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OVERVIEW

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Identifying anthropogenic legacy in freshwater ecosystems

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Abstract

The legacy of historic anthropogenic disturbance can significantly affect the structure and function of contemporary freshwater ecosystems. Environmental research and management that neglect anthropogenic legacy are likely to lead to a biased interpretation of present and future ecosystem dynamics. Yet, anthropogenic legacy remains poorly considered, mainly because of the challenges associated with its identification. Synthesizing past progress in legacy research, we present a conceptual framework for the systematic identification of anthropogenic legacy. We focus on the dynamic processes occurring during legacy formation (e.g., disturbance regime, ecosystem trajectories). Based on the review of relevant case studies, we discuss the historical and contemporary sources of information (e.g., communication, cartographic, paleoenvironmental sources) that can be employed for legacy identification. Finally, we provide practical examples of anthropogenic legacy identification in real-world freshwater ecosystems. Produced in multidisciplinary collaboration, this review presents a comprehensive approach to anthropogenic legacy to foster its informed and systematic consideration in freshwater research and management.

This article is categorized under:

Science of Water > Water and Environmental Change
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KEYWORDS

anthropogenic legacy, ecosystem dynamics, historical information, research and management

1 | INTRODUCTION

Contemporary ecosystems are the product of a long history of disturbance, which includes exceptional natural phenomena such as landslides or volcano eruptions, as well as anthropogenic interventions such as pollution or deforestation

(Bain et al., 2012; Marcucci, 2000; Vitousek et al., 1997; Wohl, 2019). Persistent effects of natural and anthropogenic disturbance on ecosystem structure and function are referred to as legacy (Higgs et al., 2014). Knowledge of the legacy derived from natural and anthropogenic disturbance (hereafter called natural and anthropogenic legacy, respectively) is fundamental for ecosystem research and management (Danneyrolles et al., 2019; Kareiva et al., 2007; Moreno-Mateos et al., 2017) as it provides the basis not only for reconstructing historical disturbance that shaped present-day ecosystems (James, 2015; Kellner & Hubbart, 2017b; Tappeiner et al., 2020), but also for developing plausible future environmental trajectories evolving from contemporary disturbance (Higgs et al., 2014; James, 2015; Perring et al., 2016; R. M. Thompson et al., 2017; Turner, 2010; Wohl, 2019; Ziter et al., 2017). Despite their relevance, natural and anthropogenic legacies have been relatively poorly investigated and have often been neglected in practical ecosystem management, mainly because of the challenges related to their identification (Bain et al., 2012; Kellner & Hubbart, 2017b; Lintern et al., 2020).

During the past two decades, natural and anthropogenic legacies have started to be considered within a variety of conceptual frameworks. Some frameworks have focused on the identification of legacies specifically in riverine (e.g., Bain et al., 2012; Wohl, 2015) and terrestrial ecosystems (e.g., Johnstone et al., 2016; Monger et al., 2015; Normand et al., 2017; Perring et al., 2016). Others have integrated natural and anthropogenic legacy into more general disturbance concepts (e.g., Gaiser et al., 2020; Grimm et al., 2017; Peters et al., 2011; Tappeiner et al., 2020), considering them a fundamental characteristic of the system after disturbance. However, no general approach or concept for a systematic identification of anthropogenic legacy exists and the information, both historical and contemporary, needed to identify them is often sporadic and scattered across a multitude of sources (e.g., literature, maps, etc.) within different scientific disciplines (Bain et al., 2012; Monger et al., 2015; Wohl, 2015).

Here, we build upon past progress in legacy research and explore new avenues for a systematic legacy identification. We focus on anthropogenic legacy in freshwater ecosystems, given their key role throughout human history, providing essential goods and services that are vital for people's survival and overall well-being (Vári et al., 2022). As a result, most freshwater ecosystems have nowadays been extensively modified and exploited, through a series of human interventions such as river channelization, construction of dams and reservoirs, overfishing, and so forth (Banaduc et al., 2022; Vörösmarty et al., 2010). This has led to an important decline in freshwater biodiversity, significantly exceeding losses in terrestrial ecosystems (Albert et al., 2021; Sala et al., 2000), and to a change, or complete disappearance, of ecosystem services and of ecosystems' societal and economic functions (Tomscha et al., 2019). Historical modifications became an integral part of freshwater ecosystems as we know them today, making the consideration of their historical past indispensable for their conservation and management. Moreover, freshwater ecosystems are particularly responsive to the modification and exploitation of surrounding ecosystems (Brain & Prosser, 2022) and, because of their intrinsic hierarchical structure, disturbances and their legacy can propagate across various levels, affecting a multitude of interconnected landscape and ecological components. We synthesize selected literature to present a comprehensive conceptualization of the legacy formation process, inspired by elements from disturbance ecology and that offers guidance for a practical consideration of legacy in freshwater research and management, for instance as input for numerical models and environmental planning. We list historical and contemporary sources of information (e.g., communication, cartography, or paleoenvironmental sources, cf. Russell, 2019) that can be explored to investigate anthropogenic legacy at different spatiotemporal scales and discuss the complexity and uncertainty associated with legacy identification. By means of practical examples, we illustrate how anthropogenic legacy can be identified in real-world freshwater ecosystems. We conclude by summarizing the benefits of identifying anthropogenic legacy through a systematic approach, ranging from streamlining legacy identification to promoting legacy consideration in management actions.

2 | DEFINITIONS AND RELATED CONCEPTS

Legacy is defined as "something that is a part of your history or that remains from an earlier time" (Cambridge dictionary). In environmental science, the term legacy—or legacy effect—has been increasingly used since the end of the 20th century (Cuddington, 2012; Wohl, 2019). Although legacy effects can be caused by natural phenomena (e.g., major flood events), legacy is commonly used to refer to persistent alterations of the ecosystem caused by past human activities (Bain et al., 2012; Cuddington, 2012; James, 2015; Johnstone et al., 2016; Wohl, 2019; Ziter et al., 2017). Particularly within the ecological domain, a series of terms and concepts related to legacy can be found: examples are "footprint" (Galli et al., 2012), "lags" (Bürgi et al., 2017; Cuddington, 2012; Ryo et al., 2019), "ecological inheritance"

(Cuddington, 2012), "ecological memory" (Johnstone et al., 2016; Peterson, 2002; Ryo et al., 2019), and "historical contingency" (Cadenasso et al., 2006; Cuddington, 2012; Fukami, 2015).

Whereas the temporal connotation is inherently included in the legacy definition (e.g., *past* disturbance, *persistent* effect), the spatial aspect is generally not specified (with few exceptions, e.g., James, 2015; Johnstone et al., 2016). This is probably due to the fact that the spatial extent of a legacy effect may depend on other factors and their interactions, including the intensity of a disturbance event, the level of spatial connectivity and the level of hierarchical organization of the system (Buma, 2015; Turner, 2010).

Depending on the context, the term "legacy" has been expanded by specifying the disturbance type or the response. For instance, a "land-use legacy" indicates that the ecosystem has been modified by past land-use practices (Maloney et al., 2008; Martin et al., 2011), whereas "legacy sediment" or "legacy pollutants" refer to alteration of the loads in sediments or pollutants as a legacy effect of past disturbance (Fleming et al., 2021; James, 2013).

