Received: 8 August 2023 | Revised: 16 October 2023 | Accepted: 27 October 2023
DOI: 10.1002/hyp.15026

Fast motion view of a headwater creek—A hydrological year seen through time-lapse photography

Laurent Pfister[1,2] | Enrico Bonanno[1,3] | Ginevra Fabiani[1,4] | Laurent Gourdol[1] | Christophe Hissler[1] | Viola Huck[5] | Jean François Iffly[5] | Richard Keim[6] | Núria Martínez-Carreras[1] | Xavier Mestdagh[5] | Alessandro Montemagno[1] | Daniele Penna[4,7] | Stanislaus Schymanski[1] | Erwin Zehe[8]

[1]Environmental Research and Innovation Department, Environmental Sensing & Modelling Unit, Catchment & Eco-Hydrology Research Group, Luxembourg Institute of Science and Technology, Belvaux, Luxembourg

[2]Faculty of Science, Technology and Medicine, University of Luxembourg, Esch-sur-Alzette, Luxembourg

[3]Institute of Hydraulic and Water Resources Engineering, Vienna University of Technology, Vienna, Austria

[4]Department of Agriculture, Food, Environment and Forestry, University of Florence, Florence, Italy

[5]Environmental Research and Innovation Department, Observatory for Climate, Environment, and Biodiversity, Luxembourg Institute of Science and Technology, Belvaux, Luxembourg

[6]School of Renewable Natural Resources, Louisiana State University, Baton Rouge, Louisiana, USA

[7]Forest Engineering Resources and Management Department, Oregon State University, Corvallis, Oregon, USA

[8]Karlsruhe Institute of Technology, Institute for Water and River Basin Management, Karlsruhe, Germany

Correspondence
Pfister Laurent, Environmental Research and Innovation Department, Environmental Sensing & Modelling Unit, Catchment & Eco-Hydrology Research Group, Luxembourg Institute of Science and Technology, 41 rue du Brill, Belvaux L-4422, Luxembourg.
Email: laurent.pfister@list.lu

Funding information
Fonds National de la Recherche Luxembourg

1 | INTRODUCTION

New observational field data have repeatedly been the source of breakthroughs in science, allowing us to learn about things we had not been thinking of or hypothesized beforehand (Pfister & Kirchner, 2017). For example, increasingly sophisticated field-deployable instruments have helped shed light on previously unknown features of catchment functioning, such as high-frequency measurements of sediment, solutes, and isotopes in stream water (e.g., Floury et al., 2017; von Freyberg et al., 2017), continuous sap flow measurements (Granier, 1987), in-situ monitoring of the isotopic composition of tree xylem water (Marshall et al., 2020) and soil water (Volkmann & Weiler, 2014), imaging of subsurface structure and water infiltration pathways with electrical resistivity tomography (e.g., Gourdol et al., 2021; Scaini et al., 2017), or time-lapse mapping of surface-saturation dynamics with thermal infrared imagery (e.g., Glaser et al., 2018; Pfister et al., 2010).

Innovative hypotheses generated from novel, integrative, observations offer the potential to free hydrological concepts from the restrictions of typical datasets. In parallel, the recent progress in technological development of field instrumentation has ultimately also revealed more complex landscape heterogeneity. While general organizing principles have been proposed for coming to grips with complex river basins (Loritz et al., 2018; Zehe et al., 2014), deciphering this heterogeneity remains an important challenge. A major difficulty lies in the understanding of similarities and contrasts between hydrologic processes occurring over a wide range of spatial and temporal scales varying by multiple orders of magnitude (Dooge, 2005), e.g., from water molecules (10^{-10} m) to watershed scale (10^{3} m) and from seconds to millennia. The drama is that we could instrument our catchments to the point of littering, and still miss out on processes or features that we were not looking for.

TABLE 1 List of time-lapse photography sequences, scenes and sub-scenes with related hydrological processes.

Sequence title	Scene title	Start video	End video	Processes (with sub-scene titles)
1. High-speed playback of pictures taken at noon from December 2020 to July 2022	Scene 1.1. Seasonal pulse of the Weierbach creek	December 2020 [00:17]	July 2022 [01:17]	Seasonal pulse, including stream-groundwater exchanges and forest litter dynamics
2. Time-lapse videos of pictures taken every 15 min showing hydrological processes in the Weierbach creek	Scene 2.1. Mechanistic fundamentals of flood hydrograph generation	12th March 2021 [07:48]	20th March 2021 [08:19]	Sub-scene 2.1.a. Double peak generation after onset of connectivity between near-stream and upslope locations
		14th July 2021 [16:02]	15th July 2021 [16:08]	Sub-scene 2.1.b. Sediment transport during early stages of major flood event on 14th July 2021, followed by contributions via delayed subsurface flow and groundwater
	Scene 2.2. Hydrograph baseflow recession periods	07th June 2021 [13:36]	27th June 2021 [14:55]	Sub-scene 2.2.a. Daily minima of discharge in summer afternoons, following a peak in evapotranspiration (also expressed in tree stem water deficit)
		27th May 2021 [12:52]	14th July 2021 [13:35]	Sub-scene 2.2.b. Circadian leaf movements of herbaceous plants near the stream bed
		10th June 2022 [38:07]	20th June 2022 [38:46]	Sub-scene 2.2.c. Sunflecks moving on the forest floor—illustrating exposition of plant leaves to sudden heat and water stress
		15th April 2021 [10:03]	30th April 2021 [11:02]	Sub-scene 2.2.d. Daily maxima in discharge caused by fluctuations in viscosity driven by changes in air and stream water temperature
	Scene 2.3. Freeze–thaw cycles	5th January 2021 [03:24]	20th January 2021 [04:23]	Sub-scene 2.3.a. Needle ice formation in the soft riparian soil adjacent to the stream, and flood wave caused by rain on snow events
		7th February 2021 [05:36]	15th February 2021 [06:07]	Sub-scene 2.3.b. Needle ice formation in the soft riparian soil adjacent to the stream, followed by a rise of nearly 10–15 cm of riparian soil thickness

Note: Start and end references relate to the time-lapse video file spanning from December 2020 to July 2022 and available at https://youtu.be/74S7DfT7Uhs.

