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The role of hydrological factors in the die-back of the European spruce in the territory of the Southeast Carpathians

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ABSTRACT

Formulation of the problem. The article is dedicated to studying the processes of European spruce stand dieback, a phenomenon that is currently relevant not only in Ukraine but also in most European countries, including the Czech Republic, Slovakia, Germany, Austria, and Poland. The focus is on an in-depth investigation of the relationships between one of the abiotic components – the hydrological factor – and the locations where European spruce dieback occurs on the southeastern slopes of the Carpathians. Geographically, the research area is outlined by the boundaries of the first and one of the largest nature parks in Ukraine, the Carpathian National Nature Park (NNP).

Purpose. The aim of the study is to identify the relationships between the processes of European spruce dieback and dynamic and quasi-static (relatively constant) hydrological descriptors in the southeastern Carpathians.

Methods. The informational basis for the study includes the results of forest pathology research conducted by specialists of the Carpathian NNP in 2022, along with long-term hydrometeorological observation data from the Carpathian Flood Monitoring Station Network (Ukrainian Hydrometeorological Center of the State Emergency Service of Ukraine). The study also utilized various remote sensing, field, dendrochronological, laboratory, analytical, comparative, cartographic, mathematical, and instrumental methods.

Research results. The research established that zones of spruce stand dieback are linked to stream source systems, associated with "meanders" in river channels, and are localized near water springs, particularly those with unique chemical water composition. These features may serve as indirect indicators of connections with regional and local tectonic disturbances. The study found a significant relationship between the annual growth of European spruce trunks and the average annual water discharge of the Prut River ($r = 0.6$) and the annual precipitation in the area ($r = 0.68$). In areas where spruce dieback is active, a distinctive evaporation mist formation regime and soil moisture patterns were observed. Temporally, the timing of spruce dieback appears to be connected to abrupt changes in annual water discharge and precipitation levels, likely indicating the impact of "water stress" on the biotic resilience of Picea abies [L.] Karst.

Conclusions. The results of this research can contribute to local, regional, or global models for spatiotemporal forecasting of spruce stand dieback processes, not only in the Carpathian region but also in other areas where this issue is relevant. The conclusions and recommendations presented in the article are important for the development of the local tourism and recreation sector, for planning forestry management activities, and for scientific and educational purposes (including conducting scientific excursions and field practices for students in natural sciences, among others).

Keywords: *European spruce (Picea abies [L.] Karst), dead trees, southeastern Carpathians, hydrography, springs, climate change, evaporation, water balance, annual average streamflow.*

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Formulation of the problem. European spruce, Norway spruce, or common spruce (Picea abies [L.] Karst), is one of the most well-known and economically and ecologically significant tree species in the forest ecosystems of Eurasia. Its natural range extends from Siberia to Fennoscandia, through the Baltic countries to the mountain ranges of Central Europe. Within and on the periphery of its natural range, there are approximately 5.7-7.3 million hectares of pure spruce forests [13]. In the Ukrainian Carpathians, spruce (locally known as "smereka") stands cover an area of about 450-600 thousand hectares, according to various estimates, and grow mainly at altitudes from 700 to 1300 meters above sea level [1]. Until recently, the species Picea abies [L.] Karst was considered biotically stable and long-lived here [2]. However, since the 1990s, the decline of spruce forests has been observed in nearly all types of forest growth conditions, on slopes of all exposures, and in stands of various ages [2].

Some researchers predict that due to increased mortality risks, the species Picea abies [L.] Karst may become unhealthy and unprofitable, and as a result, its area in Central European forests may significantly decrease [11]. The issue raised in this article is important not only from an economic perspective but also for the proper functioning of protected areas, where forest degradation threatens the existence of valuable ecosystems. For instance, according to [3], within a single year (1961), large areas of spruce virgin forests in the upper reaches of the Prut River (about 900,000 m^3 of stands) turned into deadwood. Today, this area is part of Ukraine's first and one of the largest natural parks, the Carpathian National Nature Park (NNP), which covers a significant part of the southeastern Carpathians and is the spatial boundary (territory) of our research.