Some authors have particularized the definition of legacy by explicitly providing a description of the disturbance target. For example, Bain et al. (2012) defined "structural legacy effects" as those altering the physical system and "signal legacy effects" as those altering material transport along the flow paths. Johnstone et al. (2016) used "information legacies" to refer to community or population characteristics resulting from adaptation to disturbance cycles across large spatiotemporal scales and "material legacies" to depict matter or organisms present in the ecosystem due to a specific disturbance event, thereby reflecting short-term changes at local spatial scales. Miller et al. (2021) distinguish between "biotic" and "abiotic" legacies, with "biotic" indicating the biological effects of a disturbance on a community (e.g., change in biomass) and with "abiotic" referring to the material (nonbiological) effects (e.g., erosion, sediment deposition).

3 | LEGACY FORMATION IN FRESHWATER SYSTEMS

3.1 | The legacy formation process

Contemporary freshwater ecosystems have been shaped by the concurring legacy of multiple past anthropogenic disturbances. Figure 1 presents an overview of the most frequent types of anthropogenic legacy identified in the literature (see Table S1, consisting of a collection of 40 selected case studies discussing legacy in both freshwater and terrestrial ecosystems). Note that some disturbances can be potentially assigned to more than one legacy type (e.g., fire can be assigned to both the land use/land cover and the landscape modification types).

In order to understand how anthropogenic legacy establishes and evolves, we conceptualize the legacy formation process (Figure 2). We retain the fundamental elements (= boxes in Figure 2) of a disturbance process (Grimm et al., 2017; Peters et al., 2011; Turner et al., 2003), while regarding the connections (= arrows) between them as reflection of dynamic processes and trajectories of change within an ecosystem. These dynamic processes and trajectories (i.e., traceable development of an individual variable or a set of changing variables over time; Britt, 1993; Tappeiner et al., 2020) are characterized by specific spatiotemporal regimes, which describe their timing, rate of change and duration, frequency, magnitude, location, and intensity (Fraterrigo & Rusak, 2008; Ryo et al., 2019; Turner, 2010).

To aid the description, we provide a running fictitious example—inspired by Happ et al. (1940) and Wohl (2015)—depicting the formation of a legacy of logging activity on river morphology (Figure 2). In our example, historical wood demand for industrial use or construction (disturbance driver) led to logging activity on hillslopes (disturbance type) (Madej & Ozaki, 1996). Excess erosion from the logged hillslopes increased the amount of sediment deposition in the river (disturbance mechanism), which affected the morphology of the river itself (target) (Happ et al., 1940; James, 2018). In response to an increased sediment deposition, the floodplain enlarged, and islands and sediment deposits formed near the stream banks (target response). After the cessation of the logging activity, the forest regrows on the hillslopes, preventing excess erosion. However, the river morphology is permanently modified, with larger floodplain, islands and sediment deposits still present after the conclusion of the disturbance (legacy).

A disturbance driver (Graham et al., 2021) represents any human resource demand (e.g., wood demand for industrial use or construction in Figure 2) that causes a disturbance in the ecosystem (e.g., logging). The pattern with which a disturbance evolves over time can be described as a short-term pulse, a slowly evolving ramp, or a persisting press (cf. Lake, 2000; Stanley et al., 2010). A certain disturbance type translates into tangible impacts through disturbance mechanisms (e.g., excess erosion from the logged hillslopes, increasing the amount of sediment deposition in the river and floodplain). A disturbance mechanism can be biological or physical (Peters et al., 2011). The disturbance directly or

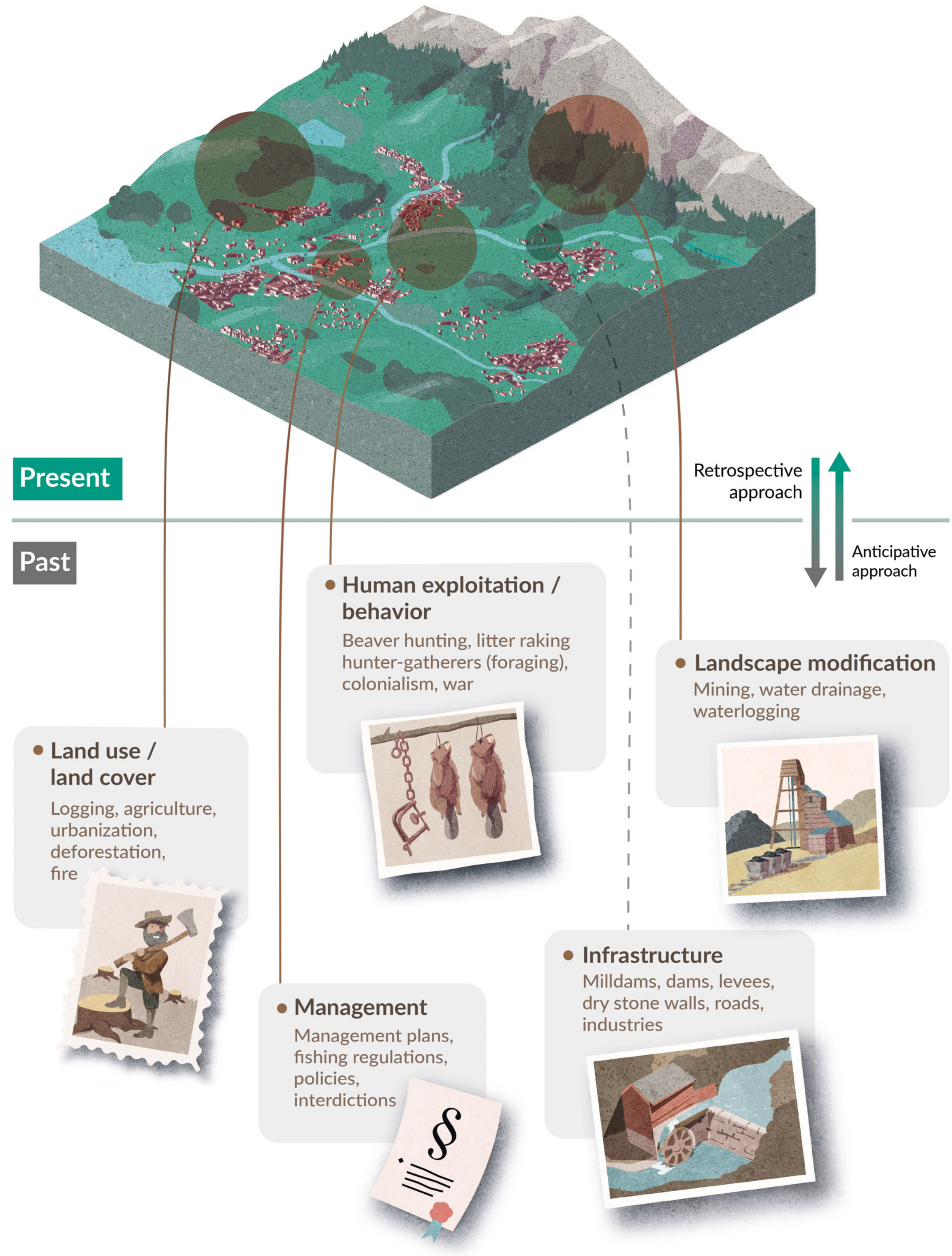


FIGURE 1 Common anthropogenic legacy types identified in the literature (gray panels) and their potential location in the present landscape (brown circles). For each legacy type (indicated in bold), examples of anthropogenic disturbances are provided. The size of the circles reflects that the spatial scale of the legacy can vary. Solid and dashed lines indicate that the occurrence and location and/or magnitude of an anthropogenic legacy can be identified with more or less certainty, respectively. The opposite arrows indicate that the characterization of a legacy can be approached starting with the consideration of the available historical information (anticipative approach) or contemporary information (retrospective approach). Eventually, this process becomes iterative. Illustration: Samuel Bucheli.