Here, we propose the use of the so-called undercranking filming technique (also known as time-lapse photography) to go further in diagnosing catchment complexity and heterogeneity. Undercranking consists in taking fewer frames with a camera for ultimately speeding up the action during playback. This offers the potential for placing in-situ measurements of individual processes in a wider spatial and temporal context, delivering an unprecedented view on the interplay between catchment characteristics (e.g., vegetation cover, soils, topography) and functioning (e.g., water storage and flux dynamics)—all constantly evolving, but at (very) different time scales. Improving our understanding of how catchment structure and functioning evolve is key for a better anticipation of future catchment trajectories (for example, under a changing climate).

2 | STUDY AREA, MATERIALS AND DATASETS

We focused on the Weierbach experimental catchment (WEC)—an interdisciplinary Critical Zone observatory dedicated to the study of hydrological, hydro-geochemical, and eco-hydrological processes. Long-term monitoring protocols in the WEC relate to water fluxes and physico-chemical parameters within different compartments of the Critical Zone. The rainfall-runoff response of the Weierbach is characterized by a strong seasonality—pronounced summer low flows (including occasionally dry periods) and winter high flows—resulting from the complex interplay of multiple eco-hydrological processes (Hissler et al., 2021).

We installed a wildlife monitoring camera (RECONYX Hyperfire 2 Professional White Flash Camera) in the WEC. The device was pointed towards the hillslope-riparian zone-stream continuum near a v-notch equipped with a recording stream gauge. Full colour night photos were obtained with a White Flash colour LED illumination that reaches up to 30 m (3 MP standard image resolution). Images were recorded every 15 min from December 2020 to July 2022 (the camera requiring only monthly battery changes). The nearly 58 000 recorded frames were assembled to form a single motion picture. An accelerated playback of this time-lapse video shows events that took place (very) slowly over time in the riparian zone. In a first sequence, we display a high-speed aggregate of frames taken at noon over 20 months. A second sequence shows aggregated pictures taken every 15 min, with a slower rendering of the interplay of various processes occurring in parallel or independently (Table 1). Both time-lapse videos of the hillslope-riparian zone-stream continuum are accompanied by graphs of hourly precipitation (mm/h), air temperature (°C), global radiation (W/m^2), tree stem radial growth (increase in maximum stem radius, μm), tree stem water deficit (deviations from past maximum stem radius, μm), soil moisture (volumetric percent of water at 10, 20, 40 and 60 cm depths), groundwater level in the riparian zone (m), and stream stage (cm). The horizontal time series plot above the time-lapse video displays recordings of soil moisture, groundwater levels, stream stage and precipitation, with a moving marker indicating the position of the current frame. On the right, three additional time series plots offer a detailed view of the diurnal variations of selected variables for the 5 days before and after the current frame. These variables include air temperature and global radiation (top), stem radial growth and stem water deficit (middle), and soil moisture, ground-water level, stream stage and hourly precipitation (bottom). The vertical axes span the range between the minimum and maximum of the data for each time series, whereas the actual values corresponding to each frame are shown in the legend box placed at the top right of the time-lapse video.

Below, we refer to different scenes and sub-scenes in the time-lapse video that exemplify selected processes (Table 1). They are identified by their time stamps, which can be easily accessed by clicking on the corresponding chapters in the video description available at https://youtu.be/74S7DfT7Uhs. Note that not all scenes of the video are described in detail in this contribution. Our selection of time-lapse videos was guided by the following criteria: (i) wetness state of the catchment, as expressed through low and high flow periods, (ii) representativeness of processes in the light of knowledge gained from prior research on hydrological functioning of the Weierbach and (iii) genuine or original character of the observations.

3 | DESCRIPTION AND DISCUSSION OF THE SELECTED SEQUENCES

3.1 | Sequence 1. High-speed playback of pictures taken at noon from December 2020 to July 2022

3.1.1 | Scene 1.1. The seasonal pulse of the Weierbach creek

The high-speed playback of pictures recorded from December 2020 to July 2022 [start video 00:17–end video 01:17] reveals a comprehensive view of winter, spring, summer and autumn seasons with their cohort of gradually changing processes and feedback mechanisms (Figure 1). In winter, for example, temperatures below zero are accompanied by several snowfall events—triggering a slow but gradual snow-fed groundwater recharge (recorded by soil moisture probes and groundwater wells). Balmy weather in spring comes with the onset of leaf sprout and a recession in groundwater levels and hydrographs. In summer, vegetation is most dynamic (exhibiting diurnal signals in stem water deficit and an almost continuous radial stem growth), while groundwater levels and discharge evolve between high and low levels along successive dry and wet sequences. With the onset of cooler temperatures and wet weather in autumn, leaf abscission commences, and vegetation gradually enters the dormant season, while the groundwater system switches to a rain-fed recharge state.