As of 2016, the area of spruce forest dieback in the Carpathian region exceeded 36,000 hectares [9]. In the 21st century, large-scale spruce dieback has been documented in northern Austria, parts of Germany, Poland, Slovakia, the Czech Republic [11], Slovenia [14], Switzerland [10], and other countries. Thus, across Europe, there is a growing shift in the range and composition of tree species in forests.

The effective development and implementation of strategies to prevent or slow down the dieback of European spruce, as well as to mitigate its negative consequences, require a deep, comprehensive, and thorough study of this issue. This is the subject of research across a number of scientific fields, particularly the natural sciences.

Analysis of publications by research topic. As early as the 1990s, numerous hypotheses and theories were formulated to explain the causes of spruce forest dieback. In their research, American scientists R. Peet and N. Christensen noted that difficulties in interpreting tree mortality in forests result from the complexity of natural mortality processes, which can be allogenic – caused by exogenous abiotic or biotic factors – or autogenic, due to tree aging and competitive dynamics [20].

Today, the primary factors contributing to the death of spruce trees are considered to be the mass cultivation of the species *Picea abies* [L.] Karst outside its natural range; the cultivation of pure spruce stands; a reduction in stand density due to forest management practices; the cultivation of spruce ecotypes with low biological resilience; and climate change. As noted by Yu. M. Debrynuk, tree damage from phytodiseases and pests is not the root cause of tree mortality – they merely infest weakened stands, acting as secondary factors [2].

Currently, the climate theory is the most popular. Its proponents come from various scientific schools in different countries. The theoretical foundations and practical results of studying the role of climate as a regulating factor for forest stand resilience are highlighted in a number of works: joint research by scientists from the Warsaw University of Life Sciences and the Swiss Federal Institute for Forest, Snow, and Landscape Research by B. Brzeziecki, F. Kienast, and O. Wildi [10]; research from the University of Copenhagen (Denmark) and Centurion University of Technology and Management (India) by A. James and A. Manohar; and studies by staff from the Slovenian Forestry Institute – J. Kermavnar, L. Kutnar, A. Pintar, and some others.

The close relationship between meteorology and climatology with hydrology (studying the water cycle, formation, precipitation, and distribution of atmospheric moisture on Earth's surface, as well as the evaporation of water from bodies of water, soil, and plants) allows many scientists to identify hydrological factors as key in studying the degradation processes of European spruce.

According to some researchers, spruce growth, unlike certain other species, is more closely tied to water availability [21]. In studies by J. Honkaniemi et al., conducted at the Finnish Natural Resources Institute, the role of water as a key factor in the biotic resilience of trees to climate change was emphasized [13]. Meanwhile, Canadian scientists R. Hember et al. argue that so-called "water stress" is the cause of mortality in certain tree species [12]. According to M.P. Kozlovskyi and V.O. Kramarets, for spruce, water stress may result from contrasting moisture levels in the upper (30-40 cm) soil layer, where its root system is concentrated [5].

Some scientists highlight the soil-hydrological factor (particularly excessive moisture) as one of the aspects contributing to tree weakening. An example of the connection between moisture and the condition of spruce in the territory of the Carpathian National Nature Park (NNP) is the Rudyak basin bog in the Vorokhta Nature Conservation Research Department on the left bank of the Prut River. It is covered with stunted spruce sparse forest, 1-4 meters tall, of site class V, with a crown closure of 0.1 or less [6]. Spruces that found themselves within the dammed lake, formed on the Meresny stream after a 2020 landslide, also died off.

Detailed research by scientists from the University of Natural Resources and Life Sciences, Vienna (Austria), led by S. Netherer, provides empirical evidence that under conditions of limited water resources, the resistance of spruce stands to bark beetle infestation decreases [19].

Experts from the National University of Texas, including K. Kukowski, found that an important component of the hydrological niche in the study of tree degradation processes is the separation of water sources, particularly in landscapes characterized by shallow soil over fractured bedrock, where root growth is significantly restricted [18]. This fact suggests a possible connection between spruce dieback and hydrological descriptors linked to geological structures – such as river networks and natural water sources.

