Earth-Science Reviews 235 (2022) 104243

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

The effects of large-scale forest disturbances on hydrology – An overview with special emphasis on karst aquifer systems

Urša Vilhar [a,*], Janez Kermavnar [a], Erika Kozamernik [a], Metka Petrič [b], Nataša Ravbar [b]

[a] Slovenian Forestry Institute, Večna pot 2, SI – 1000 Ljubljana, Slovenia
[b] Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia

ARTICLE INFO

Keywords:
Global synthesis
Natural disasters
Climate change
Evapotranspiration
Soil hydrology
Recharge

ABSTRACT

Large-scale forest disturbances (LSFD) are an essential component of forest ecosystem dynamics. The effects of rapid loss of forest cover and other changes in forest ecosystems are inextricably linked to hydrologic processes such as evapotranspiration, soil and recharge processes. Among all hydrogeological systems, karst aquifers are important because of their exceptionally rich and unique biodiversity, biomass, and groundwater resources. At the same time, they are characterized by specific hydrological processes that make them highly vulnerable to environmental changes. Therefore, this study paid special attention to the effects of LSFD on karst hydrology. Using the PRISMA checklist, a thorough literature review of studies published between 2001 and 2020 was compiled into a comprehensive matrix dataset. In addition, an initial assessment of the global and regional distribution of forests on carbonate rocks was made based on publicly available geodatabases of forests and karst aquifers. The compiled information provides the first global overview of hydrological processes affected by LSFD, and identifies important knowledge gaps and future research challenges. The matrix dataset contained 117 full-text articles with a total of 160 case studies. Most publications were from 2011 to 2017, with more than half of the studies at the plot level and more than one-third at the catchment level. Studies on the effects of fires and pest and diseases infestations predominated. However, no articles were found on the effects of ice storms on hydrology in general or on the effects of pest and disease infestations on hydrology in karst areas. Of the 45.6 M km^2 of forested land worldwide, 6.3 M km^2 or 13.9% of all forests are underlain by carbonate rocks. Carbonate rocks cover about 15% of the land surface, which means that 31.3% of the world's karst aquifers are covered by forest. 29% of all case studies were conducted in karst areas, which is a high proportion compared to the proportion of forests in karst areas. However, these studies are unevenly distributed geographically. Most studies were conducted at the plot level, and only 21% of studies focused on natural LSFD, so forest management and land use change studies predominated. Although studies on the effects of LSFD on evapotranspiration processes between vegetation, air and soil are fairly well represented, infiltration and recharge processes in karst areas remain poorly understood and knowledge is lacking, particularly on groundwater flow and related hydrological processes. Regional studies and impacts on groundwater resources are also insufficient. The results indicate an urgent need for an integrated holistic interdisciplinary approach and a comprehensive understanding of the individual influencing factors, which would allow more accurate modelling of hydrological processes in forested karst aquifers.

1. Introduction

1.1. Scope and aims

Forest disturbances such as fires, pests or disease infestations, drought and windthrows are an integral part of forest ecosystem dynamic globally (Cannon et al., 2001; Shakesby and Doerr, 2006; Parise and Cannon, 2012; Degraff et al., 2013; Seidl and Rammer, 2017; Nunes et al., 2018). These are disruptive, discrete, more or less stochastic events in which some amount of vegetation biomass is partially removed or completely destroyed (Ebel and Mirus, 2014; Kulakowski et al., 2017). Large-scale disturbances disrupt the structure, composition

* Corresponding author.
E-mail addresses: ursa.vilhar@gozdis.si (U. Vilhar), janez.kermavnar@gozdis.si (J. Kermavnar), erika.kozamernik@gozdis.si (E. Kozamernik), petric@zrc-sazu.si (M. Petrič), natasa.ravbar@zrc-sazu.si (N. Ravbar).

https://doi.org/10.1016/j.earscirev.2022.104243
Received 8 June 2022; Received in revised form 28 October 2022; Accepted 31 October 2022
Available online 12 November 2022

and function of forest ecosystems on a larger spatial scale, usually affecting forest areas at least 10s of ha in size (Kulakowski et al., 2017; Nagel et al., 2017) and thus have far-reaching and long-lasting effect on hydrologic, landscape and ecosystem processes (Ebel and Mirus, 2014).

In recent years, events that result in the loss of forest biomass, such as wildfires that have devastated numerous European and American forests, are frequent (Kennedy et al., 2021). Other types of forest disturbances can also be destructive. One example is a massive ice storm (glaze or sleet) that hit Slovenia in 2014 (Saje, 2015). More than half of the country's forests were damaged, and in the following years they were further affected by windthrows and spruce bark beetle infestations (Marinšek et al., 2015). Since almost half of Slovenia's territory is characterized by karst and the country is also home to the Classical Karst, over 70% of the forests are found in karst terrains (Gams, 2003), which are important for their exceptionally rich biodiversity and biomass (Kutnar et al., 2015).

Karst is a special type of landscape that usually occurs on carbonate rocks and is characterized by special relief features on and below the surface, such as poljes, dolines, caves, ponors, and springs. Karst areas are estimated to occur over an area of >20 M km^2 worldwide (Goldscheider et al., 2020) and hold diverse values, such as freshwater resources and unique habitats (Culver and Pipan, 2019; Ravbar and Pipan, 2022). Their water resources already supply around a quarter of the world's drinking water needs, and in many countries and regions such as Austria, Slovenia, the Mediterranean region, and southwestern China, karst water resources provide about half of the drinking water needs (Stevanović, 2018). Some of the larger cities that rely on karst aquifers for water supply are Vienna (Austria), Montpellier and Marseille (France), Rome (Italy), Sarajevo (Bosnia and Herzegovina), Tirana (Albania), Skopje (Macedonia), Podgorica (Montenegro), Damascus (Syria), San Antonio (USA), etc. (Krešić and Stevanović, 2010; Stevanović, 2018).

Karst is formed by the dissolution of host rock along discontinuities and therefore characterized by specific water flow processes (Gabrovšek and Dreybrodt, 2001; Worthington and Ford, 2009).The recharge processes through cracks and voids in the bedrock or through swallow holes and ponors are very rapid. In the underground water flows mainly through channels and fissures, concentrating on its way to the springs (Atkinson, 1977; Jeannin and Grasso, 1997). The velocities can reach of up to several hundred meters per hour, and water storage is limited (Bakalowicz, 2005; Worthington and Ford, 2009; Hartmann et al., 2014). Because of the predominance of channel flow, the flow characteristics of karst aquifers vary greatly with hydrologic conditions. This can result in spatial and temporal changes in water table fluctuations, variations in flow direction, and shifts in catchment boundaries.

Given the dynamic nature of hydrological processes in karst aquifers, they are particularly vulnerable to the effects of various environmental changes (Goldscheider and Drew, 2007; Parise et al., 2018). The high vulnerability of karst aquifers is widely recognized (Zwahlen, 2004; Iván and Mádl-Szőnyi, 2017). In this sense, considerable efforts have been made to assess the vulnerability of karst water sources, hazards and contamination risks (Drew and Hötzl, 1999; Parise et al., 2015; Daly et al., 2022). Some studies have addressed the assessment of human disturbance on karst in general, which includes the assessment of vegetation removal or deforestation (North et al., 2009; Angulo et al., 2013). However, these studies do not address the effects of vegetation change on individual hydrological processes. Moreover, compared to other topics frequently discussed in karst hydrology (e.g., karst aquifer recharge, groundwater storage and flow dynamics, contamination problems), the effects of rapid loss of forest cover due to large-scale disturbances on karst hydrology receive less attention in the scientific community (Kovačič et al., 2020). As climate simulations consistently predict more frequent extreme weather events that could lead to forest disturbances (Dale, 2001; Frelich, 2002; Kutnar and Kobler, 2011; Čada et al., 2016) and as human pressures are increasing, the question arises whether large-scale forest degradation could have an important effect on the recharge of karst aquifer systems.

To strengthen the foundation for further research and action, a critical review of the state of the art was conducted. The main objective was to provide an overview of the hydrologic processes affected by large-scale forest disturbance. This work is based on a comprehensive review of the available literature. Given the large scope of this work, emphasis was placed primarily on four abiotic factors (fire, drought, wind, and ice/glaze) and two biotic factors (pests and disease infestation), as well as on climate change. A comparison of the effects of large-scale forest disturbances on hydrology was also made between natural large-scale forest disturbances and human-induced changes such as forest management and land use change. General information was presented first, followed by specific findings on karst. In addition, an analysis of the spatial distribution of forests underlain by carbonate aquifers was conducted, providing the first global overview. Based on the current state of science in the field, key knowledge gaps were identified, and suggestions for future research were made.

1.2. Definitions

For the purposes of this review, the term "forest" has been used to refer to coniferous, deciduous, and mixed forests, depending on the tree species described in the articles. The origin of forests can vary and includes natural forests, secondary forests, and man-made plantations. The "forest disturbances" were defined as disruptive, discrete, but more or less stochastic events in which some amount of vegetation biomass is partially removed or completely destroyed (Ebel and Mirus, 2014; Kulakowski et al., 2017). Depending on the origin of forest disturbances (Turner and Dale, 1998; Seidl et al., 2017), a distinction was made between: (i) natural disturbances caused by a biotic or abiotic factor (e.g., windthrow, ice storm, forest fire, pest and disease infestation, drought, etc.); (ii) anthropogenic disturbances (forest management and land use change); and (iii) climate change with its complex direct and indirect impacts on forest ecosystems (Lindner et al., 2010; Kutnar et al., 2021), including increases in well-mixed greenhouse gas concentrations that are altering photosynthesis rates and growth (Marshet and Fekadu, 2019), shifts in the amount and seasonal distribution of precipitation, gradual changes in average climate conditions, and weather and climate extremes (IPCC, 2021). Climate change is expected to increase the frequency and intensity of forest disturbances. Both factors together will shape future temperate forests, especially in the transition zone between central and SE Europe (Kutnar et al., 2021) and in other regions as well. Disturbances and climate change are most likely interacting, which may lead to synergistic or antagonistic ecological effects that are difficult to predict (Brook et al., 2008). For this reason, an additional category of (iv) compound disturbances was introduced, where the forest was affected by multiple linked-effects disturbances (where one disturbance alters the likelihood of subsequent disturbances) or compound effects (where an ecosystem is affected by cumulative and potentially nonlinear effects of two or more interacting disturbances) (Kulakowski et al., 2017).

The term "windthrow" refers to a range of disturbances caused by strong winds, associated with localised thunderstorms, ranging from damage to individual trees to catastrophic storm events (tornadoes, hurricanes) that cause large-scale, catastrophic blowdowns of entire stands (Nagel et al., 2006). "Ice storm" refers to a freezing rain event, that results in radial ice loading of vegetation (Gyakum and Roebber, 2001). Ice storms occur when a warm, moist atmospheric layer overlies a shallow, cold surface layer (Zhou et al., 2011). The term "forest fire" refers to uncontrolled or controlled (prescribed) burning of plants in a forest that consumes natural fuels and spreads depending on environmental conditions (e.g., wind, topography). Forest fire can be started by human actions, such as land clearing, extreme drought, or in rare cases, lightning. "Pest and disease infestations" refer to increases in insects and fungi that can feed on or infect various parts of forest trees and contribute to the death of individual aging trees (Nagel et al., 2017) or cause gaps in the canopy or even large landscapes to die during outbreaks (Worral et al., 2005). In this synthesis review, "drought" is considering definition of "ecological drought": an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems (Anderegg et al., 2013b; Unterm, 2022). Drought is one of the main factors affecting tree growth, vigour (Bertini et al., 2011; Lebourgeois et al., 2013; Sohn et al., 2013), and survival in many regions worldwide (Kramer and Boyer, 1995; Bréda et al., 2006; Granier et al., 2007; McDowell, 2011; Anderegg et al., 2013a; Park Williams et al., 2013; Vicente-Serrano et al., 2013). The increasing severity of droughts is not only caused by changes in precipitation, but also by rising temperatures that increase evaporative demand (Breshears et al., 2005).

For the term "forest management," any type of activity or technique used in forest management was considered: Canopy gap creation, tree felling, selective logging and thinning, timber harvesting, understory removal, clearcutting, harvesting, road building, reforestation, salvage logging, etc. The term "land use change" refers to any type of land use change associated with the expansion or reduction of the area used for various purposes (e.g., forest, pasture, cropland, urban) (Davis et al., 2019), as well as the conversion of land uses with high canopy cover (e.g., natural forest) to those with low canopy cover (e.g., agricultural crops, grassland, or shrubland) or vice versa (conversion of grassland to shrubland, cropland, or forest).

"Hydrologic processes" in this synthesis included the occurrence, storage, and circulation of water, matter and energy in an ecohydrologic system at different spatial and temporal scales (Bonacci et al., 2009). "Recharge" describes the flow of infiltrated water that reaches the permanent underground water table, and causes an increase in stored water (Lerner et al., 1990). Recharge depends on the interaction between input in the form of precipitation and the loss of water to the atmosphere. Loss occurs through the combined effects of evaporation (i.e., the direct evaporation of liquid water) and transpiration (the release of water vapour to the atmosphere by plants). Because these two processes are difficult to distinguish in practise, it is useful to combine them and refer to them as "evapotranspiration." Water storage in soil depends on the soil moisture deficit, which is defined as the difference between the amount of water actually present in the soil and the amount of water the soil can hold (field capacity). Precipitation replenishes the soil moisture deficit, and when field capacity is reached, direct recharge occurs. In some areas, indirect recharge bypasses the soil and infiltrates underground along macropores (Younger, 2007).

2. Methods

2.1. Review approach and protocol

To provide an overview of the effects of large-scale forest disturbances on hydrology, exploratory literature searches on the individual hydrological processes (evapotranspiration, soil hydrology, recharge dynamics) affected by various large-scale forest disturbances were complemented with a critical review based on a systematic literature search on the current state of the art. The review followed the Collaboration for Environmental Evidence methodological guidance (Pullin et al., 2018) on systematic literature reviews for orientation. The process of identifying relevant publications was documented with the PRISMA checklist (Moher et al., 2015), with a focus on the articles published during the last twenty years (from 2001 to 2020).

A review protocol was established specifying what data should be extracted from each study, who should do the extraction, and in what format the data should be collected. A multidisciplinary reviewer team of five independent reviewers (co-authors of this article) was formed to avoid errors, such as overlooking study characteristics that need to be captured or biases that can occur in studies (Moher et al., 2015).

Articles that met the search criteria were thoroughly reviewed. Key metadata and information were compiled into a comprehensive matrix dataset. The summarized results of the studies conducted were compiled into an overview of the effects of large-scale forest disturbance on hydrology in general, and with a particular emphasis on karst. The compiled information was used to make a synthesis of existing knowledge and to identify knowledge gaps.

2.2. Search and organization strategy

Given the multidisciplinary nature of relevant publications, as evidenced by recent reviews of hydrological processes following large-scale forest disturbances, ISI-Web of Science, Google Scholar, Scopus, and PubMed were selected as the main databases for article searches. Furthermore, a snowballing approach to add relevant articles into the matrix dataset by reviewing the reference section of the articles was used. In addition, recent articles that cited previously studied articles were evaluated and included as relevant in the matrix dataset. Articles published in peer-reviewed journals in English were considered. The source must have met the criteria of a peer-reviewed article or review in full text and with electronically available abstracts and texts. The search terms for the systematic search in the selected databases were developed (Table 1) following the guidance of Pullin et al. (2018).

The matrix dataset was organized in an Excel spreadsheet and used to coordinate articles by subtopic. Additional information was identified in this manner. The following categories were derived during the screening process: (i) type of article (article, review article); (ii) year of publication, title, author(s), journal; (iii) case study location, climate, ecosystem type; (iv) spatial scale: plot, catchment, region; (v) bedrock, topography, and soil type; (vi) research methodology used; (vii) large-scale disturbances addressed; (viii) hydrologic processes studied, (ix) control factors identified. If an article examined multiple hydrologic processes, it was listed in the appropriate hydrologic process categories (e.g., an article that reported on soil erosion and sediment transport was listed twice in the soil processes category). Because of the limited amount of research on natural forest disturbances, human-caused impacts were also included in this review, e. g., land use change, climate change, and forest management.

The final phase of this synthesis was to verify that articles on the

Table 1
Search terms, used for the systematic search of relevant articles.

General	Forest disturbance	Hydrological process
Forest	Wind / windthrow	Precipitation
Large-scale disturbances	Ice storm / glaze / sleet	Evapotranspiration
Karst / carbonate	Snow / snowstorm / snow damage	Transpiration
Hydrology / hydrological process	Fire / wildfire	Evaporation
	Pests / insects / disease / pathogens / fungi / bark beetle	Interception
	Infestation / outbreak	Soil water / moisture
	Drought / drought stress / water stress / water deficit	Soil hydrology
	Forest decline / tree mortality	Soil quality / nitrogen
	Land use / cover change / vegetation change	Soil erosion
	Deforestation / reforestation / afforestation	Infiltration
	Forest management / disturbance regime	Recharge
	Harvest / logging / tree removal / tree cutting	Water balance / flux / flow
	Climate change	Groundwater
		Runoff
		Water chemistry / water quality
		Nutrient leaching / loss

effects of large-scale forest disturbance on hydrology included studies in karst regions. This subset was compiled because it was assumed that certain effects of large-scale disturbance would be similar in any forest ecosystem regardless of bedrock or soil type (e.g., precipitation distribution, canopy interception, sap flow density, canopy conductivity, etc.), but could also have important implications for large-scale forest disturbance in karst aquifers.

2.3. Study selection and qualitative analysis

The study selection process followed the Preferred Reporting for Systematic Reviews and Meta-Analyses: the PRISMA statement (Moher et al., 2015). The PRISMA flowchart (Fig. 1) visually summarises the screening process and makes the article selection process transparent by reporting the decisions made at the different stages of the systematic review. If the articles were excluded at the full-text stage, the reasons for exclusion were provided.

From each article the data, results, and main conclusions were extracted to identify key research trends, knowledge clusters, and gaps. The analysis included spatio-temporal, comparative, and qualitative narrative analyses. The case studies evaluated in the articles were plotted on the world map and a searchable map was created for regions with calcareous bedrock to identify karst regions with the most studies conducted and karst regions with a deficit in hydrologic research.

In addition, forested regions with calcareous bedrock were mapped and statistically evaluated globally and by continents. The spatial distribution and statistical analyses were based on the digital World Karst Aquifer Map and Geodatabase (Chen et al., 2017) and Global Land Cover (GLC, 2013). The case studies identified were linked to publicly available information on karst hydrology in forestry. All analyses were conducted using Arc GIS Desktop from ESRI (version 10.6.1).

3. Results and discussion

3.1. Search outputs

All searches combined yielded 215 articles that were screened for eligibility. In the second phase of screening, 99 articles were excluded for the following reasons: 23 were reviews without details of the case studies presented; 8 did not evaluate any hydrological process; 9 did not evaluate the link between hydrological processes and vegetation change; 4 did not evaluate forest vegetation or vegetation was not described in detail; 49 did not evaluate vegetation change (e.g. forest vegetation remaining the same or similar: change from forest to forest plantation, change from old-growth to managed forest, etc.), and 3 articles were modelling or simulation exercises not including large-scale forest disturbances or vegetation change. As a result, 117 full-text articles were selected for qualitative synthesis.