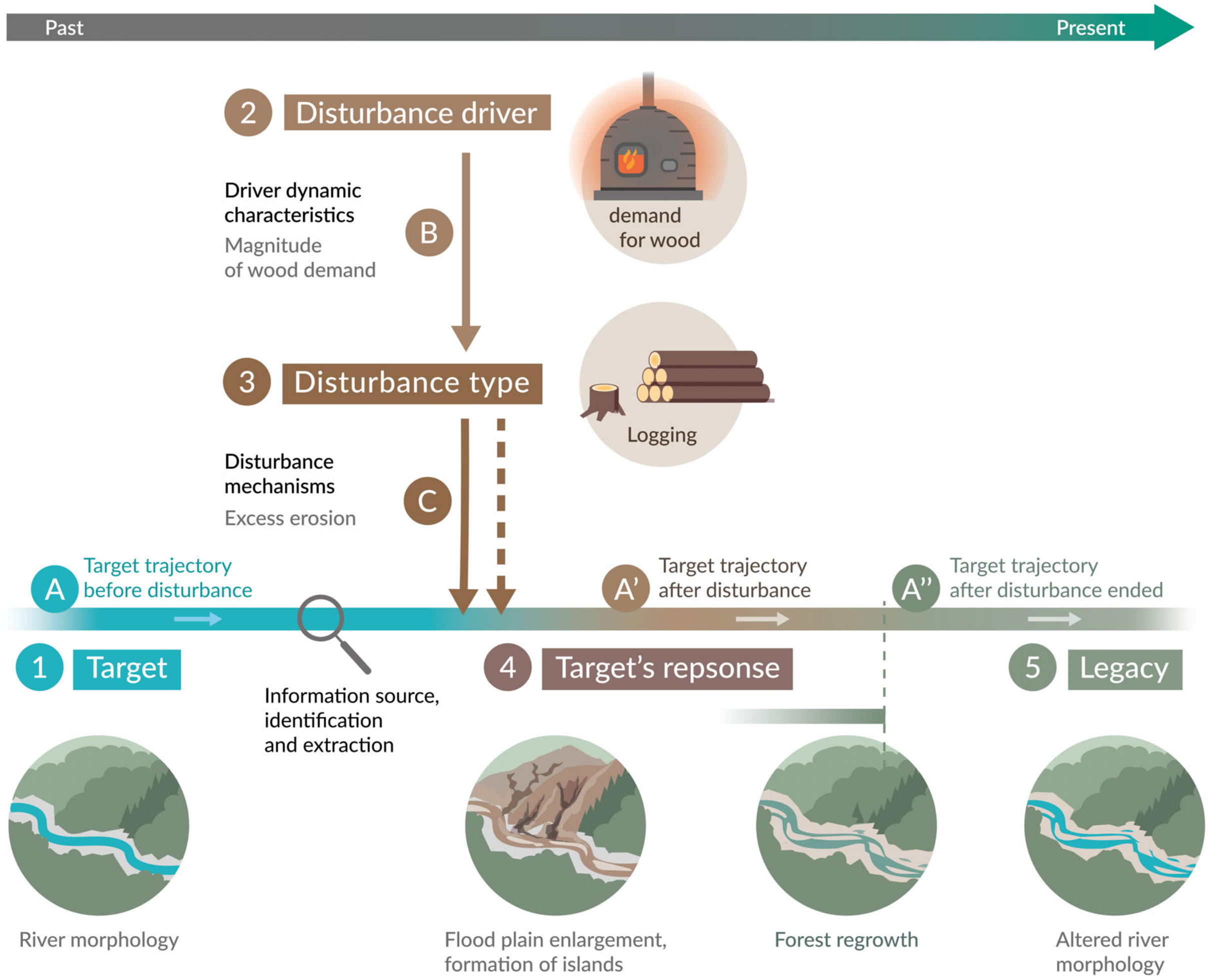


FIGURE 2 Legacy formation process. The process develops along a temporal axis. Boxes contain the fundamental elements of the legacy formation process (1–5). Connecting arrows represent dynamic processes and trajectories of change taking place within the legacy formation process (A, A′, A″, B, C). The disturbance impact on the target (arrow C) can be direct or indirect (full line and dashed line, respectively). The dashed, vertical green line marks the conclusion of the disturbance. The magnification lens indicates that the elements, dynamic processes, and trajectories within the legacy formation process can be investigated with appropriate methods, assuming that information is available (for simplicity, the magnification lens is represented only once). The illustrated example shows the formation of a legacy of logging activity on river morphology (inspired by Happ et al., 1940; Wohl, 2015). Excess erosion from logged hillslopes causes a modification of the river morphology (e.g., increased sediment deposition leads to enlarged floodplain and formation of islands), which is persistent even after forest has regrown on the hillslopes, arresting excess erosion. For sake of clarity, the interactions occurring within and between the elements of the legacy formation process are not shown. Illustration: Samuel Bucheli.

indirectly impacts a target, which can be abiotic (such as the target we consider in the example, i.e., river morphology) or biotic (e.g., riverine flora and fauna, not shown in the example). A target can be represented by specific structural and functional features of an ecosystem or by the whole ecosystem or landscape (cf. biological response variables in Perujo et al., 2021; cf. system model in Grimm et al., 2017). Any target develops over time following a certain trajectory of change (Tappeiner et al., 2020), which is subjected to inherent variability (Ryo et al., 2019).

The alteration of the original target's trajectory induced by the disturbance represents the target's response (Anderson, 2014; Bürgi et al., 2017) (e.g., modification of river morphology due to increased sediment deposition). The target's response can be immediate or time-lagged (Ryo et al., 2019; Ziter et al., 2017) and can, similarly to disturbance, evolve over time in a pulse, press, or ramp shape (cf. Lake, 2000, 2003; Ryo et al., 2019). The spatial characteristics of a target's response, such as its direction of propagation and extent (e.g., how far downstream the river morphology is impacted), are linked to the size, location, and intensity of the disturbance (Turner, 2010). Furthermore, the target's response depends on the characteristics of the target such as its disturbance-specific sensitivity, resistance, and resilience (Graham et al., 2021; Lamentowicz et al., 2019), which can be influenced by contextual factors such as the geomorphic setting of the stream (e.g., bedrock vs. alluvial streams), the presence of refugia or the degree of ecosystem heterogeneity and connectivity (Lake, 2003; Scheffer et al., 2012; Weber et al., 2013).

A legacy is generated if the target's response to the disturbance persists after the disturbance has concluded, ultimately causing the target to permanently shift from its original trajectory before disturbance (e.g., permanent modification of river morphology) (Bürgi et al., 2017; Gaiser et al., 2020; Perring et al., 2016; Ratajczak et al., 2017; Scheffer et al., 2012). This regime shift in the target trajectory eventually converts the target to a new state, characterized by potentially different properties compared to its previous state (cf. model reset in Gaiser et al., 2020; Ratajczak et al., 2017; Ryo et al., 2019). As the formation of a legacy depends on the target's ability to recover its original trajectory after the disturbance has concluded, legacy formation is influenced by the target's resilience and resistance to disturbance (Graham et al., 2021; Lamentowicz et al., 2019) and by the connectivity and heterogeneity of the ecosystem (Scheffer et al., 2012).