The 20-months long high-speed video sequence of the seasonal pulse of the WEC is representative of nearly two decades of environmental monitoring and hydrological processes research in this catchment. For example, experimental data from a network of 36 wells and seven piezometers installed in the riparian zone revealed the complex interplay between the creek and groundwater in response to precipitation events across wet and dry hydrologic conditions (Bonanno et al., 2021). The contrasting groundwater responses to rainfall in dry, intermediate, and wet conditions are controlled by a decrease in storage capacity with fractured bedrock and/or saprolite depth (with additional roles of precipitation depth and intensity). During dry conditions (e.g., August and September 2021 [start 00:40–end 00:47], July 2022 [start 01:14–end 01:17]), groundwater levels are low, and the direction of groundwater flow is typically controlled by the large anisotropy in hydraulic conductivity that characterizes the fractured bedrock. With increasing wetness, near-stream groundwater levels rise, and flow directions are controlled by the competing influence of upslope-footslope connectivity and streamwater levels (e.g., July 2021 [start 00:37–end 00:40]). During wet hydrologic conditions (e.g., November 2021 [start 00:49–end 00:53]), when hillslope-stream connectivity is restored, the hyporheic zone is compressed by water movement from the hillslope towards the stream, and advection and in-stream turbulences become the primary mechanisms controlling water movement and storage within the stream channel (Bonanno et al., 2022, 2023). The observed exchange of stream water with the adjacent groundwater has significant implications also for solute and nutrient transport within the stream reach (Bonanno et al., 2023).

Leaf abscission (e.g., October 2021 [start 00:46–end 00:49]) and the subsequent litter degradation significantly contribute to the stock

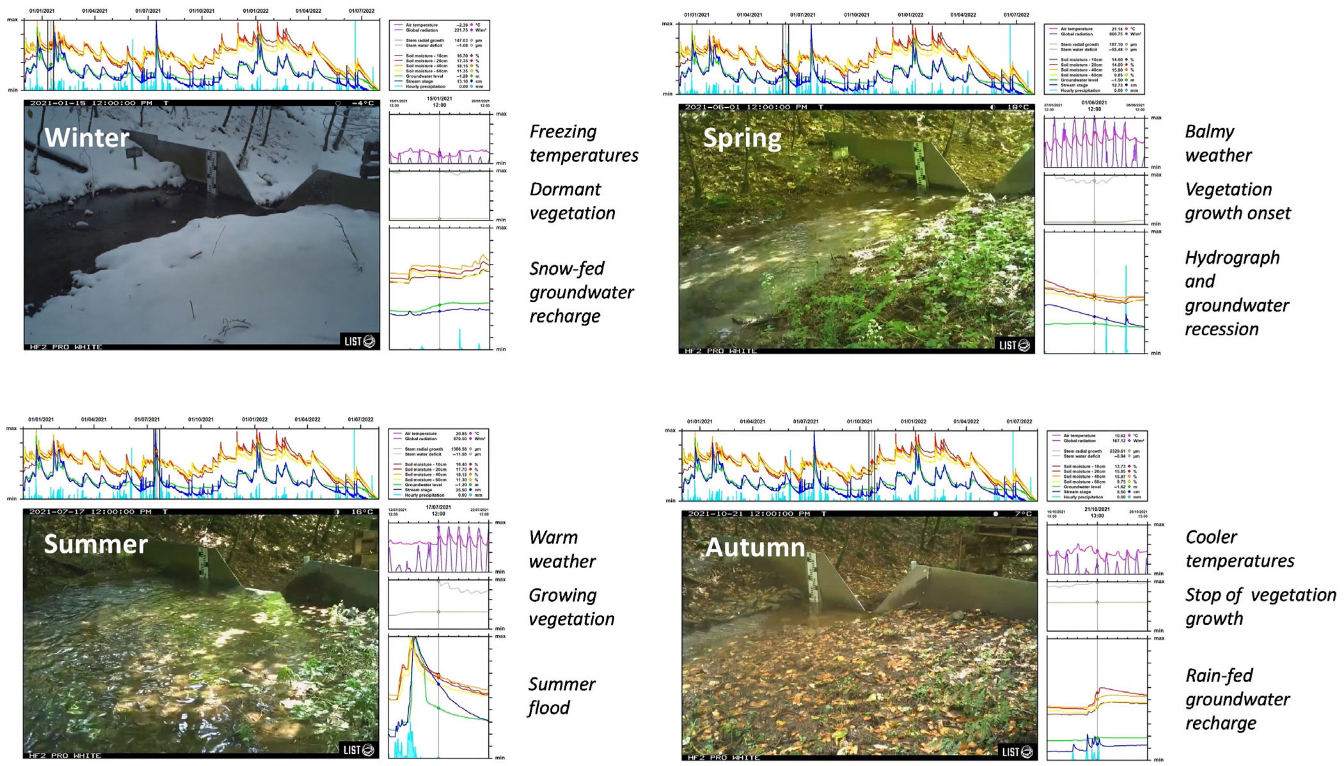

FIGURE 1 Screenshots representative of contrasting hydrological states in the Weierbach catchment during winter, spring, summer, and autumn seasons. For each picture are shown: (i) full record of hydro-meteorological recordings from December 2020 to July 2022 (top graph), (ii) 10-day windows of recorded air temperature and global radiation (upper right graph), stem radial growth and stem water deficit (centre right graph), soil moisture at different depths, groundwater level, stream levels and precipitation (bottom right graph), (iii) vertical lines in graphs indicating the exact time when the picture was taken and (iv) measurements made by the different sensors at the exact time when the picture was taken (top right box).

of nutrients available to trees in the riparian zone and are regulated by various biotic and abiotic factors—such as the community of decomposing organisms, precipitation, incident light, and temperature (Montemagno et al., 2022; Tagliavini et al., 2007).