In the first decade of the study period (2001 to 2010), the number of articles was up to four per year. Publication activity was strongest between 2011 and 2017, with peaks in 2013 with 18 publications and in 2016 with 14 publications. Thereafter, the number of articles declined (Fig. 2). Most articles were published in the following journals: Forest Ecology and Management (16 articles in total), Agricultural and Forest Meteorology (8), Journal of Hydrology (9), and Science of the Total Environment (6 articles).

Because some articles reported multiple case studies and more than one hydrologic process assessed, 160 case studies of large-scale forest disturbance impacts on hydrology were included in the matrix dataset for this study (Appendix A).

53% of these case studies were conducted at the plot level and 34% were conducted at the catchment level. Only 13% of the case studies were conducted at the regional scale. 39% of the case studies in the matrix dataset addressed the effects of natural large-scale forest disturbances, caused by a biotic or abiotic factor (e.g., windthrow, forest fire, pest and disease infestation or drought) on hydrology, with studies on

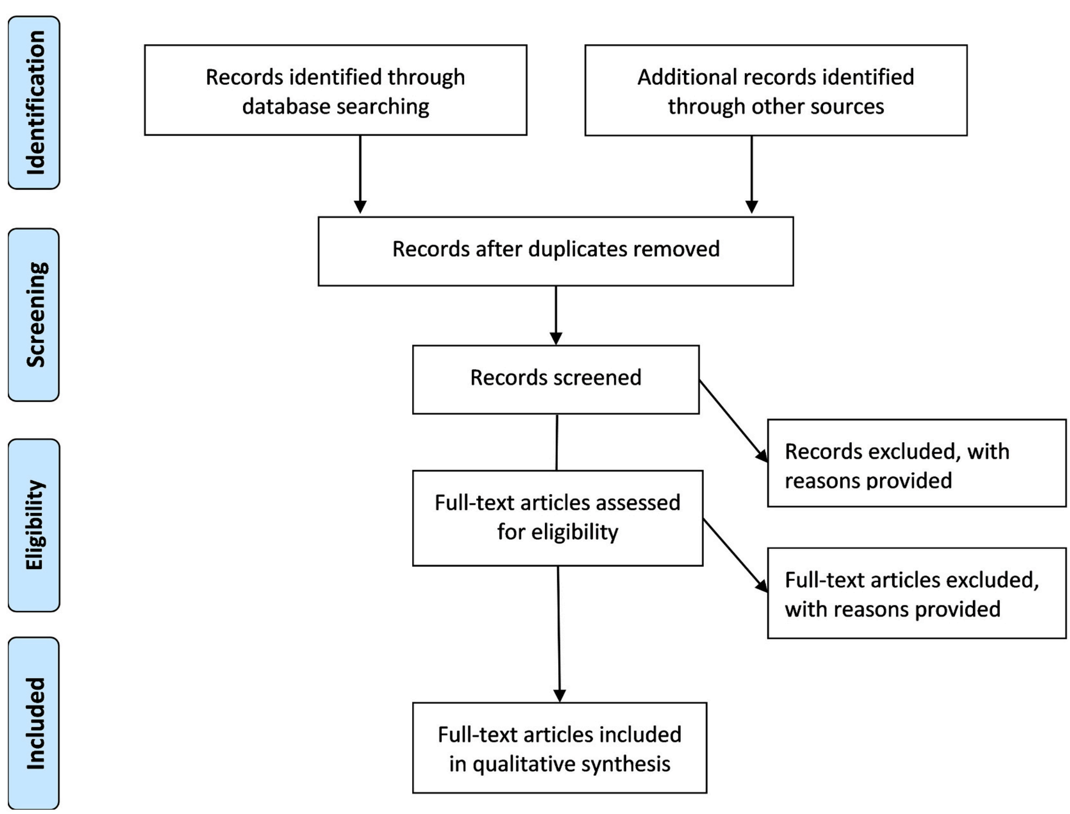

Fig. 1. The PRISMA flowchart followed the Preferred Reporting for Systematic Reviews and Meta-Analyses: the PRISMA statement (Moher et al., 2015).

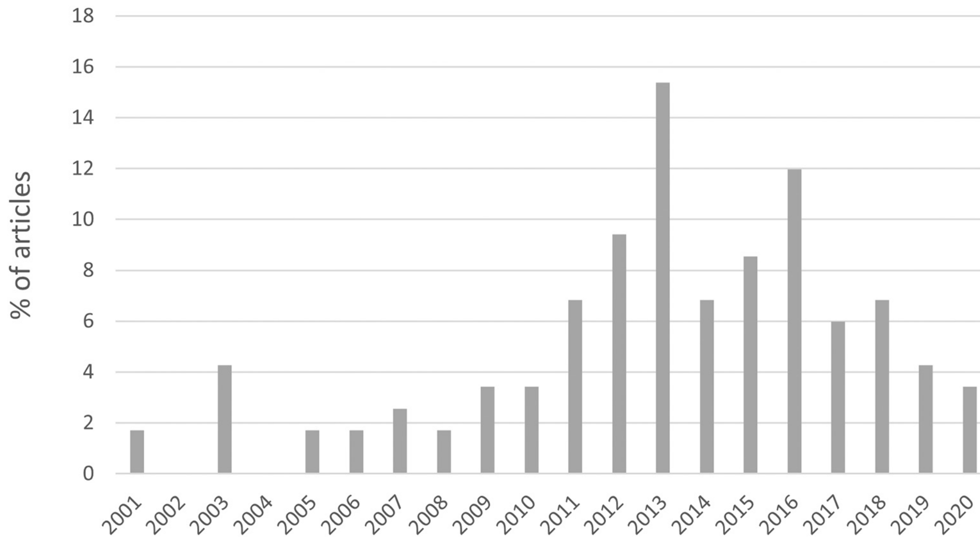

Fig. 2. Annual distribution of published articles (percentage of all articles in matrix dataset, %) in the period between 2001 and 2020.

the effects of fire and pest and disease infestation predominating (Fig. 3). More than half of the case studies on natural large-scale forest disturbances were conducted at the plot level (36 of 63), 25 of 63 were conducted at catchment level and only two were conducted at the regional level. 25% of the case studies in the matrix dataset addressed land use change impacts and 21% addressed forest management impacts on hydrology. While land use change impacts on hydrology predominated on catchment level (38%), followed by regional level (35%), and the plot level (28%), studies of forest management impacts on hydrology predominated at the plot level (17%). There were only 6 case studies (4%) on forest management at the catchment level and none at the regional level. Climate change on hydrology were examined in 5% of the case studies, most of which were at the regional level (4 of 8), 3 of the case studies were at the catchment level, and one case study was at the plot level. The effects of compound disturbances were examined in 10% of the case studies, with a preponderance of studies at the plot level (6 of 16%). However, there were 6 case studies of compound disturbances studies at the catchment level and only one at the regional level.

Most studies focused on recharge dynamics (37%), followed by soil processes (34%) and evapotranspiration processes (29%). The effects of large-scale forest disturbance on recharge dynamics were mostly studied at the catchment level (23%). Most studies that examined the effects of large-scale forest disturbance on evapotranspiration or soil processes were at the plot level (20% and 23%, respectively).

When linking large-scale disturbance and hydrologic processes examined in the case studies in the matrix dataset, the majority focused on the effects of fire on soil processes (13%), followed by the effects of land use change on recharge dynamics (11%) (10%). The effects of forest management on evapotranspiration and fire on recharge dynamics were studied in 8%. This was followed by studies of the effects of land-use change on evapotranspiration and soil processes (7%).

3.2. Forests underlain by carbonate rocks and studies focused on karst

Forests in karst areas are extremely important for the protection of water resources, biodiversity and biomass, and for their vulnerability to external changes. This study is the first detailed statistical evaluation of forests underlain by carbonate rock aquifers at global and continental

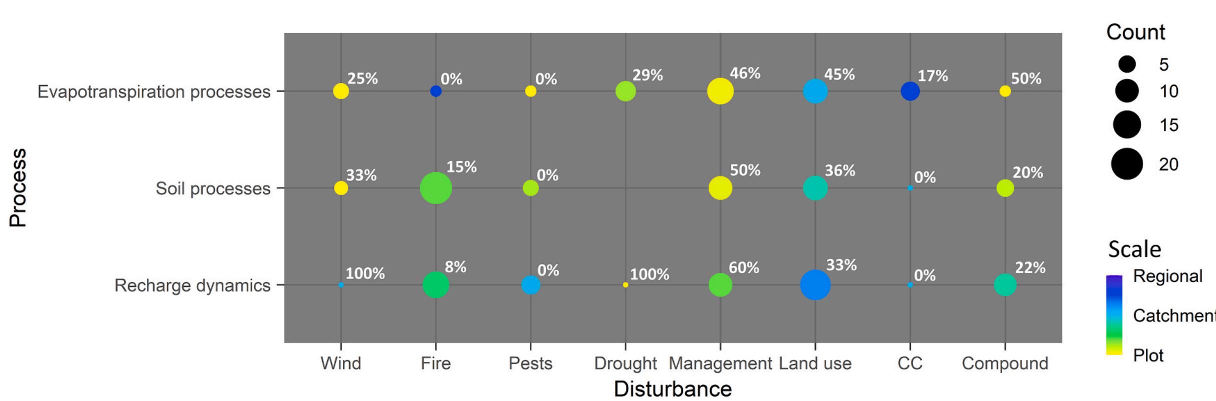

Fig. 3. Case studies investigating large-scale forest disturbances defined with 7 categories: Windthrow (Wind), Forest fires (Fire), Pest and disease infestations (Pests), Drought (Drought), Forest management (Management), Land use change (Land use), Climate change (CC), Compound disturbances (Compound) on hydrological processes including: Evapotranspiration processes, Soil processes, Recharge dynamics. This results in a total of 24 combinations. The size of a circle indicates the number of case studies (160 in total). The colour gradient defines the spatial level in a fairly "continuous" manner, ranging from plot level (yellow; 84 case studies in total) to the catchment level (turquoise; 55 case studies in total) to the regional level (blue; 21 case studies in total). The intermediate colours represent combinations with case studies that have different spatial levels. For example, the green colour means that some case studies had both plot level and a catchment level, while the light-blue colour represents combinations with both catchment level and regional level. The percentage next to each circle indicates the proportion of case studies that were conducted in karst areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scales. Globally, there are 45.6 M km^2 of forest cover (GLC, 2013) and at the same time carbonate rocks cover about 20 M km^2 (15%) of the land surface. The spatial analyses performed in this study showed that 6.34 M km^2 of forest area is underlain by carbonate rocks, which means that 13.9% of the world's forests are found in karst areas. Forests underlain by carbonate rocks cover 31.3% of all surface exposures of carbonate rocks and 4.75% of the total land area.

Forested karst areas are found on all continents (Table 2). The highest percentage is in Europe, which covers 0.76 M km^2 or 7.65% of the continent. There is also significant amount of forested karst on the largest continent, Asia (3.01 M km^2 or 6.7% of the continent) and in North America (1.39 M km^2 or 6.16% of the continent). Smaller absolute areas and percentages of forested karst are in Africa (0.65 M km^2 or 2.16%), South America (0.39 M km^2 or 2.19%), and in Australia and Oceania (0.14 M km^2 or 1.72%). Depending on the proportion of carbonate rock on the continent, the proportion of forested karst areas is highest in South America (50.65%), Asia (36.05%), Europe (35.5%) and North America (31.31%). Areas with the most widespread forests on karst are listed in Table 3 and shown in Fig. 4.

This literature review on large scale forest disturbances shows that a total of 47 (29% of 160 in the matrix dataset) case studies were conducted in karst regions (Appendix B). Most of the case studies were in the Mediterranean region, but also in other parts of the world, particularly SW China, Central Europe, Texas, and the Caribbean (Fig. 4).

Most studies in karst regions were at the plot level (74% or 35 out of 47 case studies), followed by 23% catchment level case studies and only one regional level case study (2%). They focused mainly on recharge dynamics (36% of case studies in karst regions), followed by evapotranspiration processes (34%) and soil processes (30%). Most case studies in karst regions that examined evapotranspiration or soil processes were at the plot level (30% and 28%, respectively). There was no regional study of evapotranspiration or soil processes in karst areas. Recharge dynamics were mostly studied at the catchment and plot level (17% each), and only one case study at the regional level (see also Fig. 3).

The effects of **natural large-scale forest disturbance,** caused by a biotic or abiotic factor (e.g., windthrow, forest fire, pest and disease infestations, or drought) on hydrology in karst areas were examined in 10 case studies (21%), with 9 case studies conducted at the plot level and only one at the catchment level. There were no regional study of natural large-scale forest disturbance impacts on hydrology in karst regions. Most studies in karst regions examined the effects of fire on soil processes (3 case studies) and the effects of drought on evapotranspiration (2 case studies). In addition, one case study examined the effects of fire, one examined the effects of drought, and one examined the effects of windthrow on recharge dynamics. Fire and drought were only studied at the plot level (4 and 3 case studies, respectively) and windthrow at the plot level (2 case studies) and the catchment level (one case study).

Table 2
Global and continental distribution of forests underlain by carbonate rocks. Data sources: GLC (2013); Goldscheider et al. (2020).

Continent (alphabetical order)	Continent	Carbonate rocks		Forests on carbonate rocks		
	M km^2	M km^2	%	M km^2	on the continent %	of the karst areas %
Africa	30.07	4.05	13.5	0.65	2.16	16.05
Asia	44.93	8.35	18.6	3.01	6.7	36.05
Australia & Oceania	8.15	0.5	6.2	0.14	1.72	28.00
Europe	9.94	2.17	21.8	0.76	7.65	35.05
North America	22.58	4.44	19.6	1.39	6.16	31.31
South America	17.8	0.77	4.3	0.39	2.19	50.65
TOTAL	**133.47**	**20.28**	**15.2**	**6.34**	**4.75**	**31.26**

Table 3
A selection of areas of the world's most widespread or significant forest land on carbonate rocks.

Continent (alphabetical order)	Areas of forest land on carbonate rocks – a selection
Africa	southeastern Tanzania (Tanga), Democratic Republic of Congo (northeast of the Congo River), parts of western Gabon, western Congo, northern Zambia and northwestern Angola
Asia	the Ural, Caucasus, Altai and Sayan Mountains, Central Siberian Upland, the Primorsky Range and the Priolkhonskoye Plateau, north from Lake Baikal, continuing as a wide belt to the Sea of Okhotsk in Siberia, southwestern China, northern Vietnam, central Laos mountainous western part of Myanmar, eastern Bhutan, Southern Malasia, Phillipines and Indonesia
Australia & Oceania	New Guinea, New Zealand, Maluku
Europe	the Alps and Pyrenees, the Cantabrian and Iberian Mountains, southern France, the Apennines, the Dinaric Karst, the Carpathians, northern Estonia, the Russian Highlands, the Northern and Eastern European Plains, and western Ukraine
North America	the Rocky Mountains, the Appalachian and the MacKenzie Mountains, coastal areas of southeastern Alaska, western Canada and southwestern shores of Hudson Bay, interior low plateaus of the USA, Texas, Oaxaca and Chiapas highlands, Eastern Sierra Madre, Yucatan Peninsula, the Caribbean
South America	northern parts of the Andes, Guacharo in Venezuela, Babui, Peruacu, Una, Guimaraes, Bonito and Acungui in Brasil and parts of Patagonia

There was no study of pest and disease impacts on hydrology in karst areas.

For anthropogenic disturbances, the effects of **forest management** on hydrology were studied in 36% of the case studies in karst regions, one of which was at the catchment level and all others at the plot level. There were no regional studies of forest management impacts. Most of the forest management case studies examined impacts on evapotranspiration and recharge dynamics (6 or 13% each), and 5 or 11% on recharge dynamics in karst regions. 15 or 32% of the case studies in karst regions examined the effects of **land use change** on hydrology, with 7 case studies (15%) at the plot level and 7 at the catchment level. However, at the regional scale, there was only one land use change study that included catchments with karstified bedrock. There were 6 case studies (13%) that examined the effects of land use change on recharge dynamics, 5 case studies on evapotranspiration, and 4 case studies on soil processes in karst areas.

The effects of **compound disturbances** on hydrology in karst regions were examined in 4 case studies, 3 at plot scale and one at the catchment scale. One case study examined the effects of compound disturbances on evapotranspiration processes, one on soil processes, and 2 on recharge dynamics in karst regions. The effects of **climate change** on hydrology in karst regions were only examined in one case study at the catchment scale, where evapotranspiration processes were examined.

3.3. *Effects of large-scale forest disturbances on hydrology*

Natural and anthropogenic disturbances may significantly influence short- and long-term forest dynamics (Turner and Dale, 1998; Seidl et al., 2017). Disturbance regimes, defined by the frequency, severity and/or intensity (percentage of aboveground biomass removed / destroyed), and size of disturbances (Nagel et al., 2017), affect species composition and the horizontal and vertical distribution of trees (Frelich, 2002).

