes to local climate differences. Local processes can have a significant impact on large-scale weather signals, causing a different local change in temperature and precipitation compared to that on a larger scale. Local changes may be more pronounced or more subtle compared to the changes on a regional scale. The impact of climate change can thus be highly localised and specific to a particular location, with differences occurring even between the seasons.

The annual average air temperature in Šaleška valley (where coal mine Velenje is) and in Slovenia is around 10°C. In the year 2023 average air temperature in Velenje was 1,3°C above average. Annual precipitation in Šaleška Valley is around 1200 mm (**Figure 16**).

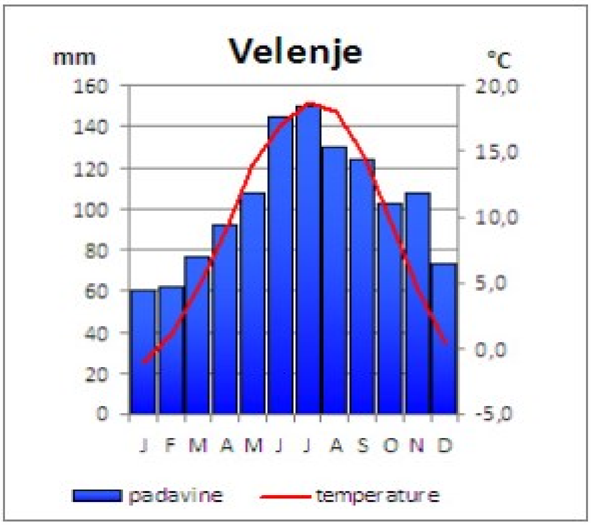

Figure 16. The annual average air temperature and precipitation in Velenje

Each year Slovenia is affected by more storms with strong winds, downpours and hail. The average power density in the years 2006-2023 as presented in Table 6, whereas a graphical representation of the distribution of wind directions and frequencies in the years 2006-2023 in the Velenje region is presented on the wind rose in Figure 17.

Table 6. Average wind power density (W/m2) at 10 meters

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
2006	0.7	0.9	3.3	2.0	1.8	2.7	2.1	1.4	0.9	1.5	2.0	1.0	1.7
2007	2.3	1.5	2.4	1.7	1.9	1.9	2.0	1.2	1.6	1.7	2.2	1.1	1.8
2008	2.1	1.6	2.3	2.6	1.7	1.5	2.2	1.4	1.5	1.0	1.1	0.9	1.7
2009	0.9	3.1	4.2	1.8	2.2	2.0	1.5	1.3	0.9	1.7	1.0	1.3	1.8
2010	1.0	1.1	2.0	2.1	4.5	3.1	1.9	1.6	0.9	1.2	0.9	1.6	1.8
2011	0.7	0.6	1.6	2.6	2.1	1.7	1.5	1.5	1.6	0.8	0.6	1.2	1.4
2012	2.1	1.7	1.4	1.6	2.3	1.3	1.7	1.2	1.1	0.5	0.6	0.9	1.4
2013	1.6	1.1	2.2	0.8	1.2	1.4	1.4	1.7	0.7	0.7	3.9	0.8	1.5
2014	0.4	0.9	2.3	2.6	5.5	1.3	1.1	0.9	1.6	2.5	0.7	1.3	1.8
2015	2.6	1.6	4.6	5.4	1.9	1.1	1.3	1.1	1.5	0.4	0.4	0.4	1.9
2016	0.8	1.7	2.4	2.3	1.8	1.0	1.8	1.2	0.7	0.4	0.9	1.6	1.4
2017	2.1	1.4	2.0	3.1	1.4	1.2	1.3	1.2	0.9	2.4	0.9	0.8	1.6
2018	1.1	0.4	0.7	1.7	0.7	1.5	1.2	0.9	0.6	1.0	0.2	0.7	0.9
2019	2.1	1.6	1.6	1.1	3.0	1.1	1.1	0.6	0.6	0.7	0.4	1.1	1.3
2020	0.5	5.1	2.5	1.2	1.8	2.5	1.4	0.9	0.6	0.9	0.3	0.2	1.5
2021	0.6	1.3	2.0	1.8	1.8	1.6	1.7	1.1	0.7	1.2	0.4	0.9	1.2
2022	1.4	3.0	1.5	2.4	1.3	2.6	1.7	1.6	0.9	0.6	1.1	0.6	1.5
2023	1.5	1.2	3.2	2.4	1.6	1.6	1.6	1.1	0.9	0.8	1.8	1.0	1.6
average wind power density	**1.4**	**1.7**	**2.4**	**2.2**	**2.1**	**1.7**	**1.6**	**1.2**	**1.0**	**1.1**	**1.1**	**1.0**	**1.5**

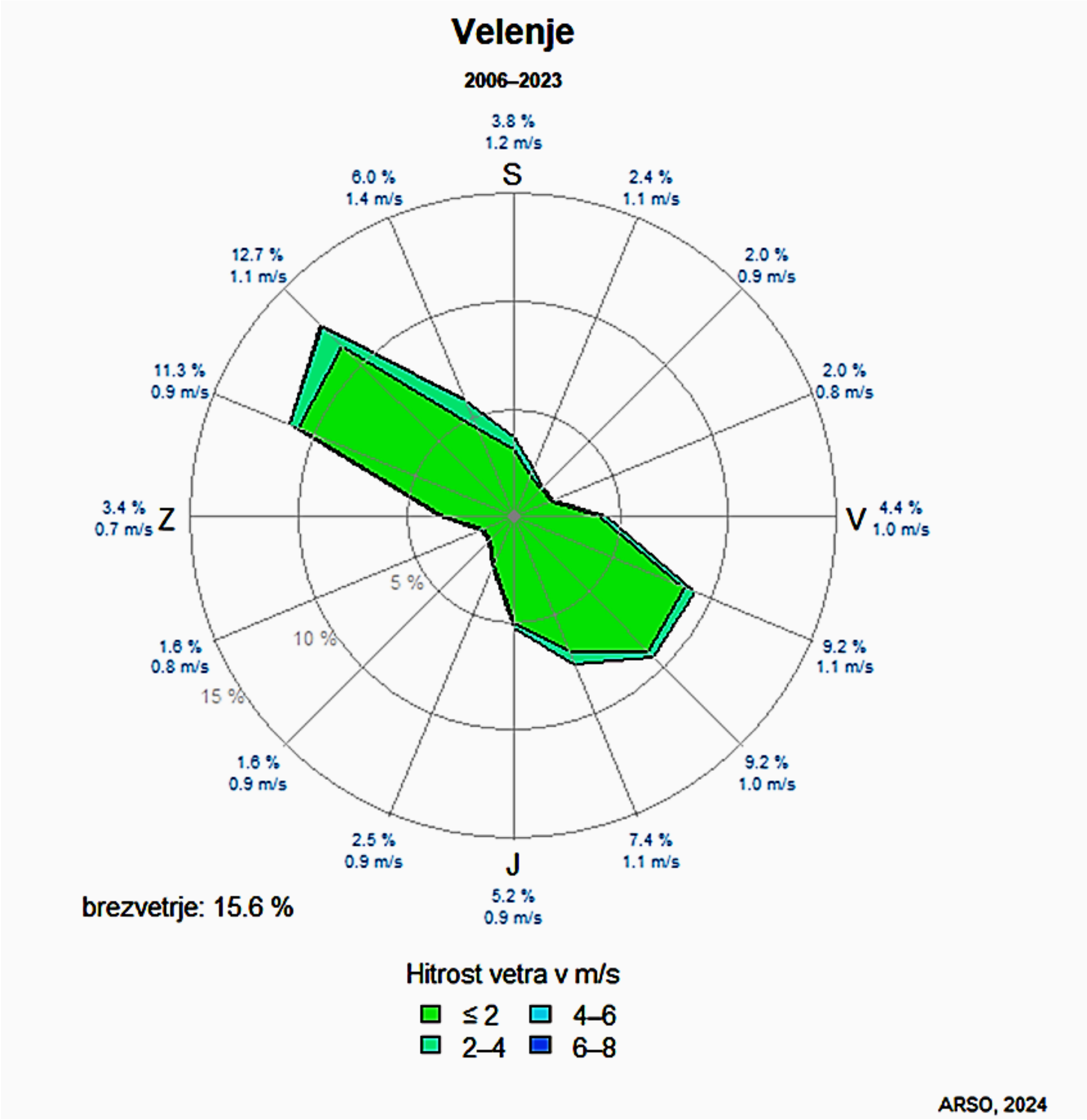

Figure 17. The distribution of wind directions and frequencies in the years 2006-2023 in the Velenje region

The height of snowfall in the period between 1961-2011 shows a statistically significant decline in a larger part of Slovenia[24]. It reaches a 20% decline per decade at some measurement stations. The decline is largest in the highlands during winter and in the lowlands during spring. There are also changes in sunshine duration and the streamflow of rivers. The temperature of surface and underground water is higher. The glaciers have shrunk to the point of being nearly unrecognisable. In the past decades, the frequency of agricultural drought is increasing. Slovenia will undergo substantial temperature rises. In the long term the amount of yearly rainfall in Slovenia will increase and due to that fact also risk of floods and landslides. This is especially affecting larger areas around the Premogovnik Velenje, specifically the Savinjsko Šaleška region, where nearby larger and smaller torrential rivers are located. In the vicinity of the Velenje coal mine or the Šaleška Valley, the impact of climate change is expected in the rise of air temperature, the occurrence of more frequent and stronger storms and downpours and as a result the occurrence of a greater number of windbreaks, landslides, drought and local floods, which are the result of the increased activity of torrential watercourses.

[24] Slovenian Environmental Agency at https://www.arso.gov.si/ & https://www.meteo.si/

4. CLIMATE CHANGE SCENARIOS

Climate change refers to a change in the state of the weather patterns that can be identified by differences in the mean and/or the variability of its properties that persists for an extended period, typically decades or longer (IPCC, 2013). There is an overwhelming volume of scientific evidence, which is based on a wide range of indicators, that strongly suggest that climate change is occurring in many different regions of the (IPCC, 1995; Oreskes, 2004; IPCC, 2007; Ackerman & Staunton, 2008; Lemmen, 2008; Doran & Zimmerman, 2009; Cook et al., 2013; IPCC, 2014; Kundzewicz et al., 2017; Pecl et al., 2017; USGCRP, 2018; Climate Change..., 2019; IPCC, 2019; Janson et.al. 2020). The global climate system is warming up and will continue to do so, at least until the end of the century which is evidenced by observed increases in atmospheric and oceanic temperatures, widespread melting of snow and ice, glacier retreat and rising global sea levels. Projected changes in mean air temperature (°C) and precipitation (unitless) between 1980–2016 and 2071–2100 derived from climate model outputs are presented in Figure 18.

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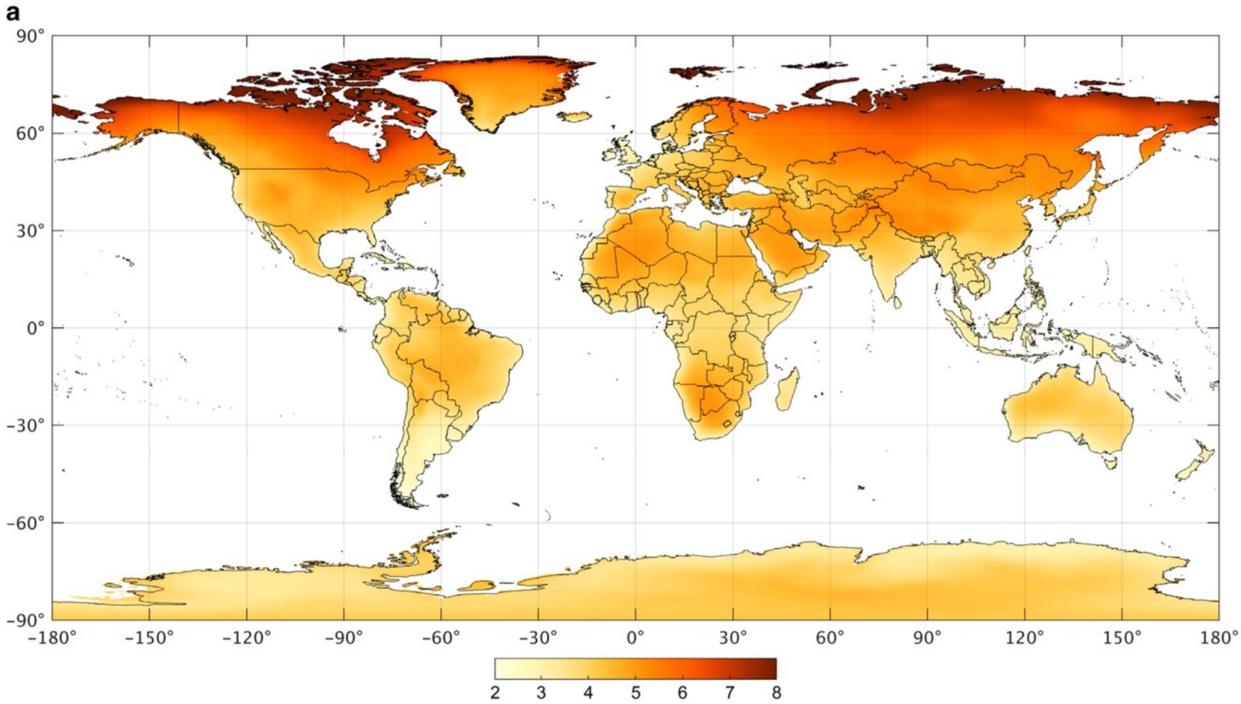

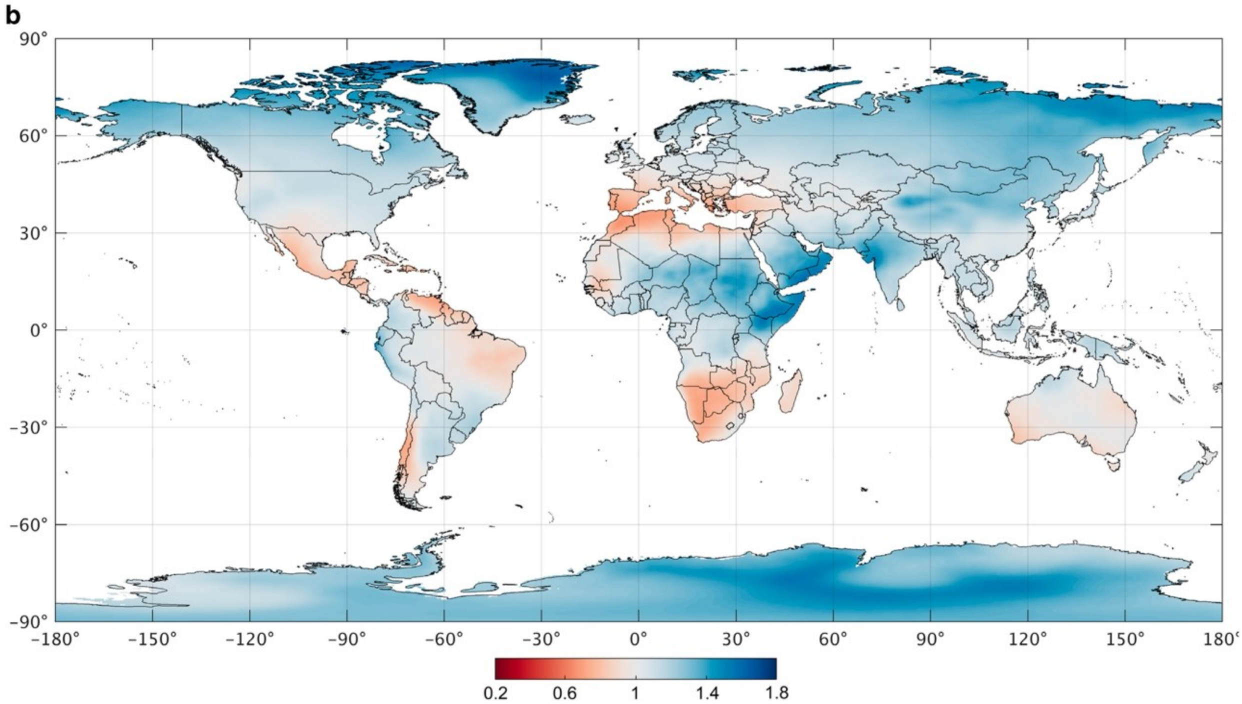

Figure 18. The projected changes in the mean air temperature (°C) and the precipitation (unitless) between 1980–2016 and 2071–2100 derived from the climate model outputs.

Source: Beck, H., Zimmermann, N., McVicar, T. et al. (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214 https://doi.org/10.1038/sdata.2018.214

The most consolidated method to assess the impacts of changing drivers on different aspects of mine rehabilitation schemes is through the downscaling of global scenarios to the local scale. This approach is called "scenario-based" or "top-down" as it moves from global scenarios to local impact assessment (Vano *et al*., 2010; Wilby and Dessai, 2010; Anghileri *et al.,* 2011; Bulovic *et.al.* 2024).

The “top-down” strategy involves a downscaling of the climate variables from Global Climate Models (GCMs), under a range of possible emissions scenarios, to the local scale through the Regional Climate Models (RCMs). The resulting local scenarios are then used to estimate the impacts, for example, the probability of flood events.

The starting point of the Scenario-Based methods are the climate scenarios provided by the IPCC (Intergovernmental Panel on Climate Change). In the year 2000, the IPCC developed the Special Report on Emissions Scenarios (SRES) for the IPCC TAR report. These scenarios denoted as A1, A2, B1, and B2, delineated four potential trajectories for future global developments in population, economic growth, and greenhouse gas emissions. Each trajectory was constructed around two key axes: one reflecting the balance between economic and environmental priorities, and the other representing the degree of globalisation versus regionalisation. Importantly, the SRES scenarios are "baseline" (or "reference") scenarios, which means that they do not take into account any current or future measures to limit greenhouse gas (GHG) emissions.

The scenarios can be summarized as follows (Nakicenovic *et al.,* 2000):

- **A1:** envisaged a world characterised by rapid economic expansion, peaking global population around mid-century, and subsequent decline, alongside swift adoption of advanced and efficient technologies.
- **A2:** portrayed a diverse and heterogeneous global landscape with a steadily increasing population, marked by regionally oriented economic growth that progressed more unevenly compared to other scenarios.
- **B1:** pictured a globally convergent trajectory with a population trajectory similar to A1 but featuring rapid shifts toward service and information-based economies, reduced material intensity, and widespread implementation of clean and resource-efficient technologies.
- **B2:** described a future where emphasis was placed on localised solutions for economic, social, and environmental challenges, with a gradually increasing but relatively lower population growth than A2, and intermediate levels of economic development.

Within these scenarios, estimation of greenhouse gas emissions and their atmospheric concentrations was starting from socio-economic factors, technological development, and energy production hypotheses. This process occurred through the carrying out of phases in succession, with a consequent accumulation of delays and a total time of approximately 10 years. Therefore, these frameworks began to show limitations as they failed to capture significant societal and economic transformations occurring globally, rendering them increasingly outdated (Hausfather, 2018).

Consequently, the IPCC has transitioned to employing two primary types of emission schemes in their reports:

- Scenarios based on anticipated greenhouse gas concentrations and other radiative forcings in the future, known as **Representative Concentration Pathways (RCPs**), were introduced in the IPCC AR5 Report.
- Scenarios are based on **shared socio-economic pathways (SSPs**), which focus on describing various trajectories of economic growth. This approach was introduced in the IPCC AR4 report.

As both options were designed to be complementary and are either still referenced and/or used, they are described in sub-chapters below.

4.1. Representative Concentration Pathways (RCP)

To reduce the time gaps and make the information more effective, climate and impact research communities have developed a parallel approach that starts from the identification of radiative forcing scenarios. Therefore, future emissions frameworks are expressed as Representative Concentration Pathways (RCPs) that essentially indicate different greenhouse gas concentrations that will result in total radiative forcing increasing by a target amount by 2100, relative to pre-industrial levels (Met Office, 2018). The radiative forcing scenarios are more effective because they are not associated with unique storylines but can result from different combinations of economic, technological, demographic, political, and institutional futures (Moss *et al.,* 2010; Change, 2014). Total radiative forcing is the difference between the incoming and outgoing radiation at the top of the atmosphere. These targets have been set at 2.6, 4.5, 6.0 and 8.5 watts per square metre (W/m^2) to span a wide range of plausible future emissions schemes and these targets are incorporated into the names of the RCPs; RCP2.6, RCP4.5, RCP6.0 and RCP8.5 - a set of four paths of radiative forcing developed as a basis for long-term and near-term modelling experiments relevant for the climate modelling community (Van Vuuren *et al.,* 2011). The four RCPs were selected to include one mitigation scenario leading to a very low forcing level (RCP2.6), two medium stabilisation scenarios (RCP4.5/RCP6.0) and one very high baseline emission scenario (RCP8.5). The main differences among the four RCPs scenarios are summarised in Table 7.

Table 7. Description of each RCP and their likely consequences

RCPs	Description	Mitigation	Likely increases in global temperatures
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	Business as usual	Likely to exceed 4ºC
RCP6	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100	Some Mitigation	Very Likely to exceed 2ºC
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100	Strong Mitigation	Likely to exceed 2ºC
RCP2.6	Peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline	Aggressive Mitigation	Not likely to exceed 2ºC

Source: IPCC, 2014

RCP2.6 is known as a peak-and-decline pathway, having maximum radiative forcing (+3.1 W/m2) around mid-century and very low GHGs levels reaching 2.6 W/m^2 in 2100. It represents a pathway where greenhouse gas emissions are strongly reduced (halved by 2050), resulting in a best-estimate global average temperature rise of 1.6°C by 2100 compared to the pre-industrial period. RCP8.5 is a pathway where greenhouse gas emissions continue to grow unmitigated, leading to a best estimate global average temperature rise of 4.3°C by 2100. RCP4.5 and RCP6.0 are two medium stabilisation pathways, with varying levels of mitigation (Met Office, 2018).

Representative Concentration Pathways (RCP) scenarios have close analogues in the SRES scenarios. For example, the old A1B scenario – used as the high-end scenario in many Pacific Northwest impacts assessments – is similar to the RCP6.0 scenario by 2100, though closer to the RCP8.5 scenario at mid-century. A comparison of RCP scenarios with the previous greenhouse gas scenarios[25] is presented in Table 8.

[25] used in the 2001 and 2007 IPCC reports, were described in the Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000

Table 8. Comparison of RCP scenarios with old scenarios

RCP scenario	Scenario characteristics	Comparison to old scenarios
RCP2.6	An extremely low scenario that reflects aggressive greenhouse gas reduction and sequestration efforts	No analogue in previous scenarios
RCP4.5	A low scenario in which greenhouse gas emissions stabilize by mid-century and fall sharply thereafter	Very close to B1 by 2100, but higher emissions at mid-century
RCP6.0	A medium scenario in which greenhouse gas emissions increase gradually until stabilizing in the final decades of the 21st century	Similar to A1B by 2100, but closer to B1 at mid-century
RCP8.5	A high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century	Nearly identical to A1FI[26]

Source: https://cig.uw.edu/wp-content/uploads/sites/2/2020/12/snoveretalsok2013sec3.pdf

In both cases, the high end is a "business as usual" scenario (RCP8.5, SRES A1FI) in which emissions of greenhouse gases continue to increase until the end of the 21st century, and atmospheric CO_2 concentrations more than triple by 2100 relative to pre-industrial levels, what can be seen in figures below.

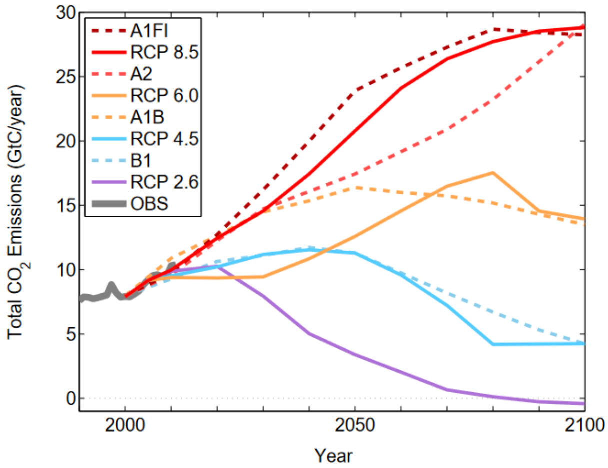

Figure 19. The annual total CO2 emissions in Gigatons of Carbon (GtC) in different scenarios.

Source: Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013 (http://tntcat.iiasa.ac.at:8787/RcpDb and http://sedac.ciesin.columbia.edu/ddc/sres/)

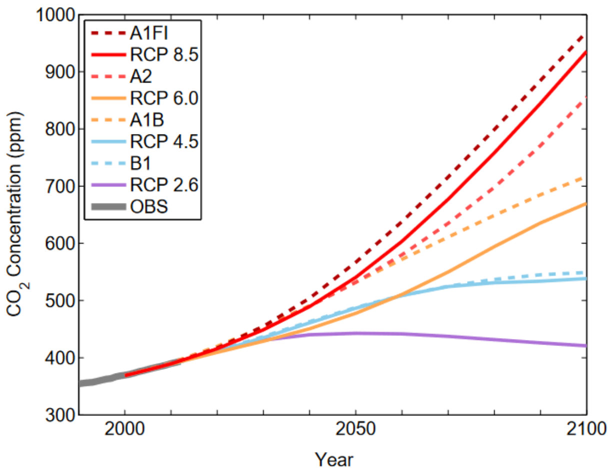

Figure 20. The annual total CO2 concentration in parts per million (ppm), for each of the greenhouse gas scenarios

Source: Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013 (http://tntcat.iiasa.ac.at:8787/RcpDb and http://sedac.ciesin.columbia.edu/ddc/sres/)

[26] The A2 greenhouse gas scenario is between the RCP6.0 and RCP8.5 scenarios

4.2. Shared Socioeconomic Pathways (SSP's)

These emission scenarios, originally developed and published in the IPCC's Special Report on Emission Scenarios (2000), served as the basis for running General Circulation Models (GCMs) in the IPCC AR4 report of 2007. SSPs have been also used as important inputs for the latest climate models, feeding into the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report[27] which was published in 2021.

The Shared Socio-economic Pathways were already part of the Fifth Report, but they take a much more central position in this novel framework and have the intent to link Impact Adaptation Vulnerability (IAV) analysis and mitigation analysis more explicitly to socio-economic development.

Scenarios, taking into consideration socio-economic factors and mitigation ambitions are translated into frameworks for greenhouse gas emissions (and associated atmospheric concentrations). The climate change projections that result from these scenarios describe a range of plausible future climates, from a pessimistic high-carbon scenario to a low-carbon scenario that meets the ambitions of the 2015 Paris Agreement.

The SSPs offer five pathways that the world could take - including sustainable development, regional rivalry, inequality, fossil-fuelled development and middle-of-the-road development (Table 9). SSPs starting assumptions outline broad characteristics of the global future and country-level population, GDP and urbanisation projections. Thus, SSPs are not scenarios themselves but their building blocks (Riahi *et al.,* 2017). Compared to previous scenarios, these offer a broader view of a "business as usual" world without future climate policy, with global warming in 2100 ranging from a low of 3.1C to a high of 5.1C above pre-industrial levels.

Table 9. Narrative for Shared Socioeconomic Pathways

SSP no	Narrative	
SSP1	Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)	The global trajectory undergoes a gradual yet comprehensive transformation towards a more sustainable direction, prioritising inclusive development while respecting perceived environmental limits. There is a gradual enhancement in the management of global resources, coupled with accelerated investments in education and health, facilitating demographic transitions. The focus on economic growth shifts towards a broader emphasis on human well-being. With a growing dedication to achieving development objectives, inequalities diminish both among nations and within societies. Consumption patterns shift towards lower material growth and reduced resource and energy intensity.
SSP2	Middle of the Road (Medium challenges to mitigation and adaptation)	The world continues along a trajectory where social, economic, and technological trends largely adhere to historical patterns. Development and income growth advance unevenly, with certain countries making substantial strides while others lag behind. Efforts by global and national institutions towards achieving sustainable development goals are sluggish. Environmental degradation persists, albeit with some pockets of improvement, and there is a gradual decline in the intensity of resource and energy usage. Global population growth remains moderate, plateauing in the latter half of the century. Income inequality persists or improves only gradually, and challenges persist in reducing vulnerability to societal and environmental shifts.
SSP3	Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)	Resurging state protectionism, coupled with concerns regarding competitiveness and security, as well as regional conflicts, drive countries to prioritize domestic or, at most, regional matters. Over time, policies increasingly pivot towards national and regional security concerns. Nations concentrate efforts on attaining energy and food security objectives within their respective regions, often at the expense of broader developmental goals. Investments in education and technological advancement decline as a result. Economic progress is sluggish, marked by material-intensive consumption patterns, while inequalities persist or exacerbate over time. Population growth rates are low in industrialised nations and high in developing countries. With environmental concerns receiving low international priority, certain regions experience significant environmental degradation.

[27] https://www.ipcc.ch/assessment-report/ar6/

SSP no	Narrative	
SSP4	Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)	Dramatic disparities in investments in human capital, coupled with escalating gaps in economic opportunities and political influence, drive a widening chasm of inequality and social stratification both within and among nations. Over time, this schism deepens between a globally interconnected society driving knowledge- and capital-intensive sectors of the global economy, and fragmented segments of lower-income, less-educated societies engaged in labour-intensive, low-tech endeavours. Social cohesion deteriorates, giving rise to heightened conflict and unrest. Technological advancements surge within the high-tech economy and sectors. The globally interconnected energy sector undergoes diversification, with investments spanning carbon-intensive fuels like coal and unconventional oil, alongside low-carbon energy sources. Environmental policies concentrate on local concerns within middle and high-income areas.
SSP5	Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)	In this world, there is a growing reliance on competitive markets, innovation, and inclusive societies as catalysts for rapid technological advancement and the cultivation of human capital, seen as crucial for sustainable development. Global markets witness increasing integration, accompanied by substantial investments in health, education, and institutional frameworks to bolster human and social capital. Concurrently, the pursuit of economic and social progress coincides with the exploitation of abundant fossil fuel reserves and the adoption of resource-intensive lifestyles worldwide. These factors contribute to a swift expansion of the global economy, coinciding with a peak and subsequent decline in the global population during the 21st century. Local environmental issues such as air pollution are effectively addressed, underpinned by confidence in the capacity to manage social and ecological systems, even resorting to geoengineering if deemed necessary.

Source of narratives for each Shared Socioeconomic Pathway, from Riahi et al., 2017 and https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/, amended

As can be noted, SSP1 and SSP5 depict relatively optimistic trajectories for human development, characterised by significant investments in education and health, rapid economic growth, and the presence of well-functioning institutions. The primary distinction lies in their approaches to energy usage: SSP5 relies on an energy-intensive, fossil fuel-driven economy, while SSP1 progressively transitions towards sustainable practices.

On the other hand, SSP3 and SSP4 paint a more pessimistic picture of future economic and social development. These scenarios involve minimal investment in education or health, particularly in poorer nations, alongside rapid population growth and escalating inequalities.

SSP2, meanwhile, represents a "middle-of-the-road" scenario where historical patterns of development persist throughout the 21st century, which is shown in Figure 21.