3.2 | Sequence 2—Time-lapse videos of pictures taken every 15 min showing hydrological processes in the Weierbach creek

3.2.1 | Scene 2.1. Mechanistic fundamentals of the flood hydrograph generation

The sub-scene 2.1.a, spanning from 12th to 20th March 2021 [start 07:48–end 08:19], is an almost perfect illustration of the occurrence of a so-called double-peak hydrograph in the Weierbach creek (Figure 2). A first discharge peak (loaded with sediment as can be inferred from the brownish colour of the water) coincides with the precipitation event, while several hours and even days later a second broader, delayed peak (with negligible sediment load, as suggested by the now almost transparent water) is observed.

Double peak hydrographs regularly occur in the WEC during wet conditions, when catchment storage has reached the threshold required for connectivity between near-stream and upslope locations. This behaviour is apparent in the almost simultaneous response of soil moisture and groundwater levels (Martínez-Carreras, Hissler, et al., 2016). During double peak hydrographs, catchment storage first increases and subsequently leads to a delayed second peak (Martínez-Carreras, Hissler, et al., 2016). Single peak events occur during dry conditions by water quickly flowing to the stream during precipitation pulses.

The sub-scene 2.1.b, spanning from 14th to 15th July 2021 [start 16:02–end 16:08], nicely illustrates that sediment transport in the Weierbach mainly occurs during first or single discharge peaks, when mobilization of channel bed sediments or sediment originating from near the stream and highly enriched in organic matter occurs (Martínez-Carreras, Schwab, et al., 2016). Suspended sediment concentrations are much lower during delayed peaks because they are dominated by delayed contributions from subsurface flow and/or groundwater.

Time-lapse photography suggests the potential use of the images to infer suspended sediment concentrations from the colour of the

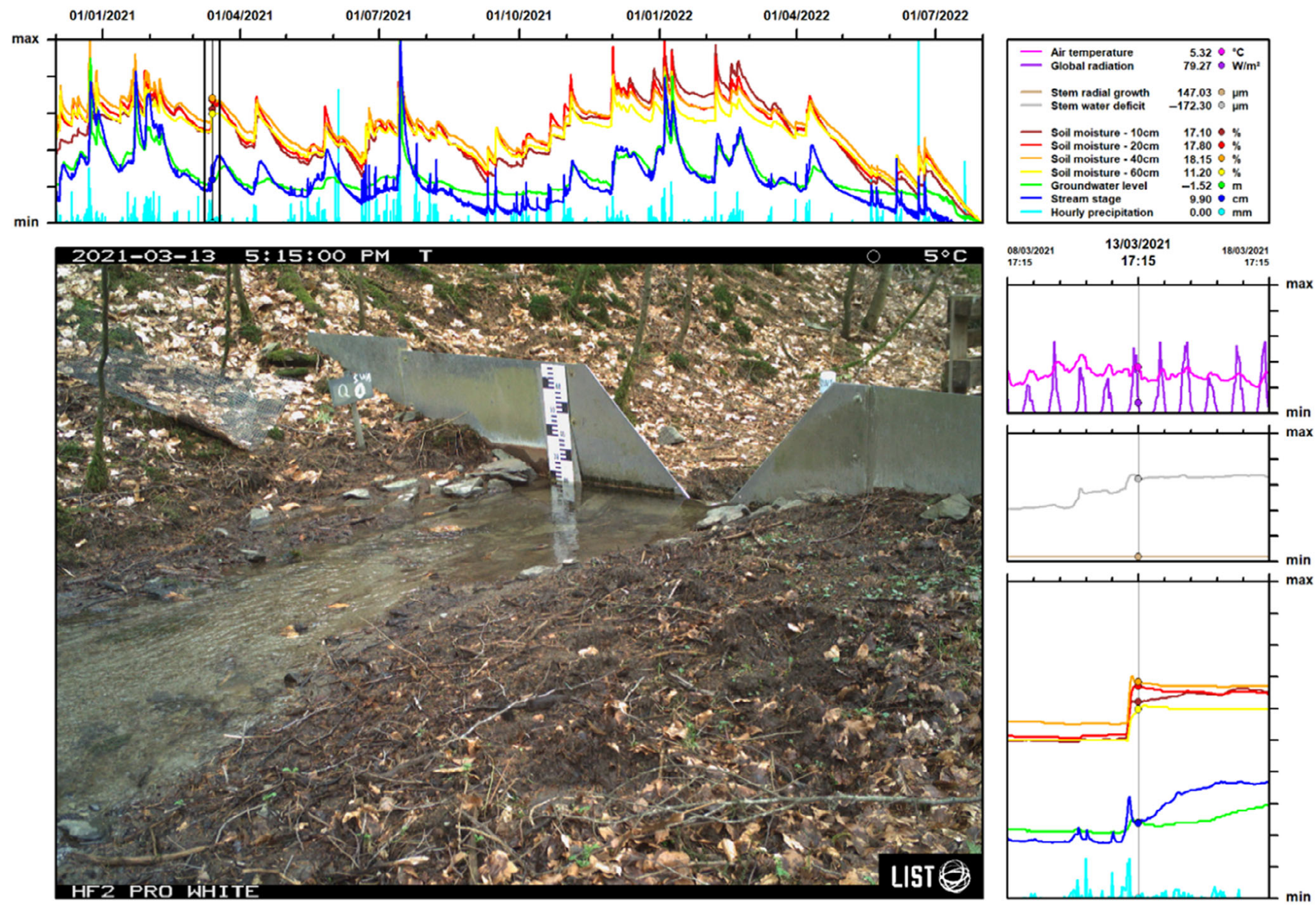

FIGURE 2 Screenshot of the video showing the picture of the Weierbach taken at 17:15 on 13th March 2021. Legend for plots with full and 10-day records of hydro-meteorological recordings identical to Figure 1.

stream surface, as recently described by Ghorbani et al. (2020). Along similar lines, sediment colour observed in the time-lapse photography may inform on changes in sediment composition (e.g., organic matter content) and origin (e.g., Martínez-Carreras et al., 2010) during runoff events.