Due to climate change in the last decades, extreme weather events, land use change and other global environmental pressures, forests worldwide have witnessed severe large-scale disturbances with

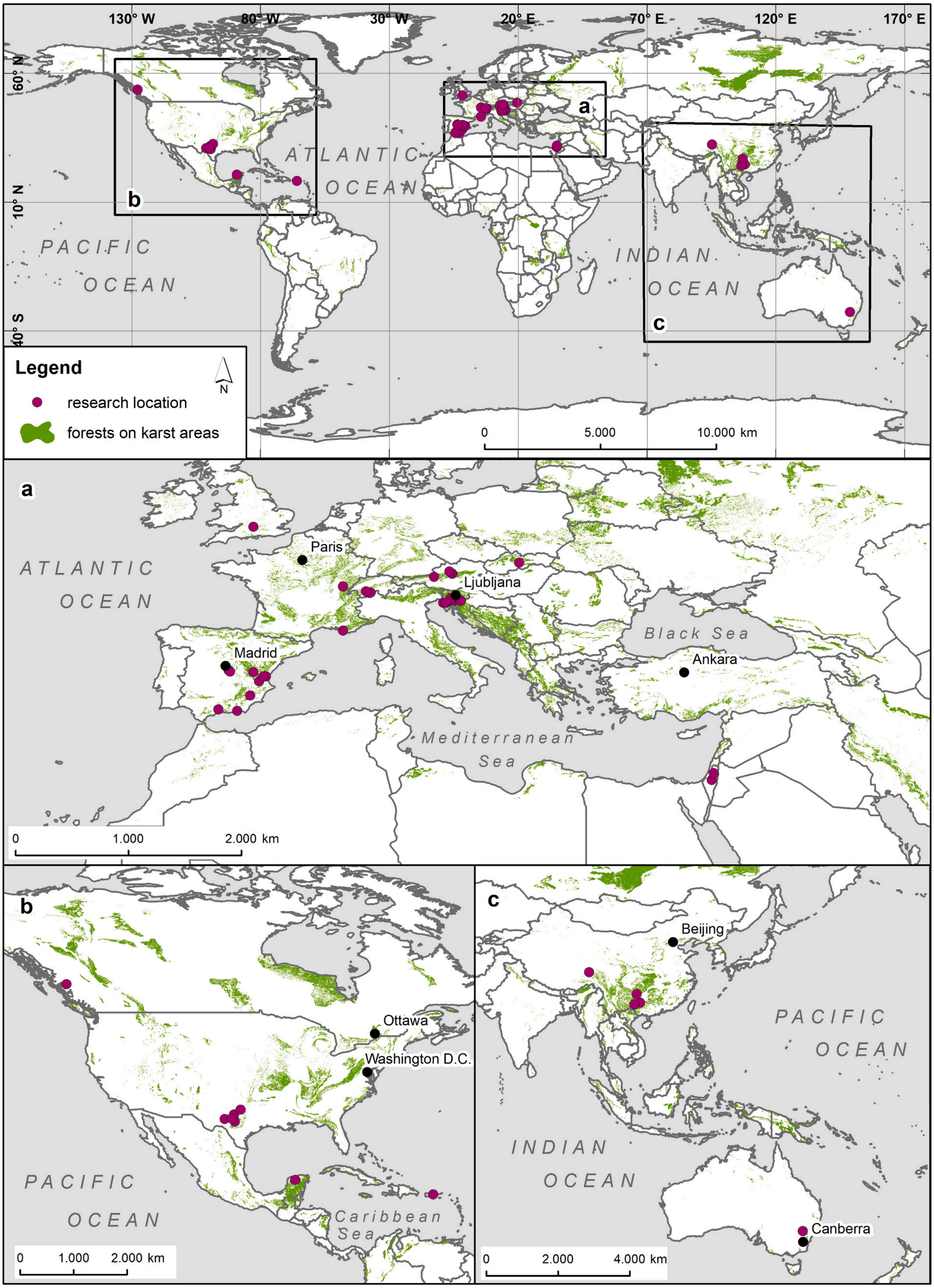

Fig. 4. Map shows geographical distribution of carbonate rocks, forests on karst and locations of case studies in karst regions identified in this review. Zooms to selected continents are provided in inserts a, b and c. Data sources: GLC (2013), Chen et al. (2017).

changing and intensifying disturbance regimes on a global level (Ebel and Mirus, 2014; Seidl et al., 2017). Post-disturbance forest management interventions (i.e., salvage logging) have additionally altered forest structure and forest vegetation cover. For example, catastrophic natural disturbances have shifted forest management in Slovenia from regular, management plan-oriented harvest interventions to prevalence of sanitary logging in the years from 2012 till 2018 (Skudnik et al., 2021) (Grecs and Kolšek, 2017).

From a hydrologic perspective, assessments of disturbance effect are complicated because small scale changes (detected on the level of monitoring plots) readily impact relevant hydrologic function and water resources at large scales (observed on catchment level) (Hlásny et al., 2013; Ebel and Mirus, 2014). Abiotic and biotic disturbances are significant factors affecting hydrology through alteration of forest cover, forest structure and soil characteristics (Fig. 5). Their effects are manifold and can not only yield direct effect on hydrological processes but also produce indirect effects on hydrology by disturbing tree growth and structure of forest stands. (See Fig. 6.)

The direct ecohydrological impacts of forest disturbance are related to changes in canopy cover and ground vegetation, which exert an important influence on many ecosystem processes (Breshears, 2006; Zhang et al., 2017). Due to reduced canopy cover, canopy interception decreases and results in altered water fluxes above and below ground. Reduced canopy cover reduces transpiration and canopy interception, which has a negative impact on overall evapotranspiration (Adams et al., 2012). However, at the same time, the loss of canopy increases wind and solar energy reaching the forest floor (Morecroft et al., 1998), which drives bare soil evaporation and understory transpiration and has positive impact on evapotranspiration. The balance of these competing evaporation, transpiration, and canopy interception responses to canopy reduction ultimately determines the magnitude of direct effects of forest disturbance on total evapotranspiration (Moore and Heilman, 2011). Reduced canopy interception means that more precipitation reaches the forest floor, potentially increasing surface runoff and causing soil erosion. Such negative impacts are most common on steep slopes, which often have shallow soils (Huang et al., 2017). Soil properties are directly related to infiltration processes, which in turn determine the availability and quality (e.g., nutrient leaching and nutrient losses) of groundwater and drinking water supplies. The relationship between vegetation and hydrology is particularly strong in areas with permeable parent rock such as carbonate rock, which is characterized by complex underground hydrology.

Tree canopy loss is also a dominant effect of logging and land use change, so hydrologic responses to these forest manipulations could provide useful insights into the hydrologic consequences of forest disturbance. In addition, a large body of literature was found on the ecohydrological consequences of tree cutting and land use change (Legesse et al., 2003; Kim et al., 2013).

Different types of disturbance most likely have different impacts on forest vegetation and soils. For example, in windthrow areas, some snags and uprooted trees are left behind, while in clearcut areas, no structural legacy is left in the surrounding area after disturbance. Although most disturbances have negative effects on hydrologic functions, certain processes may benefit from altered conditions following forest disturbance.

Finally, the response of a hydrologic process to a particular disturbance may depend on site-specific factors, such as soil conditions, local topography, vegetation characteristics or ecosystem health (Šraj et al., 2008; Gerrits et al., 2010; Kermavnar and Vilhar, 2017; Mirus et al., 2017). All of these premises suggest that the effects of forest disturbance

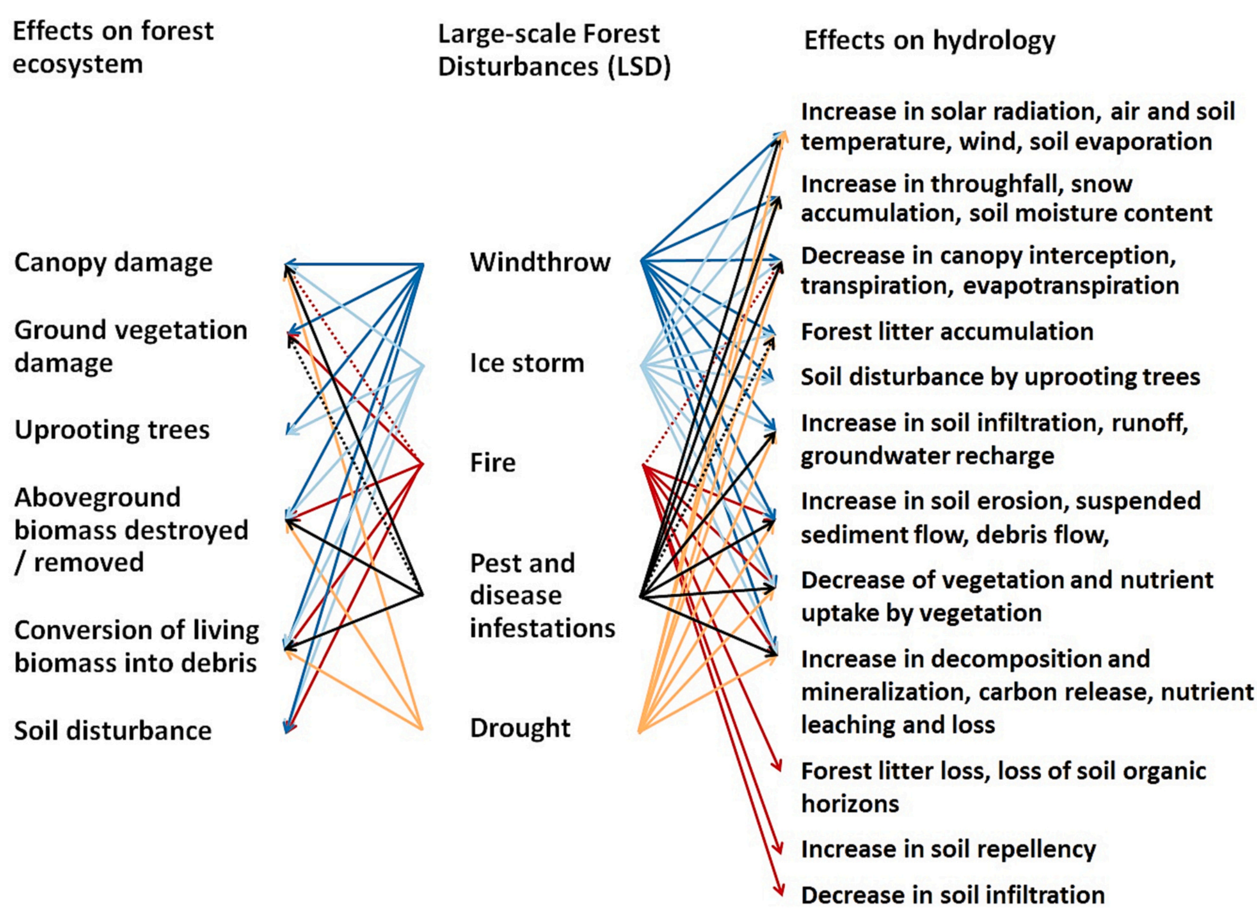

Fig. 5. Schematic illustration of the effects of large-scale forest disturbances on hydrology and the potential interrelated impacts. Solid line represents direct effects, dotted line represents indirect effects.

Fig. 6. Different types of large-scale forest disturbance: (a) windthrow in a *Picea abies* stand (photo by Aleksander Marinšek); (b) massive ice storm damage in 2014 (photo by Lado Kutnar); (c) and (d) forest fire in the sub-Mediterranean region of Slovenia (photos by Klemen Eler); (e) dieback of *Fraxinus excelsior* caused by fungal disease *Hymenoscyphus fraxineus* (Photo by Janez Kermavnar); (f) forest management after a disturbance – salvage logging (photo by Lado Kutnar).

on hydrology are likely highly variable and should be interpreted in the context of local environmental and hydroclimatic conditions. Nevertheless, some generalizable patterns of hydrologic response following forest disturbance could be outlined (Ebel and Mirus, 2014).

3.3.1. *Windthrow*

In areas where wind is prevalent as a disturbance factor, landscape-level studies show great heterogeneity in disturbance intensity (Frelich, 2002). Wind-induced disturbances are irregularly distributed and interact with forest age and structure. Wind-related disturbances are often characterized by frequent events of low severity as well as less frequent pulses of disturbance of higher severity (Nagel et al., 2014). Regardless of the severity of the disturbance, wind disturbance allows light-demanding and semi-shade-tolerant or even pioneer tree species to establish forests dominated by shade-tolerant species (e.g., European beech or silver fir) (Vilhar et al., 2015), resulting in a landscape-wide mosaic of patches at different stages of structural development rather than different stages of compositional succession (Čada et al., 2016).

When frequent thunderstorms and wet snowstorms reach high intensity, they typically cause moderately severe damage to forests at local to regional scales (Nagel et al., 2017). For example, large winter storms (e.g., Vivian, Lothar) regularly cause subcontinental damage to forests in some parts of western, central, or eastern Europe (Kramer et al., 2014). In North America, wind disturbances include hurricanes as well as tornadoes and derecho events, the latter which can cause catastrophic damage on a larger scale (Frelich, 2002; McDowell and Liptzin, 2014). Relatively large-scale blowdowns ($>$ 100 ha) also occur in other cool-temperate zone forests in monsoon Asia and in Nothofagus forests in South America (Nakashizuka and Iida, 1995; Rebertus et al., 1997). In contrast, in the Dinaric Mountains of SE Europe, most thunderstorm events that damage forests typically cause moderate damage (e.g., 20–50% of tree canopy) in areas several hectares in size (Nagel and Diaci, 2006). Such events often result in a series of damaged patches across a storm track (Nagel et al., 2017).

The main effects of windthrow disturbance include opening of the canopy by removal of leaves and branches or snapping of tree trunks, conversion of living biomass to debris deposited on the forest floor (McDowell and Liptzin, 2014), and disturbances of the soil by uprooting trees (Kulakowski and Jarvis, 2011), creating pit and mound microtopography in forest soils (Šamonil et al., 2010). The creation of gaps in the canopy due to windthrow and the associated disturbance of ground vegetation led to sudden changes in solar radiation and other microclimatic variables (air and soil temperature, precipitation, humidity and wind) (Aussenac, 2000; Vilhar et al., 2015; Hirano et al., 2017; Kermavnar et al., 2020). In addition, in canopy gaps created by windthrow, water storage in the soil during the growing season is often high due to lower evapotranspiration compared to the surrounding forest, which can lead to higher soil water runoff in gaps (Ritter et al., 2005; Dalsgaard, 2007; Vilhar and Simončič, 2012; Vilhar, 2021). Microclimate affects nutrient release through decomposition and mineralization and, together with water fluxes, influences the loss of nutrients from the forest ecosystem (Bauhus and Bartsch, 1995; Ritter, 2005). Microclimatic changes (Ritter et al., 2005; Dalsgaard et al., 2011) and undesirable nutrient losses are less pronounced in small gaps in the canopy than in large open areas (Ritter, 2005).

At the catchment level, pulsed outputs of nitrogen in stream water have been observed following windthrow in the Luquillo Experimental Forest in Puerto Rico, clearly due to interactions between canopy vegetation damage and recovery, and decomposition of detrital inputs on the forest floor (McDowell and Liptzin, 2014). The input of leaves, branches, and snags to the forest floor releases carbon, nitrogen, and other nutrients as they decompose, and thus could contribute these solutes to stream runoff. At the same time, the opening of the forest canopy due to wind disturbance reduces nutrient uptake by trees and understory vegetation.

3.3.2. Ice storm

Severe ice storms in North America and East Asia can develop over larger areas (> 200,000 km^2) (Gyakum and Roebber, 2001; Changnon, 2003; Zhou et al., 2011). In Europe, the Dinaric Mountains in SE Europe are among the areas most affected by ice storms. Nagel et al. (2016) suggest that moderate to severe ice storms are relatively common in this region and play a more important role in forest dynamics than previously thought. The main impacts of ice storms are similar to those caused by wind or snow: Damage to tree crowns due to removal of leaves and branches or snapping of tree trunks during low storm intensity (Jakša and Kolšek, 2009). Tree uprooting and soil disturbance increase with higher ice storm intensity, especially for large trees on steep slopes (Nagel et al., 2016). The input of leaves, branches, and snags to the forest floor releases nutrients as they decompose, and at the same time, the opening of the canopy due to ice storms reduces nutrient uptake by trees and understory vegetation.

3.3.3. Fire

Forest fires play an important role in the dynamics of various terrestrial ecosystems, especially in arid and semi-arid areas, such as the Mediterranean region, affecting both biodiversity and human activities (Russo et al., 2017). In recent decades, there has been an increase in the number of extremely large fires and the extent of forest fires in Mediterranean regions worldwide (Salis et al., 2014). These fires have caused significant economic and ecological losses and even human casualties (ibid.).

It is now generally accepted that the most important factors influencing the fire ignition and spread of fires are: (i) the presence of fuel (i.e., biomass/vegetation); (ii) favourable weather patterns, often enhanced by appropriate climatic conditions prior to the fire season; (iii) socioeconomic conditions affecting land use/land cover patterns, fire prevention, and fire suppression capacity; and (iv) local topography (Flannigan et al., 2000; Pereira et al., 2011).

The importance and long history of fire disturbance in forest ecosystems is evidenced by the extensive literature examining the effects of fire on hydrology. Forest fires abruptly alter ground cover by consuming the litter layer and understory vegetation. Fire can also cause soil water repellence as soil heating vaporises organic material, which condenses and combines with the cooler underlying mineral soils below (Adams et al., 2012). Immediately after fires, transpiration and canopy interception decrease because the canopy is absent, but the increased exposure of bare soil and dark charred surfaces likely leads to increased evaporation. It can be >10% higher in burned forest than in unburned forest (Nolan et al., 2015). Increased overland runoff due to a combination of soil water repellence (Varela et al., 2015) and loss of soil organic horizons can lead to significant rill formation, erosion, loss of plant nutrients (Gimeno-García et al., 2000; Díaz-Raviña et al., 2012; Cawson et al., 2013; Nyman et al., 2014; Fernández and Vega, 2016; Prats et al., 2016; Robichaud et al., 2016), surface water quality decrease (Costa et al., 2014; Ferreira et al., 2016). Increased runoff, suspended sediment flows, and debris flows (Sheridan et al., 2011; Shin et al., 2013; Nyman et al., 2015) alter stream channel morphology through loss of root strength and cohesion (Owens et al., 2013) while reducing soil infiltration (Moody et al., 2008) and increasing streamflow (Seibert et al., 2010; Feikema et al., 2013; Mahat et al., 2016; Prats et al., 2016). Low severity fires rarely have such dramatic consequences, but generally result in consumption of understory biomass and death of smaller trees, as opposed to dieback that primarily kills larger canopy elements and potentially releases understory plants for more vigorous growth. Destruction of the tree canopy and understory following fire results in a drastic reduction in air absorption. The destruction of litter and humus can severely affect the water-holding capacity of the soil. However, some studies have shown that the reduction in evapotranspiration after fire can result in higher soil moisture content than before fire (Shu-Ren, 2003).

3.3.4. Pests and disease infestation

There are many species of insects and fungi that feed on or infect various parts of forest trees. They may contribute to the mortality of individual aging trees, which is part of the relatively continuous background mortality that determines the disturbance regime at the canopy gap level (Nagel et al., 2017). For example, in Dinaric alpine silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) forests in SE Europe, bark beetles are important secondary pests contributing to mortality of susceptible conifers (De Groot et al., 2018). Major bark beetle species that attack silver fir include *Pityokteines spinidens, P. vorontzowi, P. curvidens, Cryphalus piceae,* and *Pityophthorus pityographus*, while major species that attack Norway spruce include *Ips typographus* and *Pityogenes chalcographus*. However, under drought conditions, these bark beetles can cause outbreaks in stands with a high proportion of fir and spruce, and in larger areas (> 50,000 ha) can cause the death of otherwise healthy but drought-stressed trees (Nagel et al., 2017).

In some parts of western, central, or eastern Europe, recent bark beetle outbreaks have resulted in large landscapes with almost complete dieback of *Picea abies* forests (Čada et al., 2016). In addition to insects that can cause severe mortality patches during outbreaks, several species of pathogenic fungi could play an important role in individual tree mortality. The spatial extent over which these pathogens can spread and infect individual trees is not clear. Work in North America suggests that gap-makers that cause canopy damage to gap margin trees serve as entry points for pathogen spread, and that gap-makers infected with *Armillaria* can easily spread to adjacent trees (Worral et al., 2005).

Bark beetles disrupt two basic life-support transport processes of the trees they infest. Adult beetles eat phloem tissue to build egg galleries and developing larvae feed on phloem until sextual maturity. Phloem feeding by adult beetles and larvae contributes to some degree to phloem girdling and disrupts the transport of photosynthate from the canopy to other tissues in the tree. Bark beetles also carry a variety of spores of the four major fungal genera, many of which have been shown to be phytopathogenic (Hubbard et al., 2013). Once in the tree, the fungal spores introduced by the bark beetles germinate and the spreading fungal hyphae invade the water-conducting xylem tissue in the sapwood, blocking water transport from the soil to the canopy. Both fungal infection of the xylem tissue and damage to phloem by bark beetles can lead to tree death.