In Ukraine, the study of the weakening biotic resistance of spruce stands is closely associated with specialists from the National Forestry University of Ukraine (P.Y. Slobodyan, 1999, 2003; V.O. Kramarets, G.T. Krynytskyi, 2009; Yu.M. Debryniuk, 2011; V.V. Lavnyi, 2019, et al.), the Ukrainian Research Institute of Mountain Forestry named after P.S. Pasternak (O.I. Golubchak, V.I. Parpan, et al., 2018, 2011), Vasyl Stefanyk Precarpathian National University (Yu.S. Shparyk, et al., 2014, 2016, 2020, 2021), and the Institute of Ecology of the Carpathians of the National Academy of Sciences of Ukraine (M.A. Holubets, 2005; M.P. Kozlovskyi, 2009, 2016), among others.

Specialists from the scientific department of the Carpathian NNP and its structural subdivisions – nature conservation research departments (NCRDs) – are conducting detailed studies on the problem of spruce forest dieback in the southeastern Carpathians.

Despite the significant volume of research conducted, the processes causing the death of certain tree species require further study.

Selection of previously unresolved parts of the general problem. Despite the significant amount of information and the results of various studies, the issue addressed in this article remains a matter of debate among many natural scientists. Currently, there is no unified perspective on the comprehensive causes of Europian spruce dieback, particularly regarding the role of abiotic factors. Hydrological factors, in particular, are often considered fragmentarily, indirectly and not fully. Therefore, the authors of this publication have identified the "water-tree" interaction system as a distinct block of influence on the biotic stability of Picea abies [L.] Karst and devoted it to detailed study and analysis.

The purpose of the study is to identify the relationships between the dieback processes of common spruce and dynamic as well as quasi-static (conditionally constant) hydrological descriptors in the southeastern Carpathians.

Materials and methods of research. An interdisciplinary approach was employed in this research, utilizing a range of methods from geology, geomorphology, hydrology, climatology, geobotany, and universal tools. The initial data for the study were derived from forest pathology research conducted by specialists of the Carpathian National Nature Park in 2022. The analysis of the distribution of Norway spruce dieback (SD) centers and their relationship with the hydrographic features of the area was performed using satellite images from Google Earth, as well as cartographic schemes from the nature conservation and research departments of the Carpathian NNP.

During comprehensive field research in the Carpathian NNP from 2018 to 2022 (monitoring surface waters, inventorying natural water springs, studying hazardous exogenous processes, etc.), several local dry areas within and outside the park were identified; this data was also utilized in the publication.

Additionally, a detailed study of soil and climatic conditions in the area of mass dieback of *Picea abies* [L.] Karst was conducted in the Yamnyansky district (Mykulychyn village, left bank of the Prut River). The condition of trees (forest health) was classified into three categories: Type 1 – healthy, Type 2 – showing signs of dieback, and Type 3 – deadwood. The equipment used included a portable device for measuring soil pH and moisture levels; a specialized wooden rod for snow depth measurement; and GPS coordinates of the points were recorded using a Garmin GPSmap 60Cx navigator.

To establish links between the activation of Norway spruce dieback and dynamic hydrometeorological indicators, long-term observational data from the Ukrainian Hydrometeorological Center's network (particularly in the section of the Prut River – Yaremche city) were used, and hydrological and phenological methods were applied.

The database and visualization of the research results were developed using Geographic Information Systems (GIS) and the Excel spreadsheet processor.

Thus, a variety of remote sensing, field, dendrochronological, laboratory, analytical, comparative, cartographic, mathematical, and instrumental research methods were employed in this study.

The main results of the study. The Carpathian National Nature Park is the first and one of the largest national parks in Ukraine, occupying a significant part of the southeastern Carpathians. Its area covers 504.95 km², stretching 55 km from north to south and 20 km from west to east. Hydrologically, it encompasses the headwaters of the Prut River basin, where the density of the river network ranges from 0.65 to 0.93 km/km².

In the course of the preliminary analysis of the spatial distribution of contemporary spruce dieback (SD) processes, particular attention was drawn to their correlation with specific local hydrographic conditions. (Fig. 1).