3.2.2 | Scene 2.2. Hydrograph baseflow recession periods

In summer, the Weierbach creek frequently undergoes phases of pronounced low flows and occasionally runs dry. During such extreme conditions, the links between abiotic diurnal signals in groundwater levels or discharge, and biotic signals, such as tree water uptake, become clearly apparent (Figure 3).

As shown in sub-scene 2.2.a (7th June to 27th June 2021 [start 13:36–end 14:55]), daily minima of discharge in the Weierbach typically occur in the afternoon of summer dry periods, following a peak in evapotranspiration—also expressed in tree stem water deficit recordings. Even during zero flow conditions that occurred during the growing season of July 2022, diel fluctuations were still recorded in the groundwater table beneath the streambed [start 38:47–end 41:10]. This groundwater table behaviour is linked to the water uptake by riparian vegetation, mainly consisting of trees (Bonanno et al., 2021): alders—a species that thrives in wet areas—and beeches in the near-stream domain. As a result, certain sections of the stream can undergo daily transitions between gaining and losing conditions in relation to the adjacent groundwater, depending on the antecedent conditions and the evapotranspiration of the trees in the riparian zone. Diel fluctuations in discharge have been observed in many streams and are typically attributed to the daily cycle of evapotranspiration (Wondzell et al., 2007).

The video also reveals rhythmic leaf movements of the herbaceous plants near the stream bed (sub-scene 2.2.b, from 27th May 2021 to 14th July 2021 [start 12:52–end 13:35]), which are unlikely to be triggered by environmental drivers and are consistent with circadian leaf movements driven by an internal, genetic clock that have been documented in a range of plant species (Müller & Jiménez-Gómez, 2016). An exception is the lowering of leaves during rainfall (e.g., on 22nd June 2021 from 7:30 onwards [start 13:36–end 14:55]), which is obviously triggered by environmental conditions (e.g., wind blasts, kinetic energy of precipitation). These are very different from diurnal variations in leaf and stem thickness, which reach minima in the late afternoon and maxima at night because of plant water stress