3.2 | Interactions within and among elements

Most legacy formation processes are characterized by multiple interactions occurring within and among their elements. For instance, multiple disturbance drivers can interplay to generate a disturbance and different disturbances can occur sequentially or simultaneously and generate an effect—which is generally different compared to the effect produced by the single disturbances considered separately (Figure 2) (Jackson et al., 2016; Perujo et al., 2021). When different disturbances occur sequentially, they can generate additive or nonadditive effects, such as accumulative and interactive carryover, respectively (cf. carryover in Ryo et al., 2019). Accumulative carryover occurs when the effects of sequential disturbance events within a short time add-up until a threshold is reached, causing an abrupt response of the target (e.g., regime shift; Ratajczak et al., 2017; Ryo et al., 2019). Interactive carryover occurs when a past disturbance influences the target's response to a subsequent disturbance by altering its resistance (linked disturbances) or resilience (compound disturbances) (cf. Buma, 2015). This past disturbance is not necessarily a recent event, but its effect could be present as a legacy (Figure 2). Interactions between a legacy effect and a recent disturbance develop in particular when the two are functionally connected (e.g., similar drivers, targets, and recovery mechanisms of the target; Buma, 2015). Large-scale ecological trends such as climate change and global warming, or vegetation shift can also interact with other—past or recent—disturbances (R. M. Thompson et al., 2017). In all cases, the interactions between different disturbances, legacies, and trends can be synergic or antagonistic (Orr et al., 2022; Perujo et al., 2021; Ryo et al., 2019; Turner, 2010). Interactions can also occur among different targets of the same disturbance event (Figure 2). If they show a hierarchical or nested organization (Polvi et al., 2020), alteration in the processes and functions at a certain hierarchical level is likely to resonate through other levels (Cross et al., 2015; Noss, 1990; Pickett et al., 1989). For example, depending on a species' ecological role (e.g., eco-engineer species, key species, umbrella species), the effect of disturbance on a certain target species can imply an effect on other levels (e.g., mutualism, Arnan et al., 2022; trophic interactions, Calizza et al., 2019).

4 | LEGACY IDENTIFICATION

4.1 | Preparatory reflections and decisions

A legacy can be identified by investigating the elements of the legacy formation process and particularly their dynamics and trajectories (i.e., arrows in Figure 2). An explicit selection of the target of interest (e.g., the river morphology in the logging example) increases the efficiency of legacy identification because it directs the efforts of finding and extracting information on a specific target, thus reducing the complexity of characterizing the properties and the dynamics of the entire system (e.g., defining a system model, cf. Grimm et al., 2017). To identify a legacy, the target's trajectory of change needs to be characterized with—at least—four points in time, providing enough information to compare the target's trajectory (two points in time) before disturbance (arrow A in Figure 2) with its trajectory (two points in time) after the disturbance has ended (arrow A″). Alternatively, the target's trajectory after disturbance (arrow A″) can be compared with a theoretical target's trajectory of change prior to disturbance (see example in Section 5.1). The better the target's dynamics are represented in the information sources, the less uncertain the legacy characterization will be (Bürgi et al., 2017; James, 2015; Swetnam et al., 1999). The same consideration is valid regarding the dynamics of the past disturbance event and its drivers (arrows B and C in Figure 2). In this sense, the characterization of the entire legacy formation process is susceptible to uncertainty related to the availability of information (both historical and contemporary), its quality (e.g., information accuracy or precision) and reliability (e.g., trustworthiness) (Bürgi et al., 2017; Russell, 2019; Skinner et al., 2014), and to the propagation of this uncertainty among the elements of the legacy formation process (Kirchner et al., 2021). When information is available, it may be beneficial to estimate how much information in time and space needs to be acquiring to characterize a legacy within a given ecosystem. For this purpose, value-of-information analysis (building on the benefits and costs of acquiring additional information; Canessa et al., 2015), usually used to reduce uncertainty in management outcomes and decision making (Canessa et al., 2015; Maxwell et al., 2015), could be employed. Information quality and reliability depend on the sources used to extract information, whose uncertainty should be assessed in order to reduce the uncertainty of the legacy characterization outcomes (Kirchner et al., 2021). For this purpose, exchanges and multidisciplinary collaborations with experts who have a deep knowledge of the information sources employed (e.g., cartographers, paleoecologists) can be valuable (Russell, 2019).

The availability of information, especially historical, is not always ensured, and key legacy dynamics are often to be inferred from few or scattered data (Bürgi et al., 2017). In some cases, historical information may be too scarce to provide a sound description of past trajectories and dynamics within the legacy formation process. One way to compensate for information scarcity can be to explore the dynamics of alternative targets or disturbances related to the legacy to be characterized. For example, if information on part of the trajectory of change of the target of interest is lacking, looking at a related target's response dynamics with respect to the same disturbance can help to reduce uncertainty in the characterization of the trajectory of change of the target of interest (see interactions between targets of the same disturbance in Section 3.2) (Maxwell et al., 2015).

Understanding which information is readily available and which aspects of the legacy formation process they cover determines how to approach the framework. Depending on this information, it is then possible to move along the elements of the legacy formation process. A retrospective approach (Figure 1) can be used when the current state of the selected target suggests the presence of a legacy. In this case, it needs to be determined which past anthropogenic disturbance has influenced the trajectory of the target and brought it to its current state. An anticipative approach can be used when there is knowledge of a past anthropogenic disturbance and its possible legacy on the target of interest is to be investigated (e.g., to disclose legacies that may not be visible yet). By the time more historical and contemporary information is gathered, this process becomes iterative. The most convenient way to approach the characterization of a legacy is to isolate the effects of distinct disturbance types and to disentangle their relative importance (Buma, 2015; Fraterrigo & Rusak, 2008; Peters et al., 2011). Similarly, to best characterize a disturbance type, its drivers need to be considered individually. Only subsequently can drivers and disturbance interactions be understood and analyzed. The analysis of these interactions is, however, beyond the scope of this manuscript.

It is important to note that observed changes in the target's trajectory might be the result of some other causes besides the presence of a legacy: experience and a sound knowledge of the studied system can help to isolate the effects of natural variability, such as seasonality, and recent disturbance from the possible legacy of historical disturbance. For this reason, when investigating the effects of a possible legacy, the gathering of both contemporary and historical information is equally relevant. When investigating historical disturbance, it is generally not possible to rely on the comparison with a control system (e.g., a system of analogous characteristics where the disturbance did not happen) to infer cause–effect relationships between the disturbance and the observed changes in the target's trajectory (de Palma et al., 2018). In some cases, the effects of disturbance on a target can be investigated following some particular experimental designs such as the BACI—"Before–After–Control–Impact"—approach, used when clear information about when and where a disturbance occurs, and sufficient pre-disturbance data, exist (Green, 1979). Although this approach—and its variants such as beyond BACI, and Multiple BACI—is widely used in environmental impact assessments and ecological studies, it is not free from limitations, especially when considering complex systems with many factors at play and the necessity to study the effects of historical disturbance (not of medium or short-term disturbance) (Benedetti-Cecchi, 2001; Smith et al., 1993; Smokorowski & Randall, 2017; Underwood, 1994). Methods addressing the inability to use a control system mainly consist in modeling approaches, simulating the impact of disturbances on a target and on a control (Benedetti-Cecchi, 2001), and in statistical methods (see Section 4.2) associating unexplained target variance (e.g., residuals) with the presence of a legacy (Saladin et al., 2020).