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Co-funded by the European Union

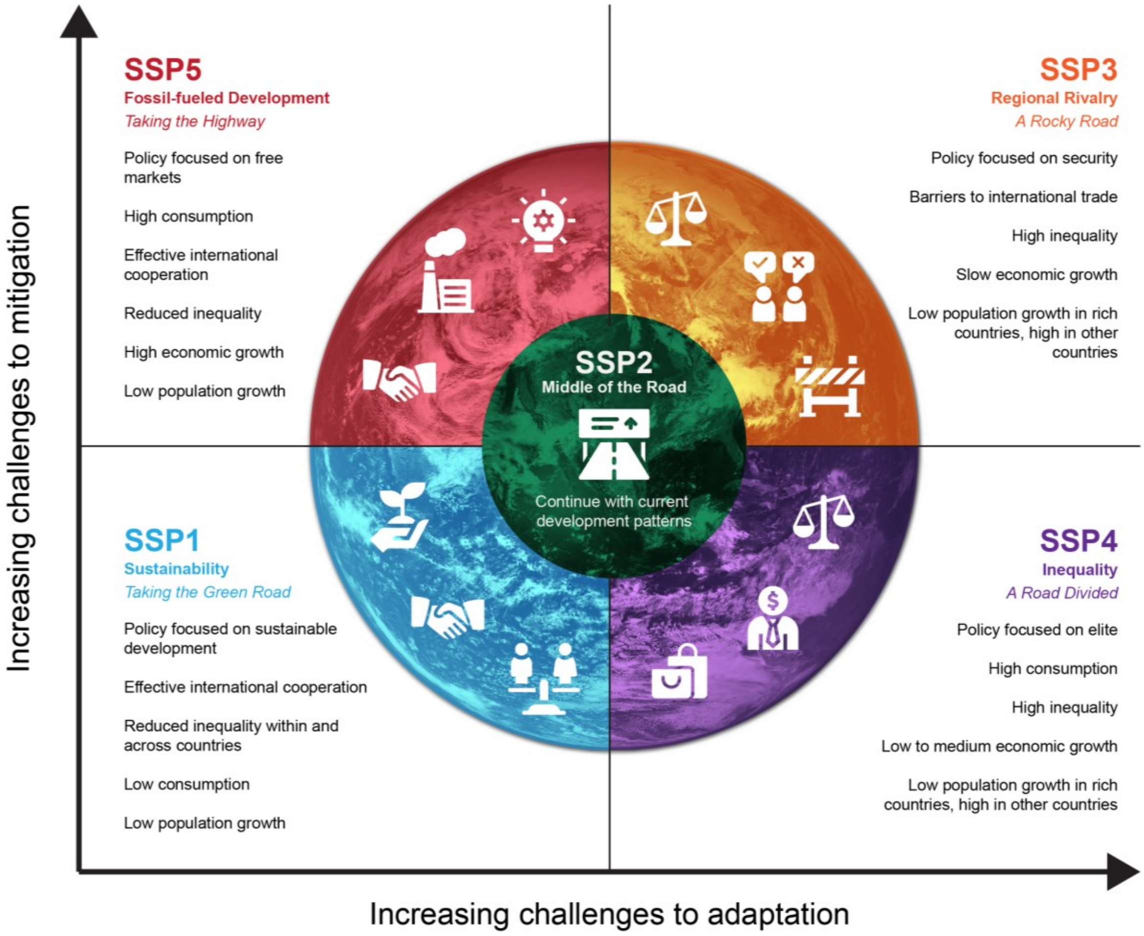

Figure 21. The visual representation of the logic behind the SSP-based scenarios categorised along the two broad axes: the challenges to mitigation and the challenges to adaptation

Source: https://climatedata.ca/resource/understanding-shared-socio-economic-pathways-ssps/, accessed 25.03.2024

As Shared Socioeconomic Pathways baseline scenarios describe a future world in the absence of new climate policies beyond those in place today, they should be considered as reference cases for mitigation, climate impacts and adaptation analyses (Riahi *et al.,* 2017). Mitigation scenarios, instead, explore the implications of climate change mitigation policies applied to baseline scenarios. These policies are chosen considering RCPs' radiative forcing levels as a target. This is carried out by applying different Shared Policy Assumptions (SPA) to baseline scenarios consistently with the combination of the overall characteristics of the narratives and the RCP scenarios.

The ecological rehabilitation and reclamation of post-mining sites, including waste dumps, supports the tenets of the SSP1 scenario, known as "Sustainable Development - the Green Way." The scenario's emphasis on inclusive development and strong environmental policies, as well as its focus on sustainable development and environmental management, directly supports the goals of ecological rehabilitation, as it emphasizes the rehabilitation of degraded land, biodiversity conservation and sustainable management of natural resources. The SSP1 scenario's commitment to reducing environmental impacts and fostering resilient ecosystems make it the most suitable path for comprehensive and effective ecological rehabilitation of post-mining areas. Additionally, SSP1 prioritises inclusive development and reducing inequalities, which are addressed through community involvement and the creation of green jobs in reclamation projects. By engaging local communities in the planning and execution of reclamation schemes, these projects can provide employment opportunities, build local capacity and ensure that the benefits of environmental restoration are shared equitably. Furthermore, the integration of green technologies and sustainable practices in reclamation aligns with SSP1's emphasis on innovation and sustainable infrastructure, promoting long-term resilience and ecological health.

At the same time, the concept of long-term maintenance of the redevelopment potential of post-mining areas secures the possibility of realisation of the SSP 5 scenarios. In the event of the necessity of execution of this development vision (e.g. due to the threat of warfare), it will be necessary to have access to well-located investment areas. Due to their genesis and degradation, post-mined (brownfields) areas should be used first to locate service and production facilities. It is in line with the concept of reuse and allows for the preservation of undeveloped land (greenfield). Until the post-mining land is reused, it should be covered with vegetation that maintains the potential for re-development and at the same time provides ecosystem services that are also valuable in terms of climate change (e.g. meadow-like vegetation). It should be emphasised that current and newly created post-mining areas offer a land resource on which climate change adaptation and mitigation actions can be implemented.

4.3. Climate change scenarios in REECOL regions

In REECOL project, to analyse interactions between climate change impacts on reclamation schemes for post-mining areas, it has been necessary to identify, analyse and assess the changes and the impacts resulting from them.

The analysis of climate changes took into consideration the climate baseline in each of REECOL project case studies sites & regions, based on meteorological data, as well as the analysis of future climate projections. For these works, we have used TEXMIN project results[28] as a piece of basic information, which has been later updated and amended.

Annual average land temperatures over Europe are projected to continue increasing by more than the global average temperature. The most substantial temperature increases are anticipated in eastern and northern Europe during winter, with southern Europe experiencing the greatest rise during summer. In terms of precipitation, northern Europe is expected to see an overall increase, while southern Europe faces a projected decrease. These trends are likely to accentuate the distinctions between presently moist and dry regions. (EEA, 2012). Figure 22 based on projections using the RCP8.5 scenario with models from Euro-Cordex, illustrates the anticipated changes in annual mean temperature and precipitation across Europe for the period 2071-2100 relative to a baseline of 1971-2000.

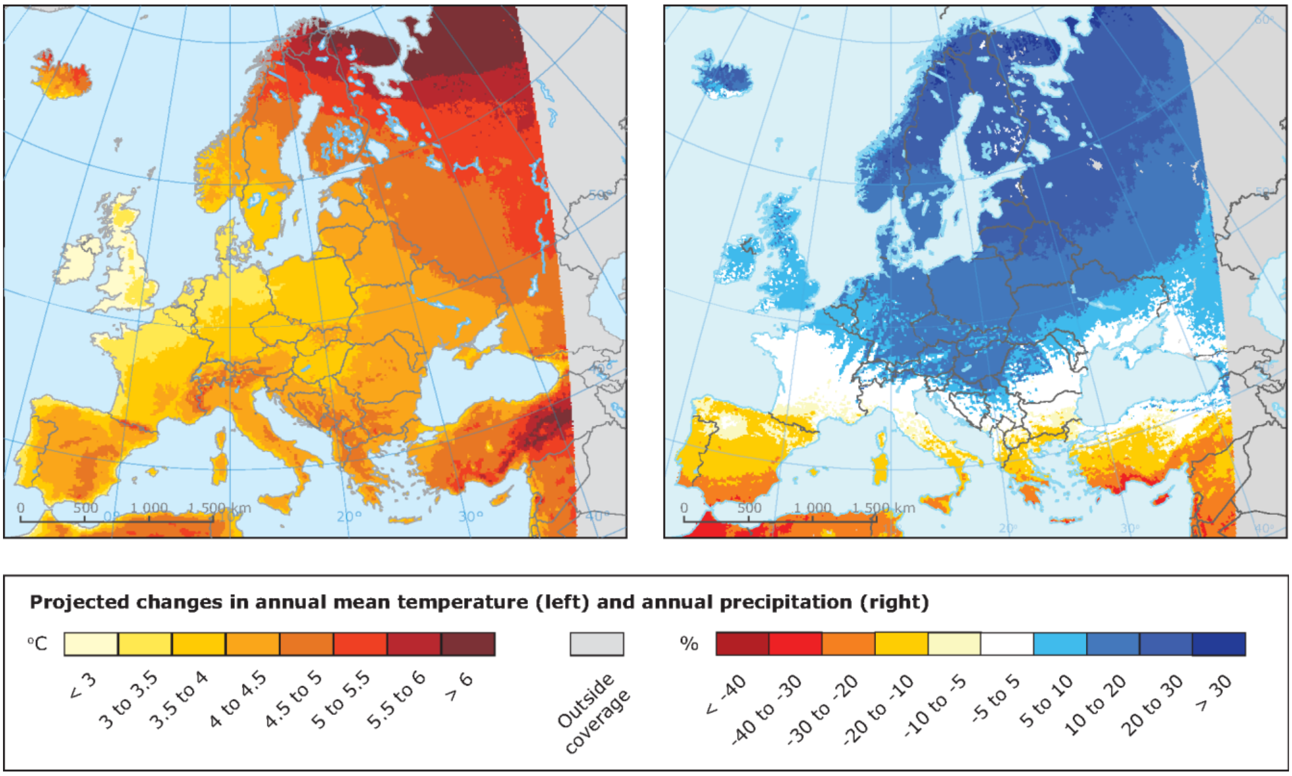

Figure 22. The projected changes in the annual mean temperature and the annual precipitation across Europe for the 2071-2100 period compared to a baseline of 1971-2000 using the RCP8.5 scenario implementing the models with Euro-Cordex (EEA, 2020).

[28] Especially Tasks 1.2 and 1.3 from TEXMIN

Source: https://www.eea.europa.eu/data-and-maps/figures/projected-change-in-annual-mean, based on Climate change projections for Europe based on an ensemble of regional climate model simulations provided by the EURO-CORDEX initiative

4.3.1. Poland

In recent decades, Poland, including both the Wielkopolska and Silesia regions, has observed significant climatic changes that are critical to understanding the ongoing and future impacts on its environment and society. Since the late 19th century, there has been a systematic trend of increasing air temperatures, with a notable rise since 1989. Precipitation patterns have not shown a unidirectional trend but are characterised by periods of varying humidity. Notably, the course structure of rainfall has changed primarily during the warm season, with occurrences of more intense, short-lived, and destructive rainfall leading to increasingly frequent severe floods and a decline in light precipitation events below 1 mm/day. Over the last 60 years, the frequency of drought phenomena has risen; between 1951 and 1981, droughts occurred six times in Poland, increasing to 18 times between 1982 and 2011, and from 2001 to 2011, droughts occurred nine times at various times of the year. The direct causes of droughts include prolonged periods (over ten days) without rainfall coupled with low air temperatures in winter—without snow cover—and high temperatures with strong solar radiation, lack of rainfall, and very weak winds during the spring and summer, lasting from 15 to 20 days.

Moreover, the effects of climate warming are evident in the increase of dangerous and extreme weather events such as droughts, hurricane-force winds, tornadoes, and hail. Since 2005, Poland has experienced 11 hurricanes with wind speeds occasionally exceeding 30–35 m/s; notably, on March 28, 1997, a storm passed over Poland that locally reached hurricane intensities. Strong and gusty winds exceeding 30 m/s have also been recorded in Wielkopolska, with the eastern part of the region being most susceptible to hurricane-force winds. Additionally, there is an upward trend in heatwave episodes (consecutive days with a maximum daily air temperature ≥30°C lasting at least three days), alongside a downward trend in the number of frosty and very frosty days (days with a maximum daily temperature ≤0°C and ≤-10°C, respectively). These changing climate parameters in Wielkopolska not only reshape the environmental landscape but also demand urgent adaptation and mitigation strategies to cope with the new climatic realities (POŚ, 2020).

KWB Konin – Jóźwin Open-Pit

Transitioning from the broader regional impacts observed across Poland and Wielkopolska, the analysis narrows to a more focused examination of Konin County (part of the Wielkopolska region), where the open-pit Jóźwin (Konin Coal Mine) is located. In this context, the implications of two Representative Concentration Pathways: RCP4.5 and RCP8.5, are considered.

The charts below illustrate a comparative analysis of mean monthly temperatures for Konin County, contrasting historical data from the decade 2011-2020 with future projections for 2051-2060 under RCP4.5 and RCP8.5. Both scenarios indicate a trend of rising temperatures throughout the year, with the increases being more pronounced under the RCP8.5 scenario, which assumes continued growth in greenhouse gas emissions. This analysis highlights a general warming trend, particularly notable during the summer months, suggesting that Konin County may experience significantly warmer summers and milder winters in the coming decades. These shifts in temperature could have profound impacts on the region's agriculture, water resources, and overall ecological balance, underscoring the importance of adopting climate adaptation and mitigation strategies.

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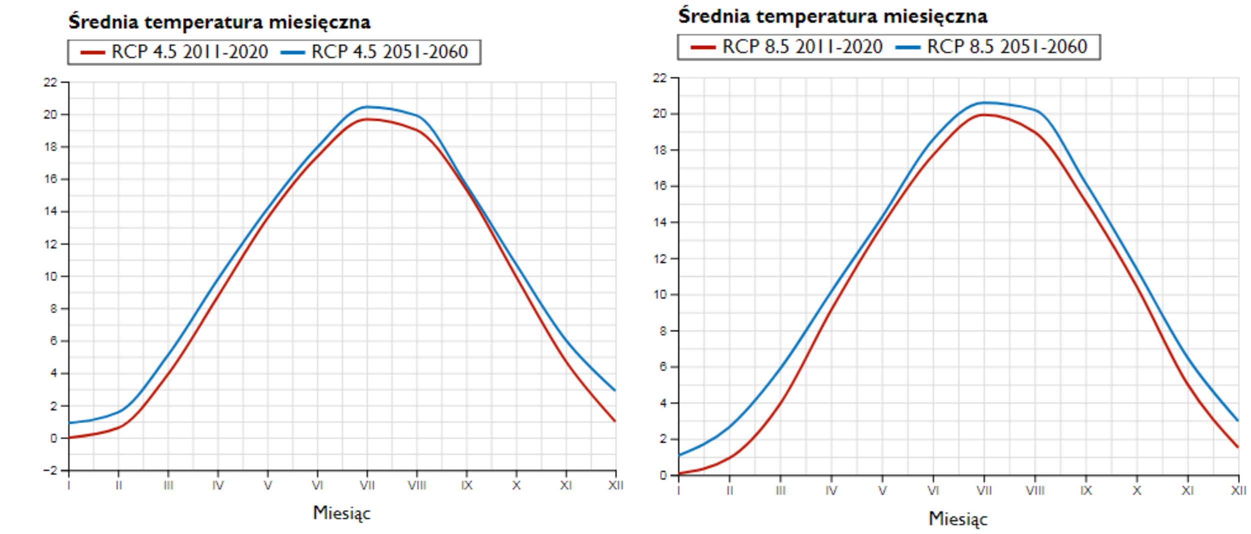

Figure 23. A comparison of the mean monthly temperature between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – at the Konin county (location of the REECOL site – KWB Konin – Jóźwin Open-Pit)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

The presented analysis of temperature distributions for Konin County RCP4.5 and 8.5 scenarios illustrates significant shifts in the frequency of frosty and extremely warm days (Figure 24). The comparative data from the 2011-2020 decade with projections for 2051-2060 reveal a marked decrease in days with maximum temperatures below 0°C and an increase in days exceeding 30°C. These shifts indicate a trend towards milder winters and hotter summers, suggesting substantial climatic changes that could impact agricultural cycles and water resource management, and pose heightened risks to public health due to more frequent heatwaves.

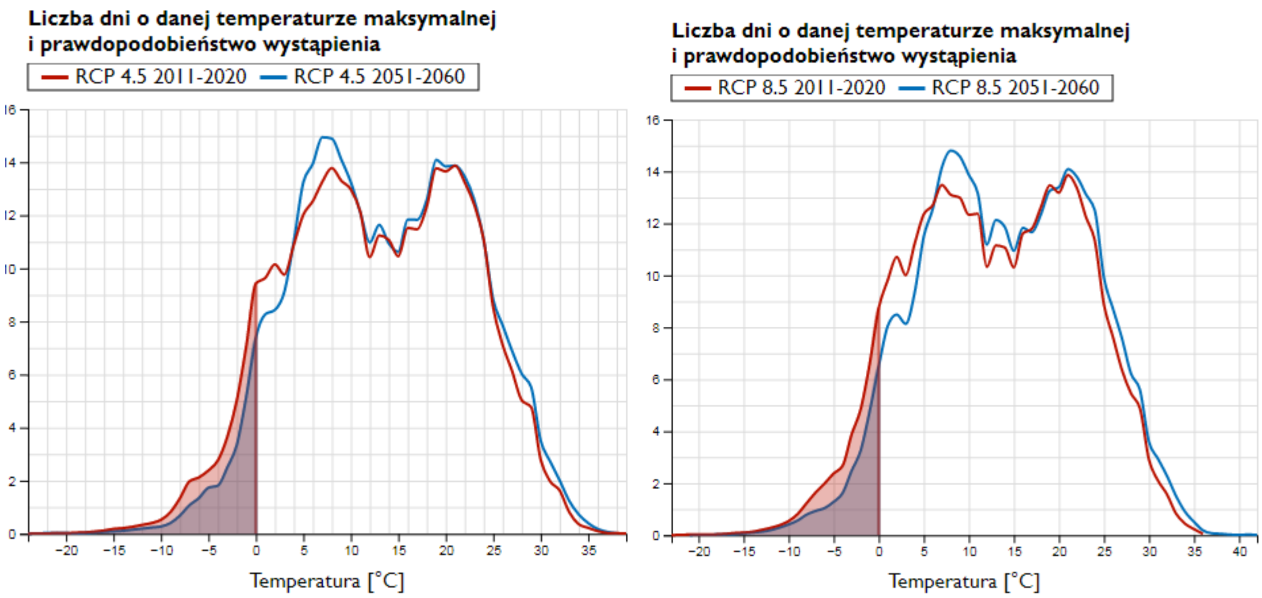

Figure 24. A comparison of the number of frosty days (Tmax <0oC) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – at the Konin county (location of the REECOL site – KWB Konin – Jóźwin Open-Pit)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

The comparative analysis of average monthly precipitation totals for Konin County, depicted through the RCP 4.5 and RCP 8.5 scenarios, highlights anticipated shifts in precipitation patterns between the historical decade of 2011-2020 and the projected decade of 2051-2060 (Figure 25). Both scenarios forecast an increase in precipitation during early spring (February and March) and a shift in the peak precipitation month to July. Under the RCP 8.5 scenario, more precipitation is expected throughout the year, with the exception of the period between May and June. These projected changes suggest a shift towards wetter early springs and midsummers, necessitating adjustments in local water management strategies, agricultural planning, and biodiversity conservation efforts in response to evolving climatic conditions.

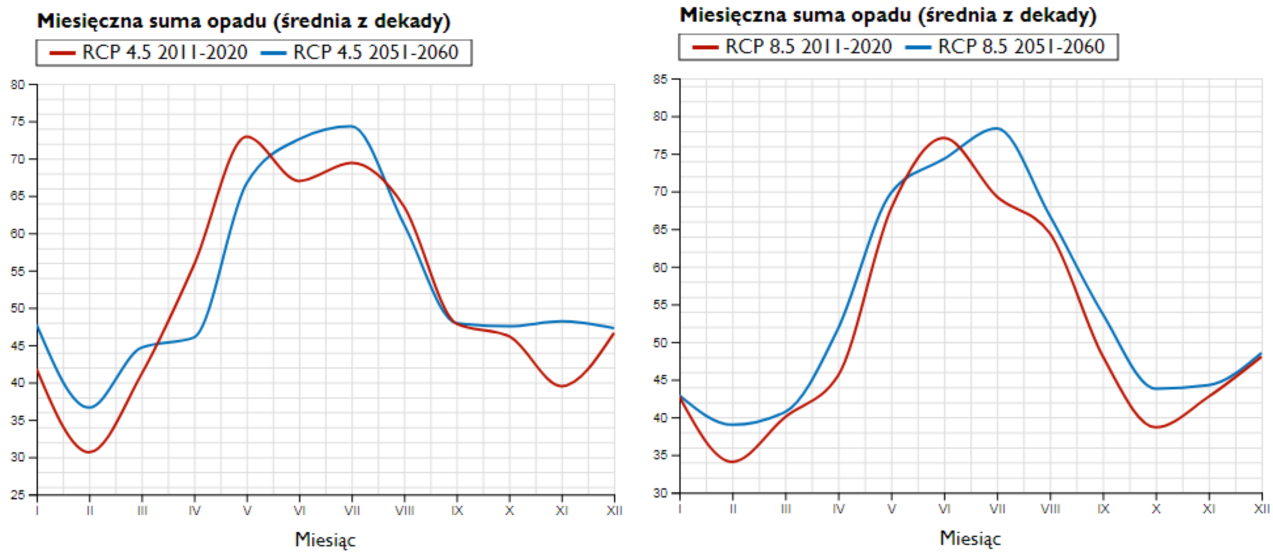

Figure 25. A comparison of the monthly precipitation (average of the decade) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – at the Konin county (location of the REECOL site – KWB Konin – Jóźwin Open-Pit)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

The reclamation strategies employed at the Jóźwin open-pit mine, as depicted on the reclamation directions map (Figure 26), are intricately designed to transform this mining landscape into a productive and ecologically balanced area. Each zone identified on the map—agricultural, forestry, water, and recreational—faces distinct challenges under the projected climate scenarios (RCP4.5 and RCP8.5), necessitating tailored adaptations to the reclamation approach.

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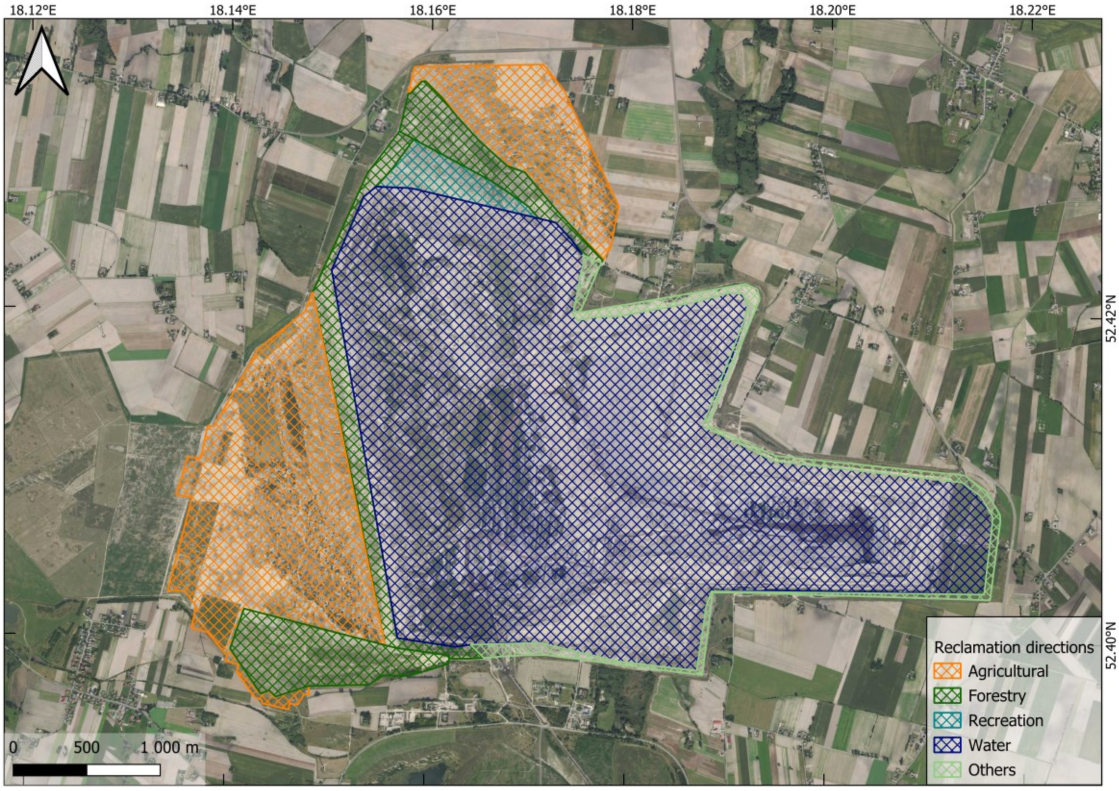

Figure 26. A Reclamation Directions Map of Jóźwin Open-Pit
Source: POLTEGOR own elaboration

In the context of **agricultural reclamation** at the Jóźwin open-pit, a range of agrotechnical measures are currently employed to rehabilitate the land for agricultural productivity. These practices, which include medium ploughing, the use of heavy and light harrowing, the application of mineral fertilisers (160 kg/ha of nitrogen, 140 kg/ha of phosphorus oxide, and 100 kg/ha of potassium oxide), and the sowing of grass and leguminous seeds (such as tufted grass and sown alfalfa), are designed to enhance soil structure, fertility, and moisture retention. However, these established reclamation methods face increasing challenges due to the impacts of climate change, particularly the projected increase in temperature and variability in precipitation patterns as outlined in the RCP4.5 and RCP8.5 scenarios. The impacts of these climatic shifts are manifold:

1) **Increased Soil Moisture Deficit and Evaporation:** Projected increases in temperature, particularly during the summer months as outlined in the RCP4.5 and RCP8.5 scenarios, are expected to lead to higher evapotranspiration rates. This increase in evapotranspiration will exacerbate soil moisture deficits, creating conditions that are less than ideal for traditional farming practices and could potentially reduce crop viability and yields.
2) **Alteration in Precipitation Patterns:** The expected increase in precipitation during early spring (February and March) and the shift in peak precipitation to July suggest changes in water availability. While these increases may benefit early crop growth phases, the potential decrease in precipitation between May and June could result in water stress during critical growth periods, necessitating effective water management strategies.
3) **Thermal Stress on Crops:** The escalation of peak temperature values during the growing season can induce significant thermal stress on crops. Such stress impairs physiological processes like photosynthesis and can drastically affect plant health and development, resulting in decreased agricultural productivity.
4) **Modified Crop Development Phases:** With warming temperatures, the phenology of various crops could shift, potentially leading to an earlier onset of growth phases. While this may extend the growing season for some crops, it also raises concerns about the synchronisation of crop development stages with the availability of water and the periods of heat stress, complicating the management of planting and harvesting activities.

Forestry reclamation at the Jóźwin open-pit, as delineated on the reclamation map in green, involves restoring the previously mined landscape by planting a diverse range of tree and shrub species. This initiative is crucial for stabilising the soil, enhancing the ecological diversity, and sequestering carbon, thereby contributing to both environmental sustainability and aesthetic landscape values. The species selected for planting include European larch, Scots pine, pedunculate oak, sessile oak, small-leaved lime, sycamore maple, common maple, beech, hornbeam, silver birch, black locust, black alder, blackthorn, and wild plum.

The biological framework for forestry reclamation encompasses planting forest-forming tree and shrub species on the internal spoil heaps and designated scarps of the final excavation site. This strategy is designed to reintegrate these areas into the surrounding natural landscape and to provide new habitats for local wildlife. Mineral fertilisation and maintenance practices are scheduled over four years to ensure the successful establishment and growth of these plantings. However, similar to agricultural reclamation, forestry reclamation faces significant challenges from the impacts of climate change:

1) **Moisture Stress and Drought Resilience:** As temperatures rise and precipitation patterns become more erratic under the RCP4.5 and RCP8.5 scenarios, newly planted trees may experience increased moisture stress. This stress can particularly affect young saplings that have not yet established robust root systems, potentially leading to higher mortality rates or stunted growth.
2) **Thermal Tolerance of Species:** The selection of tree species currently focuses on those traditionally suited to the local climate. However, with the shifting climate zones, these species may no longer be optimal. Some species may struggle with higher temperatures, especially during the critical early stages of growth, while others might not be able to adapt quickly to the changing conditions.
3) **Pest and Disease Pressure:** Warmer temperatures can also alter the prevalence and range of pests and diseases, posing new risks to the health of reforestation efforts. Species that were previously not vulnerable may become susceptible to outbreaks, which could compromise the reclamation objectives.

Water reclamation at the Jóźwin open-pit involves transforming former mining excavations into stable and sustainable water bodies, which is a critical component of ecological restoration and landscape management. The primary goal is to create a new water reservoir, Jóźwin Lake, which will serve as a significant ecological and recreational resource. This lake is projected to stabilise at a water level of approximately +93 meters above sea level, with the potential for annual water level fluctuations around 1 meter depending on rainfall variability. The lake's surface area is calculated to be approximately 840 hectares at this water level, with varying depths ranging from 43 meters to a maximum of 69 meters.

The biological aspect of water reclamation involves several techniques aimed at ensuring the structural stability and ecological viability of the new water bodies:

1) **Filling the Excavation:** The filling process for the final excavation involves natural processes such as groundwater infiltration through the bottom and slopes of the excavation, and the collection of surface water from rainfall, minus evaporation. Additionally, water from the nearby Kleczewska Stream during dry seasons and spring floods will supplement the lake's water levels.
2) **Erosion Control:** To prevent erosion of the newly formed lake shores and slopes, agrotechnical measures are implemented. These include cultivation or loosening with heavy disc harrows, application of mineral fertilisers, heavy and light harrowing, sowing of grass and leguminous plant seeds, stone removal, and light rolling. These activities help stabilise the soil and promote the establishment of a vegetative cover that resists erosion.
3) **Vegetative Cover for Slopes:** Specific seed mixtures aimed at erosion control are used for sowing on the slopes, including 25 kg/ha of red fescue, 20 kg/ha of reed fescue, 25 kg/ha of perennial ryegrass, 20 kg/ha of white clover, and 10 kg/ha of sown alfalfa, totalling 100 kg/ha.

The projected climate changes pose significant challenges to water reclamation strategies at Jóźwin:

1) **Water Level Fluctuations:** Increased variability in precipitation and higher evaporation rates due to rising temperatures could lead to more significant fluctuations in water levels. This variability can impact aquatic and shoreline ecosystems, potentially leading to periods of low water levels that may affect water quality and biodiversity.