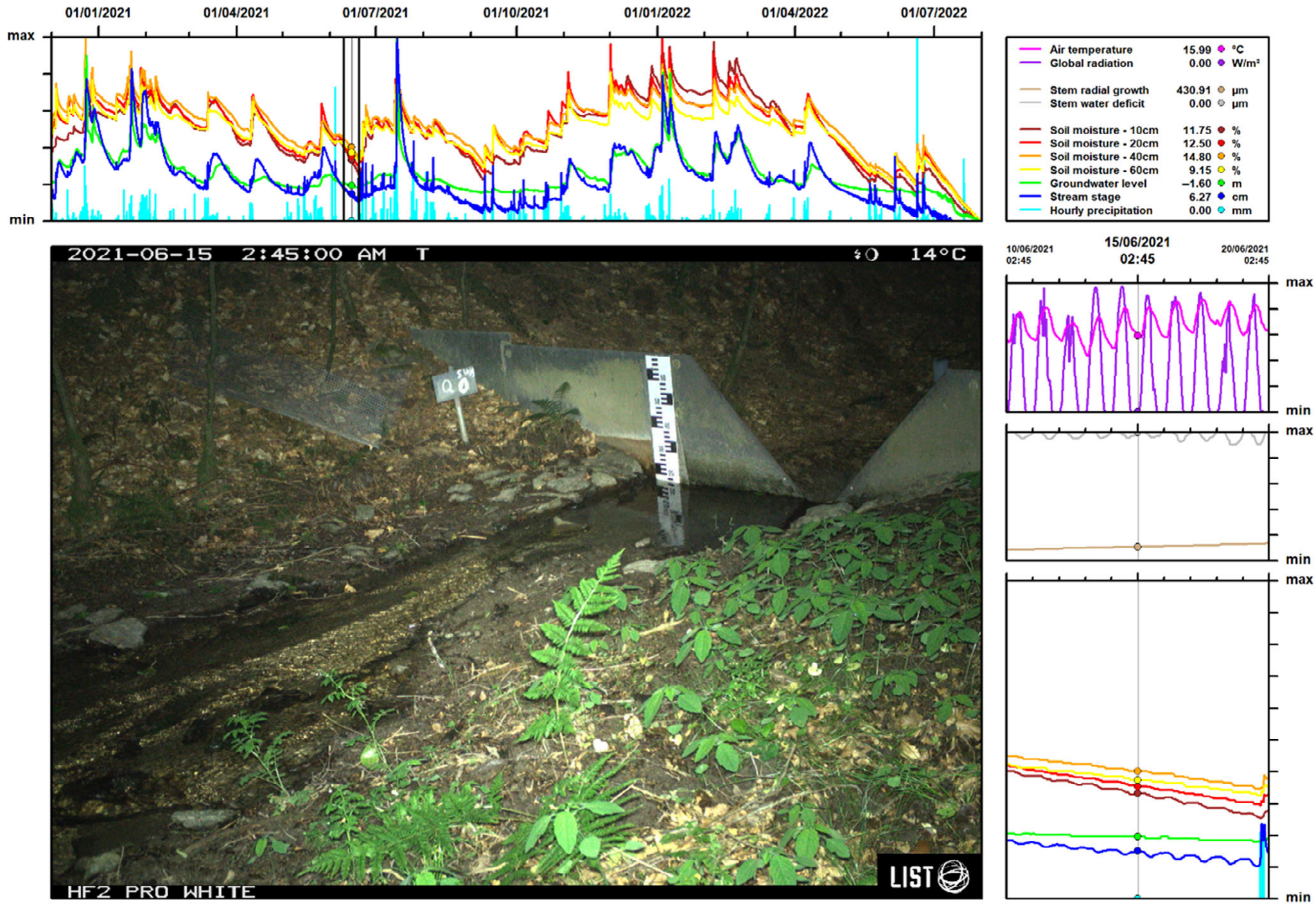

FIGURE 3 Screenshot of the video showing the frame of the Weierbach taken at 02:45 on 15th June 2021. Legend for plots with full and 10-day records of hydro-meteorological recordings identical to Figure 1.

(Zweifel & Häsler, 2001). The dynamics of sunflecks moving on the forest floor (sub-scene 2.2.c, from 10th to 20th June 2022 [start 38:07–end 38:46]) are an example of the exposition of individual plant leaves to sudden heat and water stress (Schymanski et al., 2013).

Diurnal fluctuations in the water budget are linked to water use patterns of trees. The tree water deficit (μm) (TWD) of a spruce tree located in the Weierbach catchment has been monitored using a band dendrometer. The TWD, i.e., the difference between tree radius at full hydration and the current radius (Zweifel, 2016), increases during the day (e.g., from 7th June 2021 to 27th June 2021 [start 13:36–end 14:55]) because of progressive water depletion of the elastic tissues (Dietrich et al., 2018). When transpiration ceases at night, the rehydration of xylem tissues due to root water uptake causes re-expansion of the tree diameter and the TWD decreases. The observed fluctuation in xylem moisture content at the seasonal scale in the Weierbach catchment (Fabiani et al., 2022) confirms the relevance of stem water storage, which mediates between the transpiration demand and the actual water availability.

Note that during recession periods in the dormant season, we observed day-time maxima in discharge (sub-scene 2.2.d, spanning from 15th to 30th April 2021 [start 10:03–end 11:02]), as opposed to the day-time minima during the active season described above (Figure 4). This diurnal signal in discharge can be explained by the daily fluctuation in water temperature in the upper layer of the riparian zone (Schwab et al., 2016). During the day, higher air temperature eventually warms the soil water, which in turn leads to a reduction in viscosity and an increase in hydraulic conductivity. Diurnal signals such as this can sometimes also result from temperature effects on instrumentation, and the video evidence here thus helps eliminate false interpretation of fluctuating water level data.

3.2.3 | Scene 2.3. Freeze–thaw cycles

In winter months, at times of prolonged phases of below-freezing ground temperatures, the sediments in the riparian zone of the Weierbach can undergo significant swelling. We observed several periods during which needle ice formed in the soft sediments adjacent to the stream (sub-scene 2.3.a, from 5th to 20th January 2021 [start 03:24–end 04:23], sub-scene 2.3.b from 7th to 15th February 2021 [start 05:36–end 06:07]). These events typically occur during dry and cold