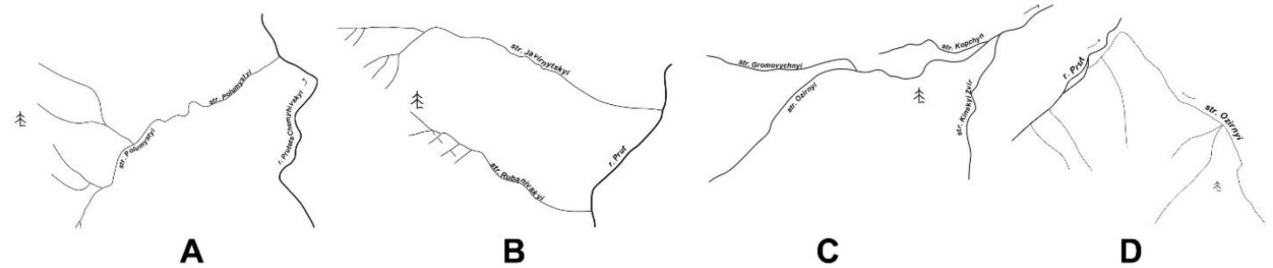


Fig. 1. The primary types of relationships between spruce dieback (SD) areas and the hydrographic network in the Carpathian National Nature Park are as follows: A) linear; B) linear-zonal; C) outer curvature; D) inner curvature

Thus, two main types of relationships were preliminarily identified: the first reflects the association of spruce dieback with the sources of watercourses, while the second pertains to changes in the configuration of river channels.

In the first case, spruce dieback is linked to the linear extension of specific points where groundwater emerges at the surface (Fig. 1.A) and within the zone of a broad linear structure formed by a system of streams, which are confined at the upper part from the points of emergence to the confluence with the main watercourse (Fig. 1.B).

Mathematically, the line to which spruce dieback (SD) is oriented can be described by the classical formula:

$$SD_{(x;y)} = \sqrt{q_{x2} - q_{x1})^2 + (q_{y2} - q_{y1})^2} \quad (1)$$

where q_{x1}, q_{x2}, q_{y1}, q_{y2} – represent the geographic coordinates of the corresponding extreme points – locations where groundwater emerges at the surface.

The conditionally predicted area of spruce dieback (SD) can be expressed as the area of an ellipse described around the line, where the semi-minor axis is defined as half of the semi-major axis (1/4 $SD_{(x;y)}$):

$$S_{(SD)} = SD_{(x;y)} \cdot \pi \cdot \frac{\sqrt{q_{x2} - q_{x1})^2 + (q_{y2} - q_{y1})^2}}{8} \quad (2)$$

In the second case, the areas of spruce dieback (SFD) are associated with the inner or outer bends of the river channel (Fig. 1.C, 1.D). Therefore, when creating a descriptive mathematical model, the river meandering coefficient (K_m) should be applied.

The systems of river sources and streams, to which spruce dieback is linked (see Fig. 1.A), are, by their nature, natural water sources. As early as 2009, some researchers asserted that dieback primarily occurs in stands located in micro-depressions with high groundwater levels [5], i.e., in areas where springs are potentially likely to emerge.

During local surveys conducted in 2021, it was discovered that near the village of Yablunytsia (Polianytsia territorial community, Nadvirna district, Ivano-Frankivsk region), a site of spruce dieback was identified on the right bank of the Pastievaty stream (a tributary of the Yablunytsia River, Prut River basin) (Fig. 2).

During a detailed survey of the areas above and below the spruce dieback site, the emergence of natural water sources was observed, with a chemical composition that somewhat differs from that of the stream water. Notably, the mineralization of the water at the spring is 1.4 times higher (Table 1).

It is worth noting that in the aforementioned case, near the dieback site of *Picea abies* [L.] Karst, a local change in the configuration of the river channel can also be observed, which can be detected through careful field inspection.

This is not an isolated instance. For example, near the "Babyna Yama" locality (Hoverla Research Natural Area), a significant number of springs are located close to areas of widespread spruce dieback [7, 15-17]. Some of these springs have a characteristic smell of hydrogen sulfide, indicating the presence of H_2S in the water of these springs.