At the catchment scale, transpiration loss due to beetle mortality may be responsible for the relative increase in groundwater contribution to streams, which is often considered a sustainable fraction of runoff and is critical to upland water supplies and ecosystems (Bearup et al., 2014; Bernsteinová et al., 2015). In western North America, bark beetles have destroyed >100,000 km^2 of pine (*Pinus contorta*) forest, causing trees to lose most of their canopy, resulting in a 20% increase in snow accumulation under the canopy over the course of a season (Pugh and Small, 2013). In the high elevations of the Bavarian Forest National Park, Germany, Europe, persistent nitrate leaching was observed in spruce forests following bark beetle infestations (Huber, 2005). Following large scale bark beetle infestation in spruce forests in southeast Germany, maximum nitrate concentrations in runoff used for drinking water supply increased significantly, but only transiently at the headwater stream level (Beudert et al., 2015). Soil moisture and soil nitrogen content increased in soils under pines killed by mountain pine beetle in northern Colorado and southern Wyoming, USA, due to reduced evapotranspiration and litter accumulation and decomposition. However, the increase in soil nitrogen levels was not reflected in stream water chemistry (Clow et al., 2011). Bark beetle infestations in pine (*Pinus contorta* var. *latifolia*) forests in the Greater Yellowstone Ecosystem (WY, USA) altered nitrogen cycling in litter, soil, and vegetation, but changes in soil nitrogen cycling were less severe than those observed following stand-replacing fire. Several lines of evidence suggest that the potential for nitrogen leaching following bark beetle infestations in lodgepole pine is low (Griffin et al., 2011). No significant changes were detected when monitoring the hydrologic cycle in bark beetle-infested infections in Šumava, Czech Republic, Europe (Bila, 2016). However, a slow decline in water quantity is predicted due to local climate changes, i.e., increase in air temperature and decrease in precipitation.

3.3.5. Drought

Prehistoric droughts affected forest species composition beyond the landscape scale and centuries after their occurrence (Pederson et al., 2014). Drought is often cited as a major cause of forest mortality, probably because clear evidence of biotic influences has not always been found, although insects and pathogens may have been ultimately responsible for tree mortality in many events (Worral et al., 2005). Drought is an important determinant of water fluxes in forest ecosystems, regardless of tree species or climate zone. Transpiration, gross photosynthesis, and respiration (Nikolova et al., 2009) decrease sharply when the relative extractable soil water index falls below about 0.4 (Granier et al., 2003). Growth depression and loss of vitality are predicted under the stressful and uncertain conditions at the lower (xeric) limit of certain tree species (Mátyás et al., 2009). In Europe, the southernmost natural and planted forests are among the areas most affected by warming-induced drought (Sánchez-Salguero et al., 2015a). Severe growth loss and widespread defoliation in planted Mediterranean pine stands in response to drought indicate that they are more vulnerable and less resilient to drought stress than natural stands (Sánchez-Salguero et al., 2012; Sánchez-Salguero et al., 2013). In addition, *Abies pinsapo*, a relict drought-sensitive Mediterranean fir from southern Spain, Europe, exhibited a strategy to avoid water stress that was manifested by rapid stomatal closure at rather positive water potentials and relatively high values of soil moisture (Sánchez-Salguero et al., 2015b). These ecophysiological characteristics were similar to those of temperate and mountain conifers, although the seasonal pattern was typically Mediterranean. In addition, high temperatures and low precipitation in the summer and fall of the year prior to growth significantly reduced tree growth of five co-occurring conifers in Switzerland and northern Italy (Europe), regardless of the species and site conditions (Lévesque et al., 2014).

3.3.6. Forest management

In managed forests around the globe, anthropogenic disturbances such as forest management have been identified as one of the most important factors controlling both diversity and composition of forest vegetation (Decocq et al., 2005; Duguid and Ashton, 2013). Disturbances, including deforestation, are the main drivers of vegetation change in temperate forests. Gaps, as empty areas within the canopy, contribute fundamentally to forest ecosystem characteristics such as structural heterogeneity, tree species composition, understory vegetation variation, and overall species diversity (Kuuluvainen, 1994). The magnitude of the effects depends on the silvicultural system used. Systems that produce uniform age structure (e.g., clearcutting) have much greater impacts on forest stand characteristics compared to less intensive management alternatives (e.g., removal of single trees or groups of trees). Soil disturbance during tree felling and hauling can affect soil properties (soil depth, water holding capacity, soil hydraulic conductivity) that are important for hydrologic processes such as infiltration (Moore and Heilman, 2011; Bui et al., 2019), soil microbial activity and biomass (Wic Baena et al., 2013). Another example is post-disturbance interventions that rehabilitate damaged forests ("salvage logging") (Wagenbrenner et al., 2016). The use of heavy forestry equipment has profound effects on soil physical and chemical conditions (e.g., soil compaction) (Venanzi et al., 2016), soil loss, and runoff (Tague and Band, 2001; De Figueiredo et al., 2012). Forest thinning has the potential to be used as a water supply augmentation strategy through the reduction of sapwood and leaf areas that also decreases stand evapotranspiration (Hawthorne et al., 2013). Mulching has been successfully used as a soil conservation measure to reduce soil and water loss in a variety of contexts, including agricultural lands, fire-affected areas (Robichaud et al., 2013), rangelands, and anthropogenic sites (Prosdocimi et al., 2016), and plowing has also been used in some studies (Vieira et al., 2016).

3.3.7. Land use change

Although land-use change is a complex of many different land transformations, studies that address the effects of land-use change can provide valuable insights into the hydrologic responses of natural or semi-natural ecosystems. Certain analogies can be derived and compared to the effects of natural large-scale disturbances. Changes in land use may play an equally important role in forest dynamics and composition, especially in regions with a long history of human activities (Giuggiola et al., 2018). Conversions of tall canopy (e.g., natural forest) to short canopy (e.g., agricultural crops) or vice versa (e.g., conversion of grassland to shrubland) alters radiation balance, aerodynamic roughness, and maximum rooting depth, which often alters evapotranspiration (Moore and Heilman, 2011; Nosetto et al., 2012; Oliveira et al., 2018). Such changes have significant impacts on canopy interception (Li et al., 2019b), evapotranspiration, soil processes (Sun et al., 2018; Kalhoro et al., 2019), recharge dynamics (Menzel et al., 2009; Salemi et al., 2012; Yang et al., 2012; Lin et al., 2015; Zuo et al., 2016; Novotná et al., 2018; Oliveira et al., 2018; Li et al., 2019a) and nutrient leaching (Tang et al., 2011; Mareschal et al., 2013).

3.3.8. Climate change

Climate change affects hydrology directly by altering the total annual amount and seasonal distribution of precipitation and indirectly through changes in forest structure (e.g., climate induced tree mortality). Gradual changes in average climatic conditions (increases in temperatures) and extreme events affect forest productivity, vigour, and composition (Ciais et al., 2005; Mátyás et al., 2009). In the temperate zone, climatic conditions are becoming less favourable for mesophilic tree species, which is reflected in their decline. These species migrate to higher latitudes or higher elevations. In contrast, thermophilic forest species are expanding their range due to warmer and drier climates. These changes result in significant changes in key hydrologic processes, such as interception by tree canopies, evapotranspiration, soil infiltration, and recharge dynamics. Climate change is believed to increase the frequency and intensity of natural and anthropogenic forest disturbances (Seidl and Rammer, 2017; Kutnar et al., 2021), resulting in more open forest stands. Climate change impacts are closely associated with extreme weather events such as heat waves and prolonged droughts. A decline in water availability is particularly detrimental to karst aquifers (Hartmann et al., 2012). The increasing frequency of meteorological droughts is expected to lead to increasing low flows throughout the year and especially during the dry months, further worsening the already difficult situation for Mediterranean karst springs (Molina-Navarro et al., 2014; Nerantzaki and Nikolaidis, 2020; Sivelle et al., 2021).

3.3.9. Compound disturbances

As the frequency, size, and severity of disturbances increase, it becomes more likely that a single forest will be affected by multiple disturbances, and interactions with linked effects or composite effects can lead to unexpected consequences (Kulakowski et al., 2017). Compound disturbances have added a whole new dimension to understanding of how disturbances can alter natural forest ecosystems. Overlapping, composite, and/or sequential disturbances in space and time are common, complicating the task of isolating the time scales and severity of disturbance impacts (Wang et al., 2012; Mirus et al., 2017). For example, forest areas affected by windthrows are highly susceptible to bark beetle outbreaks (Eriksson et al., 2008) or fungal infestations. Furthermore, fungi that cause bole and root rot likely play an important role in increasing tree susceptibility to other abiotic disturbance agents (Worral et al., 2005). The vulnerability of monodominant, even-aged coniferous stands (e. g. *Picea abies*) is increased by prolonged periods of drought, especially on south-facing limestone sites at low elevations, with rocky, shallow soils and low water-holding capacity, where site-intolerant tree species often grow at their physiological limit of drought tolerance. In addition, southern European countries are particularly affected by summer drought events, where the occurrence of extreme meteorological conditions in the preceding and concurrent months increases the risk of summer wildfires (Russo et al., 2017). Another effect of compound disturbances is shown by a long-term study at Mayson Lake and Upper Penticton Creek in British Columbia: snow-dominated hydrologic response to the compound effect of natural disturbance and logging shows a significant change in snow accumulation and ablation under natural forest disturbance and clearcutting, with the magnitude of change varying by location, elevation, orientation and type of forest cover (Winkler et al., 2014).

3.4. Influence of large-scale forest disturbances on karst aquifers hydrology

In karst water drains through an aquifer system with triple porosity consisting of matrix (primary), fracture (secondary) and conduit (tertiary) porosity, which is characteristic of karst (White and White, 2005). After rapid infiltration into underground water flows through a hierarchically organized network of hydraulically connected voids that is very complex and may allow flow over long distances (Figs. 7 and 8; (Gabrovšek and Dreybrodt, 2001, Worthington and Ford, 2009). Because of their unique hydrogeologic characteristics, karst aquifers are particularly sensitive to environmental changes. Among these, changes in soil and vegetation cover play an important role as they regulate the water infiltrating into karst systems. (See Fig. 8.)

Karst soils are generally shallow or absent, resulting in limited water storage capacity (Vilhar et al., 2005), and nutrient cycling is limited to that between the surface organic layer and vegetation (Simončič, 2001; Katzensteiner, 2003). Where karst surface lacks thicker layers of soil, it is highly permeable, which allows rapid infiltration of water into the underground, resulting in little or even negligible surface runoff (Cantón et al., 2010). Rapid infiltration also reduces the potential for evapotranspiration (ibid.). The altered vegetation cover may enhance changes in recharge conditions by reduced interception. Consequently, water balance may significantly be affected by reduced evapotranspiration (Poljanšek et al., 2018), increasing effective infiltration, and reducing filtration (Dasgupta et al., 2006). This may on the one hand signify a lack of quality water or the more frequent occurrence of floods and debris flow downstream (Parise et al., 2015; Stevanović, 2018).

With damaged or destroyed forests, karst areas often suffer from rocky desertification, especially in semi-humid and humid climates, resulting in increased soil erosion and organic matter loss. This can result in the removal of any thin soil that may have been present, leaving rocks largely exposed. If no soil is present, it is more difficult to restore the forest. Furthermore, any kind of forest damage also leads to ecosystem degradation and loss of biodiversity.

Unlike some other types of environments, changes in karst are noticeable not only on the surface but also in the underground (Fig. 9). In the underground increased infiltration may lead to changes in the chemical and microbiological status of the water and an increase in groundwater levels. Also, CO_2 composition may change, which is critical for the karstification and karst development (Urich, 2002; White, 2015). These changes can alter percolation of drips in the vadose zone and speleothem growth. Increased and accelerated infiltration is usually favoured during storm events. As a result, there may be differences in storage capacities of overlying layers, flow rates, variations in flow directions, and thus in the contribution of different parts of the aquifer to a given spring (Zhang et al., 2011; Ravbar, 2013). An increase in groundwater level can cause steeper gradients, reduce the thickness of

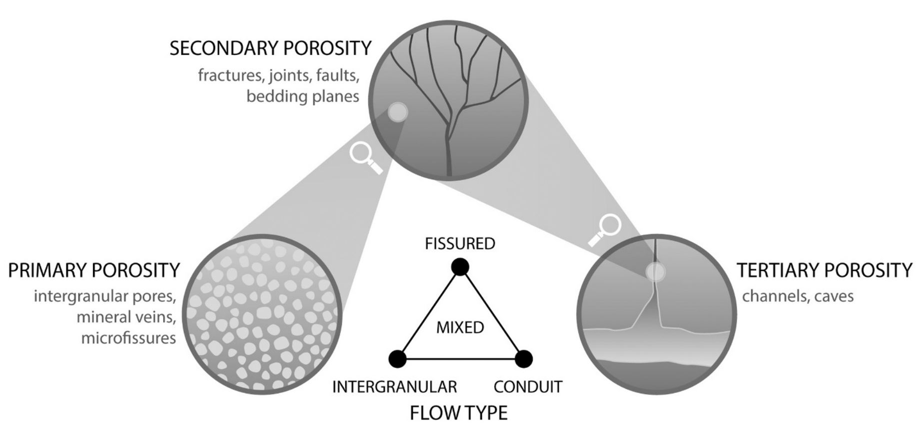

Fig. 7. Schematic presentation of the triple porosity of karst aquifers (Ravbar and Pipan, 2022).

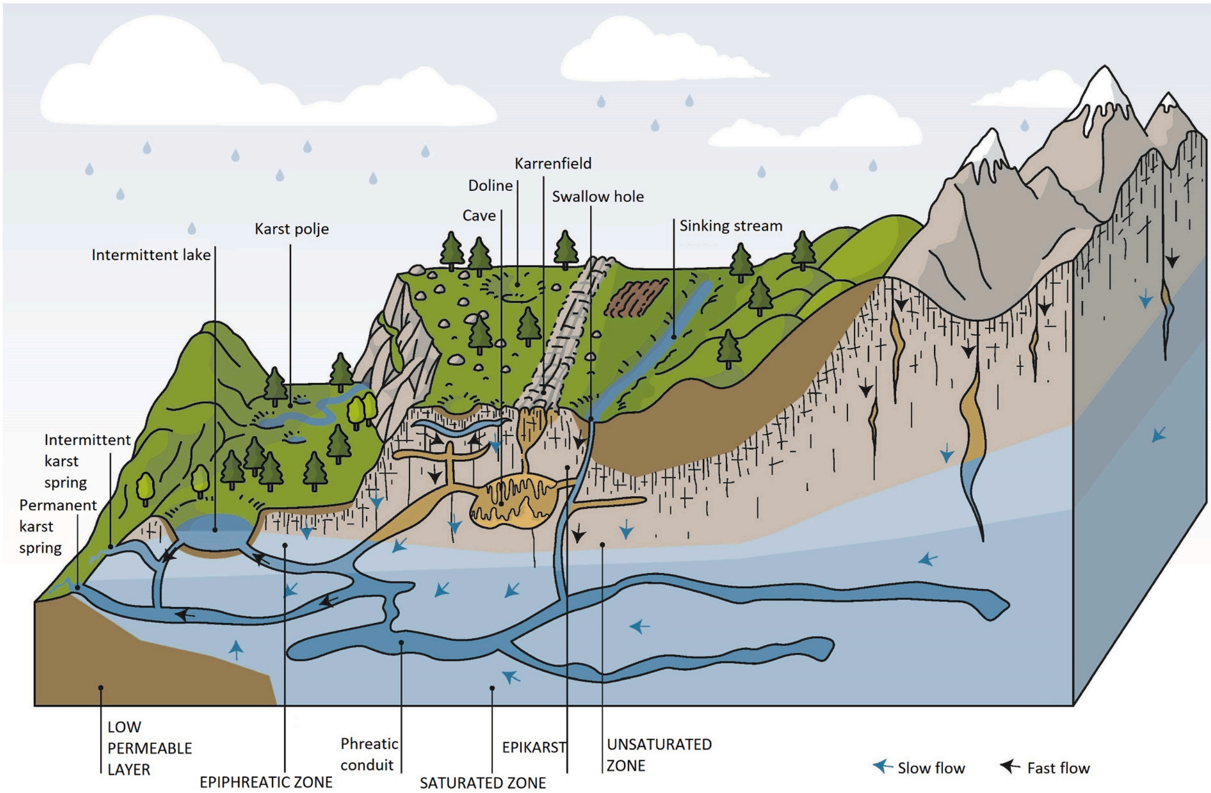

Fig. 8. A diagram showing distinctive characteristics of water infiltration and flow in karst aquifers (Ravbar and Šebela, 2015).

the unsaturated zone, and reduce the protective effect of the overlying strata. It can also lead to higher flow velocities, reducing retention in the underground. Because of the correspondingly more turbulent flow, the transport and remobilization of solutes and insoluble matter is more effective. Therefore, increased sediment transfer in the aquifer can be expected (Urich, 2002; Göppert and Goldscheider, 2008). Contamination removal processes that are time-dependent are less effective (e. g., the death of pathogenic organisms).

Regarding the effects of large-scale forest disturbances on hydrology similar general conclusions as described in Section 3.3 apply to karst aquifers. However, specific consequences may vary depending on local conditions (Zhang and Wei, 2014), because karst is very heterogeneous, and consequences may be unpredictable. Some specific findings from studies of karst are described below.

3.4.1. *Windthrow*

The study by Hartmann et al. (2016), conducted in an Austrian karst system, aimed to determine the impact of windthrow on groundwater DIN (dissolved inorganic nitrogen) and DOC (dissolved organic carbon). Based on modelling, it was found that forest disturbance by windthrow resulted in a large increase in DIN production and no significant changes in DOC concentrations.

3.4.2. *Fire*

In Aleppo pine (*Pinus halepensis* M.) forests, increased soil water repellence occurred after fire experiments and ash removal, although persistence and intensity varied greatly both spatially and temporally (Jiménez-Pinilla et al., 2016). Increasing intensity of wildfires in Mediterranean forests in central Spain was accompanied by a decrease in soil organic matter accumulation (Knicker et al., 2006). It was reported that runoff formation and soil erosion increased at Pedon level after reforestation in the Mediterranean with Aleppo pine, where holm oak (*Quercus ilex* subsp. *rotundifolia* L.) naturally dominated (Cerdà et al., 2017).

3.4.3. *Drought*

Reliable assessment of the water availability to plants and resulting drought stress is particularly important in highly permeable recharge areas such as karst landscapes (Vilhar, 2016), where long-term surface runoff may be considered negligible and potential recharge is often calculated as the difference between precipitation and evapotranspiration (Cantón et al., 2010). Since direct measurement of the components of the water balance (runoff, interception, evapotranspiration, and infiltration) is not possible in most cases, they must be estimated, often using precipitation and other meteorological data (temperature, net radiation, or saturation water vapour pressure deficit), soil properties, and plant cover characteristics. In addition, soil water balance techniques tend to fail in karst areas because of the heterogeneity of soil thicknesses. Measurements of energy and water vapour fluxes on the Edwards Plateau in Texas, USA, have shown that higher densities of woody plants do not necessarily result in higher water use, due at least in part to the limitations imposed by shallow soils with limited water storage capacity and lack of access to readily available sources of deep water (Heilman et al., 2012). Because soil depth varies widely across the plateau, the impact of woody plants on water use is highly dependent on local geology and rainfall (Dasgupta et al., 2006). In addition, native trees growing on shallow karst soils in northern Yucatan are reported to use little or no groundwater and depend mainly on water stored in the upper 2–3 m of the soil/rock profile. Water storage in underground soil-filled cavities and in porous limestone bedrock is apparently sufficient to sustain mature evergreen trees during the pronounced dry season (Querejeta et al., 2007).