4.2 | Information sources and extraction

Different information sources and techniques (communication, cartographic, remote sensing, monitoring, and paleoenvironmental sources; Table 1) can be used to describe different drivers, disturbances, and targets, as well as their dynamics within the legacy formation process (Table S1). The spatiotemporal scale of the information extracted from the sources should represent the scales of the process that has produced the legacy to be characterized (Russell, 2019; Swetnam et al., 1999). Figure 3 shows an overview of the spatiotemporal scales covered by the different sources of information. Potential (Figure 3a) refers to the larger spatiotemporal scale that can be ideally explored using a certain source, while actual (Figure 3b) refers to the spatiotemporal scale that is most commonly investigated in literature using that source (Table S1).

TABLE 1 Sources of information and techniques for extracting quantitative (qn) and qualitative (ql) data and information on the dynamic processes and trajectories of change within the legacy formation process.

Sources	Techniques	Investigated processes	Example references
Communication sources: oral history, old photographs, written sources (e.g., previous literature, history books); can be collected in archives	Questionnaires, interviews, census (ql, qn), literature reviews (ql, qn), definition of historical context, time-lines of historical events (e.g., socioeconomic and political events) (ql)	• Successions and transitions of historical events (B, C) • Evolution of target characteristics (A, A′, A″)	(Haider et al., 2019; Inamdar et al., 2021; Mensing et al., 2020)
Cartographic sources: topographic maps and land-use and land-cover (LULC) maps	Visual assessment (ql), map digitalization and extraction of environmental metrics (qn)	• Spatiotemporal landscape change (C, A, A′, A″)	(Abadie et al., 2020; Martin et al., 2011; Munteanu et al., 2015)
Remote sensing sources: aerial photographs and satellite images (black/white, multi-spectral, orthophotos). Lidar (Light Detection and Ranging)	Visual assessment (ql), automated change detection (e.g., land cover change detection) (qn)	• Spatiotemporal landscape change (C, A, A′, A″)	(Bellemare et al., 2002; Merritts et al., 2011)
Monitoring sources: data from long-term monitoring and sampling programs, long-term experiments; can be collected in databases	Monitoring and sampling of biotic and abiotic features (qn, ql), time-series analysis (qn), derivation of metrics (qn)	• Evolution of target characteristics (A, A′, A″) • Disturbance characteristics (e.g., beginning-end, regime; C) • Disturbance-effect lag time (C, A′, A″) • Disturbance-effect time ratio (ratio of effect persistence time to disturbance time; C, A′, A″)	(Fenton et al., 2017; Han et al., 2014)
Paleoenvironmental sources: paleoenvironmental records (e.g., sediment)	Analysis of soil and sediment cores (e.g., analysis of fossil pollen, phytolith, charcoal, diatoms, macrofossils, ancient-DNA) (ql, qn). (These analyses are very often accompanied by dating techniques such as dendrochronology [qn], isotopic and radiometric dating on environmental samples, tree-ring dating [qn].)	• Evolution of target characteristics (A, A′, A″) • Disturbance characteristics (e.g., beginning-end; C)	(Åkesson et al., 2020; Gell et al., 2013; Morales-Molino et al., 2021; Seersholm et al., 2018; Swinnen et al., 2020)

Note: The letters in brackets refer to the arrows in Figure 2. For the complete reviewed literature, see Table S1.

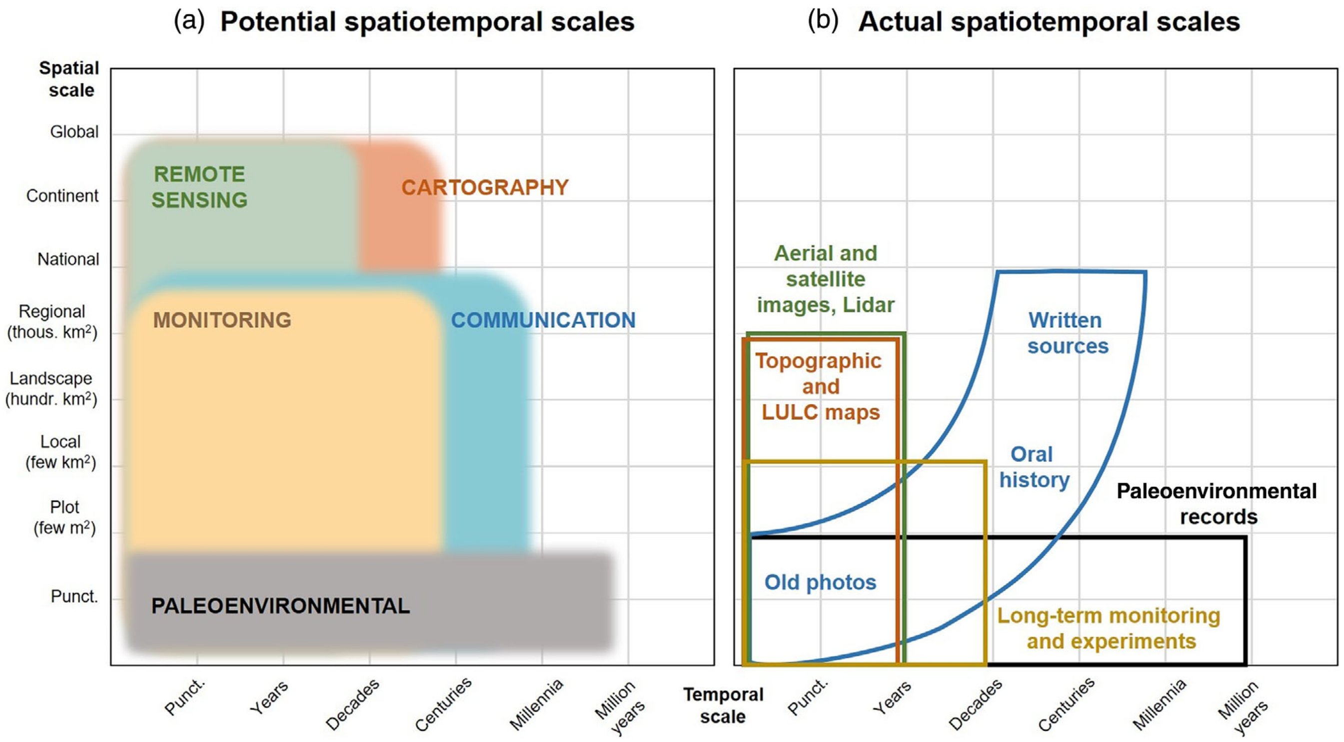


FIGURE 3 Potential (a) and actual (b) spatiotemporal scales of the information extracted from different source categories (see Table 1). Potential refers to the larger spatiotemporal scale that can be ideally explored using a certain source, while actual refers to the spatiotemporal scale that is most commonly investigated in literature using that source (Table S1).