A similar situation is observed near the village of Mykulychyn: in a rocky outcrop on the left bank of the Prut River, two springs were identified in winter 2023, which were not observed during the

August 2017 September 2020 November 2021

Fig. 2. The dynamics of forest cover in the territory of the Yablunytsia NCRD of the Carpathian NNP, based on satellite imagery from Google Earth (2017, 2020, 2021)

Table 1

Characteristics of the Pastievaty Stream and spring at the site of spruce dieback within the territory of the Carpathian National Nature Park (October 29, 2021)

Indicator / Sampling site	Water discharge (Q, ml/s)	Water temperature (t, °C)	pH	Water mineralization (M, mg/dm³)
Pasteivatyi Stream	400	3,8	7,9	77
Spring	5	7,1	8,0	106

summer period. Several springs with water, whose chemical composition differs from that of the river water, are noted on the left bank of the Meresnyi Stream (a right tributary of the Prut River), near a recent landslide (2020), where a deadwood area is also located.

The main elements of the water balance in the Carpathian region (temperature, precipitation, evaporation, runoff) are distributed extremely unevenly and can sometimes vary at the micro-level. There are numerous reasons for this, including both natural factors (forest cover, the type and characteristics of vegetation, hydrological, hydrogeological, and geomorphological conditions, including slope exposure, etc.) and human activities [8]. In this context, areas of Picea abies [L.] Karst dieback can be identified as distinct microstructures with properties and functions that differ from adjacent "healthy" forest areas.

Field research results indicate that the soil surface in spruce dieback areas heats up more compared to forested areas. The correlation coefficient between tree condition (I) and soil temperature (t_s) was found to be 0.96, indicating a very strong relationship (Table 2).

Thus, the soil surface in dieback areas receives more heat than under biotically stable units: $SR_1 > SR_2$, and consequently, the overall evaporation from the soil surface is higher here ($ES_1 > ES_2$). At the same time, a healthy spruce tree can retain up to several tons of water during rainfall (P_2), which is significantly more than on a dead tree (P_1): $P_2 > P_1$, and the interception (I – the capture or retention of atmospheric precipitation) is higher here ($I_2 > I_1$). According to the snow measurement conducted on February 10, 2023, it was found that the snow height (h_1) under dead spruces was 42% greater than that under living ones (h_2) and 10% less than on open ground. Therefore, the evaporation from the leaves of trees will be higher than in the areas with dieback ($ET_1 < ET_2$).

The aforementioned differences can be visually observed in the process of fog formation due to evaporation above dieback zones (Fig. 3). In one case, water vapor outlines the location of dieback (Fig. 3A), while in another, it forms directly above the manifestations of degradation processes (Fig. 3B).

Hydrometeorological conditions are dynamic indicators, and studying their relationship or impact on spruce dieback can serve as a basis for forecasting the activation of degradation processes over time.

There is insufficient data on the exact dates of the activation of dieback in the southeastern Carpathians. The first official mentions date back to the

Table 2

Correlation matrix of relationships among individual soil-climatic indicators in the zone of mass dieback of Picea abies [L.] Karst (village of Mykulychyn, Ivano-Frankivsk region, left bank of the Prut River, July 2018)

Indicators	Indicator of tree condition (I)	Soil temperature ($t_{s.}$), °C	Soil pH (hydrogen indicator)	Soil moisture (M), %	Soil illumination (L), con. units
Indicator of tree condition (I)*	1,00				
Soil temperature ($t_{s.}$), °C	0,96	1,00			
Soil pH (hydrogen indicator)	-0,64	-0,54	1,00		
Soil moisture (M), %	0,54	0,41	-0,81	1,00	
Soil illumination (L), con. units	0,54	0,48	-0,27	0,24	1,00

Note (correlation relationship assessment): r < 0 – inverse relationship; 0 ≤ r < 0.1 – no relationship; 0.1 ≤ r < 0.3 – weak relationship; 0.3 ≤ r < 0.5 – moderate relationship; 0.5 ≤ r < 0.7 – noticeable relationship; 0.7 ≤ r < 0.9 – strong relationship; 0.9 ≤ r < 0.99 – very strong relationship; 0.99 < r ≤ 1 – perfect relationship.