3.4.4. *Forest management*

The discussion in the forestry literature on karst is dominated by the negative impacts of deforestation on the karst ecosystem and the resulting consequences for the sustainability of economic activities (Urich, 2002). Felling of trees in experimental catchments has repeatedly been shown to increase runoff by an amount equal to the previous

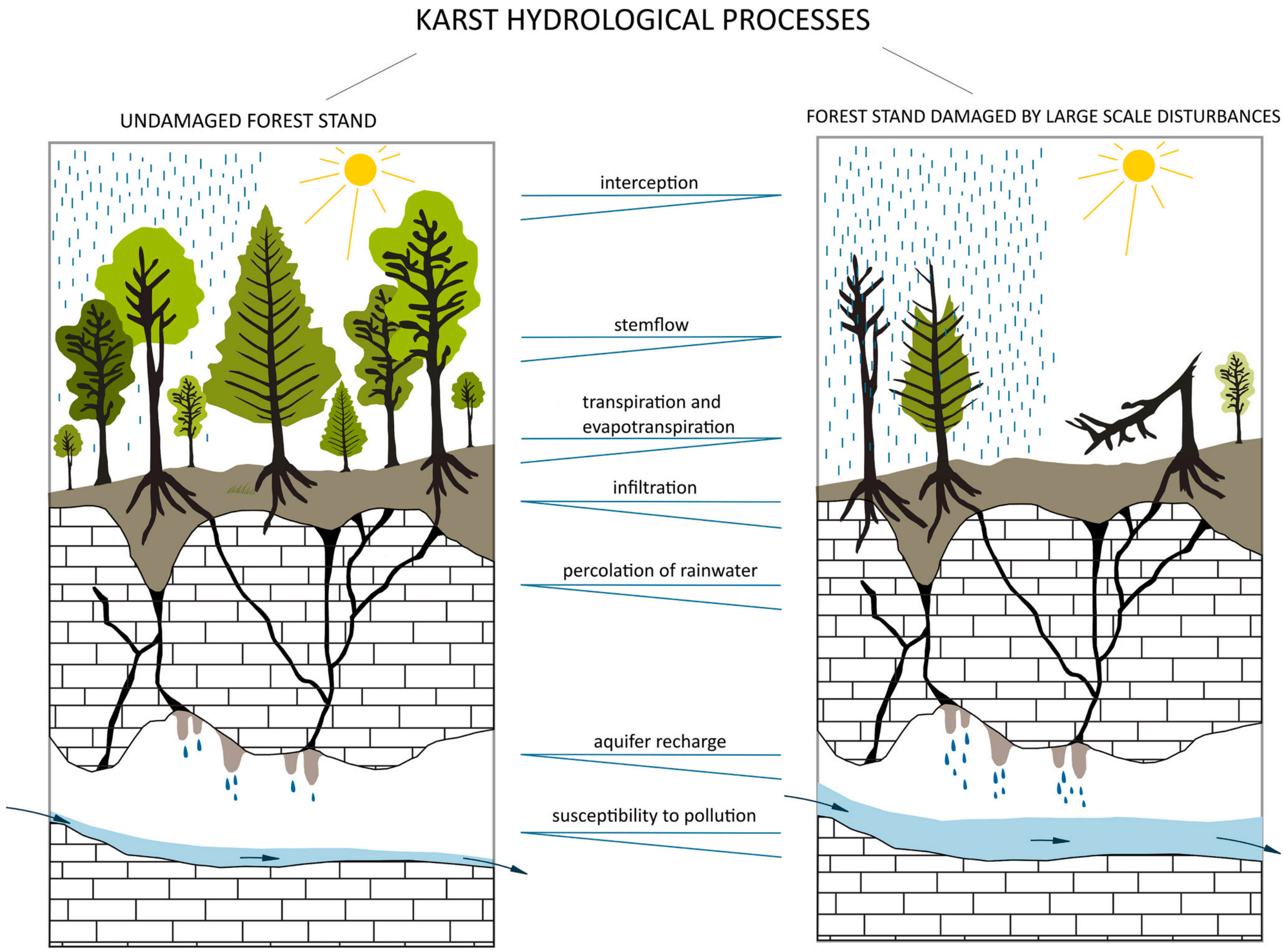

Fig. 9. Schematic representation of the characteristics of the karst aquifer and evaluation of the basic hydrological processes through the karst aquifer. In general, after large-scale forest disturbance interception and stemflow are expected to decrease because of the damaged forest. Consequently, infiltration and percolation of water through the aquifer are expected to increase, which means higher groundwater recharge and greater susceptibility to pollution. Changes in hydrological processes are indicated by the signs "greater than", "less than".

losses through evapotranspiration from the forest stand. This represents a very large increase in kinetic energy available for erosion and transport of soil and debris. Such an increase leads to downward movement of soil, especially if the protective ground cover is disturbed by burning or machinery. In addition, clearcutting results in significant soil loss and eroded soil on the limestone deposits in the epikarst and shallow microcaves. Evidence to date indicates that large trees will no longer grow on the eroded, bare limestone slopes (ibid.). To explore management implications in the context of a climate-change scenario of increasing aridity in a dryland Aleppo pine forest (*Pinus halepensis* Mill.) in Israel, Ungar et al. (2013) combined water balance data (Raz-Yaseef et al., 2012) with assumptions regarding tree minimum transpiration. This first approximation of sustainable forest density approach indicates that the Yatir forest should be thinned to stands of 250 or 190 trees ha^{-1} in order to remain sustainable under annual rainfall regimes of 200 or 150 mm, respectively (ibid.). Reduction of stand density was shown to increase drought resistance in xeric Scots pine (*Pinus sylvestris* L.) forests in Valais, a dry Inner-Alpine valley in Switzerland (Giuggiola et al., 2013), whereas the removal of the understory vegetation further decreased tree water deficit and increased sap flow of Scots pine trees (Giuggiola et al., 2018).

In the Dinaric karst forests, there is a long tradition of sustainable, close-to-natural forest management and systematic silvicultural planning (Bončina et al., 2003) to minimize the negative impacts of forest management due to historical lessons learned from catastrophic, irreversible soil degradation in the Kras region (Gams, 2003; Perko, 2016). Creating gaps in the canopy by removing only a small group of trees, or the traditional irregular shelterwood system of Matthews (1999), has been applied in the Slovenian forestry school to mimic as closely as possible the natural disturbance regimes and structural characteristics of old-growth forests (Schütz et al., 2016; Kermavnar et al., 2019). The relationship between forestry interventions and wind disturbance regimes in temperate forests of Central Europe explains the relatively large number of case studies found in this literature search comparing natural regeneration patterns and microclimatic conditions in managed, experimental or naturally occurring canopy gaps and their effects on hydrology (Vilhar et al., 2005; Vilhar et al., 2010; Vilhar and Simončič, 2012; Vilhar et al., 2015; Vilhar, 2016). In this synthesis the disturbance for such case studies was categorized as "forest management". Most of these studies are limited to the plot level and do not consider underground recharge processes on catchment or regional level.

3.4.5. Land use change

The effects of land use change on evapotranspiration processes (Moore and Heilman, 2011; Ferlan et al., 2016; Reichert et al., 2017), soil processes (Guan and Fan, 2020) and recharge dynamics (Zhang et al., 2011; Van Beynen and Bialkowska-Jelinska, 2012; Yu et al., 2015; Berthelin et al., 2020) are examined. By comparing several case studies, the complex interaction of factors affecting transpiration was illustrated and it was concluded that changes in land use do not necessarily lead to changes in transpiration (Moore and Heilman, 2011). The effect of vegetation restoration on soil quality were evaluated using the soil quality index and the benefits of different types of vegetation restoration were compared. The study concludes that it is important to select an appropriate vegetation type and recover over a long period of time in restoration projects to achieve better soil quality (Zhang et al., 2019; Guan and Fan, 2020).

The impacts of land use changes on karst hydrology are often exacerbated by impacts of climate changes (Molina-Navarro et al., 2014; Xu et al., 2018) as shown in selected case studies. Groundwater levels are expected to rise in all landscapes following timber harvest, although the magnitude and duration of this rise will vary depending on the geology and topography of the area. Changes in groundwater levels at the local scale are often more pronounced than at the regional scale (Smerdon et al., 2009). To understand the effect of restoration thinning on the water balance of semi-arid upland pine forests in the southwestern United States, the components of the forest water balance were compared between a non-thinned plot and a thinned plot. However, the results underscore the importance of drought and climate as factors determining the effects of thinning on water balance (Simonin et al., 2007). A soil moisture monitoring network was implemented at five representative sites across the globe to characterize karstic groundwater recharge and evapotranspiration processes. The measuring network will provide comprehensive data to develop and test new conceptual models of the functioning of the soil and epikarst, depending on land use and climate (Berthelin et al., 2020). Based on the analysis of runoff variation characteristics of long time series in a karst region in Southwest China, the contribution rates of climate and land use changes to net runoff variation were estimated quantitatively (Xu et al., 2018).

3.4.6. Climate change

Karst hydrology is expected to exhibit significant alterations due to climate change. As a consequence of climate change, increasing frequency of severe wildfires has been already observed (Seidl and Rammer, 2017). Furthermore, different climate change projections identified the Mediterranean as a region particularly vulnerable to climate change (Hartmann et al., 2012). Karst areas in Mediterranean region are often characterized by very dry upper layers of soil and vegetation is exposed to drought stress due to high air temperatures and quick drain of the rainfall into the karst underground (Poljanšek et al., 2018).

3.4.7. Compound disturbances

A study at the catchment level examining the effects of wind disturbances following ice storms and bark beetle infestations in Dinaric alpine silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) forests showed that large-scale forest disturbance resulted in increased effective precipitation and groundwater recharge in the Unica karst aquifer in Slovenia (Kovačič et al., 2020).

3.4.8. Detailed studies of groundwater recharge and groundwater flow

Only 3 out of 47 case studies in karst areas in this synthesis address groundwater recharge and groundwater flow in detail. The use of numerical hydrological models in karst is limited due to its heterogeneous structure and lack of field data. One possible solution is to use lumped models. One such example is the semi-distributed model LuKARS, which is based on hydrotopes, a particular landscape unit characterized by homogeneous hydrological properties as a result of similar land use and soil types (Bittner et al., 2018). Flows from each hydrotope represent a specific response of the vadose zone (soil-epikarst-infiltration zone) in a defined recharge area. The saturated zone consists of a single linear storage unit that is recharged independently by each hydrotope. In the catchment-scale case study, hydrotopes were classified based on mapped characteristics of vegetation and soil. In addition, catchment size data and a single time series of meteorological data were used. By validating the calibrated model in a period when the area of dolomite quarries in the study area nearly doubled, negative impacts of such land-use change on the water supply of the nearby town were demonstrated and quantified. A process-based, semi-distributed karst model was used to simulate solute transport through a dolomite karst system in Austria to assess the effects of windthrow on karst water quality (Hartmann et al., 2016). Variability in karst system properties is accounted for by statistical distribution functions distributed across multiple model compartments, and contaminant transport is modelled using a solute transport routine. Data on precipitation, snow water equivalent, discharge and chemical parameters of water were used. The model was calibrated and validated during a period just prior to a series of heavy storms that severely impacted the study area ecosystem. The model was then used to quantify the effects of windthrow for the entire period of disturbance. Although the area affected was relatively small, the results demonstrate that extreme events can lead to significant increases in pollutants in runoff. It was also proved that a hydrologic system can filter and delay surface loads. On a limited time scale, it can remember past loads and lead to a significant delay in pollution.

An upgrade of this model is the V2Karst V1.1 model, an integrated vegetation-recharge model used to simulate the effects of climate and land cover change in karst regions at large scales (Sarrazin et al., 2018). Advances in evapotranspiration modelling are particularly important. It includes a physically based potential evapotranspiration equation, separates evapotranspiration flux into three components (transpiration, evaporation from bare soil, and evaporation from canopy interception), and includes three soil layers. The plausibility of the simulations was demonstrated at four experimental sites. Data on precipitation, temperature, net radiation, relative humidity, wind speed, heat flux and soil moisture were used. Modelling showed that the model is able to reproduce observations of latent heat and soil moisture, and that the parameters dominating the sensitivity of the model are consistent with the perception of expected controls on recharge. The use of virtual experiments with synthetic precipitation and land cover scenarios confirmed that the model has plausible sensitivities to climate and land cover changes. Therefore, it allows the holistic investigation of the joint effects of large-scale land cover and climate changes on groundwater recharge in karst regions.

The groundwater flow system in all the models described is highly simplified, is not based on field measurements, and its characteristics are determined as part of the calibration process. Only one of the studies (Hartmann et al., 2016) actually addresses large-scale disturbances and assesses their effects on karst water resources based on real data. Thus, there is a serious lack of field-based analyses to examine the effects of various factors on the recharge process in the vegetation-soil-aquifer system in karst areas affected by large-scale forest disturbances.

4. Synthesis and key knowledge gaps

Of the 160 case studies of large-scale forest disturbance impacts on hydrology included in this study's matrix dataset, about half (53%) were conducted at the plot level and one-third (34%) at the catchment level. Only 13% of the case studies were conducted at the regional level. Most case studies addressed natural large-scale forest disturbances (39%) and were mostly conducted at the plot level; only two case studies were at the regional level. The effects of land use change on hydrology were examined in 25% of the case studies, with the catchment level dominating (38%), followed by the regional (35%) and plot level (28%). In contrast, the effects of forest management interventions on hydrology were examined in 21% of the case studies, with most (82% or 27 of 33) at the plot level. There were only six catchment-level case studies and no regional-level case studies of forest management impacts on hydrology in the matrix dataset. Climate change impacts on hydrology were mostly studied at the regional and catchment level, while compound disturbances were mostly studied at the plot level.

Hydrological processes examined in the case studies mostly focused on recharge dynamics (37%), followed by soil processes (34%) and evapotranspiration (29%). A striking number of case studies addressed the effects of fire on soil processes (13%), indicating the severity of wildfire risk. Despite the increasing risk and severity of droughts worldwide, there were no case studies that addressed the impact of drought on soil processes. In addition, there were only two case studies that focused on how evapotranspiration is affected by compound disturbances, one that focused on how recharge dynamics are affected by drought, and one that focused on how recharge dynamics are affected by windthrow.

Unfortunately, it was not possible to quantitatively analyse the results of the studies due to a lack of information that comprehensively covered various large-scale forest disturbances and selected hydrologic processes. There were studies that addressed only a single large-scale forest disturbance and specific hydrologic processes. In addition, the studies used different methodologies and research approaches, so their results were not comparable.

As indicated by the matrix dataset in this study, a growing body of literature has addressed the effects of forest management, land use change, and/or climate change on hydrologic processes in karst areas over the past 20 years. Parallels could be drawn between these human-induced changes and large-scale forest disturbances on karst aquifer hydrology, such as changes in forest cover, forest structure, soil properties, etc., and were therefore included in this literature review.

The synthesis showed that about 29% of the case studies included in the matrix dataset were on carbonate rocks. Considering that karst occupies one sixth of the land area and 4.7% of the land area is covered by karst forests, this percentage is very high. This means that the study of karst areas covered with forests is of great interest to the scientific community. However, most of the field studies conducted to date have been at the plot level (74% or 35 of 47 case studies), followed by 23% catchment-level case studies and only one regional level case study on the effects of land use change on recharge dynamics. This indicates that there are virtually no regional studies on the effects of large-scale disturbance on karst hydrology. Studies dealing with forest management (36% or 17 of 47 case studies) and land use change (32%) strongly predominate, while there are far fewer studies on natural large-scale forest disturbance (21%). Most studies examined the effects of forest management on evapotranspiration and recharge dynamics (13%), but fewer studies addressed soil processes (11%). More evenly distributed were case studies on the effects of land use change on evapotranspiration (11%), soil processes, and recharge dynamics (9% each). Among natural large-scale forest disturbances, fire impacts on soil processes were the most frequently studied (9%), while the other types of natural impacts were studied only in isolated cases. No single article was found on the effects of pest and disease infestations or ice storms on hydrology; only one study examined a compound effect of ice breakage, bark beetle infestations, and windthrow on groundwater recharge.

In addition, few studies address groundwater recharge and groundwater flow at depth. Although studies on the effects of large-scale disturbance on evapotranspiration processes between vegetation, air, and soil are well represented, infiltration and recharge processes in karst areas are poorly understood, and information on groundwater flow and associated hydrological processes is particularly lacking. Due to the insufficient understanding of the hydrological functions of soil and vegetation in relation to recharge mechanisms, there are gaps in knowledge about infiltration processes in the upper part of the unsaturated zone of karst aquifers. Therefore, these hydrological relationships to total groundwater recharge should be further investigated.

The above results are surprising, since karst water resources are very valuable and there are cases of springs drying up worldwide. The difficulty of making direct hydrological measurements is a major problem in such cases. Moreover, the use of numerical hydrological models in karst is limited due to its heterogeneous structure and lack of field data. And even in the models that could predict the described processes, the groundwater flow system is highly simplified, is not based on field measurements, and its characteristics are determined in the calibration process. Further development of modelling approaches should address these issues.

Although speleological research allows direct observation of water flow in aquifers, water caves are not always accessible and form only a part of the total water network. Other access points to subsurface karst, such as wells, provide easier access. However, there are few study areas with larger numbers of wells that would provide information that could be interpolated to larger scales. Consequently, little is yet known about how various environmental changes and stresses affect recharge conditions in karst. More in-depth research and monitoring is needed that takes advantage of karst-specific research methods and approaches (e.g., natural and artificial tracer monitoring, GIS and remote sensing, modelling).