Communication sources such as written documents and oral history are useful to delineate the historical context within which a disturbance has taken place as well as the historical socioeconomic and political disturbance drivers (e.g., Haider et al., 2019; Mensing et al., 2020). Old photographs also represent an important source for context characterization (Inamdar et al., 2021; Russell, 2019; Trimble, 2008), even though they only provide a punctual representation of the investigated system in time and space (Figure 3b). Cartographic and remote sensing sources are both used to investigate spatiotemporal changes of the landscape (e.g., changes in land use and cover, hydromorphological changes), with maps usually—but not exclusively—being deployed to delineate historical landscape conditions, whereas remote sensing methods are applied to define recent or contemporary conditions (e.g., Abadie et al., 2020; Bellemare et al., 2002; Hohensinner et al., 2004; Russell, 2019). Similarly to old photographs, cartographic and remote sensing sources are temporal snapshots of the system at a certain point in time. However, a number of almost consecutive maps or satellite acquisition could provide a good representation of the dynamics involved in a legacy formation (e.g., trajectory of change of the target of interest).

On-site data collection within the framework of long-term monitoring and sampling programs and long-term experiments allows information to be gathered on a variety of targets and disturbances, and on their dynamics. For example, long-term monitoring and sampling programs are often focused on environmental parameters which are useful to evaluate the state of the ecosystem, such as soil chemistry (e.g., Fenton et al., 2017) or surface water and groundwater quality (e.g., Nõges et al., 2020; Wang et al., 2016). In some cases, data collected from long-term programs can date back several decades (Figure 3b) and, considering the ensemble of different study locations (e.g., plot or local observations, Figure 3b), can encompass relatively large areas (e.g., in case of regional or national sampling programs; Julian et al., 2017). Finally, paleoenvironmental records such as pollen, phytolith, charcoal, and ancient-DNA (Åkesson et al., 2020; Morales-Molino et al., 2021; Seersholm et al., 2018) allow the evolution of different targets (e.g., plant and animal species) and disturbances (e.g., fire, presence of human settlements) to be reconstructed over the longest period (e.g., up to million years; Figure 3b) (J. C. Thompson et al., 2020). Similar to monitoring and sampling programs, the spatial resolution of paleoenvironmental records can be regarded as the ensemble of different punctual observations and is, moreover, proportional to the sampling effort (e.g., soil and sediment coring).

Numerical models can be employed to reconstruct the past dynamics of targets and disturbances by taking partial historical information into consideration (e.g., nitrate concentration in aquifers, Wang et al., 2016; phosphorus storage in soils and channels, Motew et al., 2017; and nutrients dynamics, Chen et al., 2018) or by simulating targets' responses to past disturbance (e.g., dynamic of forest carbon in response to land use and forest management; Thom et al., 2018). Finally, statistical models (e.g., regression models) can also be employed to investigate the presence of possible legacy. If the present status of the selected target can only partially be explained by the current environmental variability, the unexplained variance (e.g., residuals) could be associated with the presence of legacies and analyzed against historical drivers (cf. Saladin et al., 2020).

Depending on the different sources and techniques used, qualitative and/or quantitative data and information are produced (see Table 1). The translation of these data and information into Findable, Accessible, Interoperable, Reusable (FAIR) resources (Wilkinson et al., 2016) is advisable in order to raise awareness among research studies and managers about the legacy topic and the value of its characterization. The production and storage (i.e., in open-source repositories and geodata platforms), of FAIR data and information enhances the likelihood that future projects will systematically incorporate historical information.

5 | LEGACY EXAMPLES

5.1 | Legacy identification: Example from literature

In this section, we analyze a published study on land-use legacy and contextualize it by means of the proposed legacy formation process. The study by Kellner and Hubbart (2017b) is on the Hinkson Creek Watershed (HCW) in Missouri (USA), listed as impaired by "unknown" pollutants by the Missouri Department of Natural Resources since 1998, that is, no particular pollutant or group of pollutants could be identified as the main cause of the impairment (MDSN, 2010). In 2008, a series of monitoring stations for stream chemistry and discharge were installed and, in 2011, a collaborative management program was put into action in order to improve stream water quality. As part of the management program, flow reduction from urban and rural areas was implemented, assuming the source of pollutants was attributable to urban settlements within the watershed. Despite flow reduction, water quality within the HCW did not show significant amelioration over the following years.

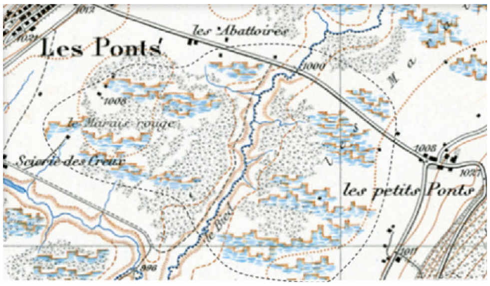
The failure of the management program prompted the authors of the study to look for additional explanations behind the HCW impairment (retrospective approach). Moving their focus from the stream chemistry (target of interest) to the dynamics of the watershed's flow regime (related target), the authors identified abnormal spatial relationships between the drainage area and stream flow in the headwater portion of the watershed (legacy) (Kellner & Hubbart, 2017a). These drainage area vs. stream flow relationships showed a clear deviation from the expected dynamics typically reported in the literature (target trajectory before disturbance, A), and suggested the presence of possible surface water sinking areas (disturbance mechanism, C). Investigation into the watershed's historical context and land-use dynamics from the annual reports of the Missouri Bureau of Mines brought to light historical shaft coal mining activity (disturbance). The mines had been excavated starting from around 1891 for about 30 years (C) as a result of the urban development in the area surrounding the city of Columbia (i.e., railway construction, driver). The shaft mines excavation (indirectly) modified the flow dynamics within the catchments (target trajectory before disturbance, A') through the alteration of the land in the proximity of the mines (e.g., subsiding, fracturing, and increasing the permeability of surface layers, C). The effects of the excavation persisted even after the cessation of the mining activity (target trajectory after disturbance ended, A''; here $A'' \neq A$, which implies a legacy effect). The historical mining activity represents only one of the natural and anthropogenic disturbances that contributed to the modification of the HCW flow regime (e.g., logging, land conversion, karst geology). However, watershed management—both in term of water quality and quantity—was ineffective as it did not consider the legacy of historical mining, but focused exclusively on contemporary land-use practices.

5.2 | Use of different information sources

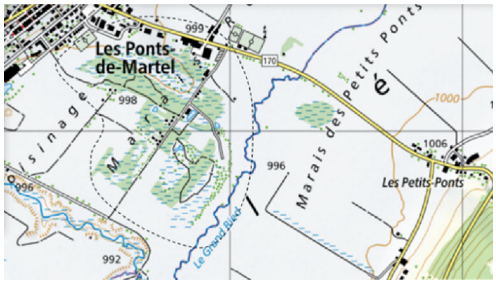
In this section, we provide six examples of how different information sources can be used to identify anthropogenic legacy (Table 2). Examples 1 and 2 show how a legacy can be identified on cartographic maps and, in particular, from the

TABLE 2 Examples of legacy identification in freshwater ecosystems from different information sources.