Fig. 3. The formation of discrete evaporation fogs above the dieback area of European spruce (village of Mykulychyn, Ivano-Frankivsk region, left bank of the Prut River)

mid- to late 20th century (1961). Some information regarding the onset of widespread deterioration of coniferous forests relates to the early 1980s and 1990s [4]. In recent decades, this indicator has been under closer scrutiny.

Therefore, for a retrospective analysis and the identification of patterns in the dieback of spruce forests over time, we conducted a series of analytical studies, which included a combination of dendrochronological and hydrometeorological approaches.

Wood samples for growth ring analysis were collected as a result of sanitary logging in the Vorokhtiansky Nature Conservation Research Department (left bank of the Prut River) in 2018. In the first stage, we examined the characteristics of the relationship between atmospheric precipitation (P) and river runoff (Q) with the annual growth of European spruce trunk radius (i).

It is interesting to note that the relationships between the annual trunk growth of the tree were more closely associated not with local hydrometeorological conditions (observational data from the settlement of Vorokhta) but with those in the control section in the city of Yaremche.

The analysis of the relationships between the annual growth of European spruce and the average annual water consumption of the Prut River, as well as the annual precipitation, allows for the preliminary identification of certain cyclic patterns: 1998-2000 showed a slight increase in annual rings; 2001-2006 marked a period of intensive growth; 2007-2011 experienced a decline in growth intensity; and 2012-2017 reflected a minor increase in annual rings (Fig. 4).

Thus, it can be hypothesized that the occurrence of spruce dieback (SDB) is linked to the cyclicity of hydrometeorological indicators. In the ini-