Another challenge in karst ecohydrology appears to be the transfer of plot level case studies to the catchment or aquifer scale. Plot-based measurements are central to most forest inventory programs around the world (Bechtold and Patterson, 2005; FAO, 2009; Ferretti and Fischer, 2013) and enable a controlled experimental setting with permanent plots tracked and remeasured over time (Bürgi et al., 2015). While some studies upscale certain forest ecosystem functions using spatially sparse measurements at plot level (Bechtold and Patterson, 2005), these estimates can exhibit considerable temporal and spatial variation and uncertainty (Xiao et al., 2011). In ecology, the "space-for-time substitution" approach is often used as an alternative to long-term studies, assuming that spatial and temporal variations are equivalent (Pickett, 1989). Although this assumption has been challenged, studies continue to rely on it out of necessity or convenience (Wogan and Wang, 2018). However, the »space-for-time substitution« approach may not be tenable for studying the effects of large-scale forest disturbance, as certain transient effects can only be determined through long-term studies (ibid.). Regarding karst hydrology, upscaling with e. g. numerical models or machine learning seems promising, but care should be taken to avoid errors and biases due to the very large heterogeneity and anisotropy of groundwater flow patterns. There are also large differences between the studies conducted in terms of geographic distribution. On the one hand, studies are concentrated, for example, in the Mediterranean region, Texas, and southwestern China, while on the other hand they are completely absent in Canada, New Zealand, South America, Africa, and elsewhere, where large forests cover karst areas. The reasons for this are partly that forests underlain by carbonate rocks are particularly common in temperate climates and often have high floristic and ecological biodiversity because of their unusual environment and isolation. In addition, forest management in some countries has traditionally been carried out according to the highest sustainability standards and with a long tradition of systematic silvicultural planning to minimize the negative impacts of forestry interventions. For example, the Dinaric alpine silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) forests in SE Europe are of remarkable conservation interest and timber production functions and form one of the best-preserved forest ecosystem complexes in Europe (Kutnar et al., 2015). Some karst areas are sparsely populated (e. g., Siberia), and forest and water potential remain untapped. Finally, financial support for research and motivation to publish articles in international journals are also important factors limiting access to information in some countries. It is necessary to find solutions to the above problems and to strengthen studies in forest-rich karst areas.

5. Conclusions

This study provides the first global overview of the effects of large-scale forest disturbance on hydrological processes. The existing literature was reviewed, and the main findings summarized.

Of the 160 case studies of the effects of large-scale forest disturbance on hydrology included in the matrix dataset of this study, about half were conducted at the plot level and one-third at the catchment level. Only 13% of the case studies were conducted at the regional scale.

Nearly 40% of the case studies addressed natural large-scale forest disturbances and were mostly conducted at the plot level. Hydrological processes examined in the case studies were primarily recharge dynamics (37%), followed by soil processes (34%) and evapotranspiration (29%). A large number of case studies (21%) addressed the effects of fire on soil processes and recharge dynamics.

Because karst aquifers are characterized by specific hydrological processes and are valuable for their many natural resources, special attention was given to the effects of large-scale forest disturbance on karst hydrology. For the first time, an analysis of the spatial distribution of forests on carbonate rocks was conducted at the global and regional scales. Forests on carbonate rocks cover 6.34 M km^2 (31.3% of all karst areas), which means that 13.9% of the world's forests are found in karst areas. They are most widespread in Asia (3.01 M km^2), North America (1.39 M km^2) and Europe (0.76 M km^2). Although large-scale forest disturbances are an integral part of forest ecosystem dynamics, any type of deforestation can significantly alter recharge processes. In karst areas, this can lead to long-term ecosystem degradation, biodiversity loss, soil erosion, reduced water storage, altered nutrient cycling and increased sediment transport. This can lead to a reduction in CO_2 levels and the efficiency of karst processes, which are essential for karst development. It can also lead to increased vulnerability of groundwater resources to contamination and altered quality and quantity of karst water resources.

Although research on karst areas covered by forests is relatively extensive (nearly 30% of the case studies included in the matrix dataset), few studies address groundwater flow in depth. In particular, very little research has been done on the processes of percolation and recharge. The overall effects of large-scale forest disturbances on water resource quality and quantity have also not been adequately studied. Studies dealing with forest management and land use change (68%) strongly predominate, while there are far fewer studies on natural large-scale forest disturbance. Most of the studies conducted to date are at the plot level. There are virtually no holistic regional studies of the effects of large-scale disturbance on karst hydrology.

This study is aimed at scientists and researchers concerned with the effects of changes in vegetation cover on hydrological processes. The work provides new insights into the subject and is an important contribution to national and international research activities and discussions in karst ecohydrology. It is an important source of information and ideas for further research in the field of natural resource protection. Because karst is a complex system, an interdisciplinary approach is needed that incorporates the multiple aspects of several disciplines, in this case primary forest ecology and karst knowledge. It is extremely important to understand the holistic influence of vegetation on surface and subsurface hydrological processes in karst. The deeper insights gained in this study can be useful for forest policy and management, especially with respect to hydrological understanding of karst systems. They can also help land-use planners make decisions for appropriate protection and management of karst water resources.

Author contributions

All authors participated significantly in the methodological preparation of the paper, data collection, their analysis and interpretation, as well as contributed to graphical production.

Urša Vilhar: Conceptualization; Data curation and analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing original draft, review & editing.

Janez Kermavnar: Conceptualization; Data curation and analysis; Investigation; Methodology; Validation; Visualization; Writing original draft, review & editing.

Erika Kozamernik: Conceptualization; Data curation and analysis; Investigation; Methodology; Validation; Visualization; Writing original draft, review & editing.

Metka Petrič: Conceptualization; Data curation and analysis; Investigation; Methodology; Validation; Visualization; Writing original draft, review & editing.

Nataša Ravbar: Conceptualization; Data curation and analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing original draft, review & editing.

All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was conducted within the context of the eLTER Preparatory Phase Project (eLTER PPP), eLTER Advanced Community Project (eLTER PLUS) and »Development of research infrastructure for the international competitiveness of the Slovenian RRI space – RI-SI-LifeWatch«, financed by the Republic of Slovenia, Ministry of Education, Science and Sport and the European Union from the European Regional Development Fund. We thank the Slovenian Research Agency for financial support within the projects Infiltration processes in forested karst aquifers under changing environment (No. J2-1743), Ecohydrological study of spatio-temporal dynamics in karst critical zones under different climate conditions (No. NK-0002), the Research Programme "Forest biology, ecology and technology" (No. P4–0107) and Karst Research Programme (No. P6-0119).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2022.104243.

References

Adams, H.D., Luce, C.H., Breshears, D.D., Allen, C.D., Weiler, M., Hale, V.C., Smith, A.M. S., Huxman, T.E., 2012. Ecohydrological consequences of drought- and infestation-triggered tree die-off: insights and hypotheses. Ecohydrology 5, 145–159.

Anderegg, L.D.L., Anderegg, W.R.L., Abatzoglou, J., Hausladen, A.M., Berry, J.A., 2013a. Drought characteristics' role in widespread aspen forest mortality across Colorado, USA. Glob. Chang. Biol. 19, 1526–1537.

Anderegg, L.D.L., Anderegg, W.R.L., Berry, J.A., 2013b. Not all droughts are created equal: translating meteorological drought into woody plant mortality. Tree Physiol. 33, 701–712.

Angulo, B., Morales, T., Uriarte, J.A., Antigüedad, I., 2013. Implementing a comprehensive approach for evaluating significance and disturbance in protected karst areas to guide management strategies. J. Environ. Manag. 130, 386–396.

Atkinson, T.C., 1977. Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). J. Hydrol. 35, 93–110.

Aussenac, G., 2000. Interactions between forest stands and microclimate: ecophysiological aspects and consequences for silviculture. Ann. For. Sci. 57, 287–301.

Bakalowicz, M., 2005. Karst groundwater: a challenge for new resources. Hydrogeol. J. 13, 148–160.

Bauhus, J., Bartsch, N., 1995. Mechanisms for carbon and nutrient release and retention in beech forest gaps. I. Microclimate, water balance and seepage chemistry. Plant Soil 168, 169, 579–584.

Bearup, L.A., Maxwell, R.M., Clow, D.W., Mccray, J.E., 2014. Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds. Nat. Clim. Chang. 4, 481–486.

Bechtold, W.A., Patterson, P.L. (Eds.), 2005. The enhanced forest inventory and analysis program - national sampling design and estimation procedures. USDA Forest Service, Southern Research Station, Asheville, N.C., USA, p. 90.

Bernsteinová, J., Bässler, C., Zimmermann, L., Langhammer, J., Beudert, B., 2015. In: Changes in runoff in two neighbouring catchments in the Bohemian Forest related to climate and land cover changes, 63, p. 342.

Berthelin, R., Rinderer, M., Andreo, B., Baker, A., Kilian, D., Leonhardt, G., Lotz, A., Lichtenwoehrer, K., Mudarra, M., Padilla, I.Y., Pantoja Agreda, F., Rosolem, R., Vale, A., Hartmann, A., 2020. A soil moisture monitoring network to characterize karstic recharge and evapotranspiration at five representative sites across the globe. Geosci. Instrum. Method. Data Syst. 9, 11–23.
Bertini, G., Amoriello, T., Fabbio, G., Piovosi, M., 2011. Forest growth and climate change: evidences from the ICP-Forests intensive monitoring in Italy. iForest -. Biogeosci. Forest. 4, 262–267.
Beudert, B., Bässler, C., Thorn, S., Noss, R., Schröder, B., Dieffenbach-Fries, H., Foullois, N., Müller, J., 2015. Bark beetles increase biodiversity while maintaining drinking water quality. Conserv. Lett. 8, 272–281.
Bila, K., 2016. Are bark beetles responsible for droughts in the Šumava Mts.? A mini-review. Eur. J. Environ. Sci. 6, 108–113.
Bittner, D., Narany, T.S., Kohl, B., Disse, M., Chiogna, G., 2018. Modeling the hydrological impact of land use change in a dolomite-dominated karst system. J. Hydrol. 567, 267–279.
Bonacci, O., Pipan, T., Culver, D.C., 2009. A framework for karst ecohydrology. Environ. Geol. 56, 891–900.
Bončina, A., Diaci, J., Gašperšič, F., 2003. Long-term changes in tree species composition in the Dinaric mountain forests of Slovenia. For. Chron. 79, 227–232.
Bréda, N., Huc, R., Dreyer, E., Granier, A., 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Ann. For. Sci. 63, 625–644.
Breshears, D.D., 2006. The grassland–forest continuum: trends in ecosystem properties for woody plant mosaics? Front. Ecol. Environ. 4, 96–104.
Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., Romme, W. H., Kastens, J.H., Floyd, M.L., Belnap, J., Anderson, J.J., Myers, O.B., Meyer, C.W., 2005. In: Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences of the United States of America, 102, pp. 15144–15148.
Brook, B.W., Sodhi, N.S., Bradshaw, C.J.A., 2008. Synergies among extinction drivers under global change. Trends Ecol. Evol. 23, 453–460.
Bui, X.D., Vu, T.H.T., Nguyen, T.M.L., Gomi, T., 2019. Temporal and spatial infiltration characteristics of soil under acacia and pine plantations in the mountainous area of Van Don, Quang Ninh,Vietnam. J. Vietnam. Environ. 51–64.
Bürgi, M., Li, L., Kizos, T., 2015. Exploring links between culture and biodiversity: studying land use intensity from the plot to the landscape level. Biodivers. Conserv. 24, 3285–3303.
Čada, V., Morrissey, R.C., Michalová, Z., Bače, R., Janda, P., Svoboda, M., 2016. Frequent severe natural disturbances and non-equilibrium landscape dynamics shaped the mountain spruce forest in Central Europe. For. Ecol. Manag. 363, 169–178.
Cannon, S.H., Kirkham, R.M., Parise, M., 2001. Wildfire-related debris-flow initiation processes, storm King Mountain, Colorado. Geomorphology 39, 171–188.
Cantón, Y., Villagarcía, L., José Moro, M., Serrano-Ortíz, P., Were, A., Javier Alcalá, F., Kowalski, A.S., Solé-Benet, A., Lázaro, R., Domingo, F., 2010. Temporal dynamics of soil water balance components in a karst range in southeastern Spain: estimation of potential recharge. Hydrol. Sci. J. 55, 737–753.
Cawson, J.G., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2013. Effects of fire severity and burn patchiness on hillslope-scale surface runoff, erosion and hydrologic connectivity in a prescribed burn. For. Ecol. Manag. 310, 219–233.
Cerdà, A., Lucas Borja, M.E., Úbeda, X., Martínez-Murillo, J.F., Keesstra, S., 2017. Pinus halepensis M. Versus Quercus ilex subsp. Rotundifolia L. Runoff and soil erosion at pedon scale under natural rainfall in Eastern Spain three decades after a forest fire. For. Ecol. Manag. 400, 447–456.
Changnon, S.A., 2003. Characteristics of ice storms in the United States. J. Appl. Meteorol. 42, 630–639.
Chen, Z., Auler, A.S., Bakalowicz, M., Drew, D., Griger, F., Hartmann, J., Jiang, G., Moosdorf, N., Richts, A., Stevanovic, Z., Veni, G., Goldscheider, N., 2017. The World Karst Aquifer Mapping project: concept, mapping procedure and map of Europe. Hydrogeol. J. 25, 771–785.
Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533.
Clow, D.W., Rhoades, C., Briggs, J., Caldwell, M., Lewis, W.M., 2011. Responses of soil and water chemistry to mountain pine beetle induced tree mortality in Grand County, Colorado, USA. Appl. Geochem. 26, S174–S178.
Costa, M.R., Calvão, A.R., Aranha, J., 2014. Linking wildfire effects on soil and water chemistry of the Marão River watershed, Portugal, and biomass changes detected from Landsat imagery. Appl. Geochem. 44, 93–102.
Culver, D.C., Pipan, T., 2019. The Biology of Caves and Other Subterranean Habitats. In: Oxford University Press, New York, p. 336.
Dale, H.V., 2001. Climate. Bioscience 25.
Dalsgaard, L., 2007. Above and belowground gaps-the effects of small canopy opening on throughfall, soil moisture and tree transpiration in Suserup Skov, Denmark. Ecol. Bull. 52, 81–102.
Dalsgaard, L., Mikkelsen, T.N., Bastrup-Birk, A., 2011. Sap flow for beech (Fagus sylvatica L.) in a natural and a managed forest - effect of spatial heterogeneity. J. Plant Ecol. 4, 23–35.
Daly, D., Dassargues, A., Drew, D., Dunne, S., Goldscheider, N., Neale, S., Popescu, I.C., Zwahlen, F., 2022. Main concepts of the" European approach" to karst-groundwater-vulnerability assessment and mapping. Hydrogeol J. 10, 340–345.
Dasgupta, S., Mohanty, B.P., Köhne, J.M., 2006. Impacts of juniper vegetation and karst geology on subsurface flow processes in the Edwards Plateau, Texas. Vadose Zone J. 5, 1076–1085.
Davis, K.F., Dalin, C., Defries, R., Galloway, J.N., Leach, A.M., Mueller, N.D., 2019. Sustainable. In: Ferranti, P., Berry, E.M., Anderson, J.R. (Eds.), Encyclopedia of Food Security and Sustainability. Elsevier, Oxford, pp. 14–20.
De Figueiredo, T., Fonseca, F., Martins, A., 2012. Soil loss and run-off in young forest stands as affected by site preparation technique: a study in NE Portugal. Eur. J. For. Res. 131, 1747–1760.
De Groot, M., Ogris, N., Kobler, A., 2018. The effects of a large-scale ice storm event on the drivers of bark beetle outbreaks and associated management practices. For. Ecol. Manag. 408, 195–201.
Decocq, G., Aubert, M., Dupont, F., Bardat, J., Wattez-Franger, A., Saguez, R., Foucault, B.D., Alard, D., Delelis-Dusollier, A., 2005. Silviculture-driven vegetation change in a European temperate deciduous forest. Ann. For. Sci. 62, 313–323.
Degraff, J.V., Cannon, S.H., Parise, M., 2013. Limiting the immediate and subsequent hazards associated with wildfires. In: Margottini, C., Canuti, P., Sassa, K. (Eds.), Landslide Science and Practice: Volume 4: Global Environmental Change. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 199–209.
Díaz-Raviña, M., Martín, A., Barreiro, A., Lombao, A., Iglesias, L., Díaz-Fierros, F., Carballas, T., 2012. Mulching and seeding treatments for post-fire soil stabilisation in NW Spain: short-term effects and effectiveness. Geoderma 191, 31–39.
Drew, D., Hötzl, H. (Eds.), 1999. Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications. Routledge.
Duguid, M.C., Ashton, M.S., 2013. A meta-analysis of the effect of forest management for timber on understory plant species diversity in temperate forests. For. Ecol. Manag. 303, 81–90.
Ebel, B.A., Mirus, B.B., 2014. Disturbance hydrology: challenges and opportunities. Hydrol. Process. 28, 5140–5148.
Eriksson, M., Neuvonen, S., Roininen, H., 2008. Ips typographus (L.) attack on patches of felled trees: "Wind-felled" vs. Cut trees and the risk of subsequent mortality. For. Ecol. Manag. 255, 1336–1341.
Feikema, P.M., Sherwin, C.B., Lane, P.N.J., 2013. Influence of climate, fire severity and forest mortality on predictions of long term streamflow: potential effect of the 2009 wildfire on Melbourne's water supply catchments. J. Hydrol. 488, 1–16.
Ferlan, M., Eler, K., Simončič, P., Batič, F., Vodnik, D., 2016. Carbon and water flux patterns of a drought-prone mid-succession ecosystem developed on abandoned karst grassland. Agric. Ecosyst. Environ. 220, 152–163.
Fernández, C., Vega, J.A., 2016. Are erosion barriers and straw mulching effective for controlling soil erosion after a high severity wildfire in NW Spain? Ecol. Eng. 87, 132–138.
Ferreira, R.V., Serpa, D., Machado, A.I., Rodríguez-Blanco, M.L., Santos, L.F., Taboada-Castro, M.T., Cerqueira, M.A., Keizer, J.J., 2016. Short-term nitrogen losses by overland flow in a recently burnt forest area in north-Central Portugal: a study at micro-plot scale. Sci. Total Environ. 572, 1281–1288.
Ferretti, M., Fischer, R. (Eds.), 2013. . Forest Monitoring. Terrestrial Methods in Europe with Outlook to North America and Asia. Developments in Environmental Science 12. Elsevier, Amsterdam, p. 507.
Flannigan, M.D., Stocks, B.J., Wotton, B.M., 2000. Climate change and forest fires. Sci. Total Environ. 262, 221–229.
Frelich, L.E., 2002. Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen-Deciduous Forests. In: Cambridge University Press, Cambridge, pp. i–iv.
Gabrovšek, F., Dreybrodt, W., 2001. A model of the early evolution of karst aquifers in limestone in the dimensions of length and depth. J. Hydrol. 240, 206–224.
Gams, I., 2003. In: Kras v Sloveniji v prostoru in času / Karst in Slovenia in time and space. Založba ZRC, ZRC SAZU, Ljubljana, p. 516.
Gerrits, A.M.J., Pfister, L., Savenije, H.H.G., 2010. Spatial and temporal variability of canopy and forest floor interception in a beech forest. Hydrol. Process. 24, 3011–3025.
Gimeno-García, E., Andreu, V., Rubio, J.L., 2000. Changes in organic matter, nitrogen, phosphorus and cations in soil as a result of fire and water erosion in a Mediterranean landscape. Eur. J. Soil Sci. 51, 201–210.
Giuggiola, A., Bugmann, H., Zingg, A., Dobbertin, M., Rigling, A., 2013. Reduction of stand density increases drought resistance in xeric Scots pine forests. For. Ecol. Manag. 310, 827–835.
Giuggiola, A., Zweifel, R., Feichtinger, L.M., Vollenweider, P., Bugmann, H., Haeni, M., Rigling, A., 2018. Competition for water in a xeric forest ecosystem – effects of understory removal on soil micro-climate, growth and physiology of dominant Scots pine trees. For. Ecol. Manag. 409, 241–249.
GLC, 2013. Global Land Cover Share Database. GLC- Share: Trees covered area. https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/ba452 6fd-cdbf-4028-a1bd-5a559c4bff38.
Goldscheider, N., Chen, Z., Auler, A.S., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., Jiang, G., Moosdorf, N., Stevanovic, Z., Veni, G., 2020. Global distribution of carbonate rocks and karst water resources. Hydrogeol. J. 28, 1661–1677.
Goldscheider, N., Drew, D. (Eds.), 2007. Methods in Karst Hydrogeology. Contributions to Hydrogeology 26, International Association of Hydrogeologists. CRC Press, Boca Raton, FL.
Göppert, N., Goldscheider, N., 2008. Solute and colloid transport in karst conduits under low- and high-flow conditions. Groundwater 46, 61–68.
Granier, A., Aubinet, M., Epron, D., Falge, E., Gudmundsson, J., Jensen, N.O., Koestner, B., Matteucci, G., Pilegaard, K., Schmidt, M.G., Tenhunen, J., 2003. Deciduous forests: carbon and water fluxes, balances and ecophysiological determinants. In: Valentini, R. (Ed.), Fluxes of Carbon, Water and Energy of European Forests. Springer - Verlag, Berlin Heidelberg, p. 270.