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2) **Temperature Changes:** Higher water temperatures could alter the lake's ecological balance, affecting fish populations and promoting algal blooms, which could degrade water quality and reduce its recreational value.
3) **Increased eutrophication**: elevated temperatures and irregularity of precipitation will exacerbate adverse changes in surface water ecosystems caused by excessive availability of nutrients (deterioration of water quality and loss of biodiversity)
4) **Increased Erosion Risks**: With expected changes in rainfall intensity and patterns, erosion control will become even more critical. Intense rain events can lead to increased runoff and erosion, threatening the stability of the lake's banks and the clarity of the water.

Recreational reclamation at the Jóźwin open-pit is intrinsically linked with the water reclamation efforts, aiming to transform the area into a multifunctional landscape that offers both aesthetic appeal and practical leisure spaces for community use. This reclamation direction emphasises creating green, usable spaces around the newly formed water bodies, thus enhancing the recreational and ecological value of the area.

The focus of recreational reclamation at Jóźwin is on developing areas that can sustain a variety of leisure activities such as walking, picnicking, and sports. These spaces are designed to be inviting and safe, contributing positively to the local community's quality of life. By integrating these areas closely with the water reclamation projects, the reclamation effort not only maximises the scenic value of the water bodies but also promotes biodiversity through the creation of habitable zones for various species.

The development of recreational areas faces several climatic challenges:

1) **Increased Temperature and Sun Exposure:** As global temperatures rise, recreational areas may experience increased sun exposure, which can reduce the comfort of these spaces during hot weather. Designing areas with adequate shade and cooling features becomes crucial.
2) **Variability in Precipitation:** Changes in precipitation patterns can affect the maintenance and usability of outdoor recreational spaces. Periods of excessive rain can lead to waterlogging, while prolonged dry spells can stress vegetation and reduce the visual and recreational quality of green spaces.
3) **Erosion and Water Management:** With the expected increase in weather extremes, managing erosion and runoff becomes vital, especially in areas adjacent to water bodies. Maintaining good water quality and stabilizing shorelines by implementing effective drainage systems are essential to maintain the integrity and safety of recreational areas.

The comprehensive reclamation strategies at the Jóźwin open-pit, spanning agricultural, forestry, water, and recreational areas, are intricately designed to restore and enhance the post-mining landscape. However, these efforts are increasingly challenged by the impacts of projected climate changes under the RCP4.5 and RCP8.5 scenarios. Rising temperatures, increased variability in precipitation, and more extreme weather events pose significant risks to the stability and success of these reclamation projects. Increased evapotranspiration rates threaten soil moisture levels critical for agricultural and forestry reclamation, while fluctuating water levels and intensified erosion could undermine water and recreational reclamation efforts. These climatic factors necessitate the integration of adaptive strategies and resilient practices to ensure that the reclamation not only achieves its immediate restoration goals but also sustains its ecological and recreational benefits under changing climatic conditions, thus contributing to long-term environmental stability and community welfare.

Silesia Region

The average maximum temperatures in the Silesia region during the period 1971-2000 were 26°C, while in the period 1981-2010, they increased to 27°C. The maximum temperatures for the period 1991-2020 were 28°C in the Subregion. The rise in average temperatures decreases the probability of extremes associated with low air temperatures and contributes to more frequent occurrences of high-temperature extremes. In a warming climate, there is a reduction in the number of extremely cold nights and days and an increase in the number of extremely warm nights and days. This also applies to the frequency and duration of heatwaves.

In this context, the implications of two Representative Concentration Pathways: RCP4.5 and RCP8.5, are considered for three chosen areas - pilot areas – focusing on active coal mines operated by PGG which in the next 10 years are planned to be closed. All three analysed areas are located in Silesia Region, in Upper Silesian Coal

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Basin – in three different counties: KWK Sośnica in Gliwice County, KWK Bolesław Śmiały in Łaziska Górne (Mikołowski county) and KWK Wujek in Katowice County. Within each of these areas, two sites have been under analysis by GIG-PIB team: the active mine area and a waste heap. Their location is presented in Figure 27. The redevelopment potential of these three chosen areas is in more depth analysed within Task 3.2 and results are presented in **Deliverable D.3.2. Identification of post-mining rehabilitation schemes regarding future land uses and affordability of the solutions**.

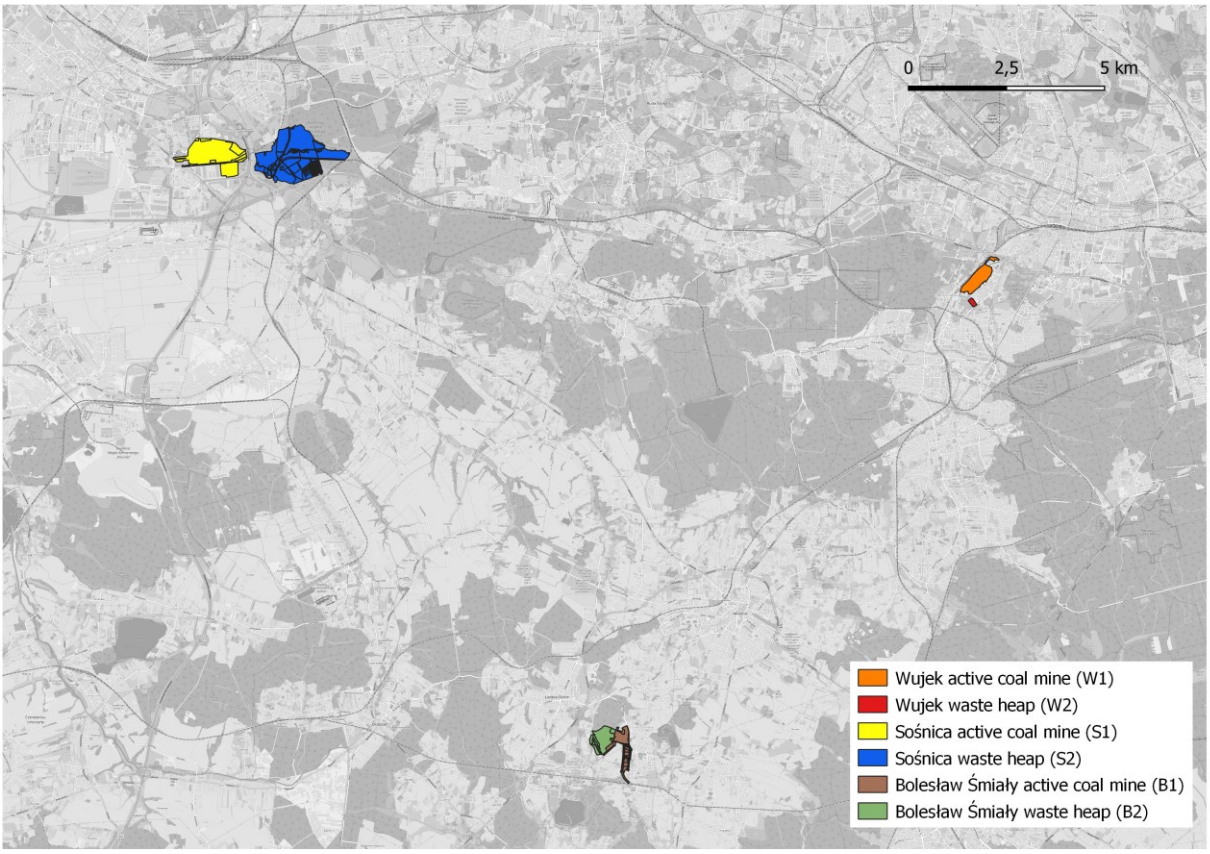

Figure 27. The chosen sites used by the GIG-PIB in the assessment of valorisation method, based on the Task 3.2.
Source: GIG-PIB own elaboration

Sośnica Coal Mine, Gliwice

The area of active coal mine KWK Sośnica is the first case study where degradation and severe mining impacts were defined. The area of degraded land is an active waste heap with natural succession and the brownfield which is the area where mining facilities (shafts, buildings and mining plant) are currently under operation (Figure 28). The exposed soil layer is covered with low vegetation, shrubs and trees, which in total occupy less than 20% of the site. The location of Sośnica Coal Mine site is in the Silesia region, the city of Gliwice.

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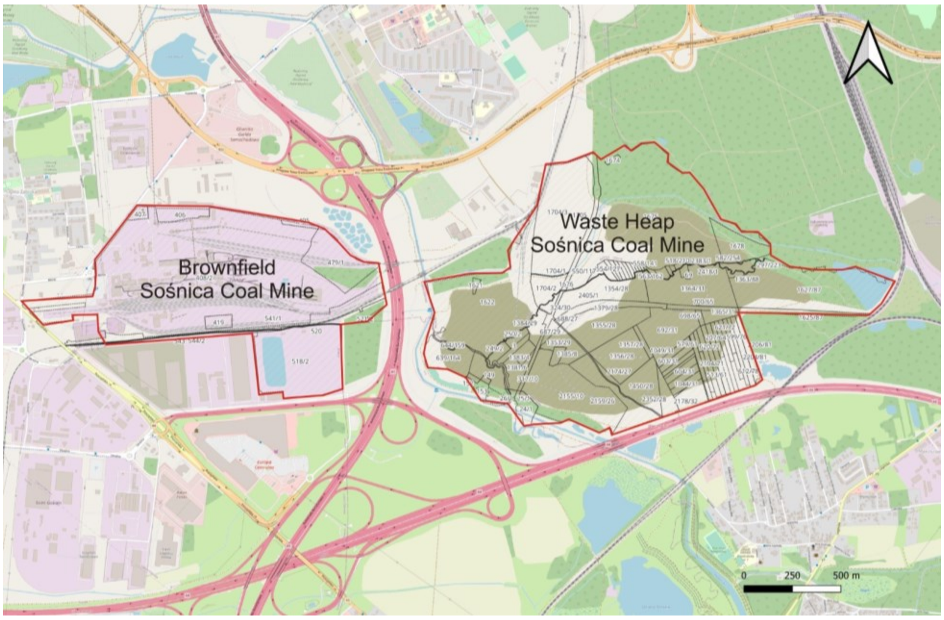

Figure 28. The location of the brownfield and a waste heap, Sośnica Coal Mine

Source: own elaboration, based on OpenStreetMap

The charts present a comparative analysis of mean monthly temperatures for Gliwice County, contrasting historical data from 2011-2020 with future projections for 2051-2060 under RCP4.5 and RCP8.5 scenarios. Both projections show a trend of rising temperatures throughout the year, with a more pronounced increase under the RCP8.5 scenario, which assumes continued growth in greenhouse gas emissions. This analysis reveals a general warming trend, particularly notable during the summer months (Figure 29).

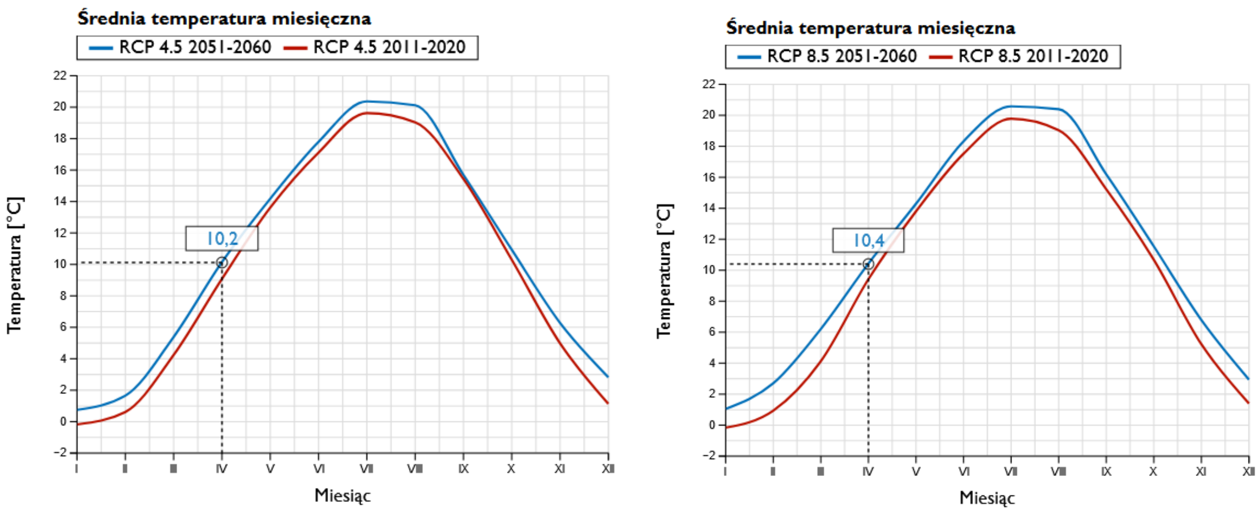

Figure 29. Comparison of mean monthly temperature between data from the 2011-2020 decade and projections for the 2051-2060 decade at RCP4.5 scenario (left) and RCP8.5 scenario (right) – at Gliwice (location of REECOL site Sośnica Coal Mine)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

Warmer mean monthly temperatures in Gliwice, particularly under the RCP8.5 scenario, will significantly influence weather patterns, with hotter summers and milder winters. This change presents both opportunities and challenges for post-mining area reclamation activities. While extended growing seasons and reduced frost risks can aid in plant establishment, heat stress, water management issues, and increased pest pressures may pose significant challenges, which is in more details described in **Chapter 5.**

The next analysis presents a comparison of temperature distributions in Gliwice. The comparative data from the 2011-2020 decade with projections for 2051-2060 reveal a marked decrease in days with maximum temperatures below 0°C (Figure 30). A simultaneous increase in the number of days with maximum temperatures above 25°C and 30°C can be observed in both in RCP4.5 and RCP8.5, although this increase is higher in RCP8.5. Higher mean temperatures can lead to more frequent and intense heat waves, which can exacerbate heat stress on both vegetation and humans. Increased temperatures lead also to higher evaporation, which can reduce soil moisture and water availability, causing the need for changes in water management to ensure sufficient water supply.

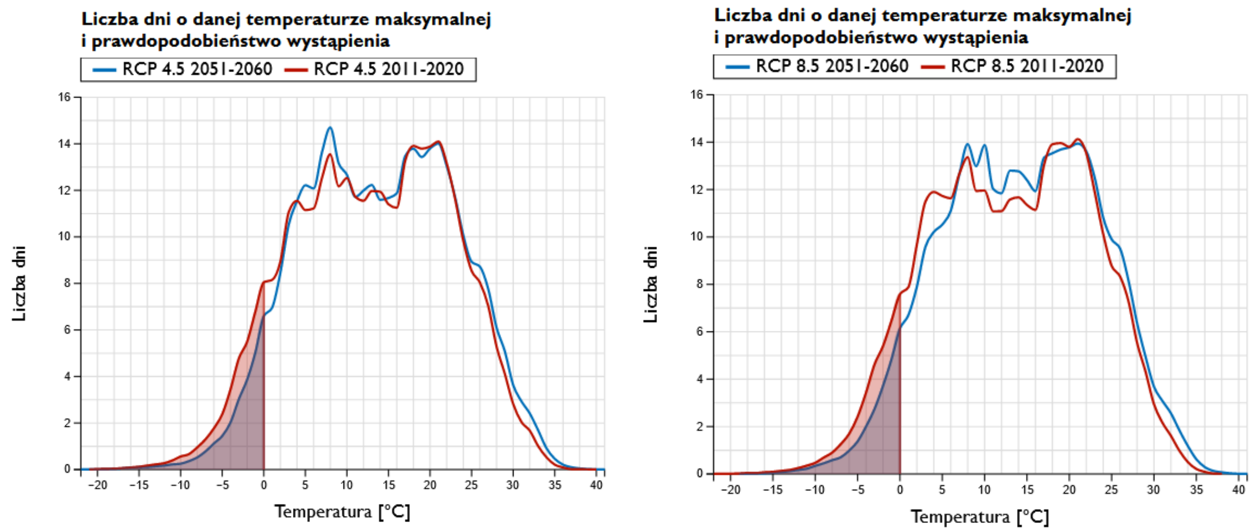

Figure 30. A comparison of the number of frosty days (Tmax <0oC) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – in Gliwice (location of the REECOL site Sośnica Coal Mine)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

The comparative analysis of average monthly precipitation totals for Gliwice County, depicted through two RCP4.5 and RCP8.5, highlights anticipated shifts in precipitation patterns between the historical decade of 2011-2020 and the projected decade of 2051-2060. In both scenarios (although more pronounced in RCP8.5), there is a trend toward an increase in monthly precipitation - especially noted in the months of mid-May - mid-July, with a decrease in precipitation by the end of summer (August) and a renewed trend toward wetter autumn months and the late winter (February -March) (Figure 31).

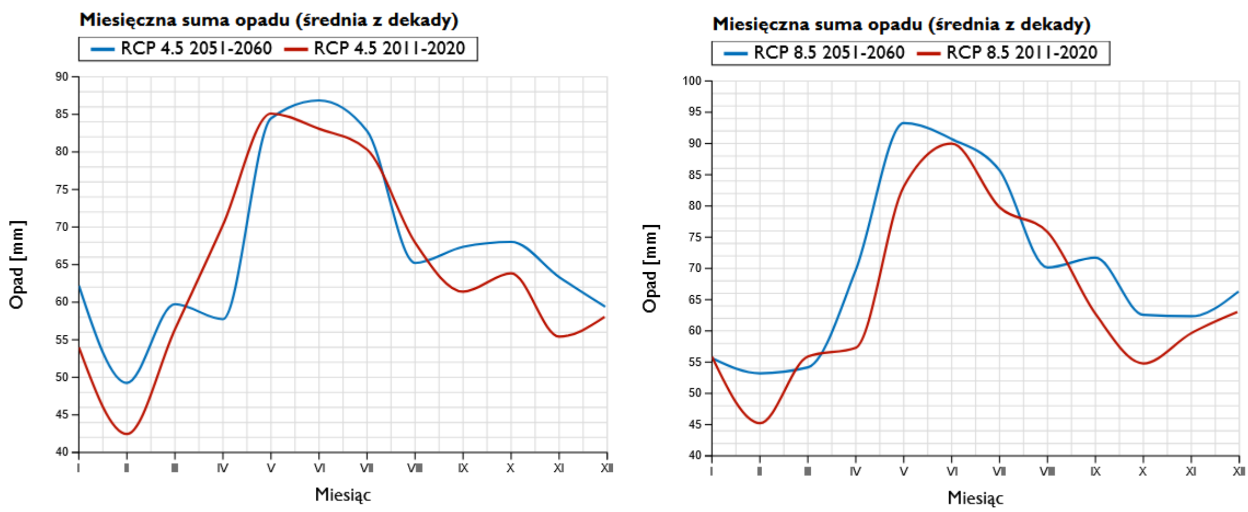

Figure 31. A comparison of the monthly precipitation (average of the decade) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – in Gliwice (location of the REECOL site Sośnica Coal Mine)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

Based on the results of the valorisation assessment of the area's redevelopment possibilities and potential land use scenarios conducted under Task 3.2, KWK Sośnica waste heap has a very high potential for industrial production scenario, whereas Sośnica brownfield's potential for any of the analysed scenarios - industrial production, housing purposes and green spaces or RES reclamation directions is very low. Therefore, the analysis of climate change's impact on the reclamation of waste heap possibilities has been focused on industrial production reclamation direction.

Higher temperatures can lead to an increased risk of initiation of internal thermal processes within a mine rock dump containing coal residues. Reclamation measures to reduce the risk of thermal processes must therefore be carried out (creation of a top cover layer with low oxygen permeability, removal of woody vegetation, etc.)

Higher temperatures can lead to heat stress for workers[29], reducing productivity and increasing health risks. Industrial operations may need to invest in cooling systems, both for worker safety and to maintain optimal operating conditions for machinery and processes that are sensitive to temperature fluctuations. These needs can increase operational costs due to higher energy consumption. In addition, increased temperatures can accelerate the degradation of materials, machinery, and infrastructure. This necessitates the use of heat-resistant materials and regular maintenance schedules to ensure the longevity of industrial facilities. Preventive reclamation actions may include the creation of water bodies and wetlands in the immediate vicinity of production facilities. In addition to regulating temperatures, these ecosystems will also retain rainwater from sealed areas.

Increased monthly precipitation, especially the extension of the period of high rainfall in the summer months can lead to intensification of soil erosion and instability, impacting the foundations of industrial structures. Therefore, intensification of the attention and effort to effective water management systems, including drainage, retention basins, and flood barriers, will be essential to protect industrial facilities from water damage. Also, more strict site preparation, including implementation of adequate soil stabilisation techniques and reinforced foundations, may be necessary to ensure structural integrity.

On the other hand, a reduction of frosty days may lower the risk of frost-related damage to industrial infrastructure, such as pipelines, storage tanks, and building foundations[30]. This can reduce maintenance costs and improve the durability of industrial installations, leading to fewer seasonal disruptions of work during the reclamation activities. Additionally, reduced cold stress on workers can improve overall health and productivity, reducing absenteeism and enhancing workforce stability in colder months.

Bolesław Śmiały Coal Mine, Łaziska Górne (Mikołowski County)

The area of active coal mine Bolesław Śmiały is the second Upper Silesia case study. The area of the degraded land is already a waste heap with a cultivated surface, and brownfield which is the area where mining facilities (shafts, buildings and mining plant) are currently under operation (Figure 32). The mine's headquarters are located in Łaziska Górne (Mikołowski county).

[29] in more details impacts of climate change on occupation safety and health issues of workers is described in chapter 5.3.
[30] The potential impact depends of course also on intensity of frost, not only the number of days.

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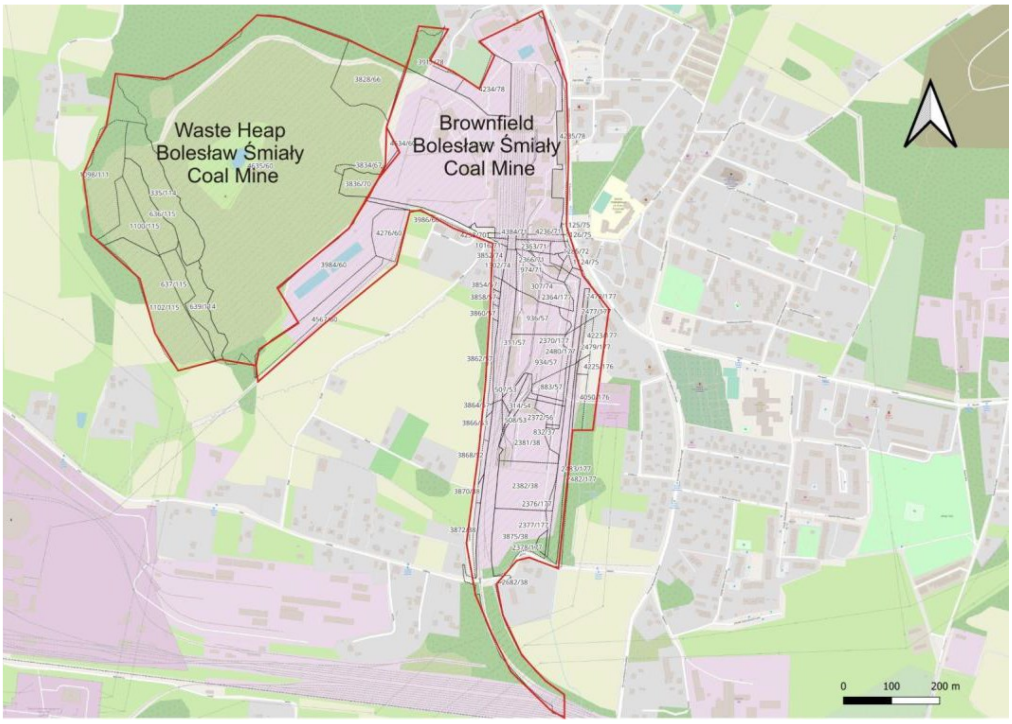

Figure 32. The location of the brownfield and a waste heap, Bolesław Śmiały Coal Mine

Source: own elaboration, based on OpenStreetMap

Figure 33 depicts a comparative analysis of average monthly temperatures for the area, contrasting historical data from the decade 2011-2020 with future projections for 2051-2060 under the RCP4.5 and RCP8.5 scenarios. Both projections show a consistent trend of increasing temperatures throughout the year, with more pronounced rises projected under the RCP8.5 scenario, which assumes continued greenhouse gas emissions growth. This analysis underscores a general warming trend, particularly noticeable during the summer months, indicating that the Mikołowski County could face notably warmer summers and milder winters in the coming decades.

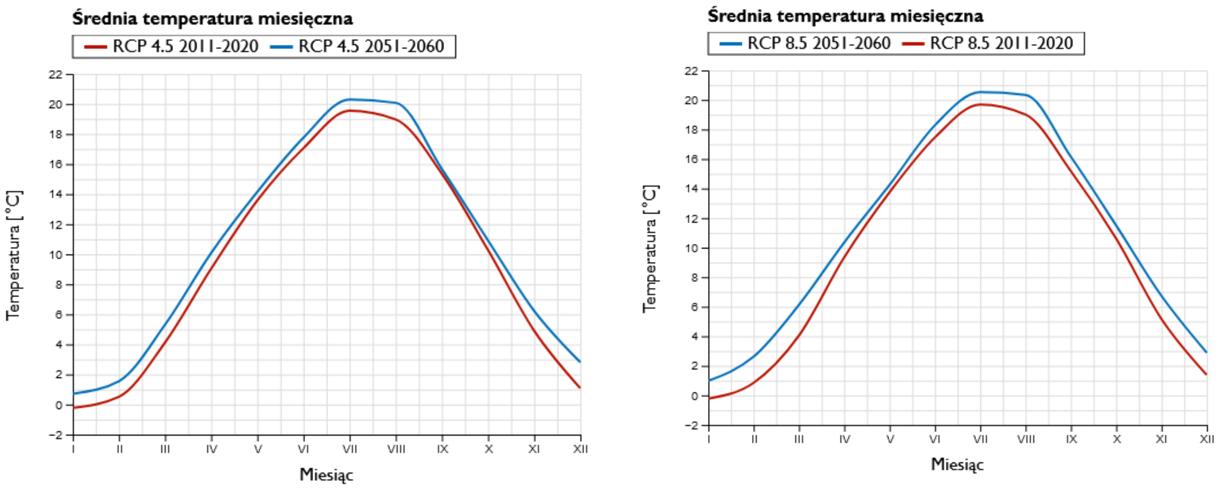

Figure 33. A comparison of the mean monthly temperature between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – at the Mikołowski County (location of the REECOL site - KWK Bolesław Śmiały)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

Higher mean temperatures can lead to more frequent and intense heat waves, exacerbating heat stress on both vegetation and humans. Increased temperatures also result in higher evaporation rates, reducing soil moisture and water availability. This necessitates changes in water management practices to ensure sufficient water supply.

The following analysis compares temperature distributions in Mikołowski County. Data from the decade 2011-2020 are compared with projections for 2051-2060, revealing a significant decrease in days with maximum temperatures below 0°C (Figure 34). At the same time, there is an increase in the number of days with maximum temperatures above 25°C and 30°C under both RCP4.5 and RCP8.5 scenarios, with a more pronounced increase under RCP8.5, as within RCP4.5

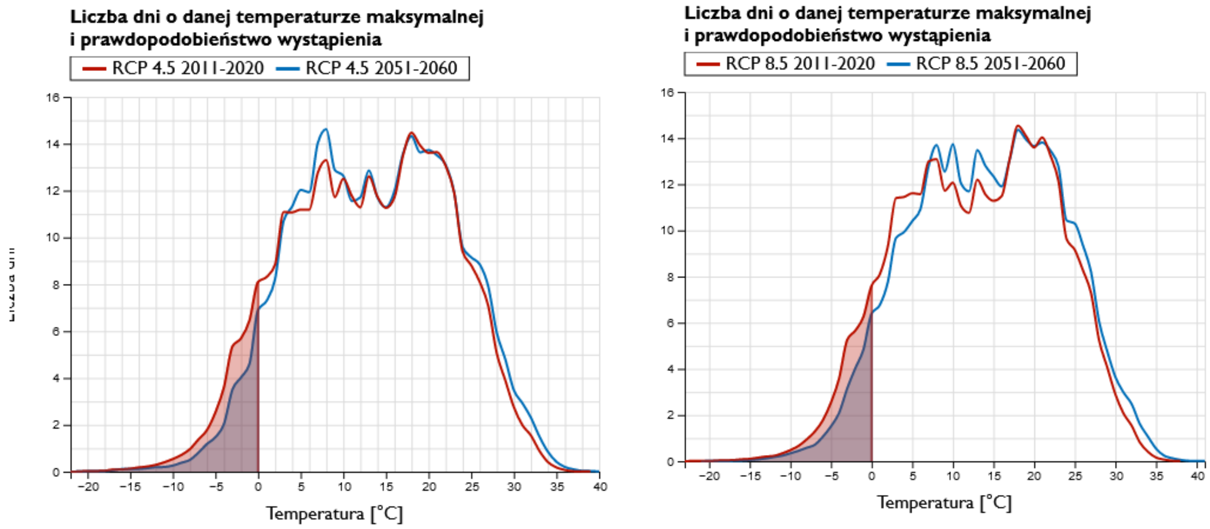

Figure 34. A comparison of the number of frosty days (Tmax <0oC) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – at the Mikołowski County (location of the REECOL site - KWK Bolesław Śmiały)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

The comparative analysis of average monthly precipitation totals for Mikołowski County illustrated through RCP4.5 and RCP8.5 scenarios, highlights – similarly as in Gliwice - shifts in precipitation patterns between the historical decade of 2011-2020 and the projected decade of 2051-2060. Both scenarios show a trend towards increased monthly precipitation, particularly from mid-May to mid-July, though this is more pronounced under RCP8.5. Additionally, a decrease in precipitation is observed by the end of summer (August), followed by a renewed trend toward wetter autumn months and late winter (February-March) (Figure 35).

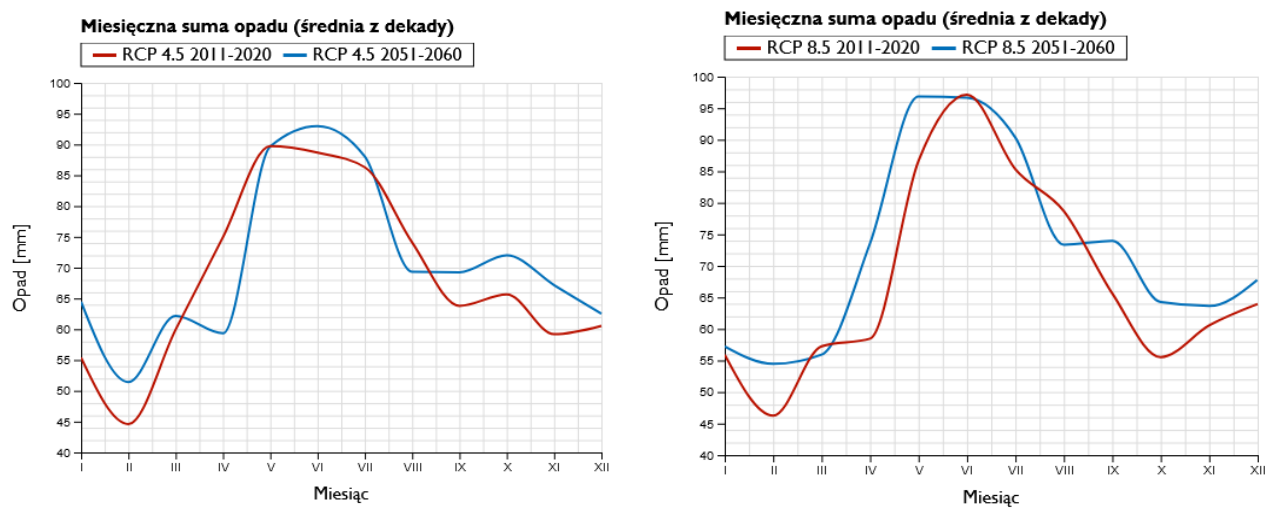

Figure 35. A comparison of the monthly precipitation (average of the decade) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) the and RCP8.5 scenario (right) – at the Mikołowski County (location of the REECOL site - KWK Bolesław Śmiały)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

As concluded from the analysis of valorisation assessment of the area redevelopment possibilities and potential land use scenarios conducted under Task 3.2, the Boleslaw Śmialy active coal mine area meets better the criteria for redevelopment into industrial production and housing purposes, whereas Boleslaw Śmialy waste heap (hałda Skalny) would be best for green spaces or RES installation development scenario.