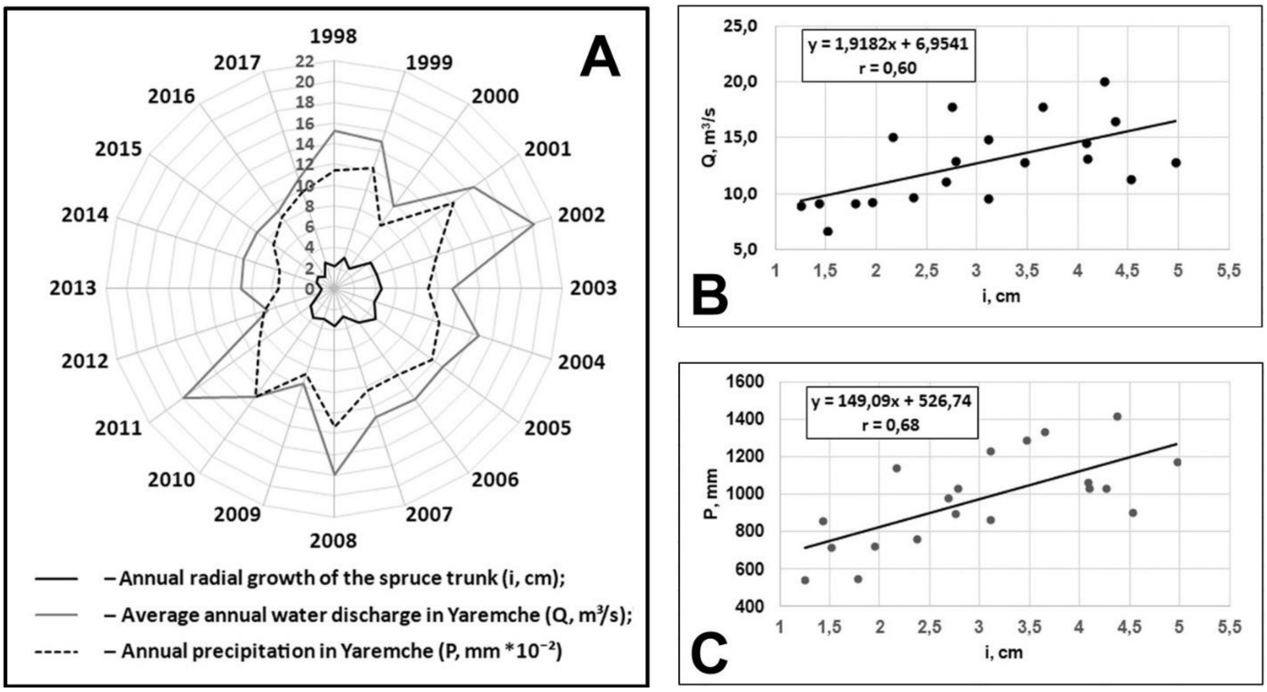


Fig. 4. The relationship between the annual trunk growth of *Picea abies [L.] Karst* with the average annual water consumption of the Prut River (A) and the annual precipitation (B) in the city of Yaremche

tial stages of analysis, this was fully confirmed.

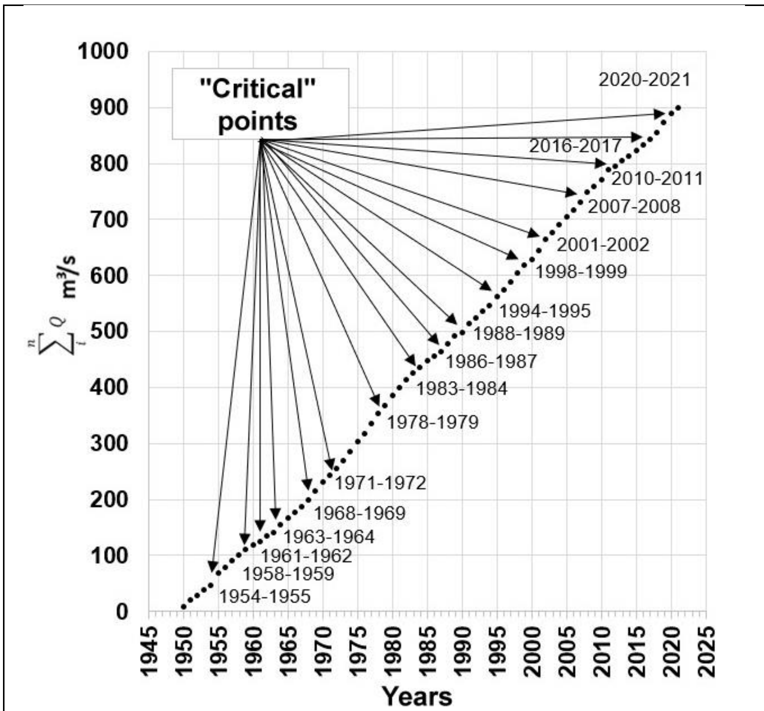
For instance, the spruce dieback observed in 1961 occurred during a period of low water flow when the average annual discharge of the Prut River in Yaremche was 5.62 m³/s (≈ 98% probability).

However, upon further analysis, these patterns were disrupted, necessitating the search for alternative approaches to address this issue. To this end, we applied the method of incremental data addition (in our case, average annual water discharge), which has proven highly effective in hydrological research and is expressed by the following formula:

$$\sum_i^n Q = f(T) \tag{3}$$

where T – represents the years, $\sum_i^n Q$ – denotes the cumulative sums of average annual river discharge values, measured in m³/s.

Theoretically, provided that the average annual



№	Period of activation of spruce dieback	
	Reliable	Forecasted
1		1954-1955
2		1958-1959
3	1961	1961-1962
4		1963-1964
5	1970	1968-1969
6		1971-1972
7		1978-1979
8		1983-1984
9		1986-1987
10		1988-1989
11	1994	1994-1995
12		1998-1999
13	2002	2001-2002
14	2007	2007-2008
15		2010-2011
16	2017	2016-2017
17		2020-2021

Fig. 5. The graph of cumulative annual water flow of the Prut River at Yaremche for the period from 1950 to 2021

climate and hydrometeorological indicators in each subsequent year were not markedly anomalous (i.e., there were no significant floods, hydrological or meteorological droughts, etc.), the series created by the cumulative addition of these indicators would resemble a straight line.