Granier, A., Reichstein, M., Breda, N., Janssens, I.A., Falge, E., Ciais, P., Gruenwald, T., Aubineth, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B., Ilvesniemi, H., Keronen, P., Knohl, A., Koestner, B., Lagergren, F., Lindroth, A., Longdoz, B., Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E., Papale, D., Peiffer, M., Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G., Tenhunen, J., Vesala, T., Wang, Q., 2007. Evidence for soil water control on carbon and water dynamics in european forests during the extremely dry year: 2003. Agric. For. Meteorol. 143, 123–145.

Grecs, Z., Kolšek, M., 2017. Naravne ujme vse bolj krojijo gospodarjenje z gozdovi. Natural disasters are increasingly affecting forest management. Gozdarski vestnik (professional Journal of Forestry) 74, 185–202 (in Slovenian).

Griffin, J.M., Turner, M.G., Simard, M., 2011. Nitrogen cycling following mountain pine beetle disturbance in lodgepole pine forests of Greater Yellowstone. For. Ecol. Manag. 261, 1077–1089.

Guan, H., Fan, J., 2020. Effects of vegetation restoration on soil quality in fragile karst ecosystems of Southwest China. PeerJ 8, e9456.

Gyakum, J.R., Roebber, P.J., 2001. The 1998 ice storm-analysis of a planetary-scale event. Mon. Weather Rev. 129, 2983–2997.

Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., Weiler, M., 2014. Karst water resources in a changing world: review of hydrological modeling approaches. Rev. Geophys. 52, 218–242.

Hartmann, A., Kobler, J., Kralik, M., Dirnböck, T., Humer, F., Weiler, M., 2016. Model-aided quantification of dissolved carbon and nitrogen release after windthrow disturbance in an austrian karst system. Biogeosciences 13, 159–174.

Hartmann, A., Lange, J., Vivó Aguado, À., Mizyed, N., Smiatek, G., Kunstmann, H., 2012. A multi-model approach for improved simulations of future water availability at a large Eastern Mediterranean karst spring. J. Hydrol. 468–469, 130–138.

Hawthorne, S.N.D., Lane, P.N.J., Bren, L.J., Sims, N.C., 2013. The long term effects of thinning treatments on vegetation structure and water yield. For. Ecol. Manag. 310, 983–993.

Heilman, J., Litvak, M.E., Mcinnes, K.J., Kjelgaard, J.F., Schwinning, S., 2012. Water-storage capacity controls energy partitioning and water use in karst ecosystems on the Edwards Plateau, Texas. Ecohydrology 7, 127–138.

Hirano, T., Suzuki, K., Hirata, R., 2017. Energy balance and evapotranspiration changes in a larch forest caused by severe disturbance during an early secondary succession. Agric. For. Meteorol. 232, 457–468.

Hlásny, T., Sitková, Z., Barka, I., 2013. Regional assessment of forest effects on watershed hydrology: Slovakia as a case study. J. For. Sci. 59, 405–415.

Huang, J., Kang, Q., Yang, J.X., Jin, P.W., 2017. Multifactor analysis and simulation of the surface runoff and soil infiltration at different slope gradients. IOP Conference Series: Earth and Environmental Science 82, 012019.

Hubbard, R.M., Rhoades, C.C., Elder, K., Negron, J., 2013. Changes in transpiration and foliage growth in lodgepole pine trees following mountain pine beetle attack and mechanical girdling. For. Ecol. Manag. 289, 312–317.

Huber, C., 2005. Long lasting nitrate leaching after bark beetle attack in the highlands of the Bavarian Forest National Park. J. Environ. Qual. 34, 1772–1779.

IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. University Press. In Press.

Iván, V., Mádl-Szőnyi, J., 2017. State of the art of karst vulnerability assessment: overview, evaluation and outlook. Environ. Earth Sci. 76, 112.

Jakša, J., Kolšek, M., 2009. Naravne ujme v slovenskih gozdovih.Natural disasters in Slovenian forests. Ujma 23, 72–81.

Jeannin, P.Y., Grasso, D.A., 1997. Permeability and hydrodynamic behavior of karstic environment. In: Gunay, G., Johnson, A.I. (Eds.), Karst Waters Environmental Impact. A. A. Balkema, Rotterdam, Netherlands, pp. 335–342.

Jiménez-Pinilla, P., Lozano, E., Mataix-Solera, J., Arcenegui, V., Jordán, A., Zavala, L.M., 2016. Temporal changes in soil water repellency after a forest fire in a Mediterranean calcareous soil: Influence of ash and different vegetation type. Sci. Total Environ. 572, 1252–1260.

Kalhoro, S.A., Ding, K., Zhang, B., Chen, W., Hua, R., Shar, A.H., Xu, X., 2019. Soil infiltration rate of forestland and grassland over different vegetation restoration periods at Loess Plateau in northern hilly areas of China. Landsc. Ecol. Eng. 15, 91–99.

Katzensteiner, K., 2003. Effects of harvesting on nutrient leaching in a Norway spruce (Picea abies Karst.) ecosystem on a Lithic Leptosol in the Northern Limestone Alps. Plant Soil 250, 59–73.

Kennedy, M.C., Bart, R.R., Tague, C.L., Choate, J.S., 2021. Does hot and dry equal more wildfire? Contrasting short- and long-term climate effects on fire in the Sierra Nevada,CA. Ecosphere 12, e03657.

Kermavnar, J., Ferlan, M., Marinšek, A., Eler, K., Kobler, A., Kutnar, L., 2020. Effects of various cutting treatments and topographic factors on microclimatic conditions in Dinaric fir-beech forests. Agric. For. Meteorol. 295, 108186.

Kermavnar, J., Marinšek, A., Eler, K., Kutnar, L., 2019. Evaluating short-term impacts of forest management and microsite conditions on understory vegetation in temperate fir-beech forests: floristic, ecological, and trait-based perspective. Forests 10, 909.

Kermavnar, J., Vilhar, U., 2017. Canopy precipitation interception in urban forests in relation to stand structure. Urban Ecosyst. 20, 1373–1387.

Kim, J., Choi, J., Choi, C., Park, S., 2013. Impacts of changes in climate and land use/land cover under IPCC RCP scenarios on streamflow in the Hoeya River Basin, Korea. Sci. Total Environ. 452–453, 181–195.

Knicker, H., Almendros, G., González-Vila, F.J., González-Pérez, J.A., Polvillo, O., 2006. Characteristic alterations of quantity and quality of soil organic matter caused by forest fires in continental Mediterranean ecosystems: a solid-state 13C NMR study. Eur. J. Soil Sci. 57, 558–569.

Kovačič, G., Petrič, M., Ravbar, N., 2020. Evaluation and quantification of the effects of climate and vegetation cover change on karst water sources: case studiesof two Springs in South-Western Slovenia. Water 11, 3087.

Kramer, K., Brang, P., Bachofen, H., Bugmann, H., Wohlgemuth, T., 2014. Site factors are more important than salvage logging for tree regeneration after wind disturbance in central european forests. For. Ecol. Manag. 331, 116–128.

Kramer, P.J., Boyer, J.S., 1995. Water Relations of Plants and Soils, 495. Academic Pres. Groundwater hydrology of springs: engineering, theory, management and sustainability. In: Krešić, N., Stevanović, Z. (Eds.), Acta Carsologica 39.

Kulakowski, D., Jarvis, D., 2011. The influence of mountain pine beetle outbreaks and drought on severe wildfires in northwestern Colorado and southern Wyoming: a look at the past century. For. Ecol. Manag. 262, 1686–1696.

Kulakowski, D., Seidl, R., Holeksa, J., Kuuluvainen, T., Nagel, T.A., Panayotov, M., Svoboda, M., Thorn, S., Vacchiano, G., Whitlock, C., Wohlgemuth, T., Bebi, P., 2017. A walk on the wild side: disturbance dynamics and the conservation and management of european mountain forest ecosystems. For. Ecol. Manag. 388, 120–131.

Kutnar, L., Eler, K., Marinsek, A., 2015. Effects of different silvicultural measures on plant diversity - the case of the Illyrian Fagus sylvatica habitat type (Natura 2000). iForest -. Biogeosciences and Forestry 1156–1162.

Kutnar, L., Kermavnar, J., Pintar, A.M., 2021. In: Climate change and disturbances will shape future temperate forests in the transition zone between Central and SE Europe, 64, pp. 67–86, 2021.

Kutnar, L., Kobler, A., 2011. Prediction of forest vegetation shift due to different climate-change scenarios in Slovenia. Šumarski list 135, 113–126.

Kuuluvainen, T., 1994. Gap disturbance, ground microtopography, and the regeneration dynamics of boreal coniferous forests in Finland: a review. Ann. Zool. Fenn. 31, 35–51.

Lebourgeois, F., Gomez, N., Pinto, P., Mérian, P., 2013. Mixed stands reduce Abies alba tree-ring sensitivity to summer drought in the Vosges mountains, western Europe. For. Ecol. Manag. 303, 61–71.

Legesse, D., Vallet-Coulomb, C., Gasse, F., 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. J. Hydrol. 275, 67–85.

Lerner, D.N., Issar, A.S., Simmers, I., 1990. Groundwater Recharge. In: Hannover, Heise, p. 345.

Lévesque, M., Rigling, A., Bugmann, H., Weber, P., Brang, P., 2014. Growth response of five co-occurring conifers to drought across a wide climatic gradient in Central Europe. Agric. For. Meteorol. 197, 1–12.

Li, F., Zhang, G., Li, H., Lu, W., 2019. Land use change impacts on hydrology in the Nenjiang River Basin, Northeast China. Forests 10, 476.

Li, G., Wan, L., Cui, M., Wu, B., Zhou, J., 2019b. Influence of canopy interception and rainfall kinetic energy on soil erosion under forests. Forests 10, 509.

Lin, B., Chen, X., Yao, H., Chen, Y., Liu, M., Gao, L., James, A., 2015. Analyses of landuse change impacts on catchment runoff using different time indicators based on SWAT model. Ecol. Indic. 58, 55–63.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of european forest ecosystems. For. Ecol. Manag. 259, 698–709.

Mahat, V., Silins, U., Anderson, A., 2016. Effects of wildfire on the catchment hydrology in Southwest Alberta. Catena 147, 51–60.

Mareschal, L., Laclau, J.P., Nzila, J.D.D., Versini, A., Koutika, L.S., Mazoumbou, J.C., Deleporte, P., Bouillet, J.P., Ranger, J., 2013. Nutrient leaching and deep drainage under Eucalyptus plantations managed in short rotations after afforestation of an african savanna: two 7-year time series. For. Ecol. Manag. 307, 242–254.

Marinšek, A., Celarc, B., Grah, A., Kokalj, Ž., Nagel, T.A., Ogris, N., Oštir, K., Planinšek, Š., Roženbergar, D., Veljanovski, T., Vochl, S., Železnik, P., Kobler, A., 2015. Žledolom in njegove posledice na razvoj gozdov - pregled dosedanjih znanj. Impacts of ice storms on forest development - a review. Gozdarski vestnik 73, 392–405.

Marshet, N.G., Fekadu, H.H., 2019. Review on effect of climate Change on Forest Ecosystem. Int. J. Environ. Sci. Nat. Res. 17, 555968.

Matthews, J.D., 1999. Silvicultural Systems. In: Clarendon Press, Oxford, p. 284.

Mátyás, C., Bozic, G., Gömöry, D., Ivankovic, M., Rasztovits, E., 2009. Juvenile growth response of european beech (Fagus sylvatica L.) to sudden change of climatic environment in SE european trials. iForest -. Biogeosci. Forest. 2, 213–220.

McDowell, N.G., 2011. Mechanisms linking drought, hydraulics, carbon metabolism, and vegetation mortality. Plant Physiol. 155, 1051–1059.

McDowell, W.H., Liptzin, D., 2014. Linking soils and streams: response of soil solution chemistry to simulated hurricane disturbance mirrors stream chemistry following a severe hurricane. For. Ecol. Manag. 332, 56–63.

Menzel, L., Koch, J., Onigkeit, J., Schaldach, R., 2009. Modelling the effects of land-use and land-cover change on water availability in the Jordan River region. Adv. Geosci. 21, 73–80.

Mirus, B.B., Ebel, B.A., Mohr, C.H., Zegre, N., 2017. Disturbance hydrology: preparing for an increasingly disturbed future. Water Resour. Res. 53, 10007–10016.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L.A., Group, P.P., 2015.). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst. Rev. 4 (1).

Molina-Navarro, E., Trolle, D., Martínez-Pérez, S., Sastre-Merlín, A., Jeppesen, E., 2014. Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. J. Hydrol. 509, 354–366.

Moody, J.A., Martin, D.A., Haire, S.L., Kinner, D.A., 2008. Linking runoff response to burn severity after a wildfire. Hydrol. Process. 22, 2063–2074.

Moore, G., Heilman, J., 2011. Proposed principles governing how vegetation changes affect transpiration. Ecohydrology 4, 351–358.

Morecroft, M.D., Taylor, M.E., Oliver, H.R., 1998. Air and soil microclimates of deciduous woodland compared to an open site. Agric. For. Meteorol. 90, 141–155.

Nagel, T.A., Diaci, J., 2006. Intermediate wind disturbance in an old-growth beech-fir forest in southeastern Slovenia. Can. J. For. Res. 36, 629–638.

Nagel, T.A., Firm, D., Rozenbergar, D., Kobal, M., 2016. Patterns and drivers of ice storm damage in temperate forests of Central Europe. Eur. J. For. Res. 135, 519–530.

Nagel, T.A., Mikac, S., Dolinar, M., Klopcic, M., Keren, S., Svoboda, M., Diaci, J., Boncina, A., Paulic, V., 2017. The natural disturbance regime in forests of the Dinaric Mountains: a synthesis of evidence. For. Ecol. Manag. 388, 29–42.

Nagel, T.A., Svoboda, M., Diaci, J., 2006. Regeneration patterns after intermediate wind disturbance in an old-growth Fagus-Abies forest in southeastern Slovenia. For. Ecol. Manag. 226, 268–278.

Nagel, T.A., Svoboda, M., Kobal, M., 2014. Disturbance, life history traits, and dynamics in an old-growth forest landscape of southeastern Europe. Ecol. Appl. 24, 663–679.

Nakashizuka, T., Iida, S., 1995. Composition, dynamics and disturbance regime of temperate deciduous forests in Monsoon Asia. Vegetatio 121, 23–30.

FAO, 2009. National Forest Monitoring and Assessment — manual for integrated field data collection. Version 2.3. National Forest Monitoring and Assessment Working Paper NFMA 37/E. Food and Agriculture Organization of the United Nations (FAO), Rome.

Nerantzaki, S.D., Nikolaidis, N.P., 2020. The response of three Mediterranean karst springs to drought and the impact of climate change. J. Hydrol. 591, 125296.

Nikolova, P.S., Raspe, S., Andersen, C.P., Mainiero, R., Blaschke, H., Matyssek, R., Häberle, K.-H., 2009. Effects of the extreme drought in 2003 on soil respiration in a mixed forest. Eur. J. For. Res. 128, 87–98.

Nolan, R.H., Lane, P.N.J., Benyon, R.G., Bradstock, R.A., Mitchell, P.J., 2015. Trends in evapotranspiration and streamflow following wildfire in resprouting eucalypt forests. J. Hydrol. 524, 614–624.

North, L.A., Van Beynen, P.E., Parise, M., 2009. Interregional comparison of karst disturbance: west-Central Florida and Southeast Italy. J. Environ. Manag. 90, 1770–1781.

Nosetto, M.D., Jobbágy, E.G., Brizuela, A.B., Jackson, R.B., 2012. The hydrologic consequences of land cover change in Central Argentina. Agric. Ecosyst. Environ. 154, 2–11.

Novotná, B., Čimo, J., Chvíla, B., Pozníková, G., 2018. River basin hydrological balance evaluation in term of the land use change impact. Acta Horticulturae et Regiotecturae 21, 5.

Nunes, J.P., Doerr, S.H., Sheridan, G., Neris, J., Santín, C., Emelko, M.B., Silins, U., Robichaud, P.R., Elliot, W.J., Keizer, J., 2018. Assessing water contamination risk from vegetation fires: challenges, opportunities and a framework for progress. Hydrol. Process. 32, 687–694.

Nyman, P., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2014. Modeling the effects of surface storage, macropore flow and water repellency on infiltration after wildfire. J. Hydrol. 513, 301–313.

Nyman, P., Smith, H.G., Sherwin, C.B., Langhans, C., Lane, P.N.J., Sheridan, G.J., 2015. Predicting sediment delivery from debris flows after wildfire. Geomorphology 250, 173–186.

Oliveira, V.A.D., Mello, C.R.D., Viola, M.R., Srinivasan, R., 2018. Land-use change impacts on the hydrology of the Upper Grande River Basin, Brazil. Cerne 24, 334–343.

Owens, P.N., Giles, T.R., Petticrew, E.L., Leggat, M.S., Moore, R.D., Eaton, B.C., 2013. Muted responses of streamflow and suspended sediment flux in a wildfire-affected watershed. Geomorphology 202, 128–139.

Parise, M., Cannon, S.H., 2012. Wildfire impacts on the processes that generate debris flows in burned watersheds. Nat. Hazards 61, 217–227.

Parise, M., Gabrovsek, F., Kaufmann, G., Ravbar, N., Parise, M., Gabrovsek, F., Kaufmann, G., Ravbar, N., 2018. Recent advances in karst research: from theory to fieldwork and applications. In: Advances in Karst Research: Theory, Fieldwork and Applications, eds.), 466, Geological Society of London, p. 0.