Example 1: Peat digging (cartographic maps)



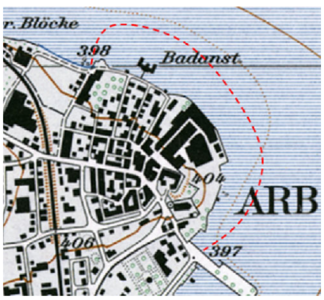
1925 (peat digging allowed)



2021 (present situation)

- *Where*: Ponts-de-Martel (Switzerland).
- *Background*: Historically, the peat bogs in Ponts-de-Martel covered an area of 15 km^2; today, their area is only 2.3 km^2. NGOs and nonprofit organizations aim to raise awareness among the public about the historical peat bog exploitation issue.
- *Legacy identification*: A shortage of wood for heating (around the 18th century) brought to an intense exploitation of peat as alternative combustible (B). To collect the peat from the wetland, the vegetation was eradicated and the water drained (C). This led to a drastic reduction of the peat bogs ecosystems (A → A′). Even after the ban on peat digging in 1987 with the "Rothenthurm initiative," the extension of the original peat bogs remains drastically reduced, resulting in loss of biodiversity (e.g., insects) and ecosystem services (e.g., flood peaks mitigation, carbon storage) (A″). This can be observed from the comparison between historical and contemporary maps (peat bogs area within dotted lines).
- *Possible effects of not considering a legacy*: Since peat bogs do not recover their ecological functions without extensive restoration interventions, further exploitation of peat bogs needs to be restricted.
- *References*: Federal Office of Topography (swisstopo), Foundation du Musée de la Tourbière (2023), Pro Natura Neuchâtel (2023).

Example 2: Leak of contaminants (cartographic maps)



1956 (dumping site open)

1961 (dumping site covered)

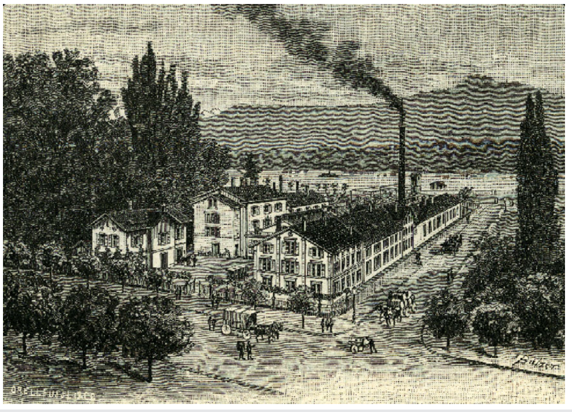
2021 (present situation)

- *Where*: Lake Constance—Arbon Seepark in Arbon (Switzerland).
- *Background*: The site is recognized by the authorities as polluted by the dumping of construction material and household waste. Investigation was conducted to understand if groundwater, contaminated by the polluted soil, reached the lake.
- *Legacy identification*: From about 1959 to 1963, the waterfront area (outlined by the red dotted line) began to be filled (C) to use the reclaimed land as a promenade and as a landfill (B; observed from the comparison between historical and contemporary maps). Today, the quality of groundwater reaching the lake has drastically deteriorated (A → A′), even after operations of removal of the contaminated soil and the sealing of the landfill (A″).
- *Possible effects of not considering the legacy*: The investigation of contaminated groundwater and its effects would not have taken place.
- *References*: Federal Office of Topography (swisstopo) (n.d.-a, n.d.-b), Eichenberger (2011).

(Continues)

TABLE 2 (Continued)

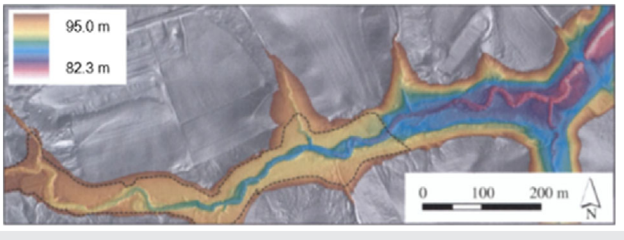
Example 3: Heavy metals (old photographs and archives)



1860 Silk dye house (CC BY SA 4.0).

- *Where*: Zürich (Switzerland).
- *Background*: The authorities of the canton of Zurich initiated the institution of an inventory of polluted sites, and soon realized the presence of contamination near former industrial sites along Lake Zurich.
- *Legacy identification*: From about 1840 to 1900, the area experienced a peak in industrialization and flourishing of silk production (B, documented in old photographs and archives), with a subsequent increase in the quantity of heavy metals released into the atmosphere. These metals reached the surface of the lake and bound to particles that eventually ended up in the sediments (C). This led to a change in the chemical composition of lake sediments ($A \rightarrow A'$, observed with sediment cores, not shown). Today, long after the closure of the industrial sites, metals form silk dyeing processes are still present in the sediment of Lake Zurich (A'').
- *Possible effects of not considering the legacy*: Nowadays, some of the former industrial sites have been transformed in recreational areas for the public (i.e., swimming areas). Before these areas could be established, contaminated sediment had to be removed to avoid the risk of remobilization of polluted sediment.
- *References*: Roethlin et al. (2022), Wassertimeline (2023), City of Zürich—Baugeschichtliches Archiv (2023).

Example 4: Sediment accumulation (Lidar observations)

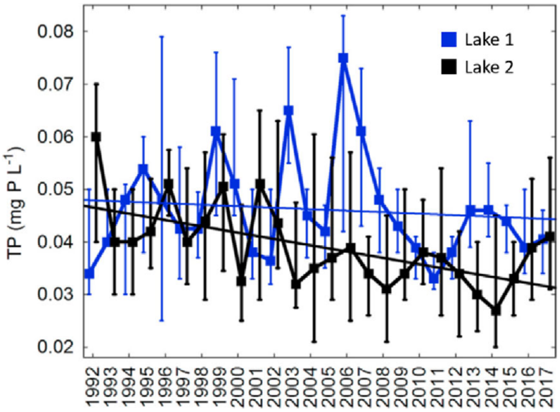


Lidar image showing the different elevation of the valley upstream (yellow) and downstream (blue) from the location of a former mill dam (modified from Merritts et al., 2011 with permission from the Royal Society).

- *Where*: Indian Run, tributary to Little Conestoga Creek (Pennsylvania, USA).
- *Background*: The authors wanted to test the hypothesis that the construction of milldams between the 17th century and the early 20th century—and their subsequent abandonment and breaching—have resulted in the transformation of stream valleys.
- *Legacy identification*: The need for waterpower for milling operations after the installment of European settlements (B) led to the construction of milldams (C, peaking from 1780 to 1860). This changed the dynamics of stream discharge and sediment load, as well as the physical and chemical characteristics of the sediment, compared to the pre-European period ($A \rightarrow A'$). Today, after the breaching of some abandoned milldams, it is possible to observe the occurrence of sediment accumulation, formation of valley-flats (observed through Lidar observations), and a reduction of valley bottom slopes (A'').
- *Possible effects of not considering the legacy*: Wrong interpretation of the mechanisms of floodplain and valley formation.
- References: Merritts et al. (2011), Walter and Merritts (2008).