The graph constructed in this manner, as shown in Fig. 5, exhibits a "wavy" pattern.

The sharp deviation of values from the theoretical graph and the formation of "critical" points (or "breakpoints") likely characterize what is referred to as "water stress", which may influence the activation of tree dieback processes

Conclusions. The results of the comprehensive studies have established a correlation between the zones of dieback of *Picea abies* [L.] Karst and the system of stream sources, as well as the broader linear system formed by several watercourses, which is bounded at the upper part by the locations of groundwater discharge to the surface before merging into the main flow.

Often, areas of tree dieback are associated with the "bends" of the river channel, both on the outer and inner parts. The proximity to natural water springs, particularly those with unique chemical compositions, along with the aforementioned characteristics, may be indirect indicators of the geological features of the area.

In the locations of dead trees, a distinctive regime of evaporation and soil moisture has been noted. Over time, a connection has been found between the timing of tree dieback manifestations and sharp changes in average annual hydrometeorological indicators (particularly water discharge and precipitation), which likely reflects the influence of "water stress" on the biotic stability of spruce stands.

The identified relationships between the processes of European spruce dieback and relatively stable hydrological descriptors over many years, alongside dynamic indicators, suggest that effective forecasting of the dieback phenomena in *Picea abies* [L.] Karst should be conducted comprehensively, taking into account the factors of place and time.

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Роль гідрологічних чинників у всиханні ялини європейської на території південно-східних Карпат

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Стаття присвячена вивченню процесів всихання ялинових деревостанів, що сьогодні є актуальним не лише в Україні, а й більшості країн Європи, зокрема Чехії, Словаччині, Німеччині, Австрії та Польщі. Основний аспект зроблено на поглибленому вивченні взаємозв'язків гідрологічного чинника з місцями проявів всихання ялини європейської на південно-східних схилах Карпат. У просторовому відношенні територія досліджень оконтурена межами першого і одного із найбільших природних парків України – Карпатського національного природного парку (НПП). Інформаційною основою для роботи були результати лісопатологічних досліджень, проведені фахівцями Карпатського НПП у 2022 р. та багаторічні дані гідрометеорологічних спостережень на мережі Карпатської селестокової станції (Українського гідрометеорологічного центру ДСНС України). У роботі також було використано низку дистанційних, польових, дендрохронологічних, лабораторних, аналітичних, порівняльних, картографічних, математичних та інструментальних методів. За результатами комплексу проведених досліджень установлено приуроченість зон всихання ялинових деревостанів до системи витоків струмків, зв'язок із «вигинами» річкового русла та приуроченість до місць виходу водних джерел, зокрема з водою своєрідного хімічного складу. Це може бути непрямими ознаками зв'язку з регіональними і локальними тектонічними порушеннями. Під час проведення досліджень виявлено помітний зв'язок річного приросту стовбура ялини європейської із середньорічною витратою води р. Прут ($r = 0.6$) та річною кількістю опадів у даній місцевості ($r = 0.68$). У місцях активізації всихання ялинових деревостанів відзначено особливий режим формування туманів випаровування та вологості ґрунту. У часовому аспекті виявлено зв'язок строків прояву ВЯД із різкими змінами середньорічних витрат води та атмосферних опадів, що, ймовірно, характеризує реакцію так званого «водного стресу» на біотичну стійкість виду Picea abies [L.] Karst. Результати проведених досліджень можуть бути частиною місцевої, регіональної або глобальної моделі для просторово-часового прогнозування процесів всихання ялинових деревостанів, і не лише у Карпатському регіоні, а й скрізь, де ця проблема є актуальною. Отримані висновки та рекомендації у статті є важливими для розвитку місцевого туристично-рекреаційного комплексу, планування лісогосподарських заходів, для наукових та навчальних цілей (зокрема проведення наукових екскурсій, практик для студентів природничих спеціальностей тощо).

Ключові слова: *ялина європейська (Picea abies [L.] Karst), відмирання дерев, південно-східні Карпати, гідрографія, природні водні джерела, кліматичні зміни, випаровування, водний баланс, середньорічна витрата води.*

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