The projected changes, particularly the increase in average monthly precipitation in late winter and early spring, can, however, have several additional impacts on the green space reclamation scheme. More precipitation, especially during late spring and early summer, can support the growth of vegetation. However, it also raises the need for effective water management strategies to handle excessive rainfall and prevent waterlogging. Proper landscape design, including rain gardens and permeable surfaces, will be crucial to manage the increased runoff. The most significant impact concerns the settling pond, which is part of the mining area. Increased rainfall may enhance water availability in the settling ponds, which can be beneficial for maintaining water levels for ecological functions, especially after appropriate water treatment. Additional water can also support the creation or enhancement of wetlands around the settling ponds, promoting biodiversity and improving water quality through natural filtration, thereby supporting ecological rehabilitation.

Higher temperatures can heavily affect terrestrial plant species selection, to favour heat-tolerant and drought-resistant varieties. On the other hand, the reduction of frosty days can extend the growing season for plants, enhancing the potential for diverse and lush vegetation. If the reclamation scheme also includes planning of recreational areas, it may need to include ample tree-covered zones and water features to provide cooling and comfort for visitors. In the temperate climate zone, those ecosystems provide significant temperature reductions during heat waves (Sierka & Pierzchała, 2022). However, the effect of increased oxygenation of the substrate in the root zone of trees on the increased risk of initiating thermal processes on the waste heap must be considered.

It can be noted, that the ongoing and predicted climate changes in both RCP scenarios—concerning average temperature and precipitation changes—are not significant enough to have a major impact on the potential use of the area for industrial or residential purposes. The effectiveness of implementing these reclamation directions will be more affected by extreme weather events, particularly excessively heavy rainfall that far exceeds norms, and heat waves, which impact human health and quality of life and can increase the risk of spontaneous combustion. Therefore, for any reclamation scheme, the first – safety – measure requires ensuring 100% combustion extinguishment of the heap, not just surface extinguishment, which was carried out in previous years.

Wujek Coal Mine, Katowice

The area of active coal mine Wujek is the case study where up to now closure process has started. The area of degraded land is a brownfield where mining facilities (shafts, buildings and mining plant) – are currently under operation, while the mine water pond (tailing) is already closed for sedimentation process. The area is located in the southern part of Katowice (Figure 36).

Figure 36. The location of brownfield and mine water pond, the Wujek Coal Mine

Source: own elaboration, based on OpenStreetMap

Figure 37 depicts a comparative analysis of average monthly temperatures for the area, contrasting historical data from the decade 2011-2020 with future projections for 2051-2060 under RCP4.5 and RCP8.5 scenarios. It can be noted, that under the RCP4.5 scenario, moderate warming is evident, with noticeable increases in temperature during the summer months. The RCP8.5 scenario shows a more significant increase in temperatures across all months, particularly in summer, indicating a higher degree of warming.

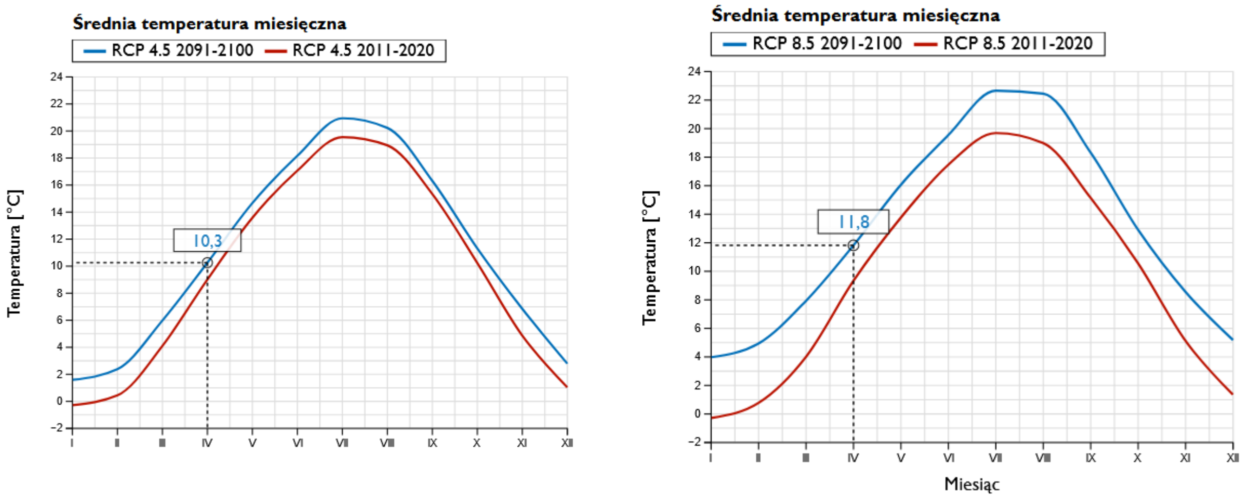

Figure 37. A comparison of mean monthly temperature between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – in Katowice (location of REECOL site KWK Wujek)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

The number of frosty days (days with Tmax < 0°C) decreases substantially from the 2011-2020 decade to the 2051-2060 decade. Under the RCP4.5 scenario, the reduction in frosty days is moderate, while the RCP8.5 scenario projects a much sharper decline, virtually eliminating frosty days in some months (Figure 38).

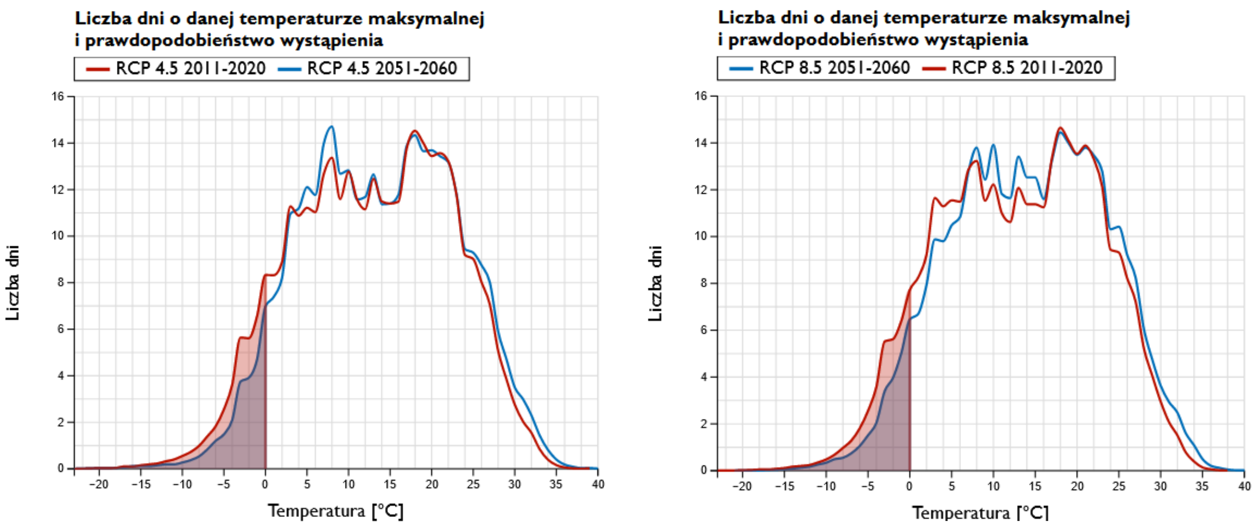

Figure 38. A comparison of the number of frosty days (Tmax <0oC) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) and the RCP8.5 scenario (right) – in Katowice (location of REECOL site KWK Wujek)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

The comparative analysis of the average monthly precipitation totals for Katowice, illustrated through RCP4.5 and RCP8.5 scenarios, highlights – similarly as both above analysed sites – shifts in the precipitation patterns between the historical decade of 2011-2020 and the projected decade of 2051-2060. The projections under both RCP4.5 and RCP8.5 scenarios indicate increased monthly precipitation, particularly from mid-May to mid-July (Figure 39).

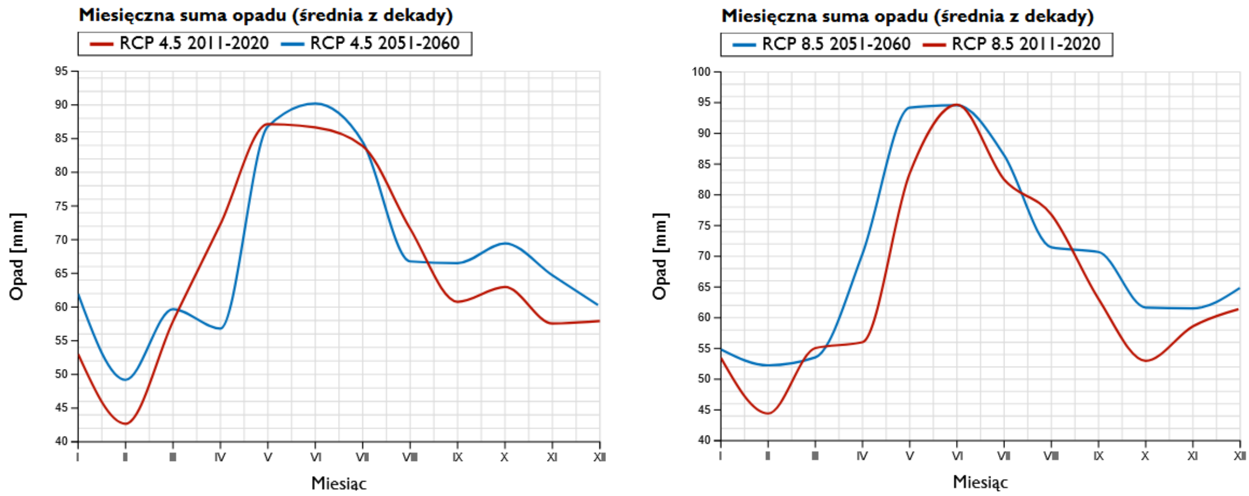

Figure 39. A comparison of the Monthly precipitation (average of the decade) between the data from the 2011-2020 decade and projections for the 2051-2060 decade at the RCP4.5 scenario (left) the and RCP8.5 scenario (right) – in Katowice (location of the REECOL site KWK Wujek)

Source: https://klimada2.ios.gov.pl/klimat-scenariusze-portal/

Based on the results of the valorisation assessment of the area's redevelopment possibilities and potential land use scenarios conducted under Task 3.2, the KWK Wujek waste heap has a very high potential for green spaces and housing reclamation directions, whereas the Wujek active coal mine area's potential for any of the analysed scenarios - industrial production, housing purposes and green spaces or RES reclamation directions isn't very high.

Therefore, the analysis of climate change's impact on the reclamation of waste heap possibilities has been focused on green spaces and housing reclamation directions. The changes projected for temperature, frosty days, and precipitation under RCP4.5 and RCP8.5 scenarios suggest significant impacts on the reclamation of waste heaps into green and recreational areas and their ecosystem services. Increased temperatures and reduced frosty days present both challenges and opportunities for vegetation. More precipitation, especially during late spring and early summer, can support the growth of vegetation. However, it also raises the need for effective water management strategies to handle excessive rainfall and prevent waterlogging. Proper landscape design, including rain gardens and permeable surfaces, will be crucial to manage the increased runoff. Higher temperatures can heavily affect plant species selection, to favour heat-tolerant and drought-resistant varieties. On the other hand, the reduction of frosty days can extend the growing season for plants, enhancing the potential for diverse and lush vegetation. If the reclamation scheme includes also planning of recreational areas, it may need to include ample shaded zones and water features to provide cooling and comfort for visitors.

The ongoing and predicted climate changes in both RCP scenarios—concerning average temperature and precipitation changes—are not significant enough to have a major impact on the potential use of the area for residential purposes. The effectiveness of implementing these reclamation directions will be more affected by extreme weather events, particularly excessively heavy rainfall that far exceeds norms, and heat waves, which impact human health and quality of life. Nevertheless, for the housing reclamation direction, anticipated climate change may drive up the cost of construction, as well as the future cost of using the built estate. Higher temperatures, especially in summer, may necessitate the use of heat-resistant materials in construction and the implementation of cooling solutions such as green roofs and shaded areas to ensure habitability and comfort. In addition, the lack of cold periods may affect the thermal comfort of residents accustomed to seasonal cold and may increase the energy demand for cooling during extended warm periods. On the other hand, fewer frosty days reduce the risk of frost heave and related structural issues in buildings. Increased precipitation can lead to waterlogging and drainage issues, requiring robust drainage systems to prevent flooding. It also necessitates careful planning to manage stormwater and prevent soil erosion, which can destabilise foundations and infrastructure in residential developments. There are no waste rock dumps within the study area that can undergo combustion processes.

4.3.2. Greece

Predictive models to forecast rainfall and temperature soon are developed for the Amynteon lignite field area (Louloudis *et al.* 2021), by implementing ARIMA and NNAR (neural network autoregression) models. The `restrictions induced by ARIMA models constrain predictions to 10 years in the future, whereas NNAR models can produce predictions for more than 10 years. For the Amynteon area, the rainfall and temperature prediction results are depicted in Figure 40 and Figure 41, where the final annual precipitation and temperature results are presented as mean values. Using the Amynteon weather station (spanning a period of 55 years, from 1964–2019), the projection shows that average annual precipitation through the end of the century is expected to decrease, while the average temperature is expected to increase.

The Intergovernmental Panel on Climate Change (IPCC) (Pachauri *et al*. 2015) reported projected changes in annual precipitation in the period 2081–2100, compared to the baseline period 1986–2005 for the forcing scenario representative concentration pathways RCP8.5. Based on multi-model mean projections average under RCP scenarios, model simulations reported by IPCC project a 10–15% decrease in precipitation. Thus, the forecast based on the Amynteon station data aligns with the IPCC forecasts. Also, the the Amynteon meteorological station, with a historical dataset over a period of 55 years, is considered to present a good time range that made the forecast more reliable.

Projected changes in the climate system are also reported by Politi *et al.* (2022), where high-resolution projections for extreme temperatures and precipitation over Greece are reported. Climatic variables were produced at 5-km grid spacing and 6-h interval, and the results are presented in the following figures (Figure 42, Figure 43, Figure 44), where surface temperature is projected to rise approximately 2°C and 3°C under scenario RCP4.5 and RCP8.5, respectively, for the Region of Western Macedonia. Also, precipitation is projected to decrease by approximately 20% and 30% under scenarios RCP4.5 and RCP8.5, respectively. Thus, the forecast based on the Amynteon station data aligns with the projected changes in the climate system for the Region of Western Macedonia.

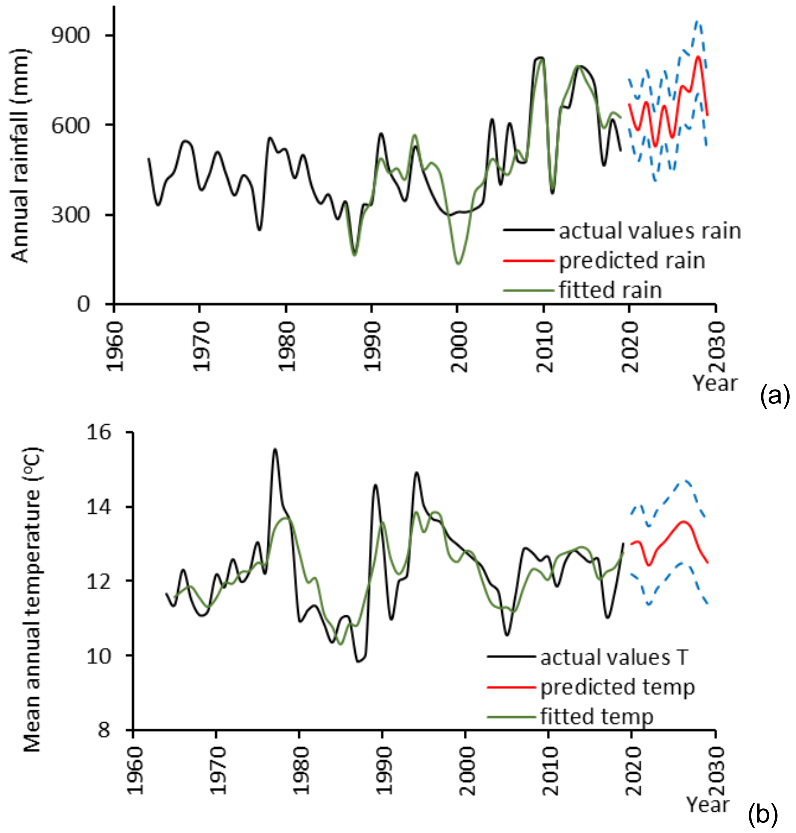

Figure 40. The projected changes in (a) the annual precipitation and (b) the annual mean temperature for the Amynteon lignite field area

Explanation: The *red line is the average value, and the blue lines present the upper and lower limits of the prediction, whereas the green lines are the fitted values.*

Source: Louloudis et al. 2021

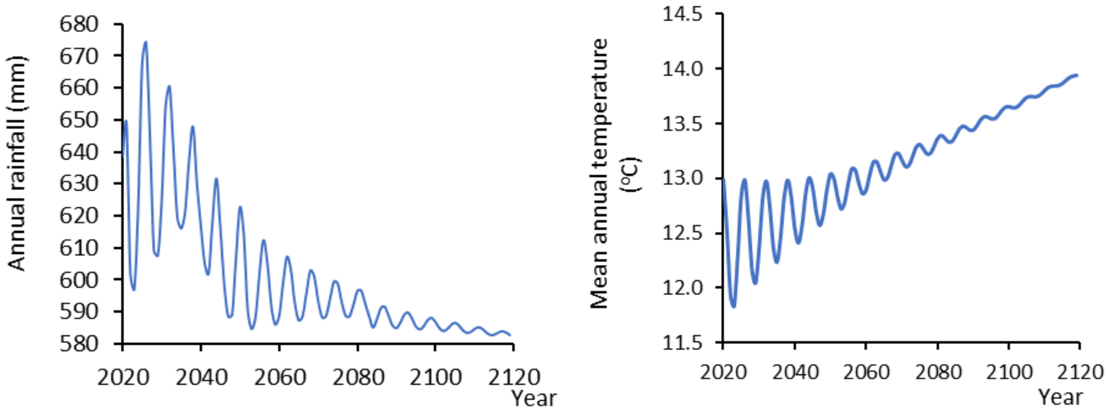

Figure 41. The Artificial Neural Network prediction (NNAR) implemented for the Amynteon lignite field area, northern Greece
Source: Louloudis et al. 2021

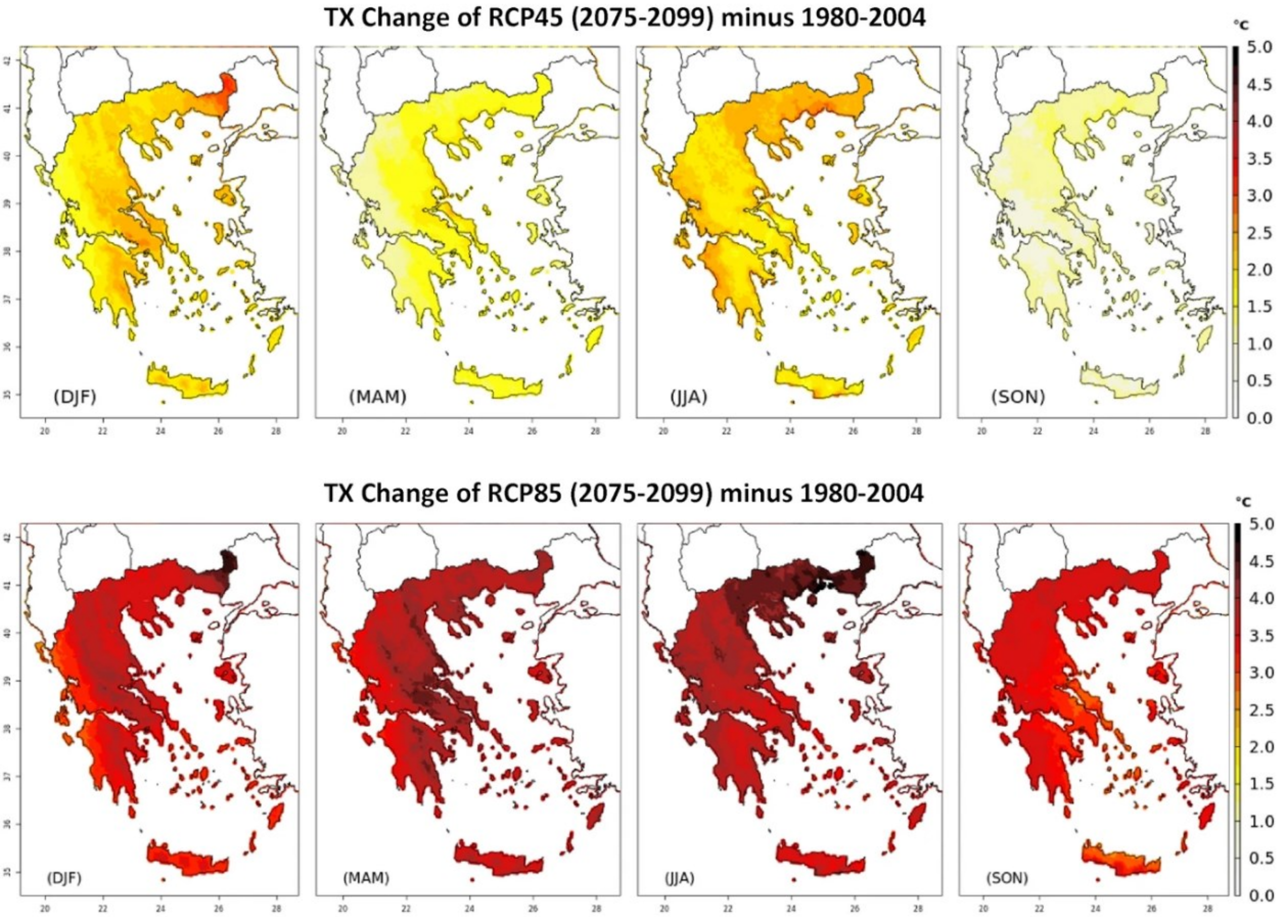

Figure 42. The WRFEC seasonal climate change for the daily maximum temperature (2075–2099 minus 1980–2004) for RCP4.5 and RCP8.5
Explanation: The initials in the map stand for the 1st letter of the month.
Source: Politi et al. 2022

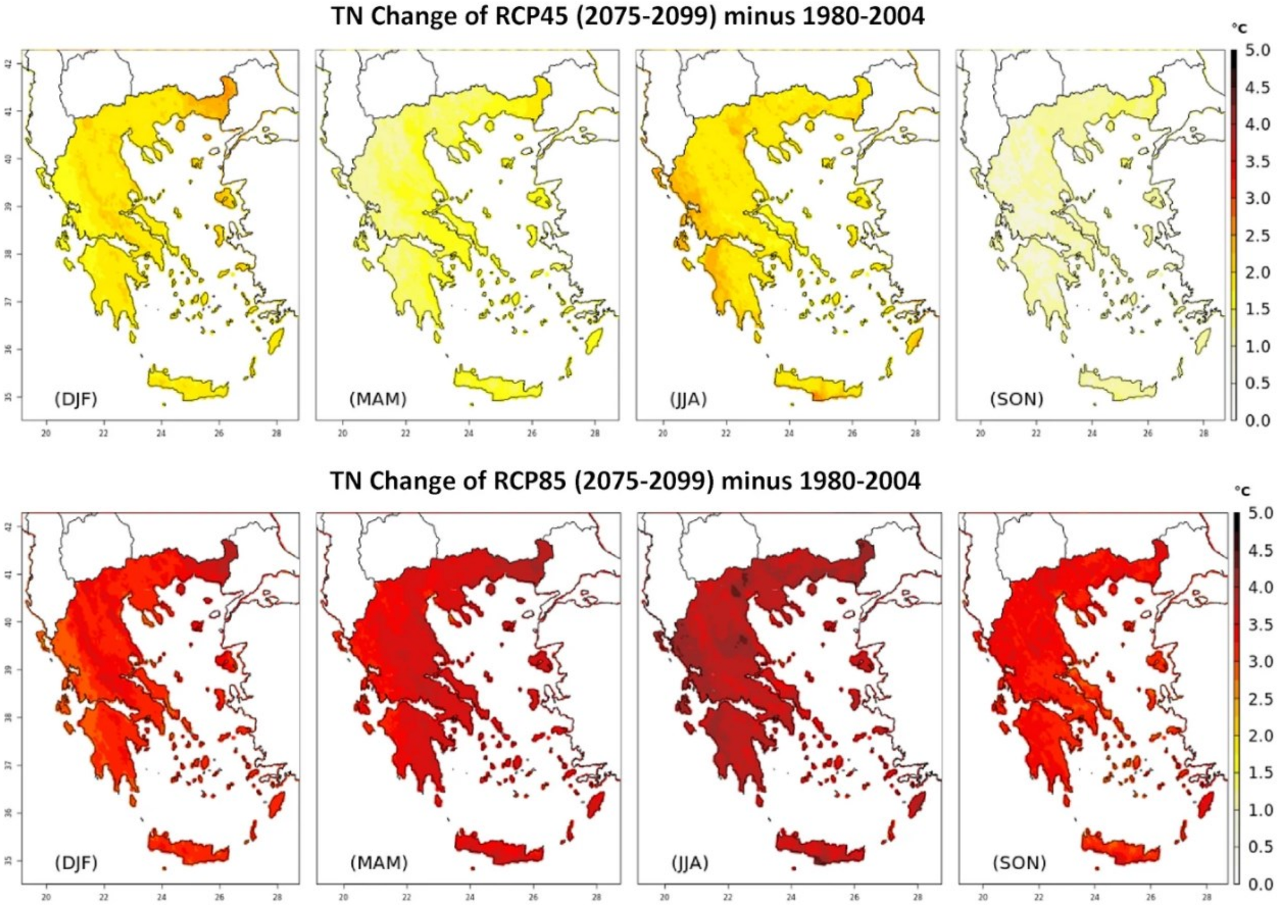

Figure 43. The WRFEC seasonal climate change for the daily minimum temperature (2075–2099 minus 1980–2004) for RCP4.5 and RCP8.5
Explanation: The initials in the map stand for the 1st letter of the month.
Source: Politi et al. 2022

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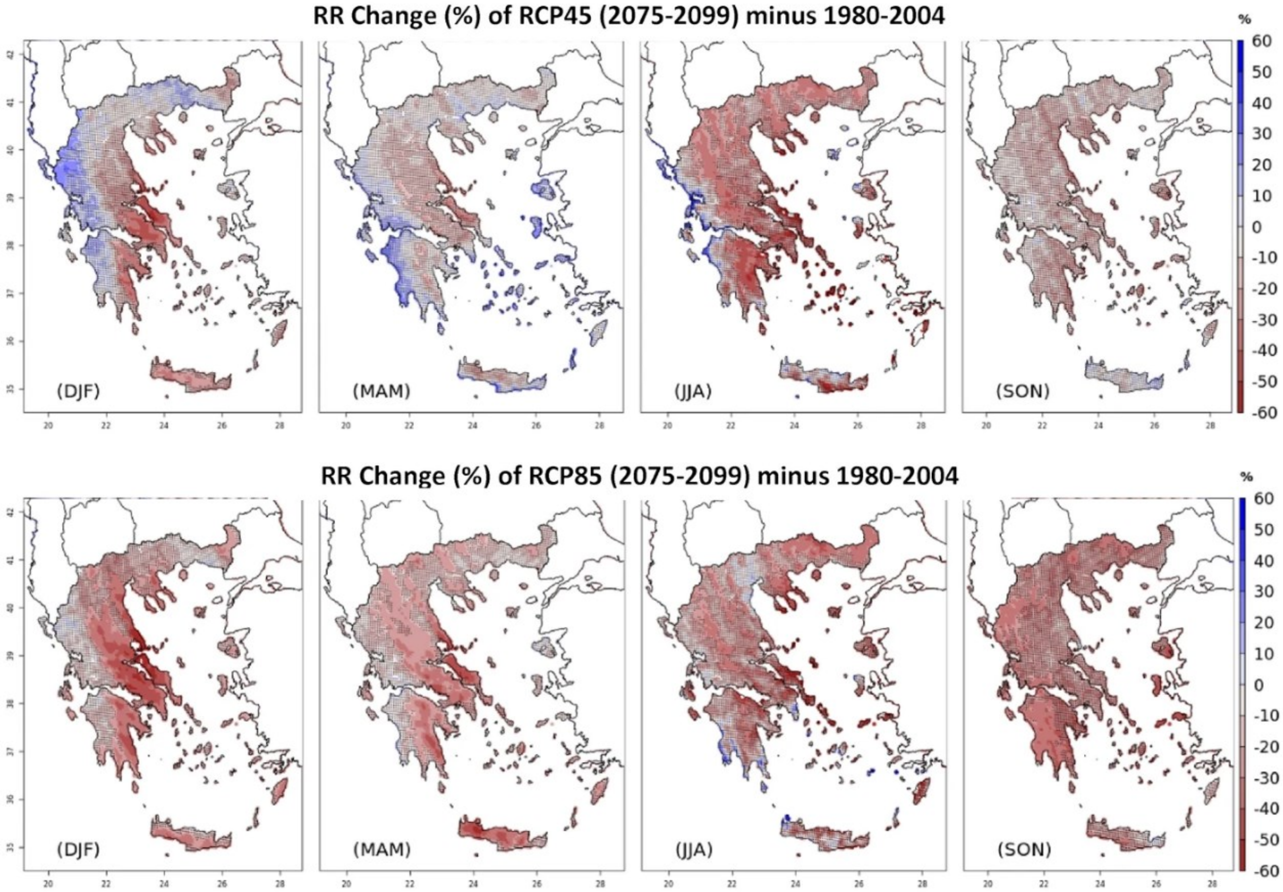

Figure 44. The WRFEC seasonal climate change for the mean precipitation (2075–2099 minus 1980–2004) for RCP4.5 and RCP8.5
Explanation: The initials in the map stand for the 1st letter of the month.
Source: Politi et al. 2022

4.3.3. France

The Nord-Pas-de-Calais region is composed of six climatic areas depending on their elevations and their proximity from the coast (Figure 45). Several climatic stations spread on all the territory are recording many climatic parameters to evaluate the impact on the climate change in the region (e.g. Lille, Boulogne-sur-Mer, Cambrai, etc.)