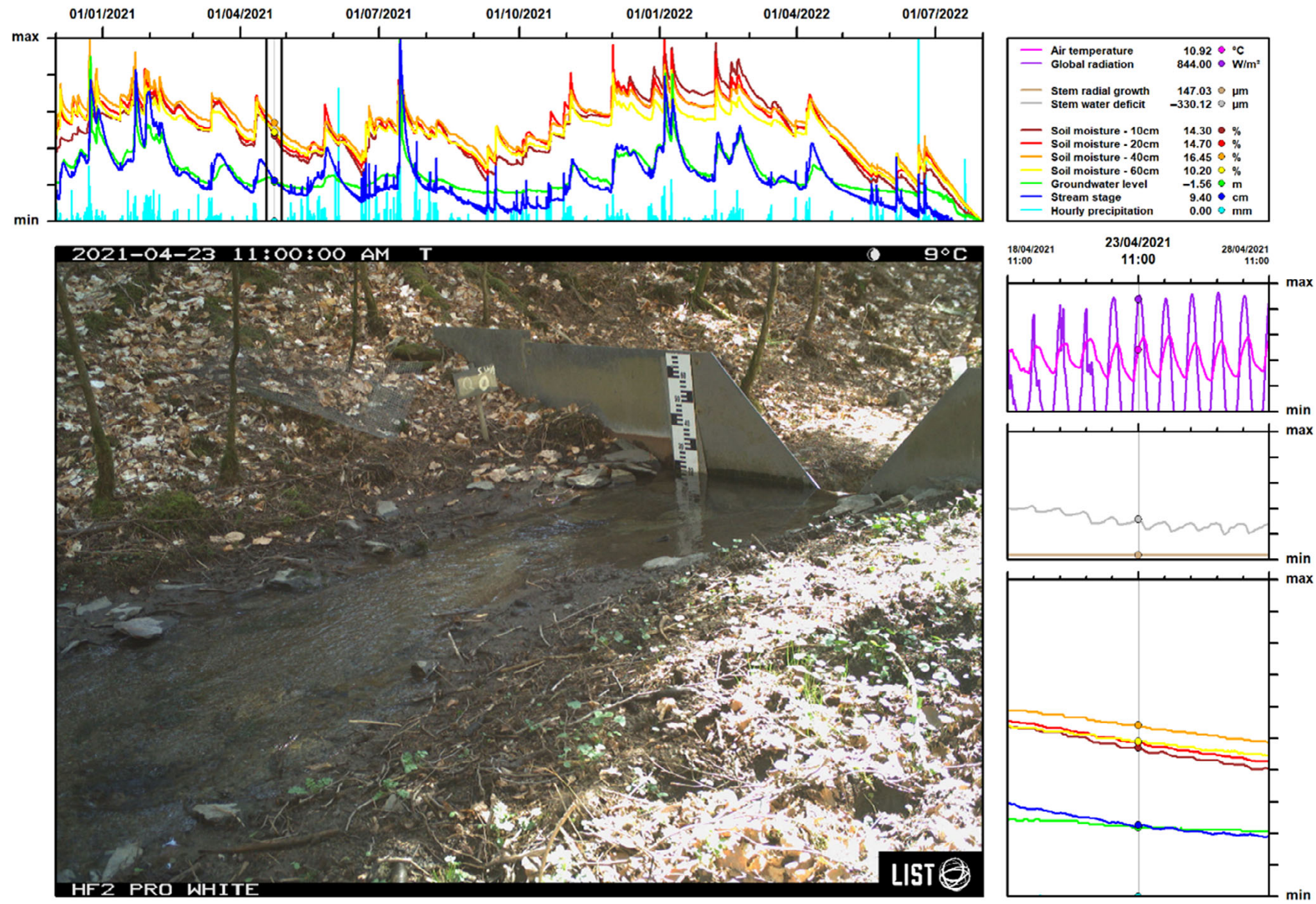

FIGURE 4 Screenshot of the video showing the frame of the Weierbach taken at 11:00 on 23rd April 2021. Legend for plots with full and 10-day records of hydro-meteorological recordings identical to Figure 1.

spells, as suggested by the observed hydrograph and groundwater level recessions (Figure 5). Because of needle ice formation, riparian soils could eventually rise by nearly 10 cm. This phenomenon occurs by ice forming as water is drawn through soil pores, and thus requires specific soil texture and moisture content as well as specific temperatures (Outcalt, 1971). Needle ice forms from below the soil surface and disturbs it, greatly increasing the sediment availability for subsequent fluvial transport (Lawler, 1993) and potentially even uprooting plants (Lawler, 1988).

4 | CONCLUDING REMARKS

For nearly two decades, the Weierbach catchment has been undergoing extensive field monitoring campaigns, alongside more and more sophisticated and high-resolution environmental sensing programmes. Altogether, these initiatives have contributed to substantially improve our understanding of the processes involved in the Weierbach's fundamental hydrological functions of water and matter collection, storage, mixing and release. While we improved step by step our perceptual model of the catchment's *modus operandi* (e.g., Hissler et al., 2021; Martínez-Carreras, Hissler, et al., 2016; Pfister et al., 2017; Wrede et al., 2015) our understanding of how the associated processes evolve and potentially co-evolve over the seasons, and even into longer time spans (for example, in response to climate change), remains fragmented. In other words, while adding and arranging the puzzle pieces, we found a much more complex picture of the eco-hydrological functioning of the Weierbach catchment than we had anticipated. Consequently, we do not yet have a fully-fledged eco-hydrological model that can simulate the complex interplay of the manifold biotic and abiotic factors at work.

While individual sensors may provide very detailed information on the onset and cessation of certain processes, we lack understanding on how and when they may influence other processes of importance. The high-speed playback of thousands of images taken every 15 min—spanning very contrasted seasons and catchment wetness states—provides entirely new vistas in this respect. Certain processes may become visible that may otherwise have been overlooked, especially when not monitored with a dedicated set of sensors (and operated at a very specific resolution). Therefore, such an alternative source of information may eventually become the starting point for a new cycle of hypothesis framing and testing. The freeze–thaw cycle is