Parise, M., Ravbar, N., Živanovic, V., Mikszewski, A., Kresic, N., Mádlszonyi, J., Kukuric, N., 2015. Hazards in karst and managing water resources quality. Chapter 17. In: 2015. Hazards in Karst and Managing Water Resources Quality. Chapter 17. In: Karst Aquifers - Characterization and Engineering. Professional Practice in Earth Sciences (Z. Stevanovic, eds.). Springer, pp. 601–687.

Park Williams, A., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., Swetnam, T.W., Rauscher, S.A., Seager, R., Grissino-Mayer, H.D., Dean, J.S., Cook, E. R., Gangodagamage, C., Cai, M., McDowell, N.G., 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. Nat. Clim. Chang. 3, 292–297.

Pederson, N., Dyer, J.M., Mcewan, R.W., Hessl, A.E., Mock, C.J., Orwig, D.A., Rieder, H. E., Cook, B.I., 2014. The legacy of episodic climatic events in shaping temperate, broadleaf forests. Ecol. Monogr. 84, 599–620.

Pereira, M.G., Malamud, B.D., Trigo, R.M., Alves, P.I., 2011. The history and characteristics of the 1980–2005 Portuguese rural fire database. Nat. Hazards Earth Syst. Sci. 11, 3343–3358.

Perko, F., 2016. In: Od ogolelega do gozdnatega krasa - pogozdovanje krasa. Zveza gozdraskih društev Slovenije, Gozdarska založba: Jutro, Ljubljana, p. 296, 2021.

Pickett, S.T.A., 1989. Space-for-time substitution as an alternative to long-term studies. In: Likens, G.E. (Ed.), Long-Term Studies in Ecology: Approaches and Alternatives. Springer, New York, New York, NY, pp. 110–135.

Poljanšek, S., Vilhar, U., Levanič, T., 2018. Green water reconstructed for Rižana watershed,SW Slovenia. Environ. Earth Sci. 77, 92.

Prats, S.A., Wagenbrenner, J.W., Martins, M.A.S., Malvar, M.C., Keizer, J.J., 2016. Mid-term and scaling effects of forest residue mulching on post-fire runoff and soil erosion. Sci. Total Environ. 573, 1242–1254.

Prosdocimi, M., Tarolli, P., Cerdà, A., 2016. Mulching practices for reducing soil water erosion: a review. Earth Sci. Rev. 161, 191–203.

Pugh, E.T., Small, E.E., 2013. The impact of beetle-induced conifer death on stand-scale canopy snow interception. Hydrol. Res. 44, 644–657.

Pullin, A.S., Frampton, G.K., Livoreil, B., Petrokofsky, G., 2018. Collaboration for Environmental Evidence. Guidelines and Standards for Evidence synthesis in Environmental Management.

Querejeta, J.I., Estrada-Medina, H., Allen, M.F., Jiménez-Osornio, J.J., 2007. Water source partitioning among trees growing on shallow karst soils in a seasonally dry tropical climate. Oecologia 152, 26–36.

Ravbar, N., 2013. Variability of groundwater flow and transport processes in karst under different hydrologic conditions. Acta carsologica 42.

Ravbar, N., Pipan, T., 2022. Karst groundwater dependent ecosystems—typology, vulnerability and protection*. In: Reference Module in Earth Systems and Environmental Sciences, eds. Elsevier.

Ravbar, N., Šebela, S., 2015. The effectiveness of protection policies and legislative framework with special regard to karst landscapes: insights from Slovenia. Environ. Sci. Pol. 51, 106–116.

Raz-Yaseef, N., Yakir, D., Schiller, G., Cohen, S., 2012. Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns. Agric. For. Meteorol. 157, 77–85.

Rebertus, A.J., Kitzberger, T., Veblen, T.T., Roovers, L.M., 1997. Blowdown history and landscape patterns in the Andes of Tierra Del Fuego, Argentina. Ecology 78, 678–692.

Reichert, J.M., Rodrigues, M.F., Peláez, J.J.Z., Lanza, R., Minella, J.P.G., Arnold, J.G., Cavalcante, R.B.L., 2017. Water balance in paired watersheds with eucalyptus and degraded grassland in Pampa biome. Agric. For. Meteorol. 237–238, 282–295.

Ritter, E., 2005. Litter decomposition and nitrogen mineralization in newly formed gaps in a danish beech (Fagus sylvatica) forest. Soil Biol. Biochem. 37, 1237–1247.

Ritter, E., Dalsgaard, L., Einhorn, K.S., 2005. Light, temperature and soil moisture regimes following gap formation in a semi-natural beech-dominated forest in Denmark. For. Ecol. Manag. 206, 15–33.

Robichaud, P.R., Lewis, S.A., Wagenbrenner, J.W., Ashmun, L.E., Brown, R.E., 2013. Post-fire mulching for runoff and erosion mitigation: part I: Effectiveness at reducing hillslope erosion rates. Catena 105, 75–92.

Robichaud, P.R., Wagenbrenner, J.W., Pierson, F.B., Spaeth, K.E., Ashmun, L.E., Moffet, C.A., 2016. Infiltration and interrill erosion rates after a wildfire in western Montana, USA. Catena 142, 77–88.

Russo, A., Gouveia, C.M., Páscoa, P., Dacamara, C.C., Sousa, P.M., Trigo, R.M., 2017. Assessing the role of drought events on wildfires in the Iberian Peninsula. Agric. For. Meteorol. 237–238, 50–59.

Saje, R., 2015. Žledolomi v slovenskih gozdovih. Ice storm damages in slovenian Forests. Gozdarski vestnik 73, 204–210.

Salemi, L.F., Groppo, J.D., Trevisan, R., Marcos De Moraes, J., De Paula Lima, W., Martinelli, L.A., 2012. Riparian vegetation and water yield: a synthesis. J. Hydrol. 454–455, 195–202.

Salis, M., Ager, A.A., Finney, M.A., Arca, B., Spano, D., 2014. Analyzing spatiotemporal changes in wildfire regime and exposure across a Mediterranean fire-prone area. Nat. Hazards 71, 1389–1418.

Šamonil, P., Král, K., Hort, L., 2010. The role of tree uprooting in soil formation: a critical literature review. Geoderma 157, 65–79.

Sánchez-Salguero, R., Camarero, J.J., Dobbertin, M., Fernández-Cancio, Á., Vilà-Cabrera, A., Manzanedo, R.D., Zavala, M.A., Navarro-Cerrillo, R.M., 2013. Contrasting vulnerability and resilience to drought-induced decline of densely planted vs. Natural rear-edge Pinus nigra forests. For. Ecol. Manag. 310, 956–967.

Sánchez-Salguero, R., Camarero, J.J., Hevia, A., Madrigal-González, J., Linares, J.C., Ballesteros-Canovas, J.A., Sánchez-Miranda, A., Alfaro-Sánchez, R., Sangüesa-Barreda, G., Galván, J.D., Gutiérrez, E., Génova, M., Rigling, A., 2015a. What drives growth of Scots pine in continental Mediterranean climates: drought, low temperatures or both? Agric. For. Meteorol. 206, 151–162.

Sánchez-Salguero, R., Navarro-Cerrillo, R.M., Swetnam, T.W., Zavala, M.A., 2012. Is drought the main decline factor at the rear edge of Europe? The case of southern Iberian pine plantations. For. Ecol. Manag. 271, 158–169.

Sánchez-Salguero, R., Ortíz, C., Covelo, F., Ochoa, V., García-Ruíz, R., Seco, J., Carreira, J., Merino, J., Linares, J., 2015b. Regulation of water use in the southernmost European Fir (Abies pinsapo Boiss.): drought avoidance matters. Forests 6, 2241.

Sarrazin, F., Hartmann, A., Pianosi, F., Rosolem, R., Wagener, T., 2018. V2Karst V1.1: a parsimonious large-scale integrated vegetation–recharge model to simulate the impact of climate and land cover change in karst regions. Geosci. Model Dev. 11, 4933–4964.

Schütz, J.-P., Saniga, M., Diaci, J., Vrška, T., 2016. Comparing close-to-nature silviculture with processes in pristine forests: lessons from Central Europe. Ann. For. Sci. 73, 911–921.

Seibert, J., Mcdonnell, J.J., Woodsmith, R.D., 2010. Effects of wildfire on catchment runoff response: a modeling approach to detect changes in snow-dominated forested catchments. Hydrol. Res. 41, 378–390.

Seidl, R., Rammer, W., 2017. Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes. Landsc. Ecol. 32, 1485–1498.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O., 2017. Forest disturbances under climate change. Nat. Clim. Chang. 7, 395–402.

Shakesby, R.A., Doerr, S.H., 2006. Wildfire as a hydrological and geomorphological agent. Earth Sci. Rev. 74, 269–307.
Sheridan, G.J., Lane, P.N.J., Sherwin, C.B., Noske, P.J., 2011. Post-fire changes in sediment rating curves in a wet Eucalyptus forest in SE Australia. J. Hydrol. 409, 183–195.
Shin, S.S., Park, S.D., Lee, K.S., 2013. Sediment and hydrological response to vegetation recovery following wildfire on hillslopes and the hollow of a small watershed. J. Hydrol. 499, 154–166.
Shu-Ren, Y., 2003. Effects of fire disturbance on forest hydrology. J. For. Res. 14, 331–334.
Simončič, P., 2001. Soil solution quality and soil characteristics with regard to clear cutting. Glas. Šum. Pokuse 38, 159–166.
Simonin, K., Kolb, T.E., Montes-Helu, M., Koch, G.W., 2007. The influence of thinning on components of stand water balance in a ponderosa pine forest stand during and after extreme drought. Agric. For. Meteorol. 143, 266–276.
Sivelle, V., Jourde, H., Bittner, D., Mazzilli, N., Tramblay, Y., 2021. Assessment of the relative impacts of climate changes and anthropogenic forcing on spring discharge of a Mediterranean karst system. J. Hydrol. 598, 126396.
Skudnik, M., Jevšenak, J., Poljanec, A., 2021. Stanje in spremembe slovenskih gozdov v zadnjih dveh desetletjih - rezultati velikoprostorskega monitoringa gozdov. Condition and changes of slovenian forests in the last two decades – results of the state and changes large-scale spatial forest monitoring. Gozdarski vestnik (professional Journal of Forestry) 79, 151–170.
Smerdon, B.D., Redding, T., Beckers, J., 2009. An overview of the effects of forest management on groundwater hydrology. 2009.
Sohn, J.A., Gebhardt, T., Ammer, C., Bauhus, J., Häberle, K.-H., Matyssek, R., Grams, T.E.E., 2013. Mitigation of drought by thinning: short-term and long-term effects on growth and physiological performance of Norway spruce (Picea abies). For. Ecol. Manag. 308, 188–197.
Šraj, M., Brilly, M., Mikoš, M., 2008. Rainfall interception by two deciduous Mediterranean forests of contrasting stature in Slovenia. Agric. For. Meteorol. 148, 121–134.
Stevanović, Z., 2018. Global distribution and use of water from karst aquifers. Special Publications 466, 217–236.
Sun, D., Yang, H., Guan, D., Yang, M., Wu, J., Yuan, F., Jin, C., Wang, A., Zhang, Y., 2018. The effects of land use change on soil infiltration capacity in China: a meta-analysis. Sci. Total Environ. 626, 1394–1401.
Tague, C., Band, L., 2001. Simulating the impact of road construction and forest harvesting on hydrologic response. Earth Surf. Process. Landf. 26, 135–151.
Tang, L., Yang, D., Hu, H., Gao, B., 2011. Detecting the effect of land-use change on streamflow, sediment and nutrient losses by distributed hydrological simulation. J. Hydrol. 409, 172–182.
Turner, M.G., Dale, V.H., 1998. Comparing large, Infrequent Disturbances: what have we Learned? Ecosystems 1, 493–496.
Ungar, E.D., Rotenberg, E., Raz-Yaseef, N., Cohen, S., Yakir, D., Schiller, G., 2013. Transpiration and annual water balance of Aleppo pine in a semiarid region: implications for forest management. For. Ecol. Manag. 298, 39–51.
Unterm, 2022. The United Nations Terminology Database.
Urich, P.B., 2002. Land use in karst terrain : review of impacts of primary activities on temperate karst ecosystems.
Van Beynen, P.E., Bialkowska-Jelinska, E., 2012. Human disturbance of the Waitomo catchment, New Zealand. J. Environ. Manag. 108, 130–140.
Varela, M.E., Benito, E., Keizer, J.J., 2015. Influence of wildfire severity on soil physical degradation in two pine forest stands of NW Spain. Catena 133, 342–348.
Venanzi, R., Picchio, R., Piovesan, G., 2016. Silvicultural and logging impact on soil characteristics in Chestnut (Castanea sativa Mill.) Mediterranean coppice. Ecol. Eng. 92, 82–89.
Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Beguería, S., Trigo, R., López-Moreno, J.I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., Sanchez-Lorenzo, A., 2013. Response of vegetation to drought time-scales across global land biomes. Proc. Natl. Acad. Sci. 110, 52–57.
Vieira, D.C.S., Malvar, M.C., Fernández, C., Serpa, D., Keizer, J.J., 2016. Annual runoff and erosion in a recently burn Mediterranean forest – the effects of plowing and time-since-fire. Geomorphology 270, 172–183.
Vilhar, U., 2016. Comparison of drought stress indices in beech forests: a modelling study. iForest -. Biogeosci. Forest. 9, 635–642.
Vilhar, U., 2021. Water regulation ecosystem services following gap formation in fir-beech forests in theDinaric Karst. Forests 12, 224.
Vilhar, U., Roženbergar, D., Simončič, P., Diaci, J., 2015. Variation in irradiance, soil features and regeneration patterns in experimental forest canopy gaps. Ann. For. Sci. 72, 253–266.
Vilhar, U., Simončič, P., 2012. Water status and drought stress after gap formation in managed and semi-natural silver fir - beech forests. Eur. J. For. Res. 131, 1381–1397.
Vilhar, U., Starr, M., Katzensteiner, K., Simončič, P., Kajfež-Bogataj, L., Diaci, J., 2010. Modelling drainage fluxes in managed and natural forests in the Dinaric karst: a model comparison study. Eur. J. For. Res. 129, 729–740.
Vilhar, U., Starr, M., Urbančič, M., Smolej, I., Simončič, P., 2005. Gap evapotranspiration and drainage fluxes in a managed and a virgin dinaric silver fir–beech forest in Slovenia: a modelling study. Eur. J. For. Res. 124, 165–175.
Wagenbrenner, J.W., Robichaud, P.R., Brown, R.E., 2016. Rill erosion in burned and salvage logged western montane forests: effects of logging equipment type, traffic level, and slash treatment. J. Hydrol. 541, 889–901.
Wang, S., Yan, M., Yan, Y., Shi, C., He, L., 2012. Contributions of climate change and human activities to the changes in runoff increment in different sections of the Yellow River. Quat. Int. 282, 66–77.
White, W., 2015. Chemistry and karst. Acta Carsologica 44, 349–362.
White, W.B., White, E.L., 2005. Ground water flux distribution between matrix, fractures, and conduits: constraints on modeling. Speleogenesis and Evolution of Karst Aquifers 3 (2). https://speleogenesis.com/pdf/seka_pdf9535.pdf.
Wic Baena, C., Andrés-Abellán, M., Lucas-Borja, M.E., Martínez-García, E., García-Morote, F.A., Rubio, E., López-Serrano, F.R., 2013. Thinning and recovery effects on soil properties in two sites of a Mediterranean forest, in Cuenca Mountain (South-eastern of Spain). For. Ecol. Manag. 308, 223–230.
Winkler, R., Spittlehouse, D., Boon, S., Zimonick, B., 2014. Forest disturbance effects on snow and water yield in interior British Columbia. Hydrol. Res. 46, 521–532.
Wogan, G.O.U., Wang, I.J., 2018. The value of space-for-time substitution for studying fine-scale microevolutionary processes. Ecography 41, 1456–1468.
Worral, J.J., Lee, T.D., Harrington, T.C., 2005. Forest dynamics and agents that initiate and expand canopy gaps in Picea-Abies forests of Crawford Notch, New Hampshire, USA. J. Ecol. 93, 178–190.
Worthington, S.R.H., Ford, D.C., 2009. Self-organized permeability in carbonate aquifers. Groundwater 47, 326–336.
Xiao, J., Davis, K.J., Urban, N.M., Keller, K., Saliendra, N.Z., 2011. Upscaling carbon fluxes from towers to the regional scale: influence of parameter variability and land cover representation on regional flux estimates. J. Geophys. Res.Biogeosci. 116.
Xu, Y., Wang, S., Bai, X., Shu, D., Tian, Y., 2018. Runoff response to climate change and human activities in a typical karst watershed,SW China. PLoS ONE 13, e0193073.
Yang, X., Ren, L., Singh, V.P., Liu, X., Yuan, F., Jiang, S., Yong, B., 2012. Impacts of land use and land cover changes on evapotranspiration and runoff at Shalamulun River watershed, China. Hydrol. Res. 43, 23–37.
Younger, P.L., 2007. Groundwater in the Environment: An Introduction. In: Blackwell Publishing, Malden, USA, p. 318.
Yu, P., Wang, Y., Coles, N., Xiong, W., Xu, L., 2015. Simulation of runoff changes caused by cropland to forest conversion in the Upper Yangtze River Region,SW China. PLoS ONE 10, e0132395.
Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., Ning, D., Hou, Y., Liu, S., 2017. A global review on hydrological responses to forest change across multiple spatial scales: importance of scale, climate, forest type and hydrological regime. J. Hydrol. 546, 44–59.
Zhang, M., Wei, X., 2014. Contrasted hydrological responses to forest harvesting in two large neighbouring watersheds in snow hydrology dominant environment: implications for forest management and future forest hydrology studies. Hydrol. Process. 28, 6183–6195.
Zhang, Y., Xu, X., Li, Z., Liu, M., Xu, C., Zhang, R., Luo, W., 2019. Effects of vegetation restoration on soil quality in degraded karst landscapes of Southwest China. Sci. Total Environ. 650, 2657–2665.
Zhang, Z., Chen, X., Ghadouani, A., Shi, P., 2011. Modelling hydrological processes influenced by soil, rock and vegetation in a small karst basin of Southwest China. Hydrol. Process. 25, 2456–2470.
Zhou, B., Gu, L., Ding, Y., Shao, L., Wu, Z., Yang, X., Li, C., Li, Z., Wang, X., Cao, Y., Zeng, B., Yu, M., Wang, M., Wang, S., Sun, H., Duan, A., An, Y., Wang, X., Kong, W., 2011. The Great 2008 Chinese ice storm: its socioeconomic-ecological impact and sustainability lessons learned. Bull. Am. Meteorol. Soc. 92, 47–60.
Zuo, D., Xu, Z., Yao, W., Jin, S., Xiao, P., Ran, D., 2016. Assessing the effects of changes in land use and climate on runoff and sediment yields from a watershed in the Loess Plateau of China. Sci. Total Environ. 544, 238–250.
Zwahlen, F.E., 2004. Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers. Final Report (COST Action 620). European Commission, Brussels, IGRAC (International Groundwater Resources Assessment Centre), 2017. World Karst Aquifer Map (WoKAM) (Accessed 9 February 2022). https://www.un-igrac.org/resource/world-karst-aquifer-map-wokam.