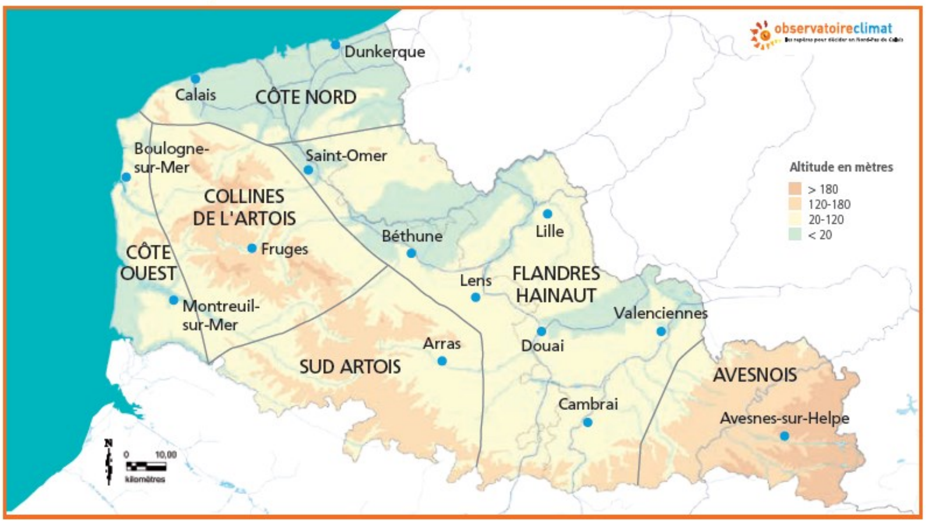

Figure 45. Location map

The annual temperature average of the region oscillates between 8.8°C and 11.9°C, over the period of 1955-2013 (calculated using annual averages of minimum and maximum temperatures). Figure 46 illustrates the trends of these data. The average maximum-minimum temperatures vary from 12 to 15°C during the year. The highest averages are found in the Lille metropolis, in Douaisis, in Valenciennes and the east of Calais. The trend curve in green shows a global increase of the average temperature of 1.37°C between 1955 and 2013 in the Nord-Pas-de-Calais region.

The French pilot site is situated about 40 km far away the Lille-Lesquin weather station. The compilation of the data collected between the years 1971 and 2020 shows an increase trend for temperature (1°C over 49 years), which confirmed the tendency revealed in Figure 46 and Figure 47.

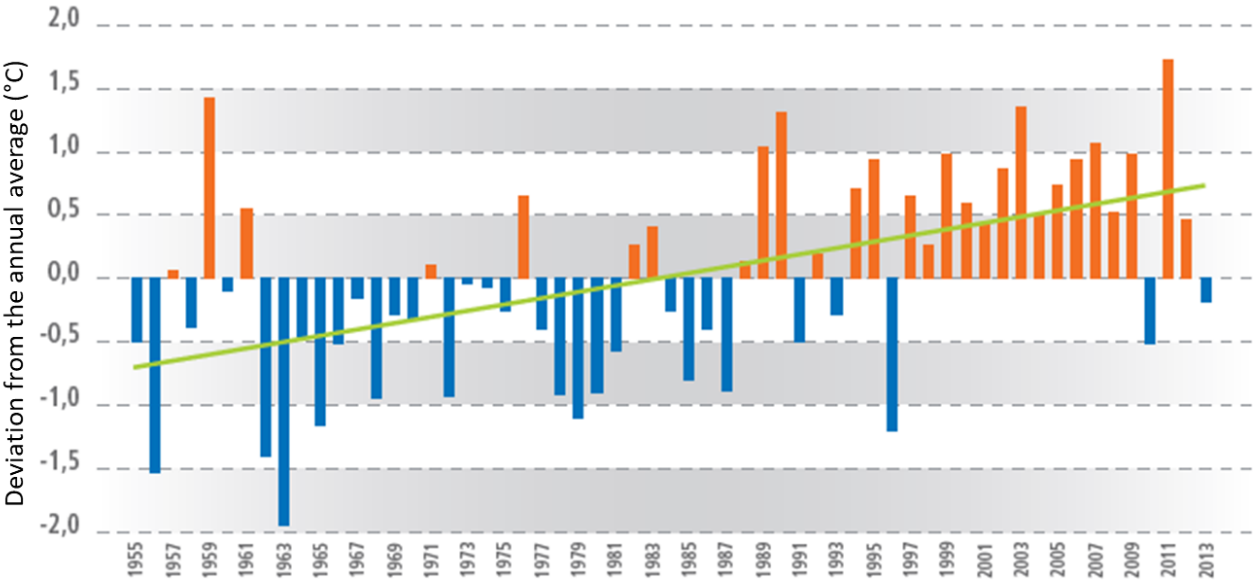

Figure 46. The aximum and minimum temperatures in Lille between 1955 and 2013 (deviation from the annual average, in °C)

Source: https://www.cerdd.org/index.php/Parcours-thematiques/Changement-climatique/Ressources-climat/Publication-Changement-climatique-Realites-et-impacts-pour-les-habitants-du-Nord-Pas-de-Calais

The extreme temperatures are a part of the most serious extreme phenomena in the Nord-Pas-de-Calais region. They correspond to the days with temperatures above 30°C; their occurrence average over the two reference climatic stations, specifically 5 days/year, + or - 3.3 days. In Boulogne-sur-Mer, hot days are still rare due to the coastal position of the station. On the other hand, an increase of their frequencies has been observed in Lille since 1955. The average number of days of high heat remains between 4 and 5 per year at Lille between 1955 and 2013. However, since 2000, we observed more than 5 days of strong heat more than every other year. The increase in this phenomenon correspond to +1 day with extreme temperatures every 13 years (Figure 47). With the global rise in the temperatures, the coastal zone will be likely at a risk of exposure in the decades to come.

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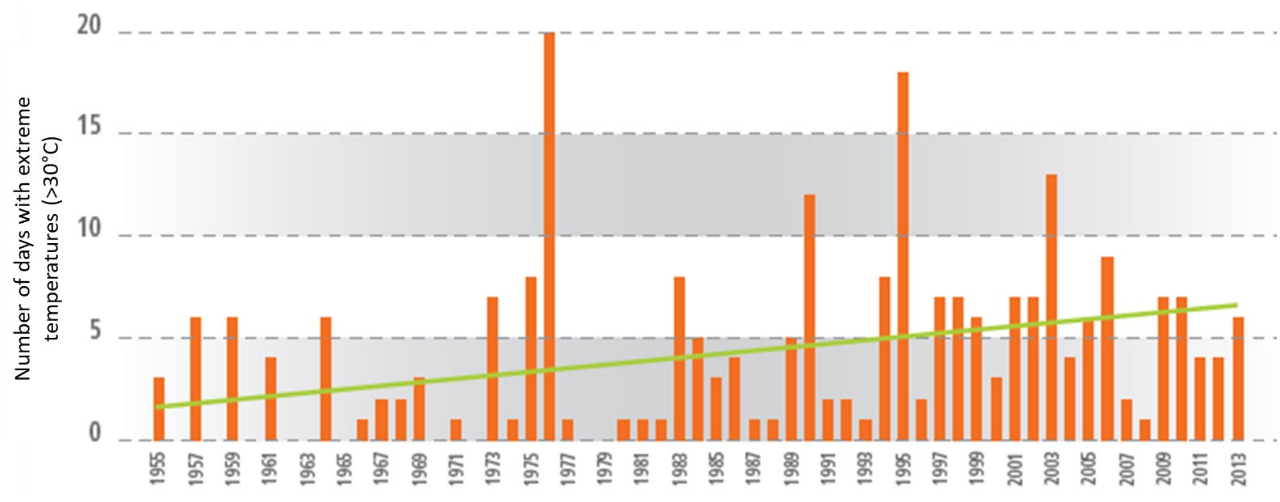

Figure 47. The number of days with extreme hot temperatures in Lille between 1955 and 2013.

Source: https://www.cerdd.org/index.php/Parcours-thematiques/Changement-climatique/Ressources-climat/Publication-Changement-climatique-Realites-et-impacts-pour-les-habitants-du-Nord-Pas-de-Calais

The high temperatures also occur closer in time and are called 'heat waves'. A 'heat wave' is defined by at least five cumulative days with an average temperature of +5°C above the reference period from 1981 to 2010. These episodes with significant cumulative number of days with high temperatures are observed in several cities in the Nord-Pas-de-Clais including Boulogne-sur-Sea and more particularly Cambrai. The average is 1.9 days/year in Boulogne-sur-Mer and 3 days/year in Cambrai (over the period 1955-2010). When looking at trends and distribution of these episodes over time, one is able to observe significant findings (Figure 48).

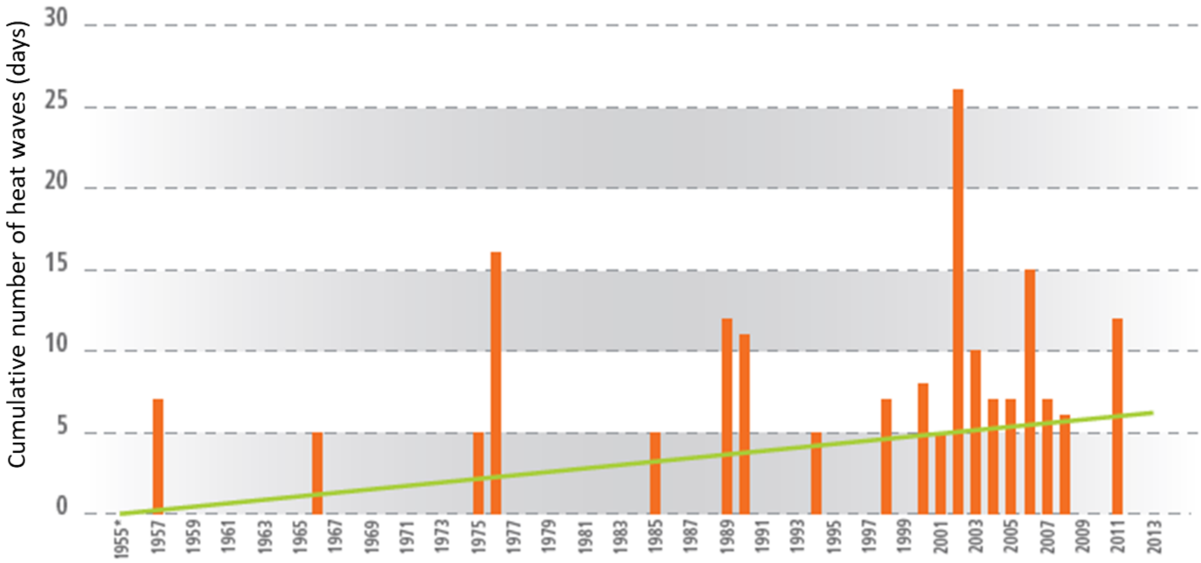

Figure 48. The cumulative number of days for the heat waves in Lille between 1955 and 2013

Source: https://www.cerdd.org/index.php/Parcours-thematiques/Changement-climatique/Ressources-climat/Publication-Changement-climatique-Realites-et-impacts-pour-les-habitants-du-Nord-Pas-de-Calai

Another temperature parameter to illustrate the state of the climate change in the region is the number of frosty days characterising the low temperature extremes. Large disparities can be observed on the frequency of the frost in the Nord-Pas-de-Calais region. For example, in Boulogne-sur-Mer, 28 days of frost on average per year are recorded, against 55 days in Cambrai and more than 70 days in Avesnois. However, for all of these climatic stations the trend is significantly downward, a speed of around -1 to -5.5 days/decade (Figure 49). This trend is particularly significant on the coast, where the number of days the frost is always less-intense.

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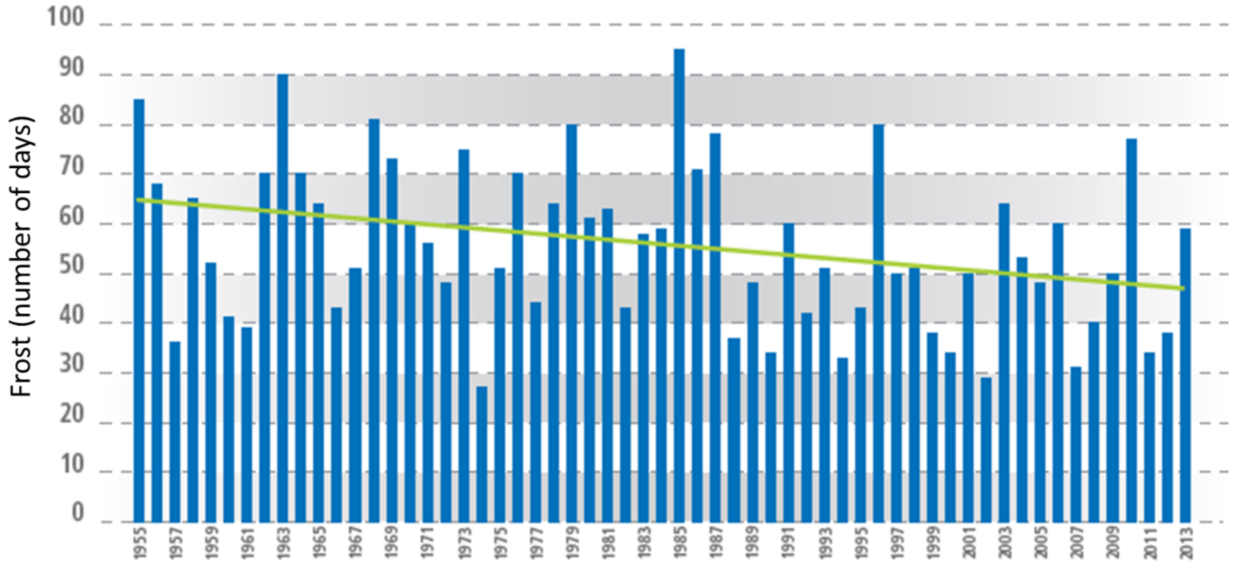

Figure 49. The number of frost days in Lille between 1955 and 2013

Source: https://www.cerdd.org/index.php/Parcours-thematiques/Changement-climatique/Ressources-climat/Publication-Changement-climatique-Realites-et-impacts-pour-les-habitants-du-Nord-Pas-de-Calais

The annual accumulation of water is the first parameter to take into account in precipitation analysis. In the long term, there are few changes in the cumulative average precipitation since 1955. In Lille, the precipitation tends to increase in winter (around +20% since 1956), without the overall accumulation being significantly impacted (Figure 50). In Boulogne-sur-Mer, the increase is not significant in volume, and precipitation vary from one year to the next, without a link as for the moment. However, the rainfall is heterogeneous depending on the territories: on a large part of Pas-de-Calais, the cumulative precipitation is greater than 800 mm per year, with a peak at 1,100 mm on Boulonnais. The Avesnois region also experiences precipitation greater than 800 mm. Elsewhere, on a large part of the North, the accumulations are lower with 700 mm on average.

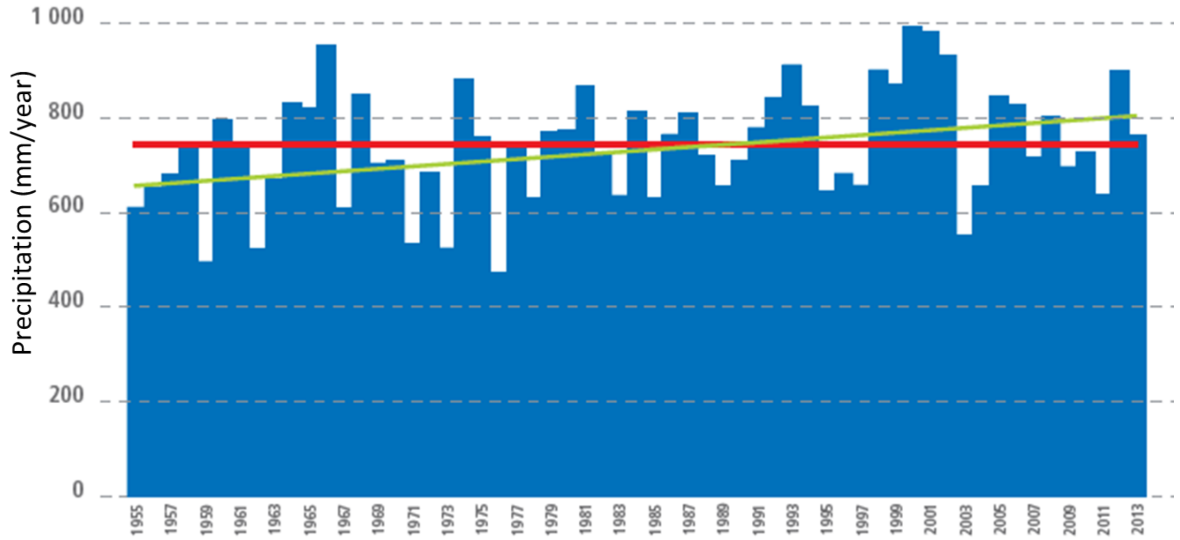

Figure 50. The total precipitation in Lille between 1955 and 2013 (mm/year)

Source: https://www.cerdd.org/index.php/Parcours-thematiques/Changement-climatique/Ressources-climat/Publication-Changement-climatique-Realites-et-impacts-pour-les-habitants-du-Nord-Pas-de-Calais)

In Nord-Pas de Calais, an evolution similar to global findings is found. The number of days of heavy rain, i.e. with the precipitation greater than 10 mm, increases slightly since 1955. This increase is significant in Boulogne-sur-Mer, with a trend of the order of +2.5 days/decade for a total average of 18 days between 1955 and 2013 (Figure 51).

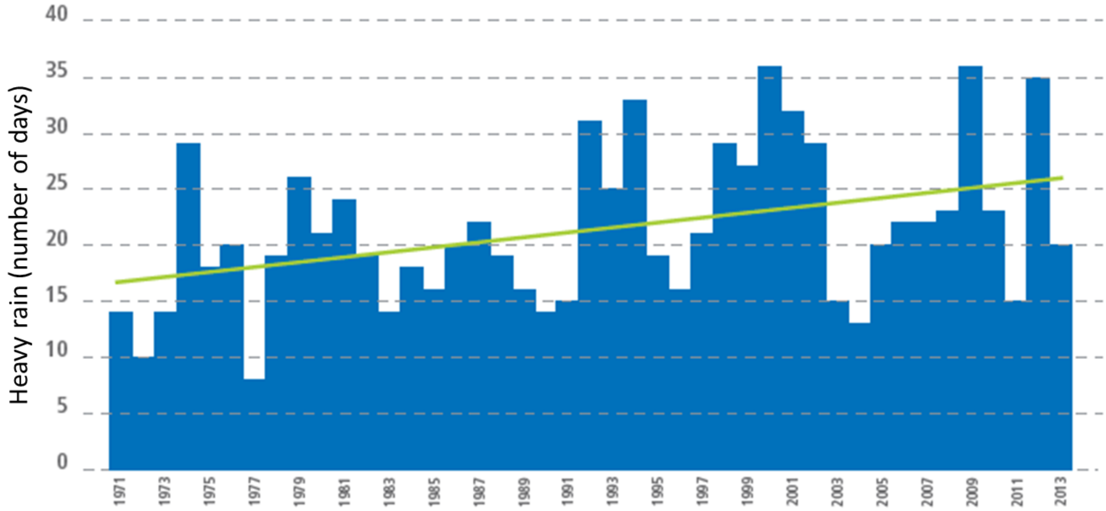

Figure 51. The occurrence of heavy rain in Lille between 1955 and 2013 (number of days)

Source: https://www.cerdd.org/index.php/Parcours-thematiques/Changement-climatique/Ressources-climat/Publication-Changement-climatique-Realites-et-impacts-pour-les-habitants-du-Nord-Pas-de-Calais

In the Nord-Pas-de-Calais region, the temperatures would continue to rise in the 21st century, even accelerated in certain RCP scenarios. A prospective exercise conducted by the Météo-France in 2011 showed evidence of an increase in the average annual temperature in 2050 between +1°C and +2°C in comparison with the 1971/2000 average and depending on the RCP scenarios (Figure 52). On the horizon of 2080, these projections show an increase from +1.5°C to +3°C, with a peak during summer. Temperatures are thus rising for all seasons of the year. These robust results illustrate the strong influence of the RCP scenarios on the socio-economic development in the future climate. During the projections, the average values sometimes seem to change in a faint proportion; the effect is on the other hand more spectacular on the evolution of the extremes. These include frost, strong heat or drought: these trends are strong due to the threshold effects.

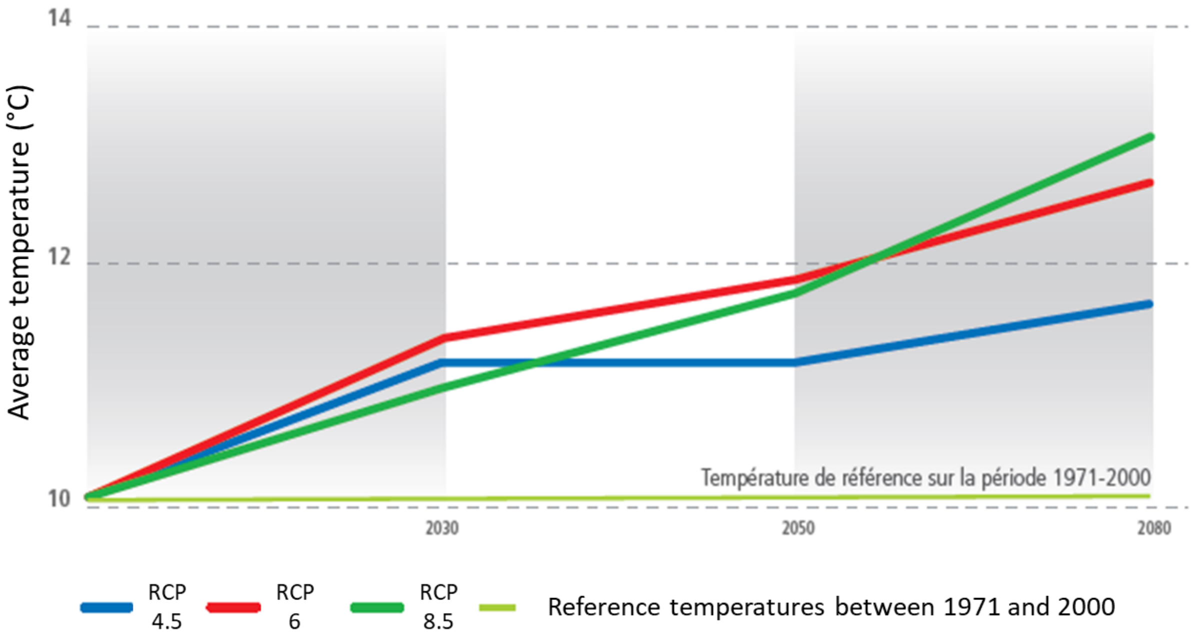

Figure 52. The evolution of average temperatures in the Nord-Pas-de-Calais region depending on the IPCC scenarios RCP4.5, RCP6 and RCP8.5

Source: https://www.cerdd.org/index.php/Parcours-thematiques/Changement-climatique/Ressources-climat/Publication-Changement-climatique-Realites-et-impacts-pour-les-habitants-du-Nord-Pas-de-Calais

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In conclusion, several parameters highlight the effects of climate change in the Nord-Pas-de-Calais region during the last decades (from 1955 to 2013), including higher average temperatures, a higher number of 'heat waves' and a higher number of heavy rains per year, and the IPCC RCP scenarios show that these trends will likely continue until 2100. At the French pilot site, because of its location inland instead of near the coast, the climatic change consequences might primarily be expected to relate to an increase in temperatures. Due to its position, it is protected from the immersive waves and tsunamis, but not from the increase of heavy rains that can cause an increase of erosion and floods, leading to soil destabilisation and pollution transfer towards unwanted areas such as the rivers or the aquifers. These very rapid climate changes will have significant repercussions on natural ecosystems (such as plant biodiversity, meso- and micro-biodiversity, ecosystem resistance and resilience, ecosystemic services, etc.), but also and perhaps more so, on the environments already weakened by significant degradation. Indeed, the strong disturbance/degradation of the ecosystems, as is the case during mining activities, already has clearly visible consequences on the environments (a reduction in the global biodiversity, establishment of invasive plants, soil erosion and pollution, etc.). Adding the climate change to the equation may prove even more consequential on these degraded ecosystems and also on the rehabilitation strategies. Above all, the change of the climate conditions might influence the health and the resilience of the vegetation selected for the reclamation as well as promote the expansion of the invasive species. Increased temperature variations and "heat waves" can significantly affect the survival of plants and seedlings, as they are particularly sensitive during the first years of growth. A reduction of frosty days may also directly affect the seed germination (breaking dormancy of seeds) or promote the development of pathogens and pests which are normally being partially eliminated during the winter period.

4.3.4. Czech Republic

Methodology of modelling

The climate scenario is an acceptable description of the climate, including the expected consequences of anthropogenic influences. It represents the difference between the current state (e.g. in the Czech Republic the 1961-1990 and 1991-2010 periods) and the future model climate for a certain time horizon, which may occur under certain expected circumstances. Climate projection is the response of the climate system to a certain scenario of the greenhouse gas and the aerosol emissions determined by the climate models.

The basic source of information are the global climate models. A number of uncertainties need to be taken into account when designing the regional climate change scenarios. It is therefore recommended to select more than one climate model for the scenarios to cover the uncertainty associated with the variance of the model outputs. It is also necessary to choose the appropriate emission scenario for the growth of the greenhouse gas emissions, or the anthropogenic aerosols.

The estimates for climate development in the period up to the end of the 21st century are mainly based on the global climate models. The Global Climate Models (GCM) are models of the general circulation of the atmosphere associated with the ocean model. These are computer models of the climate system, which are used to calculate the probable future climatic conditions. They are based on the solution of equations of motion and thermodynamics, which describe the processes in the climate system, using the methods of numerical mathematics. Because the solution of these equations is computationally very demanding, it is necessary to use the fastest supercomputers available today to implement the GCM. Regional Climate models (RCM) belong to the techniques of the so-called downscaling, which achieves a greater resolution of the model, and calculations can be performed for selected regions (e.g. for Central Europe).

For the needs of the Czech Republic, the following models were used, which represent the entire breadth of the climate spectrum:

Main models:

ALADIN-CLIMATE / CZ model. The outputs of the regional climate model ALADIN-CLIMATE / CZ controlled by the global model ARPEGE and operated in CHMI can be used to estimate the further development of the climate in the Czech Republic and specifically **the** mining area of the Northwestern Bohemia. The model is based on a numerical prediction model for a limited area, which performs the calculation of climatological characteristics for a limited area, in this case for Central Europe. Its main advantage is the ability to simulate climate with a much better spatial resolution than what global models (GCM) are capable of. While the GCMs now routinely operate with a resolution of 200–300 km, RCM ALADIN-CLIMATE / CZ has demonstrated the ability to simulate the climatic characteristics **has** sufficient quality with a resolution of 10–25 km, which is particularly important in Central European conditions. In the network of points in which the GCM works, it is **impossible** to capture with sufficient accuracy the very existence of smaller mountain areas, such as the Krkonoše Mts., the Šumava Mts., the Krušné hory Mts., and to a large extent also the Alps. The models are not even able to simulate well the influence of these mountains on the dynamics of the atmosphere, for example the existence of wind and leeward effects, etc. Each regional model works in relation to the global model. First, appropriate simulations are performed using the GCM, which will provide the necessary information about the development of large-scale processes in the atmosphere (scales of the order of 103 km). The results are then taken over by the RCM, which refines and regionali**s**es the results in more detail, up to a scale of 101–102 km. Updated regional scenarios for the Czech Republic with a probable outlook for changes in the period around 2030, 2050 and 2100 are the basis for follow-up studies of the impacts of the climate change on a national scale. Scenarios do not consider natural climate fluctuations; contributions of natural and anthropogenic climate variability can be mutually compensated or added. Due to the uncertainties of the outputs of the global climate models and methods of regional downscaling, the outputs of regional models for the territory of the Czech Republic are burdened with a higher degree of uncertainty than the outputs of the models for the territory of the European continent, resp. the whole planet. The precipitation mode projections also show a higher degree of uncertainty compared to a similar temperature regime projection.

IPSL (version IPSL-CM5A-MR) - the country of origin: France; a model best representing the median of all the GCMs tested;

HadGEM (HadGEM2-ES version) – the country of origin: Great Britain; a model representing a more significant change in the distribution of precipitation in our region (decrease in summer and autumn precipitation and increase in spring precipitation). Previous versions of this model have been used in most studies in our territory cited by the Intergovernmental Panel on Climate Change;

CNRM (version CNMR-CM5) – the country of origin: France; a model with a similar change in temperature as HadGEM, but with an increase in precipitation observed across all months, especially in spring and autumn; the previous version of this model was used as the main control model of the so-called Pretel's report from 2011;

BNU (BNU-ESM version) - the country of origin: China; represents the GCM models predicting a relatively low increase in temperature and a reduction in precipitation for our territories across all months except the summer period;

MRI (version MRI-CGCM3) - the country of origin: Japan; represents the GCM models predicting a relatively low increase in temperature and an increase in precipitation for our territory, with the exception of the end of summer and autumn.

MODELLING OF TEMPERATURE

The current trend in the development of temperature characteristics

In connection with the change in the temperature regime, the average number of days with high temperatures is also gradually increasing and the average number of days with low temperatures is decreasing. The average number of summer days during the year in the whole territory of the Czech Republic had increased by 13and tropical days by 6; on the contrary, there was a decrease in the average number of frost (by 8) and ice days (by 3 days). Changes in the maximum daily temperatures, the number of days with extreme temperatures and an alternation of extremely warm, resp. cold periods are statistically significant, especially during the summer.

A model for the temperature development until 2030:

The results of simulations with the ALADIN-CLIMATE / CZ model suggest that the average temperatures by the end of the third decade of this century would increase in the A1B scenario by values according to the following table compared to the period 1961–1990:

Table 10. Seasonal changes of the average temperature (°C) for the period around 2030 in the Northwestern Bohemia (the mining region) in comparison with the period 1961–1990, according to the simulation RCM ALADIN-CLIMATE / CZ for the scenario A1B

	spring	summer	autumn	winter	year
minimum	0.8	0.7	0.9	0.8	0.8
10% quantile	0.9	0.9	1.0	1.0	0.9
25% quantile	1.0	1.0	1.1	1.1	1.0
median	1.2	1.1	1.2	1.1	1.1
75% quantile	1.3	1.2	1.3	1.2	1.2
90% quantile	1.4	1.3	1.4	1.3	1.3
maximum	1.7	1.6	1.5	1.5	1.6

The trend of the observed increase in the average annual temperatures (0.24 °C / 10 years) corresponds to the global values as well as the values reported for Europe (0.2 °C / 10 years).