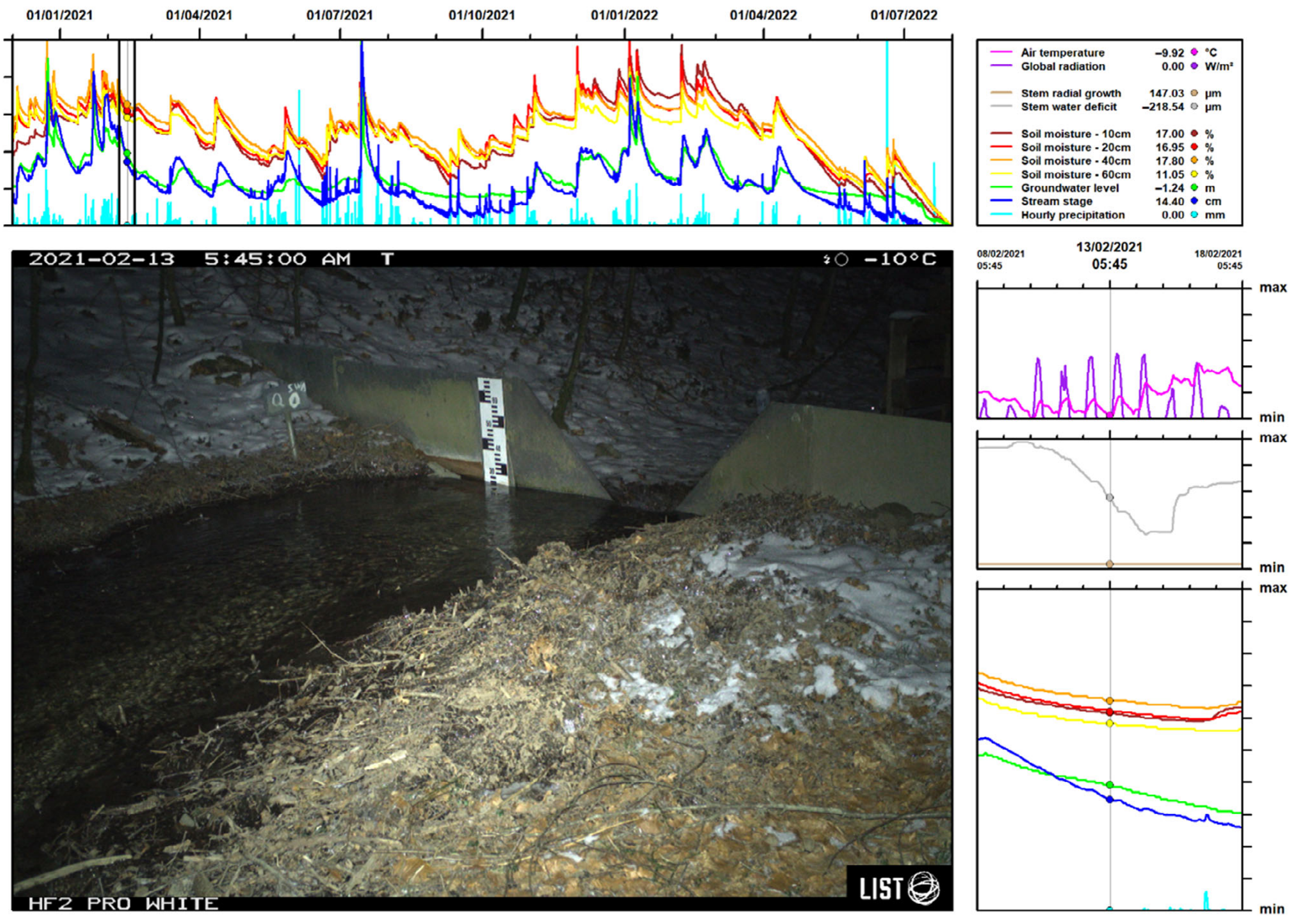

FIGURE 5 Screenshot of the video showing the frame of the Weierbach taken at 05:45 on 13th February 2021. Legend for plots with full and 10-day records of hydro-meteorological recordings identical to Figure 1.

a telling example in this regard, demonstrating how cameras deployed in a catchment may eventually complement our field sensors, alongside the (largely underrated and underused) scientists' human sensory and cognitive aptitudes (Van Stan et al., 2023). Finally, the time-lapse videos are a highly useful source of information for checking sensor readings in the validation process of recorded environmental datasets.

The combination of a four-season-long time-lapse sequence of the pulse of the Weierbach with a high-frequency multi-parameter dataset is ultimately offering a new perspective for 'bringing it all together' (Dooge, 2005)—providing an innovative opportunity for combining 'soft' and 'hard' data and improving in the process the dialogue between hydrologists and ecophysiologists (Cocozza & Penna, 2022), as well as between experimentalists and modellers (Seibert & McDonnell, 2002). As we plan to continue filming the Weierbach in the coming years, we believe the time-lapse imagery of this headwater creek to be a 'terminus a quo' for gaining a comprehensive understanding of 'catchment framing'—as achieved via the interplay of geomorphological processes, biota, and anthropogenic activities (e.g., forest management). These findings may ultimately pave the way for new plasticity and optimality-based models of catchment evolution and dynamics. The latter considering and accounting for the intrinsic non-stationary (or non-rigid) character of our catchments—as a prerequisite for reducing uncertainties in the assessment of future catchment trajectories under a changed climate.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in The Weierbach Experimental Catchment (WEC) at https://doi.org/10.5281/zenodo.4537700.

ORCID

Laurent Pfister https://orcid.org/0000-0001-5494-5753
Enrico Bonanno https://orcid.org/0000-0002-8604-456X
Ginevra Fabiani https://orcid.org/0000-0002-1977-6285
Laurent Gourdol https://orcid.org/0000-0001-5472-4942
Christophe Hissler https://orcid.org/0000-0001-9663-2042
Jean François Iffly https://orcid.org/0000-0002-1413-7863
Richard Keim https://orcid.org/0000-0003-4488-9537
Núria Martínez-Carreras https://orcid.org/0000-0003-2860-4941
Xavier Mestdagh https://orcid.org/0000-0001-7270-8997
Alessandro Montemagno https://orcid.org/0000-0003-1636-3589
Daniele Penna https://orcid.org/0000-0001-6915-0697
Stanislaus Schymanski https://orcid.org/0000-0002-0950-2942
Erwin Zehe https://orcid.org/0000-0003-0155-7276

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How to cite this article: Pfister, L., Bonanno, E., Fabiani, G., Gourdol, L., Hissler, C., Huck, V., Iffly, J. F., Keim, R., Martínez-Carreras, N., Mestdagh, X., Montemagno, A., Penna, D., Schymanski, S., & Zehe, E. (2023). Fast motion view of a headwater creek—A hydrological year seen through time-lapse photography. *Hydrological Processes*, *37*(11), e15026. https://doi.org/10.1002/hyp.15026