TABLE 2 (Continued)

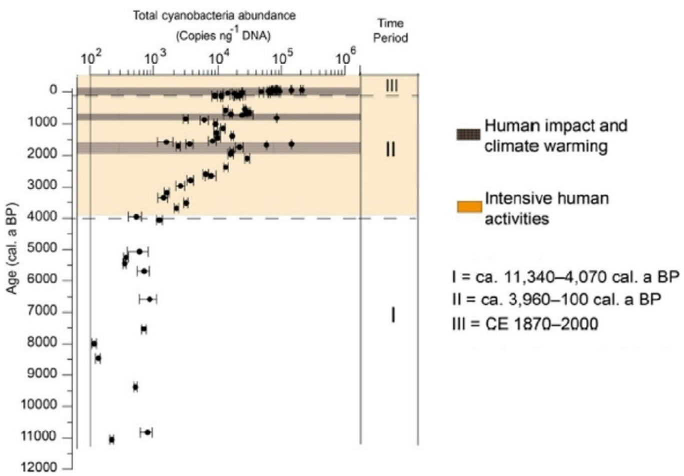
Example 5: Phosphorous in lake sediments (long-term monitoring and databases)



Total phosphorous concentration in two Estonian lakes between 1992 and 2017 (modified from Nõges et al., 2020 with permission from Elsevier).

- *Where*: Lakes Võrtsjärv and Peipsi (Estonia).
- *Background*: The authors wanted to understand the reasons behind the inertia of two Estonian lakes in responding to nutrient loading reduction (i.e., reduction of mineral fertilizers application in the post-Soviet era).
- *Legacy identification*: The Soviet agricultural system, aiming at increasing agricultural productivity (B), led to extensive mineral fertilizer application (C, mid-1980s). An increase in the total phosphorous concentration in lakes was observed from the 1980s to 1990s (during the Soviet-era) (A → A′). In the post-Soviet era, and still today, phosphorous pools stored in lake sediments cause system inertia to respond to nutrient loading reduction (A″, observed through long-term monitoring).
- *Possible effects of not considering the legacy*: Because of the presence of legacy nutrients, managers need to further limit new nutrient loads to achieve the desired results (e.g., reduce the risk of water blooms).
- *References*: Nõges et al. (2010), Nõges et al. (2020).

Example 6: Toxic organisms in lake (paleoenvironmental records)



Sediment chronology with information on cyanobacteria abundance (sediment core from Lake Tiefer See, Germany) (modified from Nwosu et al., 2023; CC BY 4.0)

- *Where*: Lake Tiefer See (Germany).
- *Background*: The authors aimed at exploring whether the presence of prehistoric settlements on the lakeshore influenced cyanobacteria community dynamics in the lake.
- *Legacy identification*: During the Bronze Age (∼1600–800 BC to ca. 3940–3100 cal. a BP), the settlement of human communities around the lake (B) and the intense deforestation (C) led to a considerable addition of nutrients into the lake. A change in total cyanobacteria abundances (observed from paleoenvironmental records) and beta-diversity (not shown) was observed when comparing the pre- and post-settlements period ('A → A′). A large cyanobacteria population and the presence of toxic taxa built up from the changes that occurred during the Bronze Age (A″).
- *Possible effects of not considering the legacy*: The misinterpretation of the timing of the initial anthropogenic influence on the lake's ecology can result in the omission of crucial data essential for managing aquatic systems at risk from the proliferation of potentially harmful species.
- *Reference*: Nwosu et al. (2023).

comparison between historical and contemporary maps. In Example 1, a legacy can be directly identified from the comparison between the two maps (i.e., the extent of the wetlands appears drastically reduced in the 2021 map, 35 years after the ban to peat digging). Example 2 shows how map comparison can be employed to reconstruct spatiotemporal dynamics in the studied area (i.e., changes of the lake shore morphology through the years) in the proximity of a site known as polluted (retrospective approach). Example 4 shows how a legacy can be directly identified from the Lidar observations (i.e., sediment accumulation). In all the other cases (i.e., Examples 3, 5, and 6), the sources of historical information are used to explain the dynamics observed in present-day ecosystems trough the presence of anthropogenic legacy (i.e., heavy metal pollution, excess of nutrients, and eco-toxicity, respectively), providing valuable insights for contemporary freshwater ecosystem management.

6 | BENEFITS AND FUTURE DIRECTIONS

The legacy of historical anthropogenic disturbance plays a pivotal role in controlling ecosystem responses to present and future disturbance and management actions (Mika et al., 2010). Despite the widely recognized importance of anthropogenic legacy, it is still rarely taken into consideration when designing management strategies (Bain et al., 2012; Kellner & Hubbart, 2017b; Lintern et al., 2020). Failure to consider anthropogenic legacy is likely to lead to a biased interpretation of present and future ecosystem dynamics, thereby increasing the risk of ineffective or potentially inadequate management outcomes (e.g., inappropriate river type selected as a reference for restoration, see Wohl, 2019). We believe that the systematic application of the legacy formation process will advance freshwater research and management in three main ways.

First, the application of the legacy formation process provides guidance for a structured and informed consideration of legacy in a given research or management project (Higgs et al., 2014; Martin et al., 2021; R. M. Thompson et al., 2017). The dynamics of interest can be prioritized and characterized based on the study needs and available information. As such, the concept is practical and enables the streamlining of legacy characterization, two assets in an often complex and multidisciplinary project setting. However, this does not mean that the inherent complexity of an ecosystem is neglected: on the contrary, this complexity can be explored and exploited to enhance our understanding of the legacy formation, for example by delineating the historical or social-economic context of an ecosystem (Marcucci, 2000). Future legacy studies would benefit from multidisciplinary collaborations and the development of optimized approaches for extracting FAIR data and information from the available sources (Bürgi et al., 2017; Wilkinson et al., 2016). Further research should focus on how much information in time and space is needed in order to identify anthropogenic legacy and to reduce the associated uncertainty.

Second, the application of the legacy formation process creates the basis for cross-comparison and transfer across multiple research and management projects covering different disciplines and fields of work (Weber et al., 2017). Systematic conceptualizations of legacy formation are highly valuable for practical research and management in that they can potentially be used for identifying and comparing legacy formation within a broad range of ecosystem conditions and stressors (Perujo et al., 2021). This can lead to a new understanding of how different ecosystems have been shaped by similar past anthropogenic disturbances. The more legacies are characterized in accordance with a standardized approach, the more researchers and managers will be able to anticipate or retrospectively identify potential legacy within a given ecosystem.

Third, the application of the legacy formation process across multiple ecosystems helps predict legacy that may develop from current anthropogenic disturbance and management actions. For doing so, it might prove valuable to develop a typology (Bailey, 2005) to group legacies based on reproducible patterns in their formation process, for instance considering specific disturbance-target interactions. A legacy typology represents an important reference source for researchers and managers (Van Loon & Van Lanen, 2012), aiding the characterization and comparison of contemporary anthropogenic legacy and improving the prediction of future legacy. The ability to predict the future implications of current management practices helps move toward informed and proactive management approaches, aimed at anticipating and possibly preventing future legacy formation (Palmer et al., 2008).

AUTHOR CONTRIBUTIONS

Marta Antonelli: Conceptualization (lead); data curation (lead); writing – original draft (lead); writing – review and editing (lead). **Patrick Laube:** Conceptualization (supporting); funding acquisition (equal); writing – review and editing (supporting). **Michael Doering:** Conceptualization (supporting); funding acquisition (equal);

writing – review and editing (supporting). **Victoria Scherelis:** Conceptualization (supporting); writing – review and editing (supporting). **Sidi Wu:** Writing – review and editing (supporting). **Lorenz Hurni:** Funding acquisition (equal); writing – review and editing (supporting). **Magnus Heitzler:** Writing – review and editing (supporting). **Christine Weber:** Conceptualization (equal); funding acquisition (equal); supervision (lead); writing – original draft (supporting); writing – review and editing (supporting).

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The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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RELATED WIREs ARTICLES

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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