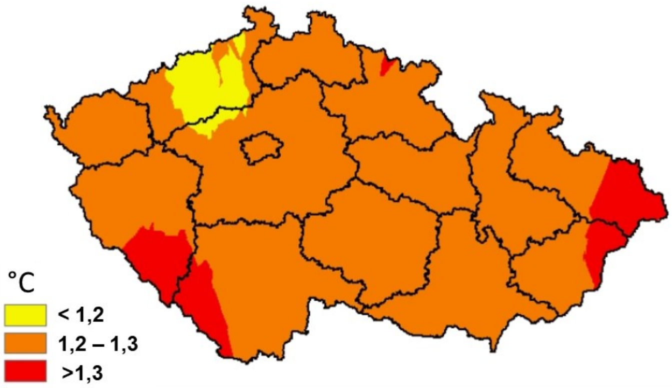

Figure 53. The distribution of changes in the average annual temperature (oC) in the Czech Republic until 2030, in comparison with the 1961–1990 period according to the RCM ALADIN-CLIMATE / CZ simulation for the scenario A1B

Like the changes in the average temperatures, maximum and minimum temperatures are likely to change. The maximum temperatures will tend to increase more markedly in winter and summer, the minimums especially in summer, partly also in autumn and winter. If we compare the model temperature trends with the current ones, it can be expected that by the end of the third decade of this century, the temperatures will rise to the level of higher quantiles. It is also possible to find an acceptable continuity of results in terms of seasonal changes and a really faster increase in the average winter and autumn temperatures.

A model for temperature development until 2100:

The climate models agree that the air temperatures will continue to rise, depending on the RCP (Representative Concentration Pathways) emission scenario. The most commonly used are RCP4.5, which allows for a slight decrease in the amount of CO_2 in the air. On the contrary, the emission scenario 8.5 is set for no change in the amount of CO_2 concentrations. By 2050, temperature growth will be the same without the influence of the emission scenario, as the landscape will no longer be able to respond to changes in greenhouse gas concentrations, but the developments in the second half of the century would be already dependent on the given emission scenario. According to RCP4.5, the warming will occur by about 2.0 °C at the end of the century, and according to RCP8.5 to 4.1 °C.

For the territory of the Czech Republic, the following graphic outputs were processed for the parameters of the average annual temperature.

Research Fund for Coal & Steel
Co-funded by the European Union

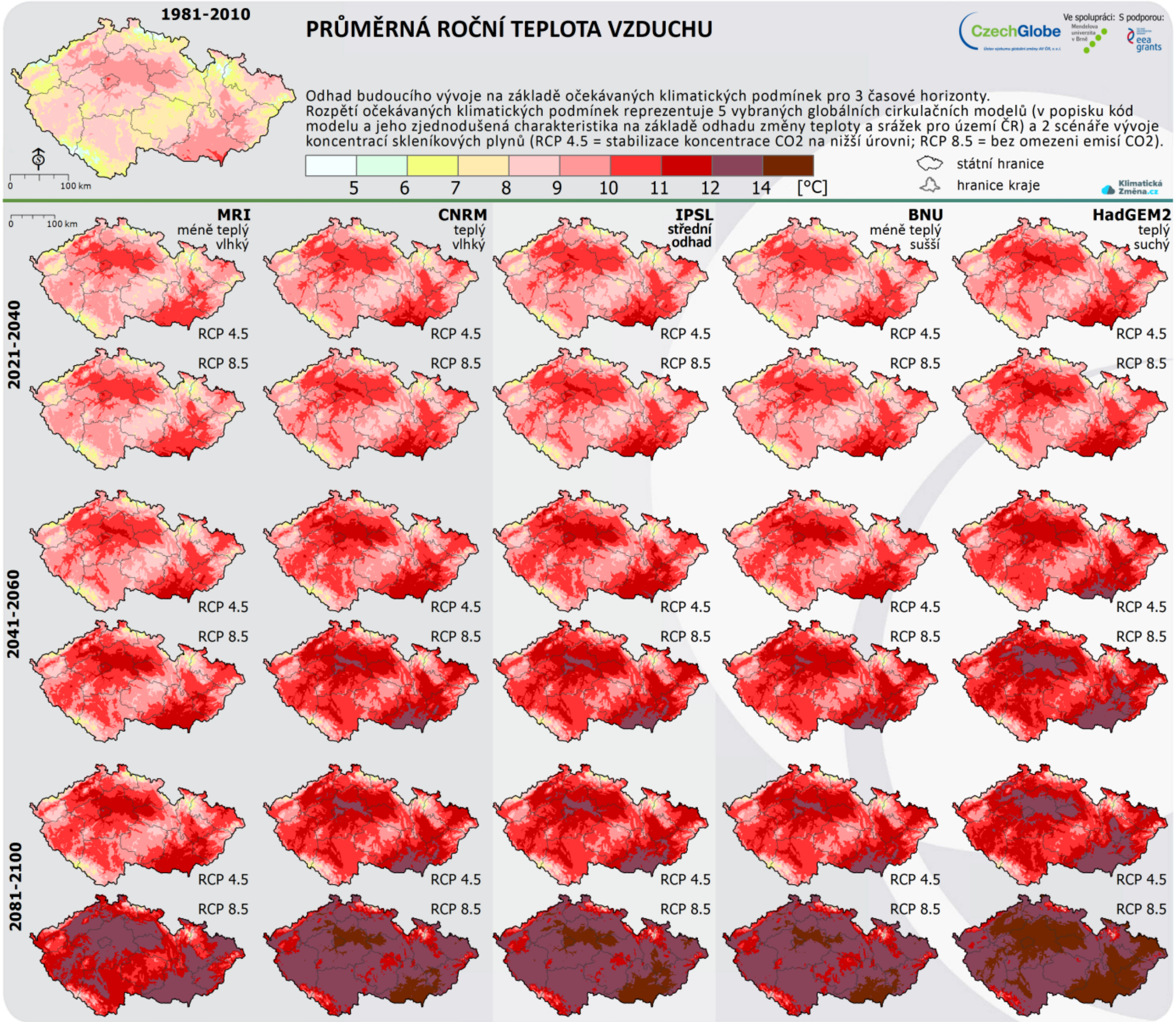

Figure 54. The development of the average annual air temperature depending on the emission scenario of the RCP according to the aforementioned global models in the outlook to the year 2100 (Source: Institute of Global Change Research of the ASCR, v. v. i.)

For the area of the Northwestern Bohemia, where the mining area of interest is located, the following average temperature values were derived for the individual climate models. A graph was also compiled for the average IPSL model (Figure 55).

Table 11. Development of the average temperature of the mining region (N – W Bohemia) for individual climate models (Met – Station Kočkov, Ústí nad Labem City)

Years	Emission scenario	Climate model				
		MRI	CNRM	IPSL	BNU	HadGEM2
1991-2010	-	9.8				
2021-2040	RCP4.5	10.2	10.5	10.5	10.5	10.6
	RCP8.5	10.4	10.7	10.8	10.8	10.9
2041-2060	RCP4.5	10.5	11.0	11.6	11.5	11.6
	RCP8.5	11.0	11.4	11.9	11.8	12.0
2081-2100	RCP4.5	11.1	11.9	12.6	12.5	13.0
	RCP8.5	12.0	12.7	13.2	13.1	13.5

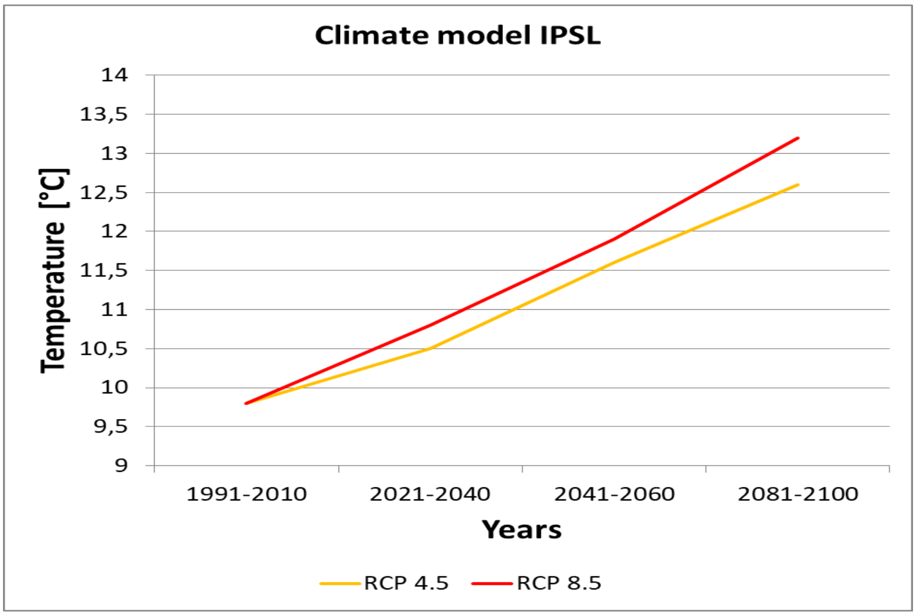

Figure 55. Projection of average temperatures in the mining region (N – W Bohemia) according to emission scenarios (Met – Station Kočkov, Ústí nad Labem City)

MODELLING OF PRECIPITATIONS

The current trend in the development of precipitations characteristics

Since the early 1990s, there has been a very slight increase in the annual total precipitation. The decrease in precipitation totals in the second half of spring and at the beginning of summer (April to June) is offset by an increase in totals in the second half of winter (especially March) and especially in July, resp. in early August; changes in precipitation totals are reflected only in the order of percentage units. However, the main features of the annual course of precipitation in the last fifty years remain - the maximum precipitation totals in summer, the minimum in winter. However, both the annual and seasonal precipitation totals show significant year-on-year variability (e.g. 138% of the precipitation normal in the Czech Republic in 2002 and 74% of the precipitation normal in the following year 2003). In our territory, there are no statistically significant changes in the average number of days with precipitation totals above a certain limit. Precipitation days with total precipitation of ≥ 5 mm and ≥ 10 mm occur in the Czech Republic throughout the year and their monthly numbers correspond to the annual course of precipitation - the most frequent occurrences are recorded in summer, the lowest in winter. The days with a total precipitation of ≥ 20 mm occur mainly in the warm half of the year. Their occurrence in the cold period is quite rare.

A model for precipitation development until 2030:

The simulated changes in precipitation totals indicate the possibility of a slight increase in the annual totals (on average by about 4% compared to the period 1961–1990), higher in winter and spring, lower in summer and autumn. The ranges between the quantile values indicate the persistence of significant variability in the average precipitation totals. The values for the second half of spring and summer, together with an increased evaporation signal the risks of an increase in soil moisture deficit.

Table 12. The seasonal changes in precipitation totals (share) until 2030 compared to the period 1961–1990 according to the RCM ALADIN-CLIMATE / CZ simulation for the scenario A1B

	spring	summer	autumn	winter	year
minimum	0.94	0.84	0.83	0.72	0.83
10% quantile	1.02	0.92	0.95	0.82	0.93
25% quantile	1.07	0.96	1.00	0.87	0.98
median	1.12	1.03	1.08	0.92	1.04
75% quantile	1.17	1.10	1.13	0.97	1.09
90% quantile	1.24	1.17	1.25	1.01	1.17
maximum	1.34	1.31	1.44	1.08	1.29

A comparison of the model precipitation totals suggests that the agreement of the simulations with the results of the existing observations is significantly lower for the precipitation. Rather, the precipitation totals can be expected to be lower, but the probability of an increase in the winter precipitation totals is high.

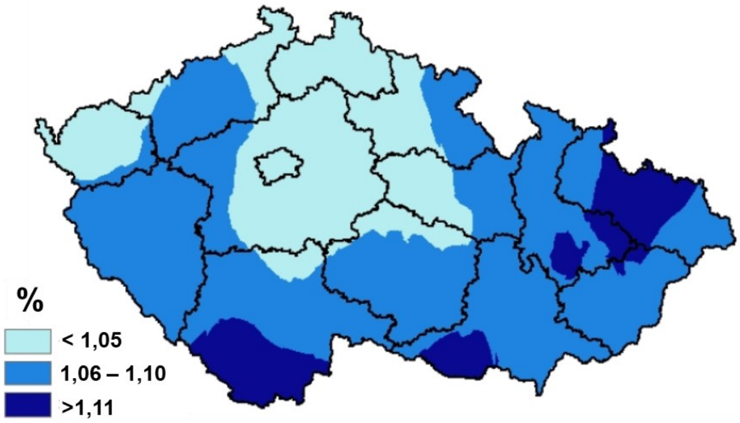

Figure 56. The distribution of changes in the annual precipitation totals (share) in the Czech Republic until 2030 in comparison with the 1961–1990 period according to the RCM ALADIN-CLIMATE / CZ simulation for the scenario A1B

A model for the precipitation development until 2100:

Modelling of the precipitation development is more difficult than the temperature modelling. For the territory of the Czech Republic, the following graphic outputs were processed for the parameters of the average annual precipitation.

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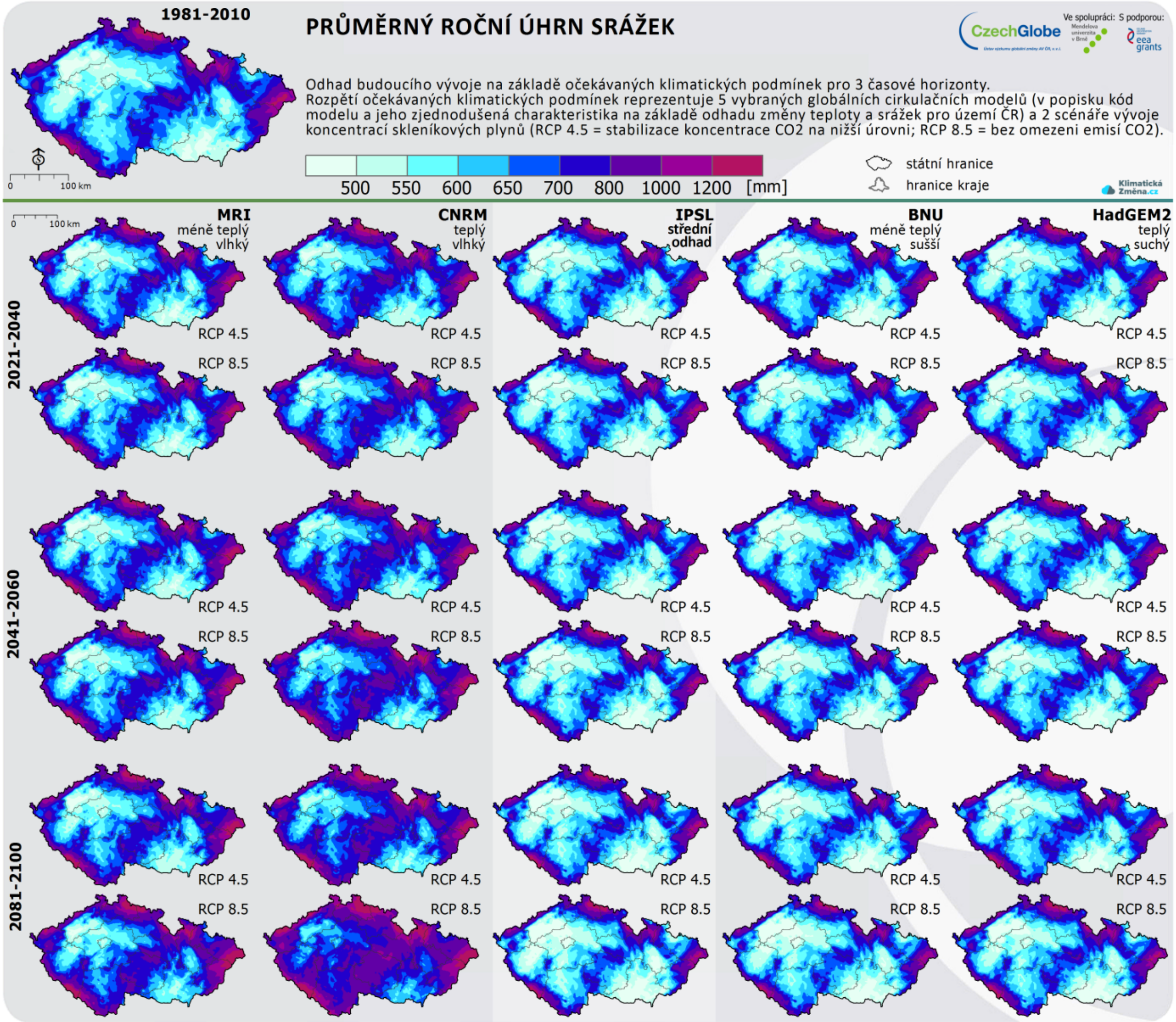

Figure 57. The development of the average annual precipitation depending on the emission scenario of the RCP according to the aforementioned global models in the perspective until 2100 (Source: Institute of Global Change Research of the ASCR, v. v. i.)

For the area of the Northwestern Bohemia region, where the mining area of interest is located, the following average precipitation values were derived from the individual climate models. A graph was also compiled for the average IPSL model.

Table 13. The development of the average precipitation of the mining region (N – W Bohemia) for individual climate models (Met – Station Kočkov, Ústí nad Labem City)

Years	Emission scenario	Climate model				
		MRI	CNRM	IPSL	BNU	HadGEM2
1991-2010	-	636				
2021-2040	RCP4.5	648	652	638	635	630
	RCP8.5	650	658	630	628	625
2041-2060	RCP4.5	661	669	625	620	622
	RCP8.5	668	684	630	618	615
2081-2100	RCP4.5	675	690	610	607	600
	RCP8.5	689	706	605	601	595

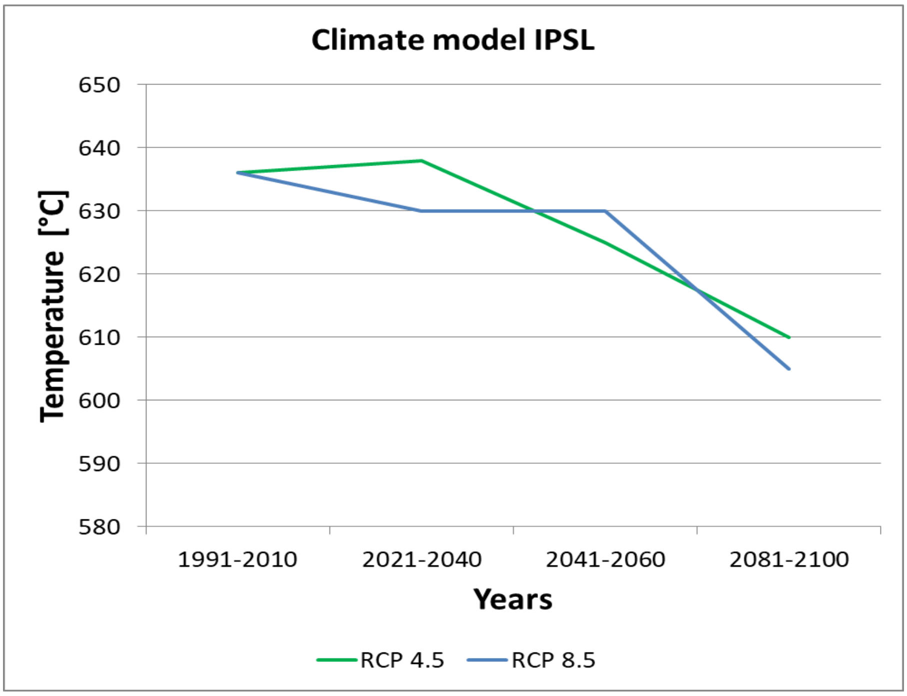

Figure 58. A projection of the average precipitation of the mining region (N – W Bohemia) according to the emission scenarios (Met – Station Kočkov, Ústí nad Labem City)

4.3.5. Slovenia

The projected changes in precipitation amount in Slovenia are not very prominent due to the fact that Slovenia is localised near or in the so-called transition zone where the precipitation change signal changes its sign: on an annual scale an increase in the precipitation amount is projected for northern Europe and a decrease is projected for southern Europe. This also contributes to a lower reliability of the precipitation amount projections and results in some differences in signals of their respective RCPs. Under the moderately optimistic RCP4.5 scenario, no significant changes in precipitation are expected initially, but signals become more pronounced over time. By the beginning of the second period, increasing precipitation signals spread from east to west across Slovenia. By 2100, an increase of approximately 10% in the annual mean precipitation is expected, relative to the reference period (1981-2010), except in the northwest, where a smaller increase is projected (Figure 59). What's important, projections concerning precipitation are most reliable for the north and east of Slovenia and less reliable for the west.

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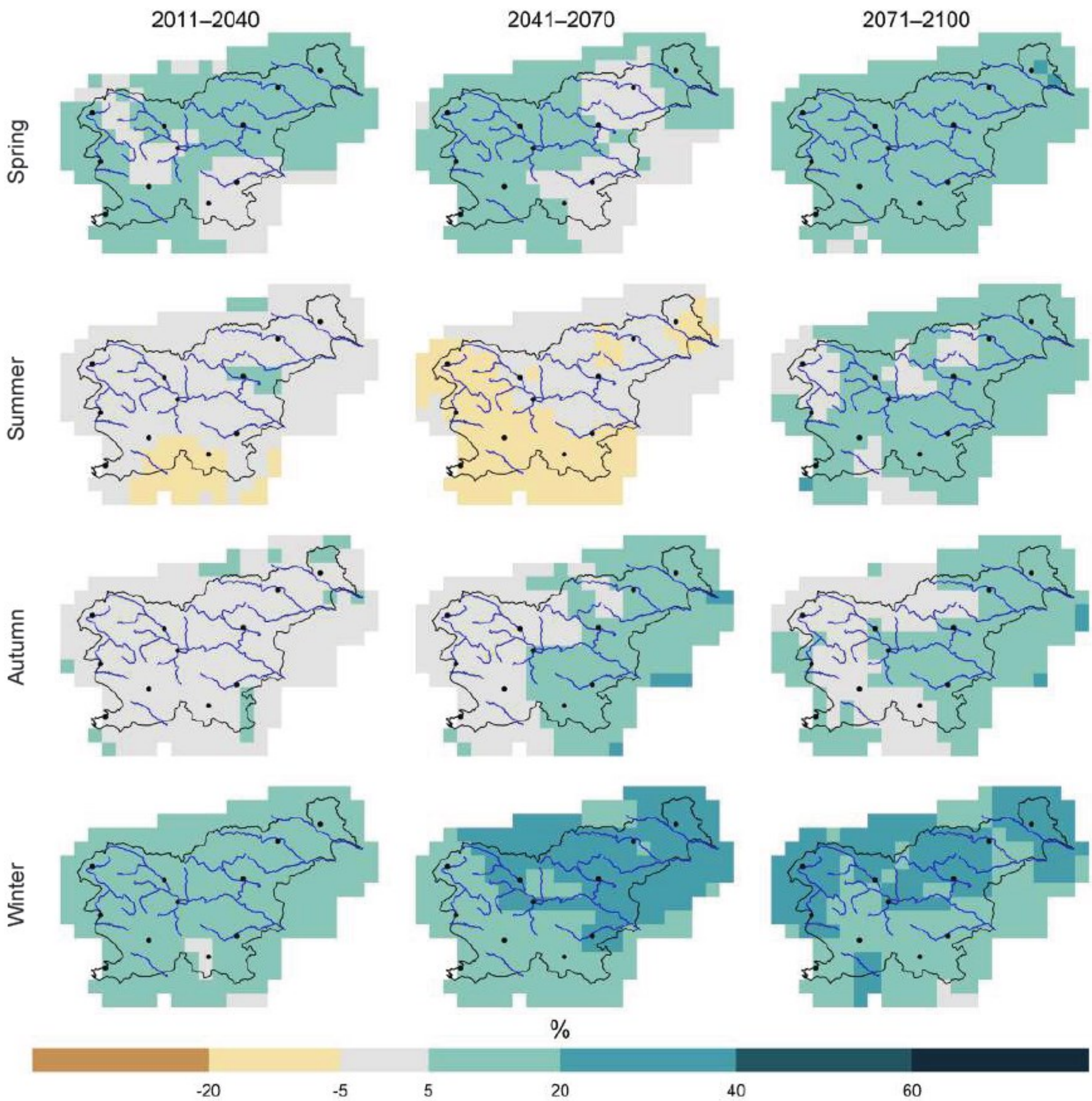

Figure 59. The spatial changes in seasonal mean precipitation in Slovenia for three projection periods under RCP4.5. The changes are shown relative to the reference period 1981-2010.

Source: ARSO METEO, 2022: Climate change projections for Slovenia over the 21st century. Temperature and precipitation summary, https://www.meteo.si/uploads/probase/www/climate/text/en/publications/OPS21_brosura_ENG.pdf

Concerning the changes in temperature, Slovenia will be subjected to a significant temperature rise, ranging from 1°C to 4°C depending on the RCP scenario. All three RCP scenarios project an increase in the annual mean temperature by 2100, RCP2.6 by approximately 1.3°C, RCP4.5 by approximately 2°C and RCP8.5 by approximately 4.1°C. The projected warming in Slovenia is fairly evenly distributed with some seasonal differences arising. The moderately optimistic scenario RCP4.5 projects air temperature to rise between 0.4°C to 1.0°C in near future, 1.1°C to 2.3°C in the middle of the century and 1.5°C to 2.6°C at the end of the century. The seasonal means are presented in Figure 60. The difference between the warming in winter and spring is statistically significant in the last two projection periods and is limited to certain parts in the north and west of the country, including but not limited to the vicinity of Velenje and the Alps (ARSO METEO 2022).

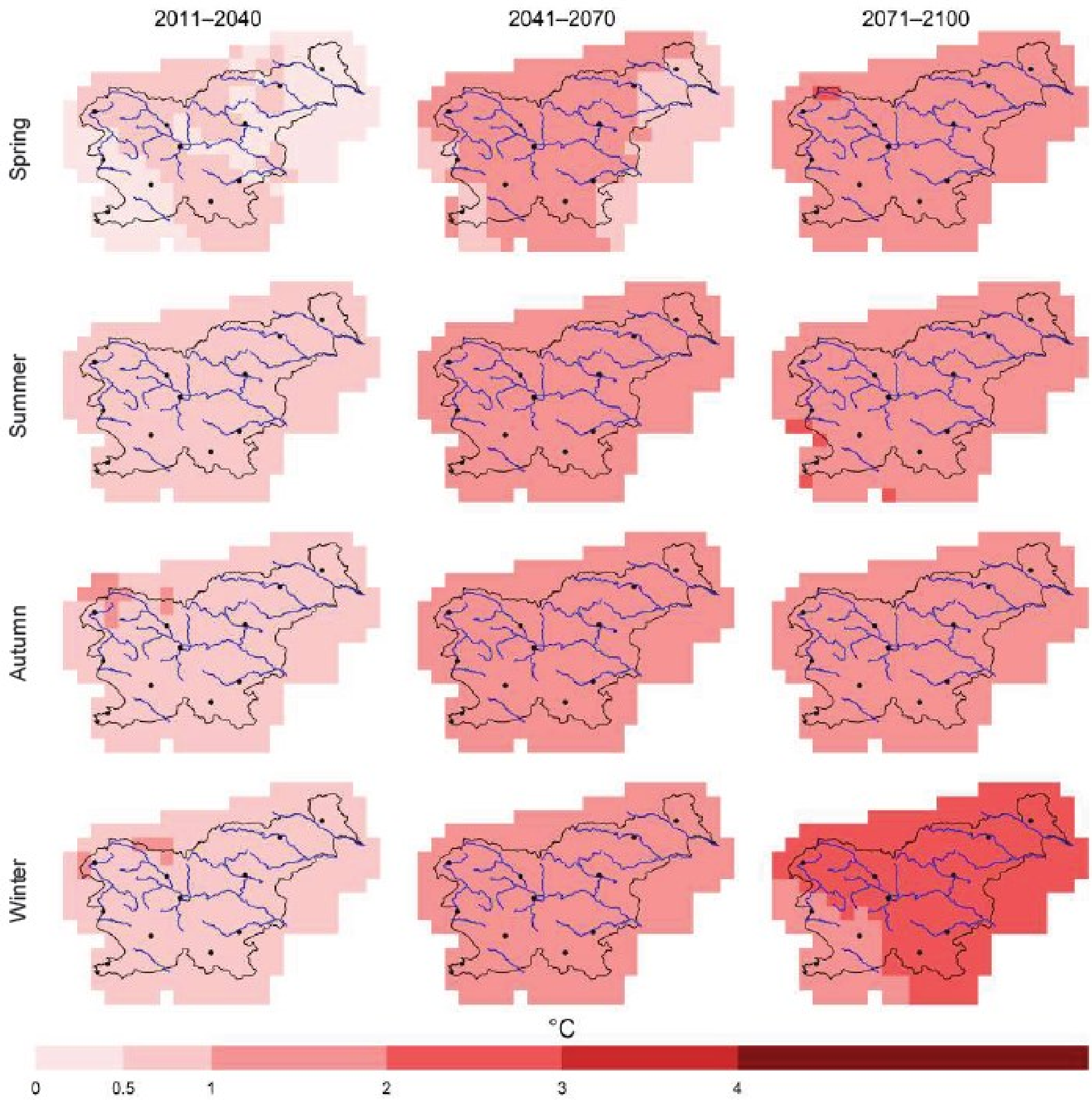

Figure 60. The spatial changes in seasonal mean air temperature in Slovenia for three projection periods under RCP4.5. The changes are shown relative to the reference 1981-2010 period.

Source: ARSO METEO, 2022: Climate change projections for Slovenia over the 21st century. Temperature and precipitation summary, https://www.meteo.si/uploads/probase/www/climate/text/en/publications/OPS21_brosura_ENG.pdf

According to all the RCP scenarios, the number of summer days with the daily maximum temperatures exceeding 25 °C is expected to rise over time. Under RCP4.5, this results in an increase of approximately 10 summer days per year in the first period, and about 20 more days in the second and third periods. Notably, by the end of the century, there is a significant difference between RCP4.5 and RCP8.5, with the latter showing up to 60 additional summer days compared to the reference period. Regardless the scenario, these projected changes vary significantly with altitude; higher elevations experience a less pronounced increase in the number of summer days (Figure 61). On the other hand, the number of cold days, when daily minimum temperature drops below 0°C, is expected to decrease with time. Under RCP4.5 the number of cold days will decrease by approximately 10 days in the first period and by approximately 20 days in the second and last period. The greatest reduction is projected in the northwest at the end of the century with approximately 40 cold days less relative to the reference period. The changes and altitude-dependent differences in changes are even more pronounced under RCP8.5 (Figure 61) (ARSO METEO 2022).

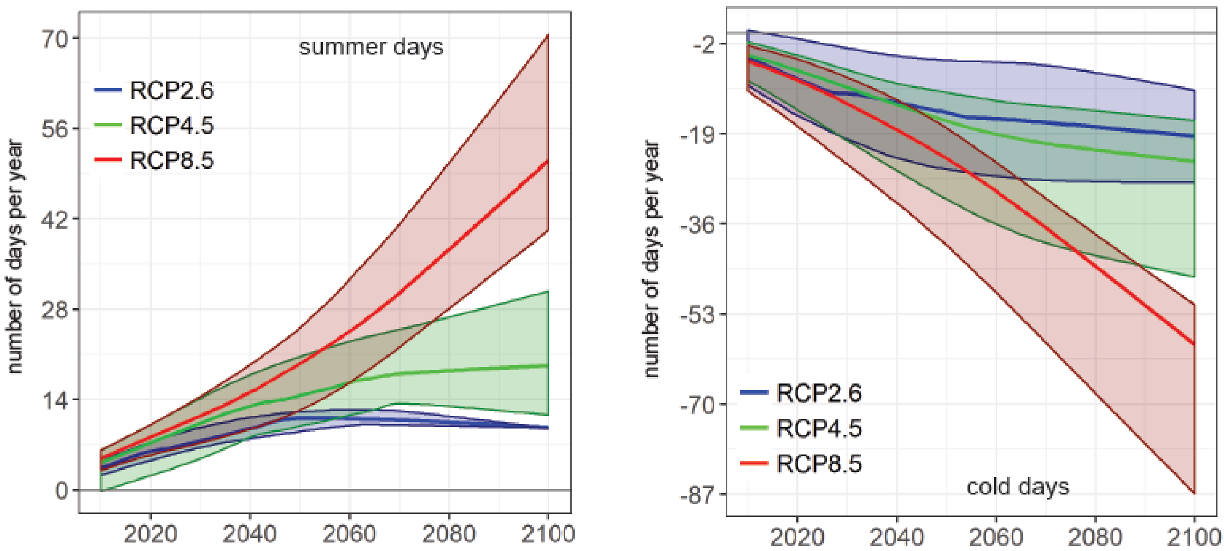

Figure 61. The course of change in the number of summer days (left) and cold days (right) in Slovenia over the 21st century relative to the reference period 1981-2010 for three scenarios: RCP.6, RCP4.5 and RCP8.5. *Bold coloured curves show model median and lighter colours show model spread.*

Source: ARSO METEO, 2022: Climate change projections for Slovenia over the 21st century. Temperature and precipitation summary, https://www.meteo.si/uploads/probase/www/climate/text/en/publications/OPS21_brosura_ENG.pdf

As the air temperatures rise, the soil's surface layer will warm, particularly during the second part of the growing season from July to September. This will affect the phenological development of plants and extend the growing season, also affecting the range of vegetation boundary conditions possible for reclamation of the post-mining areas. The site reclamation planning is affected not only by the potential change in the type of vegetation that can be used for planting, but also by the need of potential rescheduling of reclamation work resulting from a change in the growing season. According to the forecasts, spring phenological development of plants will occur earlier. In a moderately optimistic scenario, forest trees are expected to leaf out about two weeks earlier, while in a pessimistic scenario, this could be up to approximately 40 days earlier than during the reference period. Additionally, the growing season will lengthen with rising temperatures, starting earlier in spring and ending later in autumn. The frequency of spring frosts is expected to remain similar to the reference period.

5. IDENTIFICATION OF CLIMATE CHANGE IMPACTS ON REHABILITATION SCHEMES AND ECOSYSTEM SERVICES

The objective of this task is to analyse the interplay between the climate change and the rehabilitation schemes for the post-mining areas. It is widely known and accepted that the global climate is currently changing with an unprecedented speed (IPCC, 2014; Kundzewicz *et.al.* 2017; Pecl *et.al*, 2017; USGCRP, 2018; Climate Change., 2019; IPCC, 2019). The climate models project the increasing temperatures and changes in the precipitation regimes which will alter the frequency, magnitude and geographic distribution of the climate-related hazards, like flood, drought and heat waves (Janson *et. al.* 2020), in both "climate" and "weather" aspects. As the global climate changes, human well-being and ecosystem functions are increasingly impacted by the shifting geography of life. The climate-driven changes in species distributions, or "range shifts," affect human wellbeing both directly (for example, through emerging diseases and changes in food supply) and indirectly, by degrading the ecosystem health. Some range shifts even create feedback (positive or negative) on the climate system, altering the pace of the climate change (Pecl *et.al*, 2017).

The repercussions of the climate change are evident in the accelerating rise of the global sea levels, shifts in the various climate extremes, and alterations in the global water cycle. In northern and northwestern Europe, precipitation levels have generally increased, while southern Europe has experienced a decline. Additionally, Europe has witnessed a reduction in the snow cover, and the extent and volume of the Arctic Sea ice have diminished at a pace exceeding earlier projections

The observed climate change has already manifested diverse impacts on the environmental systems, economic sectors, and human health and well-being across Europe. The nature of these effects varies across the continent, influenced by the climatic, geographical, and socio-economic factors. Figure 62 provides an overview of the key observed and projected impacts of the climate change on the main biogeographical regions in Europe.

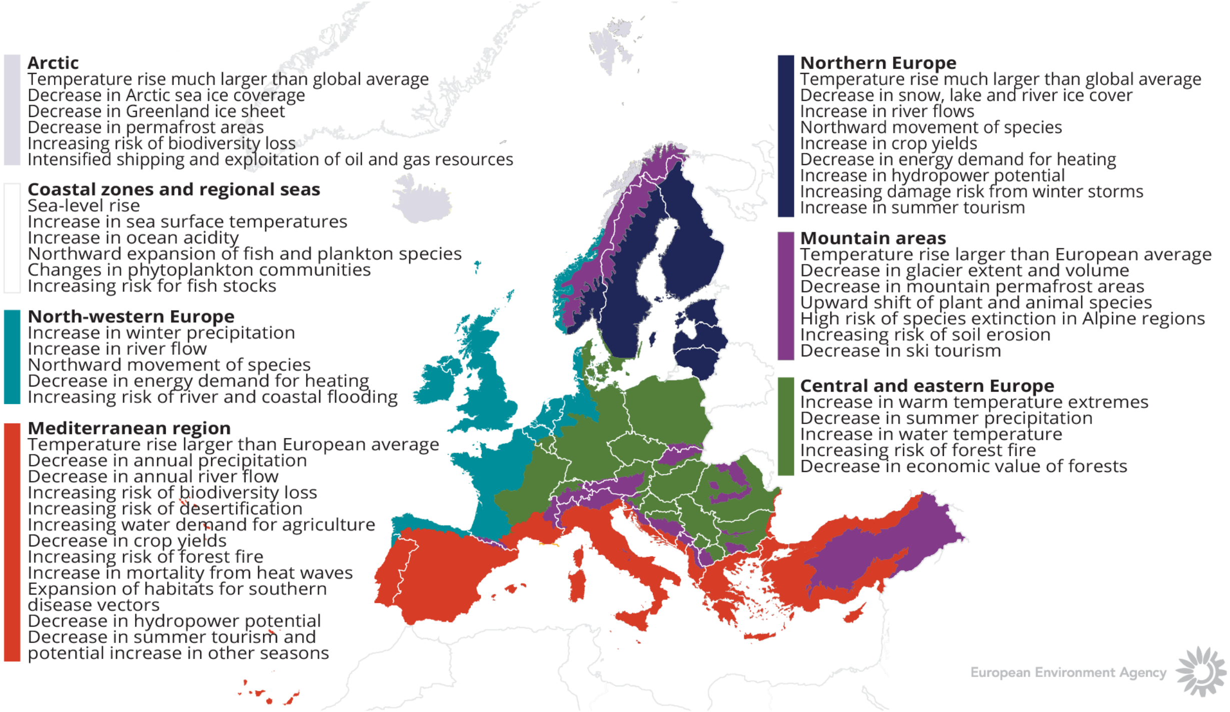

Figure 62. The key observed and projected impacts from climate change for the main regions in Europe
Source: EEA, 2012; https://www.eea.europa.eu/soer/2015/europe/climate-change-impacts-and-adaptation

The assessment of the vulnerability of the post-mining areas to the climate change and evaluating climate risks & impacts began with defining the climatic phenomena that could negatively affect the possibilities of rehabilitating the post-mining areas and returning them to the economic circulation.

5.1. Types of impact, including extreme events impacts

We use 'impacts' to mean the loses arising from the interaction of hazard, vulnerability and exposure (synonymous with consequences or outcomes), and 'risk' to mean the potential or unrealised losses, both as defined by the IPCC. Connection' incorporates and builds on the physical-hazard-based framework of 'compound' weather and the climate events. (Zscheischler *et.al*.2020).

The impacts of extreme events can be classified as direct and indirect. They both have an effect on reclamation opportunities. Direct impacts are identifiable through damage valuation (e.g., destruction of infrastructure, property, crops, etc.). Indirect effects, including the macroeconomic effects, concern the functioning of individuals and economic entities (e.g., effects of health (including psychological), reduction of employment and, consequently, of income, financial problems of the individuals and local governments and business entities, abandonment of economic activities, including the inability to implement reclamation activities, withholding of supplies, etc.

The extreme events are understood as instances of unusually severe weather or climate conditions that can cause destructive impacts on communities and agricultural and natural ecosystems. The term "weather" is used to describe what we experience on a short-term basis (e.g. daily, weekly or monthly) in terms of variables such as temperature, precipitation, humidity, wind and atmospheric pressure. The term "climate" corresponds to the weather conditions that prevail in a particular region throughout a particular period of time, typically 20-30 years. Weather-related extreme events are often short-lived and include heat waves, freezes, heavy downpours, tornadoes, tropical cyclones and floods. Climate-related extreme events either persist longer than weather events or emerge from the accumulation of weather or climate events that persist over a longer period of time. Examples include a drought resulting from long periods of below-normal precipitation or a wildfire outbreak when a prolonged dry, warm period follows an abnormally wet and productive growing season[31].

In this report, in accordance with the classification used by the Center for Research on the Epidemiology of Disasters (CRED)[32], meteorological (extreme thermal conditions, i.e. heat waves and cold waves, storms, hurricanes), hydrological (floods, landslides) and climatic (droughts, fires) phenomena were distinguished.

Due to an increasing level of knowledge about the extreme meteorological phenomena, we can observe the mechanisms of their formation and their consequences (Beniston, Stephenson, 2004). The observation of such phenomena becomes important, as they are usually associated with a potential threat to society and ecosystems. As it was identified by the CRED, storms and floods are the highest in number. This was followed by an increase in earthquakes and droughts, as shown in the Figure 63.

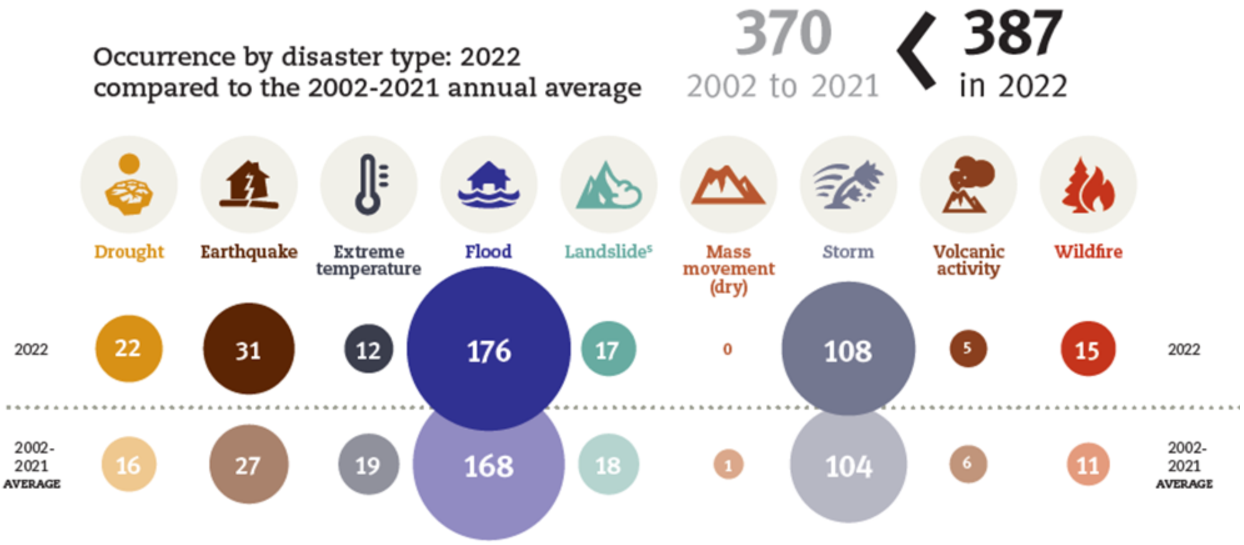

Figure 63. The occurrence of disasters in 2022, in comparison to the 2002-2021 annual average.
Source: The Emergency Event Database EM-DAT, 2022: Disasters in numbers: Climate in action; https://www.emdat.be/publications/

What's also important, the consequences of the extreme events vary from region to region. This is due to the different intensity and frequency of the phenomena (Figure 64), exposure to hazards and the vulnerability of areas, which consists of such as natural conditions, the level of wealth of societies and preventive measures taken. In a situation where a phenomenon occurs in an area with high vulnerability (e.g., in agricultural areas, densely populated areas), it can lead to much more severe consequences than when it occurs in an area where the potential for of loss of the occurrence is negligible.

[31] https://www.climatehubs.usda.gov/, accessed: 20.06.2022
[32] https://www.emdat.be/

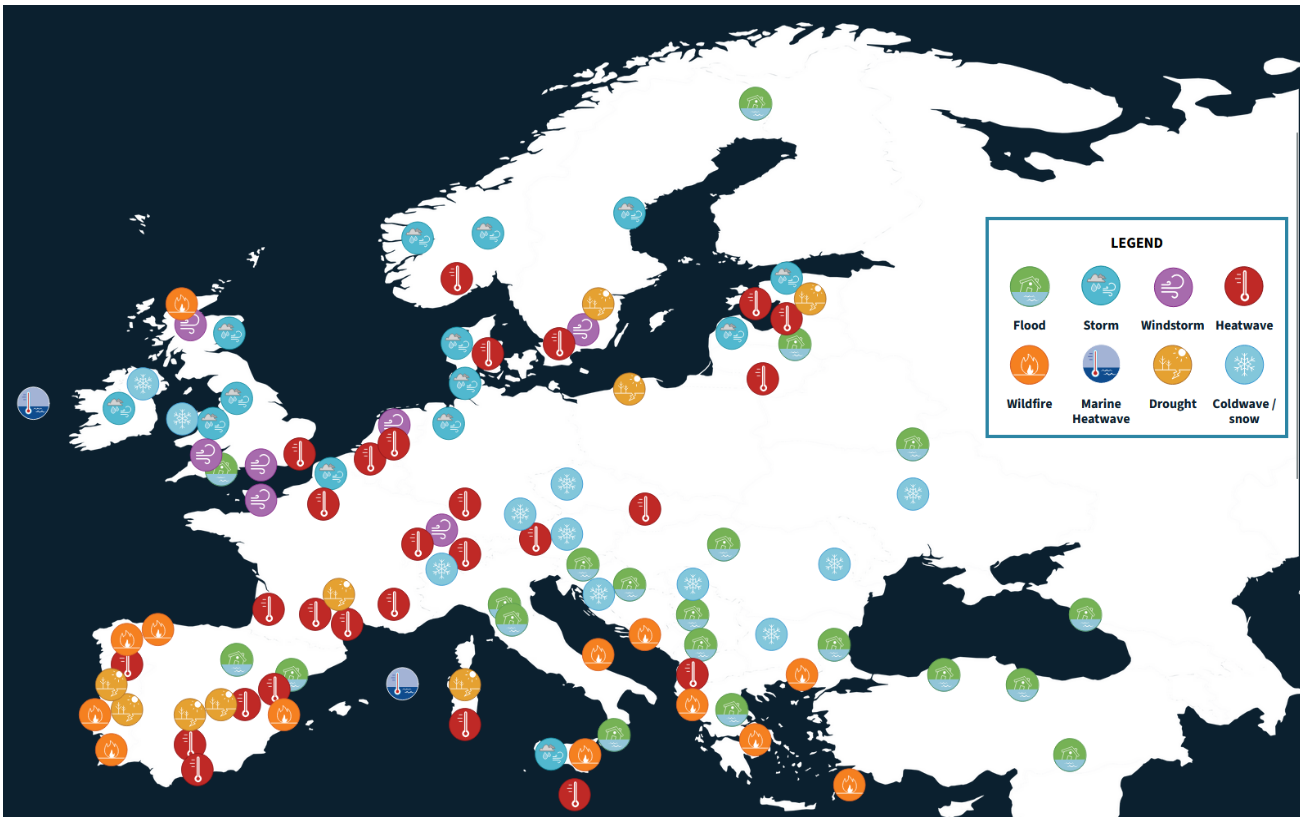

Figure 64. The European state of the climate – key events in 2023, reported in Copernicus base.
Source: https://climate.copernicus.eu/esotc/2023/key-events

The analysed phenomena are described in the figure below.

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Figure 65. A summary of the extreme phenomena potentially causing damage – relevant for the analysis of the directions of land reclamation.

Source: based on Siwiec et.al. 2022

The emerging extreme phenomena across most of Europe are permanently linked to the continent's climate - powerful storms, hurricanes or flooding have occurred in the past, causing severe damage. Therefore, also included are the results of the assessment of extreme weather events that have occurred in the past and forecasts of the likelihood of their occurrence in the future. For this purpose, the results of the TEXMIN project studies have been analysed, including the database of historical weather events that had affected the mining sector in each country represented in the TEXMIN project, which is available on project website: http://texmin.gig.eu/index.php/news/results.

5.2. ND GAIN Country Index

For the assessment of the susceptibility of individual sites, the logic of the regional approach - used in the ND-GAIN framework - was utilised, taking into account the overall susceptibility of the region affects aspects of the area's susceptibility, while it is modified by the specifics of post-mining areas and the directions and conditions of reclamation.

To assess the possibility of the region adaptation, we have based our works on the existing Notre Dame Global Adaptation Initiative (ND-GAIN) Country Index[33], which summarises a country's vulnerability to the climate change and other global challenges in combination with its readiness to improve resilience.

The ND-GAIN Country Index is composed of two key dimensions of adaptation: vulnerability and readiness to successfully implement adaptation solutions. **Vulnerability** measures a country's (i) exposure, (ii) sensitivity and (iii) capacity to adapt to the negative effects of the climate change, by considering the six life-supporting sectors: food, water, health, ecosystem service, human habitat, and infrastructure:

- Exposure is understood as a degree to which a system is exposed to significant climate change from a biophysical perspective. It is a component of vulnerability independent of socio-economic context[34].
- Sensitivity is understood as an extent to which a country is dependent upon a sector negatively affected by climate hazard, or the proportion of the population particularly susceptible to a climate change hazard. A country's sensitivity can vary over time.
- Adaptive capacity is understood as the availability of social resources for sector-specific adaptation. In some cases, these capacities reflect sustainable adaptation solutions. In other cases, they reflect capacities to put newer, more sustainable adaptations into place, therefore adaptive capacity also varies over time[35].

Readiness is measured by the ND-GAIN by considering three components:

- Economic readiness, which captures the ability of a country's business environment to accept investment that could be applied to adaptation that reduces vulnerability (reduces sensitivity and improves adaptive capacity);
- Governance readiness, which captures the institutional factors that enhance application of investment for adaptation;
- Social readiness, which captures the factors such as social inequality, ICT infrastructure, education and innovation that enhance the mobility of investment and promote adaptation actions.

The ND-GAIN Country Index measures climate vulnerability and adaptation readiness based upon compiled indicators, which in details are described on https://gain.nd.edu/our-work/country-index/methodology/indicators/

Based on these indicators, for example, researchers at Notre Dame have calculated that people living in the least developed countries have 10 times more chance of being affected by a climate disaster than those in wealthy countries each year. In Figure 66, the comparative resilience of the REECOL countries is presented on the ND-GAIN matrix.

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[33] https://gain.nd.edu

[34] Exposure indicators are projected impacts for the coming decades and are therefore invariant overtime in ND-GAIN.

[35] Source: https://gain.nd.edu/our-work/country-index/methodology/

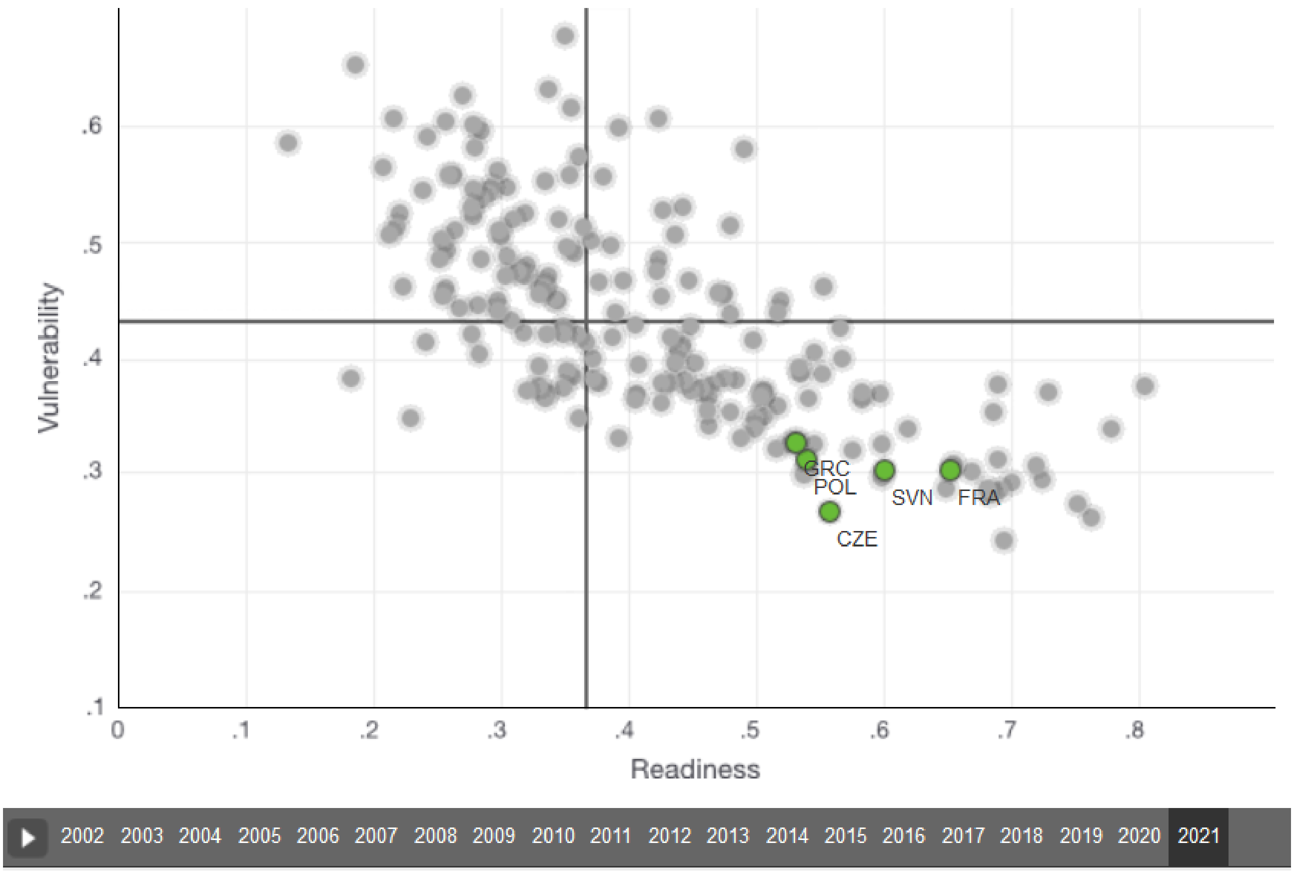


Figure 66. The comparative resilience of countries in 2021.
Source: ND-GAIN matrix, https://gain.nd.edu/our-work/country-index/matrix/

It may be noted that all regions involved in the REECOL project are located in lower right quadrant, which comprises of the countries showing low level of vulnerability to climate change and high level of readiness, therefore are well positioned to adapt. Though less vulnerable than the countries in the upper quadrant, these countries still face some adaptation challenges.

It can also be noted, that for all the indicated countries, the readiness level has improved for all countries over the past 20 years, whereas their vulnerability levels have stayed almost the same, as shown in Figure 67.

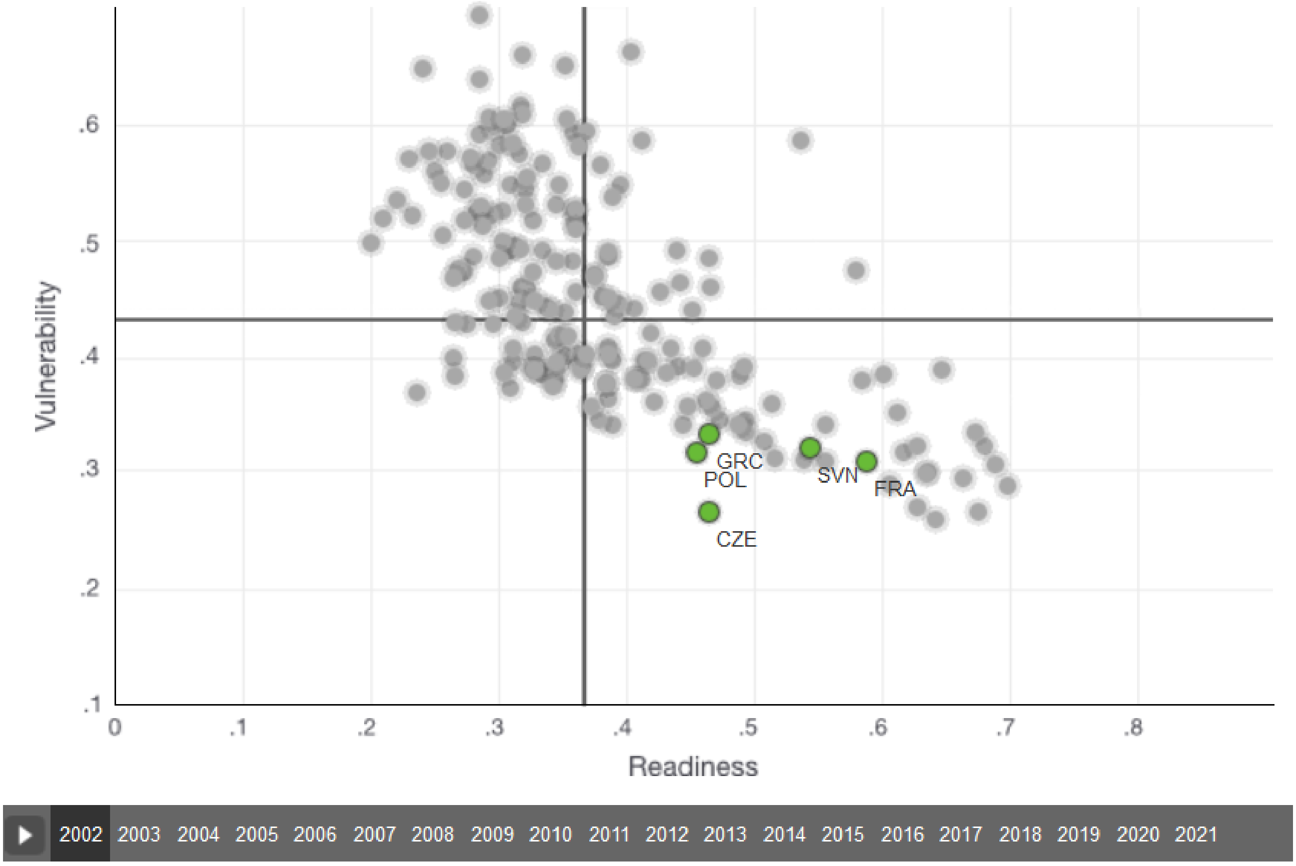


Figure 67. The comparative resilience of countries in 2002.

Source: ND-GAIN matrix, https://gain.nd.edu/our-work/country-index/matrix/

A higher level of adaptation readiness indicates that a country is better prepared to anticipate, cope with, and recover from the climate-related stresses. The level of readiness directly influences also the possibility of post-mining sites rehabilitation. A higher adaptation readiness is directly based on stronger institutional frameworks, more effective governance, and better access to financial and technical resources – factors, which contribute to the successful implementation of the rehabilitation schemes and projects. For instance, effective governance ensures that the environmental regulations are enforced and that there is accountability in the management of reclamation efforts. The financial resources allow for the necessary investments in soil remediation, reforestation, and the restoration of local ecosystems, while the technical resources provide the expertise needed to implement advanced reclamation techniques.

From the analysed reclamation schemes (indicated and described in the ***Task 3.2 report***), the development of the residential areas is most dependent on high scores in the ND-GAIN adaptation readiness. This is because transforming post-mining sites into residential areas requires a comprehensive approach that addresses numerous environmental, social, and infrastructural challenges. Residential reclamation involves creating safe, habitable environments where people can live. This requires an extensive soil remediation to eliminate the contaminants, ensuring that the land is safe for housing development. A high adaptation readiness, as measured by the ND-GAIN, indicates that a country has the necessary institutional and technical capacity to undertake such complex remediation tasks. Moreover, the residential development necessitates the construction of an infrastructure such as roads, water supply systems, sewage treatment facilities and electricity grids. Countries with high adaptation readiness are better equipped to plan, finance and implement these large-scale infrastructure projects effectively.

Furthermore, residential areas require an ongoing management and maintenance, which depends on effective governance and reliable public services. A high ND-GAIN adaptation readiness scores reflect the presence of stable institutions and efficient public administration, which are crucial for ensuring that the residential areas remain safe and well-maintained over time. Additionally, social factors play a significant role in the residential reclamation.

Countries with a high adaptation readiness are more likely to engage local communities in the planning process, ensuring that the new residential developments meet the needs and the preferences of future residents.

5.3. REECOL impact matrix tool

The set of information obtained from the analyses of the historical data and the climate scenarios about the area-specific climatic phenomena only makes it possible to identify the main threats posed by climate change to the possibility of land reclamation, their future use, as well as the living and health conditions of residents and the proper functioning of ecosystems and infrastructure.

Therefore, the analyses conducted must take into account site-specific conditions - which can then support the decision-making process.

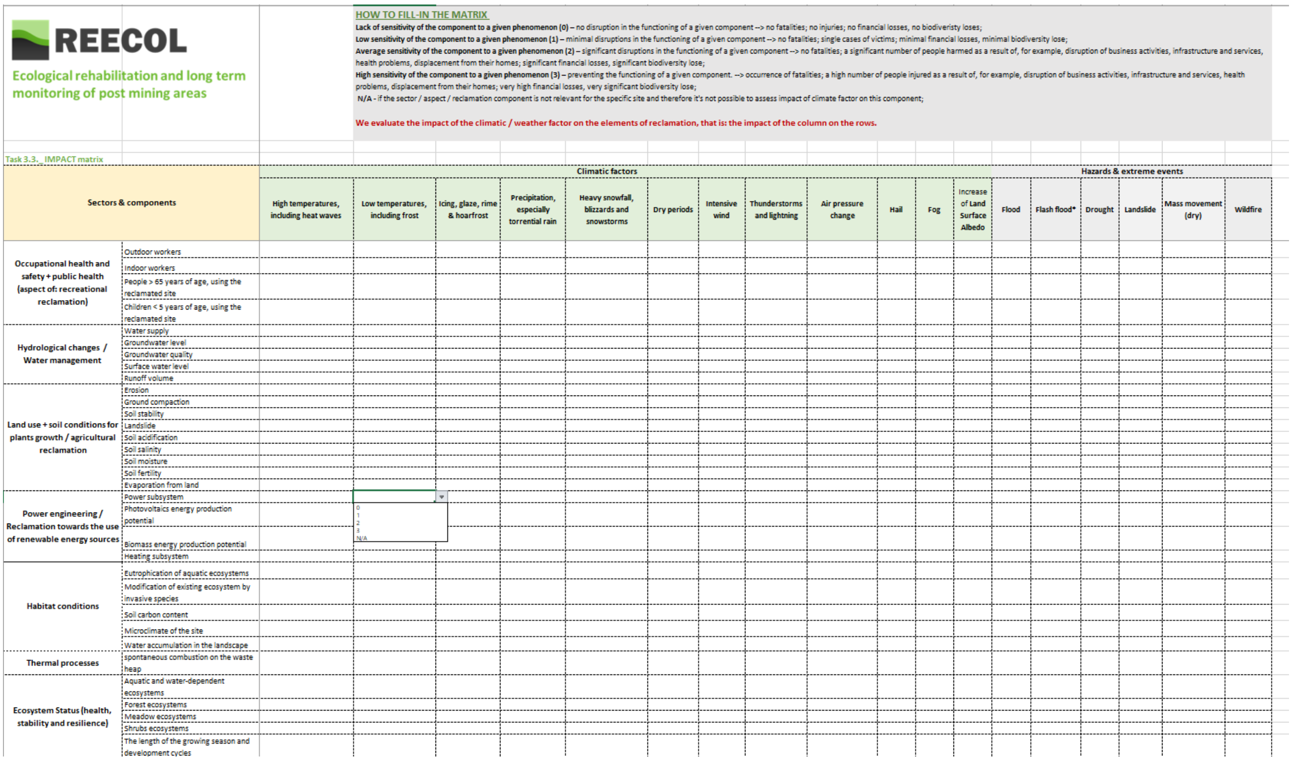
Accordingly, within this task, an impact matrix tool was developed as a part of the REECOL project, facilitating the assessment of the impact of a given climatic and meteorological factor and their derivatives on a given aspect/component relevant to the remediation process.

The logic of the matrix is to evaluate the impact of the climatic / weather factor on the sectors & components relevant for the reclamation.

The sensitivity assessment in the matrix can be descriptive or made using a scale. For greater comparability across the regions, it was decided to adopt a sensitivity scale:

- **Lack of sensitivity of the component to a given phenomenon (0)** – no disruption in the functioning of a given component. For example (depending on the component): no fatalities; no injuries; no financial loses, no biodiversity loss;
- **Low sensitivity of the component to a given phenomenon (1)** – minimal disruptions in the functioning of a given component. For example (depending on the component): no fatalities; single cases of victims; minimal financial loses, minimal biodiversity loss;
- **Average sensitivity of the component to a given phenomenon (2)** – significant disruptions in the functioning of a given component. For example (depending on the component): no fatalities; but a significant number of people harmed as a result of, disruption of business activities, infrastructure and services, health problems, displacement from their homes; significant financial loses; significant biodiversity loss;
- **High sensitivity of the component to a given phenomenon (3)** – preventing the functioning of a given component. For example (depending on the component): occurrence of fatalities; a high number of people injured as a result of, disruption of business activities, infrastructure and services, health problems, displacement from their homes; very high financial loses, very significant biodiversity loss;

In addition, to ensure that the tool can be applied to a broad spectrum of sites and reclamation directions, if the sector / aspect / reclamation component is not relevant for the specific site and therefore it's not possible to assess impact of climate factor on this component – the option N/A was implemented (Figure 68).



REECOL
Ecological rehabilitation and long term monitoring of post mining areas

HOW TO FILL-IN THE MATRIX
Lack of sensitivity of the component to a given phenomenon (0) – no disruption in the functioning of a given component --> no fatalities; no injuries; no financial losses, no biodiveristy loses;
Low sensitivity of the component to a given phenomenon (1) – minimal disruptions in the functioning of a given component --> no fatalities; single cases of victims; minimal financial losses, minimal biodiversity lose;
Average sensitivity of the component to a given phenomenon (2) – significant disruptions in the functioning of a given component --> no fatalities; a significant number of people harmed as a result of, for example, disruption of business activities, infrastructure and services, health problems, displacement from their homes; significant financial losses, significant biodiversity lose;
High sensitivity of the component to a given phenomenon (3) – preventing the functioning of a given component. --> occurrence of fatalities; a high number of people injured as a result of, for example, disruption of business activities, infrastructure and services, health problems, displacement from their homes; very high financial losses, very significant biodiversity lose;
N/A - if the sector / aspect / reclamation component is not relevant for the specific site and therefore it's not possible to assess impact of climate factor on this component;

We evaluate the impact of the climatic / weather factor on the elements of reclamation, that is: the impact of the column on the rows.

Task 3.3._IMPACT matrix

Sectors & components		Climatic factors												Hazards & extreme events					
		High temperatures, including heat waves	Low temperatures, including frost	Icing, glaze, rime & hoarfrost	Precipitation, especially torrential rain	Heavy snowfall, blizzards and snowstorms	Dry periods	Intensive wind	Thunderstorms and lightning	Air pressure change	Hail	Fog	Increase of Land Surface Albedo	Flood	Flash flood*	Drought	Landslide	Mass movement (dry)	Wildfire
Occupational health and safety + public health (aspect of: recreational reclamation)	Outdoor workers																		
	Indoor workers																		
	People > 65 years of age, using the reclamated site																		
	Children < 5 years of age, using the reclamated site																		
Hydrological changes / Water management	Water supply																		
	Groundwater level																		
	Groundwater quality																		
	Surface water level																		
	Runoff volume																		
Land use + soil conditions for plants growth / agricultural reclamation	Erosion																		
	Ground compaction																		
	Soil stability																		
	Landslide																		
	Soil acidification																		
	Soil salinity																		
	Soil moisture																		
	Soil fertility																		
	Evaporation from land																		
Power engineering / Reclamation towards the use of renewable energy sources	Power subsystem																		
	Photovoltaics energy production potential																		
	Biomass energy production potential																		
	Heating subsystem																		
Habitat conditions	Eutrophication of aquatic ecosystems																		
	Modification of existing ecosystem by invasive species																		
	Soil carbon content																		
	Microclimate of the site																		
	Water accumulation in the landscape																		
Thermal processes	spontaneous combustion on the waste heap																		
Ecosystem Status (health, stability and resilience)	Aquatic and water-dependent ecosystems																		
	Forest ecosystems																		
	Meadow ecosystems																		
	Shrubs ecosystems																		
	The length of the growing season and development cycles																		

Figure 68. The overview of the impact matrix tool

Source: own elaboration

The content of the impact matrix tool was developed and agreed upon by experts from each partner institution to include those components of reclamation directions that are potentially most relevant to most field sites. Following aspects have been taken into consideration:

- Hydrological changes & water management - important for all rehabilitation schemes,
- Soil conditions for plant growth and land use - important mostly for agricultural reclamation, forest reclamation and natural succession,
- Habitat conditions - important mostly for agricultural reclamation, forest reclamation and natural succession,
- Ecosystem Status (health, stability and resilience) - important mostly for agricultural reclamation, forest reclamation, natural succession and water reclamation,
- Power engineering – reclamation towards the use of renewable energy sources,
- Thermal processes on the site, e.g. spontaneous combustion on the waste heap (important for most rehabilitation schemes),
- Cultural heritage – important mostly for cultural & recreational rehabilitation schemes, as well as residential areas.

The agreed-upon tool is an appendix to this report (**Annex 2**) and will be made available on the project website as an aid to decision-making on the direction of reclamation in terms of considering climate change impacts.

The developed impact matrix has been tested by partners from each region, allowing confirmation that depending on the region and site characteristics, the strength of influence of each factor varies. For example, in Poland generally higher sensitivity across more factors have been observed, indicating a broader perceived impact of climatic changes on various sectors and components of reclamation, whereas Czech Republic tends to assign medium to low sensitivity ratings, indicating a lesser perceived impact compared. At the same time, Greece shows more targeted sensitivity, with high sensitivity concentrated on specific climatic factors such as high temperatures, dry periods, and wildfires. Aside of diversity of specific local conditions, differentiation of sensitivity evaluation may be caused by disparities in national policies and regional focus areas on environmental and climatic impacts, as well as differences in infrastructure resilience, adaptation measures and prioritisation of different aspects of planned reclamation schemes, which justifies the use of this tool for assessing the direction of reclamation for a site case by case.

5.4. Impacts on occupational safety and health issues

The climate change poses significant risks to safety and health of the workers involved in the reclamation of the post-mining areas and also potentially of people using the rehabilitated areas. The most important factors are an increasing temperature, ultraviolet (UV) radiation, pathogen exposure, air pollution and extreme weather events. These changes can exacerbate existing hazards or introduce new ones, leading to heat-related disorders, diseases, accidents, allergies, and cancer, ultimately raising health costs, reducing quality of life, and causing production losses. In addition, factors such as age, pre-existing health conditions, socio-economic status, and geographical location influence the severity of these risks.

Increased temperatures and heat waves can be listed as the most important threats, which can affect both indoor and outdoor workers. The extreme heat can impair concentration, cause dehydration, exhaustion and worsen cardiovascular, respiratory, and kidney conditions, potentially leading to a heatstroke or a syncope. Intense physical work further increases body heat, impairing judgment and increasing accident risks. The reclaimed post-mining areas, often devoid of natural vegetation, can experience faster heating and higher temperatures due to the heat-absorbing properties of the exposed soil and rocks and creating localised high-temperature zones. The extended periods of high temperatures during heat waves exacerbate heat stress, affecting workers' ability to cool down, even during breaks and preventing adequate recovery between shifts, especially in poorly cooled living conditions.

In addition, the UV radiation exposure also increases the risk of sunburn and skin cancer, with outdoor workers more affected than their indoor counterparts.

More intensive periods of rain (especially torrential rain significantly exceeding average rainfall values) also considerably impact the health of people working on the post-mining area rehabilitation, although these impacts may vary depending on the region and its baseline characteristics. For example, in Poland and Czech Republic, heavy rainfall can lead to an increased soil erosion and landslides in the post-mining areas. This poses a direct risk to the workers who may be caught in sudden ground movements or falling debris. The waterlogged soil can also become unstable, making it challenging to operate heavy machinery and increasing the likelihood of accidents. Additionally, a prolonged exposure to damp conditions can lead to respiratory issues. In situation of prolonged period of rainy weather, the increased humidity can exacerbate these health problems, making it difficult for workers to maintain their productivity and well-being.

Also in Greece, intensive rain periods can transform dry, post-mining landscapes into hazardous working environments. The sudden influx of water can cause flooding in the mining pits and low-lying areas, creating drowning risks and hindering movement and access. Flooded areas can also become the breeding grounds for mosquitoes, increasing the risk of vector-borne diseases. Workers in these conditions may also face challenges related to the deterioration of physical infrastructure, such as washed-out roads and weakened structural supports, which can lead to accidents and injuries. In situation of prolonged period of rainy weather, the humid and wet conditions can also promote the growth of mould and fungi, posing additional respiratory health risks.

In Slovenia and France, heavy rains can similarly destabilise the reclaimed mining areas. The increased water saturation in the soil can lead to subsidence and sinkholes, creating dangerous working conditions. The presence of water can also lead to the leaching of hazardous substances from the soil, potentially exposing workers to toxic chemicals. This chemical exposure can cause a range of health issues, from skin irritations to more severe conditions like chemical burns or poisoning. Furthermore, working in wet and muddy conditions can increase the physical strain on the workers, leading to musculoskeletal problems and increasing the risk of slipping, tripping or falling.

Despite some minor differences due to landscape and baseline climatic conditions in different regions, the combination of physical strain, unstable ground conditions and potential exposure to hazardous substances makes working in a post-mining area reclamation during periods of intensive rain particularly challenging and hazardous to workers' health (Figure 69).

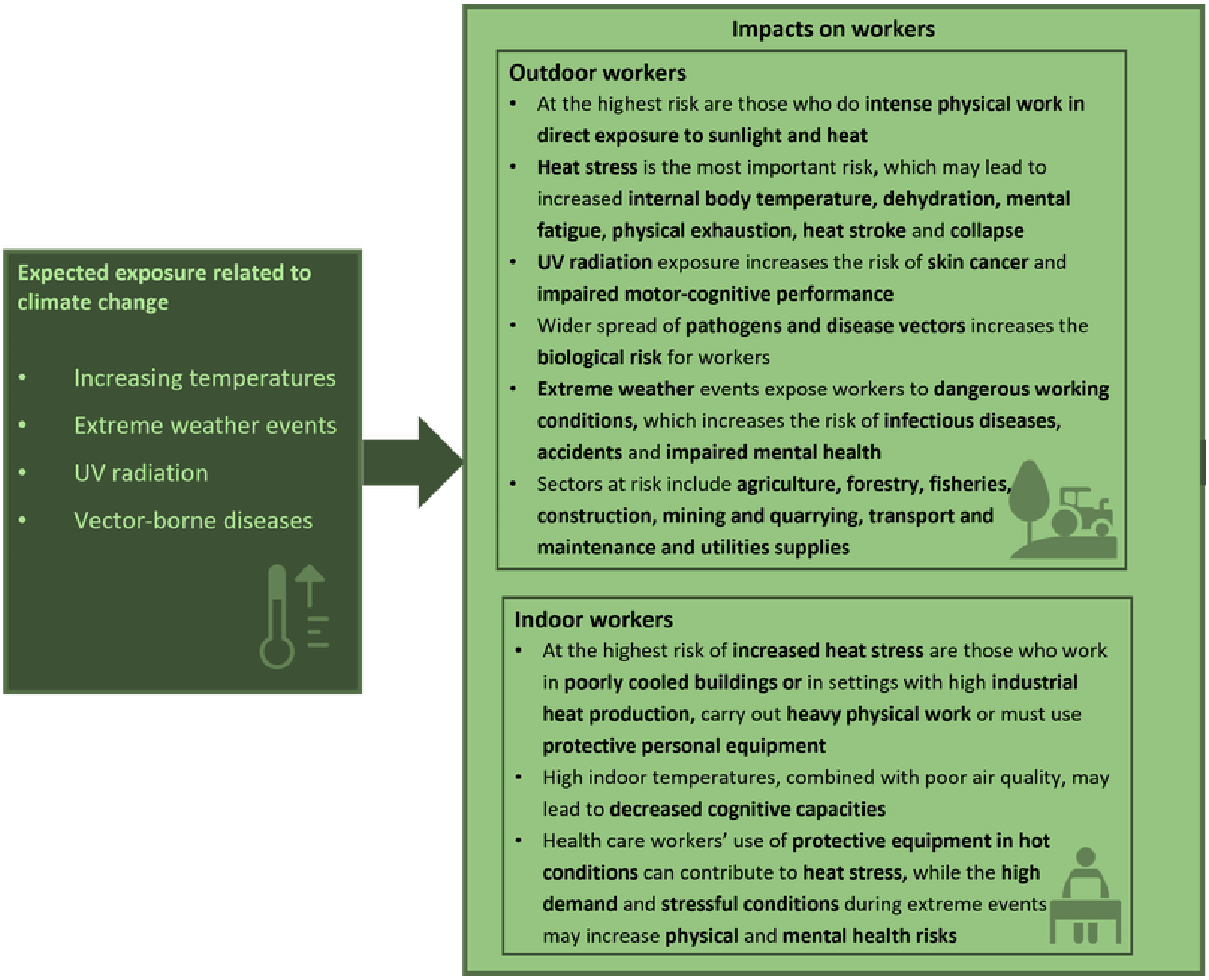


Figure 69. An overview of several major climate change related risks for occupational health and safety

Source: European Climate and Health Observatory, https://climate-adapt.eea.europa.eu/en/observatory/evidence/health-effects/occupational-health-safety

Therefore, protective measures need to be undertaken.

Concerning the threat connected with rising temperature and heatwaves, the first example of a solution might be providing ample hydration stations and cooling areas for regular breaks to reduce heat stress. Adjusting the working hours to avoid peak heat and the UV radiation exposure, increasing breaks, and implementing night shifts where feasible may also be necessary, although this could reduce concentration and increase injury risks, which also need to be taken into consideration. Erecting additional temporary shelters and shaded areas to provide relief from direct sunlight may also be necessary. Next aspect, which need to be taken into consideration is protective gear and training. In terms of workwear selection, it is necessary to pay attention to using lightweight, breathable clothing and UV protection gear. Also educating the workers on recognising heat-related symptoms and implementing emergency response protocols is crucial.

Concerning the threat of intensive precipitation events and potential flooding, effective risk management strategies, including improved drainage systems, protective equipment, and health monitoring, are essential to mitigate these risks and protect workers in these environments.

5.5. Impact on rehabilitation schemes

The knowledge of the interaction between climatic factors including unusually severe weather on environmental systems, economic sectors and human health and well-being is the foundation for effective planning and carrying out the rehabilitation of the post-mining areas. Rehabilitation activities should respond to the consequences of the projected climate change and increase the resilience of post-mining areas to its effects. The aim of properly managed rehabilitation must therefore not only be to develop vegetation cover adapted to changing weather conditions, but also to introduce plant and animal communities that provide the greatest possible potential for providing the ecosystem services demanded by the climate change (e.g. regulation of the ecosystem processes, including climate regulation, air quality regulation, water regulation, erosion regulation, water purification and waste treatment, disease and pest regulation, pollination and natural hazard regulation). Based on a detailed analysis of how climate change implies to adapt the technical solutions (species selection) and what ecosystem services are expected, the following guidelines can be formulated:

- The planning of rehabilitation measures must take into account the climate change scenarios developed for the climate region in which the measures are carried out;
- It is recommended to use the tried and tested local models developed for the climate change scenarios and, where these are lacking, to use the models developed for wider geographical areas;
- The climate factors that are projected to change should be analysed in terms of their potential impact on local economic sectors, *and human health and wellbeing;*
- The impact on local ecosystem conditions must also be taken into consideration;
- The local ecosystem types that provide the greatest capacity for adapting the analysed site to climate change must be identified;
- In order to select the optimal scenarios for rehabilitation, it is necessary to carry out a cost-benefit analysis of the different land-use options, including the valuation of eco-system services (see the Recovery project);
- The post-mining land rehabilitation schemes must take into account the best available habitat conditions for the target plant and animal communities;
- The selection of species used must take into account their ability to adapt to climate change, while at the same time the aim must be to make the created ecosystems as similar as possible to those created in non-degraded, natural habitats (reference ecosystems).

Below, there is a shortly summarised information regarding how the climate change and especially the extreme weather events such as **intensive rainfall, heatwaves, frosts, intensive winds** and **long periods of droughts** can pose additional challenges to the reclamation efforts of the post-mining areas. The impacts have been summarised taking into consideration four main schemes of rehabilitation, e.g. **agricultural reclamation, forest reclamation, hydric (water) reclamation, natural succession (reclamation close to nature)** with additional options / reclamation schemes, including **recreational reclamation, with potential of Renewable Energy Production, industrial production** or **residential areas,** as chosen and described in the ***Task 3.2 report***.

The above mentioned schemes, taking into consideration future land use directions, are understood as follows[36]:

- **Agricultural reclamation** begins with the application and spreading of organic matter, followed by ploughing, dragging, skidding, sowing of preparatory crops, their ploughing, fertilizing, and then the cultivation of target crops or grassing. In the process of agricultural reclamation, fields, meadows, vineyards or orchards are established. Also, the option of apiculture (beekeeping) can be included, depending on location.
- The result of **forest reclamation** is the creation of new forests. Different types of habitats and geographically native trees are used for planting. This type of reclamation leads to the creation of a new ecological stability of soils and landscapes and leads to soil consolidation.
- **Hydric / hydraulic reclamation** mainly covers the flooding of excavated quarries, as well as the restoration of river ecosystems, modification and improvement of the water balance.
- **Natural succession:** The essence of reclamation close to nature is to leave the course of natural succession. Instead of the expensively created and maintained recreational forest or forest park, a "new wilderness" can then emerge. Nutrient-poor soils (typically landfills) often develop communities of rare plant and animal species that have been displaced from fertile, fertilised agricultural landscapes. Monitoring for the encroachment of invasive plants must be implemented for this rehabilitation procedure.
- **Industrial Production**. This scenario likely focuses on transforming the post-mining landscapes into zones suitable for industrial activities. **This** could involve the construction of factories or other facilities that contribute

[36] For details see report from Task 3.3

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to the economic revitalisation of the area while considering environmental constraints and the availability of local resources.

- **Residential Areas.** In this scenario, the post-mining areas are envisaged as potential sites for residential development. This involves converting previously industrial or undeveloped land into habitable spaces, ensuring that they meet the living standards and infrastructure needs typical of residential neighbourhoods.
- **Recreational reclamation, including green spaces with potential of Renewable Energy Production**. This scenario focuses on ecological restoration and renewable energy projects. It could include creating parks, conservation areas, or installations of renewable energy infrastructure like solar panels or wind turbines. This aligns with the global and regional sustainability goals, offering environmental and social benefits to the local communities

Agricultural Reclamation

- **Intensive rainfall** can lead to soil erosion, nutrient leaching, and waterlogging in reclaimed agricultural lands. These effects reduce soil fertility and hinder crop growth.
- **Heatwaves** can cause heat stress in plants, reduce crop yields, and increase the demand for irrigation. They can also exacerbate soil degradation by increasing evaporation rates.
- **Unexpected frosts** can damage or kill crops, especially those not adapted to cold conditions, what can lead to significant loses. Hence, it is necessary to select vegetation types depending on the boundary conditions in the area, as detailed in Task 3.2
- **Strong winds / hurricanes** can cause physical damage to crops, increase soil erosion, and spread pests and diseases.
- **Long periods without rain & droughts** severely reduce soil moisture and increase the risk of soil degradation and desertification.

Forestry Reclamation

- **Excessive rainfall** can cause soil erosion and landslides, destabilising young trees and washing away seedlings. It also affects the establishment of a stable forest ecosystem.
- **High temperatures & heatwaves** can lead to increased tree mortality, reduce growth rates, and increase the risk of forest fires, which can devastate newly reclaimed forests.
- **Frosts** can damage young trees and reduce their survival rates, making it harder to establish a stable forest cover.
- **Windstorms** can uproot trees and damage forest structures, which can be particularly detrimental to young, recently planted forests.
- **Droughts** can lead to tree mortality, reduce growth rates, and increase the susceptibility of forests to pests and diseases. They also heighten the risk of forest fires.

Hydric Reclamation

- **Heavy rainfall** can lead to surface runoff, causing sedimentation in water bodies and affecting water quality. It may also overwhelm the drainage systems, leading to flooding.
- **Elevated temperatures** can lead to higher evaporation rates, reducing water availability in reservoirs and wetlands. They also promote algal blooms, which degrade water quality.
- **Frosts** can affect aquatic ecosystems by altering water temperatures and causing ice formation, which can impact aquatic life and water quality.
- **Intensive winds** can lead to an increased sedimentation and turbidity in water bodies, impacting water quality and aquatic habitats
- **Prolonged droughts** reduce water levels in reservoirs, wetlands, and rivers, affecting water availability and quality. They can also lead to an increase in concentration of pollutants (eutrophication risk).

Recreational Reclamation -

- **Flooding** and erosion can damage recreational infrastructure, such as trails and picnic areas, and degrade the aesthetic and functional value of these areas.
- **Prolonged heat** can make recreational areas less attractive to visitors and increase maintenance costs due to heat damage to infrastructure.

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- **Frosts** can damage plants and landscaping in recreational areas and make paths and other facilities hazardous due to ice.
- **Intensive wind** can damage infrastructure, such as benches, shelters, and signs, and create hazardous conditions for visitors.
- **Droughts** can reduce the appeal of recreational areas by diminishing water features, such as lakes and streams, and by stressing vegetation, making the landscape less attractive.

5.6. Climate change and ecosystem services

The eco-system services are critical for the climate change adaptation and mitigation. These services are provided by various ecosystems, each contributing uniquely to the overall goal of addressing climate change. Below are the key ecosystem services and the ecosystems that provide the greatest potential in this regard:

Carbon sequestration and storage:

- **Forests and shrubs ecosystems** absorb CO_2 from the atmosphere and store carbon in biomass and soil. They are one of the most significant carbon sinks.
- **Wetlands ecosystems** store carbon in their plant biomass and soils, particularly in peatlands, which are among the most carbon-dense ecosystems.
- **Grasslands** ecosystems store carbon in their extensive root systems and soils.
- **Water ecosystems**, particularly, sequester and store in bottom sediments large amounts of carbon, often referred to as "blue carbon."

Water regulation and supply:

- **Forest and shrubs ecosystems regulate water flow, reduce the risk of floods, and ensure a continuous supply of fresh water.**
- **Wetlands:** Wetlands maintain water quality by filtering pollutants and provide groundwater recharge.

Biodiversity and habitat provision:

- **Wetland and Forest:** providing habitats for numerous species which maintain ecosystem resilience.

Soil health and erosion control:

- **Grasslands and Forests:** These ecosystems stabilize soils and prevent erosion through their root systems.
- **Agroforestry Systems:** Integrating trees with crops can improve soil health, reduce erosion, and enhance resilience to climate change.

Temperature control:

- **Water** and forest ecosystem reduce temperatures most effectively during heat waves.

A critical aspect of the sustainable rehabilitation of the post-mining area, for most of the indicated directions of rehabilitation, is selecting appropriate plant species for reclamation of the given area.

The ecosystems newly created on rehabilitated post-mining areas should consist of native species and relate to the natural systems. Native species are integral to maintaining the ecological balance and functionality of reclaimed ecosystems due to their established relationships within the local ecosystem. Native plants and animals have co-evolved, developing symbiotic relationships that are crucial for ecosystem health. For instance, native plants provide food and habitat for local wildlife, which in turn may aid in seed dispersal and pest control. This interconnectedness supports biodiversity, which is essential for ecosystem stability and resilience. According to Hobbs and Harris (2001), restoring native vegetation can help re-establish the ecological processes that are critical for ecosystem recovery and sustainability. Moreover, native species are generally better suited to the local environmental conditions, including soil type, temperature ranges, and precipitation patterns. This suitability reduces the need for additional resources such as water, fertilisers, and pesticides, which are often required to sustain non-native species. From a practical standpoint, native species tend to have established root systems and growth patterns that stabilise soil and prevent erosion more effectively than non-native species. This stabilisation is particularly important in reclamation projects, where soil erosion and degradation are common issues. The deep roots of many native plants

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improve soil structure and enhance its ability to retain water and nutrients, thereby facilitating the establishment of a healthy, self-sustaining ecosystem.

In addition, incorporating native species into reclamation projects also helps in preserving the genetic diversity of the region. Genetic diversity within plant species ensures that populations can adapt to changing environmental conditions, such as climate change. This adaptability is crucial for the long-term success of reclamation efforts, as it enhances the ecosystem's ability to cope with stressors and disturbances. As noted by Young *et al.* (2005), maintaining genetic diversity is fundamental to the resilience and adaptability of restored ecosystems.

In addition to the key aspect of selecting native plants as the base for reclamation activities, other aspects are also important, including following climate indicators:

- temperature tolerance,
- precipitation patterns,
- drought resistance,
- soil type and composition,
- elevation,
- frost and freeze events,
- sunlight requirements,
- wind exposure,
- invasive species risk,
- biotic interactions,
- carbon sequestration potential.

The key recovery ecosystems services on the post-mining areas can be a very important element of climate change adaptation and mitigation efforts. Effective reclamation strategies are crucial for harnessing the full potential of these ecosystems in combating climate change.

6. CONCLUSIONS AND RECOMMENDATIONS

Assessing the impact of climate change on the post-mining area reclamation schemes is crucial for ensuring the long-term success and sustainability of such projects. Essential steps to consider are as follows:

1. **Climate Change Risk Assessment:**
   - Conducting of a comprehensive assessment of current and future climate change risks in the region where reclamation activities are planned. Crucial indicators need to be considered, including aspects such as: changes in temperature, precipitation patterns, extreme weather events and other relevant climatic variables[37].
2. **Site-Specific Vulnerability Assessment:**
   - Evaluation of the vulnerability of the post-mining area where the reclamation is planned to climate change impacts. This includes analysing the susceptibility of reclaimed landscapes to erosion, flooding, and other weather-related events.
3. **Hydrological and Hydrogeological Analysis:**
   - Assessment of changes in water availability, hydrological patterns, and groundwater recharge due to climate change. Special consideration needs to be paid to potential alterations to surface water flow and groundwater dynamics and their impact on reclamation efforts.
4. **Ecosystem services Impact Assessment:**
   - Evaluation of the potential impact of climate change on local or regional demands for ecosystem services e.g. change of climate factors can affect agricultural productivity, leading to changes in food availability and prices ecosystem services such as pollination, oil fertility maintenance, and pest control are essential for agricultural production. Climate change may therefore result in an increased need for such ecosystem services.

[37] Proposed list of climate indicators on next page

5. **Habitat Impact Assessment:**
   - Evaluation of how the changes in the climatic factors will affect the conditions of rehabilitated habitats → e.g. changes in temperature, precipitation, and other climate variables may affect the vegetation growth patterns and result in failure of ecosystem rehabilitation objectives. (e.g. checking & evaluation of the survival rate of selected species against climatic data, such as days with frost, periods of drought, number of hot days).
6. **Adaptation Strategies:**
   - Identification and implementation of the adaptation strategies to enhance the resilience of the post-mining area reclamation scheme combining different solutions and measures.
   - Examples of adaptation strategies: (i) selecting plant species that are more resilient to climate change[38], (ii) when possible, using native plant species that are well-suited to the local soil conditions, (iii) including soil improvement techniques, (iv) implementing erosion control measures, (v) exploring alternative land use options, such as agroforestry, eco-tourism, or renewable energy projects, to diversify economic activities in the reclaimed areas, (vi) incorporating flexible design elements that can adapt to changing conditions.
7. **Engagement of Stakeholders:**
   - Involvement of the local communities, government agencies, environmental organisations, and other stakeholders in the decision-making process to enhance the social and economic aspects of reclamation, fosters local support, and ensures the long-term success of the post-mining area adaptation.
8. **Monitoring and Adaptive Management:**
   - Establishment of a comprehensive monitoring system to track the performance of reclamation efforts over time, with special focus on, developed ecosystem health and habitat conditions changes.
   - Implementation of an adaptive management approach that allows for adjustments to the reclamation scheme based on ongoing climate change impacts and new scientific knowledge.
9. **Regulatory Compliance:**
   - Ensuring that the chosen reclamation scheme complies with relevant environmental regulations and standards, considering both current requirements and potential changes due to emerging climate-related policies.
10. **Long-Term Planning:**
    - Development of a long-term plan that considers the potential evolution of climate change impacts over several decades.
    - Including provisions for periodic reviews and updates to the reclamation strategy based on new climate data and evolving scientific understanding.

[38] Depending on the site, specific examples – included in Task 3.2 reclamation schemes.

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ANNEX 1: LIST OF PROJECTS

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ANNEX 2. IMPACT MATRIX

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